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AERODYNAMICS OF THE MI-4 HELICOPTER

by

M. S. Yatsunovich

371

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AERODYNAMICS OF THE MI-4 HELICOPTER

By: M. S. Yatsunovich

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ABSTRACT

(U) This book is intended for students in civil aviation educational institutions as a textbook. It is also useful for flight-technical personnel in civil aviation. In this book is described the aerodynamics of single-rotor helicopters, and the practical aerodynamics of the Mi-4 helicopter are analyzed. The rotor is analyzed in detail as well as flight conditions and other aerodynamic characteristics.

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U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}
rot	curl
lg	log

ANNOTATION

In the book the principles of aerodynamics of a single-rotor helicopter are discussed, and on their bases the practical aerodynamics of the Mi-4 helicopter is analyzed. In it there are examined in detail aerodynamics of the rotor, flight conditions of the helicopter, and also questions of balancing, controllability and aerodynamic stability of the helicopter in flight; ground resonance, conditions of the vortex ring, separation of flow, flutter of blades and other characteristic phenomena explaining the causes of flight limitations of the Mi-4 helicopter and enabling piloting it safely and competently are examined.

The book is intended as a training manual for students and audiences of educational institutions of civil aviation. It can be used in the flying and engineering-technical composition of operational subdivisions of civil aviation.

The author is grateful to candidates of technical sciences A. Yu. Liss, V. I. Nikiforov, G. P. Drobyshevskiy, K. M. Rykhlov, V. A. Yevdokimov, N. V. Chernov, and N. A. Tikhonov for their valuable recommendations in the review of the manuscript and for the practical help rendered in the work.

INTRODUCTION

Any aircraft possesses definite basic properties only inherent to it. Such properties of the helicopter are the following:

1) possibility to take off and to land vertically and to hang motionlessly at any altitude up to its ceiling of hovering;

2) ability to fly with forward velocity from zero to highest possible;

3) possibility to climb and descend with any flight-path angle to the horizon;

4) possibility to accomplish maneuvers in air when stationary and in motion;

5) ability to lift loads within limits of its load capacity;

6) ability to accomplish safe gliding in autorotation of the rotor.

A helicopter cannot have great forward velocity, and therefore it does not displace the aircraft but only supplements it, i.e., fills the speed range from minimum to zero inaccessible to aircraft. Furthermore, helicopters as yet have a short flying range and low economy.

To increase the speed and flying range and to increase the economy, at present helicopters with gas-turbine engines are used. Further improvement of characteristics of the given type of flying machines proceeds along lines of the creation of winged, combined helicopters and helicopters with stiffening of blades of the rotor.

Helicopter Mi-4 (Fig. 1) is a single-rotor wingless aircraft with rotor drive from an ASh-82V reciprocating engine through normal rigid transmission. Balancing of the reactive moment of the rotor and also the directional control of the helicopter are carried out with the help of the tail rotor. Blades of the rotor are fastened to the hub with the help of flapping, drag, and feathering hinges.

The Mi-4 helicopter has been successfully operational since 1952 both in the Soviet Union and in other countries. Earlier it was produced in a transport version for transporting passengers and cargoes and also for transporting sick persons in a lying position.

Fig. 1. Mi-4 helicopter.

A modification of transport variant Mi-4 is the Mi-4A helicopter with considerable design changes, improving its operational characteristics. It is used in transport, medical, and rescue versions.

Mi-4P helicopter is a further modification of the Mi-4A helicopter. It has a comfortable passenger cabin and can transport

10-13 passengers.

On the helicopters of the transport and rescue variants, besides the transportation of cargoes, inside the cabin the possibility is provided for transporting cargoes of large dimension on external suspension. The presence of the external suspension considerably expands the region of application of the Mi-4 helicopter in the national economy.

Since 1960 blades of all-metal construction have been mass produced. Helicopters with all-metal blades of the rotor possess the best flying characteristics and great reliability.

CHAPTER I

PRINCIPLE OF CONTROL OF A SINGLE-ROTOR HELICOPTER IN FLIGHT

For a helicopter, as for any aircraft, the following aerodynamic problems must be solved: a) the helicopter should have lift for the balancing of its weight; b) the helicopter should have tractive force for advancing forward and surmounting the force of air drag; c) the helicopter should be balanced in a steady state of flight, be well controlled, i.e., revolve around its axes on the desire of the pilot for changing conditions of flight, and possess properties of stability – independently restoring equilibrium after cessation of the action of forces causing this disturbance.

For the aircraft the propulsion system creates a tractive force, which imports to it motion surmounting drag. The wing of an aircraft, interacting with air, creates lift, which balances the weight of the aircraft (Fig. 2a). Furthermore, an aircraft having a definite form of fuselage, wings and empennage is well balanced in the steady state of flight, is well controlled owing to the great distance of all controls from the center of gravity and possesses good stability.

The blade of the rotor of the helicopter, interacting with the air, creates an aerodynamic force according to the same laws as those of the wing of an aircraft. In vertical flight conditions the thrust of the rotor T is directed vertically upwards. On hovering conditions it is equal to the weight of the helicopter G (Fig. 2b). If the thrust is increased, not changing its direction, the helicopter will accomplish vertical climb, but if one were to decrease the thrust, then the helicopter will accomplish vertical lowering. With a change in

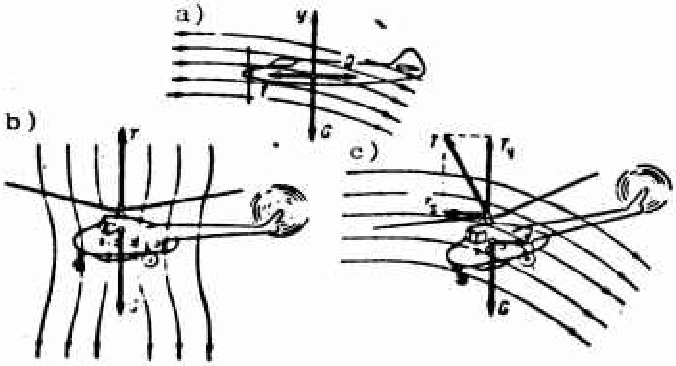

Fig. 2. Schematic diagram of the flight of an aircraft and helicopter: a) steady flight of an aircraft; b) hovering conditions of a helicopter; c) conditions of horizontal flight of a helicopter.

direction of the rotor thrust to a desirable side of the flight, the vertical component T_y will be lift and it will balance the weight of the helicopter G, and the horizontal component T_x will create motion in the direction of the flight, surmounting drag of the helicopter Q (Fig. 2c). Thus, the rotor of the helicopter replaces the wing and tractor propeller of an aircraft.

At the same time with the help of a rotor it is possible to control the helicopter in longitudinal and transverse directions. When the helicopter is in conditions of hovering, its center of gravity [cg] (Ц.Т.) is disposed approximately under the rotor thrust of T (Fig. 3a). If the direction of tractive force is deflected from the vertical forward, then between the center of gravity and direction of the force there will be formed arm ℓ, and the moment will appear rotating the helicopter around the lateral axis on diving (Fig. 3b). The helicopter will move forward. If the direction of thrust is deflected back, then there will appear a positive pitching moment, and the helicopter will move back. By the same method it is possible to force the helicopter to move to the left and to the right (Fig. 3c, d).

Consequently, the rotor replaces not only the wing and propeller, but also controls of altitude and ailerons of the aircraft. Directional control for a single-rotor helicopter is carried out with the help of a tail (steering) rotor.

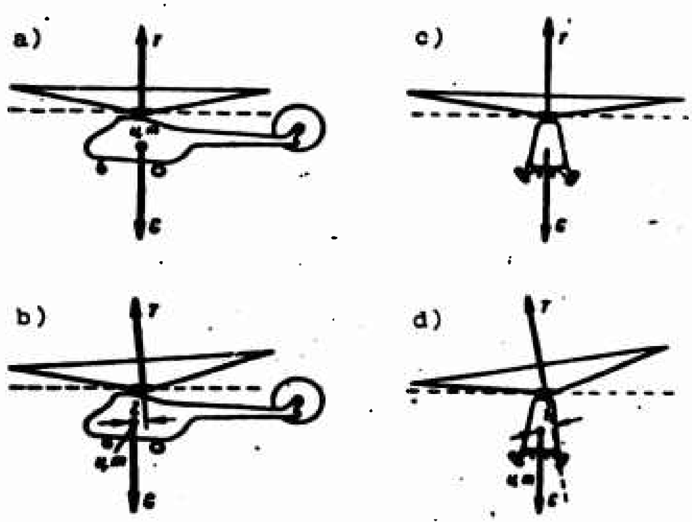

Fig. 3. Principle of control of a helicopter with the help of a rotor: a) hovering conditions (side view); b) flight forward; c) conditions of hovering (view from behind); d) flight to the left.

§ 1. Control of the Lifting System

Rotor consists of a hub and blades. Each blade is fastened to the hub with the help of three hinges: flapping [GSh] (ГШ), drag [VSh] (ВШ), and feathering [OSh] (ОШ). Revolving around the flapping hinge, the blade can move in a vertical plane, i.e., accomplish flapping. Revolving around the drag hinge, the blade accomplishes oscillations in the plane of rotation, and revolving around the feathering hinge the blade can change the setting angles (angle between the plane of rotation and chord of the blade). Flapping and drag hinges have limiters, each having them on two sides. The definite position of the blade on the feathering hinge is maintained by the cyclic pitch control (Fig. 4) through the thrust of the setting angle control. The body of the rotor hub has in the center a hole with slits by which it is put on the shaft of the main reduction gear and is centered by two cone rings. The rotor is controlled with the help of a cyclic pitch control located under the rotor hub.

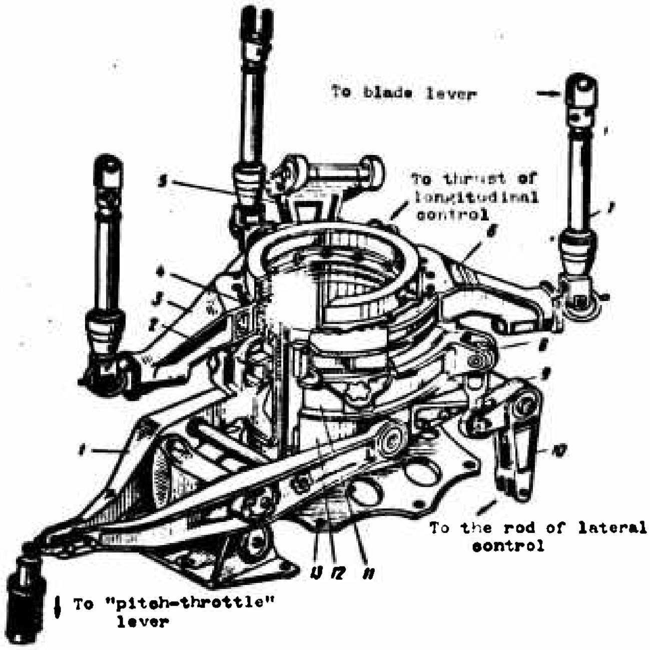

Fig. 4. Cyclic pitch control: 1 – control lever of collective pitch; 2 – internal ring of Cardan joint; 3 – lever of plate of cyclic pitch control; 4 – ball bearing of the plate; 5 – guide of the plate of cyclic pitch control (torgue arm); 6 – plate of cyclic pitch control; 7 – rod of the control of blade pitch; 8 – lug of lateral control; 9 – rod of lateral control; 10 – rocker of lateral control; 11 – external ring of cardan joint; 12 – slider of cyclic pitch control; 13 – slider.

The cyclic pitch-control mechanism consists of a guide of the slider 13, slider 12, plate 6 of the cyclic pitch control with levers 3, lever of collective pitch 1, rockers of pitch (seen on the figure) and lateral control 10, rods of pitch (not seen on the figure) and lateral control 9, rods of the control of blade pitch 7, and plate guide of the cyclic pitch control (torque arm) 5.

The guide of the slider 13 constitutes a hollow smooth steel cylinder fastened with the help of a flange to the crankcase of the main reduction gear. Inside the guide the shaft of the reduction gear passes. Moving along the guide of the slider up and down is slider 12, which constitutes a steel cylinder. On the upper part of the slider there is assembled a universal joint (Cardan joint), which consists of two rings: internal 2 and external 11. The internal ring of the Cardan joint is connected with the slider by two hinged pins through ball bearings. Similarly the external ring of the Cardan joint is fastened to the internal. Here the common axis of the fingers connecting the internal ring of the Cardan joint with the slider is located perpendicular to the common axis of fingers connecting the internal ring of the Cardan joint with the external. With such connection the external ring of the Cardan joint is connected with the slider by a universal joint, owing to which deflections of the external ring of the Cardan joint are possible in all directions, and together with it plate 6 of the cyclic pitch control, since it is set on the upper part of the external ring of the Cardan joint with the help of a two-row ball bearing 4. Fastened to the plate of the cyclic pitch control are four levers 3, to which four rods 7 are joined, and they, in turn, are connected by the other ends with levers of the blades. The plate of the cyclic pitch control is united with the hub of the rotor by means of the guide of plate 5 and revolves together with the rotor. The remaining parts of the cyclic pitch control do not revolve.

On the external side near the slider in its lower part there are two coaxial pins. One end of the lever of collective pitch 1 is joined to these pins. The second end of the lever of collective pitch is connected through a system of rods, rockers, and hydraulic boosters with the "pitch-throttle" lever located in the cockpit. Fastened to the slider in its lower parts are two brackets, on which hinged rockers of longitudinal and lateral control 10 are assembled. Some ends of these rockers are connected by rods 9 with lugs 8, available on the external ring of the Cardan joint (the lug of longitudinal control on the figure is not seen) and other ends through the system of rods, rockers, and hydraulic boosters – with the control handle located in the cockpit.

With the help of the cyclic pitch control the rotor is controlled in the following way (Fig. 5). With movement of the "pitch-throttle" lever 4 upwards the control lever by collective pitch 11 lifts the slider and together with it, the plate of the cyclic pitch control upwards. Levers of the plate through the rods act on levers of the blade 17, increasing the setting angle of each blade by the same value, i.e., collective pitch of the rotor is increased. With movement of the "pitch-throttle" lever downwards the collective pitch decreases.

With deflection of the control stick (cyclical pitch) 3 to any side this motion is transmitted through the rockers of longitudinal and lateral control 8 and 19 to the external ring of the Cardan joint and, consequently, to the plate of the cyclic pitch control. The latter is inclined together with the external ring. At the place along the circle where the inclined plate will have the highest point, the blade will have the greatest setting angle (pitch) and where the lowest – the least setting angle. During rotation of the rotor the value of the blade setting angle is changed from maximum to minimum and from minimum to maximum.

The full cycle of change of the setting angle will pass after one revolution, and therefore such a change in pitch is called cyclical.

The rotor of the Mi-4 helicopter has a counterclockwise rotation when observing from the cockpit. The position of the blade along the circle is determined in degrees of azimuth in rotation, taking for zero the position of the blades above the tail boom. The change in the setting angle of the blade ϕ after one turn occurs according to the law of sines (Fig. 6). The more the control stick is deflected, the greater the difference will be in the value of the setting angles, and the greater amplitude will be of the sinusoid.

There is full independence of the control of the collective and cyclical change of pitch of the rotor, i.e., a cyclical change in pitch with the help of deflection of the control stick does not hinder changing the collective pitch with the help of the "pitch-throttle" lever, and a change of collective pitch is not reflected on

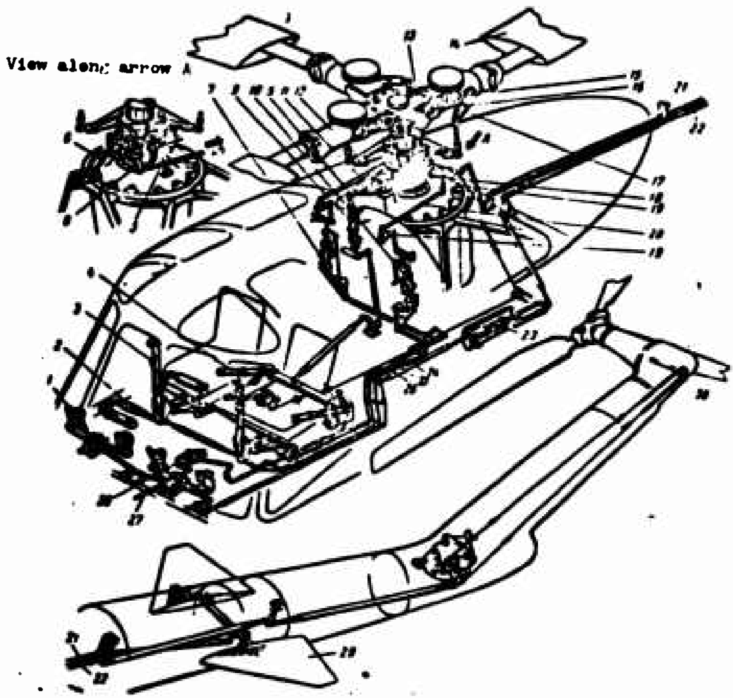

Fig. 5. Diagram of the control of the Mi-4 helicopter: 1 — pedals; 2 — spring loading mechanism; 3 — control stick; 4 — "pitch-throttle" lever; 5 — rod of longitudinal control; 6 — rod of the connection of the stabilizer control with the collective pitch control; 7 — hydraulic booster of longitudinal control; 8 — rocker of pitch control; 9 — hydraulic booster of collective pitch control; 10 — hydraulic booster of lateral control; 11 — collective pitch control lever; 12 — axial (feathering) hinge of the blade; 13 — rotor hub; 14 — blade of rotor; 15 — drag hinge of the blade; 16 — flapping hinge of the blade; 17 — blade lever; 18 — cyclic pitch-control mechanism; 19 — rocker of lateral control; 20 — rod of lateral control; 21 — rod of stabilizer control; 22 — rod of the control of tail rotor pitch; 23 — hydraulic booster of foot control; 24 — rod of foot control; 25 — rod of pitch control; 26 — rod of lateral control; 27 — rod of engine throttle control; 28 — cam mechanism of the control of the engine throttle; 29 — stabilizer; 30 — sprocket wheel of the control of the tail rotor pitch.

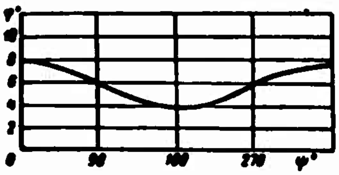

Fig. 6. Curve of the change of setting angle of the rotor blades.

the magnitude of cyclical pitch. Such an independence of control is attained owing to the articulated joint of rods of longitudinal and lateral control 5 and 20 (See Fig. 5) with rockers of longitudinal and lateral control 8 and 19. The design of the plate guide of the cyclic pitch control permits the rotor hub to drive the plate and does not hinder it in occupying any position in height and slope.

The collective pitch control of rotor is united with the engine throttle control through rod 27 and cam mechanism 28 by this principle: if one were to turn the handle of the gas corrector, then only the position of the engine throttle is changed; if one were to deflect the "pitch-throttle" lever, then the collective rotor pitch and position of the throttle will be changed. At the same time the collective pitch control of the rotor is united with the control of the setting angle of the stabilizer according to this principle: with movement of the "pitch-throttle" lever downwards the setting angle of the stabilizer decreases, and with movement upwards upwards it is increased. Such blocking is necessary to increase the reserve of control in all flight conditions and to improve the transition of the rotor to conditions of autorotation.

§ 2. Principle of Flight of the Helicopter

Having clarified the fundamental arrangement of the rotor of the cyclic pitch control of the helicopter and their joint kinematics with a change in collective and cyclical pitch, let us examine the principle of vertical conditions of flight and flight with forward velocity.

In conditions of hovering the blades, having flapping hinges, will form a cone of rotation. The total aerodynamic force of the rotor is perpendicular to the base of the cone. The essence of conditions of hovering is that the pilot, using the "pitch-throttle" lever with a completely introduced gas corrector, sets such a collective pitch and power of the engine at which there is created an aerodynamic force equal to the weight of the helicopter. By the control lever the action of this force is held in a vertical direction.

Here the mass of air passing through the rotor is rejected by the rotor strictly downwards (see Fig. 2b).

The principle of vertical climb is that the pilot, from conditions of hovering, not changing the position of the gas corrector and not changing the direction of tractive force, with the "pitch-throttle" lever increases the collective pitch and power of the engine. Here the thrust of the rotor is increased, and helicopter climbs vertically.

In this case thrust was increased because through the rotor there began to pass a large quantity of air per unit of time owing to the increase in speed of the repulsing of it downwards.

To accomplish vertical descent the reverse action is necessary: with motion of the "pitch-throttle" lever downwards the pilot decreases the collective rotor pitch and power of the engine; with this the thrust of the rotor decreases, and the helicopter descends owing to its weight. The quantity of air passing through the rotor per unit of time decreased.

Consequently, in vertical flight conditions the pilot changes only the magnitude of aerodynamic force of the rotor with the help of the "pitch-throttle" lever, maintaining vertical direction of its action with the help of the control stick.

To produce forward flight it is necessary to deflect the direction of the action of aerodynamic force of the rotor from the vertical in the direction of the flight, which is done by the pilot with the help of the control stick. By deflection of the control stick the plate of the cyclic pitch control is deflected, and a cyclical change of pitch is obtained. The cyclical change of the setting angle leads to a change of lift of the blades. In turn the change in lift leads to flapping motions of blades around the flapping hinges, i.e., to a change of position of the blades with respect to the plane of rotation. At that place on the circle, where the blade has a maximum setting angle and maximum lift it will have a maximum flapping angle, but where the setting angle and lift are minimum the blade will have a minimum flapping angle. Since such flapping motion is accomplished by every blade, the cone of rotation of the rotor is deflected in the direction of the deflected control stick. The action of the aerodynamic force will be directed to that same direction, since this action is directed perpendicular to the base of the cone, i.e., along the axis of the cone. In this case the air mass will be rejected by the rotor not only downwards but also back. Flight will be accomplished in the direction of the action of the aerodynamic force (see Fig. 2c).

Greater deflection of the control stick increases the horizontal component of aerodynamic force of the rotor and flight speed of the helicopter. With deflection of the control stick only the direction of the action of aerodynamic force of the rotor is changed, since here the power of the engine does not change. The magnitude of the aerodynamic force of the rotor can be changed only by the "pitch-throttle" lever, and here the vertical component of aerodynamic force considerably changes. This means that the pilot, in maneuvering with two control levers (magnitude and direction of aerodynamic force), can set any flight conditions of the helicopter. The speed along the trajectory depends on the position of the control stick, and the vertical velocity (according to the rate-of-climb indicator) — on the position of the "pitch-throttle" lever.

For conditions of hovering it is necessary with the help of the "pitch-throttle" lever to set the thrust of the rotor equal to the weight of the helicopter and with the help of the control stick to direct it upwards. In horizontal flight the control stick sets the necessary flight speed, and the "pitch-throttle" lever so that the vertical component of thrust of the rotor balances the weight of the helicopter. For changing the speed of flight along the trajectory in any conditions, it is necessary to change the position of the control stick and by the "pitch-throttle " lever to set the desirable vertical velocity. The direction of flight in all these cases is held by means of pedals.

§ 3. Advance in Pitch-Lateral Control

Taking into account the inertia of blades of the rotor (earlier it was not taken into account) the flapping motion of blades has the following character. Upon deflection of the control stick forward the plate of the cyclic pitch control will also be deflected forward; in this case the blade, moving from an azimuthal position of $\psi = 0°$ to $\psi = 180°$, we will obtain a stroke downwards, since the setting angles and lift of it will decrease. With further motion from $\psi = 180°$ to $\psi = 360°$, although the setting angles start to be increased, the blade by inertia will continue the stroke downwards and will cease its motion in this direction, passing along the circle of about 90°, i.e., in an azimuthal position $\psi = 270°$. Inasmuch as such flapping motion will be accomplished by each blade, the cone of rotation of the rotor and direction of action of aerodynamic force is deflected into position $\psi = 270°$, i.e., the deflection of them will lag behind the deflection of the control stick and cyclic pitch control by approximately 90° in the direction of the rotor's rotation. With deflection of the control stick and cyclic pitch control forward the cone of rotation and, consequently, the direction of aerodynamic force are deflected into position $\psi = 270°$, i.e., to the right. Flight of the helicopter will occur in the same direction. Such a control diagram is shown on Fig. 7a. Here rods of pitch and lateral control are connected to the external ring of the cyclic pitch control strictly along the longitudinal and lateral axes of the helicopter, and the point, connecting the lever of the blade with the plate of the cyclic pitch control is on the longitudinal axis of the blade.

In order to force the rotation cone of the rotor and the direction of action of aerodynamic force to be deflected in the direction of deflection of the control stick, i.e., in order to surmount the inertia of the blades in their flapping motion, an advance of control is provided.

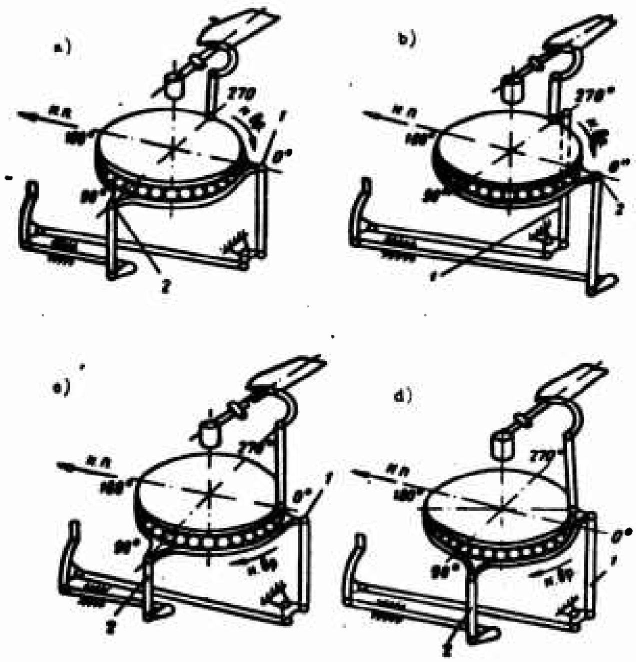

Fig. 7. Diagram of the advance of the control: a) without advance of the control; b) advance of the control of displacement of attachment points of rods of pitch and lateral control in a direction opposite the rotation of the rotor; c) advance of the control of displacement of the point of bracing of the lever of the blade with the plate of the cyclic pitch control in the rotation of the rotor; d) advance of the control of displacement of attachment points of rods of pitch and lateral control opposite the rotation of the rotor and displacement of the attachment point of the blade lever with the plate of the cyclic pitch control in the rotation of the rotor; 1 – rod of pitch control; 2 – rod of lateral control.

The advance of control can be carried out by several methods.

1. Not changing the angle between rods of the pitch and lateral control (90°), displace them in the direction opposite the rotation of the rotor by 90° (Fig. 7b). Then the rod of the pitch control will

be on the lateral axis of the helicopter and rod of lateral control — on the longitudinal axis of the helicopter. In this case upon deflection of the control stick forward, in the direction of $\psi = 180°$, the plate of the cyclic pitch control will deflect to the left — to position $\psi = 90°$, i.e., with an advance by 90°. In the azimuthal position $\psi = 90°$ the setting angle will have a minimum value, and when $\psi > 90°$ it will be increased. By inertia the blade will continue motion downwards and will cease it at position $\psi = 180°$.

The rotation cone of the rotor and the direction of action of aerodynamic force is deflected forward, i.e., in the direction of the deflected control stick. In the same direction flight of the helicopter will be carried out.

2. Leave rods of the pitch and lateral control on their axes, and displace the rod of the control of the setting angle of the blade from the axis of the blade forward in rotation of the rotor by 90° (Fig. 7c). With such a method of advance, as in the preceding method, when the blade will be in position $\psi = 90°$, it will have a minimum setting angle, since the control rod of the blade is united with the plate of the cyclic pitch control in position $\psi = 180°$.

With motion of the blade from $\psi = 90°$ to $\psi = 180°$ the setting angle will be increased, and the blade by inertia will continue the stroke downwards along the flapping hinge, and the minimum angle of the stroke will be in position $\psi = 180°$, i.e., where the control stick is deflected.

3. Displace at angles smaller than 90° attachment of rods of pitch and lateral control in the direction opposite the rotation of the rotor, and rod of control of the setting angle of the blade from its axis forward in rotation of the rotor (Fig. 7d) (such an advance scheme is provided for the Mi-4 helicopter). In the presence of such an advance of control with deflection of the control stick the cone of rotation of the rotor and direction of action of the aerodynamic force will be deflected strictly in the direction of deflection of the lever. Forward flight of the helicopter will occur in the same direction.

The plate of the cyclic pitch control will be deflected not in the direction of deflection of the lever but with a certain advance by an angle less than 90° (for the Mi-4 helicopter, 22°), which for flight has no significance.

§ 4. Decalage of the Rotor Shaft

The wing of an aircraft has a definite positive setting angle (angle between the chord of the wing and longitudinal axis of the aircraft) so that at cruising speeds of the flight the longitudinal axis of the aircraft is directed along the flight path. With this the fuselage will have minimum drag. In horizontal flight the pitch angle of the aircraft will be close to zero. At speeds less than cruising the fuselage will have a positive pitch angle and on speeds greater than cruising – a negative angle. The decalage of the rotor shaft has the same setting.

Decalage of the rotor shaft is called the angle included between the axis of the rotor shaft and vertical axis of the helicopter (Fig. 8). For the Mi-4 helicopter this angle is equal to 5°, i.e., the axis of the rotor shaft is deflected from the vertical axis of the helicopter 5° forward. If the center of gravity of the helicopter is located on the axis of the rotor shaft, then in hovering conditions the shaft will occupy a vertical position, and the pitch angle of the helicopter will have a positive value – about 5°.

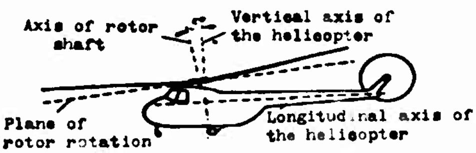

Fig. 8. Decalage of the rotor shaft.

With an increase in speed of flight owing to the deflection of the control stick the cone of rotation of the rotor and the direction of action of the aerodynamic force will be deflected forward along the flight. In the same direction there will be inclined the body of the helicopter together with the hub and cyclic pitch control. The pitch angle will decrease, and at a certain speed it will be close to zero. At precisely this speed the fuselage of the helicopter will have minimum drag. Upon further increase in speed the pitch angle will become negative.

Besides decreasing the drag of the fuselage, the decalage of the rotor shaft is useful in that its presence at cruising speeds of the flight bearings of the main reduction gear operate on axial loads.

§ 5. Reactive Moment of the Rotor and Rudder Control

A characteristic peculiarity of the helicopter is the great reactive moment of the rotor.

In hovering conditions the necessary torque of the rotor will be equal to:

$$M_{\text{кр}} = m_{\text{кр}} \frac{\rho(\omega R)^2}{2} \pi R^2 \cdot R \text{ [kgf·m]}, \quad (1)$$

where $m_{\text{кр}}$ – coefficient of torque dependent on angles of attack, i.e., of the pitch (determined by experimental means); ρ – air density; ω – angular velocity of rotation; R – radius of the rotor.

The anti-torque moment of the rotor (necessary torque of the rotor) is the numerical value of the reactive moment transmitted to the body of the helicopter. The necessary torque of the rotor is considerably greater than the torque on the shaft of the engine.

The torque of the engine is equal to:

$$M_{\text{кр}} = 716{,}2 \frac{N_e}{n_{\text{дв}}} \text{ [kgf·m]}, \quad (2)$$

and the torque transmitted to the rotor is determined by formula:

$$M_{\text{кр}} = 716{,}2 \frac{N_{\text{н.в}}}{n_{\text{н.в}}} \text{ [kgf·m]}, \quad (3)$$

where N_e – effective power of the engine; $n_{\text{ДВ}}$ – number of revolutions of the crankshaft of the engine; $N_{\text{Н.В}}$ – power of the engine transmitted to the rotor hub; $n_{\text{Н.В}}$ – number of revolutions of the rotor.

The number of revolutions of the rotor is many times less than the number of engine revolutions. Therefore, the torque on the shaft of the rotor and, consequently, reactive moment have a large value.

To balance the reactive moment on the Mi-4 helicopter there is provided a tail rotor, located at a definite distance from the center of gravity of the helicopter.

The rotor of the Mi-4 helicopter has counterclockwise rotation (when observing from the cockpit). The reactive moment of the rotor is directed to the opposite directive of rotation of the rotor, i.e., it tries to turn the helicopter to the left. The tractive force of the tail rotor in flight is directed to the left; it creates the moment of the tail rotor which tries to turn the helicopter to the right.

Rudder control of the Mi-4 helicopter is also carried out by the tail rotor. To obtain a right turn the right pedal moves forward. Here the pitch of the tail rotor and its thrust are increased, the moment of the tail rotor will exceed the reactive moment of the rotor, and the helicopter will start to turn to the right. For a left turn the left pedal moves forward; then the pitch and thrust of the tail rotor decrease, and the helicopter turns to the left.

With a change in power fed to the rotor the reactive moment of the rotor changes, and the helicopter turns. To prevent unnecessary turns, the pilot should with the pedals change the pitch of the tail rotor for balancing the appearing reactive moment. Consequently, the pilot must operate the pedals not only during the necessary turns, but also for preventing turns during the change in operating conditions of the engine. Such a phenomenon occurs because the "pitch-throttle" system on the Mi-4 helicopter is similar to the system of the constancy of the number of revolutions of an aircraft [RPO] (РПО). With an increase in pitch of the rotor by the "pitch-throttle" lever there is simultaneously increased the power of the engine, and at a certain position of the gas corrector the number of revolutions of the main and tail rotors will be constant or will be changed very insignificantly, since both rotors have collective rigid transmission. Here the reactive moment of the rotor increases (see Formula 3), and the tractive force of the tail rotor remains constant (or is insignificantly increased), and therefore the helicopter will turn to the left. To prevent a left turn it is necessary to depress the right pedal forward and thereby to increase the pitch and thrust of the tail rotor.

With a decrease in pitch of the rotor and power of the engine, it is necessary to depress forward the left pedal.

With further improvement of helicopters of single-rotor arrangement the designers have the problem of eliminating the indicated inconvenience in control in the following way: interlock the "pitch-throttle" lever with the control of the pitch of the tail rotor in such a manner so that with a change in reactive moment of the rotor, without interference of the pilot, there would automatically change by the same value the moment of the tail rotor. With such blocking of the control the pilot would have to operate the pedals only for the accomplishment of turns.

CHAPTER II

PRINCIPLES OF AERODYNAMICS OF THE ROTOR

§ 1. Distinction of Aerodynamics of the Rotor from Aerodynamics of the Wing and Propeller of an Aircraft

Before passing to an examination of aerodynamics of the rotor, it is necessary in broad terms to set the difference between conditions in which the wing, propeller of an aircraft and rotor of a helicopter operate.

1. Thrust sufficient for lifting a helicopter is created by a rotor at any flight speed of the helicopter (from zero to maximum). The wing of an aircraft creates lift sufficient for balancing the weight of the aircraft only at speeds from minimum to maximum. At speeds from zero to minimum the wing of an aircraft cannot create sufficient lift. Such a difference in the operation of a rotor and wing of an aircraft exists because blades of the rotor, having rotation around the axis of the rotor, obtain air velocity and therefore create lift when the helicopter stands or hangs in place.

2. The rotor of a helicopter operates at any angles of attack from 0 to 360°, while the wing of an aircraft can operate only in a strictly defined angular region of attack: from the angle of attack of zero lift (from 0 to -3°) to its critical (18-20°). At angles less than the angle of attack of zero lift the lift of the wing is negative, and at supercritical angles of attack separation of flow advances, which leads to a decrease in lift, an increase in drag and other undesirable phenomena. Consequently, the working angular

region of attack is very small, and the flying range is even less.

The angle of attack of the rotor is called the angle included between the plane of rotation of the rotor and the direction of incident flow of air owing to the flight, i.e., the angle between the plane of rotation of the rotor and flight path of the helicopter (Fig. 9). Above it was established that the helicopter can accomplish flight in any direction, and therefore the angle of attack can be any value. By analogy with the wing of an aircraft it is accepted to calculate angles of attack of the rotor negative from 0 to -180°, if the flow advances on the plane of rotation from above, which occurs with all forms of climb, horizontal flight, and during sloping descent with an operating engine, and positive from 0 to 180°, if the flow advances on the plane of rotation from below, which occurs during all forms of descent of the helicopter.

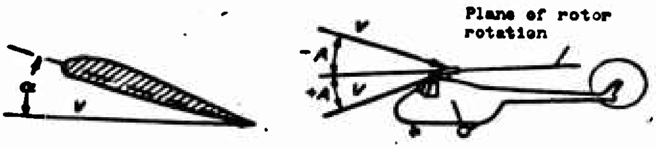

Fig. 9. Angle of wing setting α and angle of attack of rotor A.

It is necessary to note that any angle of attack of the rotor, i.e., during any conditions of flight of the helicopter, each separate blade of it works as a separately taken wing in the angular region of attack of the wing, only in more complicated conditions.

For the rotor of helicopter upon deflection of the control stick back the angles of attack of the rotor (A) are increased under any conditions of flight. With this angles of attack are increased (α) for each separately taken blade. With deflection of the stick forward the angles of attack of the rotor and each blade decrease.

3. The rotor in forward rectilinear flight has an asymmetric field of speeds, whereas the wing of an aircraft has a symmetric field of speeds with respect to its span. For blades advancing on the

flow, to the peripheral velocity is added the speed of flight of the helicopter, and for retreating blades the speed of flight is subtracted from the peripheral velocity. The asymmetric field of speeds induces an asymmetric field of aerodynamic forces on the rotor, and this leads to the necessity of application of different design attachments, which will be mentioned below.

4. The rotor, as a result of its specific work, limits the maximum speed of flight of the helicopter, whereas the wing does not limit the speed of the aircraft, if it is designed for high-speed flight. It is impossible to create great forward velocity for the helicopter, since in the azimuthal position $\psi = 90°$ the speed of flow around the blades will be higher than critical, which will elicit shock waves and additional wave drag, and in position $\psi = 270°$ separation of flow from the blades will appear in view of the low speed of the flow around. For this reason speeds of even contemporary helicopters are still very low.

5. Flows of air before and after the rotor are not so rectilinear, uniform, and stable as before and after the wing of the aircraft, in view of the low forward velocity of the helicopter as compared to the aircraft. If one were to compare a helicopter and aircraft with identical gross weights, then the rotor of the helicopter at low speed should create a thrust in the same way as the lift of the wing of the aircraft at high speed. Therefore, with a smaller mass of air passing through the rotor per unit of time, the rotor should create great inductive rake. This leads to the fact that the air flows twist, are rejected with great rake nonuniformly and nonrectilinearly.

6. The whole rotor disk plane participates in the creation of tractive force similar to the entire wing area of an aircraft. This occurs because along the whole disk surface there passes a continuous flow of air down from above (inductive bevel – v) independently of where the blades are on the surface (Fig. 10). This is explained by the fact that the air, rejected by the blade downwards, does not instantly cease its motion after the blade moves. Furthermore, the rotor has a quite great number of revolutions, and therefore blades

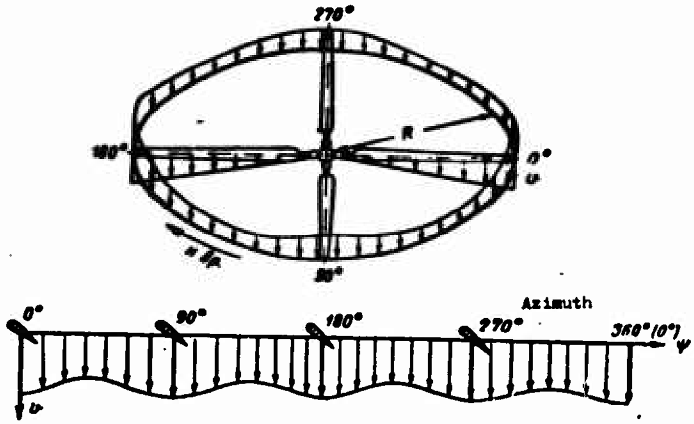

Fig. 10. Distribution of inductive speed along the surface.

in the given azimuth are changed very frequently, forming a continuous flow of air through the whole disk surface.

In order to examine the distinction in conditions of operation of a propeller and rotor, it is necessary to remember the pitch, advance ratio, and slip of the propeller.

The pitch of the section of the propeller blade is called the distance which the chord of the examined blade section would pass in an axial direction if it were screwed in the air as in a solid. The pitch of section is determined by formula

$$H = 2\pi R \operatorname{tg} \varphi \ [m/r], \qquad (4)$$

where R – radius of the propeller; ϕ – setting angle of element of the blade.

The propeller pitch with variable pitch along the blade is conditionally considered to be the pitch of the section of the blade from the axis of rotation at distance r = 0.75 R, and it is called nominal pitch.

The advance ratio of the propeller is called the distance passed by the propeller in an axial direction during one revolution equal to the ratio of projection of the speed of flight on the axis of rotation to the number of revolutions of the propeller:

$$H_{a} = \frac{60V}{n_{н.в}} \; [m/r] \tag{5}$$

where V – speed of flight, m/s; $n_{H.B}$ – number of revolutions of the rotor per minute.

<u>Slip of the propeller</u> is called the difference between the nominal pitch and advance ratio of the propeller:

$$C = H - H_{a} \; [m/r].$$

In spite of a certain community of geometric, kinematic and aerodynamic properties of propellers and rotors, between them the following basic distinctions exist.

1. For the propeller the advance ratio is absent, and slip amounts to 100% only during propeller operation on a motionless aircraft (aircraft stands on land). For the rotor of a helicopter such operating conditions will be during its operation in place and also in conditions of hovering.

2. For the propeller there can only be a positive advance ratio, since an aircraft flies only forward. For a rotor the advance ratio is also positive during all flight conditions with negative angles of attack of the rotor, but it will be negative during all forms of descent at positive angles of attack of the rotor.

3. For the propeller the advance ratio can be equal to the pitch or greater than the pitch, which occurs during gliding with the engine turned off or when diving. Here slip and thrust are absent (conditions of zero thrust of the propeller) or are a negative value. Steady flight occurs owing to lift of the wing. For the rotor there cannot be such conditions, since the helicopter has no wings. Therefore, the rotor in all conditions of flight, even in autorotation, should create a sufficient positive thrust.

4. The propeller operates basically only under conditions of direct airflow, since the flow of air during flight of an aircraft is directed along the axis of the propeller shaft. A helicopter rotor also operates under conditions of the airflow line in all vertical flight conditions. But during flight with a certain forward velocity rotor operates under conditions of oblique airflow, since the flow of air advances to the propeller at a certain angle. The study of oblique airflow of the rotor forms the basis of its aerodynamics.

There are other secondary distinctions in the operation of the rotor from the operation of the wing and propeller, which will be revealed below.

Hence there follows the conclusion that the aerodynamics of the rotor constitutes a separate theory, which it is impossible to extend completely to it the theory of the wing and propeller of an aircraft, although it is based on the latter.

§ 2. Geometric Characteristics of the Rotor

1. Diameter of the Rotor

To create the necessary thrust the diameter of the rotor should be large. If for horizontal flight of an aircraft it is required that the thrust of the propeller be less than the weight of it, then for a helicopter it is required that the thrust for hovering be equal to the weight of the helicopter, and for horizontal flight the thrust is required to be greater than the weight.

It is expedient and possible to create great thrust owing to the increase in diameter of the rotor, since the thrust is proportional to the diameter of the rotor in the fourth power and is determined for the tractor propeller by the general formula

$$T = \alpha_T \rho n_{сек}^2 D^4 \text{ [kgf]}, \tag{6}$$

where α_T – aerodynamic thrust coefficient depending on the form of the blade and angle of attack of it; ρ – air density; $n_{сек}$ – number of rotor revolutions per second; D — diameter of the rotor.

The diameter of the rotor is selected depending upon the gross weight of the helicopter (G) and the necessary unit load on the disk area (p):

$$D=\sqrt{\frac{4G}{\pi p}}\ [\mathrm{m}]. \qquad (7)$$

Diameters of rotors of contemporary helicopters vary over large limits. The rotor diameter of the Mi-4 helicopter is equal to 21 m.

2. Blade Profile

The selection of blade profile will govern the aerodynamic and flying properties of the helicopter and also problems of flight safety. Therefore, the blade profile of a rotor has the following requirements.

1. The profile should have a high lift-drag ratio. The maximum ratio of the blade profile of the Mi-4 helicopter, taking into account profile and induced drag at the most advantageous angle of attack (4.5°), is equal to 21.8.

2. The profile should have a high critical M($M_{кр}$) number:

$$M_{кр}=\frac{V_{кр}}{a}, \qquad (8)$$

where $V_{кр}$ — critical speed of flow at which in some part of the profile there appears speed equal to the local velocity of sound; a — speed of sound.

For the blade profile of the Mi-4 helicopter $M_{кр}$ = 0.72 at an angle of attack of zero lift, when the coefficient of lift c_y = 0. With an increase in angles of attach (c_y), $M_{кр}$ decreases, and at the most advantageous angle of attack at which c_y = 0.6, $M_{кр}$ = 0.64. When $M_{кр}$ = 0.64 the critical speed is:

$$V_{кр}=a\cdot 0{,}64=341\cdot 0{,}64=218\ [\mathrm{m/s}]$$

(a = 341 m/s under standard atmosphere conditions at sea level).

Consequently, during flight in such conditions the tips of the blades can have a speed up to 218 m/s without a threat of appearance of shock waves and additional wave drag, which worsen operating conditions of the rotor. Such values of $M_{кр}$ and $V_{кр}$ are attained for the blade of the Mi-4 helicopter owing to the selection of the appropriate profile, i.e., its form relative to the thickness and quality of treatment of the external surface.

During flight $M_{кр}$ changes from the change in angles of attack of blades, including from the change in pitch of the rotor, and also from altitude of flight and atmospheric conditions, since with this the speed of sound changes. Tips of blades of the Mi-4 helicopter in all conditions of flight have a speed of flow around of less than 218 m/s. Thus, for example, in takeoff operating conditions of the engine (2600 r/min):

$$u=\omega R=\frac{\pi n_{нв}}{30}R=\frac{3,14\cdot 2600}{30\cdot 13,45}\cdot 10,5=212,4\ [\text{m/s}],$$

where ω – angular velocity; 13.45 – gear ratio.

At the most advantageous speed of horizontal flight, 140 km/h (39 m/s), and in cruising revolutions of the crankshaft of 2200 r/min for the Mi-4 helicopter the true speed of flow around of the blade tip in the azimuthal position ψ = 90° will be:

$$W=u+V=\frac{3.14\cdot 2200}{30\cdot 13,45}\cdot 10,5+39=179+39=218\ [\text{m/s}],$$

where u – peripheral velocity; V – speed of horizontal flight.

Consequently, in basic flight conditions of the helicopter the blade tip operates at M numbers less than 0.64, i.e., less than $M_{кр}$, which favorably affects operation of the rotor. At speeds greater than 140 km/h the blade tips will have a speed of flow around greater than the critical. Thus, for example, at a speed of 155 km/h and at nominal turns (2400 r/min) the true speed of the flow around of the blade tip in position ψ = 90° will be:

$$W = u + V = 196 + 43 = 239 \text{ [m/s]}.$$

Such a speed exceeds its critical value. If, however, $M_{кр}$ is decreased by increasing the collective pitch, the blade will operate at a Mach number clearly larger than $M_{кр}$, which is undesirable, since here shock waves will appear, and they will lead to a decrease in lift, increase in drag and other undesirable phenomena.

3. The blade profile should have small movement of the center of pressure chordwise from the change in angles of attack (pitch of the rotor). This is necessary so that movement of the center of pressure back does not create a diving moment on the profile, which will twist the blade to a decrease in angles of attack and lift of the rotor, which can lead to the pulling of the helicopter into a dive.

For symmetric profiles at flying angles of attack, the center of pressure almost does not move and therefore for blades of the rotor of the Mi-4 helicopter a profile close to symmetric is selected. To obtain even better characteristics for blades of mixed construction from the 28th rib and for an all-metal blade from the 17th section up to the blade tip a modified profile is applied. Modification consists in the fact that the tail of the profile is elevated upwards. All these measures exclude the possibility of pulling the Mi-4 helicopter into a dive at speeds of flight permissible in operation.

4. The blade profile should be such that the blade passes well into autorotation in a large angular region of attack (pitch of the rotor), i.e., so that with failure of the engine at any pitch the rotor passes into autorotation, providing safety of further flight. This requirement is ensured by the high lift-drag ratio of the profile of the blade, the quality remaining constant (or decreases insignificantly in the large angular region of attack.

5. The blade should be made with accurate holding of the form of the designated profile and dimensions. Otherwise its aerodynamic and other characteristics are changed, which will entail impairment

of flying properties of the helicopter.

6. The blade profile should have a minimum profile drag, the value of which for the chosen profile of definite form depends on the material of covering of the blade and quality of external treatment of this material. A small profile drag is given by a metallic skin of the blades and large profile drag by plywood and linen.

Thus, for example, for the Mi-4 helicopter the rotor with all-metal blades gave an increase in thrust of about 400 kgf as compared to the thrust of a rotor with blades of mixed construction.

The high-quality external treatment of blades is necessary not only for decreasing the general drag of the blades, which leads to a decrease of the required power for rotation of the rotor, but also for increasing the critical angle at which the separation of flow advances. The worse the external treatment of the blade, the earlier (at less speed) the phenomenon of separation of flow advances.

7. Transverse centering of the blade should be to prevent vibration of blades of the flutter type. Transverse centering of blades of the Mi-4 helicopter on the average is 22-23% and is reached due to the arrangement of elements of the blade and due to counterpoises. The counterpoise for a blade of mixed construction constitutes a rectangular steel band glued into nose stringer, on the rib section from 20 to 57, and for an all-metal blade – six steel pieces inserted into the nose of the blade along its whole length.

All requirements enumerated above are satisfied by the profiles NACA-230 and NACA-230M, which are used for blades of the Mi-4 helicopter of both mixed and all-metal construction. For blades of mixed construction from the root and up to the 28th rib profile NACA-230 is applied, and from the 28th rib to the blade tip, NACA-230M. For the all-metal blades from section 2 to section 16 profile NACA-230 (without modification) is applied, and in the area from section 17 to section 23, profile NACA-230M (modified). Between sections 16 and 17 there is the transition area from the NACA-230 profile to NACA-230M profile. The profile is convexo-convex, asymmetric, and with variable relative thickness along the length of the blade. The relative thickness of the blade $\bar{c}$ of mixed construction on the area from rib 4 to 15 is equal to 12.5%, and from rib 15 the thickness gradually increases up to 14% on the blade tip Fig. 11a). For an all-metal blade the relative thickness between sections 2 and 3 is equal to 13%, between sections 4 and 10 — 12% and between sections 11 and 23 — 11% (Fig. 11b).

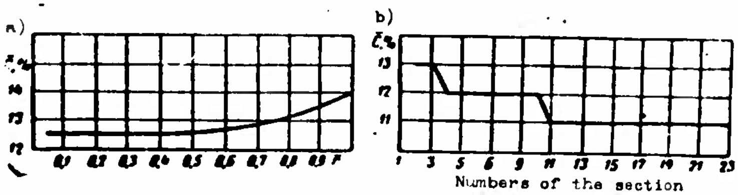

Fig. 11. Relative thickness of the blades: a) mixed construction; b) all-metal construction.

Aerodynamic data of the profile are characterized by the following parameters: the angle of attack of zero lift is equal to −1.2°, the most advantageous angle of attack is 4.5° (at which the profile has maximum a lift-drag ratio equal to 21.8), and the critical angle of attack is about 12° (here the maximum coefficient of lift c_y = 1.29).

3. Blade Planform

There are many different blade planforms, but the main ones are the following.

1. Elliptic planform. This is the most profitable form in an aerodynamic respect especially for operating a rotor in place, but such blade is complicated to produce. Therefore, at present it is not applied.

2. Blade of the N. Ye. Zhykovskiy type [NYeZh] (НЕЖ). This is a trapezoidal blade with narrowing of the chord toward the blade tip four times. A blade of such planform, other things being equal, creates greater lift as compared to other forms, since in places with low peripheral velocities it has a larger chord. But a rotor with such blades passes poorly into autorotation, which is dangerous in the

case of sudden failure of the engine. Therefore, such blades did not achieve wide application.

3. Rectangular blade. Such a blade passes well into autorotation and is simple to produce, but it creates smaller lift due to the nonuniform distribution of it along the length of the blade. Such a planform is basically used for all-metal blades in view of the simplicity of its production and the possibility of replacement of sections when they are damaged.

4. Trapezoidal blade with twice narrowing of the chord toward the blade tip. It is intermediate between blades of the NYeZh type and the rectangular. Such a blade more evenly distributes lift along the length and relatively well passes to autorotation, and therefore it has obtained the greatest application.

For the Mi-4 helicopter blades of mixed construction have a trapezoidal planform with twice narrowing of the chord toward the blade tip: from rib 1 to 4 – trapezoidal, from 4 to 15 – rectangular and from 15 to 57 – trapezoidal (Fig. 12a).

The all-metal blade of the Mi-4 helicopter has a rectangular planform with a constant chord along length equal to 0.52 m (Fig. 12b).

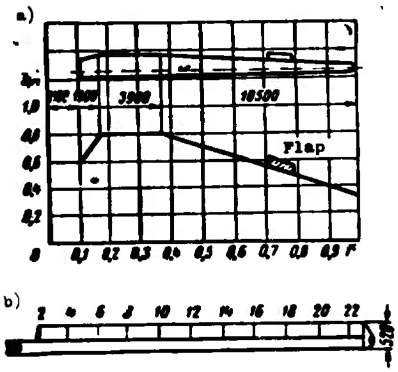

Fig. 12. Planform of blades: a) mixed construction; b) all-metal construction.

4. Geometric Twist of the Blade

The geometric twist of the blade is the difference between the setting angle at the root of the blade and at the tip. This difference at any propeller pitch remains constant. The twist is necessary for increasing lift of the blade, which leads to an increase in thrust of the rotor of the helicopter in all flight conditions on the average by 7%. Consequently, the twist permitted increasing the payload of the helicopter. Furthermore, owing to the twist the centers of pressure of the blades move to the axis of rotation by 5%, which leads to a decrease in required power for rotation of the rotor and all of this – to an increase in efficiency [KPD] (КПД) of the rotor. The twist also increases the critical stall speed and, unloads the tip part of the blade from great air loads, distributing them along the length of the blade evenly.

The blade of the Mi-4 helicopter of mixed construction has twist $\Delta\phi = 4° \ 30'$ and is carried out in the following way: on the section from the blade tip to rib 37 the setting angle is constant and equal to zero, on the section from rib 37 to 11 the setting angle is variable – is increased from 0 to 4° 30', and on the section from rib 11 to 3 – constant and is equal to 4° 30' (Fig. 13a). Consequently, the blade constructively is twisted by 4° 30' only in the middle of the blade, i.e., on the section from rib 11 to 37 the blade tip and its root are not twisted.

The all-metal blade of the Mi-4 helicopter has a geometric twist of 5°. On the area from section 2 to 4 the blade is not twisted, and then from section 4 the angle of setting gradually decreases and for section 23 it is equal to zero, with the exception of the area between sections 10-11 where the twist is equal to 3° 20' (Fig. 13b).

From what has been said it is clear that the geometric twist of blades is small. Earlier it was considered that large twist leads to the impairment of properties of autorotation of the rotor, which is not safe in case of engine failure. Recently it has been established by experiments and confirmed by practice of flights that this opinion is erroneous: the blade passes well to conditions autorotation,

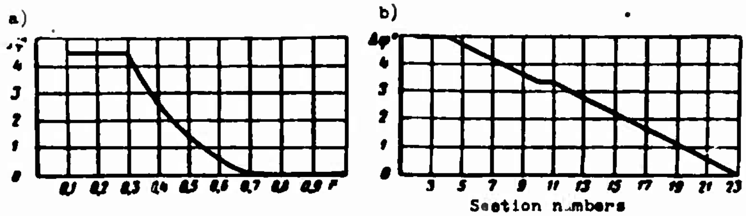

Fig. 13. Geometric twist of blades: a) mixed construction; b) all-metal construction.

even those having large twist. Thus, for example, the twist of blades of helicopters Ka-15 and Ka-18 is 10° (and for helicopter Ka-26 even larger), and they have very good properties of autorotation.

5. Number of Blades of the Rotor

From the point of view of aerodynamics, the less the number of blades, the better the rotor operates, especially the main rotor, since it has low forward velocity along the axis of rotation. But a small number of blades, especially for a heavy helicopter, requires a large diameter of the rotor and gives nonuniform operation. Thus, for example, for a two-bladed rotor with a hinged suspension of the blades there is observed increased vibration transmitted to the body of the helicopter, inasmuch as total thrust is changed in value for each full revolution. For this reason application of two-bladed rotors is limited, and if they are applied, then only on a Cardan joint for light helicopters and for tail rotors.

In the world practice of helicopter construction the number of blades of the rotor was set from two to five depending upon gross weight: for light helicopters, 2-3 blades, for medium helicopters, 3-4 blades, for heavy, 4-5 blades. Helicopters Mi-1, Mi-2, Ka-15, Ka-18, and Ka-26 have three-bladed rotors, helicopters Mi-4, Yak-24 – four-bladed, and helicopters Mi-6, Mi-10, and Mi-8 – five-bladed rotors.

6. Unit Load on the Disk Area

The unit load on the disk area is defined as the ratio of gross weight of the helicopter to the disk area:

$$p = \frac{G}{F_{ом}} \text{ [kgf/m}^2\text{]}. \quad (9)$$

The value of the unit load is selected from calculation of the obtaining of permissible vertical velocities in the autorotation regime of the rotor, since vertical velocity (V_y) in autorotation during vertical descent is directly proportional to the unit load and is determined by formula

$$V_y = \sqrt{\frac{2p}{c_R \rho}} \text{ [m/s]},[1] \quad (10)$$

where p – unit load on the disk area; c_R – coefficient of total aerodynamic force; ρ – mass air density.

But it is inexpedient to have a very small unit load for obtaining low vertical velocity in autorotation, since for this it will be necessary for the given gross weight of the helicopter to increase the rotor diameter. With an increase in rotor diameter the load on the engine shaft will increase which will lead to a lowering of efficiency of the rotor.

Besides this, the unit load must be increased for heavier helicopters, especially for twin-rotor, because of the design inconveniences of the creation of large rotors and drive mechanisms. For contemporary helicopters the unit load varies from 10 to 40 kgf/m^2 depending upon the gross weight.

The unit load for the Mi-4 helicopter with maximum permissible

[1]With vertical descent in autorotation the full aerodynamic force R is the rotor thrust and is equal to the weight of the helicopter:

$$R = G = c_R \frac{\rho}{2} F_{ом} V_y^2 \text{ [kgf]}.$$

Solving this equation with respect to V_y and equating p = G/F_{OM}, we obtain the given formula (10) of vertical velocity in conditions of vertical autorotation.

gross weight is

$$p = \frac{G}{F_{\text{ом}}} = \frac{7350}{346} \cong 21 \ [\text{kgf/m}^2],$$

where F_{OM} – disk area and is equal to 346 m^2 for the Mi-4 helicopter.

7. Rotor Solidity

Rotor solidity is determined by the ratio of the area of all the blades to the disk area:

$$\sigma = \frac{S_{\text{л}} \cdot z}{F_{\text{ом}}}, \qquad (11)$$

where $S_{\text{Л}}$ – area of one blade; z – number of blades.

Rotor solidity is an abstract number showing what part of the disk area is filled by the blades. Rotor solidity for contemporary helicopters is selected from 0.03 to 0.09 (from 3 to 9%). A too small rotor solidity, less than 3%, limits the maximum speed of the helicopter by the fact that the critical stalling speed decreases, since with the small area of the blades to create the needed thrust it is required to hold them at large pitch and this will lead to the separation of flow from the blades tips in the azimuthal position $\psi = 270°$ at a lower speed of flight. Too large rotor solidity, higher than 9%, gives high profile drag in view of the large area of the blades, which leads to a lowering of the efficiency of the rotor.

Rotor solidity of the Mi-4 helicopter with blades of mixed construction $\sigma = \frac{S_{\text{л}} \cdot z}{F_{\text{ом}}} = \frac{5.8 \cdot 4}{346} = 0.0669$, i.e., near 7%. Rotor solidity with all-metal blades

$$\sigma = \frac{4.36 \cdot 4}{346} = 0.0505, \text{ i.e., higher than } 5\%.$$

8. Blade Angle (Propeller Pitch)

Blade angle (propeller pitch) is called the angle included between the plane of rotation of the rotor (plane of the hub) and the chord of the element of the rotor blade. The setting angles to blades of the rotor are set small for the reason that the forward velocity of the rotor along the axis of rotation of it is small both under vertical conditions of flight and during flight with forward speeds, since a great part of the speed descends not along the axis of the shaft but over the plane of rotation of the rotor. The low speed along the axis of rotation will insignificantly affect the decrease in angles of attack of the blades, and in order to keep them close to the most advantageous the setting angles are made small.

On the majority of the helicopters, including on the Mi-4 helicopter there are electrical indicators of the setting angles (collective pitch of the rotor) on the instrument panel. Furthermore, the value of the collective pitch is duplicated by a mechanical collective pitch indicator placed on the toothed sector of the "pitch-throttle" lever. For the Mi-4 helicopter the collective pitch of the rotor, according to the indicators, is from 3° 30' to 14°. These values of collective pitch are conditional, since the pitch indicators are calibrated according to the setting angles of blades in the cross section of the blade ($r = 0.7R$) in the position of its plane of rotation. During flight in all conditions of the blades the angle of conicity will be formed, i.e., they are elevated above the plane of rotation, and therefore owing to the presence of the flapping control upon motion of them upwards from the plane of rotation the setting angles will decrease. For this reason the setting angles will actually be somewhat less than the pitch indicator will show.

The pitch indicator facilitates piloting of the helicopter, especially if the pilot is trained to use it during instruction. But the indicator of collective pitch of the rotor is not obligatory, since the pilot can control the power of the engine by the number of revolutions and boost pressure. Thus, for example, on helicopters Ka-15 and Ka-18 the indicator of collective pitch of the rotors is absent.

9. Plane of Rotation and Cone of Rotation of the Rotor

<u>The plane of rotation of the rotor</u> is called the imaginary plane located perpendicular to the axis of the rotor shaft and passing

through the center of the hub (it is frequently called the hub plane). Since in view of the presence of horizontal hinges the blades are not in this plane, they will form the cone of rotation. With respect to the plane of rotation setting angles of the blades (propeller pitch) and also angles of attack of the rotor are counted off (Fig. 14).

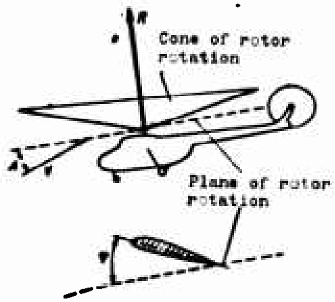

Fig. 14. Plane and cone of rotation of the rotor.

The cone of rotation of the rotor will be formed by blades during rotor operation in all conditions of flight owing to the presence of flapping hinges of the blades. The base of the cone is a plane drawn through tips of the blades; the summit of the cone is at the hub. Along the axis of cone, perpendicular to the base, the direction of action of the full aerodynamic force of the rotor R.

The cone of rotation of the rotor, in contrast to the plane of rotation, is deflected by the pilot with the control stick to the desirable side, and to the same side the direction of action of the aerodynamic force of rotor R will be deflected. The cone of rotation and the direction of action of aerodynamic force of the rotor will also be deflected and independently in forward flight owing to flapping motions and other causes, which will be discussed more specifically below.

10. Root and Tip Losses

The central part of the disk surface is occupied by the hub, and root parts of blades of the rotor have small peripheral velocity and, therefore, almost do not participate in the creation of lift. All of this constitutes root losses of the rotor.

Tip parts of blades also do not participate in the creation of lift, since along the periphery of the disk surface there occurs overflowing of air masses from the region of raised pressure under the rotor into the region of lowered pressure above the rotor. As a result of this the pressure is equalized, and this forms tip losses of rotor.

Root and tip losses are expressed in percents of the magnitude of disk area and in sum comprise from 8 to 10% of this surface. Therefore, the effective disk area is:

$$F_{эф} = (0{,}9 \div 0{,}92)\, F_{ом}.$$

These losses are rather great. Thus, for example, 10% of the losses from the disk area of the Mi-4 helicopter will be 36.6 m^2.

§ 3. Weight and Rigidity of the Blade Construction

Besides the examined geometric characteristics affecting the operation of the rotor, the following characteristics are important.

Weight of the blade. The greater the weight of the blade, the greater the inertia of rotation, the greater the reserve of time in transition to autorotation during engine failure, the less the angle of flapping and the less the avalanche of the cone and direction of aerodynamic force of the rotor back in forward flight. Consequently, the increase in weight of the blades positively affects the rotor operation. But too much weight of the blades causes great centrifugal forces, which will require ensuring the strength by increasing the section of parts, and this will lead to a further increase in weight of the construction and lowering of the payload. At low weight of the blade centrifugal forces will be insufficient, the blade will stand on rests of the hinges, and there will also be a small reserve of time for transition of the rotor to autorotation.

For these reasons the weight of blades should be fully determined for a given rotor and strictly combined with its other characteristics.

In the practice of helicopter construction it is established that the weight of the rotor of a single-rotor helicopter should be 9-13% of the total gross weight of the helicopter, and the weight of the tail rotor - 1% of the gross weight of helicopter. The weight of the rotcr blade of the Mi-4 helicopter of mixed construction is 120 kg and all-metal - 130 kg, weight of the hub - 420 kg. The weight of the whole rotor with blades of mixed construction is 900 kg, with all-metal blades - 940 kg, and this is about 13% of the normal gross weight of the helicopter - 7100 kg.

Rigidity of construction of the blade. During rotor operation the blade receives flexural and twisting deformations, and therefore it should be not only durable but also have definite rigidity. Too rigid a blade gives good controllability by the rotor in that commands passed by the pilot through the cyclic pitch-control mechanism for changing the setting angles are transmitted rapidly over the entire blade, but such a blade will have great weight, great centrifugal forces will appear, and moreover, it cannot dampen accidentally appearing aerodynamic and inertial forces. All of this will cause increased vibrations.

Although too flexible a blade will dampen accidental aerodynamic and inertial forces very well owing to its own bend and torsion, it will worsen controllability, since transmitted changes of the setting angles from the direction of the cyclic pitch control will proceed to the blade inaccurately and with delay.

The existing rigidity of blades of the Mi-4 helicopter satisfies all the requirements. During the standing of the helicopter on land with an inoperative rotor, the blades droop in view of their definite flexibility, and the impression is created that they are not durable and cannot hold the helicopter in flight. Upon operation of the rotor in flight owing to centrifugal forces, the blades are stretched and constitute a durable structure similar to the wing of a fighter airplane. Having definite rigidity, the blade is controlled well by the cyclic pitch control and, having definite flexibility, smooths well the irregularity of aerodynamic and inertial forces.

§ 4. Kinematic Characteristics of Carrying Screw

1. Kinematics of the Rotor in Vertical Flight Conditions (Straight Line Flow)

Revolutions of the rotor. In vertical flight conditions of the helicopter blades of the rotor are flowed around by air basically owing to the rotation of them in a circle.

The number of revolutions of a rotor of definite diameter is selected such that the peripheral velocity of the blade tips together with the forward velocity during maximum speed of flight of the helicopter in the aximuth position of $\psi = 90°$ would not be greater than the critical, and in position $\psi = 270°$ there would not appear separation of flow at the same speed of flight. If one were to designate a great number of revolutions, then the separation of flow will not be at high speeds in position $\psi = 270°$ but will then be the supercritical speed at position $\psi = 90°$, which will cause shock waves, and normal operation of the rotor will be disturbed. A small number of revolutions will cause separation of flow fr n tips of the blades already at low flight speeds.

Consequently, the great number of revolutions of the rotor is limited by the compressibility of air in the azimuthal position of 90°, and the small number of revolutions by the separation of flow in position 270°.

For the Mi-4 helicopter the gear ratio to the rotor is such that its number of revolutions is 13.45 times less than revolutions of the crankshaft of the engine. Then the maximum number of revolutions of the rotor in take-off operating conditions of the engine $n_{H.B} = 2600/13.45 = 193$, in normal operating conditions of the engine $n_{H.B} = 2400/13.45 = 178$, and in cruise conditions of engine operation $n_{H.B} = 2200/13.45 = 163$ r/min.

For the Mi-4 helicopter the gear ratio to the tail rotor is such that its number of revolutions is decreased 2.3 times as compared to revolutions of the crankshaft of the engine.

Pattern of streamline flow of the separate blade elements. In conditions of hovering on the element of the blade, which is at a certain setting angle ϕ (Fig. 15a), to the plane of rotation flow acts owing to the rotation of the element about the circumference (peripheral velocity $u = \omega r$). At the same time on the element there will act an inductive speed due to the flow of air passing through the rotor down from above (inductive rake). In desiring to add the peripheral and inductive speed by the triangle rule, we will attach the vector of inductive speed to the end of the vector of peripheral velocity. The total inductive flow of the whole rotor acts perpendicular to the plane rotation (in parallel to the shaft axis), and for a separately taken element this flow is directed perpendicular to the chord of the element. The closing side of the triangle is the total speed — true speed of flowing around of the element of the blade W. The angle included between the true speed of the element and chord of it is the angle of attack α. As can be seen from the figure, the angle of attack of the element owing to inductive speed is less than the setting ϕ.

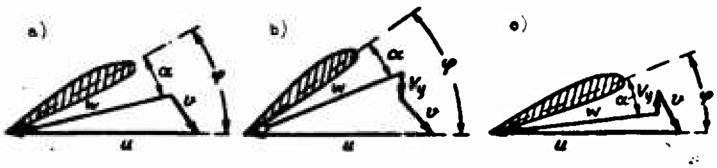

Fig. 15. High-speed polygons of the element of the rotor blade under vertical flight conditions: a) during hovering; b) during vertical rise; c) during vertical descent.

An additional factor during the vertical climb will be the speed of the vertical climb, therefore to the vector of the peripheral and inductive speeds we add the velocity vector of vertical climb V_y (Fig. 15b). The closing side of the polygon is the true speed of flowing around of the element of the blade W. As can be seen on the figure, at the same setting angle (propeller pitch) the angle of attack of the element due to the vertical velocity will be still less than that in hovering. Therefore, in order to climb the pilot should increase the angles of attack — increase the setting angle (collective pitch).

With vertical descent to the peripheral and inductive speeds will be added the speed of vertical descent, directed from bottom to top, and therefore to the vector of inductive speed we add the vector of vertical velocity of decent V_y (Fig. 15c). The closing side of the polygon will be the true speed of the element of the blade W. As can be seen from the figure, the angle of attack of the element owing to the rate of descent will be increased, and for the possibility of descent it is necessary to decrease it — decrease the setting angle (collective pitch).

The given pattern of streamline flow in all vertical flight conditions will be the one for all elements of the blades, but there will be different peripheral and inductive speeds on different radii, and also there are different setting angles owing to the twist of the blades. Having examined the high-speed polygons of elements of blades in the conditions shown, it is easy to present the pattern of streamline flow of each blade and the whole rotor. According to high-speed polygons it is clear that in all vertical flight conditions, angles of attack of the blade element are always positive and close to being the most advantageous, although angles of attack of the rotor can be different in the conditions shown both during vertical lowering and during vertical climb.

Pattern of streamline flow of the whole rotor. In vertical flight conditions through the disk area there is passed air down from above with a definite inductive speed v owing to the interaction of the rotor with the air (Fig. 16). At a certain distance from the rotor above the air is in a state of rest; in the region located nearer to the rotor the speed of suction appears, and with the approach to the rotor this speed grows and in the plane of the rotor will be equal to definite quantity v proportional to the power supplied to the rotor. Under the rotor the air is already rejected by the rotor downwards, and therefore the speed of it continues to grow, the flow narrows and at a certain distance, approximately about half of the radius of the rotor, the flow will have the narrowest section, and the speed, the maximum, equal to 2 v, i.e., twice greater than the speed in the region of the rotor itself. The diameter of the narrowest section of the flow is determined by formula

$$d=\frac{D}{\sqrt{2}}, \quad (12)$$

where d – minimum diameter of the stream under the rotor; D – diameter of the rotor.

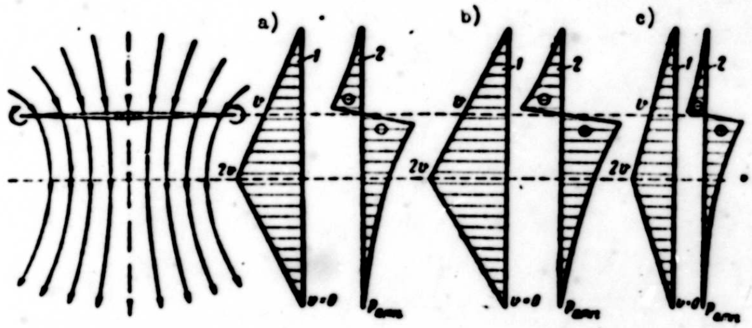

Fig. 16. Distribution of inductive speed and static pressure in the flow of the rotor in vertical flight conditions: a) hovering; b) climb; c) descent; 1 – diagram of inductive speed; 2 – diagram of static pressure.

Below more, approximately at a distance of 5 diameters of the rotor, the flow finally calms down, and its speed is equal to zero. Figure 16 gives a diagram of inductive speeds in the common form for hovering, vertical climb, and vertical descent.

Inductive speed is called the flow rate along the axis of the rotor shaft down from above, appearing as a result of the interaction of the rotor with the air. Owing to this speed the difference in pressures appears under the rotor, and above the rotor and lift (thrust) is created.

The value of the mean necessary inductive speed in vertical conditions of flight for an ideal rotor is determined from the formula of thrust of an ideal rotor

$$T=2\pi R^2\rho v^2 \text{ [kgf]}, \quad (13)$$

from which

$$v_{cp}=\sqrt{\frac{T}{2\pi R^2\rho}} \text{ [m/s]}, \quad (14)$$

where $\pi R^2 v \rho = F_{om} v \rho$ is the mass flow per second of air passing through the disk area.

The inductive speed for a real rotor is determined by a more complicated empirical formula applied for the aerodynamic design of the helicopter.

It is necessary to note that in vertical flight conditions of the helicopter, the magnitude of necessary inductive speed as compared to any other flight with forward velocity is the largest, since through the rotor a small mass of air passes per unit of time, and therefore to create thrust equal to the weight of the helicopter will require a high speed of repulsion. For this reason, as we will set below, in vertical conditions of flight high induced drag of blades is obtained, and therefore high power for the accomplishment of these flight conditions is required.

For conditions of hovering under conditions of standard atmosphere (see Fig. 16a) and for normal gross weight of the Mi-4 helicopter, the magnitude of the inductive speed in the region of the rotor (speed of suction) is numerically equal to about 8-10 m/s, and under the rotor (speed of repulsing) it is twice greater than the speed of the suction and amount to 16-20 m/s.

Static pressure in the flow from the rotor will be distributed in the following way: above the rotor where the inductive speed is equal to zero, the pressure will be atmospheric, with an increase in speed nearer to the rotor the pressure will decrease, and directly above the rotor it will be minimum. Then it will be increased and in the plane of rotation of the rotor will be again equal to atmospheric. Under the rotor the pressure grows spasmodically, and it will be maximum; with distance from the rotor downwards the pressure will decrease and where the speed will be equal to zero the pressure will be atmospheric. Figure 16 also gives diagrams of static pressures in hovering, vertical climb, and vertical descent.

Consequently, above the rotor the pressure is lowered, and under the rotor it is raised as compared to pressure in the surrounding atmosphere. Owing to the difference in pressures there appears dynamic force - thrust of the rotor. Simultaneously the flow twists in the direction of rotation of the rotor, but the angular velocity of the twisting is less than that for the propeller of an aircraft, in view of small number of revolutions of the rotor as compared to revolutions of the propeller.

As can be seen on the diagrams, the change in the speed and pressure in the flow contradicts the Bernoulli law, i.e., where the speed is maximum, and the pressure is not minimum. The examined flow is not subordinated to the Bernoulli law, since here in the path of the flow the rotor stands, which supply energy to the flow from the engine. The Bernoulli law examines the flow without removal and supply of energy. Inasmuch as energy is supplied from the engine, therefore under the rotor the great potential energy is static pressure, and the great kinetic energy is speed. Under the rotor the pressure grows rapidly, spasmodically, and the speed grows gradually in view of the inertia of air.

With vertical climb the pattern of velocity distribution and static pressure will be the same as that in hovering, and the only difference of pressures under the rotor and above the rotor will be smaller, owing to the decrease in angles of attack of blades in view of the presence of vertical velocity of climb. By further deflection of the "pitch-throttle" lever back the pilot increases the setting angles and power of the engine, inductive speeds will be greater than those in hovering, which will lead to an increase in the difference in pressures under the rotor and above the rotor, and the thrust of the rotor, necessary for vertical climb, will be increased (see Fig. 16b).

With vertical descent actions of the pilot and phenomena will be inverse to that described during vertical climb: inductive speeds will be less, the difference in pressures will be less, the tractive force will decrease, and the helicopter will descend (see Fig. 16c).

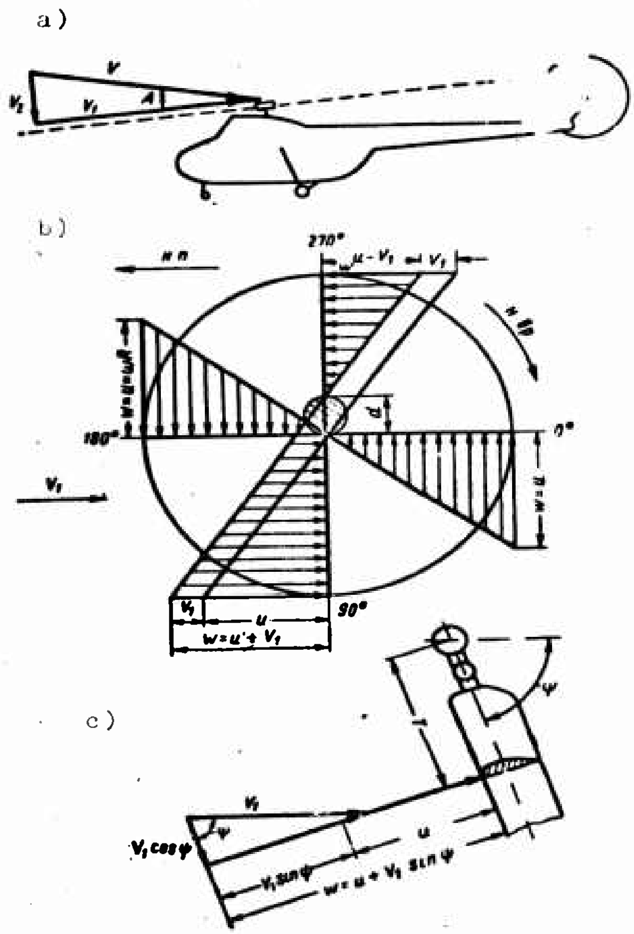

Fig. 17. Addition of speeds during forward flight: a) to the formation of speed V_1; b) values of instantaneous true speeds W of rotor blades in azimuthal positions 0, 90, 180 and 270°; c) value of instantaneous speed W in the arbitrary azimuthal position ψ.

where ω – angular velocity; r – radius of the blade element.

In position $\psi = 90°$ the true speed will be maximum, since the whole forward velocity, lying in the plane of rotation, will be added with the peripheral velocity and $\sin 90° = 1$. With further motion of the blade to $\psi = 180°$ the speed will decrease and, when it occupies position $\psi = 180°$, it will have only a peripheral velocity, since $\sin 180° = 0$ (see Fig. 17b).

Upon motion of the blade to $\psi = 270°$ it will retreat from the flow. From the peripheral velocity there will be subtracted at first part of the forward velocity, and in the azimuthal position $\psi = 270°$ – all the forward velocity V_1. Consequently, in position $\psi = 270°$ the blade will have a minimum true speed of flow. In this azimuth with the approach to the axis of rotation, for elements of the blades the peripheral velocity will decrease, and the forward velocity V_1, subtracted from the peripheral will be constant. Therefore, the true speed will decrease, and on some section of the blade it will be equal to zero, and the peripheral velocity is equal to the forward V_1.

On sections of the blade even nearer to the axis of rotation the peripheral velocity will be less than the forward V_1, and therefore the blade in these places will obtain a reverse flow, i.e., it will be flowed around not from the leading edge but from the trailing edge. To the right of the axis of rotation (for the Mi-4 helicopter during forward flight) there will be formed the zone of reverse flow around in the form of a circle (see Fig. 17b), having gotten into which part of the blade is flowed around from the trailing edge. The magnitude of this zone (its diameter) depends on the value of forward velocity and peripheral velocity (number of revolutions of the rotor): the more the speed of the flight V_1 and the less the number of revolutions of the rotor, the bigger the diameter of the zone of reverse flow will be. In the zone of reverse flow lift is not created.

As can be seen from the right triangle (see Fig. 17a), the speed lying in the plane of rotation,

$$V_1 = V \cos A. \qquad (16)$$

Let us substitute this expression into formula (15), and we will obtain the true speed of flow around of the element of the blade:

$$W = \omega r + V \cos A \sin \psi. \qquad (17)$$

From formula (17) it is clear that the velocity of flow around of the examined element of the blade depends on the angular velocity of it – ω (number of revolutions of the rotor), the radius of the blade element to the axis of rotation r, the speed of flight of helicopter V, the angle of attack of the rotor A and the azimuthal position of the blade ψ at which this element is found.

Consequently, from the pattern of streamline flow of the rotor the conclusion can be made that in forward flight the rotor has an asymmetric velocity field, i.e., for half of the disk surface where the blades, advance on the flow (for the Mi-4 helicopter the left half), the speed of flow around will be greater than the peripheral velocity, and for other half where the blades retreat from the flow (for the Mi-4 helicopter the right side), the speeds will be less than the peripheral owing to the subtraction of forward velocity. Such an asymmetric velocity field will cause an asymmetric field of aerodynamic forces in the presence of a rigid rotor.

Influence of the speed of flight V_2 lying perpendicular to the plane rotation. This speed, being added with the induced speed, will decrease the angles of attack to all elements of the blades. Figure 18 gives a velocity polygon of the element of the blade of the rotor in forward flight. If flight passed at an angle of attack equal to zero, then there would be absent the speed lying perpendicular to the plane rotation, V_2, and there would be only speed $V_1 \sin \psi$; then the true speed of the element would be W_1, and the angle of attack of the element α_1. But if flight is accomplished at speed V (in this case climb) at an angle of attack A, then this speed can be decomposed into components $V_1 \sin \psi$ and V_2 lying perpendicular to the plane

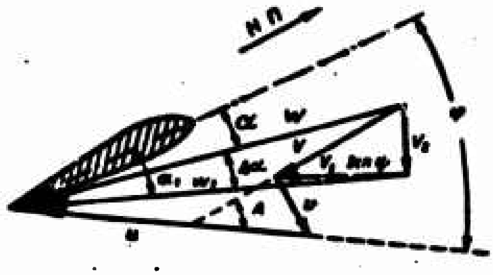

Fig. 18. Velocity polygon of the blade element of the rotor during forward flight of the helicopter.

rotation. This speed will decrease the angle of attack by $\Delta\alpha$, the true speed will be W, and the true angle of attack α is less than the former α_1.

Relative speeds. Operating conditions of the rotor or conditions of flight of the helicopter can be characterized by two relative speeds — by dimensionless quantities less than unity: characteristic of conditions μ and coefficient of flow λ.

The characteristic of operating conditions of the rotor is determined by the ratio of flight speed lying in the plane of rotation to the peripheral velocity of the blade tip of the rotor: $\mu=\frac{V\cos A}{\omega R}$, or the characteristic of the conditions can be defined as the ratio of the diameter of the zone of reverse flow around to the radius of the rotor: $\mu=\frac{d}{R}$, since $d=\frac{V\cos A}{\omega}$, and the diameter of the zone of reverse flow around d is the radius of the section in which the true speed of flow around is equal to zero:

$$W=\omega r+V\cos A\sin\psi=\omega r+V\cos A\sin 270^\circ=\omega r+$$
$$+V\cos A(-1)=\omega r-V\cos A=0,$$

then $\omega r = V\cos A$. Hence $r=\frac{V\cos A}{\omega}=d$.

Inasmuch as most frequently flights on helicopters are carried out with forward velocity and at average speeds at which the angle of attack of the rotor is small, about 5-10°, and the cosine of small angles is close to unity, the characteristic of the conditions is practically determined by the division of the speed of flight of the helicopter by the peripheral velocity of the blade tip of the rotor $\mu=\frac{V}{\omega R}$. In conditions of hovering the characteristic of operating conditions of the rotor is equal to zero, and with an increase in speed of forward flight with constant revolutions of the rotor it is increased and at maximum speed for the Mi-4 helicopter reaches the value of 0.3.

The characteristic of operating conditions of the rotor shows that part of the peripheral velocity of the blade tip is comprised by the speed of forward flight of the helicopter or what part of the length of the blade is occupied by the zone of reverse flow around.

The flow coefficient is determined by the ratio of the sum of speed of flight lying perpendicular to the plane of rotation (along the axis of the rotor) and induced speed to the peripheral velocity of the blade tip of the rotor:

$$\lambda=\frac{V\sin A+v}{\omega R};$$

The coefficient of flow has maximum value in conditions of the most advantageous climb and for the Mi-4 helicopter is about 0.2, in conditions of hovering it is less, about 0.05 (since speed V sin A is absent), and at maximum speed of horizontal flight even less, about 0.03.

The coefficient of flow shows what part of the peripheral velocity of the blade tip is comprised by the flow rate of air through the rotor down from above along the axis of the shaft (speed of flow).

The indicated relative speeds in flying practice are not encountered, but they received wide application in aerodynamic designs of helicopters.

<u>Induced speed during forward flight</u>. In vertical conditions of flight the rotor creates a tractive force owing to the rejecting of the mass of air through the rotor with a definite induced speed. The volume of this airmass per second is the volume of the cylinder with a diameter equal to the diameter of the rotor and height equal to the induced speed. The thrust of the rotor is defined as the product of airmass flow rate per second through the rotor by inductive speed (see Formula 13). Here the operation of the rotor can be compared with the operation of the propeller of an aircraft.

In forward flight operation of the rotor of a helicopter can be roughly compared with the operation of a wing — monoplane of an aircraft. From aerodynamics of an aircraft it is known that the volume of air per second participating in the creation of lift of the monoplane is equal to the volume of a cylinder with a diameter equal to the wingspan and with an height equal to speed of flight of the aircraft. Here the section of the stream of air is presented in the form of a circle with a diameter equal to the wingspan (front view). The lift of the wing can be determined by the product of flow rate per second of airmass through the wing by the speed of induced rake.

There will be such a diagram of the formation of thrust by the rotor in forward flight. The volume of air per second participating in the creation of tractive force will be equal to the disk area, on the speed of forward flight of the helicopter, and thrust will be determined by the product of this volume by the mass air density and the speed of inductive rake. But since the speed of forward flight is great, the flow rate per second of airmass through the rotor will be great, and, consequently, to create the same tractive force as that in conditions of hovering, according to theorem of momentum, there will be required a lower speed of repulsion, i.e., lower inductive speed. This means, in forward flight in the creation of tractive force there additionally participates the speed of flight, and the greater the speed of flight, the greater the flow rate per second of airmass through the lift system, and the greater the thrust of the rotor. On the basis of this the thrust of an ideal rotor in flight with forward velocity is determined by the formula

$$T=2\pi R^2\rho vV \text{ [kgf]}, \tag{18}$$

where V is the speed of forward flight of the helicopter in m/s.

Solving this equation with respect to v, we obtain the formula of the average required induced speed in forward flight:

$$v=\frac{T}{2\pi R^2\rho V} \text{ [m/s]}. \tag{19}$$

From formula (19) it is clear that the greater the speed of forward flight of the helicopter, the less inductive speed is required. On the average one can assume that at maximum speed of horizontal flight it is twice less than in conditions of hovering for a given helicopter. A decrease in inductive speed leads to a decrease in induced drag of blades of the rotor, and with an increase in flight speed of the helicopter — to a decrease in the necessary inductive power, which will be discussed more specifically below.

Formation of lateral moment in a rigid rotor and the necessity of the introduction of a flapping hinge. Above examined was the operation of a rigid rotor, the blade of which did not have a hinge. Here it established that during forward flight the rotor has an asymmetric velocity field over the span of the rotor. This, in turn, leads to the creation of asymmetric thrust along this surface. If the rotor will be rigid, then half of the disk surface where the blades advance on the flow will have greater thrust than the opposite half where the blades retreat from the flow. The resultant thrust will pass not through the axis of rotation, but nearer to the large force and will create for a single-rotor helicopter a lateral moment around the longitudinal axis of the helicopter, which will tilt the helicopter in the direction of retreating blades from the flow (Fig. 19a). Thus this was the case for the first single-rotor

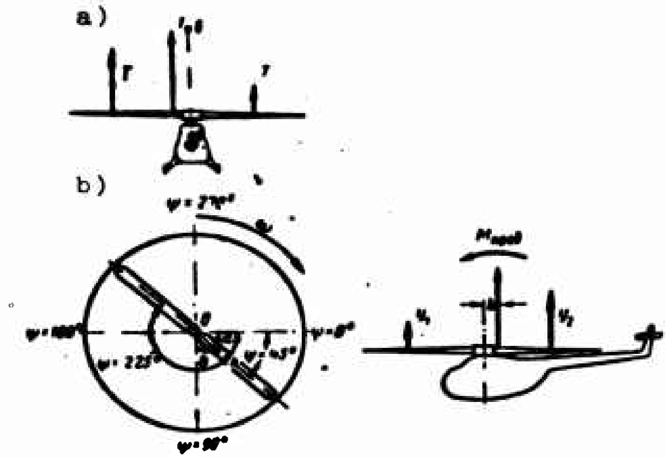

Fig. 19. Lateral and pitch moments in a rigid rotor: a) for a rotor with any number of blades; b) for a two-bladed rotor.

helicopters with rigid rotors: they could fulfill hovering, move at low speeds, but at high speed a lateral tilting moment appeared, which was impossible to parry by control. For this reason the speeds of helicopters were extremely limited.

For a two-bladed rigid rotor, besides the lateral moment a pitching moment appears around the lateral axis of the helicopter, since the asymmetry of thrusts appears and along the longitudinal axis in view of various speeds for blades which are simultaneously in various aximuthal positions, for example, in position $\psi = 45$ and 225° (Fig. 19b).

Furthermore, the blade of a rigid rotor is loaded by aerodynamic forces, and there is great bending moment at the place of attachment of the blade to the hub. In vertical flight conditions this moment does not change in magnitude in one revolution. In forward flight owing to the asymmetric velocity field and lifts the bending moment in one revolution will change for each blade from the minimum to maximum value. This will lead to fatigue stresses and breakdown of the blade. To ensure the strength of such a rotor it will be required to increase the section of bracing elements and this will lead to an increase in weight of construction of the helicopter. Then with that same power of the engine it is necessary to proceed in decreasing the useful load.

At the same time periodically changing moments will be transmitted to the helicopter, causing increased vibrations, and will harmfully be reflected on the whole construction of the helicopter, its equipment and on the organism of man. Furthermore, for a helicopter with a rigid rotor stability worsens, and it is impossible to control it with the help of the automatic pitch control.

At present different methods are applied for eliminating the above-enumerated deficiencies of the rotor with rigid blades, but the most widespread method is the hinged suspension of the blades.

3. Flapping Hinge

With stiffening of the blade to the hub lift forces $Y_{Л}$, created by it will be periodically changed in value in one revolution in forward flight, as is shown on the diagram of loads (Fig. 20a). Here the bending moments M_y, will also change in each revolution, as was shown on the diagram of moments. In the presence of a flapping hinge the bending moment at the place of sealing of the blade will be equal to zero (Fig. 20b), since through the hinge moments are not transmitted, and the sum of moments of all forces having an effect on the blade relative to the flapping hinge in the same way will be equal to zero. For this reason there will be provided a more reliable attachment of the blade to the hub and the section of the bracing parts is decreased, and therefore the decrease in weight of construction of the helicopter is possible. Since moments through the hinge are not transmitted, then vibration helicopter up to permissible limits will be decreased.

Only with the introduction of the flapping hinge is it possible to control the helicopter by a change in cyclical pitch of the rotor

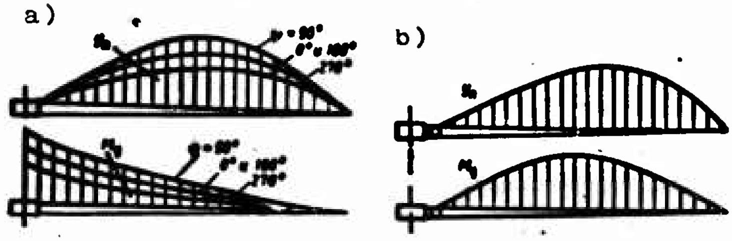

Fig. 20. Aerodynamic loads and bending moments having an effect on the blade in forward flight: a) on a rigid blade; b) on a blade having a flapping hinge.

with the help of the cyclic pitch control.

Owing to the spacing of the flapping hinges (distances from the axis of rotation to the axis of the flapping hinge) the helicopter obtained a damping moment of the rotor, which prevents the disturbance of equilibrium by external forces acting on the helicopter. But the main assignment of the flapping hinge consists in the fact that now the blade was able to accomplish flapping motions around the flapping hinge not only at the will of the pilot by cyclical change in pitch but also independently in forward flight owing to the difference in speeds and lifts. Flapping motions in the presence of a flapping hinge lead to the preservation of lift of for a separately taken blade constant in one revolution (see Fig. 20b) and to almost equal distribution of lifts over the disk surface. The uniform distribution of lift led to the elimination of lateral tilting moment, and this, in turn, made it possible to increase the speed of the single-rotor helicopter.

Consequently, by introduction of the flapping hinge the following were achieved:

a) reliable fastening of blades to the hub;

b) decrease in weight of construction of the helicopter;

c) possibility of control of the helicopter by cyclic rotor pitch;

d) decrease in the level of vibrations

e) certain static stability;

f) flapping motion of the blades, owing to which lift over the disk surface is evenly redistributed, and thereby the lateral moment is removed and other characteristics of the helicopter are improved.

<u>Forces acting on the blade in the flapping plane</u>. In order to examine the kinematics of a blade having a flapping hinge and to understand how lift from the blade is transmitted to helicopter if moments are not transmitted, we will examine forces acting on the blade in the flapping plane and their action.

Acting on the blade in the flapping plane in vertical flight conditions of the helicopter are the following forces (Fig. 21): lift $Y_{\text{л}}$, force of weight of the blade $G_{\text{л}}$ and centrifugal force $F_{\text{цб}}$. In forward flight besides these forces there will still be acting inertial forces $F_{\text{ин}}$ because of the change in acceleration of flapping motions of blades and their droop.

In vertical flight conditions the blades will form the coning angle a_0 (angle between the blade and plane of rotation of the rotor), since lift of the blade is greater than its weight. In vertical conditions of flight the coning angle is constant for all blades and in all azimuthal positions. In forward flight, owing to flapping motions, the coning angle changes, and then it is called the angle of flapping β. Owing to lift the blade does not depart high from the plane of rotation, since the centrifugal force and weight of the blade create moments acting in the opposite direction of the moment from lift. The sum of all moments with respect to the flapping hinge is always equal to zero, and the blade is set in a definite place on the flapping hinge, i.e., it will be directed along the resultant of all forces $R_{\text{л}}$ acting on the blade and will be

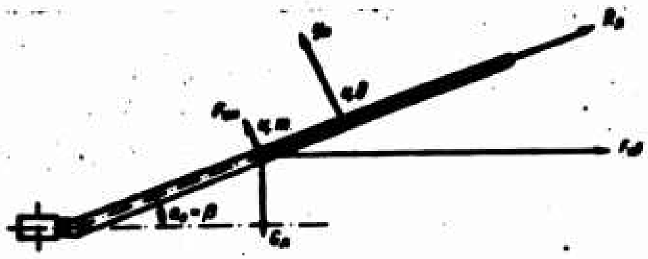

Fig. 21. Forces acting on the blade in the flapping plane.

lower than the upper rest of the flapping hing.

Lift from the blade is transmitted to the helicopter in the following way. Resultant forces of each blade $R_{л}$ are directed from the plane of rotation upwards at a certain coning angle α_0 or flapping angle β and stretch the helicopter beyond the rotor hub. If all the resultants are added pairwise by rule of the parallelogram, then we will obtain the total force — resultant of the whole rotor; it is the total thrust of the rotor or lift (depending on what conditions of flight the helicopter is in).

Forces acting on the blade in the flapping plane considerably differ from each other in magnitude. Lift of the blade is usually 12-15 times more than its weight, and centrifugal force is 10-12 times more than lift. Thus, for example, the weight of a blade of mixed construction of the Mi-4 helicopter is 120 kg and lift — 1800 kg. The centrifugal force of the blade is determined by the formula

$$F_{цб} = m r_{ц.т} \cdot \omega^2, \qquad (20)$$

where m — mass of the blade equal to $\frac{G_л}{g}$; $r_{ц.т}$ — radius of center of gravity of the blade; ω — angular velocity.

In nominal operating conditions of the engine a centrifugal force of about 20,000 kgf acts on every blade. Centrifugal force is a powerful damper of flapping motions of blades around flapping and drag hinges.

The flapping hinge of the blade has upper and lower limiters (rests). The upper rest of the flapping hinge is located so that the blade can rise 25° above plane of rotation. The lower rest permits lowering the blade 4° lower than the plane of rotation (angle of overhang), and at revolutions below 1700 per minute the angle of overhang is 1°40' owing to the centrifugal limiter of the angle of overhang.

4. Flapping Motion of the Blades

It is established that in hovering conditions and vertical conditions of flight during the rotor operation, blades of it are lifted above the plane of rotation owing to the fact that their lifts are greater than the weight. Since lift of blade does not change, then the coning angle as yet will be considered constant. If, however, in any vertical flight conditions cyclical change of rotor pitch with the help of the control stick is given, then in each revolution of the blade the setting angles from their some minimum to maximum value will be changed. A change in setting angles will lead to a change in angles of attack and lifts of the blades. As a result of the change in lifts the blades will accomplish oscillations around the flapping hinges which is called flapping motion of the blades.

But in forward flight the flapping motion of blades will be carried out independently, without interference of the pilot, since here lifts of blades will be changed owing to various true speeds of the flow around.

Independent flapping motions of blades in forward flight lead to two phenomena: redistribution of lift over the disk surface and collapse of the cone of rotation back and to side.

Redistribution of lift. When the direction of flight coincides with the plane of rotation the angle of attack of the rotor is equal to zero. Such a flight can be with oblique descent with an operating engine and with a small angle. When the blade is above the tail, it will have only peripheral velocity, since the forward velocity V acts along the blade and there is no influence on the magnitude of the angle of attack and lift of it. Therefore, it is not depicted on the velocity polygon in a zero azimuthal position (Fig. 22).

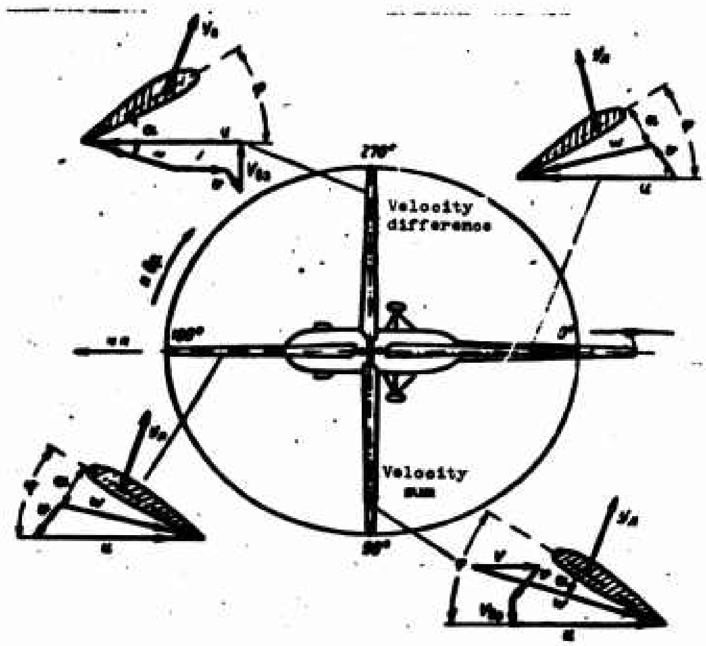

Fig. 22. Redistribution of lift over the disk surface owing to flapping motions of blades.

With motion of the blade to position $\psi = 90°$ the true speed of flow around will be increased, and lift will also be increased. But since the blade has a flapping hinge, it will flap upwards. As a result of this the blade will obtain additional speed of flap V_{B3M}. With the addition of the four speeds, peripheral, induced, forward and flapping speed in the position $\psi = 90°$, the true speed W will be directed toward the chord of the element of the blade at a smaller angle of attack α, than the true speed in position $\psi = 0$. This means that the angle of attack of the blade element decreases owing to additional flowing around from above with a flap of the blade upwards, and this leads to a decrease in the coefficient of lift c_y, which, in turn, leads to a decrease in lift, since lift of the blade

$$Y = c_y \frac{\rho V^2}{2} S \text{ [kgf]}, \tag{21}$$

where S — area of blade of the rotor.

Consequently, the blade passed through the region of high speeds, but as a result of the flap, because of the decrease in angles of attack and coefficient of lift the lift was almost maintained the former.

With motion of the blade to position ψ = 180° the speed of flow around will decrease, and when the blade occupies the azimuthal position of 180° there will be the same phenomenon as in a zero azimuthal position, i.e., the speed of flight will lie along the blade and there will be no influence on the magnitude of lift.

With motion of the blade to position ψ = 270° the speed of flow around will decrease, lift will also decrease, and in view of the presence of a flapping hinge the blade will move downwards, decreasing the flapping angle. The blade will obtain additional flow around from below, as a result of which the angle of attack and coefficient of lift will increase — lift of the blade will be preserved. Consequently, the blade passed through the region of low speeds, and lift was not changed in view of the flap downwards and increase in angles of attack and coefficient of lift.

The change in angles of attack α, coefficient of lift c_y and lift $Y_{\text{Л}}$ for a separately taken blade in one revolution during flapping motion is shown in Fig. 23. It is necessary to note that an increase in angles of attack and coefficient c_y with deviation from the flow will occur to a greater degree than will their decrease with the approach of the blade on the flow. Thus, if in position ψ = 90° the angle of attack of the blade decreased by 2°, then in position ψ = 270° it will be increased not by 2° but by a

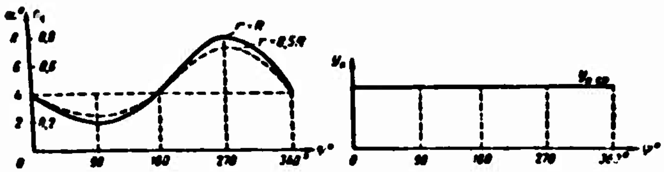

Fig. 23. Change in angles of attack of lift coefficient and lift of the blade in one revolution during its flapping motion.

greater value (in our example in Fig. 23, by 4°). This is explained by the fact that the flapping speed downwards in position $\psi = 270°$ will be greater than that upwards in position $\psi = 90°$ because of a sharper fall of the lift due to the difference in speeds. But such a different change in angles of attack leads to a more equal distribution of lift over the disk surface.

A change in angles of attack and coefficient c_y will occur to a greater degree for those elements which are located nearer the tip of the blade, since in these places the flapping speed is greater. Figure 23 shows two curves of the change in angles of attack: for the section of the blade tip and for section located in the middle of the blade (dashed curve). The nearer the section to the root of the blade, the change in angles of attack and coefficient of lift will be less, and at the blade root these changes will not occur.

The magnitude of flapping motions and also the degree of change in angles of attack and coefficient c_y depend on the speed of forward motion: the higher the speed, the more the flapping motions, and the degree of change in angles of attack and c_y will be greater, but lift will be maintained in view of its redistribution. At very high speed, higher than is permissible in operation, angles of attack in the azimuthal position of 270° can become greater than the critical; then separation of flow from blades advances, which leads to a decrease in coefficient c_y and an increase in the coefficient of drag c_x. The redistribution of lift evenly over the disk surface makes it possible to eliminate the lateral tilting moment which was with the rigid rotor and thereby obtain the possibility of increasing the speed of helicopters.

From what has been said the conclusion can be drawn that if for the wing of an aircraft in rectilinear flight along the wingspan a symmetric field of speeds, angles of attack, coefficients c_y and lifts are observed, then for a rotor with hinged blades in the same flight owing to flapping motions we observe an asymmetric velocity field, asymmetric field of angles of attack and coefficients c_y, but the symmetric field of lifts is along the span of the rotor.

Character of flapping motions and collapse of the cone of rotation. As was mentioned above, flapping motions of blades, induced by the pilot through the automatic pitch-control mechanism, caused deflection of the cone of rotation of the rotor and direction of action of aerodynamic force to an undesirable direction owing to the inertia of blades in their flapping motion. This deflection is eliminated because of the system of advance of control. In forward flight flapping motions of the blades, appearing because of the asymmetric velocity field, can also cause deflection of the cone of rotation of the rotor and direction of the action of aerodynamic force of the rotor to some direction.

If one were to consider forces of inertia of the blade with its flapping motion, it will have a minimum flapping angle in position $\psi = 270°$, where the speed of flow around and, therefore, lift are minimum. With its subsequent motion the speed of flow around, and this means lift, will increase, and the blade will start to rise, revolving around the flapping hinge, increasing the flapping angle. In position $\psi = 90°$ the flapping angle should be maximum, since here the speed is maximum. Then the blade will be lowered, decreasing the flapping angle, following to position $\psi = 270°$. But acting on the blade with its flapping motion is the force of inertia, which changes the character of the flapping motions. The force of inertia always strives to maintain the speed constant and is directed to the side opposite acceleration. This means that with the acceleration of flapping the force of inertia will be directed opposite the motion of the blade along the flapping hinge, and with deceleration of the flapping speed – in the direction of the motion of the blade.

The maximum speed of flow around is reached by the blade in position $\psi = 90°$, and therefore with motion of it to this azimuth it will flap upwards. With further motion of the blade the speed of flow around it decreases and the flapping rate decreases, but the force of inertia will be directed upwards, and therefore the blade will continue the flap upwards, increasing the angle of the flap. The blade will cease its upward motion, investigations showed, only emerging beyond the position $\psi = 180°$, about $\psi = 200°$. Here it will take the highest position with the maximum flapping angle. Then the blade will start to be lowered. After position $\psi = 270°$, although the speed will be increased, the blade will continue lowering by inertia, and it will attain the minimum flapping angle in the azimuthal position of about 20° (Fig. 24a). But since such flapping motion is accomplished by each blade, then it appears that the cone of rotation of the rotor will deviate owing to flapping motions in the direction of advancing blades on the flow, more accurately, in the direction of the azimuthal position of 20°, i.e., back and to the left (Fig. 24b, c).

The collapse of the cone of rotation of the rotor back is explained not only by the inertia of the blades in their flapping motion but also by the change in lift of the blade owing to the change in angles of attack depending upon the direction to it of the speed of flight. With flight of the helicopter forward, when the blade is ahead of the helicopter – in the second and third quarters of the circle, the flow will approach to it from beneath (Fig. 25a), and the angle of attack of the blade will become greater (Fig. 25b). An increase in the angle of attack will lead to an increase in lift, and the blade will continue flapping upwards, in spite of the fact that after the azimuthal position of 90° the speed of flow around of the blade decreases. When the blade is behind the helicopter – in the fourth and first quarters, the flow will approach it from above (see Fig. 25a), and therefore the angle of attack of

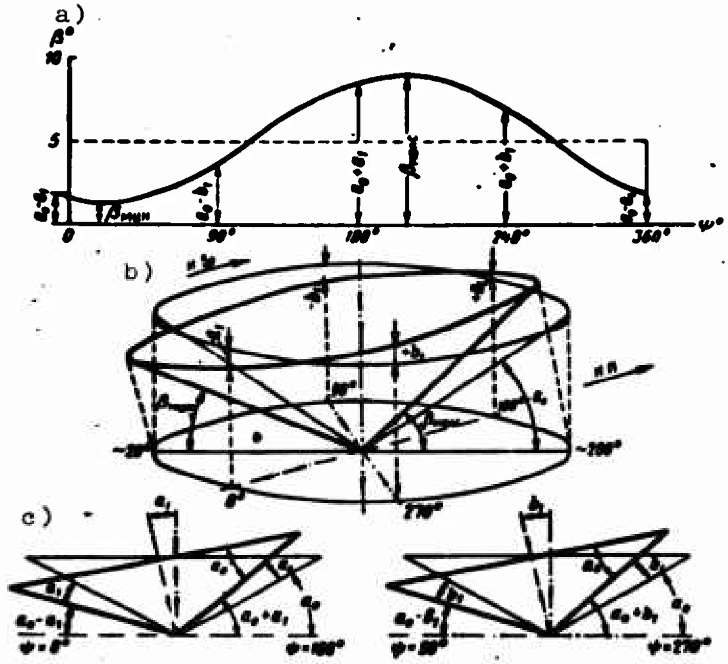

Fig. 24. Change in flapping angle and deflection of the cone of rotation of the rotor: a) curve of the change in flapping angle of the blade in one revolution; b, c) collapse of the cone of rotation of the rotor.

the blade will become less (Fig. 25c). A decrease in angles of attack will lead to a decrease in lift, and the blade will continue flapping downwards, in spite of the fact that from the azimuthal position of 270° the speed of flow around of the blade started to increase. Therefore the cone of rotation will be collapsed (blown away) back.

Such an collapse of the cone of rotation of the rotor is undesirable, since the aerodynamic force of the rotor acting perpendicular to the base of the cone (plane passing through tips of blades, which is called the effective plane of rotation of the rotor) will deviate to the same direction, i.e., back and to the left. Deflection of the direction of action of aerodynamic force of the rotor to the left creates left slip to the helicopter, and if one

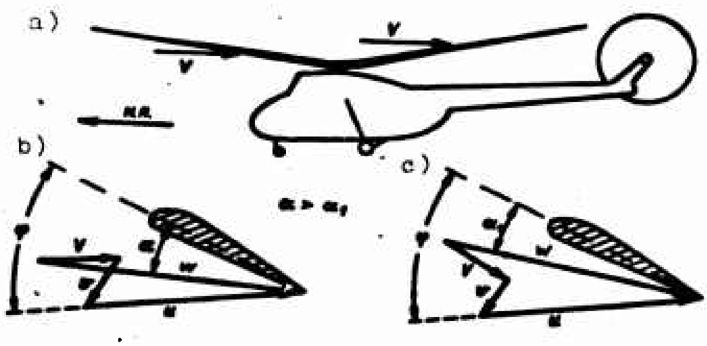

Fig. 25. Effect of incident flow at speed of flight V on angles of attack of blades: a) direction of flow on blade of rotor in horizontal flight; b) angle of attack for element of the blade passing ahead of the helicopter; c) angle of attack for element of the blade passing above the tail boom.

were to consider that tractive force of the tail rotor in flight with an operating engine also acts to the left, then there is created such a left slip with which it will be impossible to handle the control system of the helicopter. Deflection of the direction of action of aerodynamic force back will cause a longitudinal force, which will brake motion of the helicopter forward. Therefore, the flapping motion of the blades must be limited in magnitude, and it is necessary to direct the cone of rotation and aerodynamic force in the needed direction.

The powerful means limiting the flapping motion of the blades are their centrifugal forces. Moreover, the flapping motion is limited by the fact that with flapping the angle of attack of the blade is changed. This limitation received the name "aerodynamic flapping balance." But one aerodynamic balance is insufficient, since this balance is uncontrollable. Therefore, a damping device is introduced, which limits flapping even greater. Such a damping device is the flapping control (guide flapping compensation). The flapping control is provided not only as a means of a control advance but also as a means of limitation of flapping motions of the blades.

Flapping control. The essence of the flapping control (guide compensation) consists in the fact that the rod connecting the lever of the blade with the plate of the cyclic pitch control occupies strictly a definite position with respect to axes of the flapping and feathering hinges. This rod is displaced from the longitudinal axis of the blade forward on rotation of the rotor at distance b and from the axis of the flapping hinge into the depth of the blade at distance a (Fig. 26a). Such a position of the rod shown permits that with flapping of the blade upwards its setting angle decreases, and with flapping downwards it is increased (Fig. 26b). This change in setting angle occurs because the blade upon flapping rocks around the axis of the flapping hinge, and together with it the lever of the blade will rise, but the rod fastened to the plate of the cyclic pitch control remains motionless; as a result the blade is forced to rotate around the feathering hinge, changing the setting angles. The greater the distance a, the setting angle ϕ will be changed to a greater degree upon flapping of the blade. An increase in distance b of the rod control of the blade from the axis of the feathering hinge increases the degree of advance of control.

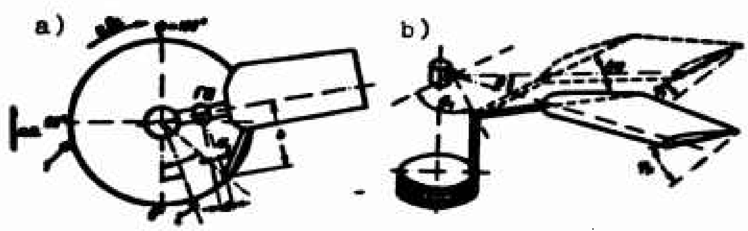

Fig. 26. Flapping control; a) kinematic diagram; b) setting angle of blade during its flapping; 1 – rod of lateral control; 2 – rod of longitudinal control.

This means that setting angles of blades $\phi_{Л}$ for the Mi-4 helicopter are changed by the "pitch-throttle" lever by the same value for all blades simultaneously and by the control stick – cyclically and independently owing to the presence of the flapping control, if they accomplish flapping motions around the flapping hinges.

The presence of the flapping control will limit the flapping motion of the blades, since upon flapping of the blades upwards a decrease in setting angle will lead to a decrease in lift and limitation of flapping upwards. With flapping downwards, on the other hand, an increase in setting angle will limit flapping of the blade downwards.

Besides such limitation of flapping motions, the flapping control will transfer the maximum and minimum angles of flapping of blades to another azimuthal position. If without the flapping control the maximum angle of flapping was in position $\psi = 200°$, and the minimum flapping angle in position $\psi = 20°$, then now the maximum flapping angle will be approximately in position $\psi = 160°$, and the minimum in the opposite position — about $\psi = 340°$. Therefore, the cone of rotation will appear deflected in the direction of $\psi = 340°$, i.e., back and to the right. To the same direction the direction of action of aerodynamic force of the rotor will deviate, and its lateral component will be directed to the right and will balance the thrust of the tail rotor acting to the left. Then flight will be accomplished without slip even with the neutral control stick in a lateral ratio if the indicated forces will be equal to each other. If, however, the lateral component of the aerodynamic force of the rotor acting to the right will not be equal to the thrust of the tail rotor, then slip will appear. Then the pilot is obliged to balance these forces by deflecting the control stick in a lateral direction.

In average speeds of flight of the helicopter the deflection of cone of rotation of the rotor and direction of action of aerodynamic force of the rotor owing to the flapping motions and presence of the flapping control of the rotor completely balances the thrust of the tail rotor, without interference of the pilot, so that the control stick can remain in a neutral position in a lateral ratio. At speeds less than medium flapping motions of the blades and deflection of the cone of rotation of the rotor are insignificant, the lateral component of aerodynamic force is insufficient and the pilot supplements it by motion of the control stick to the right. At speeds higher than average flapping motions of the blades and deflection of the cone of rotation of the rotor are unnecessary; the pilot decreases the lateral force by motion of the control stick to the left. Furthermore, the flapping control more accurately redistributes lift over the disk surface. If without the flapping control with motion of the blade to position $\psi = 90°$ its angles of attack decreased owing to the presence of the flapping rate upwards, which decreased lift, then now the flapping control will additionally decrease the setting angle, decreasing lift to a greater degree. With motion of the blade to position $\psi = 270°$ a reverse phenomenon will occur: the flapping control will increase lift owing to the increase in setting angle.

With engine failure and also when turning the engine off for the purpose of intentional gliding the flapping control promotes the better and faster transition of the rotor to autorotation. With failure or turning off of the engine the number of revolutions of the rotor decreases, this leads to a decrease of centrifugal forces of the blades, but as a result of this the coning angle increases, and flapping controls decrease the setting angles of the blades by an identical value, i.e., decrease the collective pitch without interference of the pilot. Such an action promotes transition of the rotor to autorotation.

The degree of action of the flapping control is determined by the characteristic of flapping control K. The characteristic of the flapping control is the tangent of the angle of the flapping control σ_1, i.e., the angle included between the axis of the flapping hinge and straight line connecting the point of crossing of axes of the flapping and feathering hinges with attachment point of the lever of the blade and control rod (see Fig. 26a, b): $K = \mathrm{tg}\,\sigma_1 = \frac{a}{b}$.

The characteristic of the flapping control for helicopters occurs within limits of 0 to 1. If $K = 0$, this means that distance a is equal to zero; and then with flapping of the blade its setting angle will not be changed, since the blade and its lever will revolve around one axis of the flapping hinge. If $K = 1$, then distances a and b will be equal to each other and the effect of the flapping control will be great. For the Mi-4 helicopter the characteristic of the flapping control K = 0.5. Such a vlaue of the characteristic of the flapping control ensures at average speeds of flight deflection of the cone of rotation of the rotor and direction of action of aerodynamic force so that its lateral component is equal to the thrust of the tail rotor, and flight is accomplished without slip at neutral position of control stick in a lateral direction.

Coefficients of flapping motion. From that examined earlier it follows that the cone of rotation of the rotor and, together with it, the direction of action of its aerodynamic force can be deflected to any side by the desire of the pilot. But at the same time the cone of rotation and direction of action of aerodynamic force are also deflected back and to the left owing to flapping motions in forward flight. However, in connection with the fact that the deflection to the left is irrational, then with the help of the flapping control deflection of the cone of rotation and direction of action of aerodynamic force to the right changed, and thereby balanced the tractive force of the tail rotor completely or partially, depending upon the speed of flight and magnitude of deviation.

The magnitude of flapping motions is changed (estimated) not by the magnitude of the flapping angle but by coefficients of flapping motion a_1 and b_1 (a_1 – angle of deflection of axis of the rotor cone from the axis of the rotor shaft back and b_1 – angle of deflection of the axis of the cone from the axis of the shaft to the right – Fig. 27a, b). The magnitude of flapping motions, and this means and coefficienta $a_1 b_1$, depends on the characteristic of operating conditions of the rotor μ or on the speed of flight of the helicopter V.

In conditions of hovering flapping motions are absent, and therefore coefficients of flapping motions are equal to zero. With the transition to forward flight flapping motions appear and coefficients of these motions grow, i.e., the deflection of the cone of rotation back and to the right is increased (Fig. 27c). But at any flight speed, or with any characteristic of operating conditions

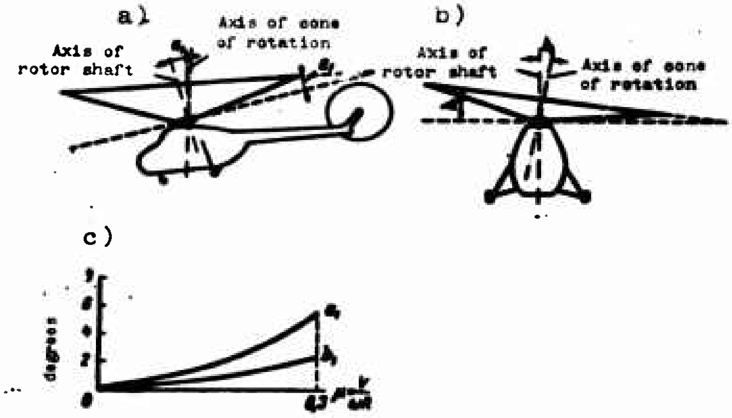

Fig. 27. Coefficients of flapping motions: a) coefficient of flapping motion characterizing deflection of the cone of rotation of the rotor back; b) coefficient of flapping motion characterizing deflection of the cone of rotation of rotor to the right; c) dependence of coefficients of flapping motion on the characteristic of operating conditions of the rotor.

of the rotor μ coefficient a_1 is greater than b_1 approximately twice, since the cone is always deflected back more than to the right. The coefficients shown are small in value. Thus coefficient a_1 at maximum speed is about 6° and coefficient b_1 – about 3°.

<u>Inertial moments of the hub owing to spacing of flapping hinges</u>. In forward flight of the helicopter on the rotor hub there are longitudinal and lateral moments from mass (centrifugal) forces of blades. These moments appear due to the presence of the spacing of the flapping hinges.

<u>Spacing of the flapping hinge</u> is called the distance from the axis of rotation of the rotor to the axis of the flapping hinge (distance ℓ in Fig. 28a). When the axis of the cone of rotation coincides with the axis of the rotor, the moment from centrifugal forces of the blades is absent, since centrifugal forces are directed along the plane of rotation of the rotor (see Fig. 28a). In forward

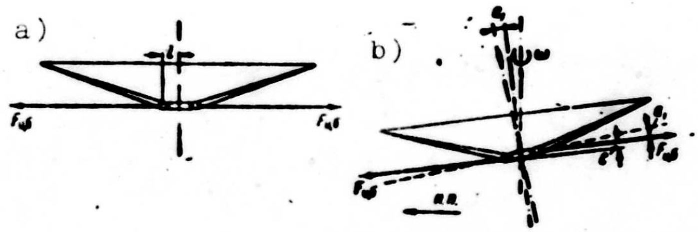

Fig. 28. Moments of the hub owing to the spacing of the flapping hinges: a) conditions of hovering; b) flight forward.

flight with oblique airflow of the rotor the cone of rotation of the rotor is deflected back, then centrifugal forces act in parallel to the base of the cone of rotation (perpendicular to the axis of the cone), but they are located in various planes and therefore will form a pair of forces with arm c (Fig. 28b). The moment of this pair of forces will be the moment of the hub owing to the difference in the flapping hinges:

$$M_{вт} = F_{цб} c \text{ [kgf·m]}.$$

In this case the moment of the hub will be longitudinal, since we took the pair of forces in longitudinal plane, and it will be pitching, i.e., directed in the direction of deflection of the cone of rotation of the rotor. If the pair of forces is examined in a lateral plane, the moment of the bushing will be lateral and directed also in the direction of deflection of the cone of rotation.

<u>Aerodynamic and automatic flapping compensation</u>. The independent flapping motion of blades in forward flight is a positive phenomenon. It is created by the introduction of flapping hinges in order to redistribute lift evenly over the disk surface, thereby to eliminate lateral tilting moment taking place for a rigid rotor and to make it possible for a helicopter to develop relatively high speed. But too high flapping motion of the blades can lead to an impact of them against the upper and lower rests of the flapping hinges. If, however, there are no impacts, then there will be great deflections of the cone of rotation of the rotor back and to the side, which is

also undesirable since there will appear great projections of aerodynamic force on the plane of rotation of the rotor, and these forces will create braking of the flight and slip. Therefore, flapping motions of the blades must be limited.

This limitation is carried out on the one hand owing to the change in angles of attack during flapping motion and bears the name of "aerodynamic flapping compensation" and on the other owing to presence of the flapping control, i.e., the change in setting angles during flapping motions of the blades; it has name of "automatic or guide flapping compensation."

5. Drag Hinge

With the introduction of flapping and drag hinges the motion of the blade was complicated, and now it consists of forward motion together with the helicopter, rotation of the blade with respect to the axis of the rotor, flapping motions relative to the flapping hinge and rotation around the drag hinge.

In order to clarify the assignment of the drag hinge, let us examine forces acting on the blade in the plane of rotation of the rotor and what influence they render on its kinematics.

The following forces, act on the blade in the plane of rotation of the rotor (Fig. 29).

1. The drag of the blade $Q_{Л}$ (circumferential force) is applied to the center of pressure of the blade and is directed to the side opposite the rotation on a tangent to circumference, which is circumscribed by the center of pressure of the blade. The drag of the blade, as also drag of the wing, consists of induced, profile and wave drag if the blade tip is flowed around with supercritical speed. In forward flight with a constant number of revolutions of the rotor the drag of the blade in each revolution, although it is changed in value owing to the asymmetric field of speeds it is

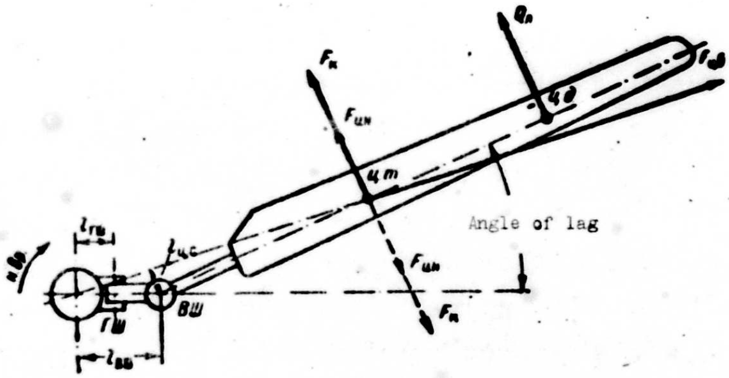

Fig. 29. Forces acting on the blade in the plane of rotation of the rotor.

insignificant, since the flapping motion of the blades and presence of the flapping control redistributes evenly over the disk surface not only lift of the blades but also their drag.

2. Forces of inertia $F_{ИН}$ acting in an opposite direction to angular acceleration. With an increase in the number of revolutions the inertial force will act to a side opposite the rotation and with a decrease in the number of revolutions, in the rotation (shown in Fig. 29 by a dashed vector). The force of inertia is applied to the center of weight of the blade.

3. Centrifugal force $F_{ЦБ}$ is applied to the center of weight of the blade and is directed from the axis of rotation of the rotor.

4. Coriolis forces (turning) $F_{К}$ acting in the rotation and opposite the rotation depending upon the flapping motion of the blades.

Coriolis force. Coriolis force is an additional force of inertia appearing with the resultant motion consisting of rotary and forward if even these motions are uniform. Coriolis force is named after the French scientist Coriolis, who first revealed this force.

For clarification of causes of the appearance of Coriolis forces, we will perform following experiment (Fig. 30). Let us force a body of defined mass M to revolve about a circumference together with a disk, i.e., give to it velocity of following ($u = \omega r$). Simultaneously let us force load M to move over the radius of rotation from the center to the periphery, i.e., let us give to it relative speed V_{OTH}. At a definite moment of time the load is in position 1 and has peripheral velocity $u_1 = \omega r_1$ and forward velocity (relative) from the center to the periphery, V_{OTH}. After some interval of time the disk together with load M will turn at angle ψ. Here load M, revolving together with the disk and moving forward (participating in resultant motion) will move to position 2. In this new position load M will already have a different peripheral velocity owing to the increase in radius, $u_2 = \omega r_2$, and the same forward velocity, V_{OTH}. The angular velocity of rotation ω and forward velocity V_{OTH} were constant, and the peripheral velocity u_2 increased as compared to the preceding peripheral velocity u_1. Therefore, the load actually moved with circumferential acceleration, the acceleration being directed in rotation. The increase in speed causes the appearance of an inertial force acting in the opposite direction of acceleration, and this will be the Coriolis force F_K.

With movement of load M in the opposite direction, i.e., from the periphery to the center of rotation, the circumferential acceleration will be directed opposite the rotation and the Coriolis force in rotation.

The appearance of turning forces can be explained on the basis of the law of conservation of energy. In this particular case the law of conservation of energy will be formulated as the law of conservation of angular momentum, mVr. In our case angular momentums of two positions of body M will have the form:

for position $1 - mu_1 r_1 = m\omega_1 r_1 r_1 = m\omega_1 r_1^2$;

for position $2 - mu_2 r_2 = m\omega_2 r_2 r_2 = m\omega_2 r_2^2$.

According to the law of conservation of angular momentum these moments in two positions should be equal to each other:

$$m\omega_1 r_1^2 = m\omega_2 r_2^2.$$

Since masses m are equal, then $\omega_1 r_1^2 = \omega_2 r_2^2$ should be equal. But since in position 2 the radius is greater then in position 1 ($r_2 > r_1$), then, consequently $\omega_2 < \omega_1$, i.e., the angular velocity in position 2 should be less than that in position 1. This decrease in angular velocity occurs owing to the appearance and action of the Coriolis force, which acts in this case opposite the rotation (see Fig. 30). With movement of load M to the center of rotation there will be the reverse phenomenon - the Coriolis force will act in rotation, increasing the angular velocity of rotation.

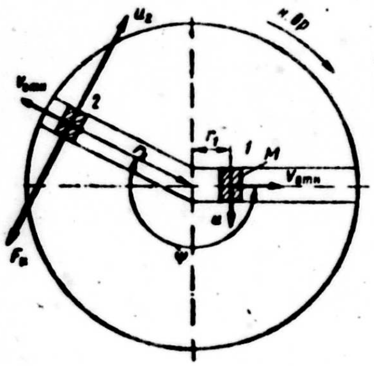

Fig. 30. Diagram of the formation of Coriolis forces.

The Coriolis force is equal to the mass of body multiplied by Coriolis acceleration:

$$F_K = mj_K, \qquad (22)$$

where j_K - Coriolisly acceleration (turning).

From mechanics it is known that coriolis acceleration[1] is equal

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[1]By the action of Coriolis forces certain interesting phenomena in nature are explained. In rivers flowing from north on south or from south to north, masses of water constantly wash the same shore: in the Northern Hemisphere - right, in the Southern Hemisphere - left. As a result of this one shore of the river always occurs steep and the other sloping. The diurnal rotation of the earth deflects the mass of air owing to Coriolis forces acting at a right angle to velocity vector of the wind to the right of the direction of the motion of wind in the Northern Hemisphere and to the left in the Southern Hemisphere. Coriolis forces act on the change in the flow of masses of water in seas and oceans.

to the doubled product of angular velocity by relative speed (perpendicular to the axis of rotation)

$$j_K = 2\omega V_{отн}. \tag{23}$$

With flapping of the blade downwards its center of gravity appears on the large radius from the axis of rotation, i.e., the mass of the blade moves further from the center (r_2 is larger than r_1) if the blade will not turn lower than the plane of rotation of the rotor (Fig. 31). Therefore, there will appear a Coriolis force acting to the side opposite the rotation, being added with the circumferential force of the blade (see Fig. 29). With flapping of the blade upwards its center of gravity will move nearer to the axis of rotation, and therefore a Coriolis force acting in rotation will appear.

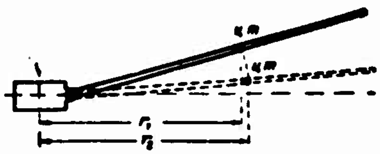

Fig. 31. Change in the radius of the center of gravity of the blade with flapping.

The appearance of Coriolis forces can be visually observed by the organization of experiments on an operational apparatus. The apparatus consists of a pedestal on which a disk revolving by an electric motor is set. On the disk two lead loads, colored with white paint are placed in grooves. The loads can move simultaneously over the radius of rotation to the center or from the center to the periphery by another electric motor through a special reduction gear. The disk can revolve both to the right and left side. A tachometer and control panel are mounted on the pedestal. The apparatus operates on direct current with a voltage of 24 V.

The setting of the experiments is produced in the following way. The disk is accelerated by an electric motor to the right up to steady revolutions, and then the motor is turned on, moving the lead loads from the center to the periphery. On the instrument one can see how the revolutions decrease, and consequently, a Cariolis force acting opposite the rotation appears. When moving the loads to the center of rotation the revolutions increase, and this means the Coriolis force is directed in rotation and increases the angular velocity.

Function of the drag hinge. Let us imagine a blade not having a drag hinge but only a flapping hinge. In vertical flight conditions when flapping motions of blades are absent, on the blade in the plane of rotation bending moments from drag will act. The greatest moment will be at the attachment point of the blade to the hub, but the magnitude of this moment does not change if the revolutions and collective pitch are constant (Fig. 32a).

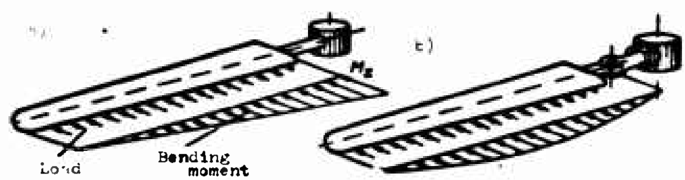

Fig. 32. Diagrams of bending moments in the plane of rotation of the rotor with stiffening of the blade (a) and with the drag hinge (b).

In forward flight there will appear Coriolis forces, which will change the magnitude of the bending moments owing to the change in direction of the Coriolis forces. With flapping of the blade upwards the Coriolis force will be directed in the rotation, decreasing the bending moment, and when flapping downwards it will be directed opposite the rotation, and, being added with drag, will increase the bending moment. Live loads will cause fatigue stresses and can lead to destruction of the blade. To provide strength will require an increase in the section of components fastening the blade to the hub, which will lead to an increase in the weight of construction of the helicopter. Moreover, live loads will be transmitted to the body of the helicopter, causing raised vibration.

By introducing the drag hinge the indicated deficiencies are eliminated, since moments through the hinge are not transmitted. At the place of the drag hinge the moment will be equal to zero (Fig. 32b). Consequently, by introduction of the drag hinge reliable bracing of the blades is ensured, the weight of construction is decreased, vibrations are decreased, and other characteristics of operation of the blades and rotor are improved.

Drag hinges have vibration dampers — frictional dampers which decrease vibrations of blades in flight, during acceleration and stopping of the rotor on land, and they prevent the possibility of the appearance of lateral oscillations of the helicopter on land (ground resonance).

Kinematics of blades in the presence of a drag hinge. The kinematics of blades in the presence of a drag hinge will be the following. In power-on flight the blades always have an angle of lag of about 4° (see Fig. 29) owing to the action of the drag. The blade does not reach the backstops of drag hinges due to the action of centrifugal forces, moments of which are directed forward in rotation. Such moments of centrifugal forces are obtained due to the spacings of the drag hinges, i.e., the distance from the axis of rotation to the axis of the drag hinges. The blades accomplish oscillations around the drag hinges owing to a change in direction of the Coriolis forces. The magnitude of these oscillations depends on the speed of forward motion of the helicopter. In conditions of hovering oscillations are absent, with an increase in speed they appear and increase within limits up to 1.5° at maximum speed. The drag hinges have backstops (limiters). On the Mi-4 helicopter the backstop is at 6° 40' from the neutral axis of the blade (perpendicular to the axis of the flapping hinge).

In autorotation of the rotor the blades have a lead angle, i.e., they are ahead of their neutral axis because of the action of aerodynamic forces on them. These aerodynamic forces drive the rotor and transmission in the same direction as power-on flight. But the blades also do not reach the front stop of drag hinges due to the action of the same centrifugal forces whose moments are directed to the side opposite the rotation of the rotor. The blades will accomplish oscillations around vertical hinges owing to the change in direction of Coriolis forces in the same limits as in power-on flight. On the Mi-4 helicopter the front stop of the drag hinge is at 13° 20' from the perpendicular to the axis of the flapping hinge.

6. Feathering Hinge

Besides flapping and drag hinges the blade of the rotor of a helicopter also has an axial (feathering) hinge, revolving around which, it changes the setting angle as is carried out for any propeller of an aircraft of variable pitch. As has already been clarified earlier, the blade of rotor will revolve around the feathering hinge upon the action of the "pitch-throttle" lever, and the angles change for all blades by the same magnitude – a change in collective pitch of the rotor occurs. But the blade revolves around the feathering hinge, and the control stick produces a cyclical change in pitch. Furthermore, the blade will accomplish rotation around the feathering hinge independently when it accomplishes flapping motion around the flapping hinge in forward flight owing to the presence of a flapping control. The feathering hinge of the blade of the Mi-4 helicopter permits changing the setting angle of the blade in the whole range of the change in collective pitch from 3° 30' to 14°.

Acting around feathering hinges of blades are aerodynamic and inertial moments, which try to change the setting angles of the blades, exerting pressure on the automatic pitch-control mechanism and twisting the blade. Too great twisting of the blade can change the aerodynamic property of the blades, and this means flying properties of the helicopter.

To decrease longitudinal moments from aerodynamic forces the profile of the blade is selected so that the center of pressure coincides with the axis of rotation or close to it. The modified profile NACA - 230M is such a profile which creates insignificant moments.

Besides aerodynamic moments, acting around the longitudinal axis of the blade are inertial moments from lateral components of centrifugal forces of the mass of the blade itself. These moments, just as for propellers of an aircraft, act on the twisting of blades in the direction of a decrease in setting angles and exert pressure on the automatic pitch-control mechanism. To decrease the indicated moments on propellers of aircraft and on rotors of heavy helicopters counterweights are installed, and moments of centrifugal forces of these act in the opposite direction.

In concluding an examination of the kinematic characteristics of a lift system, one should draw the conclusion that besides rotation around the axis of the rotor and forward motion together with the helicopter in a steady state of flight with forward velocity and with a constant number of revolutions when all control levers are stationary, the blades still have continuous motion (oscillations) around all three hinges. Around flapping hinges oscillations occur owing to the asymmetric field of speeds over the disk surface, around drag hinges – owing to Coriolis forces and around feathering hinges – owing to the presence of the flapping control. In hovering these oscillations do not appear, with an increase in forward velocity they are increased and at maximum speed they attain the greatest magnitude. These oscillations are accomplished in defined limits so that during correct flying operation of helicopter the blade does not hit against the available rests.

7. Non-Co-Conicity* of Blades of the Rotor and Driving of the Control Stick

After the setting to all blades of the rotor of identical setting angles in the process of preliminary control in the operation of the rotor it can appear that not all the blades describe an identical cone, i.e., is obtained the so-called non-co-conicity [*Translator's note: This word is not verified] of the blades.

Co-conicity of the blades can be only in the case when all blades have especially exclusively geometric, kinematic, aerodynamic and mass parameters. Since even with the most thorough manufacture of blades it is impossible to achieve the identical indicated parameters, and since every blade will have various parameters, then each of them will describe its own cone. Consequently, there will be obtained several cones of rotation of the rotor and according to the number of blades.

In the presence co-conicity of the blades the resultant of the aerodynamic forces of the rotor R will pass through the axis of rotation. In the presence of non-co-conicity of the blades the resultant of aerodynamic forces of the rotor will be displaced to the side of the axis of rotation. This will cause shaking of the whole helicopter not only in a forward motion, when the rotor will have oblique airflow, but also in vertical flight conditions in the presence of axial flow around (direct flow).

A check of co-conicity of the rotor is produced in the following way.

1. Prepare a post on the end of which fasten a package of tight paper 0.5-0.8 m high. Color the edges of blade tips with colored pencils or mastic, each blade a different color. For an all-metal blade for the protection of the glass of the contour light from a blow against the paper there is an attachment - a brush constituting the usual brush fastened under screws of bracing of the tip fairing.

2. Start the engine, switch in the transmission and to set conditions of the engine: revolutions - 1800 per minute, collective pitch - 6-7.5°. Then bring the post with paper to the blade tips of the rotor in front of the helicopter or to the left in such a manner that the paper is directed toward the axis of the rotor. After tips of the blades touch the paper, remove the post. Measure the distance on the paper between imprints of the blades. The width of washout of the imprints should be not more than 25 mm. If this distance is more,

it is necessary to reach distance 25 mm by controlling setting angles of blades with the help of control rods.

A blade whose imprint lies higher than the average imprint has a large setting angle and lift. Therefore, it is necessary to decrease its setting angle by means of decreasing the length of the rod. For a blade whose imprint is lower than the average imprint, has a smaller setting angle, it is necessary to extend the control rod of this blade. One turn of the blade control rod in the thread in the upper branching of the rod changes the setting angle of the blade 26', which changes the height of motion of the blade tip by 80 mm. A turn of the rod on one edge (1/6 of a revolution) causes a change in height of motion of blade tip of 10-15 mm.

3. Having achieved co-conicity of the blades at revolutions of 1800 per minute, it is necessary to check co-conicity at other revolutions, since the obtained co-conicity at some revolutions of the rotor can turn into non-co-conicity at other revolutions. This is explained by the fact that blades of the rotor are not absolutely rigid, and from the action of aerodynamic and inertial forces they are subjected to not only bend but also torsion. Torsion of the blade during its bend occurs because the center of gravity and center of pressure of the blade do not always coincide with the center of rigidity of it. The weight balancing designer seeks coincidence of the center of gravity with the center of rigidity, or they should be close to one another. The position of the center of pressure is not constant and depends basically on the magnitudes of angles of attack. Therefore, in turning to other revolutions, the changed moments around the longitudinal axis of the blade will twist separate blades on an increase or decrease in the setting angles. This will lead to a change in angles of attack, lift and formation of another cone of rotation by this blade.

Consequently, after there will be attained co-conicity at 1800 r/min, it is necessary not changing the magnitude of collective pitch, to increase the revolutions with the help of a throttle control up to 2300-2400 r/min and to check co-conicity in this way.

Here the imprints on the paper will be already different as compared to their imprints with satisfactory co-conicity at 1800 r/min. The blade departed from the middle position upwards has a setting angle owing to the twist by its positive pitching moment. It is necessary to decrease the positive pitching moment of this blade by bending the aerodynamic plate of the blade downwards. The blade departed from the middle position downwards has a smaller setting angle due to the twist by diving moments, and on this blade it is necessary to increase the positive pitching moment by bending the aerodynamic plate upwards. Bending the plate 1° changes the height of the imprint on the paper 40-50 mm at 2400 r/min.

The angle of bending of the plates should be not arbitrary but limited. Thus for blades of mixed construction in view of their definite characteristics, the angle of bending on each blade should be only downwards at $6^{+1^\circ}_{-2}$, counting off from the lower edge over the average angle along the length of the plate. The divergence of angles between separate blades is allowed at no more than 5°. For all-metal blades the angle of bending of the plate is allowed on each blade downwards at 4° and upwards at 6°. The divergence between angles of separate blades of the given set should not exceed 8°.

4. After obtaining co-conicity with operation of the rotor at 2400 r/min again co-conicity during its operation at 1800 r/min is checked, achieving co-conicity by a change in length of blade control rods. Then again co-conicity during rotor operation at 2400 r/min is checked, achieving it by bending of the plate.

Thus, by eliminating non-co-conicity by consecutive approach there are achieved cones of rotation of separate blades during rotor operation at 1800 r/min - the change in length of control rods of the blades, and by means of changing the position of aerodynamic plates on blades during rotor operation of 2400 r/min. In the presence of a sufficient experiment for reduction of the number of startings of the engine both these operations are produced simultaneously.

Non-co-conicity of the rotor causes not only vibration of the whole helicopter but also vibration (driving) of the control stick. This driving appears from forces transmitted along the circuit of longitudinal and lateral control from blades to the lever. If moments around the longitudinal axis for a pair of mutually opposite blades are not equal to each other, then the blade with a large moment on the decrease of the setting angle will exert pressure on the automatic pitch-control mechanism greater than the blade with a smaller moment; the plate of the automatic pitch control will be banked, and along the control circuit this motion is transmitted to the lever. But since the plate revolves together with the blades, then the control stick will make a circular motion in the direction of rotation of the rotor. The magnitude of these motions will depend on the difference of moments around the longitudinal axes of a pair of mutually opposite blades.

With a disconnected hydraulic system the driving of the control stick will be considerable, since the circuits of pitch and lateral control from the automatic pitch control to the control stick are rigid. As a result of eliminating non-co-conicity by means of bending the compensating plates in rotor operation at 2400 r/min (on the combined indicator) eliminations of lever driving are simultaneously achieved. It is necessary to achieve that driving of the lever with a disconnected hydraulic system be not more than ±10 mm.

The magnitude of lever driving is checked on land and in flight by the following method. Control of the helicopter is carried out by the left lever and to the right lever there is attached a pencil in such a manner that the point is directed upwards. Then the operating conditions of the engine or flight conditions (with a check during flight) are established. A plane table with paper is turned downwards, touching the paper to the point of the pencil and smoothly transferring the plane table in a lateral direction. On the paper a wavy line will be written. The height of the wave is divided into two, and this will be the magnitude of oscillations of the control stick. The obtained number with a disconnected hydraulic system should not exceed 10 mm. With the hydraulic system included the pulling of the cyclic pitch control from the above-cited causes will be transmitted to the hydraulic system, and in it there will be a pulsation of pressure. But since the volume of the hydraulic system, especially with the hydraulic accumulator is rather large, then this pulsation of pressure will be insignificant. The pulsation of pressure in the hydraulic system will also be transmitted along the control circuit and to the control stick, but already considerably less than with the hydraulic system disconnected. In this case the permissible driving of the lever should be not more ±3 mm.

All the indicated works on checking and eliminating non-coconicity of the rotor and driving of control stick are fulfilled with the position of the helicopter on a line with a wind of not more 3 m/s. Control of the helicopter is carried out necessarily by a member of the flying crews.

§ 5. Aerodynamic Characteristics of the Rotor

1. Force Polygon of the Element of the Rotor Blade

In order to present a picture of the formation of aerodynamic forces by the rotor, in the beginning we will examine the diagram of aerodynamic forces of a separately taken element of the rotor blade, for example, during vertical climb (Fig. 33). Acting on the element of the blade are peripheral velocity u, inductive speed v and vertical climb velocity V_y. Adding these speeds by the rule of speed polygon, we will obtain the resultant speed W, which will act on the chord of the element at a certain positive angle of attack α.

As a result of the action of flow by the element of the rotor blade there is created a total aerodynamic force of the element of the blade ΔR. In aerodynamics of a wing of an aircraft is spread this force to lift ΔY, acting perpendicular to the incident flow W, and drag ΔQ, acting in parallel to this flow to the side opposite to the motion of the blade element. In aerodynamics of a rotor it

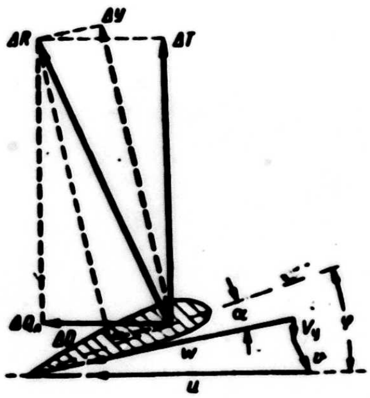

Fig. 33. Forces acting on the element of the blade during vertical climb.

is expedient to decompose aerodynamic force ΔR on thrust ΔT, acting perpendicular to the plane rotation, and drag of the blade (circumferential force) $\Delta Q_{Л}$, acting in the plane of rotation to the side opposite to the motion of the blade. The sum of all thrusts of elements along all blades will give the total thrust of the rotor, and the sum of all resisting forces of the blade will give the total resisting force of the rotor (drag to rotation), which is surmounted by torque applied to the shaft of the rotor.

Let us show that the analogous force polygon of the blade element will be along the entire length of blades of the rotor and in all conditions of flight. The only difference will be in the fact that there will be various forward velocities both in magnitude and in terms of direction depending upon flight conditions, different setting angles ϕ and different angles of attack α, but they will always be positive. Therefore, all elements of blades in all flight conditions, even in autorotation, will create positive thrust.

2. Creation of Tractive Force by the Rotor in Hovering and Vertical Conditions of Flight

A diagram of the formation of aerodynamic forces by the rotor in vertical flight conditions is shown in Fig. 34. On a blade taken separately the following forces act: lift of the blade $Y_{Л}$ is directed perpendicular to the blade and is applied to the center of pressure of it, the force of the weight of the blade $G_{Л}$ acting

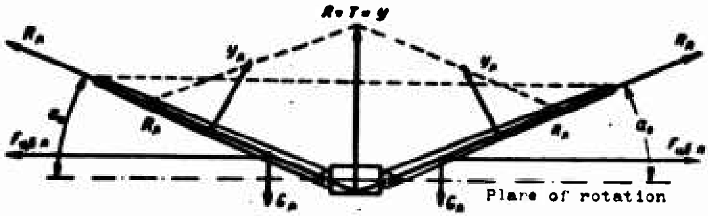

Fig. 34. Diagram of the formation of tractive force of the rotor in hovering and vertical flight conditions.

vertically downwards is applied to the center of the weight of the blade, and the centrifugal force $F_{Цб}$ acting perpendicular to the axis of rotation. Adding all these forces acting on the blade, we will obtain the resultant of all forces $R_{Л}$, which is directed along the length of the blade at a certain angle to the plane of rotation — coning angle α_0. The sum of moments of all forces acting on the blade relative to the horizontal hinge is equal to zero at a definite magnitude of the coning angle depending upon the number of revolutions and flying weight of the helicopter.

If one were to transfer resultant forces of blades $R_{Л}$ along the line of their action to the axis of rotation of the rotor and add them by the rule of the parallelogram, then there will be obtained the total aerodynamic force of the whole rotor R, acting perpendicular to the base of the cone of rotation. Figure 34 conditionally shows two blades in one plane, actually four of them, and therefore it is necessary to represent that the resultant rotor is obtained from the addition of not two $R_{Л}$ but four.

The resultant force R is simultaneously the thrust of the rotor T, since it acts perpendicular to the plane rotation, inasmuch as the plane of rotation in vertical flight conditions can approximately be considered parallel to the base of the cone. This force is also lift Y, since it balances the weight of the helicopter in these conditions.

If all blades of the rotor during rotation move along the surface of the same cone, then such <u>motion is called co-conical</u>. If any blade emerges from the common cone, then the rotor will have non-co-conicity. Then the resultant will pass not through the axis of rotation and, accomplishing a circular motion, will be cause an impermissible vibration of the helicopter. Non-co-conicity is eliminated by a change in the setting angles of the blades and folds of trimming tabs on the blades.

The magnitude of the total aerodynamic force of the rotor (thrust) is changed by the "pitch-throttle" lever: to increase it the pilot deflects the lever upwards and to decrease it – downwards. The magnitude of the total aerodynamic force (thrust) of the real rotor in conditions of hovering is determined by the formula analogous to the formula of total aerodynamic force of the wing of an aircraft:

$$R_{\text{нвр}} = c_R \frac{\rho}{2} (\omega R)^2 \pi R^2 \ \text{[kgf]}. \qquad (24)$$

But since thrust of the rotor is obtained owing to the power fed to it, it is therefore necessary to connect thrust with power of the engine so that it would be possible to judge the influence of power on the magnitude of thrust. In practical aerodynamics there was widespread application of the formula of N. Ye. Zhukovskiy with the power 2/3 with respect to the pulse theory, which shows factors affecting the magnitude of tractive force in conditions of hovering:

$$T = (a_{\text{в}} \sqrt{\Delta} \xi D N_e)^{2/3}$$

or

$$T = (33{,}25 \eta_0 \sqrt{\Delta} \xi D N_e)^{2/3}, \qquad (24a)$$

where $a_{\text{в}} = 16{,}63 \frac{c_T}{m_{\text{кр}}} = \frac{75}{4} \sqrt{\pi} \eta_0 = 33{,}25 \eta_0$ – coefficient Vell'ner [Wellner];

$\Delta = \frac{\rho_H}{\rho_0}$ – relative air density; ξ – utilization power factor; D – diameter of rotor; Ne – power of engine; η_0 – relative efficiency rotor.

From formula (24a) it is clear that thrust increases not proportional to power of the engine but slower – by the power 2/3.

In order to obtain forward flight, aerodynamic force of the rotor is deflected by the control stick through the cyclic pitch control in the direction of desirable flight, and here its magnitude in the beginning acceleration of speed does not change, and only direction changes. With the appearance of speed independent flapping motions of the blades begin, which lead to deflection of the cone and direction of action of aerodynamic force from the position assigned by pilot.

In the plane of rotation of the rotor drag forces will act on each blade, which will create drag to the rotation. The antitorque moment will be balanced by torque on the rotor shaft transmitted from the engine.

3. Aerodynamic Forces of the Rotor in Forward Flight

Force polygon of the element of the rotor blade. The force polygon of the element of the rotor blade (Fig. 35) will be the same as the force polygon in vertical flight conditions (see Fig. 33). The only difference will be in the fact that in forward flight the plane of rotation of the rotor will be directed in the direction of flight, since the pitch angle of the helicopter decreases with an increase in speed. Both the velocity force polygons, i.e., speed and force will be inclined in the direction of flight at the same angle as the plane of rotation of the rotor. Thrust of the element of the blade ΔT will be directed perpendicular to the plane rotation, drag of the element of the blade $\Delta Q_{Л}$ – in parallel to the plane of rotation and in the opposite direction of motion of the element of the blade; the resultant force of the element of the blade ΔR will obtain a corresponding direction depending upon the relationship of magnitudes of forces ΔT and $\Delta Q_{Л}$.

Aerodynamic forces of the rotor. In forward flight the cone of rotation of the rotor, the direction of action of aerodynamic

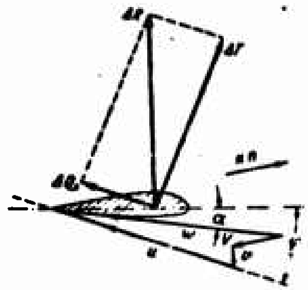

Fig. 35. Force polygon of the blade element in forward flight.

force of the rotor and, behind them, the whole helicopter are banked forward by the control stick (Fig. 36). Then owing to flapping motions the cone of rotation and force R of the rotor are deflected back at angle a_1 and to the right at angle b_1. Aerodynamic force of the rotor R, having such direction, will render a corresponding action on the helicopter. In order to analyze the action of force R of the rotor on helicopter, let us decompose it in the bound system of coordinates (along axes of the helicopter) into three components: thrust of the rotor T, longitudinal force Q_B and lateral force Z_B (see Fig. 36). For this let us use a parallelepiped, mentally set by its base on the plane of rotation of the rotor or two parallelograms in longitudinal and lateral planes. Here the total aerodynamic force of the rotor R is directed along the axis of the cone of rotation (perpendicular to the base of the cone) and is determined by the formula (24).

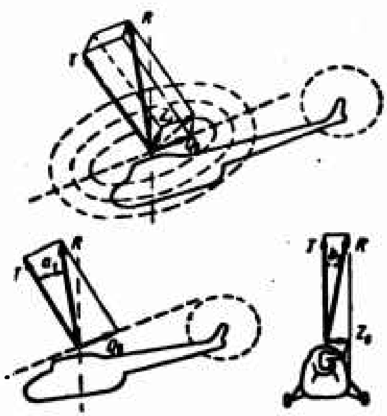

Fig. 36. Diagram of formation of aerodynamic forces of the rotor in forward flight.

The tractive force of the rotor T acts perpendicular to the plane rotation — along the axis of the shaft, and it fulfills useful work, balancing the weight and appearing drag of the helicopter in forward flight. In magnitude it differs insignificantly from the total aerodynamic force R, since angle a_1 is small and is changed within limits of 0–6° ($T = R \cos a_1$). In hovering these forces are combined and equal to each other ($R = T$); with a growth in speed the thrust decreases as compared to force R, but the difference remains insignificant. In practice these forces are equal to each other at all flight speeds from hovering to the maximum speed. The tractive force of the rotor is determined by the formula analogous to the formula of lift of the wing of an aircraft and differs from formula (24) only by the coefficient:

$$T = c_T \frac{\rho(\omega R)^2}{2} \pi R^2 \text{ [kgf]}, \qquad (25)$$

where c_T — aerodynamic thrust coefficient dependent on the same factors as those of coefficient c_R and insignificnatly differs from it in value.

This formula clearly shows factors affecting the value of thrust of the rotor, which has practical importance for the comprehension of flying properties of the helicopter and peculiarities of the piloting of it.

During flight with forward velocity on a given helicopter at a given time, at constant altitude and at constant number of revolutions and boost pressure (constant power), the tractive force of the rotor will be changed from the magnitude of forward velocity and angle of attack of the rotor owing to the change in coefficient c_T, which depends in given constant conditions on the relative speed and angle of attack of the rotor (Fig. 37).

At an angle of attack equal to zero, when the flow slips along the plane of rotation, with an increase in flight speed tractive force will be increased in view of the large mass of air passing through the lift system per unit time (see formula 18 of the thrust

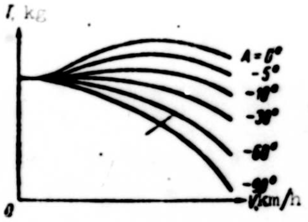

Fig. 37. Character of the change in rotor thrust from flight speed at different angles of attack.

of an ideal rotor in forward flight). If angles of attack of the rotor are decreased, the tractive force will decrease owing to the decrease in angles of attack of the blades, and when the angle of attack will be -90° (which in practice in flight cannot be), then the tractive force will decrease with an increase in speed, just as for a propeller of an aircraft. However, with acceleration of the speed of the helicopter, it has simultaneously and continuously decreased angles of attack of the rotor, since the greater the speed, even a greater slope of the rotor is required in the direction of flight. Therefore, owing to the increase in speed tractive force increases, and owing to the decrease in angles of attack it simultaneously decreases. With this, up to the economic speed the tractive force will increase, and with a further increase in speed it will decrease both due to a decrease in angles of attack and due to the expansion of the zone of reverse flow around. This means that up to the economic speed the operating condition of the rotor in oblique airflow are improved and tractive force increases, and beyond the economic speed operating conditions of the lift system worsen and tractive force decreases. This is one of the reasons for limitation of the maximum speeds of helicopter.

Besides such an independent change in thrust of the rotor from the speed of flight, the pilot can change its magnitude by the "pitch-throttle" lever changing the collective pitch and number of revolutions of the rotor.

<u>The longitudinal force</u> Q_B (see Fig. 36) acts in the plane of rotation of the rotor to the side opposite the direction of flight. This force limits the speed of flight of the helicopter, being the drag of the rotor, and is determined by the formula:

$$Q_B = c_{x_B} \frac{\rho}{2} (\omega R)^2 \pi R^2 \text{ [kgf]}, \quad (26)$$

where c_{x_B} – coefficient of longitudinal force (drag of the rotor).

In conditions of hovering the longitudinal force will be equal to zero; with an increase in speed it increases but considerably less than the tractive force in view of small angles a_1, and at maximum speed will be 6-7% of the thrust of the rotor ($Q_B = T \sin a_1$).[1]

Lateral force Z_B (see Fig. 36) acts in the plane of rotation to the right, and it balances the thrust of the tail rotor and is determined by the following formula

$$Z_B = c_z \frac{\rho (\omega R)^2}{2} \pi R^2 \text{ [kgf]}, \quad (27)$$

where c_z – coefficient of lateral force.

In conditions of hovering the lateral force is equal to zero, since flapping motions of blades are absent and the cone of rotation of the rotor and its force R are not deflected. With an increase in speed this force increases, but at any speed it is twice less than the longitudinal force (approximately), since angle b_1 is less than a_1 ($Z_B = T \sin b_1$).[1]

It is necessary to note that lateral force Z_B balances the tractive force of the tail rotor without interference of the pilot only at a definite average flight speed, and at other speeds it will be less or greater than the thrust of the tail rotor. Then the pilot will have to increase or decrease it by deflection of the control stick in a lateral direction, following the sideship indicator.

Drags of blades, acting in the plane of rotation, create antitorque moment of the rotor, which should be balanced by the

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[1]The tangent of small angles up to 6° is equal to the sine of these angles.

torque of the engine applied to the rotor shaft. The necessary torque of the rotor is determined by formula (1).

§ 6. Powers

1. Required Powers for Helicopter Flight

The required power for the flight of a helicopter is called the power necessary for certain conditions of flight which is used for surmounting forces of terrestrial gravity (weight), air drag and forces of inertia during curvilinear flights and transient conditions. The required power for helicopter flight in a steady rectilinear flight is composed of three powers: induced, profile and power of motion:

$$N_{\text{потр}} = N_{\text{инд}} + N_{\text{пр}} + N_{\text{дв}}.$$

Induced power is the power necessary for surmounting induced drag of blades of the rotor, and it is expended for the creation of induced speed, owing to which there is created lift by the rotor, balancing the weight of the helicopter. Induced power is determined by the following formula:

$$N_{\text{инд}} = \frac{Tv}{75}\ [\text{hp}]. \qquad (28)$$

In conditions of hovering induced required power is maximum, since here there is maximum induced speed, and therefore maximum induced drag occurs. With an increase in forward velocity of the helicopter induced power decreases in view of a decrease in induced speed and induced drags. In conditions of hovering the induced power is about 75% of all the required power of hovering, and with an increase in speed it decreases and at a maximum speed of horizontal flight amounts to about 15% of all the required power at this speed.

With an increase in flight altitude the induced power increases in view of the drop in mass air density, since for the creation of the same lift at smaller density there is required greater induced speed and induced drag appears for the surmounting of which high power will be required (Fig. 38a).

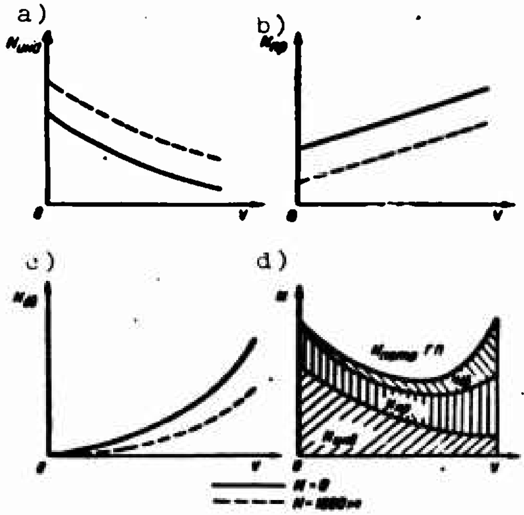

Fig. 38. Required powers for flight of a helicopter: a) induced power; b) profile power; c) power of motion; d) sum of required powers for flight on land (zero altitude).

Profile power is the power necessary for the surmounting of profile drag of blades of the rotor and also for twisting of air in the direction of rotation of the rotor for the irregularity of induced flow over the disk surface, and for tip, root and other losses. All losses henceforth will be called profile losses of the rotor and the power expended for surmounting these losses, the profile power, since of the enumerated losses the profile losses comprise the greatest magnitude.

Profile power is determined by the formula

$$N_{cp} = \frac{M_{к_{cp}}}{75}\ [\text{hp}],^{1} \qquad (29)$$

In conditions of hovering the profile power is approximately equal to 25% of all the required power of hovering. With an increase in speed of horizontal flight it insignificantly increases and at maximum speed is about 40% of all the required power at this speed.

The increase in profile power with an increase in speed is explained by the following reasons. The average speed of flow around of the blades when hovering and in forward flight is not changed, since if in the position $\psi = 90°$ forward velocity is added to the peripheral velocity, then in position $\psi = 270°$ such forward velocity is subtracted from the peripheral velocity; consequently, the average speed remains constant. If the profile drag depended on speed in the first degree, then the average profile drag, and this means required power for surmounting it, with an increase in flight speed would be constant. But profile drag, as any aerodynamic force, depends on the square of the speed, and therefore the average profile drag also increases with an increase in speed.

This means that the profile power expended for surmounting this increasing drag increases.

With an increase in altitude of flight the profile power decreases owing to a decrease in mass air density (Fig. 38b) under a condition of constancy of true flight speed of the helicopter, number of rotor revolutions and collective pitch. Practically occurs so that with a climb on altitude it is necessary to increase the revolutions and collective pitch of the rotor, and also the true

[1] This formula is obtained in the following way:

$$N_{cp} = \frac{Q_{cp} u}{75} = \frac{Q_{cp} \omega R}{75} = \frac{M_{к_{cp}} \omega}{75}\ [\text{hp}],$$

where $M_{к_{cp}}$ – moment of average profile drag equal to the product of average profile drag by the radius of the rotor:

$$M_{к_{cp}} = Q_{cp} R.$$

speed under the condition of constancy of the indicated airspeed. On this basis the profile power with a climb on altitude practically can remain the same as that for land or even be increased.

Power of motion is the power necessary for the creation of forward motion of the helicopter, which proceeds to surmount its parasite drag of the fuselage and all nonlifting parts. The power of motion is determined by formula

$$N_{\text{дв}} = \frac{QV}{75} \text{ [hp]},^{1} \tag{30}$$

where Q — drag of the helicopter equal to the product $(c_x S)\frac{\rho V^2}{2}$, for the Mi-4 helicopter $(c_x S)_{\alpha=0} = 3.2$ m^2; V — speed of forward flight of the helicopter expressed in m/s.

In conditions of hovering the power of motion is equal to zero, since there is no motion and no parasite drag. With an increase in forward velocity the power of motion considerably increases, and at maximum speed it is about 45% of all the required power at this speed.

With an increase in altitude of flight the required power of motion with the same true speed decreases in view of a decrease in the parasite drag owing to a drop in air density (Fig. 38c). If, however, with an ascent on altitude the indicated airspeed is maintained, then the true speed will be increased, and also the required power of motion will be increased according to the general laws of aerodynamics.

The sum of all required powers for horizontal flight with an increase in speed up to the economic speed decreases, and with a further increase in speed it increases (Fig. 38d). The decrease in

[1]Formulas (28, 29 and 30) are not applied in aerodynamic design, since they have general form. For calculation there are applied working more accurate and complicated formulas, which are not given here.

required power upon acceleration of speed up to the economic is explained by the considerable decrease in induced power as compared to the increase in profile power and power of motion. Beyond the economic speed the required power increases owing to the sharp increase in power of motion in view of the increase in parasite drag of the helicopter.

2. Available Power of the Rotor

Engine performance of the ASh-82V. To ensure the necessary power not only for horizontal flight but also other conditions of flight on helicopters appropriate engines are installed. The engine installed on the Mi-4 helicopter is a piston fourteen-cylinder two-row radial high-altitude engine ASh-82V with two speeds of the supercharger with a takeoff effective power of 1700 hp taken from the head of the crankshaft, taking into account power used by the fan for forced cooling of the engine.

Effective horsepower is the power of the engine taken from the head of the crankshaft. It is determined by the formula

$$N_e = \frac{M_{кр} n_{дв}}{716.2} \text{ [hp]}, \qquad (31)$$

where $M_{кр}$ – torque; $n_{дв}$ – number of revolutions of the crankshaft per minute; 716.2 – constant number.[1]

[1]This number is obtained as a result of the following actions. Let us assume that the shaft of the engine (reduction gear) is set into rotation by force F applied on radius r. The force of F in one revolution will be equal to F2πr, and the work in one minute will be equal to $F2\pi r n_{дв}$. Power is the work per second:

$$N = \frac{2\pi r F n_{дв}}{60} = \frac{\pi r F n_{дв}}{30} \text{ [kgf m/s]}, \quad \text{and} \quad rF = M_{кр}.$$

then

$$N = \frac{\pi M_{кр} n_{дв}}{30} \text{ [kgf m/s]};$$ in horsepower this will be:

$$N_e = \frac{\pi M_{кр} n_{дв}}{30 \cdot 75} = \frac{3.14 M_{кр} n_{дв}}{30 \cdot 75} = \frac{M_{кр} n_{дв}}{716.2} \text{ [hp]}.$$

By formula (31) with the help of special testing units there are constructed external and throttle performance, according to which the engine is evaluated. Any reciprocating engine is characterized by external, throttle (propeller) and altitude performances and also by conditions of operation accepted for its operation.

The external engine performance is called the change in power and specific fuel consumption with respect to the number of revolutions with full opening of the throttle and a change in the load on the rotor. The maximum power of any engine with a completely open throttle will be at a strictly definite load on the rotor (at definite revolutions). Changing the load in the direction of an increase or decrease, in both cases the power will decrease; only in the first case the number of revolutions will be less than the maximum of the given engine and in the second case greater than the maximum. The fall in power with a too lightened rotor with a completely open throttle is explained by a decrease in the average effective pressure with an increase in revolutions of the crankshaft in view of the combined influence of weight charge and mechanical efficiency on it, which with this decrease.

The throttle engine performance is called the change in power and specific fuel consumption with respect to the number of revolutions of the crankshaft with a constant load on the shaft (constant propeller pitch) and opening of the throttle.

For the ASh-82V engine it is accepted to characterize the change in effective power from boost pressure (p_K) by separate curves for different numbers of revolutions of the crankshaft. Under these same conditions fuel consumption per hour for the whole engine is given. These characteristics are given separately for the first and second speeds of the supercharger.

Figure 39 gives the indicated engine performances of the ASh-82V of the 6th series. Characteristics are taken at a barometric pressure of 760 mm Hg and air temperature of 15°C. As can be seen by the curves, the greater the boost pressure and number of revolutions of

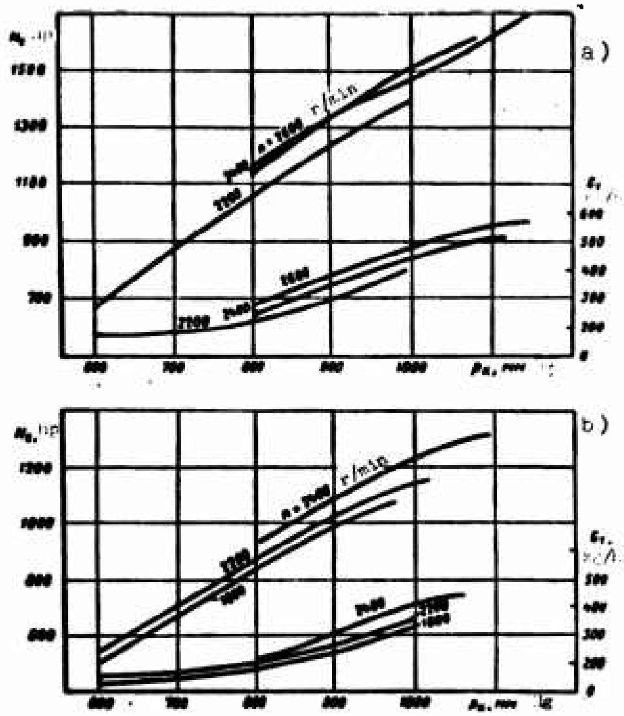

Fig. 39. Characteristics of the change in power and fuel consumption per hour by supercharging and revolutions of the crankshaft of the engine ASh-82V: a) when operating engine in first speed of the supercharger; b) when operating engine in second speed of the supercharger.

the crankshaft, the greater the power of the engine and greater fuel consumption per hour. With operation of the engine in the second speed of the supercharger at those same revolutions and supercharging, the effective power of the engine is less than during its operation in the first speed, inasmuch as for rotation of the supercharger (impeller) in the second speed high power is expended. According to the curves it also is clear that at revolutions of 2400 and 2600 per minute the difference in powers is extremely insignificant, and therefore in practice of flights during optimum revolutions under takeoff conditions of the engine frequently revolutions close to

2400 per minute are taken.

Altitude performance of an engine is called the dependence of effective power and effective specific fuel consumption on flight altitude at a constant number of revolutions of the crankshaft and with the maintaining of constant design pressure behind the supercharger from land up to an altitude, starting from which the throttle is open completely. Figure 40 shows altitude performance of the ASh-82V engine.

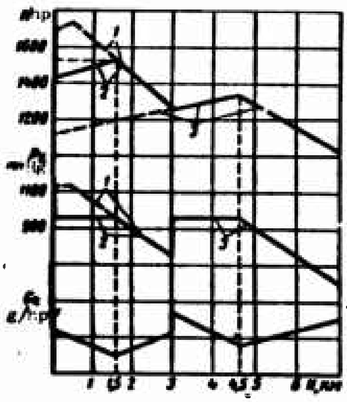

Fig. 40. Altitude performances of the ASh-82V engine: 1 – with a completely open throttle valve in the first speed of the supercharger; 2 – in normal rating in the first speed of the supercharger; 3 – in normal rating in the second speed of the supercharger.

Operating conditions of the ASh-82V engine. For each aircraft engine the most profitable, applicable in operation, basic conditions of its operation are established. Operating conditions of the ASh-82V engine are shown in Table 1.

Takeoff operating conditions of the engine are used for takeoff, landing, vertical conditions of flight, especially under complicated conditions (Alpine locality, high air temperature, low atmospheric pressure, high atmospheric humidity, overloaded helicopter), and also short duration for climbing with a forward velocity when necessary. The takeoff engine operating mode is designated by way of introduction of the gas control completely to the right and collective pitch of the rotor at about 8-9° according to the principle of "much gas – little pitch." These conditions can be applied continuously for not more than 5 minutes with respect to conditions of

Table 1.

Operating conditions of the engine	Power, hp	Revolutions of crankshaft, r/min	Pressure of mixture behind supercharger, mm Hg	Specific fuel consumption, g/hp-h
Takeoff — during 5 min of continuous operation (first speed of supercharger)	1700	2600	1125 ± 10	325—360
Nominal on land:				
at first speed of supercharger	1430	2400	970 ± 10	285—315
at second speed of supercharger	1150	2400	970 ± 10	315—340
Nominal altitude:				
at first speed of supercharger, height 155[illegible] m....	1530	2400	970 ± 10	—
at second speed of supercharger, height 4550 m....	1350	2400	970 ± 10	—
Cruising (0.75 of nominal terrestrial power):				
at first speed of supercharger	1070	2200	810 ± 10	230—250
at second speed of supercharger	860	2200	810 ± 10	250—275
Cruising (0.65 of nominal terrestrial power):				
at first speed of supercharger	930	2100	760 ± 10	215—275
at second speed of supercharger	750	2100	760—10	230—255
Cruising (0.5 of nominal terrestrial power):				
at first speed of supercharger	725	2100	660 ± 10	210—230
at second speed of supercharger	575	2100	660 ± 10	230—255

durability of the engine.

Normal operating rating of the engine is applied basically for climb with forward velocity, especially at full flight weight or overloaded helicopter and the necessity of rapid climb. Normal conditions are assigned by means of establishing nominal revolutions by the gas control, and it occupies approximately the middle position and nominal supercharging; the collective pitch should be more than on takeoff conditions, within limits of 9.5-10° depending upon the altitude: the more the altitude of flight, the greater the collective rotor pitch.

Cruising ratings of engine operation are applied mainly for horizontal helicopter flight and for climb with forward velocity with incomplete flying weight and in the absence of the necessity of a rapid climb. For the assignment of cruising rating it is necessary to set cruising revolutions by the gas control, and the control will be almost all the way to the left; by the collective pitch lever there is set the necessary supercharging, and here the collective pitch will be greater than at normal rating (near 10.5-11°) depending upon altitude of flight and flying weight of the helicopter: the more the altitude and flying weight, the greater the collective pitch.

Cruising revolutions of 2100 per minute for the Mi-4 helicopter are forbidden by the manual on flying operation of this helicopter, and the minimum permissible revolutions for all conditions of flight during operation of the engine are set at 2200 per minute. This is done in order to have a sufficient reserve for transition of the rotor into autorotation in the case of engine failure. Revolutions of 2100 per minute can be allowed only before the switching of the supercharger to the second speed and for flight with the appearance of flutter signals.

Available power of the rotor. The effective power of the engine, taken from the crankshaft of engine, is distributed for rotation of the rotor, rotation of the blower, surmounting friction in the whole transmission of the helicopter and surmounting drag to rotation of the tail rotor. Power of the engine, which is expended for rotation of the blower, transmission and tail rotor, consists of losses of power.

The available power of the rotor is called the power of the engine arriving for rotation of the rotor. It is determined by subtraction from the effective power of the engine losses to cooling and friction in the transmission and on the tail rotor:

$$N_{\text{расп}_{\text{н.в}}} = N_e - N_{\text{охл}} - N_{\text{тр}} - N_{\text{х.в.}}$$

Power of cooling is the power of the engine expended for rotation of the blower for forced engine cooling. This power comprises 6% of the effective power of the engine. The indicated percent of losses does not change from the speed of flight.

Power of friction is the power of the engine expended for surmounting friction in the whole transmission. It makes up about 4% of the effective power of the engine; the magnitude of these losses does not change from the speed of flight.

Power of the tail rotor is the power of the engine expended for surmounting drag to rotation tail rotor in air. In conditions of hovering this power is maximum and amounts to about 9-11% of the effective power of the engine, since in this regime conditions of operation of both rotors are difficult: for balancing the great reactive moment of the rotor there is required great thrust of the tail rotor, and therefore it must be assigned, great pitch. With an increase in speed of forward flight power of the tail rotor decreases, since conditions of operation of both rotors in oblique airflow are improved, and thrusts of them increase owing to oblique airflow. The power supplied to the rotor decreases, the reactive moment of the rotor drops, and therefore a smaller moment of the tail rotor is required. Thrust of the tail rotor owing to oblique airflow continues to grow up to a speed greater than the economic, and therefore the tail rotor must be placed at smaller pitch, which will lead to a decrease in drag to rotation and decrease in losses of power for surmounting it.

At the maximum speed of horizontal flight the power of the tail rotor will be approximate twice less than that for hovering. For vertical climb power for the tail rotor will be required greater than that for hovering.

The indicated power losses of the engine on a helicopter are considered the utilization power factor of the engine.

Utilization power factor of the engine is determined by the division of the available rotor power by the effective power of the engine:

$$\xi = \frac{N_{\text{расп}_{\text{н.в}}}}{N_e}.$$

The utilization power factor of the engine for a single-rotor helicopter, depending upon conditions of flight, is within 0.8-0.9. For the Mi-4 in conditions of hovering it is equal to 0.8, and with an increase in speed it is increased and at a maximum is 0.87. The utilization power factor of the engine considers losses of effective power of the engine on the helicopter and shows what part of this power goes to the rotor.

3. Losses of Available Power an- -lative Efficiency of the Roto

Available power of the rotor through the utilization power factor will be equal to: $N_{расп_{н.в}} = N_e \xi$. Since the sum of all losses with an increase in flight speed will decrease owing to a decrease in losses on the tail rotor, i.e., the utilization power factor will be increased, then the available power with constant power of the engine with an increase in speed of flight will be significantly increased.

Not all the available power of the rotor supplied to it is used in useful work for the creation of tractive force and accomplishment of forward flight. On the rotor there are in turn losses to the surmounting of profile drag of the blades, twisting of the stream of air in the direction of rotation of the rotor, heating of air and blades owing to their mutual friction, tip and root losses, and also because of the disregard of true distribution of induced speeds over the disk surface by the rotor and others. All these losses amount to 25% in hovering up to 40% in maximum speed of the available power of the rotor. The losses shown can be referred to required power for flight of the helicopter as the profile power, which was mentioned above. Consequently, the rotor has its own efficiency. It is not possible to apply to the rotor the usual efficiency applied for propellers, since in conditions of hovering of such efficiency will be equal to zero and will not correctly reflect operation of the rotor:

$$\eta_в = \frac{N_в}{N_e} = \frac{TV}{N_e} = \frac{T \cdot 0}{N_e} = 0.$$

Therefore, to evaluate the operation of the rotor there is chosen a relative efficiency of the rotor, which is determined by a different method as compared to the efficiency of air-tractor propeller.

The relative efficiency of the rotor is determined by the ratio of power, which it is necessary to supply to the ideal rotor (not having losses), to the power supplied to the real rotor having losses, i.e., to the available power of the rotor under the condition that both these rotors (ideal and real) will create identical thrust:

$$\eta_0 = \frac{N_{\text{ид}}}{N_{\text{расп}_{\text{н.в}}}}.$$

For creation of identical thrust to ideal and real rotors, it is necessary to supply to the real rotor greater power than that to ideal rotor, and therefore the relative efficiency of the rotor is less than unity by the magnitude losses on the real rotor.

For contemporary rotors, including for the rotor of the Mi-4 helicopter with blades of mixed construction, the relative efficiency is within 0.6-0.75. The value of this coefficient depends on the design shaping of the rotor and quality of external treatment of the blades. This coefficient can be increased by the application of rotors with a large number of blades and low revolutions.

For a rotor with all-metal blades the relative efficiency is more than for a rotor with blades of mixed construction in view of smaller profile and other losses. Therefore, flying properties of a helicopter with such a rotor are better than those with a rotor having a blade of mixed construction.

The relative efficiency considers losses on the rotor and shows what part of power supplied to the real rotor is expended for useful work, i.e., for the creation of tractive force.

4. Balance of Powers

Figure 41 shows in general form the balance of all earlier

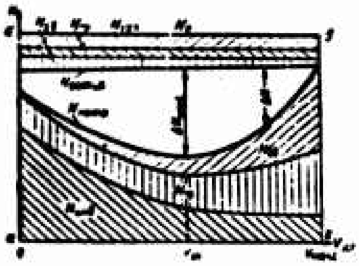

Fig. 41. Balance of powers.

examined powers. Here it is shown how all powers are changed from the speed of flight at definite assigned operating conditions of the engine.

In Fig. 41 dotted along the axis of the ordinates is the effective power of the engine ($N_{эф}$), for example, on the normal rating of its operation; plotted along the axis of the abscissas is the true speed of flight of the helicopter ($V_{ист}$). The effective power of the engine does not change from the speed of flight, and therefore this power is depicted by a straight line parallel to the axis of the speeds. The area of the rectangle a, b, c, d is conditionally taken as the effective power of the engine in selected conditions of operation. This power is distributed along four channels; rotation of blower – power of cooling ($N_{охл}$), rotation of all transmission – power of friction ($N_{тр}$), rotation of tail rotor – power of tail rotor ($N_{х.в}$) and rotation of rotor – available power ($N_{расп.в}$). Above there are plotted consecutively powers of cooling, friction and tail rotor. The power of cooling and friction do not change from speed but the power of the tail rotor decreases with an increase in speed. The available power of the rotor, as can be seen, with an increase in speed will be considerably increased owing to the decrease in losses on the tail rotor.

On the same graph all required powers, for example, for horizontal flight are plotted: induced ($N_{инд}$), profile ($N_{пр}$) and power of motion ($N_{дв}$), constructing one above the other. The sum of all necessary powers should fit into the area of available power in order to ensure horizontal flight in the entire speed range; at the same time, it is desirable also that there be a surplus of power for the possibility of accomplishment of other, more complicated conditions of flight.

The sum of all required powers, as can be seen from Fig. 41, with an increase in speed decreases and at a certain speed it will be minimum, and therefore this speed is called economic speed. With a further increase in speed beyond the economic the required power will be increased. The required power for horizontal flight up to the economic speed will decrease owing to the considerable decrease in induced power beyond the economic speed the required power is increased owing to the sharp increase in power of motion.

The surplus of power (ΔN), will be maximum at economic speed, at other speeds – less than or greater than the economic speed – it will be less and at maximum flight speed will be equal to zero.

Subsequently, for consideration of flying characteristics of the helicopter in all flight conditions there will be used only curves of available and necessary powers without subdivision of the necessary power into its components and without representation of lost powers to cooling, friction and the tail rotor.

In aerodynamic design the necessary and available powers, depending upon flight speed of the helicopter at various altitudes, are represented in the form of a change of the necessary and available torques through coefficients of these moments $m_{\text{кр}}$ from the characteristic of operating conditions of the rotor (flight of the helicopter) μ with respect to altitudes (Fig. 42). Furthermore, by aerodynamic design there are determined necessary and available angles of attack of the rotor A and collective pitch of it with respect to altitudes depending upon the performance characteristic μ_1; these changes are presented for clarity in the form of curves. These data are not given here, since they are not of great practical importance for rules of piloting a helicopter, but the physical meaning of them and the practical application are examined in detail

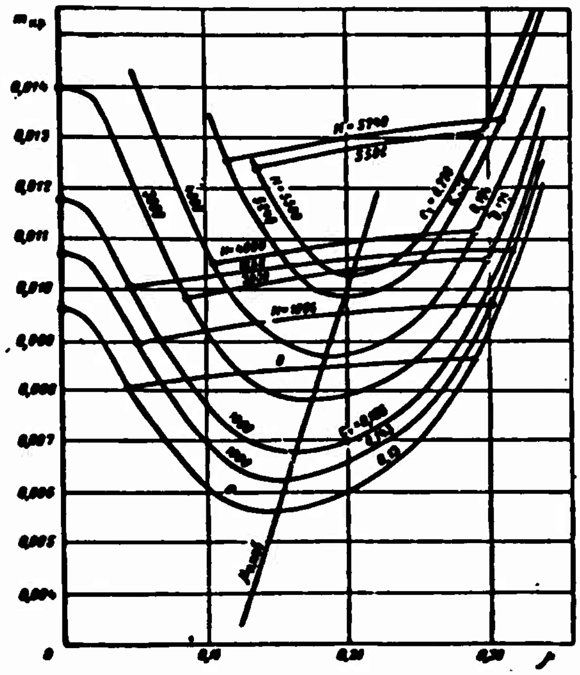

Fig. 42. Necessary and available
torques of the Mi-4 helicopter.

in this paragraph and will be examined during the study of conditions of flight.

Operation of the tail rotor is not investigated separately, since its design shaping and operation are almost analogous to the design and operation of the rotor. For the tail rotor there are provided the same constructive elements as for the main rotor, with the exception of that blades of it do not have drag hinges in view of small their mass and, therefore, insignificant Coriolis forces. The plane of rotation of the tail rotor is located perpendicular to the plane rotation of the main rotor.

For the tail rotor there is produced a change in collective pitch, and the blades accomplish flapping motions revolving around the flapping hinges. Limitation of flapping motions occurs owing to the presence of the flapping control. In oblique airflow the tail rotor, just as the main rotor, has deflection owing to flapping motions, and the thrust of it therefore creates longitudinal and lateral forces.

The tail rotor has its reactive moment acting in the direction of pitching of the helicopter.

CHAPTER III

HOVERING AND VERTICAL FLIGHT CONDITIONS OF THE HELICOPTER

§ 1. Hovering

1. General Characteristic

Hovering is the basic rated conditions of the flight of a helicopter. The helicopter is created basically so that it will accomplish hovering, vertical climb and vertical lowering for take-off and landings even from temporary, hastily built heliports. Hence there emanates the basic advantage of the helicopter over other aircraft: the possibility of transporting loads and people over an assigned distance without the building of special expensive airfields.

Hovering is at the same time a difficult flight regime, since conditions of operation of both rotors in place in direct airflow are worsened, and therefore high power is required, and conditions are not economical. Furthermore, in conditions of hovering stability is absent — the helicopter occupies neutral equilibrium, and there is small power reserve and reserve in deflection of all control levers, especially on the limiting centerings. Therefore, the piloting technique of a helicopter when hovering is complicated and requires special attention on the part of the pilot. On this basis hovering is limited and is applied only when this is justified by a acute necessity.

Application of conditions of hovering. Hovering is used for checking the operation of the engine, transmission, control, determination of power reserve and centering before every flight, for loading and unloading of the helicopter during an impossibility of landing. Hovering is used for various kinds of assembly, construction, rescue and other special works, and in the military – with different tactical purposes, and also for the instruction of flying personnel. Besides everything mentioned, hovering is a component part (element) of any vertical takeoff and landing, since they are most frequently fulfilled through short-term hovering.

2. Necessary and Available Powers

In conditions of hovering most interest lies in values of necessary and available powers, since the surplus of power depends on their values and relationships, and the value of the ceiling of hovering depends on the value of surplus of power. This will reflect flying properties of the helicopter in vertical conditions of flight, and this means its load capacity and takeoff and landing performances.

Required power for hovering is the power necessary for the creation by the rotor of a tractive force equal to the weight of the helicopter. The required power for hovering consists of induced power, which is expended for the creation of induced speed owing to which there will be formed thrust of the rotor equal to the weight of the helicopter, and profile power expended for surmounting profile and other losses on the rotor:

$$N_{\text{потр}_{\text{вис}}} = N'_{\text{инд}} + N_{\text{пр}}.$$

Induced power, as was established earlier, with an increase in altitude of flight is increased at all speeds of flight, including in conditions of hovering. Profile power with an increase in altitude of flight depending upon conditions can decrease, remain constant or be increased, which depends on the change in revolutions and collective pitch of the rotor. Altogether the required power for hovering with a rise on altitude will be increased (Fig. 43).

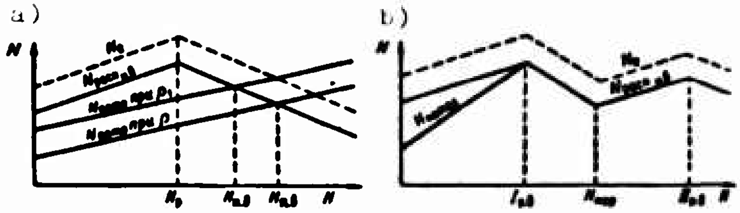

Fig. 43. Necessary and available powers of hovering of the helicopter: a) for a helicopter with the engine operating at one speed of the supercharger; b) for a helicopter with the engine operating at two speeds of the supercharger.

Required power also depends on flying weight of the helicopter and atmospheric conditions: the more the flying weight and the less the mass air density (high temperature, low atmospheric pressure), even greater power will be required for hovering and conversely (see Fig. 43a, b).

The total required power for hovering is determined by the formula

$$N_{потр_{вис}} = \frac{M_{кр}\omega}{75} \text{ [hp]}, \qquad (32)$$

where $M_{кр}$ is the necessary torque determined by formula (1). Replacing $M_{кр}$ in terms of its value by formula (1), we will obtain the expression for the required power when hovering:

$$N_{потр_{вис}} = \frac{1}{2 \cdot 75} m_{кр} \rho \pi R^2 (\omega R)^3 \text{ [hp]}. \qquad (33)$$

With an increase in altitude of hovering, which will lead to a decrease in mass density, or with a decrease in mass density at the same altitude from a change in atmospheric conditions, the required power for hovering in both cases will increase, since although a decrease in density leads to a decrease in required power in view of the decrease in torque, but with this it is required to increase the power factor ($m_{кр}$) or number of revolutions (angular velocity ω)

with the help of the "pitch-throttle" lever, which will lead to an increase in both induced and profile powers.

<u>The available power in hovering</u> is the power of the engine arriving on the rotor hub. It less than the effective power of the engine by the magnitude of losses to cooling, friction and to the tail rotor: $N_{расп_{вис}} = N_e \cdot$. For the Mi-4 helicopter $N_{расп_{вис}} = N_e \cdot 0{,}8$.

The magnitude of available power in hovering on land will be proportional to the power assigned to the engine. With an ascent on altitude the utilization factor of power of the engine ξ is not changed, and therefore the available power will be changed, since the power of the engine with ascent on altitude is changed. If the engine is unboosted (AI-14VF on the helicopter Ka-15), then the available power with ascent on altitude will decrease as does the power of the engine, only it will be less by the magnitude of losses:

$$N_{расп_{вис}} = N_e \xi \cdot A, \tag{34}$$

where A = f(H) – coefficient of drop in power of the unboosted engine according to the altitude shown in the table of standard atmosphere.

Since the required power for hovering of the helicopter with assigned flying weight with ascent on altitude is increased, and the available power decreases, then at a certain altitude these powers will be equal to each other in takeoff operating conditions of the engine. This altitude ($H_{п.в}$) will be the ceiling of hovering of the helicopter with this takeoff weight.

<u>The ceiling of hovering of a helicopter</u> is called the limiting altitude at which given the helicopter can hover in air. With a change in flying weight of the helicopter and atmospheric conditions the ceiling of hovering will be changed: the more the flying weight and the worse the atmospheric conditions (the less the mass air density), the ceiling of hovering will be less and conversely. In practice the ceiling of hovering is changed in large limits so that

it can be lower than the level of the place where the helicopter is, i.e., the helicopter in this case cannot hover or will hover only owing to the effect of the air cushion. From this it is seen that to increase the ceiling of hovering, and this means to improve takeoff and landing properties of the helicopter and to increase the payload a high altitude engine is necessary, which is provided on the helicopters Mi-1 and Mi-4.

In the presence on the helicopter of a high-altitude engine with a supercharger (AI-26V on the Mi-1 helicopter) the available power of the rotor in normal rating of engine operation will be increased up to the rated altitude (H_p = 2000 m) and beyond the rated altitude will decrease. In this case the curve of available power also repeats the altitude engine performance and passes below by a magnitude of the losses (Fig. 43a). Since on the Mi-4 helicopter there is the ASh-82V engine with two speeds of the supercharger, then the available power of the rotor will be changed from altitude as the power of the engine on normal rating of operation (Fig. 43b).

The rated ceiling of hovering of the Mi-4 helicopter is equal to 1500 m for a flying weight of 7100 kg under standard atmospheric conditions. Practically as for any helicopter, the ceiling can be changed in great limits so that it can be below the level of the place at which the helicopter is, then it will not hover or will hover because of the effect of the air cushion.

3. Thrust of the Rotor and Effect of the Air Cushion

The thrust developed by a real rotor in conditions of hovering is determined by the formulas (24) and (24a). On land in takeoff operating conditions of the engine the rotor develops maximum thrust. With ascent on altitude the rotor thrust will decrease in view of the decrease in power of the engine and decrease in mass air density. The rotor of the Mi-4 helicopter with blades of mixed construction, according to aerodynamic design on land (at standard atmosphere) during takeoff operating conditions of the engine develops thrust of about 6500 kgf outside the effect of the air cushion. Since in hovering rotor thrust should be equal to the flying weight of the helicopter, then 6500 kg will be the maximum permissible flying weight of the helicopter for hovering (takeoff) outside the zone of the influence of the air cushion.

With ascent on altitude the thrust developed by the rotor will be decreased on takeoff conditions, and therefore the maximum permissible flying weight of the helicopter will be decreased for hovering (takeoff) outside the influence of the air cushion. In normal operating rating of the engine the thrust of the rotor will be less than that on takeoff conditions and will be about 6000 kgf (Fig. 44). With ascent on altitude in these conditions thrust will be increased, in view of the increase in power of the engine, and at a rated altitude of 1900 m will be 6200 kgf.

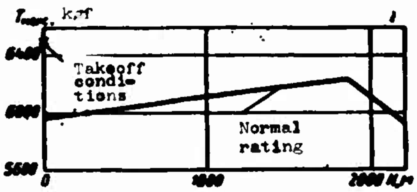

Fig. 44. Maximum thrusts of rotor in hovering.

The rotor with all-metal blades has a high relative efficiency η_0, and therefore in all conditions of flight it develops greater thrust than the rotor with blades of mixed construction (see formula 24a). This difference is about 400 kgf. Therefore, the payload of the helicopter with all-metal blades is increased by this amount.

The magnitude of traction developed by the rotor in hovering, is greatly influenced by atmospheric conditions: temperature, pressure, humidity and wind. The higher the air temperature, the less thrust created by the rotor, since an increase in temperature leads to a decrease in power of the engine and decrease in the actual thrust owing to a decrease in air density. An increase in temperature of ambient air each 10° leads to a decrease in thrust of the rotor of the Mi-4 helicopter by 160 kgf. An increase in atmospheric pressure leads an increase in thrust of the rotor, since the engine power and mass air density increase.

An increase in atmospheric humidity leads to a decrease in power of the engine, and this means thrust developed by the rotor. An increase in atmospheric humidity by 20 mm Hg leads to a decrease in thrust of the rotor of the Mi-4 helicopter by 230-240 kgf. Wind in hovering gives an increase in thrust to the rotor as velocities of the flight increase approximately by the quadratic law.

In aerodynamic design of a helicopter the change in thrust of a rotor in place (hovering) is accepted to depict in terms of thrust coefficient c_T depending upon the coefficient of torque $m_{\text{кр}}$. The curve showing the dependence of thrust coefficient on coefficient of torque is called the polar of the rotor analogous to the polar of a wing of an aircraft. Here coefficient c_T is analogous to the coefficient of lift of a wing c_y, and the coefficient of torque $m_{\text{кр}}$ is analogous to the coefficient of drag c_x. The polar of the rotor in place (in hovering) for the Mi-4 helicopter with blades of mixed construction is shown in Fig. 45. As can be seen from the polar, the greater the coefficient of torque, i.e., the greater the torque is applied to the rotor, the greater will be the thrust coefficient and this means the greater the thrust of the rotor.

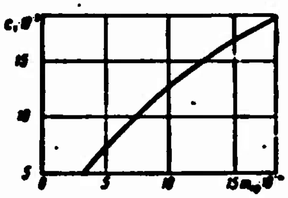

Fig. 45. Polar of a rotor in conditions of hovering $\mu = 0$; $\sigma = 0.067$.

A considerable increase in thrust of the rotor is obtained with hovering of the helicopter near land owing to the so-called air cushion.

Influence of air cushion. With hovering of the helicopter near land the rotor creates greater thrust at the same power than faraway from it because of the influence of the air cushion formed under the rotor. The essence of the phenomenon of the air cushion consists in the fact that induced flow, repulsed by the rotor downwards, encounters a screen — the earth's surface — and cannot freely disperse in space as when hovering faraway from land. The flow under the rotor, encountering the earth's surface, is expanded, static pressure in it grows, the difference in pressures under the rotor and above the rotor becomes greater, and therefore the helicopter is required less power for balancing the flying weight (Fig. 46). If, however, the power is not decreased, then the rotor will create great thrust, and therefore it is possible to accomplish hovering with increased flying weight of the helicopter.

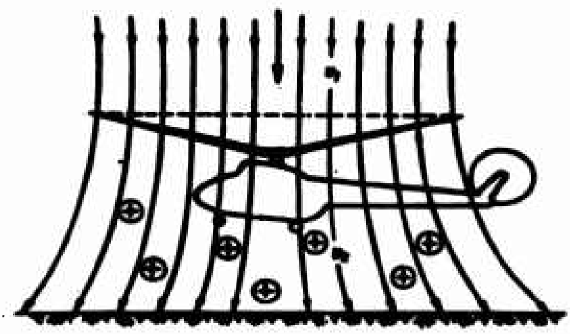

Fig. 46. Principle of the creation of an air cushion.

The influence of the air cushion for helicopters has great importance. For takeoff and landing of the helicopter the greatest power is required. All helicopters are constructed with a design that they should takeoff and land with the use of the air cushion, but this will require installing on the helicopter engines with less power leading to an increase of economy. For forward flight of the helicopter there is required power almost twice less than that for takeoff landing.

The influence of the air cushion starts from the distance from land to the wheels of the helicopter equal to the diameter of the rotor. For the Mi-4 helicopter the influence of the air cushion starts from the height of 15 m from the wheels to land. In practice the perceptible influence of the air cushion on the creation of thrust for the Mi-4 helicopter will be at a distance of 10 m of the wheels from land, and the less the height, the greater the effect of the air cushion. Thus, for example, if in takeoff conditions faraway from land the rotor creates thrust equal to about 6000 kgf, then at a height of 2 m the thrust will be equal to 7250 kgf (Fig. 47). The air cushion gives a maximum increase in thrust directly near land and amounts to about 15% as compared to the thrust developed by the rotor faraway from land at the same power of the engine.

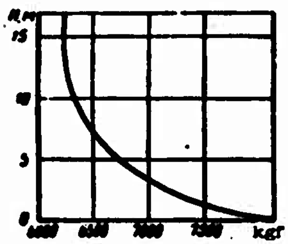

Fig. 47. Change in thrust of the rotor depending upon height owing to the influence of the air cushion with location of the heliport at an elevation of 500 m and at constant power of the engine ($n_{ДВ}$ = 2400 r/min, p_K = 1125 mm Hg).

For hovering on the air cushion with the given flying weight there will require less power of engine than for hovering outside the zone of influence of the air cushion. The change in necessary supercharging and collective pitch of the rotor for hovering of the Mi-4 helicopter with various flying weights at various heights at 2400 r/min (heliport at 500 m) of the engine crankshaft is shown in Fig. 48. As can be seen from the curve, the greater the flying weight, the greater the boost pressure is required and the greater the collective pitch. At the same time it is clear that for a helicopter with a flying weight of 6065 kg at a height of more than 10 m the necessary supercharging and collective pitch are fixed and almost constant.

At heights of less than 10 m, when there will start to appear the influence of the air cushion, the necessary supercharging and collective pitch decrease, and the less height of hovering, the less

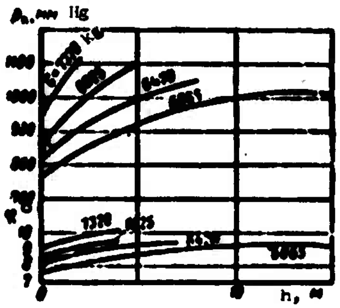

Fig. 48. Dependences of necessary supercharging of the engine (p_k) and collective pitch ϕ of the rotor on the height of hovering and flying weight of the helicopter at $n_{ДВ}$ = 2400 r/min and elevation of heliport 500 m.

the supercharging and collective pitch. Thus, for example, for a helicopter with a flying weight of 6065 kg up to a height of 12 m the necessary supercharging for hovering is constant and is equal to 1015 mm Hg, and the collective pitch is equal to 9.3°, and at height 2 m for the same flying weight supercharging is about 850 mm Hg and collective pitch, 8.3°. Such a pattern of the decrease in necessary supercharging and collective pitch with the approach to land will be the case for other flying weights, which confirms the increase in the influence of the air cushion with the approach to land.

When hovering in the zone of influence of the air cushion the helicopter is more stable than when hovering faraway from land, since with the appearance of bank stabilizing moments appear, which restore equilibrium to the helicopter. The appearance of stabilizing moments is explained by the fact that with a bank the lowered part of disk creates greater thrust than does the raised part in view of their different distance to land.

The influence of the air cushion in hovering with a wind or in the presence of forward velocity of the helicopter decreases. The greater the wind in hovering or the greater the velocity of flight, the less the influence of the air cushion. Thus, by tests it is established that with a wind of 10 m/s the influence of the air cushion completely vanishes already at a height of 10 m, and at a wind of 20 m/s the influence of the air cushion vanishes at a height of 2 m; with acceleration of the indicated speed of the Mi-4 helicopter up to 50 km/h the influence of the air cushion vanishes at a height of 4-5 m. Although an increase in wind in hovering or an increase in forward velocity of the helicopter lower the effect of the air cushion, but then there appears oblique airflow of the rotor, which provides an increase in thrust of it to a greater degree than a decrease in it owing to the disappearance of the influence of the air cushion.

This circumstance indicates the fact that the wind in hovering or acceleration of velocity always leads to a decrease in the required power or increase in permissible flying weight at the same power.

The higher the area above sea level above which the helicopter hovers, the less the height from which there begins to appear the effect of the air cushion owing to a decrease in air density. Thus, flight tests have established that with the location of a heliport at an elevation of 500 m above sea level the influence of the air cushion completely vanishes at a height of hovering of 15 m, and with the location of the heliport at 2000 m its influence vanishes already at a height of hovering of 10 m.

When hovering above a water surface the effect of air cushion decreases in view of the freer dispersion of air over the smooth surface of the water. If we consider that hovering above the water surface is permitted at a height of not lower than 7 m, then in practice during calculation of flying weight for operating above the water the effect of the air cushion is not considered.

When hovering and flying at low speed and at a height above forests and shrubs, even if they are dense, the air cushion will not be formed, and therefore a decrease in required power for such a flight will not occur.

4. Forces and Moments Acting on the Helicopter in Hovering

With steady hovering the following forces and moments act on helicopter (Fig. 49): traction of the rotor T, thrust of the tail

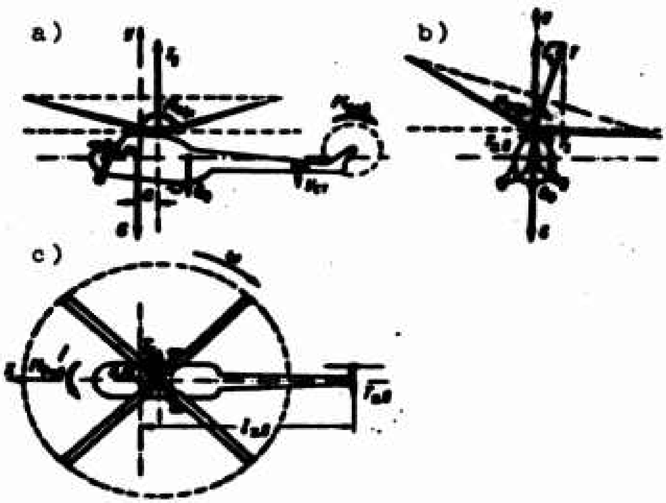

Fig. 49. Diagram of forces and moments acting on the helicopter in hovering and vertical conditions of flight: a) view on the left; b) rear view; c) top view.

rotor $T_{X.B}$, drag of the fuselage Q_{Φ} — owing to airflow of it by induced flow, lift of stabilizer Y_{CT} — owing to airflow of it by induced flow of the rotor, weight of the helicopter G, reactive moment of the rotor $M_{p_{H.B.}}$, yawing moment of the tail rotor, reactive moment of tail rotor $M_{p_{X.B}}$ and longitudinal and lateral moments of the hub due to the spacing in flapping hinges $M_{z_{BT}}$ and $M_{x_{BT}}$.[1]

Thrust of aerodynamic force of the rotor is directed perpendicular to the base of the cone of rotation of the rotor, and it, together with the cone of rotation, is deflected to the right and is spread according to the rule of the parallelogram on the vertical component T_y and lateral horizontal component T_z. Thrust of the tail rotor is directed to the left and on the arm $\ell_{X.B}$ creates a yawing moment of the tail rotor to the side opposite to the reactive moment of the rotor.

[1]Furthermore, in conditions of hovering, as in all other conditions of flight, longitudinal, lateral and yawing moments of the fuselage act on the helicopter. In order to avoid complication of the material, these moments are not examined in detail in the book.

Fuselage drag owing to blowoff by the flow from the rotor Q_{Φ} is directed downwards is applied in the center of pressure of the fuselage, which is beyond the center of gravity and creates stalling moment. The magnitude of this force for a single-rotor helicopter is about 1.5% of the flying weight of the helicopter and for the Mi-4 helicopter is about 100 kgf.

Lift of the stabilizer Y_{CT} owing to blowoff by the flow from the rotor is directed downwards and creates to the helicopter positive pitching moment. Lift of the stabilizer is insignificant in value and in practice its value will be disregarded, although the moment created by it is considered.

Weight of the helicopter G is applied to the center of gravity which more frequently is located ahead of the axis of the rotor shaft, and therefore thrust with respect to the center of gravity creates a negative pitching (diving) moment.

The reactive moment of the rotor $Mp_{H.B.}$ is directed in an opposite direction to the torsional (active) moment of the rotor, i.e., in the opposite direction of rotation of the rotor. The reactive moment of the tail rotor $Mp_{X.B.}$ is also directed in the opposite direction of rotation of the tail rotor and creates to the helicopter a positive pitching moment.

Longitudinal moment of the hub $M_{z\,BT}$ owing to the spacing of the flapping hinges creates a positive pitching moment to the helicopter, since it is directed in the direction of deflection of the cone, and the cone of rotation of the rotor in this case is deflected back (for parrying of the diving moment from the tractive force — in Fig. 49 the deflection back is not shown). The lateral moment of the hub $M_{x\,BT}$ because of the spacing of the flapping hinges is directed to the right, since the cone of rotation of the rotor is filled by the pilot to the right by the control stick.

For balancing the helicopter in steady hovering there should be observed the following relationship between forces and moments acting on the helicopter. The vertical component of rotor thrust T_y should balance the weight of the helicopter G and drag of the fuselage owing to the airflow by the rotor Q_Φ (for observance of the constancy of hovering altitude): $T_y = G + Q_\Phi$. The horizontal component of thrust – the lateral force T_z, which acts to the right, should be equal to the thrust of the tail rotor $T_{X.B}$, which acts to the left for the absence of lateral movements of the helicopter: $T_z = T_{X.B}$. The reactive moment of the rotor $M_{P_{H.B.}}$, which turns the helicopter to around the left (in the opposite direction of rotation of the rotor – active moment), and yawing moment of lateral force T_z, which acts in the direction of the reactive moment, should be balanced by the yawing moment of the tail rotor, which turns the helicopter around to the right (for maintaining the direction of hovering): $M_{p_{n.s}} + T_z \cdot a = M_{x.s} = T_{x.s} \cdot l$.

The sum of all longitudinal moments acting around the lateral axis of the helicopter Z should also be equal to zero (for maintaining longitudinal equilibrium of the helicopter in hovering): $\Sigma M_z = 0$. The helicopter usually hovers with positive pitch angle, depending on the centering of the helicopter: the more it is back, the greater the pitch angle and conversely.

The sum of all lateral moments around the longitudinal axis X also should be equal to zero for the observance of lateral equilibrium of the helicopter in hovering: $\Sigma M_x = 0$. The Mi-4 helicopter hovers with a small right bank of about 2° in view of the action to the right side (to the side of deflection of the cone) of the lateral moment of the hub because of the spacing of the flapping hinges – $M_{x_{BT}}$. Therefore, the helicopter not only hovers with a right bank but also produces vertical landing, touching land at first by the right wheel and then left. In the same way the helicopter is detached during vertical takeoff: at first the left wheel is detached and then the right wheel. For this reason the helicopter will have a right bank in forward flight.

5. Peculiarities of Piloting and Maneuvering a Helicopter in Hovering

In order to accomplish steady hovering and attain the indicated scheme of forces and moments and relationships between them, the pilot should hold all levers in a fixed position.

In hovering the control levers must not be in a neutral position but should have the greatest deflection from neutral position as compared to any established regime of flight with forward velocity.

The control stick with average centering of the helicopter in a longitudinal relation should be deflected back, since its neutral position by intention of the designer is provided for average[1] flight speed. In connection with the fact that average speed the helicopter is found in the part of the time of flight, then the neutral position of the lever is the most convenient. Moreover, in the speed range from zero to maximum the control stick should move only forward. Therefore, at speeds less than the average the stick is moved back, and at speeds greater than average, back. The designer reached such a principle of control on the Mi-4 helicopter by means of deflecting the plate of the cyclic pitch control forward 45' with a neutral control stick in a longitudinal relation, which is attained with control of the control system.

In hovering the plate of the cyclic pitch control in a longitudinal relation should be horizontal, and then the action of the aerodynamic force of the rotor will be directed vertically (see Fig. 49). This can be achieved by means of deflection of the control stick from the neutral position back. But here it is necessary to note that in spite of such a principle of control, the position of the control stick in hovering in a longitudinal relation will still depend to a greater degree on the centering of the helicopter.

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[1]By average speed is implied the speed between minimum and maximum.

In a lateral relation the control stick should be deflected to the right for deflection of the cone of rotation and thrust of the rotor to the same side in order to obtain the horizontal component of thrust — T_z, which balances the thrust of the tail rotor. Moreover by deflecting the lever to the right there should be selected the deflection of the plate of the cyclic pitch control of 20', which is provided with the position of the lever in the neutral lateral relation and is set with setting of the control. Here also on the intention of the designer, for convenience of control the neutral position of the control stick in a lateral relation is provided for the average flight speed. And since in the whole speed range from zero to maximum the control stick in a lateral relation should move only to the left, then at speeds less than average it will be to the right of the neutral position (all the more so in hovering) and at speeds greater than average — to the left.

The reason for needing such a movement of the lever in a lateral relation from the speed of flight will be examined later in the account of horizontal flight.

The load from the control stick must be taken by longitudinal and lateral trimmers, using an eight-position trimmer switch or a pushbutton in the presence on the helicopter of semiautomatic trimmers.

In conditions of hovering there be given forward right pedal, approximately half of its movement. Here also on the intention of the designer, for convenience of control there is provided a neutral position of the pedals in average speed of flight. And since in the whole speed range from zero to maximum the pitch to the tail rotor must be decreased by movement of the left pedal forward, then at speeds less than average forward right pedal will be given and at speeds greater than average, forward left pedal.

In the regime of hovering the conditions of operation of main and tail rotors are difficult, and for balancing the great reactive moment there is required great thrust of the tail rotor. The tail rotor operates under conditions of direct airflow and, in order to create great thrust it must have great pitch, which is attained by deflection of the right pedal forward.

In conditions of hovering the gas control completely should be put fully to the right, and the magnitude of collective pitch depending upon the flying weight and height of hovering can be different, but not more than for takeoff conditions of the engine, 8-9°. Here the power is set as for takeoff of an aircraft according to the principle "much gas - little pitch." With such a position of the control of throttle and collective pitch maximum relative efficiency of the rotor will be attained, and these will be high maneuverability of the helicopter in hovering and vertical flight conditions.

The constant height of hovering is maintained by movement of "pitch-throttle" lever, and therefore in hovering it on the stop is not placed. Hovering above the assigned place is maintained by the control stick and the direction of hovering by the pedals; more accurately the helicopter is held in hovering by coordinated movements of all the control levers.

In principle hovering can be accomplished at any altitude up to the ceiling of hovering but in practice — only at low altitudes near land. Without any limitations it is possible to hover up to a height of 10 m, since in the case of engine failure from such height the helicopter will land safely in view of the gradual drop in revolutions and decrease in thrust of the rotor after engine failure. At heights from 10 to 200 m hovering is permitted but only during extreme necessity (upon takeoffs and landings from temporary heliports, limited high obstacles, during rescue works, during works with external suspension and others). Limitation in this case is introduced because upon engine failure the height for conversion of the helicopter from vertical autorotation to forward flight is insufficient, and safe landing is not ensured.

At heights of more than 200 m hovering cannot be carried out for other reasons. From these heights the pilot can no longer judge movements of the helicopter over land and at the same time use the speed indicator. The latter is explained by the fact that on helicopters thus far there have been installed the usual aircraft indicators US-250 with air pressure receivers located on struts of the front chassis – in the region of action of the stream from the rotor. In connection with this the speed indicator gives stable readings only at a speed of not less than 50 km/h, and the pilot cannot judge movements of the helicopter when it is less than this value. With the necessity of hovering or flight at speeds less than 50 km/h at heights of more than 200 m, in each separate case there is produced a method of orientation or supply of commands to the pilot prior to the application of television installation onboard the helicopter.[1]

Hovering above a water surface in principle must be accomplished at greater height than it is above land. This is explained by the difficulty in the determination visually of the height of hovering and also the possibility of great heaving, which hampers the operation on unloading and loading of the helicopter. With the taking onboard of people or cargoes, hovering must be accomplished at heights of not less than 7 m, and the height of hovering must be controlled by radio altimeter. For the same causes, for hovering above water and the fulfillment of works there is required a great reserve of power of the engine, which can be obtained by decreasing the flying weight of the helicopter. The maximum permissible flying weight of a helicopter for the execution of works by loading and unloading above the water surface for the Mi-4 helicopter must be determined by a nomograph, according to which there is determined the maximum flying weight of the helicopter for takeoff and landing with hovering outside the influence of the air cushion when using maximum power of the engine.[2]

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[1]Indicators of low speeds are created, and with installation of them on helicopters this limitation can be taken.

[2]This calculation will be described more specifically in Chapter V.

Maneuvering in hovering also has certain peculiarities of piloting of the helicopter.

Turns in hovering are fulfilled by deflection of the pedal in the direction of the desirable turn; here the pitch of the tail rotor and its thrust is changed, the equilibrium of yawing moments is disturbed and helicopter turns in the direction of action of the large moment. With a turn to the right the helicopter loses height, and with a turn to the left it climbs, expecially if these turns are made vigorously. This is explained by the fact that when depressing the right pedal forward for a right turn the tail rotor is loaded by a large pitch. But inasmuch as it has a common linkage by transmission with the rotor, then with the same power fed from the engine the whole transmission, and this means the rotor, decreases the revolutions, thrust of the rotor drops, the helicopter descends and turns to the right owing to the increasing yawing moment of the tail rotor. With a left turn the opposite is obtained: the helicopter climbs. Therefore, when turning the height of the hovering is maintained by a change in the collective pitch of the rotor by the "pitch-gas" lever: during a right turn – increase in collective pitch, during a left turn – decrease in collective pitch. For easing the piloting technique and decreasing the load on the tail boom and tail rotor, the speed of turns in hovering should be not more than 12°/s, i.e., one turn should be carried out during the time of not less than 30 s. With a change in the direction of rotation the rate of change in deflection of the pedals should be during the time of not less than 3 s.

Hovering above the assigned place must be accomplished windward, since such hovering is stable, it constitutes flight with respect to air with the speed of wind, and the greater the speed of the wind, the greater the air speed of the flight, the stabler the helicopter and less power for hovering is required.

Turns in hovering with the wind require even greater, special attention on the part of the pilot, since the wind affects speed of turns and changes the pitch angle, and this requires the pilot to maintain a constancy of speed in the turns by the appropriate action of the pedals and with the control stick to prevent lowering or lifting of the nose of the helicopter. Moreover, to eliminate drift during turns the control stick should always be deflected to the windward side. The helicopter is unstable, and in a yawing relation it is difficult to maintain in a desirable direction: it tries to put its nose windward. In connection with this on the Mi-4 helicopter it is permitted to turn windward at any angle up to 360° only with a wind up to 5 m/s, and with a wind of more than 5 m/s it is possible to turn windward only at an angle of not more than 90°.

With movements the main and tail rotors and also the fuselage of the helicopter enter into complicated conditions of flow, and therefore thrusts of the rotors are changed, and piloting of the helicopter is complicated. As is known, the thrust of the rotor in hovering is deflected only to the right (see Fig. 49), and therefore with movements forward or back the vertical component of thrust T_y will decrease and the helicopter, moving because of the appearance of the horizontal component, will simultaneously descend. For preventing descent of the helicopter it is necessary to increase the total thrust of the rotor T by the addition of power by the "pitch-throttle" lever with such calculation in order to maintain altitude, and for balancing the increasing reactive moment it is necessary to push right pedal forward. But such phenomenon will occur only in the beginning of the movement up to acceleration of speed of about 5 km/h, and with further increase in speed both rotors, obtaining oblique airflow, increase the thrust and the helicopter will start to climb. Consequently, for maintaining altitude it is necessary to decrease the power, moving the "pitch-throttle" lever downwards, and to decrease the pitch to the tail rotor by decreasing the pressure on the right pedal.

With movement to the right the helicopter also in the beginning loses height, since the vertical component of thrust T_y decreases upon deflection of the control stick to the right, and the increasing lateral force T_z will move the helicopter to the right. To maintain altitude it is necessary also to increase the total thrust of the rotor T by the addition of power. But soon the helicopter will start to climb, since the oblique airflow of the rotor will increase its thrust and the direct airflow of the tail rotor on the right will increase the angles of attack and thrust to tail rotor. Increasing the thrust of the tail rotor and lateral pressure on the fuselage will turn the helicopter in the direction of the movement, i.e., to the right. In order to prevent a turn, the pilot will have to depress the left pedal forward, which inturn will facilitate transmission. The facilitation of transmission will lead to an increase in revolutions and an increase in thrust of the rotor. To maintain altitude with further movement it is necessary to decrease the power by movement of the "pitch-throttle" lever downwards. Approximately such a pattern is obtained with hovering or vertical takeoff with a right wind. Therefore, experienced pilots sometimes use this phenomenon for easing of takeoff with respect to the conditions of power, although the reserve of control decreases and the technique of takeoff is complicated.

With movement to the left the vertical component of thrust T_y increases and, if one were not to consider operation of the tail rotor, the helicopter should climb. But when moving to the left the angles of attack of the tail rotor decrease, its thrust drops, and the helicopter tries to be turned to the left not only owing to the drop in thrust of the tail rotor, but also due to the lateral pressure on the fuselage. For preventing a left turn it is necessary to increase the thrust to the tail rotor by movement of the right pedal forward, the transmission is loaded, revolutions and thrust of the rotor decrease and therefore the tendency to climb from an increase in vertical component T_y will not occur. For this reason upon moving to the left in the beginning the helicopter also tries to descend but to a lesser degree than when moving to the right. With further acceleration of speed owing to the oblique airflow of the rotor, thrust of it increases and for maintaining altitude the power must be decreased.

In view of poor stability and complexity of piloting, movements of the helicopter are permitted only with a speed of not more 10 km/h at a height of 5 to 10 m, above obstacles — at a height of not less than 10 m, and above aircraft — at a height of not less than 25 m.

Maneuvers in hovering with maximum centering, in general, are difficult, and therefore they are forbidden; and if they are extremely necessary, then smooth movement of the control stick must be fulfilled very carefully, since it is not possible to have the reserve of deflection of the control vanes for creation of the desirable safe position of helicopter when maneuvering.

Maximum centering of the Mi-4 helicopter is obtained in the case when it is not loaded, and onboard there is a crew of four persons and fuel less than 200 ℓ. With such centering the nose of the helicopter is lowered, the shaft, hub, pitch-control mechanism and its plate are deflected forward, and therefore the blades obtain a cyclical change in pitch; the cone of rotation and thrust of the rotor are also deflected forward, and the helicopter moves forward. For retention of the helicopter in place the pilot will be forced to pull the control stick back more than should be and use all or almost all its movement and deflection of the plate of the cyclic pitch control back. With forward centering there cannot be enough reserve of deflection of the control vanes, especially in the presence of wind, since in hovering and with average centering all control levers by intention of the designer have the greatest deflection from the neutral position as compared to any established regime of flight with forward velocity.

Piloting a helicopter in hovering with a load on the external suspension is more complicated with a load in the fuselage for several reasons. In connection with the fact that for hovering with a load on the external suspension greater altitude is necessary, i.e., such an altitude when there will be no effect of the air cushion, the reserve of power decreases, and this means the permissible flying weight of the helicopter is possible. Furthermore, the load, especially of great dimension, distorts the induced flow under the rotor, and this worsens the stability of the helicopter. The length of the suspension should be as little as possible: the more the length of the suspension, the greater the amplitude of swaying of the load, the more complicated the piloting. For this reason suspension of loads is allowed from the helicopter at a distance of 3 to 20 m depending upon the relief of the terrain and dimension of the load. Maneuvering in hovering with a load on external suspension is not recommended, since piloting is complicated and it is not possible to have reserve of power for maneuvering. Hovering with loads on external suspension is allowed only with a wind up to 10 m/s.

6. Flying Limitations in Hovering

Altitude of hovering. The altitude of hovering is permitted without any limitations up to 10 m, and from 10 to 200 m only in special cases by assignment. At heights of more than 200 m it is necessary to maintain by instrument a speed not less than the minimum permissible in horizontal flight at a given height (for the Mi-4 helicopter 50 km/h up to a height of 2000 m), since otherwise the pilot cannot from such heights estimate movement of the helicopter without an instrument, and the speed indicator US-250 at speeds less than 50 km/h gives incorrect readings.

The height of hovering with standard vertical takeoff and landing should be 2-3 m, with vertical takeoff with the use of the air cushion — at a height of not less than 1.5 m, and with vertical takeoff outside the effect of the air cushion — at a height of 10 m above obstacles. The altitude of hovering during takeoff and landing with loads on the external suspension should be such that the distance of the load to land is not less than 2 m.

Speed and altitude of movements. Movements to any side should be with a speed of not more 10 km/h in view of the absence of directional stability of the helicopter and the complexity of piloting. If movements are conducted above a level terrain, then the altitude should be within limits of 5 to 10 m, since at an altitude of more than 10 m it is difficult to judge the speed of movement. Movements above obstacles should be conducted at an altitude of not lower than 10 m and above aircraft and helicopters at an altitude of not lower than 25 m.

Wind. Hovering and also takeoffs on the Mi-4 helicopter are permitted with a wind up to 18 m/s and with loads on the external suspension – up to 10 m/s. It is desirable to accomplish hovering windward, since such hovering requires less power and gives a certain directional stability. Such hovering constitutes flight with respect to air with the wind speed. It is possible to turn windward at any angle in the whole 360° with a wind up to 5 m/s and with loads on the external suspension up to 4 m/s. With such a wind the pilot can rather easily cope with piloting of the helicopter. With a wind from 5 to 18 m/s it is possible to turn into the wind at an angle of not more than 90°. With the approach to uncoupling of the load on the external suspension at any wind, the approach should be at an angle of not more than 90° windward.

Speed of rotation. The angular velocity of turns in hovering must not exceed 12°/s, i.e., it is necessary to make one turn during the time of not less than 30 s. Upon cessation of rotation or a change in direction of rotation full change in the deflection of the pedals during the time of less than 3 s is not permitted. Such limitations are set for the easing of piloting and for preventing the appearance of great loads on the blade of the tail rotor.

When hovering with maximum centering. With maximum forward centering it is necessary to hover only with a head wind, maneuvering in this case is forbidden, since there is not enough reserve of control. In the case of emergency movements by control levers should be smooth and careful, especially the control stick forward.

When hovering above a water surface. When hovering above a water surface for unloading or loading a helicopter, the latitude of hovering should be within 7-10 m and there should be greater reserve of power than for hovering above land under the same atmospheric conditions. The maximum permissible flying weight for hovering above the water surface is determined by the same nomograph as that for takeoff and landing outside the zone of the effect of the air cushion, if the temperature of the external air is higher than 20°C and the atmospheric pressure is less than 745 mm Hg. At an air temperature up to 5°C and atmospheric pressure of not less 745 mm Hg, the flying weight should not exceed 7000 kg, at an air temperature of not more 15°C and atmospheric pressure of not less 745 mm Hg – 6800 kg, at an air temperature of not more than 25°C and pressure of air of not less than 745 mm Hg – 6600 kg; on a helicopter with a rotor of mixed construction in any case the flying weight should not exceed 6600 kg.

§ 2. Vertical Climb

1. General Characteristic

Conditions of vertical climb are, just as hovering, difficult conditions of flight, since for their fulfillment even higher power than for hovering is required. In view of small surplus of power the vertical velocity of climbing is insignificant and is therefore an uneconomic regime. Using these conditions, it is possible to gain only the ceiling of hovering of the helicopter, which in magnitude is many times less than the ceiling of the helicopter. With vertical climb, besides the small reserve of power, there is also little reserve in deflection of the control levers (less than that in hovering), the helicopter does not possess stability and these conditions are complicated by the piloting technique. For the enumerated reasons the application of conditions of vertical climb is limited, and it is applied only when there is a justified necessity.

Application of vertical climb. This regime is a component part of vertical takeoff of a helicopter. Since vertical takeoff for the Mi-4 helicopter is the basic form of takeoff, therefore vertical climb has obtained wide application. In other cases vertical climb is applied only with the impossibility to be lifted to an assigned altitude because of the presence of obstacles.

Scheme of forces and moments acting on the helicopter during vertical climb. With the steady state of vertical climb the same forces and moments as in conditions in hovering act on the helicopter, only the numerical value of them will be different (see Fig. 49). Thus, for example, drag of the fuselage Q_Φ and lift of stabilizer Y_{CT} will be greater in value as compared to their value in conditions of hovering, since in addition to induced flow there will be added flow on the fuselage and stabilizer owing to movement of the helicopter upwards. Therefore, a great vertical component of thrust of rotor T_y will be required for balancing of the increasing drag $T_y = G + Q_\Phi$. If, however, climb will occur with acceleration, then the thrust will be required even more, since it will have to balance in this case not only the weight of the helicopter, parasite drag, but also the force of inertia acting in the opposite direction of acceleration, i.e., in the direction of the parasite drag: $T_y = G + Q_\Phi + F_{ин}$.

For the augmentation of thrust of the rotor T and its vertical component T_y high power will be required; then the reactive moment of the rotor will increase, and the helicopter will try to turn left. For preventing this turn the pilot will be forced, in lifting the lever of collective pitch upwards, to depress the right pedal forward for increasing pitch to the tail rotor and increasing its thrust. As a result of this the yawing moment of the tail rotor will increase, and the increasing reactive moment of the rotor will be balanced: $M_{р_{н.в}} = M_{x.в} = T_{x.в} l_{x.в}$.

In order that the helicopter does not move to the left owing to the increasing thrust of the tail rotor, by moving the control stick to the right the pilot should increase the lateral force: $T_z = T_{X.B}$.

However, in connection with the fact that steady climb is accomplished, there should be maintained a condition of equilibrium around all axes of the helicopter, i.e., for balancing the helicopter in these conditions the sum of all moments with respect to all axes of the helicopter should be equal to zero: $\Sigma M = 0$.

2. Required and Available Powers and Thrust

The required power for vertical climb will be expended for surmounting induced and profile drag of blades of the rotor and parasite drag of the fuselage and for lifting helicopter vertically. As was established earlier, for hovering the required power is composed of induced and profile powers. For vertical climb there will be required greater power than for hovering: $N_{потр_{наб}} = N_{инд} + N_{пр} + \Delta N = N_{вис} + \Delta N$.

Hence it is clear that vertical climb is possible only in the presence of greater power than which is required for hovering, i.e., with a surplus of power. The power surplus is determined by the difference between available and required power for hovering: $\Delta N = N_{расп_{вис}} - N_{потр_{вис}}$ (see Fig. 43). Here the power surplus will be expended for accomplishment of climbing with a fixed vertical velocity V_y:

$$\Delta N = \frac{GV_y}{75} \text{ [hp]}. \qquad (35)$$

The available power of the rotor, as was established earlier, with an ascent in altitude is changed, since the effective power of the given engine installed on the helicopter is changed (see Fig. 43). For the Mi-4 helicopter the available power of the rotor up to the rated altitude is increased as is power of the ASh-82V engine, and beyond the rated altitude it decreases. The required power for hovering with ascent in altitude is increased. The power surplus with ascent in altitude decreases, and therefore vertical climb is possible up to an altitude at which the power surplus will be equal to zero, i.e., up to the ceiling of hovering.

The required thrust for vertical climb will be composed of a magnitude of flying weight of the helicopter and drag of the fuselage:

$$T_{потр_{наб}} = G + Q_ф.$$

The available thrust of the rotor with ascent in altitude for the Mi-4 helicopter will be changed approximately, since the power of the engine is changed with the altitude in normal operating conditions, i.e., up to a certain altitude it will be increased and then will decrease both owing to the decrease of power of the engine and owing to the decrease in air density (see Fig. 44).

From this the conclusion can be drawn that for the possibility of vertical climb the pilot should increase the power of the engine by the "pitch-throttle" lever owing to the available surplus of power. And as soon as the whole reserve of power will be expended, the climb will be ceased, and the helicopter will be at the ceiling of hovering.

Vertical climb velocity. Vertical climb velocity is determined from formula (35):

$$V_y = \frac{75 \cdot \Delta N}{G} \text{ [m/s]}.$$

From the formula it is clear that vertical climb velocity is directly proportional to the surplus of power ΔN and inversely proportional to the weight of the helicopter G. Since the surplus of power for the Mi-4 helicopter in these flight conditions is small, then the vertical velocity of climb cannot be great. In connection with this with vertical ascent the pilot carefully operates the "pitch-throttle" lever, not allowing high speeds of climb and rotor heaviness.

3. Peculiarities of Fulfillment of Vertical Climb

After lift-off of the helicopter from land during takeoff or from hovering, vertical climb is fulfilled by motion of "pitch-throttle" lever upwards, not changing the position of the throttle control, which was moved completely to the right while still on land before takeoff. When moving the "pitch-throttle" upwards there are insignificantly increased revolutions of the whole transmission, and thrust of the tail rotor simultaneously increase at the former position of the pedals. But the yawing moment of the tail rotor will be increased by a smaller value as compared to the increase in reactive moment of the rotor, and therefore the helicopter will turn to the left. To prevent this turn one should deflect the right pedal forward. Then the thrust of the tail rotor will be increased by a greater value than will the horizontal component of thrust of the rotor T_z, and the helicopter will start to move to the left. To prevent this movement the pilot will have to increase lateral force T_z by moving the control stick to the right. At the same time when moving the "pitch-throttle" lever upwards the pitch angle of helicopter is changed, since the center of gravity does not lie on the axis of rotation of the rotor and airflow of the body of the helicopter and stabilizer is changed, and therefore the helicopter will start to move in a longitudinal relation. The pitch angle can be decreased or be increased depending upon the value of centering of the helicopter, but most frequently it decreases, and therefore the helicopter tries to move forward. By moving the control stick in a longitudinal relation the pilot will have to parry the tendency of the helicopter to longitudinal movements.

After achievement of the assigned altitude, the pilot by a smooth and insignificant motion of the "pitch-throttle" lever downwards inpedes the helicopter from further rise and holds it at this height, not placing the "pitch-throttle" lever on the stop.

Consequently, we see that for moving the helicopter only upwards with preservation of the direction coordinated motion by all control levers is required. The magnitude and direction of such deflections is selected by the pilot depending upon concrete conditions of piloting of the helicopter.

It is necessary to note that not only with vertical climb but also under any conditions of flight even with forward speeds and at any position of the throttle control, with deflection of the "pitch-throttle" lever upwards, it is necessary to deflect forward the right pedal for preventing a left turn and deflect the control stick to the right for preventing movement to the left in vertical conditions or preventing left slip with forward flight. These positions always remain correct in view of the imperfect control system on a single-rotor helicopter.

4. Flying Limitations During Vertical Climb

Here the limitations remain only in altitudes (other maneuvers are forbidden). A climb can be conducted without any limitations up to an altitude of 10 m, at altitudes from 10 to 200 m – during an emergency, and at altitudes of more 200 m – to hold the indicated speed at not less than the minimum permissible. But one should note that the altitude from 10 to 200 m during a climb is more dangerous than when hovering. During a climb the collective pitch is more than in hovering and in the case of engine failure there will be great drag to rotation, and consequently, a smaller number of revolutions of the rotor. Therefore, the energy of rotation of the rotor during landing will be less – less effect will be from the action of the "pitch-throttle" lever on the decrease in vertical velocity before landing, and the landing can be rougher than landing during engine failure from conditions of hovering.

In the case of the necessity to conduct ascent in altitude of more than 200 m with a forward velocity of less 50 km/h or strictly vertically, then there are produced in each separate case special methods of orientation, which are mentioned above.

§ 3. Vertical Descent

1. General Characteristic

Conditions of vertical descent, as hovering and vertical climb, are difficult conditions; for their fulfillment high power is required, and therefore these flight conditions are uneconomical. In conditions of descent the reserve of power and reserve in deflection of the control levers are small; the helicopter has insufficient stability, and depending upon this complicated piloting technique. If one were to allow great vertical velocity of descent (more 3 m/s), then the rotor can enter into conditions of the vortex ring. This means that at low altitudes and near obstacles these conditions to a certain degree are unsafe.

For the enumerated reasons the application of vertical descent is limited. It is applied only during an emergency when its application is justified in conditions which have formed. If, however, it is possible there is attempt to conduct descent with forward velocity. Then the enumerated deficiencies are eliminated.

Vertical descent is a component part of vertical landing of a helicopter. Since this landing for a helicopter is the basic form of landing, vertical lowering has obtained wide application.

Force and moments acting on a helicopter during vertical descent. During the steady state of vertical descent the same forces and moments as during hovering and vertical climb will act on a helicopter, only the numerical value of them will be different (see Fig. 49). The resisting force of the fuselage Q_{Φ} and lift of the stabilizer Y_{CT} will be directed also downwards, only the magnitude of them will be less than in conditions of hovering, since the rate of descent is directed upwards, and it will be subtracted from the speed of induced flow directed downwards. In connection with this the total flow downwards will be less than that in hovering, and means the aerodynamic forces will be less. As a result of this there will be required less vertical component of thrust of the rotor T_y for balancing the same weight of the helicopter and decreased drag:

$$T_y = G + Q_{\Phi}.$$

If, however, vertical descent will be conducted with acceleration, the thrust required will be even smaller, since to the opposite side of acceleration will act the force of inertia (it will be directed in this case upwards):

$$T_y = G + Q_{\Phi} - F_{ин}.$$

To decrease thrust of the rotor T and its vertical component T_y less power on rotor will be required; then the reactive moment of the rotor will decrease, and the helicopter will try to turn right. To prevent this turn it is necessary to lower lever of collective pitch downwards and simultaneously depress the left pedal forward. Thereby pitch of the tail rotor will decrease, its thrust will decrease, and with a decrease in yawing moment of the tail rotor the direction of the helicopter will be preserved: $M_{р.н.} = M_{х.в} = T^{х.в} l_{х.в}$.

In order that the helicopter does not move to the right owing to a decrease in thrust of the tail rotor, one should decrease the lateral force T_z by movement of the control stick somewhat more to the left than the position which it occupied in hovering: $T_z = T_{х.в}$.

So that vertical descent is established there should be maintained the condition of equilibrium around all axes of the helicopter, i.e., for balancing the helicopter in this conditions the sum of all moments with respect to all axes should be equal to zero: $\Sigma M = 0$.

2. Peculiarities of the Fulfillment of Vertical Descent

Vertical descent from hovering is fulfilled by moving the "pitch-throttle" lever downwards, not changing the position of the throttle control, which in conditions of hovering occupies the extreme right position. With a decrease in the collective pitch there will be decreased revolutions of the whole transmission, and consequently also the reactive moment of the rotor and thrust of both rotors will decrease, and then the total balancing of the helicopter will be disturbed. In ler to maintain a strictly vertical trajectory of descent and preserve the fixed direction of the helicopter, it is necessary to operate in coordination other control levers.

When moving the "pitch-throttle" lever downwards there is an insignificant decrease in revolutions of the whole transmission, and thrust of the tail rotor is at the former position of the pedals. A decrease in thrust of the tail rotor will lead to a decrease in yawing moment of the tail rotor but by a smaller magnitude than the reactive moment of the rotor will decrease. Therefore together with the descent the helicopter will turn to the right. To prevent this turn the pilot will have to deflect the left pedal forward. With this the thrust of the tail rotor will decrease by a greater magnitude than the lateral force T_z, and the helicopter will start to move to the right. Then to prevent this movement one should decrease the lateral force T_z by moving the control stick to the left of its position which it occupied in hovering.

At the same time when moving the collective pitch lever downwards the pitch angle of the helicopter will change, and this inturn will lead to the fact that the helicopter will start to move forward or back depending upon the centering of helicopter. It follows to parry this movement in a longitudinal relation by the control stick of the helicopter.

With vertical descent the "pitch-throttle" lever is deflected downwards smoothly and insignificantly in order not to allow a vertical velocity of descent greater than 3 m/s. Actions by the control stick and pedals must be smooth, short and double.

After achievement of the assigned altitude by a smooth and insignificant motion of the lever of collective pitch upwards the pilot delays the helicopter from further descent and holds at this height, not placing the "pitch-throttle" lever on the stop.

Thus, for moving the helicopter only downwards along a vertical trajectory with preservation of the direction, motion by the control levers is required, but in the opposite direction as compared to their motion during a vertical climb. The magnitude and direction of such movements by the control levers is made by the pilot, as when climbing, holding the direction of the helicopter along selected reference points.

In the practice of flights conditions can be complicated for many reasons: character, direction and force of the wind, conditions of approach to the heliport, character of the heliport and others. Then the pilot should consider all these circumstances and act depending upon the conditions forming and behavior of the helicopter.

During vertical descent and during descent with any forward speeds and at any position of the throttle control, with deflection of the "pitch-throttle" lever downwards, it is necessary simultaneously to deflect forward the left pedal for preventing of a right turn and deflect the control stick to the left (or to actuate it with the help of a tab) for preventing movement and slip to the right.

3. Flying Limitations During Vertical Descent

1. In altitude flying limitations for the Mi-4 helicopter during vertical descent are the same as for hovering and vertical climb. From an altitude of 1000 to 200 m it is possible to descent only with a forward indicated velocity of not less than 50 km/h. From an altitude of 200 to 10 m vertical descent is permitted only upon the necessity of such descent during forming circumstances. The reasons for such limitations are the same as those for hovering and vertical climb.

2. During vertical descent it is forbidden to produce simultaneously any other maneuvers in order not to complicate the piloting technique.

3. Vertical descent velocity should be not more than 3 m/s both with vertical descent and descent with forward indicated velocities less than 50 km/h. When exceeding the indicated speed the rotor enters into conditions of the vortex ring.

4. Conditions of the Vortex Ring

Physical meaning of conditions of the vortex ring. In conditions of hovering (Fig. 50a) air from all sides approaches (is sucked) the rotor, so that at a certain distance from it (over the spheric surface) the speed of suction will be equal to zero. Under the rotor the air will be repulsed downward at a fixed rate. The

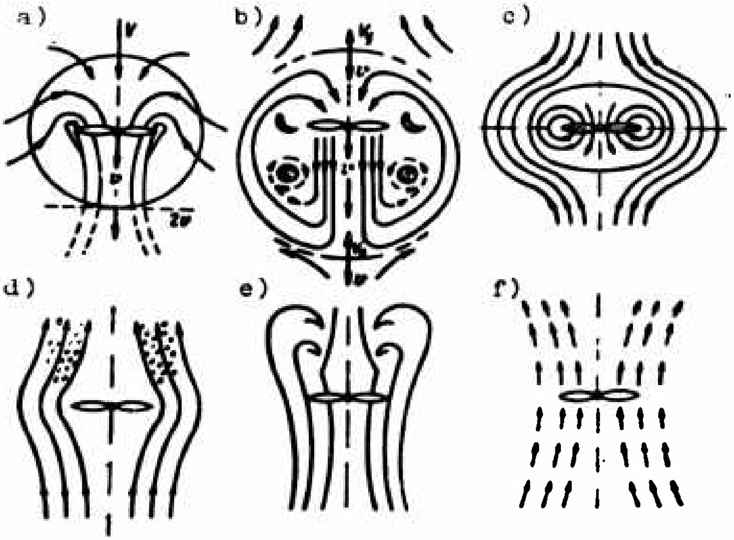

Fig. 50. Diagram of the formation of conditions of the vortex ring: a) hovering; b) descent with low speed; c) conditions of vortex ring; d) conditions of ideal autorotation; e) beginning of the transition to conditions of vertical autorotation; f) vertical autorotation.

air partially will also overflow from the region of raised pressure under the rotor along the periphery of the rotor in the region of lowered pressure above the rotor. This overflowing is insignificant, and there is no harmful influence on the operation of the rotor; it only partially decreases the thrust owing to the leveling off of pressures under the rotor and above the rotor, which consists of tip losses of the rotor.

With vertical descent (Fig. 50b) induced flow under the rotor is directed toward the flow due to the descent. At a certain distance from the rotor below and above where the induced speeds will be equal to the rates of descent ($v = V_y$) there will be formed interfaces of flow in which the total speed is equal to zero. Between these interfaces under the rotor vortexes and annular flows appear owing to the repulsion of flow from the lower interface. At a small rate of descent (up to 3 m/s) these vortexes do not have a harmful effect on the operation of the rotor, just as with hovering. But with an increase in the rate of descent of more 3 m/s the interfaces approach, and then the streams reflected from the lower interface go upwards and enter into the region above the rotor, are drawn in and again pass through the rotor several times. The interfaces are unstable - they oscillate; vortex flows under the rotor are also unstable, since they are continuously destroyed by the main flow. Part of power supplied to the rotor is expended on all of this vortex. In connection with this the thrust of the rotor drops, oscillations of the helicopter occur and shocks on the rotor and on control stick and control of the helicopter worsens.

With an even greater rate of descent (7-8 m/s) the interfaces approach even more and join around the rotor and then there will be formed a spheric surface with zero speed - "air body" (Fig. 50c). Inside the "air body" air from the lower border of the interface, not having kinetic energy, is drawn in by the rotor, passes through it, accelerates, and again the same process is repeated. This means that the "air body" constitutes flow circulating around the rotor. The "air body" is flowed past by the total flow because of the descent. But such flow cannot exist for a long time, since it is unstable and sharply decreases the tractive force. Therefore, it disintegrates, being turned into the flow described earlier (see Fig. 50b). Again tractive force is increased, and then the phenomenon is repeated, as a result of which a pulsation of air appears. All of this causes bumps of the helicopter from side to side, and the control even more worsens. Such conditions are conditions of the vortex ring.

In certain cases (during definitely created conditions) the rotor can be briefly flowed past as a flat plate set to the flow at an angle of 90° (Fig. 50d). Such a case of flow around received the name: "Conditions of ideal autorotation."

With further increase in the speed of vertical descent (more than 8 m/s) the vortex ring will lag behind the rotor upwards owing to the great support of air from below. This is the end of the vortex ring with which controllability is again (Fig. 50d).

With an even greater rate of descent (12-15 m/s) the rotor passes over to conditions of vertical autorotation, not requiring power for its rotation, and conversely, will be itself transmit power to the rotor shaft (Fig. 50f).

In flying practice conditions of the vortex ring can appear during vertical descent or descent with low forward speeds under the condition if the pilot allows high speeds of vertical descent, for the Mi-4 helicopter higher than 3 m/s. This can occur, for example, in the case of the extinguishing of forward velocity prior to hovering without the addition of appropriate power (although there is reserve of it), in the case of decreasing the speed prior to hovering for landing with a deficiency of power in view of an overloaded helicopter, high-mountain terrain, high temperature of the external air and low atmospheric pressure.

Consequently, in order to prevent entrance of the helicopter into conditions of the vortex ring, it is necessary to produce vertical descent carefully, not allowing great vertical velocities. Upon extinguishing forward velocity prior to hovering before landing, it is necessary simultaneously to increase the power, not allowing high speeds of vertical descent. Landing should always occur with sufficient power reserve. Therefore, before the flight it is necessary to load the helicopter in such a manner so that its landing weight is not more than the maximum permissible for given atmospheric conditions.

Criteria of conditions of the vortex ring are the following:

1) spontaneous increase in vertical velocity of descent, which the pilot notices on the approach to land or on the rate-of-climb indicator;

2) increased vibration of the whole helicopter;

3) impairment of controllability;

4) bumps of the helicopter from side to side, especially in the second part of the vortex ring at rates of descent higher than 7-8 m/s.

Method of guiding the helicopter from conditions of the vortex ring. When the helicopter is in conditions of vortex ring it is dangerous, especially at low altitudes and near obstacles. Therefore, with the appearance of the first criteria of such conditions it is necessary by the "pitch-throttle" lever to increase the power and bring the rate of descent to that required. If, however, there is no reserve of power or conditions of the vortex ring was developed so that the addition of power does not give results, and vertical velocity does not decrease, it is necessary to put the helicopter in forward flight by the control stick in a direction free from obstacles. With great vertical velocity of descent, the longitudinal controllability can be so worsened that the helicopter will not react to actions of the control stick. In this case it is necessary to lower immediately the "pitch-throttle" lever and put the helicopter in autorotation. When controllability is restored one should transfer the helicopter to forward flight and then emerge from conditions of autorotation on powered flight.

In the case of the appearance of the beginning of conditions of the vortex ring upon decreasing the speed less than 50-40 km/h, it is necessary in the first place to increase the speed by the control stick and after achievement of it up to 60-70 km/h decrease the vertical descent velocity by moving the "pitch-throttle" lever upwards.

Conditions of the vortex ring can also appear for the tail rotor during a sharp left turn of the helicopter, which can be upon maneuvering in conditions of hovering or when decreasing the speed prior to hovering before landing. In the first case conditions of the vortex ring can appear with a left turn at great angular velocity, when the tail rotor moves to the right; in the second case the vortex ring can appear for the tail rotor when the pilot sharply moves the "pitch-throttle" lever upwards, not parrying at the proper time the tendency of the helicopter to turn left owing to the increasing reactive moment by deflection of the right pedal forward. Here the same phenomenon as that for the rotor occurs, which leads to a spontaneous decrease in thrust of the tail rotor and rapid involuntary further turn of the helicopter to the left. With this the control of the tail rotor, as the control of the main rotor, also worsens, and an increase in pitch of it by moving the right pedal forward can not produce desirable results.

If conditions of the vortex ring appeared for the tail rotor, and the helicopter continues to revolve to the left with a right pedal completely deflected forward, it is necessary with the control stick to transfer helicopter to forward flight and simultaneously deflect the lever to the right. The appearing oblique airflow will improve operation of the tail rotor, the thrust of it will be increased, and the right slip owing to deflection of the lever to the right will create lateral pressure on the right, which will try to turn the helicopter to the right.

CHAPTER IV

HORIZONTAL FLIGHT OF THE HELICOPTER

§ 1. Diagram of Forces and Moments in Horizontal Flight

In horizontal flight the following force and moments act on the helicopter (Fig. 51): total aerodynamic force of the rotor R, thrust of the tail rotor $T_{\text{х.в}}$, drag of the helicopter Q, weight of the helicopter G, reactive moment of the rotor $M_{\text{р.н.в}}$, yawing moment of the tail rotor $M_{\text{х.в}}$ longitudinal aerodynamic moment of the total aerodynamic force of the rotor (diving), longitudinal moment of the stabilizer, longitudinal reactive moment of the tail rotor $M_{\text{р.х.в}}$, longitudinal moment of the hub owing to the spacing of the flapping hinges $M_{z_{\text{вт}}}$, lateral moment of the hub due to the spacing of the flapping hinges $M_{x_{\text{вт}}}$, lateral moment of the tail rotor $T_{\text{х.в}}$ and lateral moment of the lateral force Z.

In horizontal flight the cone of rotation of the rotor is deflected forward by the control stick by a magnitude dependent on the flight speed. To the same side is deflected the direction of action of the total aerodynamic force of the rotor R, since it is directed perpendicular to the base of the cone. Force R creates a diving moment, and therefore following the cone of rotation of the rotor the body of the helicopter is deflected forward, and owing to flapping motions of the blades and the presence of the flapping control the cone of rotation and together with it force R are deflected from the former assigned position by the control stick back and to the right.

In the bound system of coordinates force R is spread over three components: thrust of the rotor T, longitudinal force Q_B and pain force Z_B; tractive force T is directed along the axis of the shaft (perpendicular to the plane of rotor rotation), longitudinal force Q_B is directed along the plane of rotation in a direction opposite the flight, lateral force Z_B is directed along the plane of rotation to the right. In turn the thrust of the rotor T in the high-speed (continuous) system of coordinates spread according to the rule of the parallelogram on T_y – vertical component, directed along Y axis upwards, and T_x – horizontal component directed along the X axis forward in flight. Hence force T_y will be lift and T_x – thrust. Longitudinal force Q_B is also spread in the high-speed system of coordinates on Q_{B_y}, acting in the direction of force T_y (superimposed on force T_y), and Q_{B_x}, acting along the X axis in the direction opposite the direction of flight. This force is drag of the rotor.

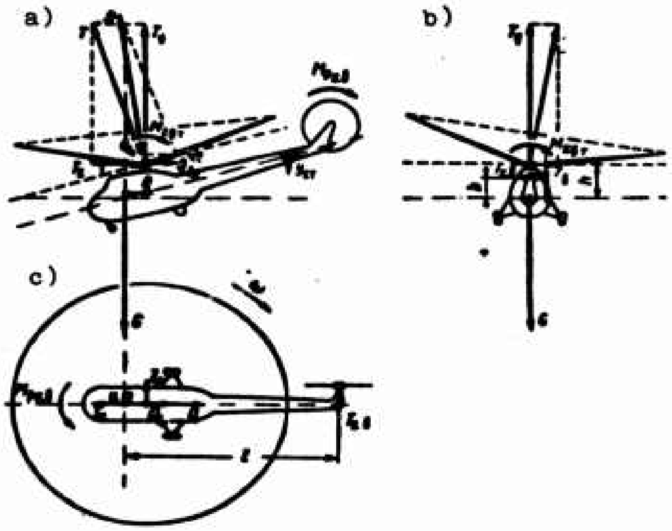

Fig. 51. Diagram of forces and moments acting on the helicopter in horizontal flight: a) view on the left; b) rear view; c) top view.

Thrust of the tail rotor $T_{т.в}$ in horizontal flight is always directed to the left.

Drag of the helicopter Q appears owing to airflow of the fuselage by basic and induced flow and is directed in the direction opposite the flight. The point of application of this force can be located higher than the center of gravity, below it or in the center of gravity of the helicopter depending upon flight conditions.

The force of weight of the helicopter G is directed vertically downwards.

In a steady horizontal flight at a fixed speed following equations of equilibrium of forces must be observed:

a) during rectilinear and horizontal flight forces T_y and Q_{B_y} balance the weight of the helicopter $G: T_y + Q_{B_y} = G$;

b) during uniform flight force T_x balances force Q_{B_x} and $Q: T_x = Q_{B_x} + Q$;

c) in the absence of slip during flight the lateral force Z_B balances the tractive force of the tail rotor $T_{x.B}: Z_B = T_{x.B}$;

d) with the observance of total balancing of the helicopter (longitudinal, lateral and directional) the sum of all moments with respect to each axis of the helicopter is equal to zero:

$$\Sigma M = 0.$$

The indicated diagram of forces and moments in Fig. 51 is given for a fixed speed of flight. If the flight occurs at another speed, then the diagram of forces and moments and the relationship between them will be the same, only at high speed of flight there will be great drag of the helicopter Q and horizontal component of longitudinal force Q_{B_x}. Therefore, to balance them will require great thrust T_x and, consequently, thrust of the rotor T. The thrust of the tail rotor $T_{x.B}$ and lateral force Z_B will also be different in magnitude.

§ 2. Required and Available Thrusts and Powers for Horizontal Flight

1. Required and Available Thrusts

The required thrust for horizontal flight is thrust which is required for conditions of horizontal flight for balancing the weight and drag of the helicopter. It can be defined by this formula[1]:

$$T_{потр}=G\sqrt{1+\left(\frac{Q}{G}\right)^2}. \tag{36}$$

From this formula it is clear that for conditions of hovering there is required thrust equal to the weight of the helicopter, since in hovering the expression $\sqrt{1+\left(\frac{Q}{G}\right)^2}$ will be equal to unity (Q = 0). With the transition to horizontal flight the required thrust will be increased, since it will have to balance the constant weight of the helicopter G and increasing drag of it Q (Fig. 52).

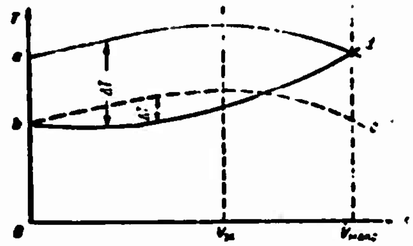

Fig. 52. Required and available thrusts for horizontal flight of the helicopter.

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[1]This formula is obtained in the following way. Earlier we accepted that the total aerodynamic force of the rotor R in practice can be equated to thrust of the rotor T, then longitudinal force Q is not considered. The thrust is the hypotenuse of a right triangle for which one leg is the vertical component of thrust T_y and the other, the horizontal component T_x (see Fig. 51). According to the Pythagorean theorem: $T^2=T_y^2+T_x^2$ or $T^2=G^2+Q^2$, then $T=\sqrt{G^2+Q^2}$. Converting this expression, will obtain the above-cited formula (36).

With an increase in altitude of flight the required thrust for horizontal flight at that same indicated airspeed is not changed, since the weight and drag remain constant.

With an increase in flying weight of the helicopter the required thrust for horizontal flight is increased and can be determined depending upon the weight by formula

$$T_2 = T_1 \frac{G_2}{G_1}, \tag{37}$$

where T_2 – required thrust for increased weight of the helicopter (G_2); T_1 – thrust required for less gross weight (G_1).

<u>The available thrust</u> of the rotor is called thrust which is created by the rotor at a definite assigned power of the engine. As was determined earlier, the thrust of an ideal rotor in forward flight is determined by formula (18) and a real rotor – by formula (25). If in conditions of hovering at a definite assigned power of the engine the rotor creates thrust equal to the weight of the helicopter, then with an increase in speed up to the economic the available thrust will be increased owing to the improvement of conditions of operation of the rotor in oblique airflow (see Figs. 37 and 52). The growth in thrust at constant power is explained by the increase in the flow rate per second of air through the rotor, which is clear from formula (18), i.e., the rotor per second interacts with the large mass of air at the same induced rake and with that same induced power. But such a growth in thrust is observed only up to economic speed. With a further growth in speed with that same input power, the thrust of the rotor is decreased owing to the impairment of conditions of the rotor operation at high speeds. This is explained by the fact that at speeds higher than the economic profile drag is increased both due to the increase in speed and owing to the expansion of the zone of reverse flow around. At these speeds the consumption of power supplied to the rotor for surmounting the profile drag is increased, and less of it remains for surmounting the induced drag, i.e., for the creation of thrust. Moreover, with an increase in speed angles of attack of the rotor are decreased, and it passes from conditions of oblique airflow to conditions of

direct airflow, i.e., to conditions of operation of a tractor propeller, for which in the whole speed range thrust decreases with an increase in speed.

If the power fed to the rotor decreases, then the available thrust also decreases, but the character of its change from the speed of flight remains the former, i.e., it will be maximum at an economic speed, and with a decrease or increase in speed the thrust will decrease. Consequently, at the economic speed of flight conditions of operation of the rotor are best, and it develops maximum thrust. This circumstance conditions the special flying properties of the helicopter in contrast to an aircraft, including such as the necessity to feed to the rotor different power depending upon the flight speed.

For maintaining horizontal flight at various speeds the task of the pilot is to ensure that the available thrust is always equal to the required; otherwise a steady state of flight will not occur. This means that for hovering it is necessary to set such power of the engine so that the rotor develops thrust equal to the weight of the helicopter. In other words, so that the available thrust in hovering is equal to the required, for this it is necessary to combine point a on the curve of available thrust with point b on the curve of required thrust (see Fig. 52). With transition to horizontal flight from hovering, the required thrust with an increase in speed will increase, the available thrust will also increase, but to a greater degree than the required (curve bc). Therefore, there will appear a surplus of thrust ΔT, owing to which climb will be accomplished. In order to maintain horizontal flight, it will be necessary to decrease the available thrust, i.e., to combine bc with curve bd. It is possible to decrease thrust only owing to a decrease in power of the engine.

The aerodynamic design of horizontal flight for the [Mi-4] (Ми-4) is conducted only by the method of powers, and therefore curves of required and available thrusts for horizontal flight are shown in general form in order to show the change in flying properties of the helicopter in the speed of flight.

2. Required and Available Powers

<u>The required power for horizontal flight</u> is the power required for the accomplishment of horizontal flight of the helicopter at a certain speed, i.e., for the creation of required thrust for this half of the flight. The required power for horizontal flight is composed of induced and profile power and power of motion.

The required power for horizontal flight with an increase in speed up to the economic decreases owing to the improvement of conditions of operation of the rotor and growth in its thrust more than the required (it is necessary to decrease thrust). With an increase in speed greater than the economic, the required power is increased in view of the impairment of conditions of rotor operation at high speeds and decrease in its thrust. In this case it is necessary to increase the thrust up to the required. At speeds greater than the economic profile drag of the rotor is considerably increased, and drag of the fuselage increases. For surmounting these drags it is necessary to increase the thrust (Fig. 53).

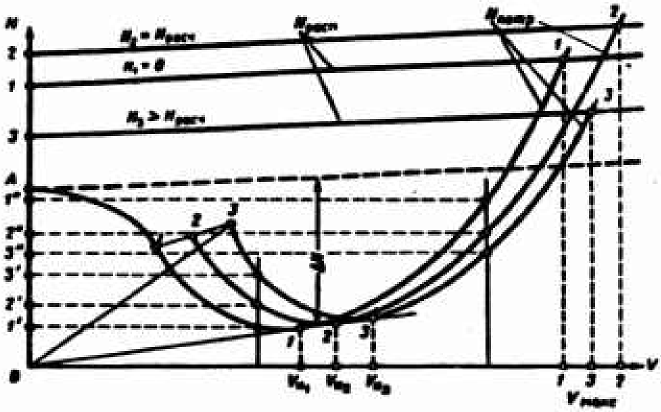

Fig. 53. Required and available powers for horizontal flight of the helicopter.

The magnitude of required power for horizontal flight depends on the flying weight of the helicopter, number of revolutions, pitch of the rotor, dimensions of loads on the external suspension and altitude of the flight. An increase in weight will require great induced power for the creation of great lift. With a change of number of revolutions and collective pitch the profile power will be changed: the more the pitch and greater the number of revolutions, the greater the power will be required. If loads are placed not in the cabin but on the external suspension, then high power will be required for maintaining the assigned speed in horizontal flight.

The available power of the rotor is called power proceeding to the hub of the rotor. It is less than the power of the engine by the magnitude of losses to friction, cooling and power for rotation of the tail rotor, and it is determined by the product of effective power of the engine by the utilization power factor. The available power with an increase in speed at constant power of the engine is insignificantly increased owing to a decrease in power transmitted to the tail rotor, i.e., because of the growth in power factor ξ.

For execution of the steady state of hovering or horizontal flight, it is necessary that the available power always be equal to the required power; otherwise, the steady hovering or horizontal flight will not occur. On the graph the curve of the available power should pass through point A. With an increase in speed the available power grows, and the required power decreases up to the economic speed. Therefore, it is necessary to decrease the engine power so that at any speed the available is equal to the required power. With a further increase in speed the pilot should increase the power of the engine in order to maintain horizontal flight. Consequently, with an increase in speed it is necessary to change the power of the engine in such a manner that the curve of available powers will pass along the trace of the curve of the required powers. With this the available thrusts will be equal to the required.

In flying practice it is also necessary for the pilot to do the following: with an increase in speed from the minimum up to the economic he decreases the power of the engine, and with further increase in speed he increases the engine power; with an increase in speed from maximum to the economic he decreases the power, and with further decrease in speed he increases it.

With an increase in flight altitude with the maintaining constant indicated airspeed, the required power is increased in any speed range, as is the true speed of flight, by a value of the altitude speed factor according to the general laws of aerodynamics:

$$N_{\text{потр}_H} = N_{\text{потр}_0}\sqrt{\frac{\rho_0}{\rho_H}}, \qquad (38)$$

where $N_{\text{потр}_H}$ – required power on altitude; $N_{\text{потр}_0}$ – required power on land; $\sqrt{\frac{\rho_0}{\rho_H}}$ – altitude speed factor.

Curves of required powers for high altitudes will be located above along the axis of the powers and to the right along the axis of speeds, as is shown in Fig. 53.

At speeds less than the economic (under the condition of constant true speed) with an increase in altitude of flight the required power is increased owing to the growth in necessary induced power from altitude because of a decrease in air density (point 1', 2', 3'). At speeds greater than the economic with an increase in altitude of flight, the required power decreases due to the sharp decrease in power of motion at these speeds also because of a decrease in air density (1", 2", 3").

The available power of the rotor from the altitude of flight will be changed exactly as the effective power of the engine is changed. In connection with the fact that on the Mi-4 helicopter the [ASh-82V] (АШ-82В) engine with two speeds of the supercharger is installed, then in the normal rating of operation up to the first rated altitude it will be increased, and after the rated altitude it will be decreased. After switching to the second speed of the supercharger the power will increase up to the second rated altitude (4550 m), and above it will decrease (see Fig. 40).

Figure 53 shows curves of required and available powers for horizontal flight of the helicopter with a high-altitude engine on it at three different altitudes in the general form. Figure 54 gives concrete curves of required and available powers with respect to the speed of flight on land and at an altitude of 1000 m for the Mi-4 helicopter with a flying weight of 7100 kg. This graph is obtained as a result of the conversion of available and required coefficients of torques $m_{кр}$ from the characteristic of conditions of flight μ depicted in Fig. 42.

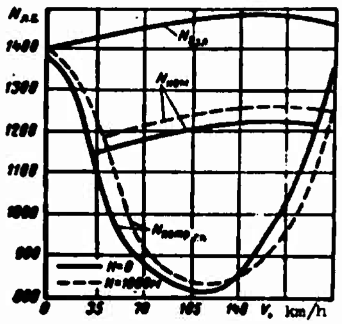

Fig. 54. Available powers on rotor and required powers for horizontal flight of the Mi-4 helicopter with a takeoff weight of 7100 kg.

The aerodynamic design of horizontal flight is conducted by the method of powers. According to the obtained of calculation and flight tests, there are constructed curves of required and available powers and different tables of other data by which it is very convenient to judge the flying characteristics of the helicopter.

§ 3. Characteristic Speeds of Horizontal Flight

On the helicopter is is possible to accomplish horizontal flight in the whole speed range from zero to maximum. But there exist characteristic speeds applied in practice, depending upon conditions of the flight, and also limiting speeds.

The Mi-4 helicopter has four characteristic speeds in horizontal flight: minimum, economic, optimum and maximum.

1. Minimum Speed

The minimum speed of horizontal flight of the helicopter is the speed at which the helicopter can hold in horizontal flight at a given altitude in takeoff conditions of the engine.

The minimum speed of horizontal flight for any helicopter at altitudes from land to the ceiling of hovering in principle is equal to zero, and higher than the ceiling of hovering it is gradually increased up to the economic speed at the ceiling of the helicopter. Such a change in minimum speed from altitude of the flight occurs in view of the presence of laws of change in the required and available powers for horizontal flight in speeds and altitudes.

The required power for hovering and horizontal flight with ascent to altitude at speeds up to economic is increased, and with an increase in speed from zero up to the economic it is decreased. The available power with an ascent to altitude decreases, especially beyond the rated altitude. Therefore, the higher the altitude above the ceiling of hovering, the greater should be the minimum speed of horizontal flight. At the ceiling of the helicopter (dynamic) the minimum speed will be equal to the economic speed, since at this speed for horizontal flight minimum power is required. Consequently, with an increase in speed from zero to the economic there is gradually freed a surplus of power, which is expended in the climb.

Minimum speeds of horizontal flight for a given helicopter can be obtained both by aerodynamic design and in practice with the help of flight tests.

The change in minimum speed from the altitude of flight in the takeoff regime of operation of the engine for the Mi-4 helicopter is represented conditionally (theoretically) by curve a in Fig. 55.

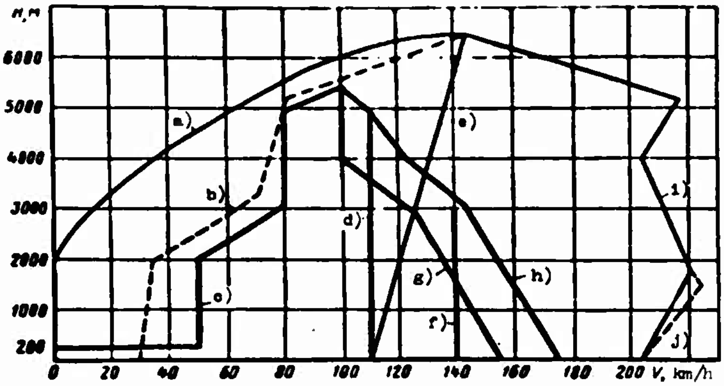

Fig. 55. Characteristic speeds of horizontal flight; a) minimum true speeds of horizontal flight in takeoff operating conditions of the engine (theoretical); b) minimum true speeds in normal rating of the engine; c) minimum indicated airspeeds set by manual on flying operation of the Mi-4 helicopter with the ASh-82V engine; d) economic indicated airspeed; e) economic speed true; f) most advantageous indicated airspeed; g) maximum indicated airspeeds set by the manual on flying operation of the Mi-4 helicopter with the ASh-82V engine; h) maximum indicated airspeeds set by the chief designer on conditions of strength of the rotor and separation of flow; i) maximum true speeds of horizontal flight according to the power of the engine obtained by aerodynamic design; j) maximum true speeds according to the power of the engine obtained by flight tests.

But since in takeoff conditions the engine can operate for a short duration, then it is accepted to determine the minimum speeds in the normal rating of operation of the engine. Minimum speeds of horizontal flight for the Mi-4 helicopter with a flying weight of 7100 kg in normal rating of operation of the engine, obtained as a result of aerodynamic design, are represented by curve b. The helicopter in normal rating of operation of the engine on land can have a speed of not less than 30 km/h, i.e., in these conditions of the engine it is not able to hover. With ascent to altitude the minimum speed of horizontal flight is increased depending upon the speed of operation of the supercharger and on the position of the throttle of the engine.

But in practice of flights minimum speeds are limited even to a greater degree by conditions of vibrations, complexity of the piloting at low speeds and imperfection of aircraft speed indicator. For the Mi-4 helicopter of all modifications by the manual on flying operation the minimum indicated airspeeds of horizontal flight are set in the following limits (see curve b, Fig. 55):

Altitude, m	Speed, km/h
0–200	0
200–2000	50
2000–3000	50–80
3000–5000	80
5000–5500	80–100

2. Economic Speed

<u>The economic speed of horizontal flight</u> is the speed during flight at which minimum power of the engine and minimum consumption of fuel per hour are required. In economic speed with the given fuel reserve the greatest duration of flight is obtained, and for flight in the assigned time its minimum quantity will be expended.

Table 2 gives results of flight tests of the Mi-4 helicopter in conditions of horizontal flight for altitudes of 500, 1000, 2000 and 3000 m, converted for the standard atmosphere, with fuel servicing of fuel of 960 ℓ (main tank) and servicing of 1460 ℓ (with an auxiliary tank) and for two flying weights: normal – 7100 kg and maximum permissible – 7350 kg. The table shows data only for horizontal flight with deduction from full fuel servicing of consumption in climbing and descending from an assigned altitude and also a navigational reserve for 30 minutes of flight (130 ℓ), nondepleted surplus (10 ℓ) and consumption of fuel during operation on land (30 ℓ). Values shown in the numerator pertain to data when refueling of the main tank – 960 ℓ, and in the denominator – the main and auxiliary tank – 1460 ℓ.

Table 2.

Flying weight kg	$V_{пр}$, km/h	$V_{ист}$, km/h	n, r/min	$p_к$, mm Hg	Fuel consumption per kilometer, ℓ/km	Fuel consumption per hour, ℓ/km	Distance of horizontal flight km	Duration of horizontal flight, h, min
$H_{ст}$=500 m. Reserve of fuel for horizontal flight 751/1251 ℓ								
7100	160	172	2230	770	1,64	283	457/764	2—39/4—25
7100	150	162	2200	755	1,60	259	469/782	2—54/4—50
7100	140	152	2200	740	1,58	240	475/792	3—08/5—44
7100	130	142	2200	730	1,60	226	469/782	3—19/5—32
7100	120	132	2200	725	1,66	219	452/755	3—25/5—44
7100	110	122	2230	723	1,76	217	422/703	3—27/5—46
7100	100	112	2200	720	1,95	219	385/642	3—25/5—44
7100	90	102	2200	723	2,20	225	340/568	3—20/5—32
7100	80	92	2200	725	2,60	239	288/482	3—09/5—14
7100	70	82	2200	735	3,12	256	240/402	2—56/4—53
7350	160	172	2230	775	1,79	308	418/700	2—26/4—04
7350	150	162	2200	755	1,75	283	428/715	2—39/4—25
7350	140	152	2200	743	1,72	262	436/728	2—52/4—47
7350	130	142	2200	735	1,73	246	433/723	3—03/5—05
7350	120	132	2200	730	1,79	236	418/700	3—10/5—18
7350	110	122	2200	727	1,92	234	390/652	3—12/5—21
7350	100	112	2200	730	2,12	237	354/592	3—10/5—18
7350	90	102	2200	735	2,39	244	314/524	3—05/5—08
7350	80	92	2200	740	2,78	256	270/450	2—56/4—53
7350	70	82	2200	750	3,32	272	225/377	2—45/4—36
7350	60	72	2200	760	4,13	297	181/303	2—32/4—14
$H_{ст}$=1000 m. Reserve of fuel for horizontal flight 718/1218 ℓ								
7100	160	175	2230	764	1,70	298	422/716	2—54/4—04
7100	150	165	2200	746	1,65	272	436/738	2—41/4—33
7100	140	155	2200	733	1,66	258	433/733	2—47/4—44
7100	130	145	2200	723	1,65	238	436/738	3—03/5—10
7100	120	135	2200	716	1,69	228	425/720	3—09/5—21
7100	110	125	2200	714	1,79	224	402/680	3—12/5—27
7100	100	115	2200	715	1,98	228	363/615	3—09/5—21
7100	90	105	2200	717	2,23	234	322/546	3—04/5—12
7100	80	95	2200	721	2,58	245	278/472	2—56/4—58
7100	70	85	2200	728	3,10	263	232/393	2—44/4—38
7100	60	75	2200	738	3,80	286	189/320	2—30/4—16
7350	160	175	2230	768	1,82	318	395/668	2—15/3—49
7350	150	165	2200	748	1,76	290	407/692	2—28/4—12
7350	140	155	2200	733	1,72	267	417/708	2—41/4—33
7350	130	145	2200	725	1,74	252	413/700	2—52/4—49
7350	120	135	2200	720	1,78	240	403/684	3—00/5—06
7350	110	125	2200	718	1,90	236	378/641	3—01/5—07
7350	100	115	2200	720	2,09	241	342/582	2—59/5—03
7350	90	105	2200	724	2,37	249	303/513	2—53/4—54
7350	80	95	2200	731	2,65	261	271/460	2—45/4—40
7350	70	85	2200	739	3,27	278	220/372	2—35/4—23
7350	60	75	2200	753	4,04	303	177/302	2—22/4—02

In analyzing data of flight tests for altitude 500 m and a flying weight of 7100 kg, we see that the minimum comsumption of fuel per hour will be at the indicated airspeed of 110 km/h and will be 217 ℓ/h. Consequently, for the Mi-4 helicopter under these conditions the economic indicated airspeed is equal to 110 km/h. When flying at this speed the helicopter has a maximum duration of

Table 2 (Cont'd.)

Flying weight kg	$V_{пр}$, km/h	$V_{ист}$, km/h	n, r/min	$p_к$, mm Hg	Fuel consumption per kilometer, ℓ/km	Fuel consumption per hour, ℓ/km	Distance of horizontal flight, km	Duration of horizontal flight, h, min
$H_{ст}$=2000 m. Reserve of fuel for horizontal flight 651/1151 ℓ								
7100	140	163	2250	722	1,66	270	302 [illegible]	2—24 4—16
7100	130	153	2240	713	1,68	253	390 690	2—34 4—33
7100	120	142	2220	707	1,70	242	383 678	2—41, 4—45
7100	110	132	2220	703	1,78	236	365 647	2—45 4—52
7100	100	121	2220	703	1,96	238	332 583	2—43 4—50
7100	90	110	2220	707	2,20	243	296 524	2—40 4—44
7100	80	99	2230	712	2,56	255	254 410	2—33 4—31
7100	70	88	2230	720	3,09	272	211 371	2—24 4—14
7100	60	78	2230	732	3,82	298	172 302	2—11/3—51
7350	140	163	2260	725	1,71	280	360 674	2—20/4—07
7350	130	153	2240	715	1,72	263	378;670	2—28/4—22
7350	120	142	2230	710	1,77	252	368,651	2—34/4—34
7350	110	132	2230	707	1,88	240	346/612	2—36 4—37
7350	100	121	2230	708	2,08	252	313 553	2—34;4—34
7350	90	110	2230	712	2,35	259	277/490	2—30/4—26
7350	80	99	2230	720	2,72	270	240/423	2—24 4—15
7350	70	88	2240	731	3,27	288	200/352	2—15/4—00
7350	60	78	2240	745	3,97	310	164/290	2—06,3—42
$H_{ст}$=3000 m. Reserve of fuel for horizontal flight 589/1089 ℓ								
7100	130	160	2280	705	1,68	270	360/615	2—11 4—02
7100	120	149	2260	695	1,71	256	345/638	2—18 4—15
7100	110	138	2250	693	1,80	249	327,606	2—22 4—22
7100	100	127	2230	694	1,95	248	302 560	2—23 4—[illegible]
7100	90	115	2240	698	2,20	254	268/495	2—20 4—18
7100	80	104	2250	704	2,52	263	234 433	2—14 4—09
7100	70	93	2250	714	3,02	281	195/360	2—06 3—53
7100	60	82	2250	730	3,78	310	156,288	1—54,3—31
7350	130	160	2300	708	1,73	277	340 630	2—07 3—56
7350	120	149	2270	699	1,79	267	329 609	2—12 4—04
7350	110	138	2260	697	1,91	264	308 570	2—14 4—07
7350	100	127	2250	697	2,09	266	282 520	2—13 4—03
7350	90	115	2250	702	2,36	272	250 460	2—10 4—00
7350	80	104	2260	710	2,72	283	216 402	2—05,3—51
7350	70	93	2270	724	3,20	297	181 340	1—59 3—40
7350	60	82	2270	742	3,88	318	152,280	1—50,3—25

flight of 3 h 27 min with full refueling of the main tank and 5 h 46 min with servicing of still the auxiliary tank.

With a change in flying weight the economic speed both on the instrument and true does not change and only the consumption per hour changes and accordingly — duration of flight. The greater the flying weight, the greater the required power for flight at the same economic speed, the greater the consumption per hour and the less the duration of flight. Thus, for a flying weight of 7350 kg at an altitude of 500 m at an economic indicated airspeed of 110 km/h the consumption of fuel is 234 ℓ/h, and the duration is 3 h 12 min with servicing the main tank and 5 h 21 min with the auxiliary tank.

From the table it is also clear that with an increase in altitude of flight the economic indicated airspeed remains constant, and the true speed increases (curves g and d in Fig. 55). But the more the altitude, the greater the required power for flight at the same indicated airspeed, and therefore the consumption of fuel per hour will be increased, and the duration of flight decrease. Thus, for example, for a flight at the economic speed of 110 km/h at an altitude of 1000 m with a flying weight of 7100 kg the consumption of fuel is 224 ℓ/h and the duration of flight is 3 h 12 min with servicing the main tank and 5 h 27 min with servicing the auxiliary tank. For great flying weight at this altitude the consumption per hour will be even greater and the duration less. Such a law of the change in consumption of fuel per hour and duration of flight from weight and altitude remains correct for all altitudes and flying weights.

The economic speed is used for patrolling, instructed flights and other forms of works not connected with the necessity of surmounting distances.

The magnitude of economic speed of horizontal flight for any helicopter can be determined by the curve of required powers for horizontal flight of a given helicopter by means of drawing a tangent to the curve in parallel to the asix of speeds; the perpendicular from the point of contact on the axis of speeds will indicate the magnitude of economic speed (see Fig. 54).

The economic speed of horizontal flight will be the optimum speed of climb, since at this speed there is maximum surplus of power.

3. Optimum Speed

The optimum speed of horizontal flight is the speed at which there is obtained the minimum fuel consumption per kilometer. At this speed the helicopter has a maximum flight range, and for passage of the assigned distance the minimum quantity of fuel will be expended.

With the analysis of data obtained during tests of the Mi-4 helicopter with a flying weight 7100 kg at an altitude of 500 m, it is clear that the minimum fuel consumption per kilometer at this altitude will occur at the indicated airspeed of 140 km/h and will be 1.58 ℓ/km. With this the maximum range of flight, 475 km will be obtained with full servicing of the main tank and 792 km with full servicing of the main and auxiliary tanks. Consequently, for the Mi-4 helicopter the optimum indicated airspeed is equal to 140 km/h.

On the basis of the general laws of aerodynamics the optimum speed depends on the flying weight of the aircraft: the higher the flying weight, the greater the optimum speed and conversely. In practice with a change in flying weight the optimum indicated airspeed does not change, but fuel consumption per kilometer and, accordingly, flying range will change: the higher the flying weight, the greater the fuel consumption per kilometer and the less the flying range. Thus, for example, for the same altitude of 500 m with the maximum permissible flying weight of 7350 kg at a speed of 140 km/h, the consumption per kilometer will be 1.72 ℓ/km, and the flying range is 436 km with full servicing basic tank and 728 km with servicing of the auxiliary tank. This circumstance facilitates the operation of the helicopter, since the pilot need not make complicated calculations before the flight for obtaining a more economic flight.

With an increase in flight altitude, other things being equal, the optimum true speed is increased, and the indicated airspeed remains constant (see Fig. 55, curve f), which is clear from data of Table 2. But in separate cases the experiments can give certain deviations from the general laws.

For the Mi-4 helicopter, starting from the altitude of 2000 m and above, the optimum indicated airspeed is greater than the maximum permissible for conditions of flow separation and reserve of strength of the rotor, and therefore flight tests were conducted only up to an altitude of 3000 m.

The optimum speed is used for usual cruise flights. This speed gives the most economic flight, and therefore it has received wide application.

The maximum range of flight for helicopters with nonsupercharged engines is obtained with flight near land. For helicopters with high-altitude engines the maximum range in practice is not changed during flight at any altitude up to the rated altitude, since the fuel consumption per kilometer in altitude of flight practically does not change. With flight at an altitude greater than the rated, the flying range insignificantly decreases.

In desiring to obtain maximum flight range or minimum fuel consumption at the assigned distance, it is necessary to set the optimum indicated airspeed and maintain the minimum permissible revolutions (for the Mi-4 helicopter 2200 r/min), and with this it is necessary to consider the change in flying weight owing to consumption of fuel and direction of the wind. With a decrease in fuel it is necessary to maintain the speed of flight constant but gradually decrease the power by the "pitch-throttle" lever for maintaining horizontal flight position.

With a headwind it is necessary to hold the speed higher than the optimum and with a tailwind – less than the optimum. If there are accurate curves of required power for horizontal flight of the given helicopter, then the magnitude of the optimum speed of flight, taking wind into account, can be determined, as is shown in Fig. 56. Such a change in the optimum speed depending upon wind is explained in the following way. The consumption of fuel per hour is proportional to the required power for flight of the helicopter, and therefore the character of the of flow rates per hour from the speed

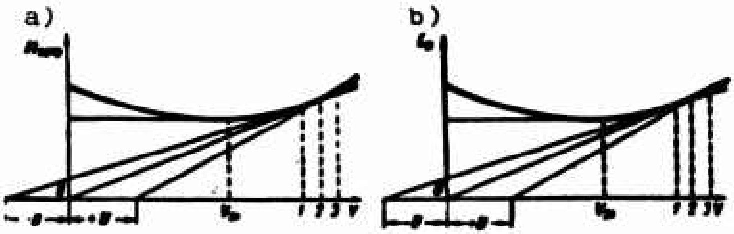

Fig. 56. Changes in optimum flight speed from wind; a) by required power; b) by consumption of fuel per hour; 1 – optimum speed with tailwind; 2 – optimum speed in the absence of wind; 3 – optimum speed with headwind.

will be the same as that of the required power from the speed. The optimum flight speed will occur with the minimum fuel consumption per kilometer, which is determined by the division of the consumption per hour by the groundspeed of the flight: $C_{к}=\frac{C_h}{V}$.

During a calm the optimum speed can be found by drawing a tangent to the curve of consumptions per hour from the origin of the coordinates, since at the point of contact there will be the minimum value of the ratio C_h/V. With a headwind the minimum consumption per kilometer will be at the minimum ratio C_h/V, and therefore for finding the optimum flight speed the tangent to the curve of consumptions per hour must be drawn not from the origin of the coordinates but from a point located to the right of the origin of the coordinates, i.e., from the end of the vector of the headwind. Dropping a perpendicular from the point of contact on the axis of the abscissas, we will obtain the optimum flight speed; it will be greater than the speed during a calm. With a tailwind the minimum consumption per kilometer will be at the minimum value $\frac{C_h}{V+W}$, and therefore the tangent to the curve of consumptions per hour must be drawn not from the origin of the coordinates but from the point located to the left of the coordinates, i.e., from the end of the vector of the tailwind. The optimum speed here will be less than the optimum speed during a calm.

4. Maximum Speed

For the Mi-4 helicopter there are three maximum speeds.

1. Maximum speed according to the power of the engine. This speed is changed depending upon the altitude of flight and power of the engine in the normal rating of its operation. Up to the first rated altitude it is increased, and then it decreases; after inclusion of the second speed of the supercharger it again starts to be increased up to the second rated altitude; after the second rated altitude it decreases down to the economic speed at the ceiling of the helicopter. Values of maximum speeds according to the power of the engine in normal rating with respect to altitudes for the Mi-4 helicopter, obtained by aerodynamic design, are confirmed by flight tests: near land, 203 km/h, at an altitude of 1500 m 225 km/h, the greatest value (see Fig. 551). At the indicated speeds it is forbidden to operate the helicopter according to strength conditions of the rotor and separation of flow from blade tips [tip stall].

2. The maximum speed set by the chief designer with respect to conditions of strength of the rotor and separation of flow. This indicated airspeed for the Mi-4 helicopter with normal flying weight with respect to flight altitude is changed in following limits (see curve h, Fig. 55):

Altitude, m	Speed, km/h
0	175
1000	165
2000	155
3000	145
4000	125
5000	110
5500	100

This speed up to an altitude of 2500 m is limited up to the shown limits with respect to conditions of strength of the rotor and at high altitudes with respect ot conditions of separation of flow from blades of the rotor.

For the Mi-4 helicopter with maximum flying weight the maximum indicated airspeed is limited over altitude to the following limits:

Altitude, m	Speed, km/h
0	130
1000	120
2000	115
3000	110
4000	100

3. Recommended maximum speed. This speed increases the safety factor of the rotor, and it is economic, since it is close to the optimum speed; and therefore it is accepted in the operation of the Mi-4 helicopter with the ASh-82V engine in civil aviation. These indicated air and altitude speeds (independently of flying weight of the helicopter) are set in the following limits (see curve g, Fig. 55):

Altitude, m	Speed, km/h
0	155
1000	145
2000	135
3000	125
4000—5500	100

5. Separation of Flow [Stall]

From the aerodynamics of an aircraft it is known that the wing is flowed past smoothly only at small angles of attack — up to the critical. Beyond the critical angles of attack separation of flow advances, as a result of which coefficient of lift c_y decreases, the coefficient of drag c_x is increased, lift-drag ratio of the wing decreases, the center of pressure of the wing shifts both chordwise and along the span, and the aircraft stalls. Blades of the rotor can appear in the same conditions of flow.

At high speeds of flight and especially at minimum revolutions of the rotor in the aximuthal position of 270° the true speed of flow around will prove to be the minimum. Deceleration will lead to a decrease in lift of the blades, and this, in turn, will lead to an increase in speed of flapping of blades downwards. An increase in the speed of flapping downwards will lead to an increase in angles, and they can appear higher than the critical; then separation of flow advances, which will increase the lift divergence more owing to the decrease in the lift coefficient. There will appear a bank in the direction of blades retreating from the flow, vibration and other undesirable phenomena. The separation area begins to appear at position $\psi = 270°$ in the first place on tips of the blades, since at this place the speed of flapping of the blade downwards is the greatest.

With an increase in flight speed the separation area will be expanded (Fig. 57). Simultaneously, with an increase in speed the area of reverse flow around will be expanded. But since both these areas decrease the lift, the right side of disk surface, will create less lift than the left, and therefore for the helicopter a right bank with forward flight will appear. Moreover the helicopter will sway in longitudinal and lateral directions and react poorly to deflections of the control levers, i.e., controllability and stability of helicopter become worse.

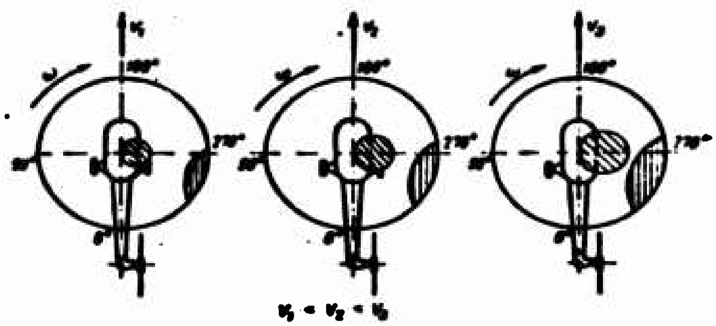

Fig. 57. Expansion of areas of separation and reverse flow around with an increase in speed of flight of the helicopter.

In flying practice the phenomenon of separation of flow can advance in the following cases:

1. With an increase in speed of flight above the maximum permissible (higher than the critical stalling speed) in horizontal

flight, climb with the use of power of the engine, during descent with an operating engine and descent in autorotation.

2. With an increase in speed above the permissible at different altitudes. The maximum permissible speed in altitude is always less than that near land, since it is necessary to maintain high pitch because of the lesser air density. In this case angles of attack of the blades will be greater, and separation advances at a lower speed than during flight near land (Fig. 58a).

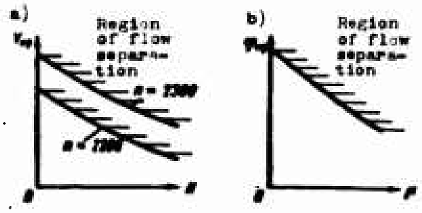

Fig. 58. Influence of different factors on separation of flow: a) change of critical stalling speed depending upon the altitude of flight H and number of revolutions of the crankshaft of the engine; b) change in critical stall pitch depending upon operating conditions of the rotor μ.

3. With a decrease in revolutions of the crankshaft of the engine $n_{ДВ}$ at high speeds of flight, since with this the peripheral velocities are less, and the separation of flow in position $\psi = 270°$ advances at a lower flight speed. From this it follows that the more the revolutions, the higher the critical stalling speed. Therefore, upon the necessity of flight at high speeds it is recommended to hold the increased revolutions of the rotor in order to avoid stalling.

4. With an increase in collective pitch of the rotor during flight, especially at high speeds. With an increase in pitch the angles of attack of the blades will be greater, and the separation

of flow advances at a lower speed, which is lower than the critical stalling speed in normal pitch. Consequently, the critical stall pitch (pitch at which separation advances) will be greater, the less the speed of flight and the greater the revolutions, i.e., the less the characteristic of operating conditions of the rotor μ (Fig. 58b).

5. During flight at speeds less than the minimum permissible at altitudes beyond the static ceiling according to the power of the engine. With this owing to the deficiency in power at these altitudes, the helicopter will descend, which will lead to an increase in angles of attack of the blades from all azimuthal positions, and in position $\psi = 270°$ they can become higher than the critical.

6. Periodically with flight at high speeds under conditions of atmospheric turbulence, when horizontal gusts in front increase the true speed of the helicopter and ascending gusts increase the angles of attack of the blades, which causes short-term phenomena of separation of flow. Therefore, when flying in such conditions it is not recommended to maintain high speeds of flight, since at high speeds the separation of flow will advance more frequently, even with insignificant horizontal and vertical gusts.

7. With great overload during the flight, for example, in steep turns and sharp guiding from a steep descent with an operating engine or gliding. In these cases angles of attack of the rotor and, consequently, of the blades are also increased, which leads to a separation of flow from the blades in position $\psi = 270°$.

The criteria of separation of flow from blades of the rotor are the following:

a) raised shaking of the helicopter, which gradually grows with an increase in speed;

b) right bank;

c) sharp swaying of the helicopter in a longitudinal and, especially, in lateral directions, which is accompanied by descent of the helicopter and steering of the control stick;

d) impairment of stability and controllability.

To guide the helicopter from conditions of separation of flow, it is possible to use deceleration of flight, increase in the number of revolutions of the rotor, decrease in collective pitch of the rotor and altitude of the flight.

Coming out of a stall by the method of decreasing the altitude is a long process, and it is inexpedient to emerge at high speeds by increasing the number of revolutions. The most effective measures of exit from conditions of a stall are the decrease in collective pitch of the rotor up to the permissible limit depending upon the altitude, up to autorotation, with a simultaneous deceleration of flight by the control stick. With a decrease in collective pitch it is necessary to observe the revolutions and not allow them to become lower than the permissible – 2200 r/min. After the cessation of criteria of the stall it is necessary to turn to the standard flight. This method is recommended by the manual on flying operation of the Mi-4 helicopter and is most frequently applied in practice.

§ 4. Peculiarities of Horizontal Flight and Its Fulfillment

1. Peculiarities of Horizontal Flight

Flight at low altitude. Horizontal flight at low altitude with different purposes can be fulfilled at altitudes of 5-10 m. The acceleration of speed from the position of hovering is fulfilled by deflection of the control stick back, maintaining with this the flight altitude by the "pitch-throttle" lever. With such flight, especially at low speeds, it is necessary to consider that it is carried out with influence of an air cushion, i.e., with decreased power. In the case of lowering of the relief the air cushion vanishes. Then the assigned power will be insufficient for flight, and the helicopter will descend. In this case for maintaining the altitude of flight, it is necessary to increase the engine power but with such calculation in order not to overbalance the rotor and not to worsen the position, since with overbalancing of the rotor the number of revolutions of it and thrust will decrease, and the helicopter will obtain even greater descent. During flights at low altitudes and speeds the gas control should be completely moved to the right, and, furthermore, it is necessary to have a sufficient reserve of pitch power owing to the decrease in ' · 'ght of the helicopter.

To ensure flight safety, it is recommended to fly above broken terrain (ravines, gorges) at an altitude of not lower than 10 m with a speed of not less than 60 km/h, when the influence of the air cushion is absent and relief will not affect the flight.

If horizontal flight at low altitude is produced windward at a speed less than the economic, and the wind will suddenly cease or will decrease (gusts), then the helicopter can also descend. In this case sudden cessation of the wind will lead to a decrease in airspeed, and at speeds less than the economic, as is known, there will be required higher power for horizontal flight (see Fig. 54). If, however, flight is accomplished at speeds higher than the economic, then cessation of the headwind will cause a decrease in airspeed and soaring upwards of the helicopter. Therefore the power set earlier will appear unnecessary and because of the surplus in power the helicopter ascends upwards. The same phenomenon will occur with any change in magnitude and direction of the wind and speed of flight or with a turn downwind.

During a flight with a tailwind the phenomena will be the very same, but the influence of them on the helicopter will be the opposite: with flight at a speed of less than the economic, with cessation of the wind, the helicopter is lifted, and with flight at a speed greater than the economic the helicopter will descend. This means that a strong gusty wind is dangerous for flight at low altitude. The pilot must not allow losses of airspeed and descent of the helicopter when flying at low altitudes. The presence of a sufficient power reserve permits him to maneuver well vertically and prevent such descent.

During flights at low altitudes it is necessary to remember also the sufficient reserve of movement of the control stick, which depends on the magnitude of centering, direction of the wind and speed of flight. The greater the centering, the less the speed of flight and greater tailwind, the less the reserve of movement of the control stick back. Therefore, during a flight with a tailwind with limiting forward centering, the pilot should be especially attentive. If the reserve of movement of the control stick is absent in such a flight, then it will be impossible to get the helicopter to hover. In this case it is recommended before hovering to turn windward or to change the centering, the reserve of movement of the lever back will be increased, and it is possible to produce hovering, landing and other maneuvers.

During flight at low speed and altitude, in view of the unstable readings of the speed indicator [US-250] (УС-250), it is recommended to maintain a speed being oriented with respect to the land.

Movement by all control levers during flights at low altitudes and speeds must be smooth.

Flight at high altitudes. Peculiarities of horizontal flight at high altitudes (higher than the ceiling of hovering) consist in the following. With a rise on altitude the speed range of horizontal flight decreases (see Fig. 55), and therefore at these altitudes it is impossible to allow the speed to be greater than the maximum permissible at the given altitudes and less than the minimum permissible. In both cases there will appear the phenomenon of stall and loss of altitude. It is known that flight at high altitudes because of lowered air density occurs at great pitch of the rotor, and therefore separation of flow advances at lower speeds. For the Mi-4 helicopter the speed range of horizontal flight is maintained sufficiently great up to the altitude of 3000 m (Fig. 55, curves c, g). At an altitude of 3000 m the range is 125 - 80 = 45 km/h, at altitude 4000 m, 100 - 80 = 20 km/h, and at altitude 5500 m the range will be equal tc zero, since here the maximum and minimum speeds are equal with each other and are 100 km/h.

With the rise on altitude the surplus of power is decreased, and therefore maneuvering properties of the helicopter worsen. Together with that stability and controllability worsen, and piloting of the helicopter is complicated. For these reasons at altitudes of more than 2000 m turns must be accomplished with a bank of not more than 20°, actions by the control levers must be smooth, and also there should be a thorough observation of the speed of flight and position of the helicopter.

Position of control levers on the whole speed range of horizontal flight. The position of the control levers in horizontal flight is different at different speeds. In conditions of hovering the control stick in a longitudinal relation is deflected back (the reason for such position of the lever was analyzed earlier in examining conditions of hovering). With an increase in the speed of flight the lever should be deflected forward and at an average speed of flight occupy a neutral position, the most convenient speed at which prolonged flights occur. With further acceleration of speed it is necessary to deflect the lever back for great deflection of the cone of rotation of the rotor and its thrust forward.

In a lateral relation in conditions of hovering the control stick is deflected to the right for creating lateral force, which balances the thrust of the tail rotor directed to the left. With the acceleration of speed the cone of rotation owing to flapping motions is deflected to the right, and if the position of the handle in a lateral relation is left the former, the helicopter will accomplish flight with a right slip. Therefore, so there will not be slipping, with an increase in speed the control stick must be deflected to the left (take pressure from it by the lateral tab) and at an average speed of flight set neutrally in a lateral relation.

With further increase in speed the control stick must be continued to be deflected to the left, since flapping motions continue to grow and the cone of rotation of the rotor all the more deflects to the right.

As was discussed earlier, the right pedal in conditions of hovering should be depressed forward. This position of the pedal was explained by the necessity of maintaining great pitch of the tail rotor during operation of it in direct airflow. With an increase in flight speed both rotors fall into conditions of oblique airflow; then their thrusts increase, and the power of the rotor and its reactive moment decrease, and therefore smaller yawing moment of the tail rotor is required. But since the tail rotor itself increases the thrust owing to oblique airflow, the augmentation of thrust proves to be superfluous, and in order to decrease the thrust it is necessary to decrease the pitch to the tail rotor, which one should do by gradual setting of the pedals in a neutral position at an average flight speed.

With further acceleration of speed, it is necessary to continue to move the left pedal forward, since, although the rotor is assigned high power and the reactive moment of it increases, the tail rotor continues to increase the thrust owing to the oblique airflow (economic speed of the tail rotor is greater than the economic speed of the rotor). Only at speeds close to the maximum, and above them is it necessary to increase the pitch to the tail rotor by moving the right pedal forward. Since in the whole speed range from hovering and almost up to the maximum speed, pitch to the tail rotor must be decreased (move the left pedal forward all the time), then by intention of the designer control of the tail rotor is carried out so that at an average speed of flight the pedals must be in a neutral position. Then there will be maximum reserve of the deflection of pedals with the control of the tail rotor, just as there will be maximum reserve of deflecting of the control stick in a longitudinal and lateral relation.

With the acceleration of speed in horizontal flight from zero to maximum the position of the "pitch-throttle" lever and gas control should change accordingly. When hovering and at low speeds of flight the gas control should be moved completely to the right, since for these conditions high power and relatively little pitch are required. At flight speeds of more than 50-60 km/h the required power is considerably reduced, and therefore it is necessary to move the gas control to the left and to increase the collective pitch for loading of the rotor in view of the decrease in angles of attack of the rotor and blades with an increase in speed. At speeds greater than the economic it is necessary to add power by the "pitch-throttle" lever, and at speeds close to the maximum and at the maximum it is necessary to move the gas control again to the right for increasing the number of revolutions up to the nominal. This is done for preventing the phenomenon of stall and nonadmission of a right bank, and then the reserve of control stick in a lateral relation is increased. The method of balancing of the helicopter in all conditions of flight and speeds with the help of control levers will be discussed more specifically in the last chapter.

Dependence of the pitch angle on the flight speed. In connection with the fact that tractive force of the rotor is applied to the rotor hub, the pitch angle depends on the flight speed: the more the speed, the less the pitch angle and conversely. In view of the presence of the decalage of the rotor shaft, which for the Mi-4 helicopter is equal to 5°, in conditions of hovering with neutral centering the pitch angle will be positive and of small value. With an increase in flight speed it decreases and at an average speed is close to zero. With further increase in speed it continues to be decreased and at a maximum speed is about -4°. Furthermore, the pitch angle depends on the centering of the helicopter: the more the centering forward, the less the pitch angle, and conversely.

Slip and angle of roll during horizontal flight. The Mi-4 helicopter in horizontal flight can be balanced with a left slip without bank or without slip but with right bank. If lateral force Z is equal to the thrust of the tail rotor $T_{т.в}$ (see Fig. 51), then flight is accomplished without slip but with right bank in view of the action of the lateral moment of the hub owing to the spacing of horizontal hinges of moment $M_{x_{BT}}$. In flight both right and left slip with various banks can be permitted.

It is recommended to accomplish flights without slip, since with slip drag is increased which leads to an increase in consumption of fuel and impairment of controllability. To prevent slip at all speeds of flight the lateral force should always balance the tractive force of the tail rotor. The absence of slip is determined by the slip indicator.

Flights with loads on external suspension. During horizontal flight with loads on the external suspension, the helicopter has much drag, which leads to an increase in power for flight, expended fuel per kilometer and a decrease in flying range and load capacity of the helicopter. Thus, for the Mi-4 helicopter a flying weight of not more than 7100 kg is set, and the load on the external suspension is allowed at not more than 1300 kg. Flight speeds are also limited: if flights are accomplished at great distances, the indicated airspeed should be not more than 100 km/h, and if the distance is short, up to 20 km, then the speed should be 70-80 km/h.

In piloting technique flights with loads on the external suspension are more complicated have a number of peculiarities. Swaying of the load on suspension leads to a swaying of the helicopter, especially in a longitudinal relation, and therefore it is more difficult to hold the assigned speed. To prevent rocking of load and the helicopter, the pilot should balance the helicopter more attentively and with great care; movement by control levers must be smooth and proportionate. It is necessary to make strictly coordinated turns with a bank of not more than 10°. Uncoordinated turns lead to great rocking of loads and the helicopter. For piloting the helicopter with loads on the external suspension, the pilot should have sufficient experience.

Flight during failure of the airspeed indicator. Upon failure of the airspeed indicator it is necessary to switch it to a second pitot-static tube, and if after that the airspeed indicator does not give the correct readings other instruments for preservation of the needed balancing and endurance of required speed must be used.

Such instruments are the gyrohorizon, rate-of-climb indicator and altimeter. In this case it is necessary to hold the silhouette of aircraft of the gyrohorizon from the artificial horizon at the same level as that at the given flight speed. Furthermore, the needed speed of flight can be approximately held by projection of the natural horizon on the canopy of the pilots, and for this it is necessary to remember at what characteristic places it is projected when hovering and at other flight speeds. For the best maneuverability and controllability with failure of the airspeed indicator, it is desirable to set increased revolutions but not more than 2300 per minute and sufficient supercharging.

2. Peculiarities of the Fulfillment of Horizontal Flight

For horizontal flight the speed is selected from conditions and flight mission: this will be the flight with minimum fuel consumption per hour for obtaining greatest duration of flight, with minimum fuel consumption per kilometer for obtaining the maximum range of flight or a flight at which it is necessary to expend minimum time. According to the selected speed, altitude of flight and flying weight, there is determined the necessary operating conditions of the engine with respect to revolutions and boost pressure, and also fuel consumption according to tables of cruise flight settings placed in the Manual on Flying Operation of the Mi-4 Helicopter (see Table 2). These conditions are obtained by flight tests of the Mi-4 helicopter with flying weights of 7100 and 7350 kg and are reduced to standard temperature both on land and in altitudes. If, however, the actual temperature at the given altitude of flight will differ from the standard in the direction of a decrease or increase by more than 10°C, then data shown in the table will be inaccurate. In this case operating conditions of the engine and fuel consumption on the given flight are determined by a cruising graph placed in the Manual on Flying Operation of the Mi-4 Helicopter with the ASh-82V engine.

For horizontal flight the following are recommended:

a) range of cruising speeds from 90 to 150 km/h;

b) in order to obtain maximum range – the optimum indicated airspeed of 140 km/h at engine revolutions of 2200 per minute;

c) in order to obtain the greatest duration – economic indicated airspeed of 110 km/h at engine revolutions of 2200 per minute.

It is necessary to pilot the helicopter in horizontal flight and in turns without slip, since otherwise the economy of the flight descends and the control of the helicopter is complicated. Slip on the indicator is allowed when deflection of ball from the middle position will be at a value of not more than one diameter of it.

Guiding from slip must be produced by smooth movements of the control levers.

In order to transfer the helicopter from conditions of hovering to conditions of horizontal flight, it is necessary to deflect the control stick forward, holding with this the helicopter from descent by the smooth increase in collective pitch of the rotor.

In order to transfer the helicopter from conditions of horizontal flight to conditions of hovering, it is necessary to extinguish the speed by the control stick and, starting from the speed of 50-60 km/h, simultaneously increasing the power in order to prevent descent. Starting from the speed of 40 km/h and below, it is necessary to parry the tendency of a left turn and lift of the nose by moving the right pedal forward and deflecting the control stick forward.

In order to transfer the helicopter from conditions of horizontal flight to conditions of descent with an operating engine, it is necessary to decrease the collective pitch of the rotor up to the obtaining of the necessary vertical velocity of descent. Revolutions of the crankshaft of the engine must be held within 2200 per minute, and it is necessary to balance helicopter by corresponding position of the control levers, maintaining the constancy of the flight speed of the helicopter.

For transition from conditions of descent with an operating engine to conditions of horizontal flight, it is necessary to increase the collective pitch of the rotor up to cessation of the descent and balance the helicopter in conditions of horizontal flight.

With horizontal flight under conditions of bumpiness of average intensity the indicated airspeed can change within 15-20 km/h, and for retention of the constancy of conditions it is necessary to make great movements by the control levers.

During flights in powerful and storm bumpiness the speed will be changed within 50-60 km/h, and here insignificant vibrations and also thrusts of the helicopter up and down appear. When the helicopter enters into airflows of great speed, there is created the impression of the loss of controllability, and in this case it is necessary to key the helicopter in horizontal flight. If the speed is increased and reaches 200 km/h and more, it is necessary to impart to the helicopter a positive pitch angle of 8-10° by pulling the control stick back and simultaneously decreasing the collective pitch. If the helicopter loses speed and reaches 60 km/h and, furthermore, has tendency to decrease, by deflecting the control stick forward, it is necessary to create a negative pitch angle of 5-7°.

When piloting under conditions of bumpiness the control levers can reach their extreme positions, and movements of the control levers should be smooth but powerful. When the helicopter enters into conditions of storm bumpiness the pilot should take measures for the urgent departure from this zone.

3. Flight Limitations in Conditions of Horizontal Flight

1. The maximum indicated airspeed of horizontal flight, independently of the flying weight of the Mi-4 helicopter, should not exceed with respect to altitudes the following limits:

Altitude, m	Speed, km/h
0	155
500	150
1000	145
2000	135
3000	125
4000—5500	100

2. The minimum indicated airspeed of horizontal flight with respect to altitudes should be not below the following limits:

Altitude, m	Speed, km/h
0—200	0
200—2000	80
3000—5000	80
5500	100

3. The speed of horizontal flight with a load on the external suspension during flight at a distance up to 20 km should be 70-80 km/h and at a distance of more than 20 km – 100 km/h. In the case of light loads of great dimension on the external suspension, the speed of horizontal flight should be not more than 60-70 km/h since at high speeds the loads are subjected to much rocking, and a great diving moment is obtained.

4. The maximum altitude of horizontal flight is 5500 m. With a flying weight of 7350 kg the maximum altitude of flight is 4200 m with operation of the engine at the first speed of the supercharger. The maximum altitude of the [Mi-4P] (Ми-4П) helicopter (passenger) is 4000 m.

5. Above rugged terrain the flight altitude should be not lower than 10 m and the speed – not less than 60 km/h.

6. Revolutions of the crankshaft of the engine in horizontal flight should be not lower than 2200 per minute. Such revolutions are set proceeding from conditions of minimum fuel consumption and the possibility of successful transition of the rotor to conditions of autorotation in case of engine failure. Depending upon the flying weight of the helicopter and altitude of flight, the revolutions will be selected according to Table 2.

§ 5. Vibration of the Flutter Type

On the wing of an aircraft and blade of a rotor at high speeds of flow by airflow bending-torsional flutter can appear. Both for any form of vibration and for this, definite energy is required. For this form of vibration energy to blade is supplied owing to the counterflow at great speed, which appears both owing to rotation of the rotor at a great number of revoluitons and due to the high speed of flight.

Development of vibration of the flutter type is influenced by the rigidity of construction of the blade for bending and twisting, the position of the center of pressure of the blade, the magnitude of the characteristic of the flapping control, and the basic effect is the position of the center of gravity of the blade chordwise with respect to the center of rigidity. Position of the center of gravity of the blade is determined by its lateral centering. With a definite combination of the indicated parameters and upon achievement of stalling speed of flow with respect to flutter, the blade can receive vibration of this type.

Stalling speed of flow around or critical number of flutter revolutions are called revolutions and speeds at which the feed of energy from the flow is equal to losses of it for operation of the internal elastic forces of construction of the blade. Critical flutter revolutions decrease with an increase in speed of flight of the helicopter, since the blade obtains high speed of flow around owing to the forward velocity and great amplitude of flapping motions. At a speed or at revolutions less than the critical all the energy from the flow is expended for operating the internal elastic forces, but at a speed and at revolutions higher than the critical with respect to flutter the surplus of the supplied energy causes this vibration.

The designer always tries to increase the critical speed and flutter revolutions, which depend on the mutual location of the center of rigidity and gravity, rigidity of control, torsion and bending rigitity of the blade, characteristic of the flapping control, moment of friction of feathering hinges, geometric forms of the blade and other design parameters. In selecting the defined indicated parameters, the designer tries to have the critical flutter revolutions and speed higher than the speeds and revoltuions applied in operation in all flight conditions.

If blade has the defined indicated parameters, and one of them, the center of gravity of it is located behind the center of rigidity, and if it will obtain initial bend downwards for some reason (great flapping motion owing to the high speed or great and sharp deflection of the control stick), then this bend will promote twisting of the blade around the axis of rigidity for decreasing the setting angle, since with this the mass of the blade, concentrated in the center of gravity, will lag behind the bend by inertia. This twisting for decreasing the setting angle will lead to a decrease in lift and to even greater tendency of the blade downwards (Fig. 59a). With motion of the blade upwards, it will twist for increasing the setting angle, which will lead to an increase in lift and greater tendency upwards. With this the amplitude and frequency of flexural and torsional vibrations will be increased up to destruction of the blade.

If the center of gravity of blade will be placed in the center of rigidity of it, then in obtaining the indicated bends it will not twist, and if it does, then it is for other reasons.

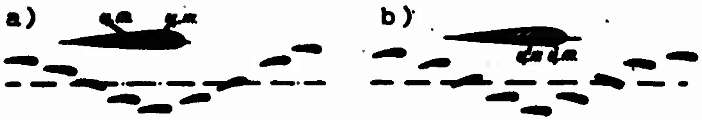

Fig. 59. Influence of lateral centering of the blade on vibration of the flutter type: a) rear centering; b) forward centering.

If, however, centering will be more forward, i.e., the center of gravity will be located ahead of the center of rigidity (Fig. 59b), then the phenomenon will be reverse to that described with rear centering. Upon bending of the blade downwards, the mass concentrated in the center of gravity of it will lag by inertia from the motion of the blade, and it will twist for increasing the setting angle, which will lead to an increase in lift and decrease in amplitude of motion downwards. With motion of the blade upwards, the setting angle and also the tendency of the blades to move upwards will decrease. Such twisting of the blade around the axis of rigidity will lead to damping of the flexural oscillations and cessation of vibration.

The phenomenon of flutter of the wing of an aircraft was first revealed when aircraft started to develop a speed of more than 600-700 km/h. At present flutter of the wing of an aircraft and blade of a rotor is well studied, and with their designing it is prevented beforehand. The phenomenon of flutter on helicopters is less dangerous than it is on aircraft, since the speed of flow around of the blades changes depending upon the azimuthal position of the blade, and therefore it first enters into flutter when advancing on the flow and then emerges from it when retreating from the flow. In connection with this flutter for a helicopter advances not instantly as for aircraft, but there appear so-called "flutter signals," which warn of the approach of flutter, and the pilot can succeed in taking measures for guiding the helicopter from flutter.

To decrease the lateral centering of blades of the Mi-4 helicopter both of mixed and all-metal construction, antiflutter loads are placed in them. For blades of this helicopter the critical flutter revolutions and speed is higher than revolutions and speed applied in operation, and therefore vibration of this type on the Mi-4 helicopter does not appear under the condition of a correct technical and flight operation of it. Despite the fact that the designer succeeded by selection of the indicated parameters in avoiding the phenomenon of flutter at operational revolutions and speeds of the Mi-4 helicopter, the blades in the process of production and operation pass a ground check for flutter (this is provided by Instructions on the Operation and Maintenance of the Mi-4 Helicopter). For operation sets of blades are allowed at which criteria of flutter did not appear at 2000-2450 r/min when checking them on a line with artificially increased centering with the help of standard loads (on every blade there is attached on the tab plates 860 g each).

The ground check of blades for flutter in subdivisions is conducted in the following cases:

a) after repair of the blades, before the beginning of operation of the blades, which are stored under conditions of increased humidity;

b) when preparing the helicopter for winter or summer operation or not less than once per year, if such a preparation is not conducted in special climatic conditions;

c) upon statements of the pilot of appearing criteria of flutter during flight.

In spite of all the measures undertaken for preventing vibration (flutter) and in spite of the fact that this form of vibration is extremely rare for the Mi-4 helicopter, the pilot should know the criteria of flutter and methods of getting out of it if it ever appears.

The appearance of flutter of blades of the rotor is most probable at high speeds in horizontal flight of the helicopter, but it can appear during operation of the rotor on land, in hovering and in other conditions of flight.

The criteria of flutter (flutter signal) are:

1) the falling out of separate blades from the total cone of rotation, well visible from the cockpit, while during the check for co-conicity this was not observed; here the blade tip describes a curve, leaving after itself a dark trace;

2) increased shaking of the control stick or the "pitch-throttle" lever with variable frequency and amplitude (jerks);

3) increased vibration of the helicopter in conditions of flight with increased revolutions or in autorotation during revolutions exceeding the optimum; vibration of the helicopter with variable frequency and amplitude ("shuddering");

4) impairment of stability of the rotor, leading to swaying of the helicopter and hampering the control of the helicopter under conditions of bumpiness;

5) driving of the control stick, which is difficult to eliminate by usual measures in the process of control.

The actions of the pilot upon the appearance of criteria of flutter are:

1) if criteria of flutter appear upon operation of the rotor on land it is immediately necessary to decrease the revolutions with the help of shifting the throttle control to the rest of little throttle;

2) upon the appearance of criteria of flutter in hovering, it is necessary to move quickly the throttle control to the left to the limit and land, softening the landing by moving the "pitch-throttle" lever upwards;

3) upon the appearance of flutter criteria in flight at low altitude, it is necessary to move the throttle control to the left, decrease the collective pitch and speed, and then land;

4) if flutter criteria appear in usual flight in altitude, then one should immediately move the throttle control to the left, lower the "pitch-throttle" lever to a value necessary for descent with an operating engine; then turn to horizontal flight with the minimum permissible revolutions — 2100 per minute; if flutter criteria are repeated, then it is necessary to make a forced landing.

CHAPTER V

TAXIING, TAKEOFF AND CLIMB WITH FORWARD VELOCITY

§ 1. Taxiing

1. General Positions

With helicopters taxiing is allowed and even recommended, since it is considerably more economic in comparison with an approach at low altitude. With an overloaded helicopter or during flights it is impossible to manage without taxiing in general. With such flying weight there is expended about 1/3 of the rated power on taxiing. Furthermore, it is expedient to apply taxiing during takeoff from dusty sites and with freshly falling snow, since the forming vortex does not make it possible to accomplish approach at low altitude in view of poor visibility.

Taxiing by the piloting technique is simpler than an approach at low altitude. But on the other hand, taxiing can be applied only over even, hard ground and for short distances. The helicopter has a high position of the center of gravity, and in connection with this it is difficult to set symmetry of forces acting it, and therefore on land it possesses poor stability. If, however, conditions for taxiing are absent, then it is recommended to make an approach -- movement at low altitude. Furthermore, the helicopter when moving over land is subject to the phenomenon of "ground resonance." In order to ensure safety when taxiing, a special method of taxiing is set and definite limitations are established.

Besides taxiing forward, it is possible for the helicopter to accomplish theoretically during an emergency backward movement on land and also accomplish turns in place to both sides at any angle by decreasing or increasing the thrust of the tail rotor. With deflection of the left pedal thrust of the tail rotor decreases, the helicopter turns to the left because of the reactive moment of the rotor and partially because of the change in direction of thrust of the tail rotor (if the left pedal is deflected far). With deflection of the right pedal forward the tractive force of the tail rotor is increased, and the helicopter turns to the right because of the increasing moment of the tail rotor as compared to the reactive moment of the rotor.

2. Diagram of Forces and Moments Acting on the Helicopter When Taxiing

When taxiing with a helicopter the following forces and moments act: tractive force [thrust] of the rotor T, thrust of the tail rotor $T_{X.B}$, drag of the helicopter Q, force of friction of wheels against the ground F_{Tp}, force of weight of the helicopter – G, force of reaction of the ground $F_{p.3}$, reactive moment of the rotor $M_{p_{H.B}}$, reactive moment of the tail rotor – $M_{p_{X.B}}$ and yawing moment of the tail rotor on the arm $\ell_{X.B}$ (Fig. 60). The tractive force of the rotor T is deflected by the control stick forward and to the right, and therefore it is spread to three components: vertical component T_y, longitudinal component T_x directed forward, and lateral component T_z directed to the right. The tractive force of the tail rotor $T_{X.B}$ is directed to the left, drag of the helicopter Q – to the side opposite the motion of the helicopter, frictional force of wheels against the ground – to the side opposite the motion of the helicopter, force of weight of the helicopter G – vertically downwards, and the force of reaction of the ground $F_{p.3}$ – vertically upwards. The reactive moment of the rotor $M_{p_{H.B}}$ acts to the left, since the rotor revolves to the right. The reactive moment of the tail rotor $M_{p_{X.B}}$ creates positive pitching moment to the helicopter. Yawing moment of the tail rotor on the arm $\ell_{X.B}$ is directed to the right. Furthermore, tractive force of the rotor T creates a diving moment to the helicopter with respect to supports of the wheels, the lateral force T_z with respect to the point of supports of the right wheels creates a moment banking the helicopter to the right, and thrust of the tail rotor $T_{x.B}$, with respect to points of supports of the left wheels, a moment banking the helicopter to the left.

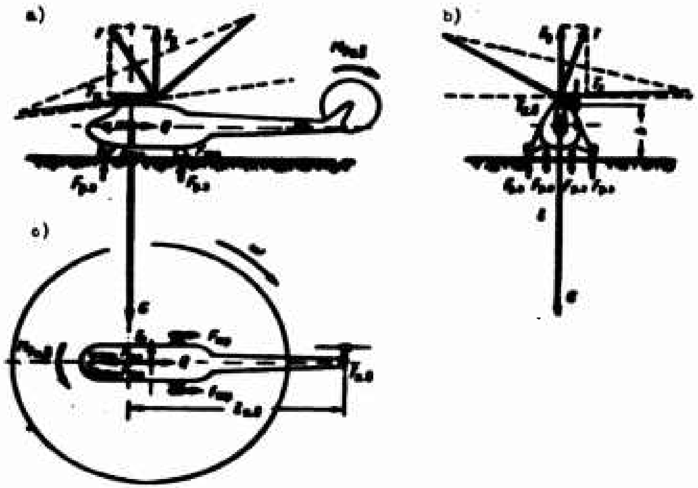

Fig. 60. Diagram of forces and moments acting on the helicopter during taxiing: a) view on the left; b) rear view; c) top view.

For the uniform and rectilinear motion of the helicopter on land, there should be observed the following equality of forces and moments acting on the helicopter. For uniform motion it is necessary that the longitudinal component of thrust of the rotor T_x be equal to drag of the helicopter Q and frictional force of all wheels against the ground $F_{тр}$: $T_x = Q + F_{тр}$. In order that there is no slip of the helicopter over land [YuZ] (Ю3) [Translator's note: only abbreviation for this refers to southwest], and also for preventing lateral pressures on tires of the wheels and a tendency of tilting of the helicopter to any side, it is necessary that the tractive force of the tail rotor $T_{x.B}$ be completely balanced by the lateral component of thrust of the rotor T_z: $T_{x.в} = T_z$. For the observance of rectilinearity of motion it is necessary that the reactive moment of the rotor $M_{p_{H.B}}$ be completely balanced by the yawing moment of the tail rotor $M_{y_{X.B}}$:

$$M_{p_{H.B}} = M_{y_{X.B}} = T_{X.B} l_{X.B}.$$

Furthermore, for a stable position of the helicopter on land it is necessary that the vertical component of thrust of the rotor T_y be considerably less than the weight of the helicopter $G: T_y < G$.

3. Possibility of Tilting of the Helicopter on the Side

The diagram shown on Fig. 60 of forces and moments and also the relationship between them are ideal, i.e., desirable for complete safety in taxiing. But it is rather difficult for the pilot to observe such a diagram of forces and moments in taxiing, since there is not complete possibility of controlling the magnitude and relationship between all the indicated forces and moments. If one were to consider that the center of gravity of the helicopter has a high position, then it is possible to bank it, and this means tilting on the side.

Thus, for example, according to the constancy of speed and rectilinearity of motion of the helicopter, it is possible to judge the equality of force of the longitudinal component of thrust of the rotor T_x to drag forces Q and friction of the wheels against the ground F_{Tp}, and also the equality of the reactive moment of the rotor $M_{p_{H.B}}$ to yawing moment of the tail rotor $M_{y_{X.B}}$. But it is impossible to control the equality of lateral forces and moments. In the same way it is difficult to control the magnitude of the vertical component of thrust of the rotor T_y. Therefore, in order that this force is necessarily less than the weight, there is established the corresponding limitation in magnitude of the set power of the engine both in revolutions and in collective pitch. For balancing the thrust of the tail rotor $T_{X.B}$ and lateral moment from this force around the point of support of the left wheels on arm h (see Fig. 60), it is necessary to deflect the thrust of the rotor to the right and cause the lateral component of it T_z with the help of the lateral trim tab. But as to how far to deflect this thrust to the right there is nothing on which to judge; it is possible to do this only approximately. If the lateral component of thrust of the rotor T_z is made insufficient, then there will appear a tendency of a left slip of the helicopter on the ground, a lateral load on tires of the wheels and tilting on the left side. If, however, the lateral force is made greater than the thrust of the tail rotor, then there will be a tendency of helicopter to shift and bank to the right. If one were to consider that the ground is uneven and there can be sharp shocks in a lateral relation, or it is soft and with a slip to the external side of the wheels a roller preventing lateral shift will be formed, and then evident conditions on tilting of the helicopter will be created on right or left side.

Let us consider conditions under which the danger of tilting of the helicopter on left side can appear. Let us assume that the lateral force T_z is absent or it is considerably less than the thrust of the tail rotor $T_{x.B}$. With respect to the point of support of the left wheel on the helicopter, there will act the following moments (See Fig. 60b): moment of thrust of the rotor $T_y l$ directed to the left, lateral moment of thrust of the tail rotor $T_{x.B}h$ directed to that same side, and the moment of force of weight Gl directed to the opposite side. If thrust of the rotor will be less than the weight of the helicopter, the moment from the force of weight will be greater than the sum of moments from thrust of the main and tail rotors: $Gl > Tl + T_{x.B}h$. The more this inequality, the more the helicopter is stable on land.

If for some reasons the helicopter is banked to the left, for example, from the force of the blow of the right wheel during taxiing over uneven ground at a certain angle to the horizon, then the tractive force of the main and tail rotors and the force of the blow will create moments in the direction of the increase in the bank, and the force of the weight — in the direction of a decrease in the bank (Fig. 61). The appearing bank will change the relationship of these moments so that with an increase in bank the moment of the force of weight will decrease owing to a decrease in arm l, since the center of gravity will approach the point of support of the left wheel. In view of the decrease in the moment from the force of

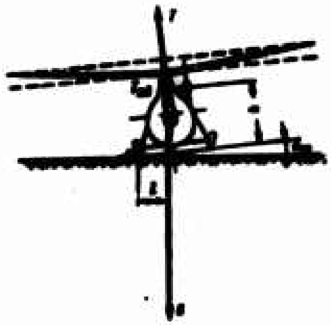

Fig. 61. Diagram of forces and moments acting on the helicopter with a bank (rear view).

weight, the stability of the helicopter will decrease. Upon achievement of the critical angle of bank the rolling moments from thrusts of the rotors will be equal to the moment appearing from the weight of the helicopter: $Gl = Tl + T_{x.B}h$. Then the helicopter will obtain neutral equilibrium on points of supports of the left wheels, and with small vertical separation of rolling moments above the moment of force of weight $(Gl < Tl + T_{x.B}h)$ the helicopter will continue to increase the bank, and if urgent measures are not taken it will overturn on its left side.

Such a danger of tilting will occur on the right side if there appears for accidental reasons a right bank with lateral force T_z, and all the more so if this force is greater than the thrust of the tail rotor $T_{X.B}$ (see Fig. 60).

But the danger of tilting on the right side is less probable in view of the presence of the constantly acting force of thrust of the rotor to the left.

The critical angle of bank $\gamma_{кр}$ for a given helicopter is not a constant value. It depends on the width of the track of the landing gear, altitude of the center of gravity of the helicopter, values of tractive force of the main and tail rotors, and also on the value of lateral force T_z during a right bank.

The more the width of the landing gear track, the lower the center of gravity, the less the thrust of the main and tail rotors, the greater the critical angle of bank $\gamma_{\text{кр}}$ and the more stable is the helicoptor on land.

With the appearance of bank it is necessary immediately to lower the "pitch-throttle" lever downwards to the limit, the force of thrust of both rotors will decrease, their moments will also become less than the moment from the force of weight, and the helicopter will restore the equilibrium. If, however, bank will be obtained great and the decrease in collective pitch does not guarantee restoration of the equilibrium, then it is necessary to lift the helicopter from land by a smooth but energetic motion of the "pitch-throttle" lever upwards.

Moving the pedal in the direction of the bank and moving the control stick in the opposite direction of the bank with a simultaneous decrease of the collective pitch will not give a great positive result, since with a decrease in collective pitch thrusts of both rotors will decrease and an attempt to move them to the opposite side of the bank will not produce result, and guiding of the helicopter from the bank will only be complicated.

On the basis of everything considered conditions of taxiing of the helicopter on the ground represent definite difficulties and therefore requires special attention and much experience from the pilot and strict fulfillment of all limitations set for taxiing.

Furthermore, on taxiing the helicopter can obtain a special oscillation mode — "ground resonance."

4. "Ground Resonance" of the helicopter

"Ground resonance" of the helicopter pertains to the type of self-excited oscillations in contrast to the usual oscillations, and therefore it is called "natural oscillations of the helicopter." Since such oscillations spread to dangerous ones more frequently when the helicopter is on the ground or upon contact with it and for the first time they are revealed here, then these oscillations are called "ground" although they can appear in the air during flight. The indicated oscillations are also called "lateral oscillations" inasmuch as they appear only in a lateral plane of the helicopter.

"Ground resonance" is the interaction of two vibrating systems: the lift system (of blades relative to the drag hinges) and helicopter on its landing gear.

"Ground resonance" appeared only as a result of the introduction of the drag hinge of the blades. All helicopters without exception, having drag hinges without dampers, are certainly subject to "ground resonance." Dampers of drag hinges serve only for eliminating "ground resonance," and in the remaining operation of the rotor they are an interference. Therefore, the designer always tries to decrease tightening of dampers of the drag hinges up to zero. Usually it is made so that the frequency of natural oscillations of the helicopter on the landing gear is lower than the frequency of oscillations of the lift system, since in this case even with the accretion of oscillations of these two systems they will pass with lower intensity and will require smaller damping. The low frequency of natural oscillations of helicopter is attained by smaller rigidity of the supports. The less the rigidity of the supports, the less at low revolutions appears "ground resonance," and the easier it is to depart from it. But the rigidity of the supports can be decreased to definite limits, which depends on the necessary damping of the whole helicopter.

"Ground resonance" depends on the flying weight of the helicopter, characteristics of shock absorbers of the landing gear, tires of the wheels and tightening of dampers of the drag hinges. For the Mi-4 helicopter the designer selected a volume of fluid and initial air pressure in shock absorbers and initial pressure in tires of wheels and moment of tightening of the dampers of the drag hinges so that the frequency of oscillations of the lift system does not coincide with the natural frequency of oscillations of the helicopter found on land, and therefore with correct technical and flying operation of "ground resonance" is eliminated.

But this does not mean that "ground resonance" will not appear.

If one were to deviate from the mentioned norms: not to maintain the necessary level of liquid and air pressure in the shock absorbers of the landing gear and also pressure in the tires of the wheels, to make nonuniform and incorrect tightening of the dampers of the drag hinges, to allow error in testing the operation of the engine and transmission on a line not to obey limitations when taxiing, takeoff, and landing like an aircraft, to allow error during vertical takeoffs and landings, then "ground resonance" is possible.

As is known, blades in forward flight accomplish oscillations around the drag hinges owing to Coriolis forces and also partially owing to the change in aerodynamic drag depending upon their azimuthal position, and upon motion of the helicopter on land these oscillations are increased in view of its natural rocking. With this the blades will appear in various places with respect to the drag hinges, i.e., between the blades there will not be the angle of 90° but one greater or less. For this reason the common center of gravity of the blades is displaced from the axis of rotation of the rotor, and on the rotor hub there appears an unbalanced centrifugal force, which sways the lift system with a fixed frequency. With this the trajectory of the center of gravity can have the form of a circle or the form of a complicated closed curve, and in all the lift system will accomplish oscillations.

When the helicopter is in flight, these oscillations are insignificant. They are transmitted to the helicopter but do not coincide with natural oscillations of it and cause no harm. When the helicopter moves over the ground or is near it, the oscillation of the lift system is increased in view of great motion of the blades on the drag hinges, and the helicopter itself is in suspension, then the frequency of oscillations of the lift system can coincide (enter into resonance) with the frequency of natural oscillations of the helicopter. The cause for the beginning of such oscillations can be some immaterial factor: accidental unevenness of the surface of the land, sudden gusts of wind, sharp or great deflection of the control stick from the position corresponding to the absence of the cyclical change of setting angles (pitch), high speed of motion on land and others. The combination of the enumerated factors with incorrect parameters of tightening of dampers of the drag hinges, charging of shock absorbers of the landing gear and pressure in tires can create favorable conditions for the development of lateral oscillations of the helicopter. The coincidence of frequencies of oscillations of the two systems will lead to a rocking of the helicopter, from this the axis of the shaft will start to be deflected in space more and more and will lead to an increase in the radius of rotation of the center of gravity, and this will amplify the motion of the blades on the drag hinges. Therefore, the unbalanced centrifugal force will increase, and oscillations of the whole helicopter will rapidly progress.

The source of energy for lateral oscillations of the helicopter is the operating engine. When rotor revolutions are low any appearing oscillation of the lift system is damped by shock absorbers of the landing gear, tires of wheels and dampers of the drag hinges. With an increase in revolutions the work of forces causing oscillations increases, and the work of damping forces decreases in view of the increase in thrust of the rotor and decrease in connection with this the stroke of shock absorbers of the landing gear and tires of the wheels.

Starting from certain revolutions, the flow of energy from the engine, which sways the lift system, will be greater than the energy of its dispersion in all the shock absorbers and dampers, and therefore oscillations will increase, and, if one were not to take urgent measures, destruction of separate parts of the helicopter is possible. The oscillations will be developed not in all directions, but only in a lateral plane, since the lateral moment of inertia of helicopter is considerably less than the longitudinal moment. In beginning of oscillations the contact of the tires of the wheels with land is not disturbed but then with an increase in amplitude of oscillations the contact is disturbed. Wheels of the landing gear are alternately detached and hit against the ground first on the right and then on the left side. In connection with this the magnitude of the banks will increase and blades of the rotor will start to hit against rests of the drag hinges, and since in plane of rotation they have great rigidity, then they can be destroyed.

Tail rotor will lag behind lateral oscillations of the helicopter and therefore the tail and end beam can be deformed up to destruction. Oscillations of the helicopter can lead to a blow by tips of the blades against the ground, destruction of the landing gear and tilting of the helicopter.

To prevent the possibility of appearance of "ground resonance" of the Mi-4 helicopter, it is necessary to obey the following rules of technical and flying operation.

1. The moment of tightening of dampers of the drag hinges should be identical for all blades and not lower than 16 ± 0.5 kgf (half-sum of the measured forces in two directions applied to blade at the 54th rib of mixed construction or at the 21st section of all-metal construction.

2. The charging of shock absorbers of the landing gear struts by a mixture by both air in volume and in pressure should be within limits of the set norm: mixtures in damping struts of main wheels of the landing gear – 2400 cm^3, in struts of the front wheels – 730 cm^3, initial pressure of air in shock struts of main wheels of the landing gear – 36 kgf/cm^2, and in struts of the front wheels – 18 kgf/cm^2.

3. The filling of tires of the wheels with air should be within the norm: initial pressure in tires of the main and front wheels is 4 ± 0.2 kgf/cm^2.

4. A stand for testing the operation of the engine and transmission in a moored state should be equipped in accordance with technical conditions.

5. With the testing of the operation of the engine and transmission on a line the control stick must be held in the position at which cyclical change of the setting angles is absent. For this the mechanism of longitudinal control according to the trim tab indicator should be set one graduation back, and the mechanism of lateral control – in a neutral position. Do not allow sharp jerks of all control levers.

6. When taxiing on land observe the following limitations. Speed of taxiing must not exceed 10 km/h. Perform taxiing only with a wind of not more than 12 m/s, do not taxi over great distances,

on uneven and soft ground and in deep and friable snow. The collective pitch of the rotor when taxiing must not exceed 4-5°, and the number of revolutiohs (on the combined indicator) should be within 1700-2000 per minute.

7. With takeoff like an aircraft in training purposes strive for the minimum length and time of run, do not allow a lift-off speed greater than 30 km/h. With the necessity of takeoff like an aircraft in industrial conditions, accomplish lift-off at the minimum possible speed, depending on flying weight, atmospheric conditions, barometric altitude of the site and experience of pilot.

8. When landing like an aircraft in training purposes do not allow a landing speed of more than 25 km/h, and after landing immediately move the "pitch-throttle" lever downwards to the limit. To decrease the landing run use the rotor and the brakes. When landing like an aircraft in industrial conditions perform landing at the minimum possible landing speed, depending on gross weight, atmospheric conditions, barometric altitude of the given site and experience of pilot.

9. With vertical takeoff do not hold the helicopter for a long time in semisuspension prior to lift-off of the wheels from the ground and near the ground after lift-off.

10. With vertical landing do not hold the helicopter for a long time near the ground and in semisuspension after the contact with the ground by the wheels.

The beginning of "ground resonance" is easily determined. The criteria of it are rapidly growing lateral oscillations of the helicopter with subsequent variable separation and blows first by the right and then left main wheel of the landing gear against the ground.

In all cases and in all stages of "ground resonance" it is necessary to extinguish the source of energy of these oscillations, the operating engine, stroke the shock absorbers, cease the flapping motion of the blades around the flapping hinges and oscillations of them around the drag hinges. For this it is necessary to move the gas control rapidly to the left, simultaneously lower the "pitch-throttle" lever downwards to the limit, set it on the stop and turn off engine. Then transfer the control stick in a longitudinal direction at a position corresponding to hovering conditions (back), be prepared for parrying of a right turn and, as soon as the helicopter starts to turn to the right, vigorously depress the left pedal forward to the limit.

It is not recommended to cease lateral oscillation of the Mi-4 helicopter by the method of lift-off from land, since the reserve of power for lift-off can not always be sufficient, and if it is sufficient it is inexpedient to lift into air in view of the possible damages to the helicopter during the time of the mentioned oscillations on the ground. It is possible to cease oscillations by the method of lift-off only in the case of their appearance during vertical takeoff, but such cases can be very rare (on the Mi-4 helicopter they are not recorded).

One also should not try to cease lateral oscillations of the helicopter by action of the control stick in a lateral relation. Such actions cannot be means of cessation of oscillations in view of the presence of considerable delay of control by the rotor and for other reasons.

The helicopter subjected to "ground resonance" undergoes a thorough inspection to eliminate malfunctionings obtained from "ground resonance", and only after this can it be allowed to fly.

5. Peculiarities of the Fulfillment of Taxiing

Before taxiing it is necessary to set the trim tabs in a takeoff position: the longitudinal — one division forward and the lateral — half division to the right. Move the gas control to the right to the limit and set the collective pitch 4-5°, then with a smooth motion of the control stick forward to transfer the helicopter to taxiing. If the helicopter does not start moving, it is necessary to increase insignificantly the collective pitch, but not by more than 5°. The tendency of the helicopter to turn left is warded off by depressing the right pedal. Revolutions (on the combined indicator) during taxiing are maintained within 1800-2000 per minute and not less than 1700 r/min for preventing blows of the blades against the centrifugal limiters. Revolutions of more than 2000 per minute and a collective pitch of more than 5° will create too much thrust, which decreases the stability of the helicopter on land. The speed should be held at not more than 10 km/h, controlling it by the cyclical pitch lever.

Perform turns by a smooth motion of the pedal to the corresponding side with preliminary deceleration of the taxiing speed.

Wind, especially strong and gusty, complicates taxiing, and therefore taxiing is permitted with a wind of not more than 12 m/s, and during a strong gusty wind it is necessary to maintain revolutions greater than those set for normal taxiing by 50-100 r/min. During a crosswind the helicopter tries to be turned opposite to the wind, and the cone of rotation and thrust of the rotor is deflected downwind. In connection with this it is necessary to keep the helicopter from turning by pedals and deflect the control stick windward. With prolonged taxiing with a crosswind it is necessary to take the pressure off of the control stick by the lateral trim tab.

During taxiing it is necessary to look at the ground in taxi strip, conduct the necessary circumspection, and also attend to the operation of the engine. With the appearance of banks or "ground resonance," it is necessary to act as was indicated above.

To stop the helicopter it is necessary to deflect the control stick back to the full stop of the helicopter and only then decrease the collective pitch of the rotor. Upon the necessity of a fast stop of the helicopter it follows simultaneously with deflection of the control stick back to increase the collective pitch of the rotor and apply the brakes. A reduction in collective pitch for such a stop will not bring the needed results, since with this the thrust of the rotor will decrease and deflection of the control stick back will not give the needed effect, and the helicopter will continue inertial motion.

6. Limitations with Engagement of the Transmission and Taxiing

1. It is possible to engate the transmission before the beginning of taxiing at any position of the helicopter windward, if the wind is not more 10 m/s. If, however, the wind is from 10 to 18 m/s, then it is necessary to set the helicopter by its nose or left side windward. To engage the transmission with the force of the wind from 10 to 18 m/s with the direction of it on the right or from behind is prohibited, since the peripheral velocities will be less than the speed of the wind, the blades of the rotor will create negative lift and be lowered lower than the set level, and therefore blows of blades against the tail boom are possible.

With a wind of more than 18 m/s it is prohibited to start the transmission and accomplish taxiing and takeoff.

The same limitations with respect to the wind and for the same reasons are set when stopping the transmission.

2. When taxiing revolutions of the rotor must be within limits of 1700-2000 per minute and the collective pitch, 4-5°.

3. The speed of taxiing must not exceed 10 km/h.

4. Taxiing must be done with a wind of not more than 12 m/s, and during a strong wind instead of taxiing it is necessary to make an approach to the necessary place at an altitude of 5-10 m.

5. It is prohibited to taxi over viscous, uneven ground and deep and loose snow.

6. It is prohibited to taxi for great distances. In this case it is expedient to replace taxiing with an approach at low altitude.

§ 2. Takeoff of the Helicopter

1. General Information

On the Mi-4 helicopter two forms of takeoffs are applied depending upon conditions: like a helicopter (vertical) and like an aircraft. Combined takeoff was proposed, but it did not receive application in view of the complexity of the method of fulfillment and absence of some advantages as compared to the indicated forms of takeoff.

Vertical takeoff for the helicopter is the basic form of takeoff, even if takeoff is accomplished from airfields and heliports of the first type. Although such a takeoff is less economic as compared to the takeoff like an aircraft (greater required power), but in view of the ease of technique of its fulfillment, which ensures higher safety of the flight, it received wide application.

Takeoff like an aircraft requires less power, and therefore it is possible to accomplish it with great flying weight, but it is complicated in piloting technique, which does not always ensure safety and therefore requires higher qualification and experience of the pilot. With the accumulation of operational experience and improvement of flying and technical properties of helicopters, takeoff like an aircraft will gradually be applied more extensively in the presence of conditions for such a takeoff. Vertical takeoff should gradually turn into the second plan and will be applied only with an impossibility to accomplish takeoff like an aircraft.

Maximum operating conditions of the engine in combination with the rotor, as is already known, correspond to revolutions of 2600 per minute. But in vertical takeoffs with the maximum permissible flying weight, when maximum power is used in the absence of oblique airflow of the rotor, the maximum thrust is obtained with supercharging of 1125 mm Hg and revolutions of the crankshaft of the engine of 2400 per minute. Consequently, the optimum revolutions for such takeoffs are 2400 per minute. At these revolutions the rotor has a maximum relative efficiency, and these revolutions must be maintained during takeoffs from heliports located at altitudes up to 800 m above sea level. To obtain such revolutions it is necessary to load the rotor with a completely introduced throttle control. At altitudes higher than 800 m above sea level the optimum revolutions for such takeoffs will be 2500 per minute. At these altitudes on the rated power of engine with a completely open throttle and decreased air density the rotor develops maximum thrust at 2500 r/min.

As a result of flight tests of Mi-4 helicopters, there are obtained the following possible trajectories and takeoff distances depending upon flying weight, which are reduced to standard atmospheric conditions (Fig. 62).[1]

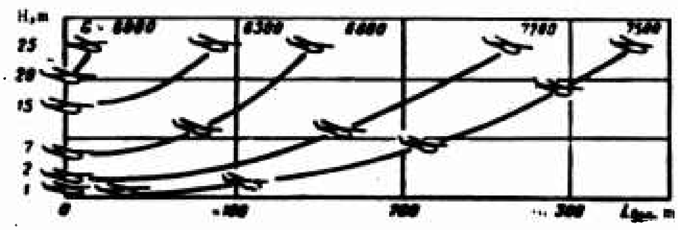

Fig. 62. Takeoff distances of the helicopter depending upon flying weight when T_{HB} = 6300.

Vertical takeoff, in turn, depending upon conditions is subdivided into the following forms:

1) lift-off of the helicopter vertically at an altitude of 2-3 m with subsequent acceleration of forward velocity;

2) lift-off of the helicopter vertically with subsequent

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[1]A nomograph for the determination of takeoff run and takeoff distance does not exist. Takeoff is carried out from permanent and temporary heliports of the first and second type, the dimension and approaches to which are determined by order of the chief of the Main Administration of the Civil Air Fleet [GUGVF] (ГУГВФ) No 784 from 20 December 1963.

acceleration of forward velocity in the zone of influence of the air cushion;

3) lift-off of the helicopter vertically at an altitude more than 10 m with subsequent acceleration of forward velocity outside the zone of influence of the air cushion.

2. Lift-off of the Helicopter Vertically at an Altitude of 2-3 m with Subsequent Acceleration of Forward Velocity

This form of vertical takeoff is applied in favorable conditions from airfields and also permanent and temporary heliports of the first type with open approaches, when the pilot is absolutely sure of a favorable outcome of takeoff and is not required to produce any calculations before takeoff. This form of takeoff consists of the following elements: vertical lift-off at an altitude of 2-3 m, short-term hovering at this height, acceleration of speed up to the optimum climb speed (100 km/h) with a gradual departure from land and transition to climb at this speed (Fig. 63).

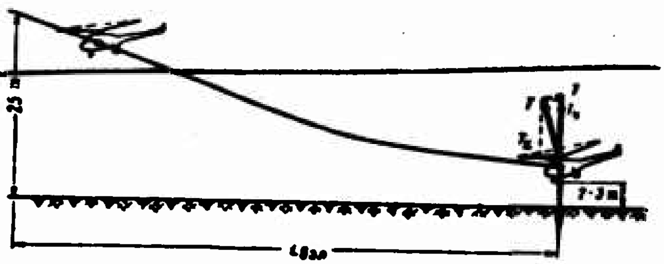

Fig. 63. Profile of takeoff by the method of lift-off vertically with subsequent acceleration of speed.

With vertical lift-off the so-called "overloading of the rotor" is possible, which lies in the fact that during rapid motion of the "pitch-throttle" lever an increase in collective pitch of the rotor leads the increase in supercharging of the engine corresponding to this pitch. With this the thrust, owing to the inertia of rotation of the rotor, can increase, and the helicopter can leave the ground and even climb; but then the rotor revolutions will fall, inasmuch as it is loaded, and the power of the engine corresponding to this pitch still will not manage to increase, the thrust will decrease and the helicopter will start to descend. Therefore, transition from 1400-1500 r/min to the normal rating should be accomplished by motion of the "pitch-throttle" lever slowly, not less than 5-7 seconds. If, however, the motion is faster, then overloading of the rotor will be obtained. With the appearance of such overloading it is necessary to decrease the collective pitch insignificantly and hold the helicopter in a horizontal position – the helicopter hovers or lands. After that it is necessary to decrease the collective pitch and repeat takeoff with a smoother motion of the "pitch-throttle" lever upwards.

In the beginning of the acceleration of speed from hovering the helicopter tries to descend, since the thrust of the rotor T is deflected forward by the control stick and its vertical component T_y becomes less than the weight of the helicopter. Therefore, to prevent descent it is necessary by deflecting the control stick to increase simultaneously the thrust of the rotor by motion of the "pitch-throttle" lever upwards. Then in banking, the thrust will be increased, and its vertical component T_y will not decrease and will be maintained equal to the weight (see Fig. 63).

The following peculiarity of the acceleration of speed after hovering is the appearance of increased vibration – "shaking conditions" in the velocity range of 20-40 km/h.

Increased vibration during the acceleration of speed in the speed range of 20-40 km/h is regular for the helicopter and to be free from it completely is impossible; it can only be decreased in magnitude, and it is possible to reduce the duration in time. The cause of the appearance of the indicated vibration consists in the reconstruction of the axial vortex system in conditions of hovering into the vortex system of the rotor in forward flight.

In conditions of hovering, as is known, the flow is set so that the air passes through the rotor down from above, and along the periphery of the rotor there occurs overflowing of air from bottom to top owing to the difference in pressures under and over the rotor. In forward flight inducted flow down passes also through the rotor from above, but it is beveled by the main flow back. Beyond the tips of blades of the rotor (regions of azimuths of 90° and 270°), as beyond tips of a wing of an aircraft, there is observed twisting of the flow owing to the overflowing of air from bottom to top and the continuously incident flow with motion of the helicopter forward. Reconstruction of steady flow in hovering to steady flow in forward flight occurs in beginning of the acceleration of speed. During this reconstruction the vortex system of the rotor becomes unstable, and therefore an increased vibration – "shaking conditions," is created.

This vibration will be greater, the lower the altitude of hovering, since the air repulsed by the rotor, being reflected from the ground, resonates with the frequency of oscillations of the rotor. At high altitudes, outside the influence of the air cushion, "shaking conditions" are considerably less.

The magnitude of vibration also depends on the flying weight of the helicopter. Thus, for example, for the Ka-15 helicopter this vibration is absent, for the Mi-1 helicopter it is insignificant, and for the Mi-4 helicopter it is considerable and at the same time more with flying weight than with full flying weight than with an empty helicopter. Besides this, the magnitude and duration of this vibration depends on the rate of acceleration of speed: the slower the acceleration becomes, the higher and longer the vibration. In order to reduce the magnitude and duration of this vibration, it is necessary to pass the indicated speed range faster.

"Shaking conditions" are also observed when reducing the speed to hovering for the same reasons, i.e., owing to the reconstruction of the vortex system in forward flight to the vortex system in hovering. With this the magnitude of vibration is higher than that with the acceleration of speed.

The next peculiarity of analyzed form of takeoff lies in the fact that with an increase in speed balancing of helicopter in yawing lateral and longitudinal directions changes. Therefore, to maintain travel, the absence of banks and slip and to prevent pitching, the pilot should actuate in an appropriate way all control levers. In a directional relation with the acceleration of speed the helicopter tries to turn right, since the tail rotor enters into oblique airflow and its thrust is increased. Therefore, the pilot should with the acceleration of speed depress the left pedal forward for decreasing pitch and thrust of the tail rotor. In a lateral relation with the acceleration of speed, the helicopter tries bank and slip to the right because of the increase in collapse of the cone of rotation of rotor to the right with an increase in speed. Therefore, to prevent a bank and slip the pilot should, by deflecting the control stick forward, simultaneously move it to the left for decreasing lateral force. In a longitudinal relation with the acceleration of speed, especially with the approach toward a speed of 40-50 km/h, the helicopter tries to pitch owing to the obtaining of airflow of the stabilizer. To prevent this phenomenon the pilot should deflect the control back more energetically, thereby parrying the tendency of pitching.

The trajectory of takeoff even with open approaches should be such that upon the achievement of optimum speed of 100 km/h the altitude is not less than 25 m. The acceleration of speed with the simultaneous departure from land is necessary so that in the case of engine failure it is possible to land safely in autorotation at any point of the trajectory of takeoff. Failure of the engine will lead to an unbalance of the helicopter, and if there is little altitude, the pilot will not succeed in balancing the helicopter in conditions of autorotation and also will not succeed in reducing the speed to ensure normal landing. Consequently, the helicopter during takeoff should be higher than the dangerous zone b (Fig. 64). On the other hand, with the acceleration of speed it is impossible to gain high altitude, since the helicopter will enter into another dangerous zone of low speeds, just as in the case of engine failure (Fig. 64, zone a).

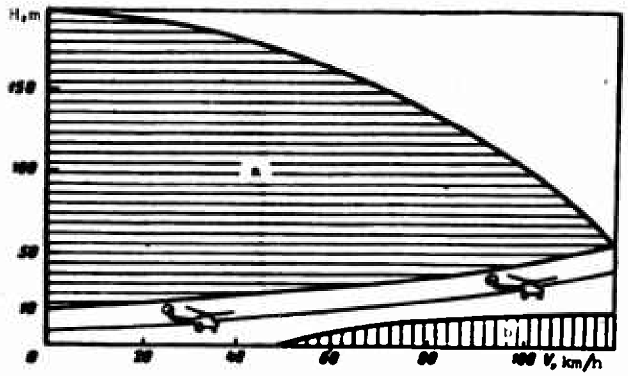

Fig. 64. Dangerous zones for hovering, flight at low speeds and takeoff in the case of engine failure: a) dangerous zone for hovering and flight at low speeds; b) dangerous zone for takeoff.

As is already known, the altitude from 10 to 200 m is dangerous for hovering, since in the case of engine failure this altitude will be insufficient for the acceleration of forward velocity from conditions of autorotation in order to land successfully. With the acceleration of speed from hovering the dangerous zone of altitudes narrows. Its upper edge is lowered, since the more the forward velocity of flight, from a lower altitude it is possible to gain the necessary speed for landing after engine failure. The lower edge of the dangerous zone with an increase in speed rises, because the more the speed, the less the angles of attack of the rotor will be after engine failure, the slower the revolutions will decrease, and this means the greater will be the reserve of energy of rotor rotation, and the slower the vertical descent velocity increases. Consequently, the high altitude will be enough to land the helicopter in the inertia of rotation of the rotor and by the moment of touchdown the maximum vertical velocity in autorotation will not manage to increase. Then, in order to decrease the speed necessary for landing, a great effect can be reached by loading the rotor by the "pitch-throttle" lever.

Thus, during takeoff in the case of engine failure the helicopter should follow a safe "corridor" (see Fig. 64).

At the end of acceleration at a speed of 90 km/h the helicopter is transferred into a climb regime by deflection of the control stick back and by converting conditions of the engine to nominal by simultaneous moving of the throttle control to the left and increasing the collective pitch of the rotor, and then the speed 100 km/h is established.

Vertical takeoff should be produced into the wind, since with this less power is required for takeoff, and the piloting technique is facilitated. When necessary it is possible to takeoff both with a crosswind up to 5 m/s with the direction of it up to 90° in relation to the helicopter and with a wind up to 7 m/s and direction of it 45-50°.

Takeoff with a lateral right wind is more complicated than that with left. Wind on the right requires great consumption of power in view of the necessity of great deflection of the thrust to the right. Furthermore, the reserve of deflection of the control stick in a transverse relation decreases, since the lever should be deflected in a windward direction for the parrying of drift, but it in hovering and at low speeds even with a headwind occupies a right position.

Method of takeoff. Before takeoff the throttle control is moved completely to the right and the tabs are placed in the takeoff position: the longitudinal tab at one division forward, the transverse tab at a half division to the right, the foot tab on zero according to the trim tab position indicators. Having obtained takeoff clearance, it is necessary to look at the ground to the left of the longitudinal axis of the helicopter 20-25° and forward 10-15 m. Unlock the "pitch-throttle" lever and with a smooth upward motion with the simultaneous pushing of the right pedal forward and deflection of the control stick back and to the right produce vertical lift-off at an altitude 2-3 m. At this height establish short-term hovering and balance the helicopter. Then with a smooth motion of the control stick back with a simultaneous insignificant lifting of the "pitch-throttle" lever, transfer the helicopter to acceleration of speed, not allowing much lowering of the nose and descent of the helicopter.

When moving the "pitch-throttle" lever upwards watch that the magnitude of collective pitch does not exceed the value of takeoff conditions – 8.5-9° ($n_{ДВ}$ = 2600 r/min, $p_{К}$ = 1125 mm Hg); otherwise, there can be overloading of the rotor which will decrease the thrust, and the helicopter can descend to landing. The tendency of a right turn, bank and shift to the right should be warded off by motion of the left pedal forward and deflection of the control stick to the left. Upon achieving a speed of 90 km/h, by the control stick it is necessary to put the helicopter in climb, set the speed of 100 km/h and decrease operating conditions of the engine by moving the throttle control to the left and loading the rotor by the "pitch-throttle" lever to normal rating or to another necessary regime for climbing depending upon the conditions.

3. Lift-Off of the Helicopter Vertically with Subsequent Acceleration of Forward Speed in the Zone of Influence of the Air Cushion

This form of vertical takeoff is applied in complicated conditions (high-altitude heliport, high temperature of external air, low atmospheric pressure, absence of wind, with a complicated assignment with respect to loading) when the pilot is not sure of the sufficient reserve of power for takeoff. The reserve of power for such a takeoff should be such that the helicopter stably hovers at an altitude of 1.5-2 m. In order to obtain such a power reserve, the pilot should select the takeoff weight from a nomograph and load the helicopter in accordance with the obtained calculation. Such a takeoff is possible from heliports (permanent or temporary) of the first type, which allow conducting acceleration of forward velocity near the ground in the zone of influence of the air cushion.

Before takeoff it is necessary to determine the magnitude of the maximum permissible flying weight, depending upon the barometric elevation of the heliport, air temperature, speed of headwind and atmospheric humidity from a nomograph, which considers the increase in thrust of the rotor in takeoff conditions owing to the influence of an air cushion (Fig. 65).

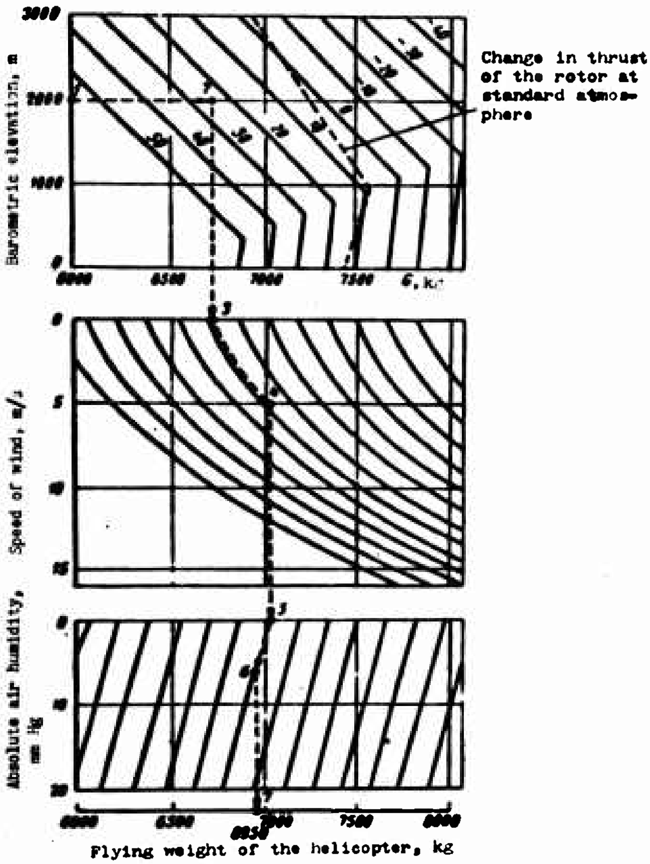

Fig. 65. Nomograph for the determination of maximum weight of the helicopter with blades of the rotor of mixed construction with which vertical takeoff is ensured in the zone of influence of the air cushion with the use of maximum power of the engine.

The nomograph constitutes a graphic change in maximum thrust of the rotor in conditions of hovering, taking into account the influence of the air cushion at an altitude of 1.5-2 m with the operation of the engine in takeoff conditions (and this means at the maximum permissible weight of the helicopter on takeoff). With this the barometric elevation of the heliport from which takeoff is produced, temperature of ambient air, speed of the headwind and absolute atmospheric humidity are taken into account.

The nomograph consists of three graphs. In this case the nomograph for a rotor with blades of mixed construction is examined.

The upper graph shows the change in thrust of the rotor (takeoff weight of the helicopter) under the indicated conditions depending upon barometric elevation of the heliport and temperature of the ambient air. From the curves of this graph one can see the following: the lower the temperature, the greater the rotor creates thrust owing to the increase in mass density, the greater the permissible flying weight for takeoff and conversely. Together with this the change in air temperature for each 10°C changes the thrust and this means flying weight of 160 kg. The broken line on the graph shows the change in thrust of the rotor in takeoff conditions at an altitude of hovering of 1.5-2 m, depending upon the barometric elevation of the heliport under conditions of standard atmosphere.

As can be seen from curves of the upper graph, with an increase in barometric elevation of the heliport the thrust up to a fixed altitude is increased and then decreases, and the lower the air temperature, the increase in thrust occurs up to a high altitude. In exactly the same way the maximum permissible takeoff weight of the helicopter from the barometric elevation of the heliport will be changed. Such an increase in thrust in takeoff conditions of the engine with a rise in altitude is explained by the increase in takeoff power of the engine up to a fixed altitude up to which the boast control [RPD] (РПД) maintains constant takeoff supercharging (for the ASh-82V engine — 1125 mm Hg). With this the power of the engine and thrust of the rotor, and this means the maximum permissible takeoff weight of the helicopter, will be increased. With further climb (with a completely open throttle) the power of the engine, and this means thrust of the rotor, will decrease. This depends on the ambient temperature: the lower the temperature, the greater the throttle will be covered at the same takeoff supercharging (1125 mm Hg), and up to high altitude power of the engine will increase, and this means there will be more thrust of the rotor and permissible takeoff weight of the helicopter.

The middle graph shows the change in thrust of the rotor (takeoff weight of the helicopter), depending upon the magnitude of the headwind during takeoff. The greater the wind, the greater the tractive force owing to the obtaining of oblique airflow of the rotor, in spite of the fact that the wind decreases the effect of the air cushion. From the graph one can determine, for example, that the headwind by a force of 5 m/s increases the thrust by 300 kgf and a wind at 10 m/s — by 800 kgf. When using this graph during calculation of the limiting flying weight, the wind speed must be taken at its minimum value.

The lower graph shows the change in thrust of the rotor depending upon the absolute atmospheric humidity: the more the humidity, the less the thrust because of the decrease in power of the engine. A change in humidity each 10 mm Hg leads to a change in thrust (this means weight of the helicopter) on the average by 100 kgf.

Example. Solve the problem on determination of the maximum permissible weight of a helicopter for vertical takeoff with the use of an air cushion, if at the heliport for vertical takeoff there are the following atmospheric conditions: barometric altitude of the site of takeoff, 2000 m (one can determine it with an altimeter), air temperature, +25°C, wind speed 5 m/s, absolute humidity, 6 mm Hg.

On the first graph one should plot the barometric altitude of 2000 m (point 1). Then from the obtained point one should draw a horizontal line up to the crossing with the curve of temperature 25° (point 2 — in the middle between curves for the temperature of 20° and 30°). Further from point 2 drop a vertical on the middle graph (point 3); from point 3 draw a curve to the intersection with the straight line corresponding to the wind speed of 5 m/s (point 4) in such a manner that it divides the distance between the two neighboring curves accordingly as is divided by point 3; from point 4 drop a vertical on the lower graph (point 5); from point 5 draw a straight line parallel to the nearest slanted line up to the intersection with the horizontal line corresponding to the humidity of

6 mm Hg (point 6); from point 6 drop a vertical on the scale of the helicopter's flying weight (point 7), and at this point to read the maximum permissible flying weight of the helicopter for vertical take-off with the use of an air cushion under given atmospheric conditions (6950 kg).

Consequently, for takeoff by the method shown it is necessary that the helicopter be loaded in such a manner that its flying weight is not more than 6950 kg, and then such takeoff is possible.

Having calculated the maximum permissible flying weight on the nomograph, the pilot should determine the flying weight of a given helicopter. For this it is necessary to know the permanent weight of the given series of the helicopter, which includes the weight of the empty helicopter, crew, oil in the system and service equipment; one should add also the payload, consisting of the weight of fuel and weight of the commercial load, to the fixed weight.

The correctness of the calculation and loading of the helicopter is checked with a check hovering: if the helicopter hovers in takeoff conditions at an altitude of 1.5-2 m, then the calculation and loading have been carried out correctly and it is possible to take off; if the helicopter hovers at lower altitude or does not lift off from the ground, then the calculation of the flying weight or loading have been performed incorrectly. In this case it is necessary to decrease the flying weight, but if this is impossible to do, then it is necessary to take off like an aircraft or to wait for a change in atmospheric conditions or take other measures. Such a check of the flying weight in check hovering is needed not only because during calculation and loading errors can be assumed, but also because for different helicopters the thrust of the rotor in takeoff conditions can not be identical.

If by the nomograph a flying weight of more than 7350 kg is obtained, then it is necessary to load the helicopter in such a manner that its flying weight is not more than the maximum permissible (for the Mi-4, 7350 kg), and the atmospheric conditions are such that it was possible not to calculate the flying weight.

The nomograph shown is of great practical importance and has received wide application in flying practice. It makes it possible to load the helicopter correctly taking into account atmospheric conditions and ensure a sufficient reserve of power for possibility of maneuvering vertically.

The nomograph gives absolute atmospheric humidity (elasticity) expressed in mm Hg. If, however, the pilot has available relative humidity in percent , which is most frequently applied, then it is necessary to use the graph of the conversion of relative humidity to absolute and back (Fig. 66).

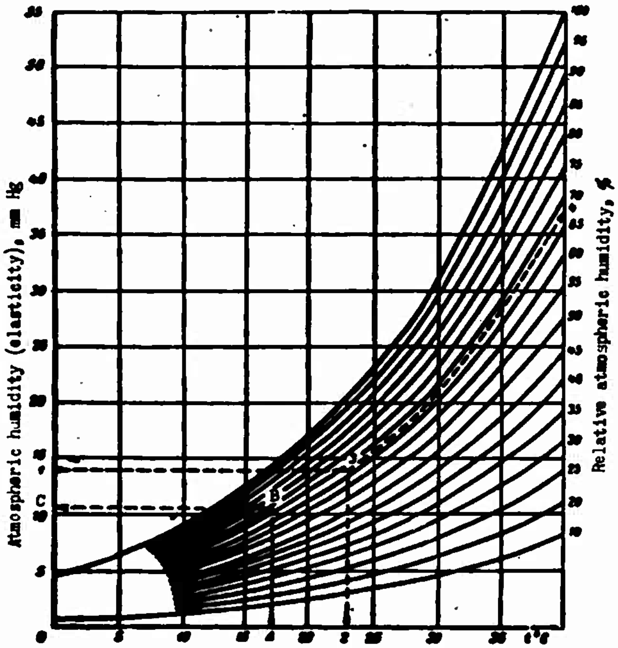

Fig. 66. Graph of the conversion of relative atmospheric humidity to absolute and back.

The graph is constructed on the basis of a table and formula of meteorology.

Two examples of the conversion of relative humidity to absolute and back.

1. The relative atmospheric humidity of 75% at a temperature of 17°C is given; determine the absolute humidity in mm Hg.

From point A which corresponds to temperature 17°C on the axis of temperatures, it is necessary to draw a line parallel to the axis of absolute humidity up to the crossing with the curve corresponding to 75% of the relative humidity (point B). Then from point B it is necessary to drop a perpendicular to the axis of the absolute humidity, and at point C read the absolute value of humidity (10.7 mm Hg).

2. The absolute humidity of 14 mm Hg at a temperature of 23°C is given; determine the relative humidity in percent.

From point 1, corresponding to an absolute humidity of 14 mm Hg, and from point 2, corresponding to a temperature of 23°C, draw two perpendiculars. The perpendiculars crossed at point 3 – in the middle between the two curves of relative humidity of 65% and 70%. From point 3 one should draw a line in the middle of the curves shown, and at point 4 read the relative humidity (67.5%).

The profile of a vertical takeoff with the use of an air cushion for the acceleration of forward velocity is shown in Fig. 67. This takeoff consists of such stages as the preceding: vertical lift-off at an altitude of 1.5-2 m, short-term hovering at this height, acceleration of speed up to 50-60 km/h and transition to ascent.

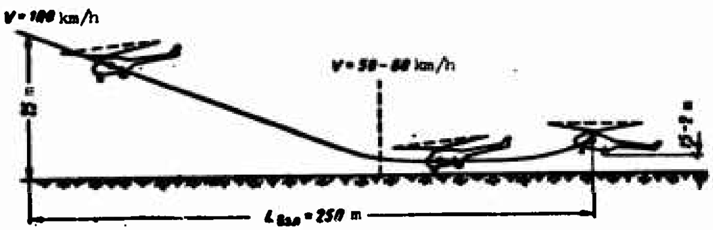

Fig. 67. Profile of takeoff of a helicopter in the zone of influence of an air cushion.

With vertical lift-off the "pitch-throttle" lever must be moved upwards smoothly, since in the opposite case there can be overloading of the rotor. Furthermore, even if there is not overloading of the rotor, then with an energetic lift of the "pitch-throttle" lever it is possible to bring the helicopter beyond the ceiling of hovering, which in this case is very low, and then the helicopter will start to descend and the pilot cannot cope with the control of the helicopter. In this case the acceleration of speed after hovering proceeds with lowering in the zone of the influence of the air cushion, because the helicopter is hovering in takeoff conditions and there is not enough power to prevent such descent.

The acceleration of speed must be conducted carefully, so that the helicopter does not touch its wheels on the ground. At a speed of 50-60 km/h with a smooth deflection of the control stick back, the helicopter is put into a climb. With this in the case of engine failure the helicopter should pass along the safe "corridor," as in the preceding takeoff (see Fig. 64).

In the speed range of 20-40 km/h there will also be felt "shaking conditions" but more intense than during takeoff, shown in Fig. 63, since the helicopter is nearer to the ground in the zone of the greatest influence of the air cushion.

Limitations downwind for the examined form of takeoff are accepted as the same as for the preceding form of takeoff.

<u>The method of fulfillment</u> of vertical takeoff in the zone of influence of the air cushion is the same as the standard vertical takeoff described in § 2. The only difference will be that with the acceleration of speed from hovering it is impossible to use collective pitch for preventing descent, since in hovering the takeoff power is set. The acceleration of speed must be conducted powerfully but not sharply, in order not to allow great descent and contact of the wheels against the ground. Putting the helicopter into a climb must be started from a speed of 50-60 km/h: at this speed owing to the oblique airflow of the rotor much surplus of thrust is obtained, allowing a powerful departure from the ground, and the air cushion at this speed absolutely vanishes.

4. Lift-Off of the Helicopter Vertically at an Altitude of More Than 10 m with Subsequent Acceleration of Forward Velocity Outside the Zone of Influence of the Air Cushion

Theory of takeoff. This form of takeoff is applied also in complicated conditions from heliports of the permanent or temporary second type of small dimensions and limited by obstacles not allowing takeoff by other methods. It is also applied during takeoff with loads on the external suspension, when the length of the suspension is more than 10 m.

Vertical takeoff with the acceleration of forward velocity outside the zone of influence of the air cushion consists of the following stages: vertical lift-off and climb to 10 m higher than obstacles, short-term hovering at this height, acceleration of speed up to the economic speed outside the zone of influence of the air cushion and transition to climb on this speed (Fig. 68).

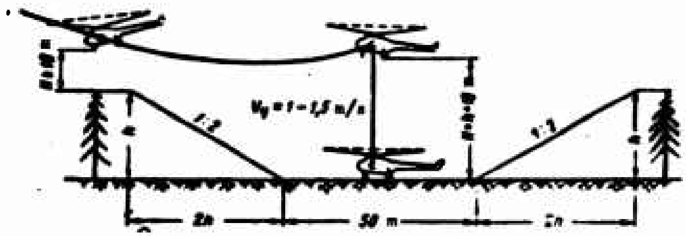

Fig. 68. Profile of vertical takeoff of the helicopter outside the zone of influence of the air cushion.

Vertical climb is conducted carefully at a speed of not more than 1-1.5 m/s up to an altitude of 10 m higher than obstacles. A too powerful climb and with great speed can lead to the helicopter gaining altitude higher than the ceiling of hovering for the given conditions, after which it will start to descend spontaneously. In this case the pilot should cease the increase in collective pitch, and if it proved to be more than that which is required for takeoff conditions, then it is necessary to decrease it, holding the helicopter in a horizontal position. The vertical velocity of descent with the approach to the ground will decrease owing to the influence of the air cushion and the helicopter can hover or land at low vertical velocity.

With this form of takeoff, the vertical climb and acceleration of speed are conducted in the dangerous zone in the case of engine failure (see Fig. 64, zone a). Therefore, such a takeoff is applied only in exceptional cases, when the appropriate necessity requires this.

The maximum permissible flying weight for such a form of takeoff, depending upon atmospheric conditions, is determined on the nomograph, not considering influence of the air cushion (Fig. 69.

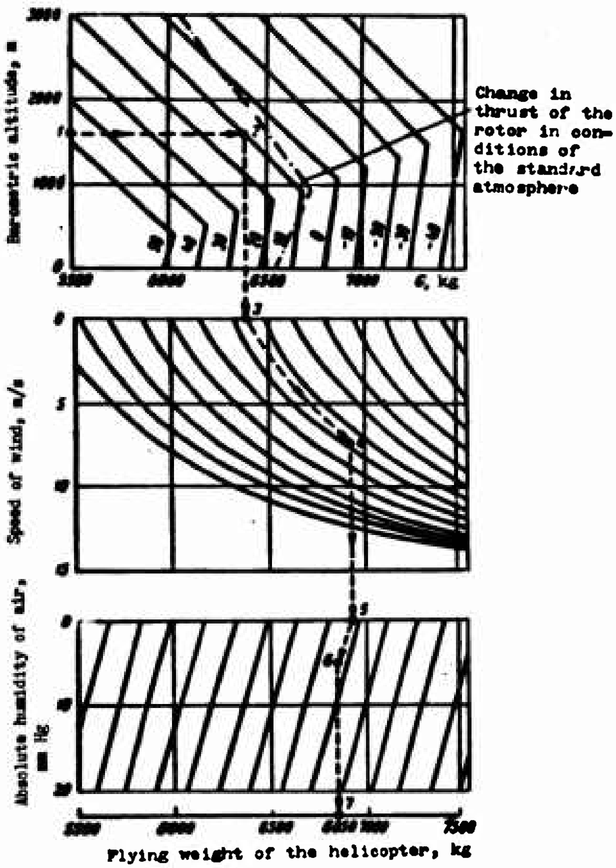

Fig. 69. Nomograph for the determination of maximum flying weight of the Mi-4 helicopter with blades of the rotor of mixed construction with which vertical takeoff and landing with hovering are ensured outside the influence of the air cushion with the use of the maximum power of the engine.

The nomograph is constructed from the same principle as the preceding one; only it reflects the value of maximum thrust in hovering depending upon atmospheric conditions, neglecting the influence of the air cushion. Therefore, thrust of the rotor under those same atmospheric conditions, and this means the permissible flying weight of the helicopter will be less than when taking into account the influence of the air cushion.

The order of determination of the maximum permissible flying weight by this nomograph remains the same as that from the preceding nomograph. An example of the determination of the weight of the helicopter by the nomograph depicted in Fig. 69 is shown by broken lines with arrows and is designated by points 1, 2, 3, 4, 5, 6, 7.

The correctness of the calculation of the weight by the nomograph and loading of it is checked during the actual takeoff: if the helicopter climbs 10 m higher than obstacles, then the calculation and loading are performed correctly. If, however, the helicopter does not gain such an altitude, then the calculation and loading are performed incorrectly, and it is necessary to decrease the flying weight and obtain thereby a sufficient reserve of power for such form of takeoff.

By this nomograph and by the same method the maximum permissible flying weight for the case of vertical landing of the helicopter is determined.

A nomograph for the determination of the maximum permissible flying weight for the Mi-4 helicopter with all-metal blades, taking into account the influence of the air cushion, is given in Fig. 70, and neglecting the influence of the air cushion – in Fig. 71.

As can be seen from these nomographs, the maximum permissible flying weight for this helicopter, owing to the best quality of the rotor under those same atmospheric conditions, is greater.

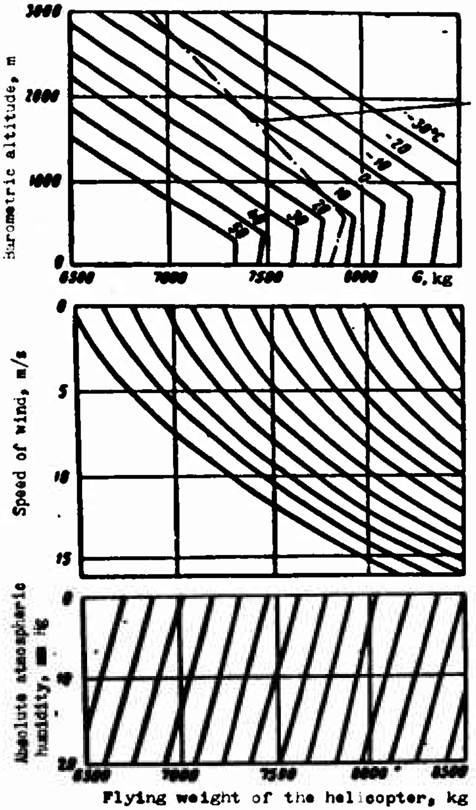

Fig. 70.

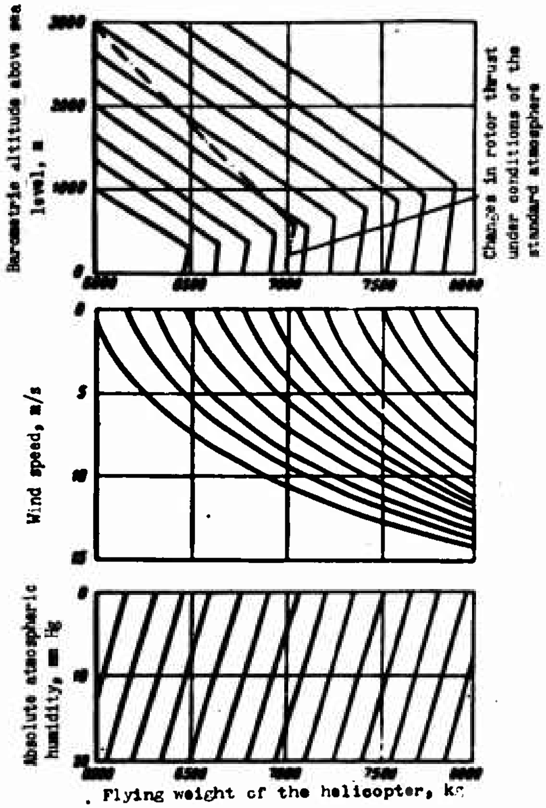

Fig. 71.

Fig. 70. Nomograph for the determination of maximum weight of the Mi-4 helicopter with all-metal blades of the rotor with which vertical takeoff and landing in the zone of influence of the air cushion are ensured with the use of maximum power of the engine.

Fig. 71. Nomograph for the determination of maximum weight of the Mi-4 helicopter with all-metal blades of the rotor with which vertical takeoff and landing with hovering are ensured outside the zone of influence of the air cushion with the use of maximum power of the engine.

Takeoff with loads on the external suspension is more complicated with respect to piloting technique and requires great reserve of power. The maximum permissible flying weight for takeoff with a load on the external suspension is determined by the nomograph, not considering the influence of the air cushion (see Fig. 69), if the altitude of the suspension is 10 and more meters. If, however, hovering with a load occurs with a length of the suspension up to 10 m, then the obtained flying weight from the nomograph must be added to 200-250 kg owing to the influence of the air cushion, but the total flying weight must not exceed 7100 kg.

After hooking up the load it is necessary to conduct check hovering at an altitude at which the load would be 1.5-2 m from the ground. Then the correctness of centering and sufficiency of power reserve are checked, and only after that is the helicopter converted to the acceleration of speed. The acceleration must be produced smoothly by deflection of the control stick forward with a gradual climb.

The wind, especially unstable wind, complicates the piloting technique during takeoff with loads on the external suspension, and therefore such takeoffs are permitted only when the wind is less than 10 m/s.

<u>The method of fulfillment</u> of takeoff with vertical climb 10 m higher than obstacles is the following. In the beginning it is necessary to set the helicopter into the wind as much as possible. Then move the throttle control completely to the right with a smooth but energetic motion of the "pitch-throttle" lever upwards to lift the helicopter off the ground, holding it from turning the right pedal and from moving along the horizontal by deflection of the control stick back and to the right. In hovering one should balance the helicopter and by smooth motion of the "pitch-throttle" lever upwards put the helicopter into vertical climb with a speed of 1-1.5 m/s. After climbing 10 m above obstacles, smoothly deflecting the control stick back it is necessary to convert the helicopter to acceleration of forward velocity. If there is a reserve of power, then the acceleration of speed must be conducted with climb. If, however, there is no reserve of power, the helicopter in the beginning will descend, and with the approach to obstacles it will already have forward velocity, for which there will appear a surplus of power, making it possible to maneuver. With such takeoff collision with

obstacles is excluded in all cases, if the heliport or site from which flight is accomplished, will correspond to technical requirements for heliports of the second class.

5. Takeoff Like an Aircraft

Theory of takeoff. This form of takeoff is applied in cases when there is not enough power for vertical takeoff for the reason of great loading or in adverse weather conditions when the engine power drops (high temperature of the external air, low atmospheric pressure, high atmospheric humidity, calm, high-altitude heliport). Takeoff like an aircraft is also applied for training purposes. Such a takeoff is possible from airfields or heliports of the first type, allowing a takeoff run over the ground and acceleration of speed after lift-off from a great takeoff distance. If the reserve of power is such that the helicopter in takeoff conditions of the engine hovers at an altitude of 1.5 m and below or does not lift off the ground, then it is necessary to take off only like an aircraft.

For an aircraft lift during a run increases from zero in the beginning of the run up to a magnitude equal to the flying weight of the aircraft at the end of the run, where the aircraft lifts off the ground (Fig. 72). The helicopter usually lifts off vertically, i.e., at a lift-off speed equal to zero. But with an increase in forward velocity for the rotor of a helicopter thrust is increased, as was already established earlier. Therefore, if for some reasons the power and thrust are insufficient for vertical takeoff, then the helicopter can accomplish takeoff like an aircraft, making a run over the ground. This occurs because at a certain forward velocity on the run the rotor develops great thrust owing to the oblique airflow, and the helicopter lifts off the ground. But the lift-off speed of an overloaded helicopter will be less than an overloaded aircraft, since the helicopter at a speed equal to zero has a fixed thrust. When standing on the ground the aircraft does not have lift.

The takeoff like an aircraft consists of the following stages: takeoff run over the ground, lift-off, further acceleration in the

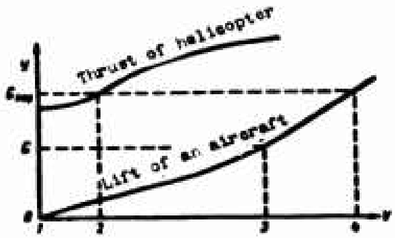

Fig. 72. Change in thrust of the rotor of a helicopter and lift of an aircraft from the speed of flight and speed of their lift-off during takeoff: 1 – lift-off speed of the helicopter; 2 – lift-off speed of an overloaded helicopter; 3 – lift-off speed of an aircraft; 4 – lift-off speed of an overloaded aircraft.

zone of influence of the air cushion up to a speed of 50-60 km/h and transition to climb at this speed with a subsequent increase of it up to the optimum speed of climb (Fig. 73).

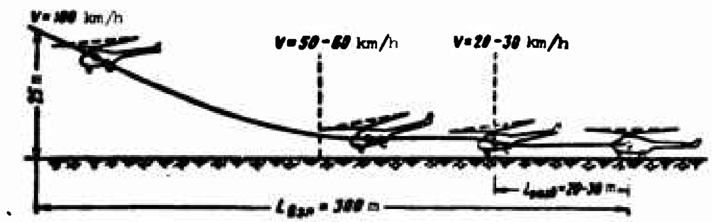

Fig. 73. Profile of the takeoff of a helicopter like an aircraft.

Before the takeoff like an aircraft it is recommended to set the takeoff conditions for the engine, so that during takeoff the pilot is not distracted from piloting for the accurate setting of the supercharging and pitch, since this can lead to error and overloading of the rotor, and the overloading of the rotor can lead to a decrease in thrust and impairment of takeoff properties of the helicopter.

Takeoff power is established in the following way. With a completely depressed throttle control, the "pitch-throttle" lever is raised up to the beginning of the drop in revolutions. If with this the helicopter does not lift off vertically, then at such power it is necessary to start a takeoff run. If, however, with the takeoff power the helicopter hovers at a certain altitude less than 1.5 m, it is necessary to set the power less so that the helicopter is on the ground, and then the helicopter will have a power reserve in pitch and in boost pressure. In this case in the process of the actual takeoff run, this surplus can be used by moving the "pitch-throttle" lever upwards and thereby decreasing the lift-off speed and reducing takeoff distance. But it is necessary to add power carefully in order not to overload the rotor.

With takeoff like an aircraft for training purposes, when the helicopter is not overloaded and takeoff is possible vertically, the power for takeoff is set in the following way. With a completely introduced throttle control to the right by moving the "pitch-throttle" levers upwards, one should lift the helicopter vertically from the ground, note with this the magnitude of collective pitch, and then lower the helicopter to the ground and set the collective pitch at 0.5-1° less as compared to the reading of collective pitch during lift-off. After that, not changing power, by moving the control stick forward transfer the helicopter to the acceleration of speed. With the achievement of a speed of 20-30 km/h, it is necessary to deflect the control stick somewhat back, and thereby unload the front wheels, prevent shuddering of the helicopter, facilitate and to accelerate lift-off owing to the increase in angles of attack of the rotor.

If the Mi-4 helicopter has such power reserve that it in takeoff conditions can hover at an altitude of 1.5 m, then it lifts off at a speed of 20-30 km/h; the takeoff distance will be about 20-30 m. If the reserve of power is less, then the lift-off speed, and the takeoff distance will be greater.

After lift-off it is possible to lift the helicopter from the ground to 1.5-2 m and continue acceleration of speed in the zone of active influence of the air cushion up to a speed of 50-60 km/h. At this speed, by deflection of the control stick back, put the helicopter into a climb. After a climb of 25 m convert the engine to normal rating by moving the control to the left and by loading the rotor in such a manner that supercharging is 970 mm Hg, and the revolutions on the combined indicator are about 2400 r/min.

With such form of takeoff the whole trajectory of takeoff passes along the safe "corridor" (see Fig. 64).

With takeoff like an aircraft the appearance of vibration of the "ground resonance" type is possible, and therefore it is necessary to see to it that the lift-off speed and takeoff distance are as minimum as possible.

The takeoff distance during takeoff like an aircraft on the average is about 300 m.

<u>Method of takeoff like an aircraft</u>. Having obtained takeoff clearance, it is necessary to set the power for takeoff, set the trim tabs in the takeoff position, then by smooth deflection of the control stick forward put the helicopter into a takeoff run; the tendency to turn to the left is warded off by depressing the right pedal. With the approach to lift-off speed, the helicopter will start to jump insignificantly, and therefore at this instant it is necessary with the control stick to help the helicopter be lifted off. At the time of lift-off it is necessary to watch the maintaining of balancing of the helicopter.

After lift-off of the helicopter from land, one should let it climb to 1.5-2 m, and then produce further acceleration of speed at this height in the zone of influence of the air cushion.

After achievement of a speed of 50-60 km/h put the helicopter in a climb, since the air cushion has already vanished, and departure from land is necessary for a more successful landing in the case of engine failure.

Climbing to more than 25 m, it is necessary by moving the throttle control to 2400 r/min and by loading the rotor to set the normal rating of engine operation; the boost pressure should be 970 mm Hg.

6. Flying Limitations During Takeoff

1. The maximum permissible takeoff weight of the Mi-4 helicopter is 7350 kg for takeoff from heliports of the first type. The maximum permissible takeoff weight for takeoffs from heliports of the second type and also during takeoff with loads on the external suspension is 7100 kg.

2. Takeoff is possible with a headwind up to 18 m/s and with loads on the external suspension, up to 10 m/s. With a crosswind up to 90° takeoff is possible with a wind up to 5 m/s and a wind direction of 45-50° – with a wind up to 7 m/s.

3. Takeoff is possible only from airfields, permanent and temporary heliports, and also from sites corresponding to technical requirements for heliports of civil aviation affirmed by the order of the chief of GUGVF No 784 from 20 December 1963.

§ 3. Climb with Forward Velocity

1. General Characteristic

A climb with forward velocity is the basic form of climb by the helicopter and is applied in all cases when conditions permit. Such a climb requires less power as compared to vertical climb, and, consequently, it is more economic. With such a climb, in view of the presence of great surpluses of powers, there is obtained greater load capacity, better stability of the helicopter and greater reserve in the deflection of the control vanes, and therefore in these conditions the piloting technique of the helicopter is easier.

Forward velocity for the helicopter has great importance. Thus, for example, if it is possible to climb vertically up to the ceiling of hovering, then with forward velocity it is possible to climb to the ceiling of the helicopter (dynamic), which for all helicopters, including the Mi-4 helicopter, is many times more than the ceiling of hovering, in spite of the fact that the power of the engine at high altitudes is less than that at the ceiling of hovering.

The optimum rate of climb is the economic speed of horizontal flight of the helicopter, since at this speed there is the maximum surplus of power, and therefore it is possible to reach the maximum vertical velocity of climb.

The optimum indicated rate of climb with a rise in altitude up to the ceiling does not change and for the Mi-4 helicopter is 110 km/h (see Fig. 55d). The true optimum speed with a rise in altitude is increased (see Fig. 55e). For the convenience of piloting, the Manual on Flying Operation of the Mi-4 Helicopter the optimum indicated rate of climb is given at 100 km/h.

The minimum permissible revolutions for the climb regime, just as for horizontal flight, are 200 r/min, which are safe in the case of transition to autorotation of the rotor with engine failure.

2. Forces and Moments Acting on the Helicopter

When climbing with forward velocity, just as in horizontal flight, on the helicopter the following force and moments act: total aerodynamic force of the rotor R, tractive force of the tail rotor $T_{X.B}$, drag of the helicopter Q, weight of the helicopter G, reactive moment of the rotor $M_{p_{H.B}}$, longitudinal, transverse and yawing moments of the tail rotor, longitudinal and lateral moments of the rotor hub owing to the spacing of the flapping hinges, longitudinal moments of the aerodynamic force of the rotor, stabilizer and transverse moment of the lateral force Z_B (Fig. 74).

During climb with forward velocity, just as in horizontal flight, the cone of rotation and direction of action of the aerodynamic force of the rotor are inclined in the direction of flight with the help of the appropriate position of the control stick. Just as in horizontal flight, the aerodynamic force of the rotor R is decomposed in the bound system of coordinates into three components: thrust of the rotor T, longitudinal force Q_B and lateral force Z_B. Thrust of the rotor is directed along the axis of the shaft, longitudinal force — along the plane of rotation in the direct opposite of the flight, and lateral force is directed along the plane of rotation to the right.

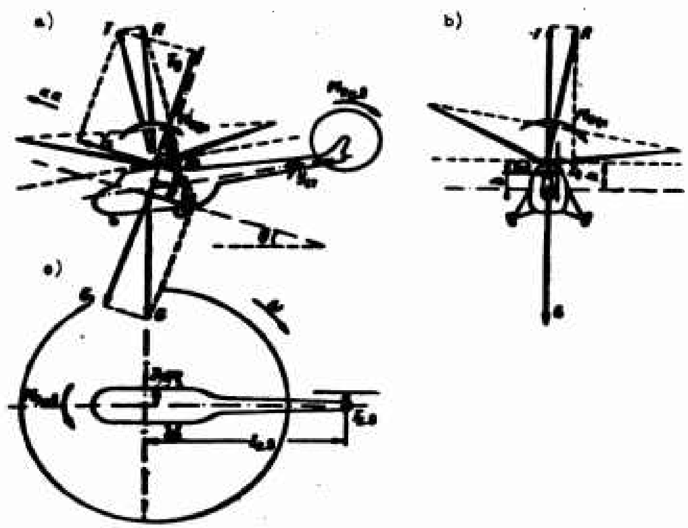

Fig. 74. Diagram of forces acting on the helicopter in a climb with forward velocity: a) view on the left; b) rear view; c) top view.

Thrust of the rotor T is decomposed in the high-speed (continuous) system of coordinates according to the rule of the parallelogram into force T_y, directed perpendicular to the flight path, and T_x – in the direction of the flight. Here force T_y is lift, and T_x – pulling. The longitudinal force Q_B is decomposed in the same system of coordinates into Q_{B_x}, directed along the flight path in the opposite sirection, and Q_{B_y}, directed in the direction of action T_y. Here Q_{B_x} is the drag of the rotor, and Q_{B_y} will supplement the lift T_y.

Thrust of the tail rotor $T_{X.B}$ is directed to the left. Drag of the helicopter Q appears owing to the airflow of the fuselage by basic and induced flow and is directed into the direction opposite the flight.

The force of weight G will be decomposed in a continuous system of coordinates into G_2, acting along the flight path into the cirection opposite the flight, and G_1, directed perpendicular to flight path downwards.

In steady climb with forward velocity the following equilibrium of forces should be observed:

a) for rectilinear climb with the setting angle θ forces T_y and Q_{B_y} should balance part of the weight of the helicopter G_1: $T_y + Q_{в_y} = G_1$;

b) for uniformity of flight the thrust T_x should balance the component of longitudinal force Q_{B_x}, drag of the helicopter Q and component of weight $G_2: T_x = Q_{в_x} + Q + G_2$;

c) for the absence of slip the lateral force should balance the tractive force of the tail rotor $T_{х.в}: Z_в = T_{х.в}$;

d) for holding the direction of the flight the reactive moment of the rotor should be balanced by the yawing moment of the tail rotor: $M_{р_{н.в}} = M_{р_{х.в}} = T_{х.в} l_{х.в}$;

e) for the observance of balancing relative to other axes the sum of all moments with respect to these axes should be equal to zero: $\Sigma M = 0$.

The indicated diagram of forces and moments in Fig. 74 is given for a fixed flight speed.

If the flight passes to another speed, then the diagram of forces and moments, and also the relationship between them, will be the same, but the values of them will be different.

The indicated diagram of forces and moments constitutes an intermediate diagram between diagram of forces and moments in horizontal flight and with vertical climb.

In flight the pilot strives for steady climb with forward velocity of the helicopter and its balancing, and this means the indicated equations by the action of all control levers, following readings of the instruments and position of the helicopter relative to the natural horizon.

3. Vertical Velocity and Time of Climb

Climb is the regime of flight at which power is set greater than that which is required for horizontal flight, and therefore owing to the available surplus of power not only forward flight is accomplished, but also climb with a definite vertical velocity. The magnitude of vertical velocity during climb is determined, just as for aircraft, by the formula

$$V_y = \frac{\Delta N \cdot 75}{G} \text{ [m/s]}. \quad (39)$$

The surplus of power, and this means vertical velocity of climb, will depend on the value of the power set for the engine by the pilot, altitude of flight, atmospheric conditions at the given altitude, speed of forward flight and weight of the helicopter. Atmospheric conditions and flying weight of the helicopter in a given flight and on a given helicopter are constant factors and not dependent on the will of the pilot; their effect on the vertical speed is known and in this case will not be examined. The magnitude of the speed, set power and flight altitude are changed in flight on the desire of the pilot; and therefore the dependence of the vertical speed on these factors is of practical interest.

Let us trace how vertical velocity is changed from every indicated factor separately. With a fixed power of the engine and limiting altitude of flight, the vertical velocity will change from forward velocity of flight in the following way. The maximum vertical velocity will be at the economic forward velocity, since in view of the minimum required power for horizontal flight at this speed there will be maximum surplus of power (Fig. 75). Decreasing or increasing the forward velocity with ascent by deflection of the control stick back or forward, in both cases the vertical climb velocity will decrease because of a decrease in power surplus in both these cases. This is explained by the fact that with economic forward velocity conditions of rotor operation in oblique airflow are the best; the rotor

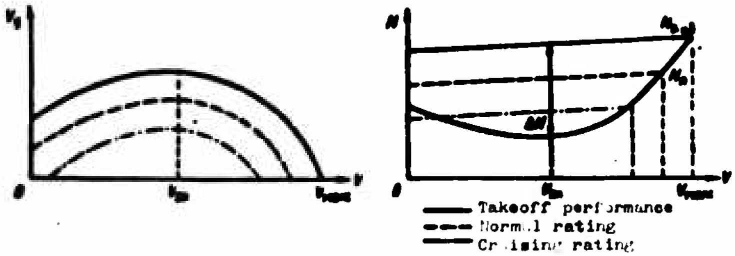

Fig. 75. Dependence of vertical velocity on forward velocity and operating conditions of the engine (altitude and weight are constant).

creates maximum thrust at any installed capacity, and therefore the surplus of power at this speed is maximum. At all other speeds the rotor operates in the worst conditions and the thrust of it less, and therefore the surplus of power and vertical rate of climb decrease (see Fig. 75).

By changing the power to the engine at a definite rate, it is possible thereby to change the vertical velocity in the direction of an increase or decrease, because in these cases various surpluses of powers appear. But at any set power the maximum vertical velocity will remain only at the economic flight speed.

With a rise in altitude the vertical velocity will be changed in connection with the fact that the power of the engine and surplus of power will be changed both due to the change in available power of the rotor and due to the change in required power for horizontal flight. For the Mi-4 helicopter engine ASh-82V is high-altitude, and therefore with the ascent in altitude up to the rated the power in normal rating will be increased, and together with it the vertical climb rate will be increased. Beyond the rated altitude, in view of the decrease in power, vertical climb rate will decrease.

The change in vertical climb rate depending upon the altitude at the optimum speed of climb (100 km/h) and normal rating of operation of the engine in standard atmospheric conditions is shown in Fig. 76. Curve 1 shows the change in vertical velocity from the

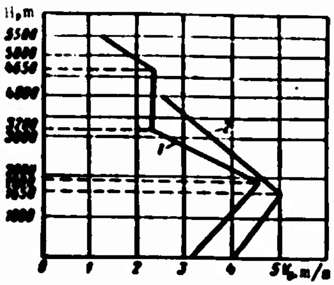

Fig. 76. Change in vertical velocity of the Mi-4 helicopter from the altitude of flight at the optimum speed and normal rating of operation of the engine: 1 – with blades of mixed construction and flying weight of 7150 kg; 2 – with all-metal blades and flying weight of 7350 kg.

altitude of flight with blades of mixed construction and a flying weight of 7150 kg (at the first speed of the supercharger up to an altitude of 3200 m and at the second speed of the supercharger at altitudes higher than 3200 m); curve 2 shows the change in vertical velocity with all-metal blades and a flying weight of 7350 kg. As can be seen from the figure, flying properties of the helicopter in the climb regime with all-metal blades are higher than those with blades of mixed construction.

If one were to change the power from the normal rating or change the speed from the optimum climb rate or change them simultaneously, then in all cases flying properties of the helicopter in the rate of climb will be different from that indicated above.

The absolute ceiling of the Mi-4 helicopter with a normal flying weight is 6500 m, and the service ceiling is 6000 m. The chief designer limits the service ceiling to an altitude of 5500 m and for the passenger version Mi-4P – to 4000 m because of the complication of piloting, necessary high pitch of the rotor and approach to the phenomenon of separation of flow from the blades.

The time of climb to 5500 m for the Mi-4 helicopter with a flying weight of 7150 kg and blades of mixed construction is 33 minutes. The time of climb to any altitude of a helicopter with metallic blades is less than for a helicopter with blades of mixed construction. Thus, in one of the test flights the time of climb to 3000 m of the Mi-4P helicopter with a flying weight of 7350 kh and metallic blades composed 11.3 minutes, which is 2.8 minutes less than that for a helicopter with blades of mixed construction.

4. Peculiarities of Climb and Its Fulfillment

Position of control levers. With a comparison of the rate of climb and horizontal flight with equal speeds, the position of all control levers in climb will be different from their position in horizontal flight. This is explained by the fact that for climb at the same speed higher power will be required, and the change in operating conditions of the engine will lead to the unbalance of the helicopter. Therefore, in order to balance the helicopter in climbing, it is necessary to change the position of all control levers. For example, in horizontal flight at a speed of 100 km/h the control stick is neutrally in a longitudinal and lateral relation, and the pedal also occupies a neutral position. With an increase in operating conditions of the engine for climb the helicopter will try to turn left, and therefore it is necessary to depress the right pedal forward. In view of the increase in thrust of the tail rotor the helicopter will try to slip left, and therefore to prevent slip it is necessary to move the control stick to the right (remove pressure by trim tab) and thereby even the lateral force with the thrust of the tail rotor (see Fig. 74). Consequently, the greater the operating conditions of the engine, the greater the deflection of control levers.

In a steady climb without slip the helicopter will be balanced with a small right bank, just as in horizontal flight, owing to the action of lateral moment of the hub $M_{X_{BT}}$.

The angle of roll will be greater than that in horizontal flight in view of greater assigned power, greater reactive moment of the rotor, and greater required thrust of the tail rotor, and this means greater necessary loading of the cone to the right.

Pitch angle. With a climb at the same speed at which horizontal flight was accomplished, the pitch angle remains practically constant, since its value depends basically on the speed of flight. Therefore, readings of the gyrohorizon in a steady state of climb will be the same as that in horizontal flight.

The change in operating conditions of the engine leads to an insignificant change in pitch angle, but this change can be disregarded.

Ceiling of the helicopter. If with vertical climb it is possible to reach only the ceiling of hovering, then when climbing with forward velocity at the optimum speed of climb it is possible to reach the ceiling of the helicopter (dynamic), which is many times more than the ceiling of hovering. The service ceiling of the Mi-4 helicopter is 6000 m, and it is limited by the chief designer to 5500 m. The increase in ceiling of the helicopter with forward velocity is explained by the improvement of operating conditions of the rotor with oblique flow and increase in its thrust because of this. As a result a surplus of power appears, which is expended in the climb.

Climb with a load on the external suspension. With a load on the external suspension piloting of the helicopter when climbing is complicated in view of the fact that the load sways and the helicopter oscillates around all axes, especially around the lateral and vertical. The greater the dimension of the load, the more complicated the piloting of the helicopter.

Maintaining the desired speed is also hampered, and therefore the pilot must more frequently interfere in the control of the helicopter. Motions by the control levers should be smooth, and the speed of climb should be less than when climbing with a load inside the cabin. An excess in speed leads to a decrease in pitch angle and a tendency of the helicopter to dive.

The vertical velocity in climbing is recommended at not more than 3 m/s: the more the dimension of the load, the less the vertical velocity should be.

The presence of wind even more complicates the piloting, and therefore all flights with loads on the external suspension, including climbing are permitted only at a wind up to 10 m/s and in the absence of bumpy air.

Peculiarities of climb. Climb with forward velocity must be produced at an indicated air speed of 100 km/h in normal rating of the engine. In the case of extreme necessity, climb may be carried out in takeoff conditions with a time of not more than 5 minutes.

In order to maintain normal rating of the engine up to the rated altitude, it is necessary periodically to move the "pitch-throttle" lever upwards for loading the rotor and decreasing the revolutions to 30-50 per minute lower than the nominal. With climb, in view of the decrease in air density, the number of rotor revolutions increase. With this, when the revolutions become higher than nominal by 30-50 per minute, one should repeat loading of the rotor down to revolutions lower than nominal by the same value. With such action by the "pitch-throttle" lever the boost pressure will also be maintained about nominal (970 mm Hg), since with ascent in altitude the pressure decreases.

Beyond the rated altitude the increase in collective pitch will not be required: the power will decrease and the number of revolutions will not increase. In the process of climbing it is necessary to watch that the revolutions are maintained within 2400 r/min.

At an altitude of 3000-3200 m it is necessary to switch to the second speed of the supercharger, for which before switching it is necessary to lower the revolutions by the combined indicator to 2100 r/min. After switching to the second speed of supercharger the boost pressure will be higher than 970 mm Hg, and therefore it is necessary to set the supercharging at 970 mm Hg and again increase the revolutions up to 2400 r/min.

When necessary climb can be carried out in the cruise regime of operation of engine.

Upon achievement of the assigned altitude it is necessary to transfer the helicopter into conditions of horizontal flight. For this one should set the corresponding speed, lower the operating conditions of the engine down to the required, balance the helicopter in new conditions by all control levers, and then remove the pressure from the lever and pedals by the trim tabs.

5. Flying Limitations When Climbing with Forward Velocity

1. The ceiling of the Mi-4 helicopter is limited by the chief designer with a flying weight of 7150 kg to an altitude of 5500 m, with a flying weight of 7350 kg – down to 4200 m, and for the passenger version Mi-4P – down to 4000 m.

2. The rotor revolutions on the combined indicator should be not lower than 2200 r/min in a climb.

CHAPTER VI

DESCENT WITH FORWARD VELOCITY AND LANDING WITH AN OPERATING ENGINE

§ 1. Descent with Forward Velocity

1. General Characteristic of Conditions

Descent with forward velocity with an operating engine is the main form of descent and is applied in all cases when conditions permit. Such descent requires less power as compared to vertical descent, and, consequently, it is more economical. With such descent there can be obtained any low vertical velocity and any small angle of descent, and in this way it will be compared favorably with descent in conditions of autorotation. In descending with forward velocity there is good stability and good reserve in deflection of the control vanes, and therefore under these conditions piloting technique is easier. The rotor operates with oblique airflow, which increases thrust to it at any power. Descent with forward velocity excludes the possibility of the rotor's entrance into conditions of the vortex ring, and in connection with this, such descent is safe.

The minimum permissible revolutions when descending with an operating engine both in horizontal flight and in climb are 2200 r/min. This ensures successful transition of the rotor to conditions of autorotation in the case of engine failure.

2. Forces and Moments Acting on the Helicopter

When descending with forward velocity with an operating engine the following forces act on the helicopter: total aerodynamic force of the rotor R, thrust of the tail rotor $T_{X.B}$, drag of the helicopter Q and force of weight G (Fig. 77).

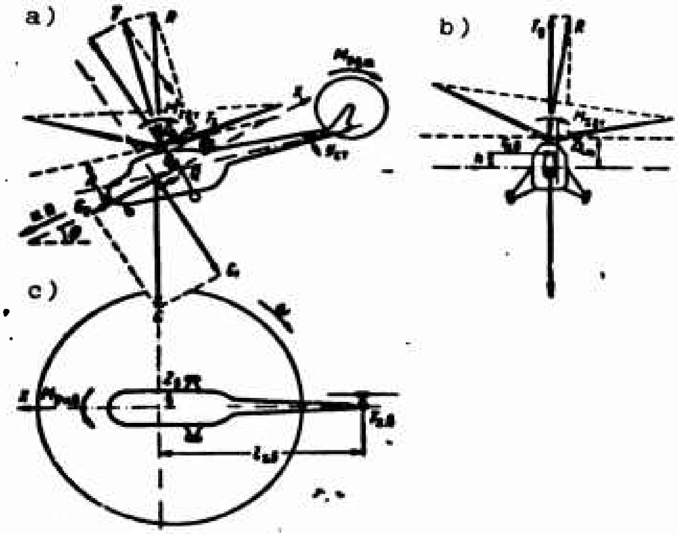

Fig. 77. Forces and moments acting on the helicopter when descending with an operating engine: a) view on the left; b) rear view; c) top view.

The total aerodynamic force of the rotor R acts perpendicular to the base of the cone of rotation of the rotor. The cone of rotation and force R are deflected in the direction of the flight with the help of an appropriate position of the control stick. But owing to flapping motions in forward flight the cone of rotation and force R are deflected from the plane of rotation and from axis of the shaft back and to the right. Force R can be decomposed in a bound system of coordinates into three components: thrust of the rotor T, longitudinal force Q_B and lateral force Z_B. The rotor thrust T is directed along the axis of the shaft, the longitudinal force Q_B – along the plane of rotation in a direction opposite the flight direction and lateral force Z_B – along the plane of rotation to the right.

In the continuous system we decompose the tractive force T into T_y, directed perpendicular to the flight path upwards, and T_x, directed along the flight path in a direction opposite the motion of the helicopter.

Longitudinal force Q_B can also be decomposed in a continuous system of coordinates into Q_{B_y}, directed perpendicular to the flight path downwards, and Q_{B_x}, directed along the flight path in a direction opposite the direction of flight. The direction of the component of longitudinal force Q_{B_y} depends on the angle of attack of the rotor. At a positive angle of attack, as is depicted in Fig. 77, it is directed downwards. At a negative angle of attack, which occurs in a more sloping descent with an operating engine, in horizontal flight and in climb with forward velocity, force Q_{B_y} is directed perpendicular to the flight path upwards. At zero angle of attack of the rotor this force will be absent, since the longitudinal force Q_B will be directed along the plane of rotation coinciding with the flight path and will not be decomposed into the components.

Tractive force of tail rotor $T_{x.B}$, just as in other flights with an operating engine, is directed to the left. Drag of the helicopter Q is directed along the flight path to the side opposite the motion.

The force of weight G can be decomposed in the continuous system of coordinates into G_1 and G_2.

When descending with forward velocity with the engine operating the following moments act on the helicopter:

a) longitudinal – aerodynamic moment from the total aerodynamic force of the rotor, moment of stabilizer, moment from the action of resisting force of the fuselage, reactive moment of the tail rotor and moment of the hub owing to spacing of the flapping hinges;

b) yawing – reactive moment of the rotor and moment of the tail rotor;

c) lateral – moment of the tail rotor, moment of lateral force and moment of the hub owing to the spacing of the flapping hinges.

When descending at steady rate with forward velocity the following equilibrium of forces should be observed:

a) for observance of rectilinear flight and constancy of the angle of descent θ the force T_y should balance the component of weight G_1 and component of longitudinal force Q_{B_y}:

$$T_y = G_1 + Q_{B_y};$$

b) for the uniformity of flight the sum of the component of thrust T_x, component of longitudinal force Q_{B_x} and parasite drag should balance the component of weight G_2: $T_x + Q_{B_x} + Q = G_2$;

c) for flight without slip the lateral force Z_B should balance the thrust of the tail rotor $T_{X.B}$: $Z_B = T_{X.B}$;

d) for maintaining the general equilibrium around all three axes the sum of the moment around these axes should be equal to zero:

$$\Sigma M = 0.$$

In flight the pilot seeks to observe the indicated equations by the appropriate deflection of all control levers and setting of definite operating conditions of the engine, following readings of the instruments and position of the helicopter relative to the natural horizon.

The diagram of forces and moments in Fig. 77 will be correct for all cases of descent with an operating engine with forward velocity, and it is an intermediate diagram between diagrams of forces and moments during horizontal flight and vertical descent. When descending with an operating engine the angles of descent can be of any value from zero degrees – horizontal flight up to 90° – vertical descent.

3. Rates of Descent

Descent with forward velocity with the engine operating is such a regime of flight at which such power to the engine is set where the available power of the rotor is less than the required power for horizontal flight. In connection with this descent of the helicopter with an operating engine is produced with a definite vertical velocity (Fig. 78a, b).

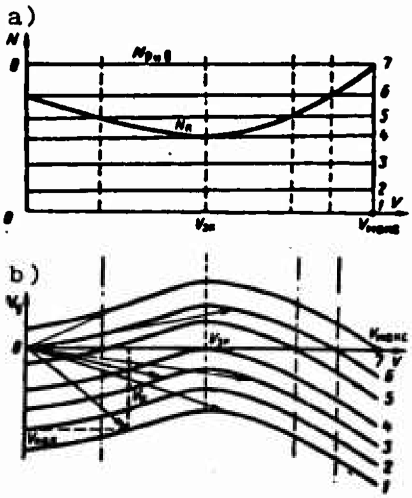

Fig. 78. Flight conditions of the helicopter: a) necessary and available powers for flight; b) change in vertical velocity of descent and climb from the speed of flight and operating conditions of the engine.

The magnitude of vertical velocity when descending with an operating engine depends on the magnitude of set power of the engine, established forward speed, flying weight of the helicopter, atmospheric conditions and altitude. If, however, we examine a given flight on a given helicopter, the weight and atmospheric conditions are constant, and if we disregard the change in speed from the flight altitude, the vertical velocity of descent will depend on and be changed only from the value of set speed and power of the engine, which is of practical interest, since these factors can be changed by the pilot.

At any set power of the engine, the minimum vertical velocity will be at the economic forward velocity, since at this speed the rotor develops maximum thrust, and deficiency of power for horizontal flight is minimum (see Fig. 78). By increasing or decreasing the speed from the economic speed with the help of the control stick, not changing the power of the engine, in both cases the vertical velocity of descent is increased, since conditions of operation of the rotor worsen and it develops with this smaller thrust. Moreover, at high speeds of flight drag of the helicopter is increased sharply.

At any speed of forward flight the vertical velocity can be to change by a change in the power of the engine by the "pitch-throttle" lever.

Figure 78b, with the help of curves, shows all conditions of flight that the helicopter can accomplish. Curve 1 shows the change in vertical velocity from the forward velocity into autorotation of the rotor. Under this condition rates of climb of descent are maximum at all speeds of forward flight, since here power from the rotor is taken completely (Fig. 78a, line 1). If one were to transfer the helicopter from autorotation into powered flight at low power, then at all speeds of forward flight the rates of climb will be less as compared to autorotation (Fig. 78b, curves 2). With a further increase in power the vertical velocity will even more be decreased and at a certain position of the "pitch-throttle" lever it can become equal to zero at the economic speed of flight (Fig. 78a, b, curve 4), i.e., this will already be the regime of horizontal flight. If, however, the power is increased more, then at certain speeds close to the economic the rate of climb will be accomplished, but at low and high speeds there will be descent (Fig. 78a, b, curves 5). If, however, the engine is set at maximum operating conditions, then at all speeds from zero to maximum in horizontal flight there will be climb, and only at speeds less maximum will there be descent (Fig. 78a, b, curves 7).

With the connection of the straight line between the origin of the coordinates and any point on the curves (Fig. 78b) there will be obtained a flight path with a distorted angle to the horizon as compared to the true, since the system of coordinates is constructed in various scales. If, however, one drop perpendiculars to the axis of the coordinates from the end of the velocity vector of the helicopter flight, then it is possible to read on the axes of values of forward and vertical velocities in given conditions of the helicopter flight.

There can be obtained any magnitude of vertical velocity of descent but not more than it will be in autorotation at a given speed of forward flight. At the economic speed of flight (100 km/h) vertical velocity during autorotation for the Mi-4 helicopter (flying weight is 7350 kg in the standard atmosphere above sea level) is on the average 8.5 m/s. With an increase or decrease in forward velocity from the economic, in both cases the vertical velocity will be increased and in vertical autorotation will be about 15 m/s. This means that climb rates when descending with an operating engine can be of any value but less than those shown in conditions of autorotation.

At flight speeds less than 50 km/h, in order that the helicopter does not enter into conditions of the vortex ring, the vertical velocity of descent should be not more than 3 m/s. At high speeds of forward flight the rates of climb can be higher, but the recommended rate is 1.5-2 m/s, especially if there are passengers on board the helicopter.

The magnitude of forward indicated velocity when descending with an operating engine in practice of operation of the Mi-4 helicopter is allowed in a great range over altitudes is:

Altitude, m	Speed, km/h
Higher than 3000	90—100
2000	70—120
1000	80—145
500	80—180

It <u>is prohibited</u> to hold the speed higher than the maximum permissible, especially at altitudes near the ceiling, because there can be cases of the pulling of the helicopter into a dive owing to the shift in the center of pressure of blades back to the trailing edge. The shift in center of pressure back occurs in view of the decrease in angles of attack of the blades, since with descent collective pitch decreases, and to increase the speed the control stick is deflected forward. Both these actions lead to a decrease in angles of attack and then to a shift in the center of pressure of the blade back; in connection with this the blade twists in the decrease of the setting angle, which leads to a decrease in its lift. In this case thrust of the rotor decreases, and the helicopter is pulled into a dive.

The recommended speeds of forward flight when descending with an operating engine (independently of flight altitude) are those at which minimum speeds of vertical descent and minimum angles of lowering are obtained. Such speeds for the Mi-4 helicopter are indicated airspeeds in the range of 100-120 km/h.

4. Peculiarities of Descent and its Fulfillment

<u>Peculiarities of reading the gyrohorizon</u>. At average speeds of flight (conditions of greatest distance) the longitudinal axis of the aircraft lies along the flight path independently of what conditions of flight the aircraft accomplishes, horizontal flight, climb or descent, since the angle of attack of the wing under these conditions and speeds on the average is almost equal to the setting angle of the wing. Therefore, the pitch angle in horizontal flight will be equal to zero, with ascent — positive, and with descent — negative. Consequently, readings of the gyrohorizon will be normal, i.e., in horizontal flight the silhouette of the aircraft will coincide with the fixed index (artificial horizon), and with ascent

it will be above and with descent, lower than the index (Fig. 79). Such phenomena on an aircraft are explained by the fact that thrust of the propeller is applied to the nose of aircraft and therefore in the same direction where the nose will be directed, and flight will approximately be carried out.

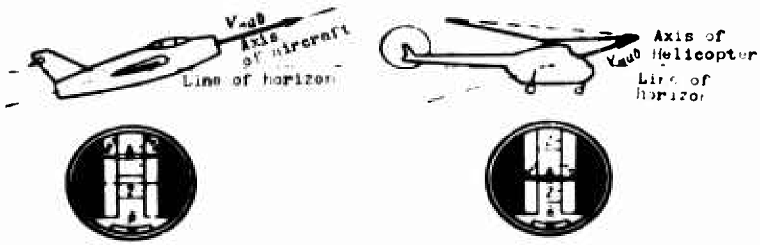

Fig. 79. Readings of the gyrohorizon on an aircraft and a helicopter.

For the helicopter the pitch angle does not depend on what conditions are accomplished, horizontal flight, climb or descent, but only on the speed of flight, since thrust of the rotor is applied to the upper part of the helicopter (rotor hub). And due to the fact that the pitch angle for the helicopter in conditions of hovering is positive, then at average speeds of steady flight it will be equal to zero independently of flight conditions of the helicopter. The angle of pitch only insignificantly changes from the magnitude of the set power to the engine, and therefore this change at present can be disregarded. As a result in all the indicated conditions of flight the silhouette of the aircraft of the gyrohorizon will be combined with the index – the line of the artificial horizon. At speeds less than average in all the indicated conditions of flight, the gyrohorizon will show a climb, and at speeds greater than average – a descent.

Consequently, it is impossible to determine conditions of steady flight by the gyrohorizon, and it is possible to determine only approximately the speed of flight from it: the greater the speed of flight, the less the pitch angle, the lower the aircraft silhouette of the gyrohorizon. The gyrohorizon without delay shows a change in angles of pitch in transient conditions of flight and banks, which facilitates the piloting of the helicopter.

It is necessary to note that the pitch angle of the helicopter, and this means readings of the gyrohorizon, depend not only on the speed of flight but also on the centering of it: the more it is front, the less the pitch angle and conversely.

The position of the control levers when descending with forward velocity and an operating engine will be different as compared to their position in horizontal flight at the same flight speed of the helicopter and all the more so with their position during a climb.

Descent with an operating engine at the recommended speeds is usually conducted with the derived correction and with revolutions of the crankshaft of the engine at 2200 r/min upon setting the necessary vertical rate of descent by the "pitch-throttle" lever. With this the power of the engine is insignificant, the reactive moment of the rotor is small, and therefore thrust to the tail rotor must be decreased by moving the left pedal forward. But since flapping motions of blades are the same as those in horizontal flight at the same speed, then the cone of rotation of the rotor will be deflected to the right by the same magnitude. The lateral force will appear greater than the thrust of the tail rotor, and the helicopter will slip to the right and bank to the right. For this reason the control stick must be deflected to the left of the neutral position which it occupied during horizontal flight at an average flight speed. Then the lateral force will be decreased and brought up to a value equal to the thrust of the tail rotor. The less the power of the engine is set, i.e., the greater the vertical velocity, then it is necessary to deflect all control levers in the direction shown by a great magnitude. With this it is necessary to follow readings of the appropriate instruments and the position of the helicopter relative to the natural horizon.

Consequently, if at some definite speed in horizontal flight for balancing the helicopter in a steady state, the control levers occupy a fixed position, then with descent, inasmuch as the power transmitted to the rotor is decreased by the "pitch-throttle" lever, to balance the helicopter it is necessary to push the left pedal forward and move the control stick to the left. In a longitudinal relation with transition from horizontal flight to descent with an operating engine, it is necessary to deflect the control stick forward to maintain the necessary speed.

To remove the pressure from the control stick and pedals in new flight conditions it is necessary to use the trim tabs.

The angle of attack of the rotor upon descent with forward velocity and an operating engine can be negative if the descent will be sloping, with a small angle, when the flow due to the flight speed will advance on the plane of the rotation of the rotor from above; it can be equal to zero when the flow will approach strictly along the plane of rotation with a steeper descent; but it can be positive with even steeper descent when the flow will approach the plane of rotation of the rotor from beneath (see Fig. 77).

Peculiarities of the fulfillment of descent. Fulfillment of descent with forward velocity and an operating engine consists in the following. For transferring the helicopter from horizontal flight to descent it follows to decrease the pitch to the rotor with the "pitch-throttle" lever up to the obtaining of the desirable rate of vertical descent and simultaneously by the control stick set the necessary speed of forward flight (recommended for all altitudes of 100-120 km/h), and by the throttle maintain 2200 r/min.

In the process of descent it is necessary to observe the temperature rate of the engine and maintain it in the recommended limits by controlling the position of vanes of the outlet of cooled air and vanes of the oil cooler, if the latter do not ensure the needed temperature of the entering oil with the position of them on the "Automatic."

For the transition from conditions of descent with forward velocity and an operating engine to horizontal flight, it is necessary to increase the collective pitch of the rotor and cease the descent, maintaining the assigned altitude; with the throttle control one should maintain the cruising revolutions and with the control stick – set the necessary flight speed.

On single-rotor helicopters, including the Mi-4 helicopter, descent with forward velocity and an operating engine is possible when necessary and by the method of the descending spiral. Descent by the method of slip on single-rotor helicopters is not permitted, since on these helicopters great slip is impermissible in view of the short distance from the center of gravity of the helicopter to the rotor hub along the vertical axis.

5. Flying Limitations when Descending with Forward Velocity

1. When descending with an operating engine forward velocities with respect to altitudes should be maintained for the Mi-4 helicopter in following limits by instrument:

Altitude, m	Speed, km/h
5500—3000	90—100
2000	70—130
1000	80—145
500	50—150

2. At speeds less than 50 km/h the vertical velocity should not be higher than 3 m/s.

3. Rotor revolutions should not be lower than 2200 r/min.

§ 2. Landing

1. General Information

On a single-rotor helicopter two methods of landing are used depending upon the conditions, vertical and like an aircraft. A combined method of landing was proposed, but it did not receive application in view of the complexity of fulfillment and absence of some advantages as compared to the mentioned methods of landing.

Vertical landing for the helicopter is the basic form of landing, even if it is produced on airfields and heliports of the first type, allowing accomplishment of landing like an aircraft. Although such a method of landing is less economic as compared to landing like an aircraft, in view of the ease in technique of its fulfillment, ensuring greater flight safety, it has received wide application.

Landing like an aircraft requires less power, and therefore it can be applied for a helicopter with great flying weight. However, such landing is more complicated in piloting technique, not always ensuring safety, and therefore it requires higher qualification and experience of the pilot. With the accumulation of experience and improvement in flying-technical properties of the helicopter, landing like an aircraft will be applied much wider. Vertical landing should gradually turn into the second plan and will be applied only when it is impossible to accomplish landing like an aircraft.

Landing distances are approximately equal to takeoff distances, and therefore landing is produced on the same airfields, permanent and temporary heliports of the first and second types.

Vertical landing can be accomplished with hovering using the influence of the air cushion, if it is produced at heliports of the first type, and with hovering outside the influence of the air cushion, if it is produced at heliports of the second type, not allowing a rapid approach to land because of presence of obstacles.

2. Vertical Landing with Hovering in the Zone of Influence of the Air Cushion

Theory of landing. This form of landing is applied on airfields or permanent and temporary heliports of the first type with open approaches, which permit approaching land with forward velocity. Such landing is produced in cases when the pilot is sure of the sufficient reserve of power for hovering before landing. If there is no such assurance, then before departing it is necessary to determine the maximum permissible gross weight for such landing by a nomograph neglecting the influence of the air cushion (see Figs. 69 and 71). For such calculation it is necessary to know the atmospheric conditions at the landing site.

Calculation of flying weight for landing must be conducted on the nomograph neglecting the influence of the air cushion. If, however, calculation is made by the nomograph, taking into account its influence (Figs. 65 and 70), then excessive flying weight will be obtained and there is not enough reserve of power for approaching the site at low speed and sufficiently great altitude where the influence of the air cushion still does not appear. To decrease the speed at low altitude so that there is formed the influence of the air cushion is impossible in view of the complexity of piloting.

Calculation of the flying weight by the nomograph, neglecting the influence of the air cushion and loading of the helicopter, according to this calculation completely guarantees the sufficient reserve of power and safety of landing.

Vertical landing with the use of the influence of the air cushion consists of the following stages:

a) decreasing the speed down to hovering, starting from an altitude of 40-50 m, with a simultaneous increase in operating conditions of the engine after achievement of a speed of 50-60 km/h;

b) short-term hovering at an altitude of 2-3 m;

c) vertical landing with a speed of 0.1-0.2 m/s (Fig. 80).

Although this landing is the most simple and safe, its fulfillment has certain peculiarities requiring sufficient practice and attention on the part of the pilot.

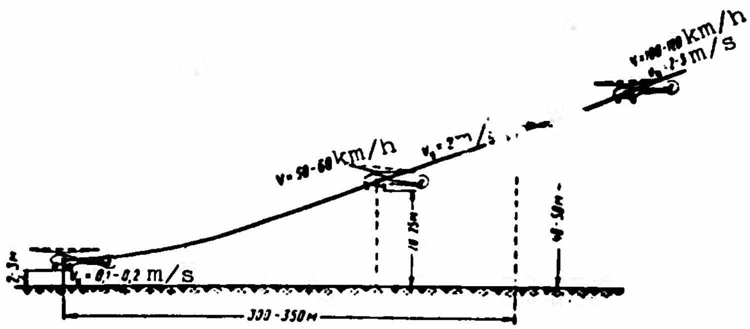

Fig. 80. Profile of vertical landing with hovering in the zone of influence of the air cushion.

1. If when lowering with an operating engine the throttle control is moved to the left, the collective pitch is set to that necessary, the control stick is deflected to the left and the left pedal is forward, then by the moment of hovering it is necessary for a short interval of time to transfer all control levers to the necessary position for conditions of hovering.

Upon achievement of the decreasing speed of 50-60 km/h, it is necessary to increase operating conditions of the engine, starting from moving the throttle control completely to the right with a subsequent increase in collective pitch in order to maintain it, and then decrease the vertical velocity of descent. As a result of the increase in power of the engine the reactive moment will grow, and therefore it is necessary to parry it by moving the right pedal forward, and since the lateral force decreases with the decrease in speed, then it is necessary to increase it by moving the control stick to the right.

2. In the speed range of 40-20 km/h there is observed raised vibration of the helicopter — "shaking conditions," as occurs with acceleration of speed on takeoff in the same speed range. Here the vortex system of the rotor with forward flight is reconstructed into the vortex system in conditions of hovering, but if with the acceleration of speed this vibration could be decreased owing to the increase in the rate of acceleration, then during landing the

rate of decreasing the speed cannot be increased, and therefore "shaking conditions" appear more pronounced in landing.

3. Before hovering it is necessary to deflect the control stick forward at such a moment with such a rate and so much that after hovering the helicopter does not move back, since for decreasing the speed the lever and pull rod of the rotor were deflected back.

The trajectory of the landing is such that it passes through the safe "corridor," just as was done in takeoff (see Fig. 64).

Vertical landing must be carried out upwind. When necessary it is also possible to land with a crosswind up to 5 m/s with the direction of it at 90° to the direction of landing and up to 7 m/s — with a wind direction of 45-50°.

Landing with limiting nose-heaviness of the helicopter must be produced only upwind. Limiting nose-heaviness can be at the end of a flight with an empty helicopter and the remainder of fuel of less than 200 ℓ. To ease the piloting technique during landing the mechanic must go to the end of the cargo compartment.

If landing for some reason is cancelled, then it is possible to depart for a second circle. To depart for a second circle, it is necessary to increase the collective pitch and accelerate the helicopter by the control stick, and then put it into a climb. With departure for a second circle a takeoff distance of 350 m is required (for surmounting obstacles 25 m in height) at a speed of 90-100 km/h and 250 m at a speed of 60 km/h.

If the pilot is not sure of a sufficient power reserve for hovering, and the dimension of the heliport (site) and ground permit a landing run, then it is necessary to land with a run (like an aircraft).

If upon approaching the ground the pilot is convinced that there is not enough power reserve for hovering or landing like an aircraft or departing for a second try is impossible, then as an extreme measure one can land with great pitch of the rotor. The following is the essence of landing with great pitch. The moment of the assigned maximum power is determined by the initial drop in revolutions with full throttle control and the "pitch-throttle" lever moved upwards. Before touchdown and at the moment of touchdown, in spite of the maximum assigned power, further increase in pitch is possible up to a maximum for the short-term increase in rotor thrust by loading it and using the inertia of rotation. The vertical speed is decreased, and the impact of the helicopter against the ground is softened. The drop in revolutions here is not dangerous, since after landing a high number of revolutions is not needed.

Vertical landing with hovering in the zone of influence of the air cushion is the main form of landing and is used at heliports of the first type, which even allow landing like an aircraft, but preference is given to this form of landing because such landing has a number of advantages, although it is less economic as compared to landing like an aircraft. The technique of piloting in vertical landing is simpler than that when landing like an aircraft. In view of the absence of vibration of "ground resonance," such landing is safer.

Method of fulfillment. The approach and calculation for landing is produced by means of constructing a rectangular route or with a straight line if the crew knows the heliport well. It is desirable to make the landing approach upwind. The usual descent is carried out down to an altitude of 40-50 m with a forward speed of 100-120 km/h and vertical speed of 2-3 m/s with such calculation that at this altitude the helicopter would be 300-350 m from the site of touchdown. If this distance is less than 300 m, then before hovering there can be a high vertical speed; but if this distance is more than 350 m, it is possible that the helicopter will be in the 40-30 km/h speed range for a long time, in which the "shaking regime" will appear. Therefore, to carry out landing conditions indicated in Fig. 80 a fourth turn should be made so that after coming out of this turn at an altitude of 100 m the distance from the landing site will be 1100 m, and when emerging at an altitude of 150 m the distance will be 1500 m.

In the stage of descending down to 40-50 m, it is necessary to set the trim tabs at a position corresponding to their position in hovering.

From the altitude of 40-50 m it follows to begin decreasing the speed with such calculation that upon reaching 50-60 km/h the altitude will be 20-25 m. With this it is necessary that the vertical velocity at the indicated altitudes be 2 m/s, for which in the beginning of decreasing the speed it is required to decrease somewhat the collective pitch.

Upon achievement of a speed of 50-60 km/h for decreasing the vertical velocity of descent it follows to start increasing the power of the engine by moving the throttle control completely to the right, further moving the "pitch-throttle" lever upwards, and moving the control stick back to produce a decrease in forward velocity.

Before hovering, to prevent lowering of the tail, the control stick must be deflected forward, thereby giving the helicopter landing position and preventing movement of it back after hovering. Simultaneously with an increase in power of the engine, the helicopter must be balanced in a longitudinal, lateral and yawing position with such calculation that the helicopter hovers at a height of 2-3 m without lateral movements and with maintaining the selected direction.

After balancing in hovering by a smooth movement of the "pitch-throttle" lever downwards, vertical landing is produced at a speed of 0.1-0.2 m/s. Then, being convinced that the helicopter stands on solid ground, lower the "pitch-throttle" lever downwards to the minimum value.

3. Vertical Landing with Hovering Outside the Zone of the Influence of the Air Cushion

Theory of landing. This form of landing is used at heliports of the second type, which have high obstacles on the border and do not allow approaching the ground rapidly and also with loads on the external suspension, when the length of suspension is more than 10 m. Therefore, for such landing it is necessary before departure to determine the maximum permissible flying weight, depending upon atmospheric conditions at the landing site by a nomograph, neglecting the influence of the air cushion (see Figs. 69 and 71), and load the helicopter in such a manner so that its flying weight at the moment of landing is not more than it is by calculation. If during takeoff it was possible to check the correctness of the calculation and loading of the helicopter on the actual takeoff, then during landing such a possibility is excluded. In this case it is necessary to calculate the maximum permissible flying weight and conduct loading more thoroughly, so that there is full confidence in the sufficient power reserve for such a landing.

Vertical landing with hovering without the influence of air cushion consists in the following stages:

a) descent with an operating engine with simultaneous decreasing of the speed and increasing of operating conditions of the engine for the purpose of approaching the center of the heliport;

b) short-term hovering at a height of 3-5 m higher than the obstacles;

c) vertical descent at a speed of 1-1.5 m/s;

d) vertical landing at a speed of 0.1-0.2 m/s (Fig. 81).

With this form of landing decreasing of the speed and vertical descent are conducted in the dangerous zone in the case of engine

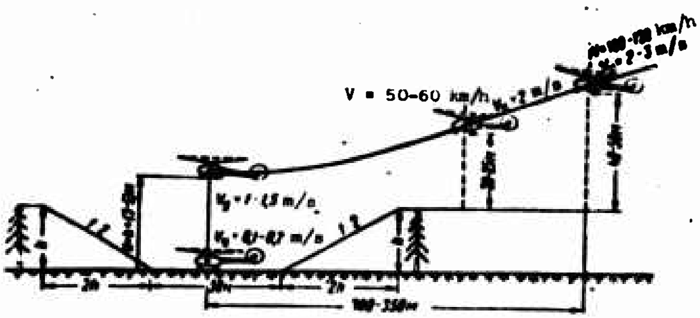

Fig. 81. Profile of vertical landing with hovering outside the zone of influence of the air cushion.

failure (see Fig. 64, zone a). Therefore, such landing is applied only in exceptional cases when this requires the appropriate necessity.

Limitations with respect to wind for such a landing are provided in the same way as those for landing with hovering with the influence of an air cushion.

Method of fulfillment. The method of fulfillment of such a landing prior to the moment of hovering does not differ from the method of vertical landing in the zone of the influence of the air cushion.

It is necessary to produce as far as possible the landing approach upwind and to hold the speed during descent at 100-120 km/h. From a height of 40-50 m one should start decreasing the speed by moving the control stick back with a simultaneous increase in power of the engine; hovering should be at a height of 3-5 m higher than obstacles.

After complete balancing of the helicopter in hovering by smooth movement of the "pitch-throttle" lever downwards, put the helicopter in a vertical lowering with a speed of 1-1.5 m/s. After achievement of a height of 3-5 m from the ground, with a smooth motion of the "pitch-throttle" lever upwards start decreasing the vertical velocity with such calculation that by the instant of touchdown it is equal to 0.1-0.2 m/s.

Being convinced that the helicopter stands on solid ground after landing, with a smooth motion of the "pitch-throttle" lever downwards decrease the collective step to a minimum value.

4. Landing Like an Aircraft

The essence of landing. Landing like an aircraft is applied in cases when there is not enough power for vertical landing because of great loading, or in complicated atmospheric conditions because of the decrease in engine power (high temperature of external air, low atmospheric pressure, high atmospheric humidity, high-altitude heliport). This landing is applied also for training purposes.

Landing like an aircraft can be produced at heliports of the first type, allowing a run along the ground after landing.

This form of landing is validated by the same phenomena for takeoff like an aircraft. If there is not enough power for development of thrust equal to the weight in hovering, then it can be obtained due to forward flight, but in this case landing must be produced with forward velocity.

Descent precedes landing with a forward velocity of 100-120 km/h and vertical rate of 2-3 m/s. More precise definition of the calculation for landing after the fourth turn should be such that at 350-400 m down to the point of landing the helicopter is at a height of 25-30 m (Fig. 82).

The actual landing like an aircraft consists of the following stages: leveling off from a height of 25-30 m, holding off from a height of 3-5 m, landing and landing run.

The stage of leveling off starts from a height of 25-30 m by the control stick and after achievement of a speed of 80 km/h — an

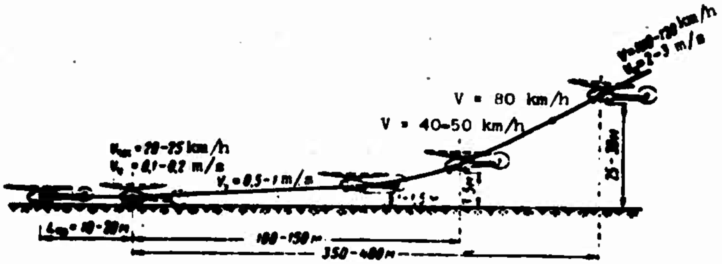

Fig. 82. Profile of landing a helicopter like an aircraft.

increase in power of the engine at first by moving the throttle control and then an increase in collective pitch of the rotor. Here forward and vertical velocity decrease. Leveling off is produced with such rate that after 100-150 m up to the place of landing the height would be 3-5 m, and the speed with this is 40-50 km/h.

Conduct the stage of holding off with a vertical velocity of 0.5-1 m/s, continuing to decrease the speed by the control stick back and gradually increase the power of the engine by moving the "pitch-throttle" lever upwards.

During landing for training purposes the "pitch-throttle" lever is raised with such calculation that at the time of landing at a speed of 20-25 km/h the vertical velocity is 0.1-0.2 m/s. With this the value of the collective pitch will be different depending upon the flying weight and atmospheric conditions.

When landing in industrial conditions, when this landing is produced on an overloaded helicopter for given atmospheric conditions and the power of the engine is insufficient for keeping the helicopter at low speeds, the "pitch-throttle" lever is raised with such calculation that by the instant of touchdown the collective pitch corresponds to takeoff conditions of 8-9°. Here the landing speed and landing run will be variable, and they will depend on the magnitude of the power: the less the reserve of power, the greater the landing speed and landing run. The moment of maximum set power of the engine with a full throttle control is determined according to the value of the collective pitch and beginning of drop in revolutions upon moving the "pitch-throttle" lever upwards.

Before the actual landing and at the time of landing, in spite of the maximum set power, further increase is possible in the collective pitch up to the maximum for the purpose of using the inertia of rotation of the rotor and short-term augmentation of thrust owing to the overloading of the rotor. Here vertical velocity decreases and the impact of the helicopter against the ground is softened. A decrease in the number of revolutions because of loading here is not dangerous, since after landing the revolutions are not needed. Such a landing is called landing on great rotor pitch, it can be used if it were not possible to decrease the vertical velocity down to a minimum at the instant of touchdown.

At the time of short-term holding off before landing it is necessary to move the control stick somewhat forward with such a calculation in order to prevent impact against the ground by the tail support and carry out landing on the main wheels.

When landing like an aircraft for training purposes, in view of the sufficient power reserve of the engine any landing speed and landing run desired can be obtained, but for the Mi-4 helicopter the speed of 20-25 km/h is recommended; here the landing run will be 10-20 m. Such a landing speed and landing run exclude the possibility of the appearance of "ground resonance."

To decrease the possibility of the appearance of "ground resonance" it follows in all cases to try to achieve as low a landing speed as possible, but after landing it is recommended to decrease the collective pitch of the rotor rapidly to a minimum.

Landing like an aircraft is possible with crosswind, but in this case drift is dangerous, since in view of the high location of the center of gravity of the helicopter, tilting is possible. Wind on the right is the most dangerous. In this case for combating drift deflection of the control stick to the right will be required. It is already in the right position. Therefore, at low speeds there cannot be enough reserve of movement of it to eliminate drift.

The trajectory of landing like an aircraft passes through the safe "corridor" in the case of engine failure (see Fig. 64).

Method of fulfillment. Before landing descent is produced with forward velocity of 100-120 km/h and with a vertical rate of 2-3 m/s.. It is necessary to refine the calculation in such a manner that at a distance of 350-400 m to the place of landing the height is 25-30 m. Prior to this height it is necessary to set the trim tabs in a position corresponding to hovering.

From a height of 25-30 m one should start decreasing the forward and vertical velocities at first by the control stick, and upon achievement of a speed of 80 km/h by moving the throttle control and a further increase in the collective pitch. With this the rate of movement of the control stick and "pitch-throttle" lever should be such that at a height of 3-5 m the speed is 40-50 km/h, and vertical velocity is 0.5-1 m/s. A further decrease in speed must be made in such a manner that at the time of landing the forward velocity is 20-25 km/h, and the vertical velocity is 0.1-0.2 m/s.

Before landing it is necessary to deflect the control stick forward and to impart to the helicopter a landing position on the main wheels. After landing one should lower the "pitch-throttle" lever and carry out braking in the second part of run by both the control stick and the brakes.

5. Flying Limitations During Landing

1. Maximum permissible flying weight of the Mi-4 helicopter:

a) for landing on airfields and heliports of the first type — 7350 kg;

b) for landings at heliports of the second class and corresponding to their sites selected from the air, – 7100 kg;

c) for landing with loads on the external suspension – 7100 kg.

2. Landing can be accomplished with a crosswind up to 5 m/s with its direction at 90° to the line of landing and up to 7 m/s with a direction of 45-50°.

3. Landing of a helicopter with limiting nose-heaviness should be accomplished only upwind.

CHAPTER VII

GLIDING AND LANDING IN CONDITIONS OF AUTOROTATION OF THE ROTOR

§ 1. Gliding

1. General Positions and Diagram of Forces and Moments Acting on the Helicopter

The essence of gliding consists in that the potential energy of a helicopter lifted to a definite altitude passes into kinetic energy of a return flight, i.e., to rotation of the rotor and creation of thrust for safe gliding. Therefore, for such gliding it is necessary to design a rotor so that owing to incident flow from below it revolves in the same direction and creates the same thrust as in a flight with an operating engine; otherwise, the potential energy of a lifted helicopter can be turned into energy of the impact against the ground and into its destruction.

With gliding in the regime of autorotation of the rotor the following force and moments act on the helicopter (Fig. 83). The total aerodynamic force of the rotor R together with the cone of rotation, as on any forward flight, is deflected forward by the control stick. Force R is decomposed in the bound system of coordinates into three components: thrust T, longitudinal force Q_B and lateral force Z_B. Here the lateral force acts to the left along the plane of rotation.

In the continuous system of coordinates the thrust T and longitudinal force Q_B are decomposed each separately into two components T_x and T_y; Q_{B_x} and Q_{B_y}. Tractive force of the tail rotor is directed to the right. Drag Q and weight of the helicopter G acts on the helicopter, and the weight is decomposed into two components G_1 and G_2.

The following moments act on the helicopter: longitudinal moment of the aerodynamic force of the rotor, which turns the moment of the rotor, directed to the right, yawing moment of the tail rotor, longitudinal and lateral moments of the hub owing to the spacing of the horizontal hinges, lateral and longitudinal moments of the tail rotor, lateral moment of lateral force and longitudinal moment of the stabilizer.

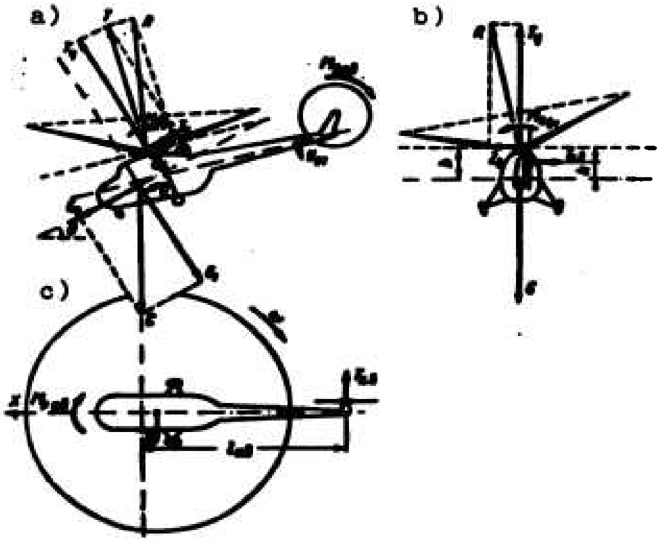

Fig. 83. Diagram of forces and moments acting on the helicopter in autorotation of the rotor: a) view on the left; b) rear view; c) top view.

When gliding in the autorotation regime of the rotor there should be observed following equilibrium of forces:

a) for the observance of rectilinear flight and constancy of gliding angle planning θ, force T_y should balance the component of weight G_1 and component of longitudinal force Q_{B_y}:

$$T_y = G_1 + Q_{B_y};$$

b) for the uniformity of flight the sum of forces of the component of thrust T_x, which consists of the longitudinal force Q_{B_x} and drag of the helicopter Q, should balance the component of weight G_2:

$$T_x + Q_{B_x} + Q = G_2.$$

c) for flight without slip the lateral force Z_B should balance the thrust of the tail rotor: $Z = T_{X.B}$;

d) for the observance of yawing equilibrium the travel turning moment of the rotor should balance the yawing moment of the tail rotor;

$$M_{к.в} = M_{x.в} = T_{x.в} l_{x.в};$$

e) for the observance of longitudinal equilibrium the sum of all longitudinal moments with respect to the lateral axis should be equal to zero: $\Sigma M_z = 0$;

f) for the observance of the lateral equilibrium the sum of all lateral moments around the longitudinal axis should be equal to zero:

$$\Sigma M_x = 0.$$

If we add the total aerodynamic force of the rotor R and drag of the body of the helicopter Q by the rule of the parallelogram, then their resultant will be directed strictly vertically upwards, balancing the total weight of the helicopter G, as occurs with the gliding of an aircraft.

In autorotation of the rotor the pilot seeks the observance of the indicated equations by corresponding deflection of all control levers, following readings of instruments and the position of the helicopter relative to the natural horizon.

2. Property of Autorotation of the Element of the Rotor Blade

In order to establish how the separate element of the blade operates in conditions of autorotation, it is necessary to recall its operation in flight with the engine operating. In any such flight, even with vertical descent, air passes through the rotor down from above owing to induced flow, since the magnitude of this flow in all conditions is greater than the speed of vertical descent. The flow approaching to the rotor, for example, in horizontal flight with a speed of $V_{г.п}$ is decomposed into the part of the flow lying in the plane of rotation, V_1, and into the flow lying perpendicular to the plane rotation, V_2 (Fig. 84a). The flow rate of V_2, together with the induced speed v, is directed through the plane of rotation down from above, and therefore these speeds decrease the angles of attack of the blades, beveling the total flow W downwards (Fig. 84b). The lift of the element of the blade Y is directed perpendicular to the beveled flow W, and therefore the projection of it on the plane of rotation Y_1 will be directed to the side opposite the rotation of the blade, and it will exert drag to the rotation. The projection of drag Q on the plane of rotation Q_1 is also directed opposite the rotation. Consequently, so that blade and rotor will revolve in flight, it is necessary to apply to it torque from the rotor hub, and to the hub from the engine – through the transmission, and then powered flight with any small angle of attack of the rotor will be accomplished.

On conditions of gliding the airflow passes through the rotor from bottom to top, since the induced flow v is less than the speed of flight lying on the axis of the rotor shaft (Fig. 84c). The angle of attack of the rotor A is always positive and large in magnitude. Angles of attack for a separate element of the blade are also large, since the component of flight speed along the axis

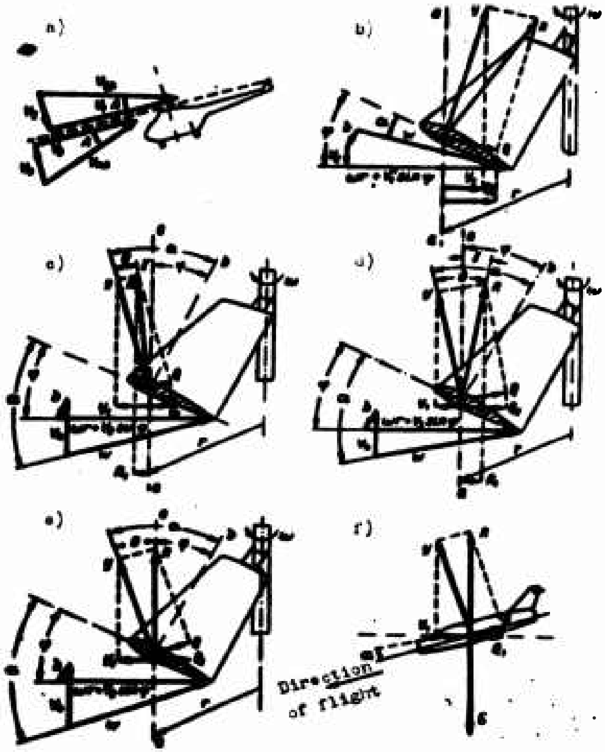

Fig. 84. Properties of autorotation of the element of the rotor blade: a) direction of flow through the rotor during flight with an operating engine and in autorotation; b) speeds and forces acting on the element of the blade during flight with an operating engine; c) case of accelerated autorotation; d) case of delayed autorotation; e) case of steady autorotation; f) case of gliding of an aircraft.

of the shaft V_4 is greater than the induced speed of the given element. An increase in angles of attack α leads to a deflection of the full aerodynamic force of the blade element R forward, which is decomposed into lift Y, acting perpendicular to the true flow rate W, and into drag Q, which acts in parallel to flow W and to the side opposite the rotation. Having projected lift and drag on the plane of rotation, it is possible to see that the projection of lift Y_1, acting along the rotation, is greater than the projection of drag Q_1, acting opposite the rotation. Therefore, the element will obtain accelerated autorotation.

Consequently, so that the element of the blade will have autorotation, for this it is necessary that the total aerodynamic force R of the element of blade be directed from the parallel to the axis of rotation (a-a) forward along the rotation, and then its projection on the plane of rotation R_1 will also be directed along the rotation. Between the setting angle ϕ of the element of the blade, its angle of attack α and angle of quality θ there should be following relationship: $\phi < \alpha - \theta$.

Means, the condition of accelerated autorotation is the indicated inequality, and the greater it is, the better the conditions of autorotation. The indicated inequality is obtained in the following way. In Fig. 84c the setting angle ϕ, angle of attack α and angle of quality θ are transferred to the upper part of the element of the blade, like angles formed by mutually perpendicular sides. To obtain the accelerated autorotation it is necessary that the angle γ between the parallel line to the axis of rotation (a-a) and aerodynamic force R be greater than zero, i.e., so that this force be inclined forward from the parallel to the axis of rotation. Then $\gamma=(\alpha-\theta-\varphi)>0$, and $\alpha-\theta=\varphi+\gamma$ or $\alpha-\theta>\varphi$.

Consequently the less the setting angle (rotor pitch), the greater the angle of attack of the element of the blade and the less the angle of quality, the better the element of the blade passes into autorotation. From this it is seen that for the best transition of the rotor to autorotation, it is necessary to decrease the collective pitch and the blade profile should have great aerodynamic quality [lift-drag ratio] with small angle of quality; this is attained by selection of the profile and setting it during autorotation at the optimum angle of attack.

The relationship of the speeds and indicated angles can be such that the total aerodynamic force of the blade element R can be directed in the opposite direction from the parallel to the axis of rotation of the rotor (Fig. 84d). Then its projection on the plane of rotation R_1 will be directed to the side opposite rotation. The projection of lift Y_1 on the plane of rotation will be less than the projection of drag Q_1, and the element will obtain delayed autorotation. The rotor can cease rotation and will start to rotate in the opposite direction. In this case angle γ is less than zero, i.e., negative, then $\varphi > \alpha - \theta$.

However, there can be selected such conditions (relationships between shown speeds and angles) that force R of the element will be directed strictly in parallel to the axis of rotation of the rotor (Fig. 84e), and then its projection on the plane of rotation will be equal to zero. Projections of lift Y_1 and drag Q_1 on the plane of rotation will be equal to each other, and the element will obtain steady autorotation. In this case the angle γ will be equal to zero:

$$\gamma = (\alpha - \theta - \varphi) = 0, \text{ and } \varphi = \alpha - \theta.$$

For an even better understanding of the essence of autorotation of the blade element, let us compare its operation with the operation of a wing during gliding of an aircraft. It is known that during a steady glide the total aerodynamic force R, directed perpendicular to the horizon upwards acts on the wing of an aircraft (Fig. 84f). Let us decompose force R into lift Y and drag Q and project them on the horizontal plane. We see that projections of their $Y_1 Q_1$ are equal and directed to the opposite sides. This means that the aircraft moves forward in view of the presence of lift formed by the wing. With this the aircraft will not fly horizontally, even more so with lift, but will fly with descent, since besides lift the force of its own weight acts on it.

Further let us imagine mentally that the aircraft is secured behind the right cantilever of the wing hinged tc some body as is done for the rotor: the blade is joined to the rotor shaft through the hub. Then we will obtain the picture depicted in Fig. 84e, i.e., the aircraft will not accomplish rectilinear motion but will revolve around the body, simultaneously descending, as occurs with a separately taken blade. In these cases we will obtain conditions of steady glide of the aircraft and autorotation of the blade element, but these conditions can be both for an aircraft and for an element of the rotor blade with acceleration or deceleration, which is depicted in Fig. 84c, d.

Reserve of autorotation. Angle $\alpha - \theta$ constitutes the reserve of autorotation: the greater this angle, the better the element of the blade passes to autorotation and conversely. But this angle depends on the angle of attack of the blade element of α. On the polar of the given profile it is possible to construct a curve of the dependence of the angle $\alpha - \theta$ on angles of attack of the blade element α; then this will be the graph of the reserve of autorotation of the given profile (Fig. 85).

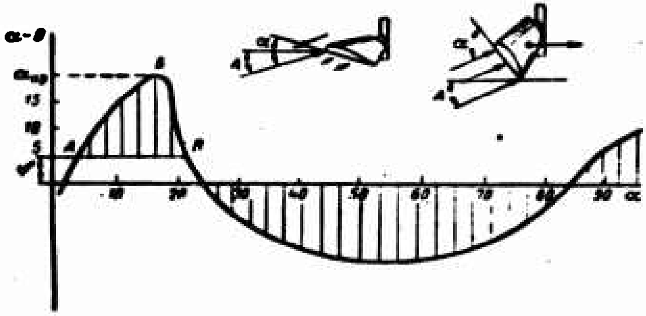

Fig. 85. Graph of the reserve of autorotation of the blade element.

As can be seen from the graph, angle $\alpha - \theta$ is increased up to the critical angle attack, beyond the critical it decreases, and at angles attack from 20° to 80° it takes a negative value. If, however, on the vertical axis of $\alpha - \theta$ we plot the angle corresponding to the angle of blade element ϕ (collective pitch), for example, 5°, and draw a horizontal line intersecting the curve, then we will obtain zones corresponding to the accelerated, steady and delayed autorotation of the blade element. At angles of attack from zero to point A the element will have delayed autorotation, since here the setting angle ϕ is greater than angle $\alpha - \theta (\phi > \alpha - \theta)$. At angles of attack from point A to point B the element will have accelerated autorotation, since here $\alpha - \theta > \phi$. Point A at angles of attack corresponding to points A and B will be steady autorotation, since here $\phi = \alpha - \theta$.

Steady autorotation of the blade element will occur only on the section of angles of attack from point A to point B, at large angles of attack the element will operate under conditions of separation of flow and stable autorotation of it cannot occur. Point A at angles of attack of the blade element with a negative value of the angle $\alpha - \theta$ will be the reverse rotation of the element.

From the graph it is also clear that the smaller the setting angle, then in a large region of angles of attack the element will have accelerated autorotation. Consequently, for the best transition of the whole rotor to autorotation, a decrease in its collective pitch is necessary.

3. Property of Autorotation of the Blade and Rotor

Property of autorotation. Along the length of the blade there are different peripheral velocities, various setting angles owing to the twist and various angles of attack, and therefore separate elements of the blade, depending upon the distance to the axis of rotation, will have unequal properties of autorotation.

Investigations have established that elements of the blade, located from the root to 0.7 of the radius of the rotor, operates in conditions of accelerated autorotation in view of low peripheral velocities. Angles of attack for these elements are large and the inequality $\alpha - \theta > \phi$ is obtained in spite of the fact that the setting angles at these places are larger due to the geometric twist (Fig. 86). Elements of the end part of the blade operate in conditions of delayed autorotation; in view of the high peripheral velocities the angles of attack are small, and even with the smallest pitch of the rotor it is impossible to obtain the inequality

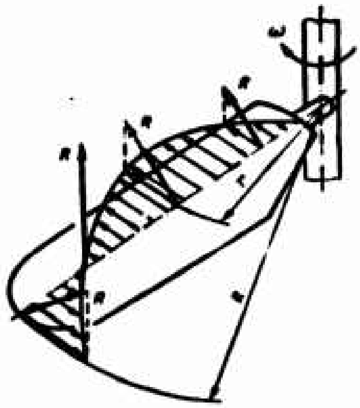

Fig. 86. Properties of autorotation of the rotor blade.

$\alpha - \theta > \phi$ or equality $\alpha - \theta = \phi$, and only the inequality $\phi > \alpha - \theta$ is obtained. Only one element, the transition element, will operate in conditions of steady autorotation (see Fig. 85, point A).

If torques of the root part of the blade, which provide acceleration, are equal to the braking moments of the blade tip, which provided deceleration, then the blade as a whole will obtain steady autorotation; if they are greater than the braking moments, the blade will obtain autorotation, and if the torques are less braking, the blade will obtain delayed autorotation.

It is impossible to consider deceleration of the end part of the blade a negative phenomenon, since if these moments were not present, then it would be impossible to achieve steady autorotation for the blade, which would lead to acceleration, great centrifugal forces and its destruction.

Properties of autorotation of the whole rotor will be composed of properties of autorotation of each separate blade. If torques of all blades are equal to braking moments of ends of the blades, then the rotor will obtain steady autorotation with a constant number of revolutions. If, however, torques are greater than the moments of braking of ends of blades, then the number of revolutions will be increased, and if torques are less than the braking moments, the rotor will decrease the revolutions.

But in autorotation not only one rotor revolves, but the whole transmission and tail rotor, which have friction and drag. To maintain the constant number of revoltuions of the whole transmission, it is necessary that torques of root parts of blades balance the braking moments of end parts of the blades, and also friction in the whole transmission and drag to rotation of the tail rotor.

Revolutions of the rotor in autorotation. From what has been examined it is clear that revolutions of the rotor in autorotation can be controlled by the collective pitch of the rotor. If the collective pitch is decreased, the properties of autorotation of the blades are improved, accelerated autorotation for each blade and rotor as a whole advances, and the number of revolutions of it is increased. With this number of revolutions will not increase infinitely but will be set corresponding to the assigned collective pitch. This occurs for the following reasons: a decrease in pitch leads to an improvement in properties of autorotation of the root part of the blade and an increase in revolutions, but an increase in revolutions leads to an increase in peripheral velocity of ends of the blades, and this in turn – to a decrease in angles of attack. Thereby the large inequality $\phi > \alpha - \theta$ advances, which, by increasing deceleration of the end parts of the blades, ceases a further increase in the revolutions.

With an increase in collective pitch of the rotor there will occur the same phenomena, only in reverse order: properties of autorotation of root parts of blades will worsen, which will lead to a drop in revolutions of the rotor; with this the peripheral velocities of end parts of the blades will decrease, angles of attack will increase, deceleration will decrease and the decrease in revolutions will be ceased, i.e., again the constant number of revolutions of the rotor corresponding to the given pitch, advances.

From this, of course, it does not follow that it is possible to increase the collective pitch of the rotor to any value of it and always with this to obtain a steady number of revolutions. Conversely, it is dangerous to load the rotor, since with this it can cease autorotation.

The optimum (most advantageous) numbers of revolutions of the rotor in autorotation are considered the nominal revolutions of powered flight at which the rotor develops maximum thrust and thereby ensures minimum vertical velocity of descent. This means that in autorotation it is necessary to maintain by collective pitch the nominal number of revolutions (for the Mi-4 helicopter — 2400 r/min on the combined indicator). But it is difficult to hold only these revolutions, since constant attention on the part of the pilot is required. On this basis in practice there is established a rather large range of permissible revolutions in autorotation. Such a range of permissible revolutions for the Mi-4 helicopter are revolutions from cruising to nominal (2200-2400 r/min). Within limits of the indicated range of revolutions the thrust of the rotor remains maximum, and it ensures the minimum vertical velocity of descent depending upon the revolutions.

A decrease in altitude of flight with autorotation and constant pitch leads to a decrease in revolutions of the rotor owing to the increase in air density and in connection with this the increase in drag. Therefore, with the approach to the ground it is necessary to watch the revolutions on the combined indicator, not allowing them to be lower than 2200 r/min, and with a decrease in them lower than this number it is necessary to decrease accordingly the collective pitch of the rotor. Therefore, the lift system should be regulated in such a manner so that near the ground with a completely decreased pitch and with the minimum possible flying weight the rotor in autorotation develops not less than 2200 r/min (according to needle "R"). Then in the whole range of altitudes and for any flying weight the revolutions can be maintained within permissible limits with the help of the "pitch-throttle" lever.

Autorotation of the helicopter. The Mi-4 helicopter well accomplishes vertical autorotation, but with this a high speed of descent is obtained, and the piloting technique is complicated. On this basis vertical autorotation in flight practice is forbidden. However, such autorotation can be needed in the case of engine failure in vertical conditions of flight. Flight in autorotation of the rotor with forward velocity has considerable distinctions from vertical descent.

In forward flight the rotor obtains oblique airflow, which complicates streamline flow and the whole rotor operation. Furthermore, in different aximuthal positions the blades have different properties of autorotation, since speeds of flow, angles of attack and setting angles owing to flapping motions change. But in spite of this, the rotor obtains steady autorotation. With oblique airflow conditions of operation of the rotor are improved, and it develops great thrust, and therefore vertical velocity of descent of the helicopter decreases.

At the economic flight speed the rotor develops maximum thrust, and therefore at this speed the minimum vertical velocity of descent decreases; it is twice less than that in vertical autorotation. Besides that, during flight with forward velocity stability and controllability are improved, which considerably facilitates the piloting technique and ensures complete safety of the flight and landing.

4. Rates of Descent

Forward velocity. On the Mi-4 helicopter any forward velocity in autorotation of the rotor in principle can be allowed in the range of permissible speeds in horizontal flight with respect to altitudes. But for the simplification of the piloting technique and complete safety of flight the following permissible indicated speed range with respect to altitudes is set:

Altitude, m	Speed, km/h
Above 3000	90—100
" 2000	70—120
" 1000	60—140
" 500	50—150

The permissible safe speed range is necessary in the case of correction of the calculation for landing in autorotation of the rotor. An indicated forward velocity irrespective of altitude is recommended at 100 km/h. At this speed the minimum vertical velocity of descent is obtained.

Vertical rate of descent. The magnitude of vertical velocity when gliding in autorotation of the rotor has a high value, since this is connected with the safety of landing in this regime of flight during engine failure or for other reasons. The magnitude of vertical velocity depends on the flying weight of the helicopter (specific load), flight-path speed, collective pitch of the rotor (number of revolutions), altitude of flight and atmospheric conditions.

With a decrease in the altitude of flight the vertical rate of descent, other conditions being equal, decreases in view of the increase in air density.

An increase in air temperature and decrease in its pressure lead to a decrease in mass density, and therefore the vertical velocity, other conditions being equal, is increased and conversely: with a decrease in temperature and increase in pressure the vertical velocity decreases.

An increase in flying weight, other conditions being equal, leads to an increase in the vertical rate of descent.

If we examine a concrete flight of a given helicopter and in given time, its flying weight and atmospheric conditions do not change, and then the vertical velocity will change only because of a change in forward velocity, the number of revolutions and altitude of the flight. If, however, the revolutions are taken as the optimum at which the vertical velocity from revolutions is minimum, and the change in vertical velocity from the altitude of flight is disregarded in view of its insignificant decrease with a decrease in altitude of the flight, then the vertical velocity will be changed only from the speed of the flight path, which is expedient to examine in connection with the great practical importance of this problem.

The greatest vertical rate of descent will be during vertical autorotation and can be determined in the standard atmosphere at sea level by the formula

$$V_y = 4\sqrt{p}\ [\text{m/s}], \tag{40}$$

where p — specific load on the disk surface.

The minimum rate of descent can occur during forward flight and is determined for the same conditions by the formula

$$V_y = 1{,}4\sqrt{p}\ [\text{m/s}]. \tag{41}$$

To determine the vertical rate of descent in conditions of autorotation at any forward velocity the following formula can be applied:

$$V_y = \frac{75 \cdot N_{r.a}}{G}\ [\text{m/s}]^1. \tag{42}$$

In the aerodynamic design of the Mi-4 helicopter the vertical velocity in autorotation with a collective pitch of 5° is determined by the formula

$$V_y = V_{\text{m}} \sin\theta, \tag{43}$$

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[1]With gliding the action of the force of weight of the helicopter per second (power) $\frac{GV_y}{75}$ is equal to the required power for flight of the helicopter $N_{r.n}$. Solving this equation with respect to V_y, we will obtain formula (42).

where θ — gliding angle.

According to the given formulas, and also as a result of flight tests, it has been established that the minimum vertical velocity, just as when descending with an operating engine, will occur at the economic forward velocity, since the rotor at this speed has the best conditions of operation and develops maximum thrust with other conditions being equal. For the Mi-4 helicopter with a flying weight of 7350 kg in standard atmospheric conditions at sea level, the minimum vertical velocity with a forward indicated velocity of 100 km/h will be 8.5 m/s.

By increasing or decreasing the forward velocity form the economic, in both cases the vertical velocity is increased in view of the impairment of conditions of operation of the rotor and decrease in its thrust. Thus, at a speed of 140 and 60 km/h the vertical rate of descent will be 12 m/s and during vertical autorotation — about 16 m/s. For a helicopter with all-metal blades the vertical rate of descent at all forward velocities is less than that for a helicopter with blades of mixed construction in view of the higher dynamic properties of this rotor.

Figure 87 shows curves of the change in vertical rate of descent in autorotation of the rotor during gliding of the Mi-4 helicopter obtained in one of the test flights.

Consequently, in order to obtain the minimum vertical rate of descent, it is necessary in autorotation to hold the flight-path speed at the economic — for the Mi-4 helicopter it is 100-110 km/h and the optimum number of revolutions is 2200-2400 r/min.

5. Gliding Angle and Distance of Gliding

In contrast to an aircraft the range of permissible angles of gliding for the helicopter is rather large — from minimum to 90°. Large gliding angles at low speeds make it possible to surmount obstacles on borders of sites where forced landing should be

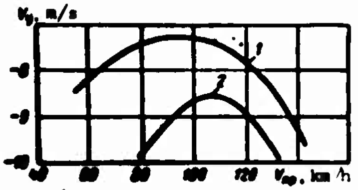

Fig. 87.

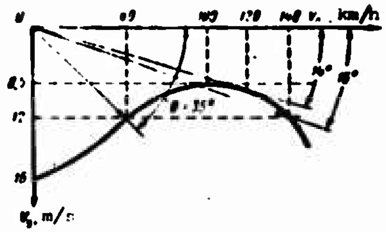

Fig. 88.

Fig. 87. Vertical rate of descent in autorotation of the rotor: 1 – with all-metal blades at an altitude of 1000 m when t = -7°C, $G_{пол}$ = 7125 kg and $n_{дв}$ = 2200 r/min; 2 – with blades of mixed construction at an altitude of 1100 m at t = 10°C, $G_{пол}$ = 7200 kg and $n_{дв}$ = 2200 r/min.

Fig. 88. Change in angles of gliding and rate of vertical descent in autorotation of the rotor with a flying weight of the helicopter of 7350 kg.

performed. Small gliding angles give accordingly great distance of gliding and the possibility of selecting a good site for landing.

The gliding angle can be determined by the formula

$$\theta = 57{,}3\frac{V_y}{V_{na}}\ ^{1}. \qquad (44)$$

The minimum gliding angle, and this means maximum range of gliding, will be at the optimum speed of horizontal flight (gliding). It has been established by flight tests that the minimum gliding angle for the Mi-4 helicopter with a flying weight of 7350 kg will be at an indicated forward velocity of 120 km/h and will be 14° (Fig. 88). By decreasing or increasing the forward velocity, the gliding angle in both cases will be increased. At a speed of 60 km/h it will be 35°, and at a speed of 140 km/h – 16°.

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[1] $\frac{V_y}{V_{na}} = \sin\theta$, but since θ is small, then $\frac{V_y}{V_{na}} = \operatorname{tg}\theta$, and the tangent of small angles is equal to the actual angle expressed in radians, and therefore the gliding angle in degrees is expressed by formula (44).

At a speed of 120 km/h there can be obtained the maximum range of gliding

$$L_{\text{пл}_{\text{макс}}} = H \operatorname{ctg} \theta_{\text{пл}_{\text{мин}}}, \tag{45}$$

where H is the altitude from which gliding starts.

Substituting the value of the minimum gliding angle, we will obtain the maximum range of gliding for the Mi-4 helicopter: $L_{\text{пл}_{\text{макс}}} = H \cdot \operatorname{ctg} 14° = H \cdot 4{,}011$, i.e., the maximum range of gliding higher than the altitude of flight by four times. According to these data it is possible to judge approximately the lift-drag ratio of the helicopter. As can be seen from the given example, the maximum ratio for the Mi-4 helicopter on the average will be equal to 4. Because of the small lift-drag ratio of the helicopter, its gliding properties are low.

Being guided by the magnitude of velocity of gliding at which the gliding angle is minimum and the distance is maximum, it is possible to judge the method of refinement of the calculation on forced landing when gliding in autorotation of the rotor. If the speed of gliding is less than 120 km/h, then with an undershot to the landing site it is necessary to increase the speed but not more than 120 km/h. Then the gliding angle will decrease, and distance will be increased; in an overshot it is necessary to decrease the speed, thereby reducing the distance of gliding.

6. Processes Occurring During the Transition of the Helicopter from Powered Flight to Gliding During Engine Failure [Throttle Down]

The gliding of a helicopter without the engine operating is not an emergency flight, but a standard strictly calculated and safe flight, just as the gliding of an aircraft. This form of flight is applied not only when the engine fails but also in other cases: for urgent descent, for training purposes, during all forms of abnormal behavior of the helicopter and malfunctionings appearing in flight.

Processes occurring during engine failure or intentional throttling down for the purpose of the transition to gliding are absolutely analogous. Let us imagine that during some flight the engine failed, or the pilot throttled down. Then this will lead in the first place to a decrease in the number of rotor revolutions and to a decrease in its thrust, and the helicopter will acquire vertical velocity to descend. Descending will lead to an increase in angles of attack of the rotor and angles of attack each separate blade, which will promote transition to autorotation of the rotor. A decrease in revolutions of the rotor immediately after turning off the engine will lead to a decrease in centrifugal forces of the blades. The angle of conicity will be increased, and the flapping controls will automatically decrease the setting angles for all blades by the same value, i.e., will automatically decrease the collective rotor pitch (not through the automatic pitch-control mechanism, but through the flapping control). A decrease in setting angles, as established earlier, will also lead to an improvement in properties of autorotation of every blade and the rotor on the whole.

Furthermore, the pilot decreases the collective rotor pitch as during engine failure just as with intentional transition to autorotation. A decrease in collective pitch through the automatic pitch-control mechanism even more promotes transition of the rotor to autorotation. Therefore it is recommended, especially during engine failure, independently of flight altitude, to decrease immediately collective pitch for 1-2 s down to the minimum, and only then set the necessary revolutions by the corresponding position of the "pitch-throttle" lever. The greater the altitude of flight, even greater should be the collective pitch, and with descent it must be periodically reduced for maintaining revolutions within the optimum, since owing to the increase in air density with descent the revolutions at constant pitch will decrease.

With the action by the collective pitch lever the stabilizer operates, since control of it is interlocked with the control of the collective pitch. Therefore, when lowering the "pitch-throttle" lever downwards the adjusting angle of the stabilizer will decrease, and when lifting it – the angle is increased. Consequently, when lowering the "pitch-throttle" lever the stabilizer will create great positive pitching moment, which will begin to prevent the pulling of the helicopter into a dive, observable in autorotation.

The pitching created by the stabilizer will lead to an increase in angles attack of the rotor and blades, and this also will promote the best transition of the rotor in autorotation.

After engine failure (throttle down) in view of the disappearance of active torque, the reactive moment also vanishes and the helicopter tries to turn right both because of the remaining yawing moment of the tail rotor and due to the turning moment of the rotor (friction in the transmission and drag of the tail rotor). To prevent such a turn the pilot should depress the left pedal forward and thereby shift the pitch of the tail rotor to negative and create thrust in the opposite direction (to the right). The yawing moment of the tail rotor will act to the left and will balance the moment of the rotor. However, flapping motions and deflection of the cone of rotation of the rotor will remain the former, and therefore the lateral force Z_B will be directed to the right and together with thrust of the tail rotor will create to the helicopter a right slip and bank. The pilot will have to shift the control stick to the left, thereby deflecting the cone of rotation and directing the lateral force to the left. Then this force will balance the thrust of the tail rotor, and the helicopter will accomplish gliding without bank and slip (see Fig. 83).

For transition from powered flight at a speed of 100 km/h to a steady glide for the Mi-4 helicopter about 8-10 s is required. During that time an altitude of about 80 m is lost.

7. Peculiarities of Gliding and Its Fulfillment

Before transferring the helicopter to the regime of autorotation of the rotor, it is necessary to set the indicated speed at 100-120 km/h, decrease the collective pitch to a value corresponding to the steady state of autorotation at the given altitude, and throttle down to the divergence of needles of the combined indicator at 100-200 r/min. Revolutions of the rotor should be maintained by the "pitch-throttle" lever within 2200-2400 r/min (by the needle "R"), and engine revolutions should be less than rotor revolutions by 100-200 r/min (by the needle "M"). The higher the altitude of flight, an even greater pitch is necessary for retaining the optimum revolutions. The approximate value of collective pitch with respect to the altitudes will be the following: at altitudes over 3000 m – 6°, at the altitude of 2000 m – 5°, at the altitude of 1000 m – 4°, and at altitudes lower than 500 m – 3°. But it is necessary certainly to be guided by the numbers of rotor revolutions. If the revolutions are low, it is necessary to decrease the collective ptich, and if they are high – increase the collective pitch. With such action by the "pitch-throttle" lever, revolutions of crankshaft of the engine will be changed. Therefore, in order to prevent convergence of needles of the tachometer and thereby avoiding sharp blows in the transmission with an increase in pitch, it is necessary to move the throttle control to the left.

During gliding the control levers will occupy the following position. By the "pitch-throttle" lever the collective pitch necessary for maintaining optimum revolution is set. The throttle control occupies such a position at which the needles of the tachometer are separated by 100-200 r/min. The left pedal is moved forward for preventing in autorotation a turn of the helicopter to the right because of friction of the transmission and drag of the tail rotor. The control stick is deflected to the left in order to balance the thrust of the tail rotor directed to the right (flight occurs without bank and slip). In a longitudinal relation the control stick occupies a position necessary for retention of the assigned speed, but as compared to a flight with an operating engine at the same speed its position will be somewhat deflected back (in gliding the helicopter has a tendency to dive).

Pressures appearing on the lever and pedals are removed by the "trim tabs."

Gliding turns are allowed with a bank of not more than 20°, since there cannot be enough reserve of deflection of the control vanes for creation of the correct turn.

Transition to powered flight is produced by a smooth reduction of the tachometer indicators by the throttle control with subsequent increase in power by the "pitch-throttle" lever. Then it is necessary to balance the helicopter by all control levers for such a flight.

There can be cases when with the reduction of the tachometer indicator the tachometer indicator of the crankshaft of the engine (M) will exceed readings of revolutions of the rotor (R). This will indicate the fact that the freewheeling clutch did not connect the transmission with the engine. In such case it is necessary to make one more attempt of transition to powered flight by smooth repeated matching of the tachometer indicators with the help of the throttle control. If such an attempt will not connect the transmission with the engine, it is necessary to land in autorotation of the rotor, preliminarily turning off the ignition.

With engine failure it is necessary with an energetic motion of the "pitch-throttle" lever downwards to decrease the collective pitch down to that necessary for autorotation at a given altitude. Simultaneously with this, depress the left pedal forward and control stick to the left, and then balance helicopter. If the speed of flight is great, it is necessary by deflection of the control stick to decrease it down to 100 km/h; remove pressure from the control stick and pedals by the trim tabs. Rotor revolutions must be maintained not lower than 2200 r/min. After that turn off the ignition of the engine. Hold the speed of 100 km/h down to an altitude of 100-150 m. At this height decrease the forward velocity down to 70-80 km/h and be prepared to land in autorotation.

8. Flying Limitations for the Mi-4 Helicopter in Autorotation

1. Maintain forward velocity depending upon the altitude on the Mi-4 helicopter in the following limits:

Altitude, m	Speed, km/h
Above 3000	90—100
2000	70—130
1000	60—140
500	50—150

2. Hold the rotor revolutions in the range of 2200-2400 r/min (by the needle "R").

3. Make turns with a bank of not more than 20°.

§ 2. Landing

1. General Positions

Landing in autorotation of the rotor is applied during engine failure, breakdown of the transmission, failure of the tail rotor, fire in the engine section and for training purposes.

When gliding with a forward velocity the helicopter possesses a reserve of energy of motion of the helicopter and rotation of the rotor. The physical meaning of landing of the helicopter in autorotation of the rotor is that the energy of motion of the helicopter and rotation of the rotor are used by the pilot with action by control levers for decreasing the forward velocity and rate of vertical descent down to a minimum at the time of the landing.

If, however, the "pitch-throttle" lever is energetically moved upwards, then move energetically the control stick of the rotor back and then angles of attack of the rotor and each blade separately are increased, conditions of their autorotation will be improved, the number of rotor revolutions will increase, as well as the thrust, and the helicopter will decrease both the forward velocity and vertical rate of descent. With this energy of the motion of the helicopter is used.

If during gliding in autorotation the nonincrease of the collective pitch at high revolutions will lead to a short-term augmentation of thrust of the rotor, as a result of which the vertical rate of descent will decrease. Here energy of rotation of the rotor is used.

Revolutions of the rotor will decrease and, if such loading of the rotor is produced far from the ground, then after a short-term decrease in vertical velocity it will increase, and the rotor will cease rotation.

The problem of landing of the helicopter in autorotation of the rotor is that it is necessary to activate the control levers so that forward and vertical velocity are minimum only prior to the instant of touchdown. A low forward velocity gives a short run after landing, and a low vertical velocity ensures smooth landing without damage to the helicopter.

Depending upon what kind of energy is used for landing, it is possible to present for a single-rotor helicopter three methods of landing in autorotation. If only the energy of motion of the helicopter is used, then such landing is called "aircraft" and is fulfilled as the landing of an aircraft only by control stick. If only the energy of rotation of the rotor is used, then such a landing is called "with application of the collective pitch" and is fulfilled only by the "pitch-throttle" lever. If, however, for landing both energies of motion and rotation are used, then such a landing is called "combined" and is fulfilled by both control levers.

With this in all cases for holding the direction the pedals are used.

For a concrete helicopter depending upon its peculiarities, there is developed a special method of carrying out every form of landing. Selection of the method of landing depends on the character of the failure of the equipment of the helicopter and on peculiarities of the site where the landing should be performed, which is decided by the pilot in concretely forming conditions.

2. Landing Like an Aircraft

<u>Theory of landing</u>. This form of landing is applied only when for some reason it is impossible to use the "pitch-throttle" lever for landing. When landing like an aircraft only kinetic energy of the motion of the helicopter is used, and it is fulfilled, as the landing of the helicopter, only by the control lever. Since with this form of landing only the energy of motion is used, then it is desirable in gliding before the landing to hold a high speed (for the Mi-4 helicopter not less than 100 km/h).

This form of landing consists in the following stages: approach to land, leveling off, short-term holding off, landing on the main wheels and a run with shift of the helicopter to the front wheels (Fig. 89).

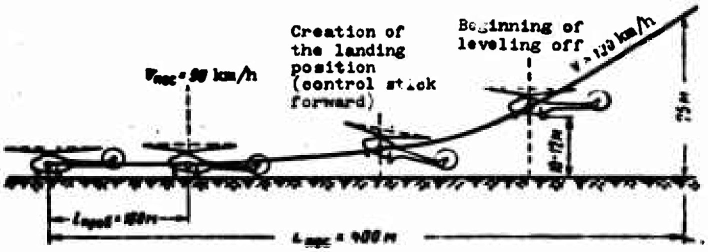

Fig. 89. Landing like an aircraft in autorotation of the rotor.

From an altitude of 10-12 m leveling off is produced by an energetic motion of the control stick back. Here the angles of attack of the rotor are increased, conditions of autorotation are improved, revolutions and thrust of the rotor increase, and forward and vertical velocity decrease.

If the speed of gliding is low, then in view of the insufficient reserve of the energy of motion, deflection of control stick back will not give a desirable result. Furthermore, in spite of the fact that the speed is high, it is necessary to deflect the control stick back quite energetically and at great magnitude in order to considerably increase the angles of attack and thereby decrease both the vertical and forward velocity. With this the tail support will appear below the level of the main wheels. Therefore, before the actual landing by deflection of the control stick forward it is necessary to put the helicopter in a landing position on the main wheels. The helicopter lands at high speed (for the Mi-4 helicopter about 90 km/h), and therefore a long run is obtained — not less than 160 m.

Landing like an aircraft in autorotation has the following deficiencies. In view of the high landing speed there is required a rather large, even and hard surface, which cannot always be found during engine failure. The landing run of the helicopter is also long and on the average is about 160 m, and the landing distance is over 400 m. Furthermore, with this method of landing breakdown of the tail rotor is possible, since to obtain a low vertical velocity it is necessary to deflect the control stick back energetically and at great magnitude for increasing the angle of attack of the rotor. Before landing it is necessary by moving the control stick forward to put the helicopter in a landing position, which is not always successful in view of the short time interval and also the insufficient controllability, which usually leads to breakdown of the tail rotor.

In the presence of such deficiencies this method of landing, although it was applied earlier for training in airfield conditions, at present is not recommended by the manual Flying Operation of the Mi-4 Helicopter. It can be applied only in exceptional cases when it is impossible to apply other methods, for example, because of the jamming of the "pitch-throttle" lever or if it is in the upper position.

3. Landing with the Application of Collective Pitch of the Rotor

<u>Theory of landing</u>. As was shown earlier, when landing with the application of general pitch kinetic energy of the rotation of the rotor is used. For the Mi-4 helicopter the method of this form

of landing is such that in this case there is used energy of rotation of the rotor and energy of motion of the helicopter, and it approaches nearer to the combined form of landing, although the name has been preserved as for landing with the application of collective pitch.

The method of landing with the application of collective pitch is the simplest and the safest, and therefore it has obtained wide application both for training and in industrial conditions.

A deficiency of this method of landing is that it can be applied only in the presence of an even surface and area sufficient in dimensions, since such a landing must occur with a run. For the Mi-4 helicopter landing run composes on the average of about 100 m, and the landing distance is 170-190 m. On this basis landing with the application of collective pitch cannot always be applied, especially where there is a limited site or greatly rugged terrain.

The speed in gliding before landing of the Mi-4 helicopter must be held in the range of 70-120 km/h, the recommended speed at which the method of piloting is simplified and a short run is obtained — 70-80 km/h. The landing approach should be fulfilled, as far as possible, into the wind or with the wind on the right. A landing approach with a wind of more 3-5 m/s on the left can lead to the fact that there will not be enough reserve deflection of the control stick to the left to eliminate drift, because in autorotation of the rotor for balancing the helicopter it is deflected to the left.

A headwind increases the curvature of the glide path, and a tailwind decreases it, and therefore in order to obtain a glide path corresponding to the speed of 70-80 km/h in a calm, it is necessary with a headwind to increase the speed, but not by more than 110 km/h, and with a tailwind decrease it, but not less than 60 km/h. Maneuvering at speeds for a landing calculation should be finished at an altitude of not lower than 50 m.

Leveling off must be started at an altitude of 25-35 m by deflection of the control stick back (Fig. 90). The greater the

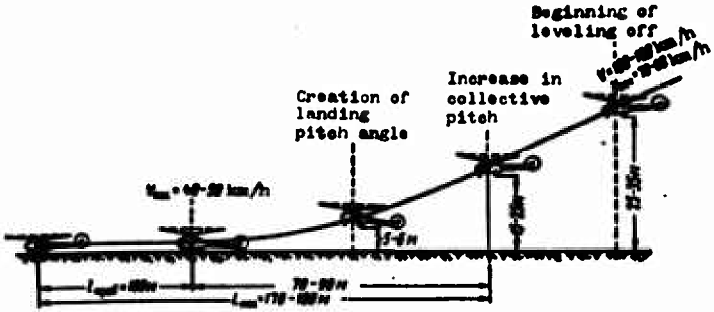

Fig. 90. Profile of landing in autorotation of the rotor of the helicopter with the application of collective pitch.

speed of gliding, the less the altitude needed to start leveling off. After this from an altitude of 15-25 m it is necessary by smooth motion of the "pitch-throttle" lever upwards to start increasing the collective pitch of the rotor with such calculation that at the instant of touchdown of the helicopter the collective pitch is maximum. It is necessary to remember that it is possible to use the energy of rotor rotation by motion of the "pitch-throttle" lever upwards only once.

Figure 91 gives the dependence of the altitude of the beginning of leveling off by the control stick and the altitude of the beginning of the increase in collective pitch of the rotor by the "pitch-throttle" lever depending upon the speed of gliding in autorotation for the Mi-4 helicopter with a normal flying weight.

With such leveling off the pitch angle can be about 15°, for which the tail support will appear lower than the main wheels of the landing gear (three-point position of the helicopter will be an angle of pitch of 9°). To put the helicopter into a landing position, it is necessary from an altitude of 5-6 m to move the control stick forward in such a manner that landing occurs on the main wheels or on all wheels simultaneously (see Fig. 90).

The magnitude of the landing speed for a given flying weight will depend on the velocity of gliding: the higher the speed of

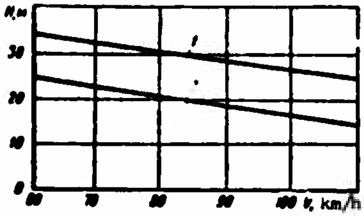

Fig. 91. Dependence of altitude of the beginning of the action by control levers on the speed of gliding in landing with the application of collective pitch: 1 – beginning of leveling off by the control stick; 2 – beginning of the increase in collective pitch by the "pitch-throttle" lever.

gliding, the higher the landing speed (Fig. 92).

The magnitude of the run depends on the landing speed, which in turn depends on the speed of gliding. The dependence of the magnitude of the run after landing on the speed of gliding is shown in Fig. 93. As can be seen from the figure, at a gliding speed of 80-82 km/h the run will be 100 m.

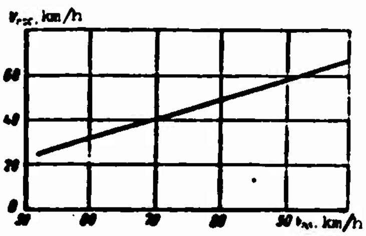

Fig. 92.

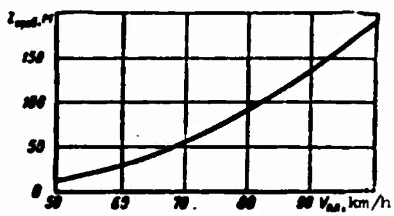

Fig. 93.

Fig. 92. Dependence of landing speed on the speed of gliding in autorotation of the rotor for the Mi-4 helicopter with a flying weight of 7100 kg.

Fig. 93. Dependence of landing run on the speed of gliding autorotation of the rotor for Mi-4 helicopter with a flying weight of 7150 kg.

The vertical rate of descent at the time of landing and the overload depend on the speed of gliding before landing: the higher the speed of gliding, the less the vertical velocity and overload. Thus, at a speed of gliding of 70-80 km/h the vertical velocity at the time of landing will be about 2 m/s, and the overload at the time of landing - about 1.75. The average gliding angle from an altitude of 25 m will be about 15°, and the time of descent from an altitude of 50 m will be about 10 s. At the time of landing the rotor will have 1700 r/min.

Method of fulfillment. Landing in autorotation of the rotor with the application of collective pitch for training purposes is fulfilled in the following way. It is necessary to transfer the rotor into autorotation and balance the helicopter by all control levers. After divergence of the needles of the combined tachometer one should turn off the engine by the manual lever of control of the pump NV-82V, disengage the clutch, turn off the ignition and cover the fire valve. Then it is necessary to set the speed at 70-80 km/h and revolutions of the rotor at 2200-2400 r/min. From an altitude of 25-35 m it is necessary to start leveling off by the control stick, deflecting it back, and from an altitude 15-25 m by smooth motion of the "pitch-throttle" lever upwards increase the collective rotor pitch with such calculation that at the instant of touchdown it is maximum. At an altitude of 5-6 m deflect the control stick forward to put the helicopter into a landing position. After landing it is necessary to decrease the collective pitch down to a minimum, and to decrease the landing run apply braking of the wheels.

During engine failure such a landing is fulfilled in the following way. After engine failure one should quickly decrease the collective pitch to a value necessary for obtaining revolutions of the rotor within 2200-2400 r/min at a given altitude. Then balance the helicopter in these conditions by the control stick and pedals. If the speed with this is high, it is necessary to decrease it to 100 km/h and turn off the ignition. After that at an altitude of 100-150 m set the speed at 70-80 km/h and refine the landing pattern by changing the speed of gliding. Further actions should be the same as when landing for training purposes.

4. Combined Landing

In general with this method of landing, as was established earlier, the energy of motion of the helicopter and rotations of the rotor by both control levers are completely used for short-term augmentation of thrust of the rotor and decrease in forward and vertical velocities to the minimum possible at the instant of touchdown. Therefore, this method permits landing without a run or with a very short run. This method of landing is applied when it is necessary to produce it on a site limited in dimensions, with poor approaches or a greatly dissected terrain when a run after landing is impossible.

Since the Mi-4 helicopter is heavy, a special method of this landing has been developed for it.

1. The speed in gliding decreases beforehand and it must be reduced to the minimum permissible with autorotation of the rotor (50-60 km/h). With this the vertical rate of descent is great and will be about 10 m/s for a helicopter with blades of mixed construction and about 8 m/s for a helicopter with all-metal blades (Fig. 94).

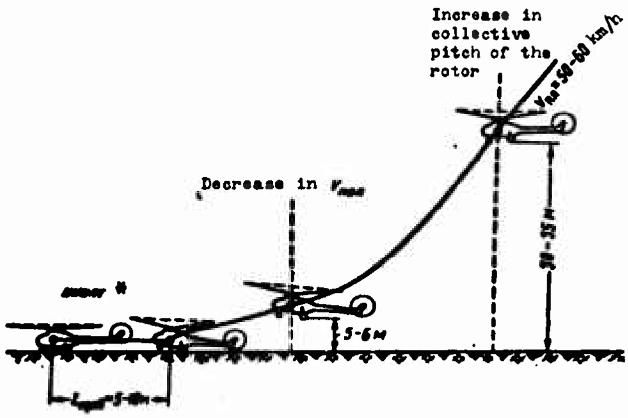

Fig. 94. Combined landing in autorotation of the rotor.

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*Translator's Note: Unverified but possibly Scientific Research Institute of Aviation Technology.

2. From an altitude of 30-35 m it is necessary to start a smooth increase in the collective pitch with such calculation that at the instant of touchdown it is maximum. Here the thrust will be increased, and the forward and vertical velocities decrease.

3. From an altitude of 5-6 m by deflecting the control stick back one should decrease the forward velocity to the minimum possible. The vertical speed remains high before landing, about 3-3.5 m/s. Landing occurs without a run or with a short run of about 5-10 m.

A deficiency of such landing is that the high vertical velocity at the time of landing causes an overload of 3 and therefore does not guarantee complete safety. Furthermore, with such a landing destruction of the tail rotor and tail boom is possible also. On this basis this method of landing for trainings is not applied, but it is recommended by the manual Flying Operation of the Mi-4 Helicopter in the case of engine failure or breakdown of the main shaft of transmission above the place where it is impossible to land by the preceding method.

§ 3. Laboratory Work on the Study of Properties of the Rotor in Autorotation

Properties of the rotor in autorotation when gliding and landing can be visually observed by setting experiments on a special operational installation. This installation constitutes a mockup of a helicopter with freely revolving rotor. The mockup is secured on a truss with the help of a spherical mounting. Such bracing permits placing the helicopter at any angle to the flow of air created by a blower set in the housing below the mockup of the helicopter. Together with the housing the blower can revolve in horizontal and vertical planes, which permits directing the flow from it to the mockup of the helicopter also at any angle and thereby simulating gliding of the helicopter with any gliding angle. The operational installation permits clearly demonstrating the following properties of the rotor in autorotation.

Experiment 1. Blades of the rotor are set at fixed positive setting angles. The rotor does not revolve, and flow is created by the blower on the rotor from below. Then from incident flow the rotor starts to revolve in a right direction. This means the rotor did not pass to autorotation, since revolutions before the beginning of gliding were not assigned.

Experiment 2. The rotor is accelerated manually (by the engine) in a left direction (according to the usual direction of rotor rotation of the Mi-4 helicopter — counterclockwise with observation from cockpit). Then the acceleration is ceased (the engine stopped), and simultaneously flow is created by the blower. The rotor continues to revolve in the same direction, creating a fixed constant number of revolutions. Consequently, the rotor passed into autorotation.

Experiment 3. The rotor stops, and the blades are transferred to smaller setting angles. Then the rotor is again accelerated and flow is created. The rotor obtains a set number of revolutions, but more than before (greater revolutions than large setting angles). Thereby the influence of the magnitude of collective pitch on the number of rotor revolutions in autorotation is proved.

Experiment 4. Large angles to blades of the rotor are set, the rotor is accelerated in the usual direction of rotation, and then acceleration is ceased and flow is created. The rotor decreases the revolutions, stops and starts to revolve in the opposite direction. Consequently, the rotor does not pass into autorotation if he has great collective pitch, i.e., if the pitch is not decreased after failure of the engine.

Experiment 5. The rotor is put into steady autorotation and the tail of the mockup is lowered, which increases the angles of attack of the rotor in autorotation. With that same flow rate the number of rotor revolutions is increased. Consequently, the number of revolutions increases, and this means thrust of the rotor with an increase in angles of attack by deflection of control stick back during landing in autorotation. With this owing to the increase in thrust the vertical and forward velocity decrease, which is necessary for landing in autorotation of the rotor.

CHAPTER VIII

TURN OF THE HELICOPTER

§ 1. Peculiarities of the Turn

On a helicopter the correct turn (without slip) will be in the case when, moving over the correct circumference in a horizontal plane with a fixed angular velocity, it will simultaneously revolve around its vertical axis with the same angular velocity (Fig. 95). The helicopter will shift over the circumference of the turn at 90°, and then it should turn during the same time around its vertical axis also at 90°. With this the longitudinal axis of the helicopter should always be directed along the tangent to the circumference of the turn. A correct turn is obtained only with a coordinated deflection in the direction of the turn of the control stick and pedal with a simultaneous increase in power of the engine by the "pitch-throttle" lever. If the pedal is deflected more than is necessary, then a turn with an external slip will be obtained. If it will be deflected insufficiently, a turn with an internal slip will be obtained.

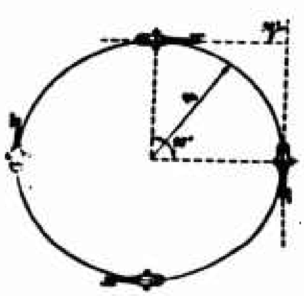

Fig. 95. Correct turn of a helicopter.

It is known that during rectilinear flight with forward velocity owing to flapping motions of the blades and the presence of a flapping control the cone of rotation of the rotor and direction of action of its aerodynamic force are deflected to the right. In a right turn the rotor obtains airflow on the right, and therefore the tendency to deflection of the cone of rotation to the right will be increased inasmuch as the left "cantilever" of the rotor will have a higher speed and the right less speed than the airflow, which is analogous to the increase in speed of flight of the helicopter. In a left turn, conversely, the rotor will obtain airflow on the left, and therefore deflection of the cone of rotation and direction of action of aerodynamic force to the right will decrease as compared to the deflection in rectilinear flight (Fig. 96). This phenomenon positively affects the fulfillment of turns, especially right turns. Great deflection of the cone of rotation of the rotor and directions of action of the aerodynamic force promote fulfillment of the right turn, because the reserve of deflection of the control vanes is increased. In a left turn a decrease in deflection of the cone rotation and direction of action of the aerodynamic force to the right promotes fulfillment of a left bank, since in this case less deflection of the control stick of the helicopter will be required in the direction of the turn (the reserve of deflection of control vanes will also be great).

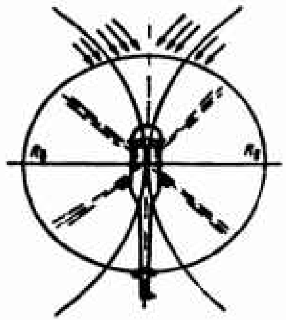

Fig. 96. Airflow of the rotor during right and left turns.

During a correct turn the following forces act on the helicopter. The total aerodynamic force of the rotor R, as with any forward flight, is decomposed into a bound system of coordinates into thrust of the screw T, longitudinal force Q_B and lateral force Z_B.

The tractive force of the rotor is directed along the axis of the shaft and together with the helicopter is inclined forward and in the direction of the turn (Fig. 97). Tractive force T is decomposed in the continuous system coordinates into three components: vertical T_y, horizontal T_x, and horizontal T_z. Here the horizontal component T_x is directed along the flight and is tangent to the circumference of the turn, and T_z is directed along the radius to the center of the turn and is centripetal force distorting the flight path. Drag of the helicopter Q and weight of the helicopter G also acts on the helicopter. The tractive force of the tail rotor is balanced by the lateral force and their sum is equal to zero (they are not shown in Fig. 97). The longitudinal force Q_B, directed along the plane of rotation in a direction opposite the flight, is decomposed in a continuous system coordinates, as in any flight, into Q_{B_x} and Q_{B_y}.

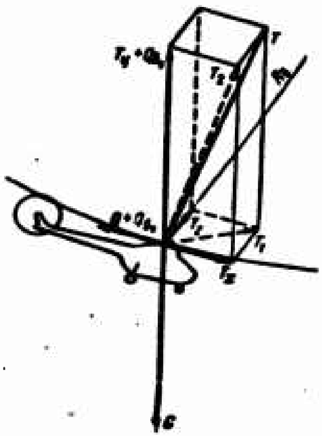

Fig. 97. Diagram of forces acting on the helicopter during a turn.

During a correct turn with a constant radius the following relationship between the mentioned forces should be observed:

a) to obtain flight in a horizontal plane the vertical component of the thrust force T_y and vertical component of the longitudinal force Q_{B_y} must balance the weight of the helicopter G: $T_y + Q_{B_y} = G$;

b) for uniformity of flight the horizontal component of thrust force T_x should balance the drag of the helicopter Q and horizontal component of the longitudinal force Q_{B_x} : $T_x = Q + Q_{B_x}$;

c) to obtain a turn of definite radius an unbalanced centripetal force, directed to the center of the turn should be present. Such a force is the horizontal component of thrust T_z.

The radius and time of turn are determined by the well-known formulas of aerodynamics of an aircraft and the magnitude of them depending upon the indicated speed in the turn, and also the angle of roll for the Mi-4 helicopter is shown on Table 3.

Table 3.

Speed of turn, km/h	Bank, deg	Radius, m	Time, s
100	10	448	101
120	10	644	122
120	15	422	79.5
120	25	243	46

Turns on the helicopter are fulfilled by coordinated deflection of the control stick and pedal in the direction of the desirable turn with a simultaneous increase in power for maintaining the flight altitude. But since the thrust of the tail rotor both in right and left turns is directed to the left, therefore the helicopter in both turns is balanced in a longitudinal relation with various pitch angles and in a transverse relation with various bank angles.

Furthermore, during the fulfillment of turns the main and tail rotors accomplish complicated curvilinear motions, and therefore they manifest properties of gyroscopes.

For the enumerated reasons to execute right and left banks, with identical speeds and angles of banks on the instruments different power will be required. Here the turns will be of different radius, will have a different time for the accomplishment of one circle of turn, and will also demand a different deflection of the control stick both in longitudinal and in lateral relations.

§ 2. Influence of Thrust of the Tail Rotor

Thrust of the tail rotor both in right and left turns is directed to the left, and therefore it balances the helicopter in a longitudinal relation with different pitch angles and in a lateral relation with different bank angles in both turns.

In a right turn the thrust of the tail rotor will be directed to the left upwards (Fig. 98a), and its vertical component $T_{y_{x.B}}$ will be directed upwards. It creates a negative pitching moment for the helicopter, and therefore the helicopter in a right turn will be balanced with a negative pitch angle ν. In a left turn, conversely, the vertical thrust component of the tail rotor $T_{y_{x.B}}$ will be directed downwards and will create for the helicopter a positive moment (Fig. 98b). Therefore, the helicopter will be balanced with a great pitch angle, i.e., with an elevated cowling. At an angle of bank of the turn of γ = 30° the vertical thrust component of the tail rotor will already be half of all the thrust of the tail rotor: $T_{y_{x.B}} = T_{x.B} \sin 30° = T_{x.B} \cdot 0.5$. Consequently, the large vertical component of thrust of the tail rotor on the large arm equal to the length of the tail boom will create a large moment, which will change the pitch angles considerably. With a flying weight of 6500 kg and tractive force of the tail rotor of 300 kgf for the Mi-4 helicopter during a turn with a bank of 30°, the pitch angle will be changed from a diving or positive pitching moment of the vertical component of thrust of the tail rotor by 6°. This means that if the pitch angle in horizontal flight at any speed is equal to -2°, then in a right turn with the same speed the pitch angle will be -8°, and in a left turn, 4°.

A change in pitch angle will lead to a change in the speed in the turns, and therefore to maintain the assigned speed the appropriate deflection of the plate of the cyclic pitch control will be required by the control stick. If the bank angle of the turn is large, then there cannot be enough reverse of deflection of the control vanes for the accomplishment of a correct turn. For this reason bank angles in turns and banks for the Mi-4 helicopter up to 30° in powered flight and up to 20° in autorotation of the rotor are limited.

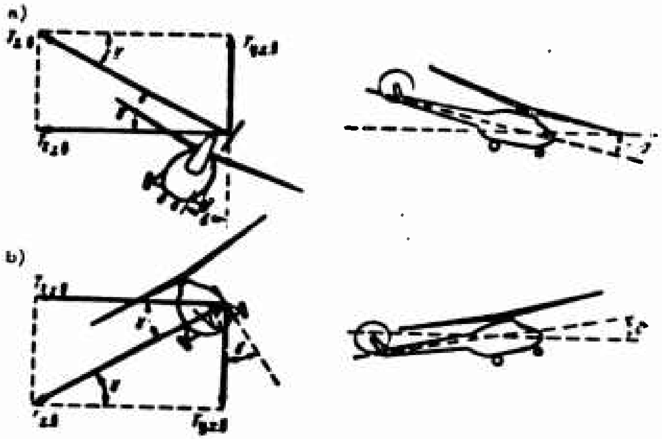

Fig. 98. Longitudinal balancing of the helicopter in turns: a) in a right turn; b) in a left turn.

Furthermore, these limitations are set by the overload on the rotor. If, however, the pilot tries to maintain identical pitch angles in right and left turns, then the speed will be changed. Therefore, in right and left turns at identical speed, the pitch angles will be different.

Since the helicopter is balanced in both turns in a longitudinal relation with various angles of pitch, and inasmuch as the thrust of the tail rotor is directed in both turns only to the left, the helicopter is also balanced in a lateral relation with various bank angles, if the control stick will be deflected in a lateral relation for the accomplishment of turns at the same magnitude. In a right turn the tail of the helicopter is lifted, and the moment of thrust of the tail rotor $(T_{x.s} h_2)$ is created for guiding the helicopter from the bank (Fig. 99a). In a left turn the tail of the helicopter is lowered, the thrust of the tail rotor creates a moment $(T_{x.s} h_2)$, acting on the increase in the bank angle of the turn (Fig. 99b). Consequently, in the right and left turns there will be various angles of bank owing to the action of thrust of the tail rotor. Here the pilot can interfere into the control and can establish the identical bank angle, not changing the speed in the turns.

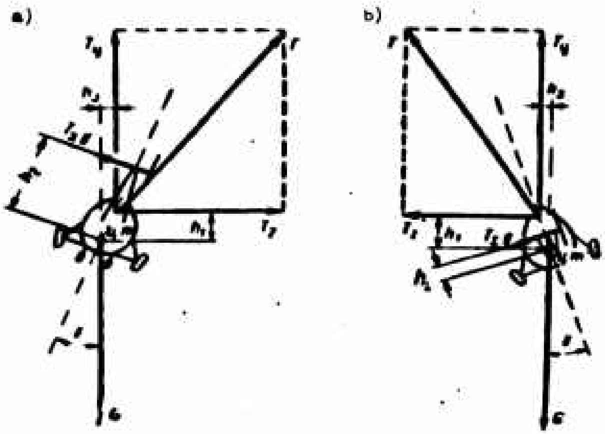

Fig. 99. Lateral balancing of the helicopter in turns: a) in a right turn; b) in a left turn.

In order to obtain a right turn with the same angle of bank as that of the left, in the right turn it is required to deflect the thrust of the rotor by the control stick more to the right than in a left turn to the left. Therefore, the great horizontal component of thrust of the rotor T_z, acting to the center of the turn, will be obtained. A condition of the equilibrium of the helicopter in a right turn with a definite angle of bank will be the equality of moments:

$$T_z h_1 = T_{z.v} h_2 + T_y h_3.$$

In the left turn $T_z h_1 + T_{z.v} h_2 = T_y h_3$. It follows from this that in the right turn $T_z = \frac{T_y h_3 + T_{z.v} h_2}{h_1}$, and in the left turn $T_z = \frac{T_y h_3 - T_{z.v} h_2}{h_1}$. Since arms h_1 in the right and left turns are equal, then from the last equations it is clear that T_z in the right turn is larger than that in the left. Therefore, in the right turn great deflection of the cone of rotation and direction of actions of aerodynamic force of the rotor in the direction of the bank will be required. But in connection with the fact that components of thrust of the rotor T_y in right and left turns must be equal, in view of the identical weight of the helicopter, then the total thrust of the rotor T in a right turn should be greater than that in a left turn. To create great thrust in the right turn higher power than in the left turn will be required.

Thus it is established that for the execution of both right and left banks, higher power will be required than for horizontal flight at the same speed, but for a right turn higher power will be required than for the left upon fulfillment of them with identical angles of bank. Furthermore, in a right turn a greater thrust of the tail rotor will be required, for creation of which high power will be required. For the execution of a left bank less power will be required than for a right turn. To carry out a left turn with a bank up to 15°, it is not required to increase the power as compared to horizontal flight at the same speed.

The horizontal component of thrust T_z in the right turn is larger than that on the left. In this case these forces are centripetal, the value of which governs the radius of the turn. On this basis the radius of the right turn will be less than the radius of the left bank, other things being equal:

$$F_{цб}=\frac{mV^2}{R},$$

where $F_{цб}$ – centrifugal force; m – mass. Hence

$$R=\frac{mV^2}{F_{цб}}=\frac{mV^2}{T_z}\ (\text{m}). \qquad (46)$$

In view of the fact that we compare the right turn with the left at equal speeds of forward flight, and the radius of the right turn is less than that of the left, then the time of accomplishment of a right turn will be less than that of the left:

$$t_в=\frac{2\pi R}{V}\ (\text{s}). \qquad (47)$$

The overload on the right turn will be more than that on the left, since the total thrust of the rotor on the right turn is more:

$$n=\frac{T}{G}. \qquad (48)$$

It is necessary to note that the difference in the required power, radius, in time and in overload on right and left turns is insignificant, especially at small angles of roll. Therefore, they are practically almost imperceptible for the pilot during the fulfillment of turns.

§ 3. Influence of Gyroscopic Moments and Peculiarities of the Fulfillment of Turns

1. Influence of Gyroscopic Moments

The main and tail rotors possess characteristic properties of a gyroscope — precession, since in process of rotation they constitute powerful gyroscopes.

The essence of the phenomenon of precession is that if to the axis of a revolving body (rotor, propeller) force is applied, which should change the direction of the revolving mass of the body, then there will appear a force of inertia, represented in the form of a moment turning the axis of the body in a direction perpendicular to the applied force. This moment is called gyroscopic.

The direction of the gyroscopic moment is determined according to the following rule of precession: the direction of movement of any point on the axis of gyroscopes in which a force is applied will be determined if one were to turn the direction of the acting force 90° around the axis of the gyroscope in the direction of rotation of the rotor. According to this rule, with the appearance of the diving moment for the helicopter gyroscopic moment of rotor will appear, creating a right bank of the helicopter, since with the diving moment of the helicopter to the axis of the rotor (shaft of the rotor) a force is applied, deflecting the axis of the rotor back. The direction of the gyroscopic moment is determined by the turn of the force, deflecting the shaft back 90° with respect to the rotation of the rotor, i.e., the shaft will move to the left, creating a right bank to the helicopter. According to this same rule, with the appearance of a positive pitching moment the gyroscopic moment of the rotor creates a left bank to the helicopter.

In these two cases the tail rotor will not create gyroscopic moments, since with diving or pitching of the helicopter the tail rotor moves in its plane of rotation, and its axis and then the mass of the rotor do not change the direction of rotation.

With the creation of a right bank of the helicopter the gyroscopic moment of the rotor creates a pitching moment. With this simultaneously, the gyroscopic moment of the tail rotor creates a right turn.

With banking of the helicopter to the left, the gyroscopic moment of the rotor creates a diving moment, and the gyroscopic moment of the tail rotor creates simultaneously a left turn. Gyroscopic moments of the tail rotor (in view of the smaller dimension of the tail rotor) will have less influence than moments of the rotor.

The action of gyroscopic moments of both rotors from various evolutions helicopter is given in Table 4.

Table 4.

Evolution of the helicopter	Gyroscopic moment of the rotor	Gyroscopic moment of the tail rotor
Dives	Right bank	Absent
Pitches	Left bank	Absent
Right bank	Pitching	Right turn
Left bank	Diving	Left turn

The indicated gyroscopic moments of the main and tail rotors act simultaneously only at the time when the helicopter enters into a turn and comes out of it. But they act effectively, and therefore it is necessary to parry them. Thus, for example, when the helicopter goes into a right turn, the helicopter, owing to the gyroscopic moment of the rotor, pitches. In connection with this it is necessary by deflecting the control stick forward to parry this moment (it is better if before going into a right turn move the stick forward beforehand to prevent the appearance of a pitching moment). When going into a left turn, conversely, the gyroscopic moment of the rotor creates a diving moment, and therefore by deflecting the control stick back it is necessary to parry this tendency toward diving.

As soon as helicopter enters into the turn and obtains a steady motion, the action of the indicated gyroscopic moments vanishes. In a steady turn gyroscopic moments of the main and tail rotors will act in view of their complicated motion along the circumference of the turn with the simultaneous slope of them and rotation of the helicopter around the vertical axis.

It has been established by investigations that in a right steady turn the cone of rotation of the rotor is inclined forward and to the right, in the whole extent of the turn the gyroscopic moment acts on the pitching (loss of velocity) and on coming out of the bank. The gyroscopic moment of the tail rotor also acts on the coming out of the bank, being added to the action of gyroscopic moment of rotor.

In a left turn the gyroscopic moment of the rotor acts on the diving (increase in speed) and on the increase in bank of the turn. The gyroscopic moment of the tail rotor, just as in a right turn, acts on the coming out of the bank, counteracting the moment of the main rotor.

For clarity the action of gyroscopic moments of both rotors in right and left turns is given in Table 5.

Table 5.

Evolution of the helicopter	Gyroscopic moment of the rotor	Gyroscopic moment of the tail rotor
Right turn	Pitching and coming out of the bank	Coming out of the bank
Left turn	Diving and increase in the bank	Coming out of the bank

It should be noted that gyroscopic moments in a right turn appear greater than those in a left turn, since in a right turn the pitch angle is less (nose of the helicopter is lowered), and moments of both rotors on coming out of the bank are added, whereas in a left turn the moment of the tail rotor counteracts the moment of the main rotor by an increase in bank.

The action of gyroscopic moments of both rotors in right and left turns and also different balancing, in view of the action of tractive force of the tail rotor to the left, condition the different method of fulfillment of right and left banks.

2. Peculiarities of the Fulfillment of Turns

To execute any turn it is necessary to deflect smoothly the lever and pedal in the direction of the fulfilled turn, simultaneously increasing the power of the engine by the "pitch-throttle" lever for maintaining flight altitude. After achievement of the assigned angle of roll banking is ceased by motion of the lever in the opposite direction. With this the control stick is held in such a position at which the helicopter is balanced with the assigned angle of roll and velocity along the trajectory.

At the time the helicopter enters into a right turn the gyroscopic moment of rotor creates a pitching moment, the action of which continues in the whole extent of entrance into the turn. Therefore, it is necessary by deflecting the control stick forward to counteract this moment (it is better before entering into the turn to "press" the helicopter by the lever forward). As soon as the bank is set constant, this moment disappears and the helicopter will lower its nose, being balanced with a lowered nose by an additional diving moment appearing from the vertical component of thrust of the tail rotor. In the process of fulfillment of a turn the constant moment of the rotor acts on the helicopter, striving to bring the helicopter out of the bank and creating pitching with a loss of speed. The gyroscopic moment of the tail rotor also acts on the exit from the bank. Therefore, in order to maintain the assigned bank and speed in a right turn, it is necessary to deflect the control stick forward along the diagonal to the right.

In the process of putting the helicopter in a left turn the gyroscopic moment of the rotor creates a diving moment whose action continues for the whole extent of the entrance into the turn. For this reason one should restrain the helicopter by the control stick, pulling it back. As soon as the bank is set this moment disappears, and the helicopter will be balanced with an elevated nose by a pitching moment appearing from the vertical component of thrust of the tail rotor. In the process of a sustained left bank a constant gyroscopic moment of the rotor acts on the helicopter, creating diving and an increase in bank, and the gyroscopic moment of the tail rotor acts on the exit from the bank. Therefore, in order to maintain the assigned bank and speed in a left turn, it is necessary to hold the control stick, pulling it back and to the right but to the right — less than in a right turn.

In turns with small angles of bank the indicated difference in the method of fulfillment of right and left banks is hardly noticeable. During steep banks and turns sharp entrances into a bank and turn, this difference is perceptible and requires advanced motions of the control stick and appropriate attention in the process of the turn itself. With fulfillment of steep banks and turns there can not be enough reserve of deflection of the control vanes for execution of correct turns; they will be obtained with a slip, and great slip for a single-rotor helicopter is not permissible. On this basis definite limitations in banking and turns are set.

Banks and turns are possible also with a simultaneous climb or descent — ascending and descending spirals. The method of their fulfillment is the same as that of usual banks and turns, only instead of a constant altitude is maintained constant vertical rate of climb or descent by the rate-of-climb indicator.

§ 4. Flying Limitations for the Mi-4 Helicopter in Banks and Turns

1. Carry out turns and banks with bank up to 20° at indicated speeds of 80 to 155 km/h.

2. The maximum permissible angle of roll for a turn and bank is equal to 30° at indicated speeds of not less than 60 km/h.

3. At the maximum permissible flying weight of 7350 kg the maximum permissible angle of roll for turns and banks is -20°.

4. At altitudes of more than 2000 m fulfill turns and banks with angles of bank of not more than 20°.

5. In autorotation of the rotor fulfill turns and spiral with a bank of not more than 20° with revolutions of the crankshaft of the engine not higher than 2400 r/min.

6. With the transport of loads on the external suspension carry out turns with a bank of not more than 10°.

CHAPTER IX

BALANCING, CONTROLLABILITY AND STABILITY OF THE HELICOPTER

§ 1. Balancing

Balancing of the helicopter is called the state of it when acting force and moments with respect to all axes of the helicopter are balanced. According to the three axes of rotation three forms of balancing (equilibrium) exist: longitudinal, lateral, and directional. Lateral and directional balancing are sometimes called lateral balancing.

1. Longitudinal Balancing

Longitudinal balancing is called such a state of the helicopter when the acting moments do not revolve it around the lateral axis, and acting force do not cause acceleration (deceleration) in a direction of the longitudinal axis. We examined conditions of the equality of forces along the longitudinal axis earlier, and here conditions of the equality of longitudinal moments around the lateral axis will be examined (Fig. 100).

The following longitudinal moments act on helicopter in any conditions of flight around its lateral axis (center of gravity):

a) moment of the rotor, consisting of the moment of thrust T, moment of longitudinal force Q_B and moment of the hub owing to the spacing of the flapping hinges $M_{z_{BT}}$;

b) longitudinal moment of tail rotor $M_{p_{X.B}}$ consisting of the reactive moment and moments from longitudinal and lateral forces of the tail rotor;

c) moment of the fuselage M_{Φ} owing to airflow by counterflow and flow from the rotor;

d) moment of the stabilizer ($Y_{CT} \ell_{CT}$).

The tail rotor in forward flight, just as the main rotor, creates its longitudinal and lateral forces ($Q_{X.B}$ and $Z_{X.B}$) owing to the flapping motions and collapse, which act in the longitudinal plane of the helicopter and create longitudinal moments. The total moment of the tail rotor (reactive from longitudinal and lateral forces) is insignificant in magnitude and is accepted for the Mi-4 helicopter at 0.015 of the reactive moment of the rotor.

The moment of thrust of the rotor is a diving moment with nose-heaviness of the helicopter and pitching with tail-heaviness; moments of the longitudinal force and rotor hub owing to the spacing of the flapping hinges are pitching, and their total moment — moment of the rotor — is always diving in all conditions of flight.

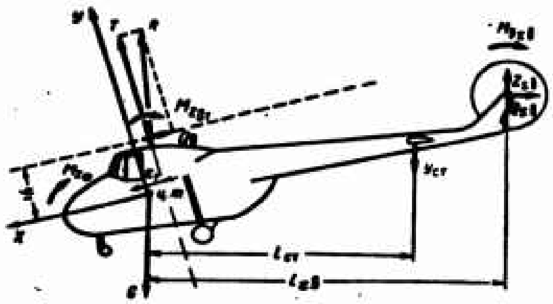

Fig. 100. Longitudinal balancing of the helicopter in forward flight.

The longitudinal moment of the tail rotor and the moment of the stabilizer are pitching.

The longitudinal moment of the fuselage owing to airflow from the rotor in all flight conditions is pitching and owing to the drag from the counterflow will be pitching only in autorotation of the rotor and diving in all remaining conditions of powered flight. The total moment of the fuselage from the counterflow and airflow by the rotor will be pitching in autorotation of the rotor, in hovering and at low speeds in flight with the engine operating and diving in all conditions at high flight speeds, starting from $\mu = 0.2$.

The condition of longitudinal balancing of the helicopter is the equality of diving and pitching moments, i.e., so that the sum of all longitudinal moments around the lateral axis is equal to zero (see Fig. 100):

$$M_{\phi} - T \cdot x_{т} + Q_{в} \cdot y_{т} + M_{z_{вт}} + M_{ф_{г.в}} + Y_{ст} \cdot l_{ст} = 0.$$

In flight in all conditions the pilot seeks longitudinal balancing of the helicopter by appropriate deflection of the plate of the cyclic pitch control with the help of the control stick in a longitudinal relation. To balance the helicopter in a longitudinal relation in all conditions of flight, the designer sets a strictly definite deflection of the plate of the cyclic pitch control both forward and back. Thus, for the Mi-4 helicopter the limiting deflection of the plate of the cyclic pitch control forward is 5° 30' and back, 4° 15'.

Each speed of flight corresponds to a strictly definite deflection necessary, for this speed, of the plate of the cyclic pitch control in a longitudinal direction. This necessary deflection of the cyclic pitch control depends not only on the speed of flight but also on operating conditions of the engine and to the degree of what conditions of flight are accomplished at this speed: climb, horizontal flight, motor reduction, or autorotation.

The necessary deflections of the cyclic pitch control $\chi°$ and movement of the control stick also depend on the magnitude of centering of the helicopter x_T, angle of setting of the stabilizer and on flying weight of the helicopter. Figure 101 gives an example balancing curves of the necessary deflection of the plate of the cyclic pitch control as a function of the speed of flight with three different centerings: in climb, in takeoff operating conditions of the engine and in conditions of gliding (autorotation) for the Mi-4 helicopter. As can be seen from the balancing curves, in the climb regime from the speed of 40 km/h to 100 km/h the necessary deflection of the plate of the cyclic pitch control almost does not change, and with an increase in speed of flight greater than 100 km/h for balancing the helicopter in a longitudinal relation deflection of the cyclic pitch control somewhat back is required. This is explained by the fact that with an increase in speed of flight the helicopter is less stable with respect to the speed.

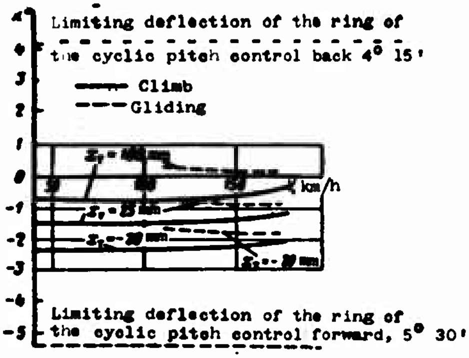

Fig. 101. Necessary deflections of the ring of the cyclic pitch control κ° in a longitudinal direction as a function of the speed of flight with various centerings.

In order to maintain the needed speed, it is necessary at first to deflect the cyclic pitch control forward, and then so that the speed does not increase further, it is necessary to deflect the plate back for balancing the helicopter.

From the balancing curve it also is clear that the more the power of the engine, the greater the deflection of the plate of the cyclic pitch control forward is required as compared to its deflection in lower operating conditions of the engine. By the broken curves balancing curves in autorotation of the rotor are shown. As can be seen from these curves, with removed throttle deflection of the plate forward is required less than with full throttle with the same centerings. With an increase in speed of flight in conditions of autorotation it is required to deflect plate more forward.

Figure 101 gives three curves for three centerings: 180, 25, and -20 mm. From these curves it is clear that the more the nose-heaviness of the helicopter, the less deflection of the plate of the cyclic pitch control forward is required and, conversely; the more the tail-heaviness (-20 mm), the greater the deflection of the plate forward is required.

The magnitude of the setting angle of the stabilizer is governed by the necessary deflection of the plate in the following way. In flight with an operating engine the more the setting angle of the stabilizer, the less deflection of plate forward is required and conversely. This is explained by the fact that at a large angle of setting of the stabilizer there appears a smaller positive pitching moment from it, and this means less movement of the plate and lever of the cyclical pitch forward is required for the acceleration of speed. In conditions of autorotation the phenomenon is the reverse to powered flight: the more the setting angle of the stabilizer, the greater the deflection of the plate forward is requi. d for the acceleration of speed or retention of the assigned speed.

Figure 101 gives curves taking into account the action of the stabilizer whose control is interlocked with the control of "pitch-throttle" lever by such a principle: if the collective rotor pitch is increased, then the setting angle of stabilizer is increased. With maximum pitch the setting angle of the stabilizer is equal to 10° and with minimum pitch – a minus 7°; for a helicopter with all-metal blades the maximum angle of setting of the stabilizer is 5° and the minimum – minus 12°. A controllable stabilizer thus decreases the necessary deflection of the plate of the cyclic pitch control in a longitudinal relation both in flights with an operating engine and in autorotation and thereby the reserve of deflection of the control vanes is increased. Thus, for example, with transition of the rotor into autorotation the "pitch-throttle" lever is lowered downwards to decrease the rotor pitch, then the stabilizer decreases the setting angle, and the positive pitching moment of the stabilizer increases; and therefore, there will not be required great deflection of the plate and control stick back for preventing diving. With the acceleration of speed in powered flight the collective rotor pitch is increased, the angle of setting of the stabilizer is also increased, the positive pitching moment of the stabilizer decreases and, therefore, smaller deflection of the plate and control stick forward will be required.

Consequently, the stabilizer expands the range of permissible centerings and plays the role of an aerodynamic trim tab, allowing the balancing of the helicopter in the great range of speed and centerings with a relatively small angular range of pitch, necessary deflection of the plate of the cyclic pitch control and movement of the cyclical pitch lever.

From a change in flying weight of the helicopter the necessary deflection of the plate of the cyclic pitch control in a longitudinal relation is changed insignificantly: the more the flying weight of helicopter, the greater the deflection of the plate forward is required for balancing the helicopter at the same speed. This phenomenon is explained by the fact that for much weight high power will be required, and as was established earlier, the more the power, the greater the movement of the plate forward is required for the same speed. This is explained by the great airflow of the fuselage and stabilizer by flow from the rotor and by the increase from this positive pitching moment.

Each position of the plate of the cyclic pitch control requires a definite position of the control stick: with great deflection of the plate of the cyclic pitch control forward great deflection of control stick is required.

Figure 102 shows the interconnection of the deflection of the ring of the cyclic pitch control κ° and movement of the cyclic pitch control lever in a longitudinal direction for the Mi-4 helicopter. As can be seen from the figure, with a neutral position of the control stick in a longitudinal relation, the plate of the cyclic pitch control has 45' slope forward. Such deflection of the plate of the cyclic pitch control forward with a neutral control stick is attained with an adjustment of the longitudinal control.

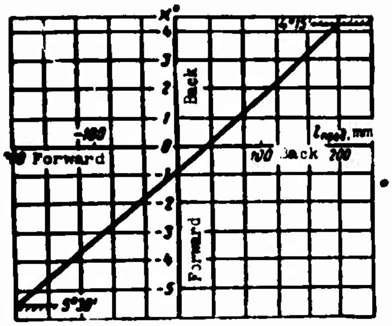

Fig. 102. Interconnection of the deflection of the ring of the cyclic pitch control κ° and movement of the control stick in a longitudinal direction $\ell_{пред}$.

This is necessary so that at average sp eds of flight in which the helicopter is found most of the time, the control stick in a longitudinal relation would occupy a position close to being neutral, which is the most convenient for piloting. Then at speeds less than the economic the control stick will be deflected back, and there will be a sufficient reserve of movement of it for hovering with maximum nose-heaviness and a tailwind. At speeds greater than the economic the control stick will occupy a position somewhat after the neutral forward.

At each flight speed the helicopter is balanced in a longitudinal position with a definite pitch angle: the more the speed of flight, the less the pitch angle. Figure 103 gives as an example balancing curves of angles of pitch ν from speed in the rate of climb with full throttle and in autorotation (broken curves) with three different centerings for the Mi-4 helicopter. As can be seen from the curves, the more the speed, the less the pitch angle. Furthermore, it also is clear from the curves that with centering more to the rear x_T = -20 mm) in autorotation at all speeds of flight the pitch angle will be larger than it is in the rate of climb. But this difference is insignificant, and with an increase in centering (moving the center of gravity of the helicopter forward) this difference decreases, and with centering equal to 25 mm, the pitch angle will already be less than in the rate of climb with the same centering. Such a picture will occur with a centering of 180 mm. At the same time the pitch angle to a great degree depends on the centering of the helicopter at the same speed: with more rear

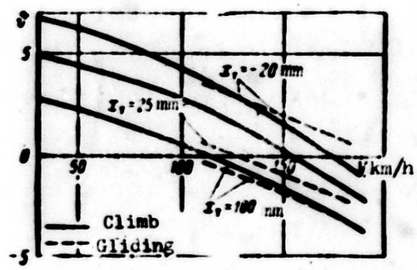

Fig. 103. Change in pitch angle as a function of speed of flight of the helicopter with various centerings.

centering, the greater the pitch angle and conversely.

Centering of the helicopter considerably affects the longitudinal balancing and controllability, changing in great limits the necessary deflection of the plate of the cyclic pitch control and control stick in a longitudinal position. These deflections become especially great on hovering and at high flight speeds. Therefore, there can be cases of the deficiency of the reserve of deflection of control vanes for the creation of desirable flight conditions, especially with the disturbance of limits of permissible centerings. For this reason centering of the helicopter is of great practical interest, since its value is changed from the character of loading of the helicopter, in which the crew participates directing.

2. Centering and Loading of the Helicopter

Centering of the helicopter is determined by the position of the center of gravity by two dimensions: along the longitudinal and vertical axes in the bound system coordinates. For the Mi-4 helicopter the origin of the coordinates is accepted as the point of crossing of the axis of the rotor shaft with the plane of rotation. A diagram of the coordinate axes for reading the centering of the helicopter is given in Fig. 104.

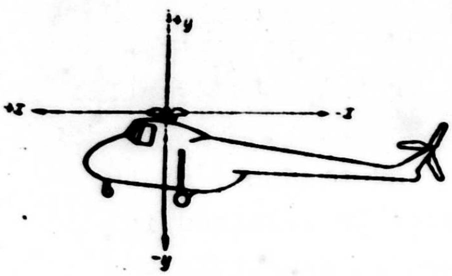

Fig. 104. Diagram of coordinate axes for reading the centering of the helicopter.

With all possible variants of the loading of the helicopter the center of gravity of it can shift in great limits along the longitudinal X axis, which considerably affects the controllability and balancing of the helicopter. Along the vertical Y axis possibilities of a shift in the center of gravity are less probable and these shifts to a lesser degree affect the controllability and balancing. Therefore, in practice attention is turned only to the shift of the center of gravity of the helicopter along the longitudinal axis. On this basis centering of the helicopter will be called the distance of the center of gravity of the helicopter along the X axis from the axis of the rotor shaft expressed in meters of millimeters (x_T). If the center of gravity is ahead of the shaft, the centering is taken with a plus sign, and behind the shaft — with a minus sign.

The range of permissible operational centerings is conditioned by the magnitude of deflection of the plate of the cyclic pitch control in a longitudinal position and is designated therefore strictly fixed for each helicopter. Proceeding from conditions of the arrangement of the helicopter and distribution of equipment and loads in it, for the Mi-4 helicopter all modifications are set: maximum forward centering $x_T = 0.3$ m, maximum rear $x_T = -0.07$ m.

In operating the helicopter it is necessary to observe strictly limits of permissible operational centerings, since if with loading of the helicopter centering will emerge beyond the limits of that permissible, then the reserve of deflection of the control vanes will appear insufficient for the creation of desirable conditions of flight or maneuvering. The disturbance of centering in vertical conditions of flight, takeoff, during landing and at high speeds of flight will be expressed especially negatively.

Thus, for example, if there is much forward centering, then there will be required in conditions of hovering and other vertical conditions great deflection of the cyclic pitch control and control stick back. This is necessary for preventing the tendency of the helicopter to move forward, since the helicopter is balanced in hovering with a small pitch angle (lowered nose). With this the cyclic pitch control together with the whole helicopter will be deflected forward, and the cyclical change of pitch of the rotor will be set, which will cause deflection of the cone of rotation and thrust of the rotor forward. In this case it will be difficult to maneuver the helicopter in hovering and accomplish takeoff and landing, especially with tailwind.

Also too much rear centering will be expressed negatively. In these cases the phenomena will be reversed: at high speeds of flight there will be little reserve of deflection of the control vanes, especially during a climb and in transient conditions for a climb. For these flight conditions greater deflection of the cyclic pitch control and the control stick forward is required than that for horizontal flight at the same speed (see Fig. 101). The absence of a sufficient reserve of deflection of the control vanes can prevent the pilot from fulfilling correctly evolutions of the helicopter and also may cause special difficulties, for example, during flight in bumpy air when he cannot cope with piloting of the helicopter. The small reserve of movement of the control stick forward is also dangerous in vertical conditions: with lowering of the tail of the helicopter for some reason the pilot is not able to prevent this lowering.

The magnitude of permissible operational centerings is selected from the calculation that the reserve of control be sufficient for execution of all flight conditions, including for hovering with a tailwind and under conditions of bumpy air.

To ease the loading of the helicopter for the purpose of observing permissible centerings, on the Mi-4 helicopter in the transport variant in the cargo cabin there is marking for the distribution of different cargo (Fig. 105). The stencil of marks consists of blue arrows (ahead of the axis of the rotor shaft) and red arrows (behind the axis of the rotor shaft) with an inscription of numbers. It is necessary to place the loads in such a manner that the total center of gravity is between the blue and red arrows corresponding to the total weight of the load: with this it is desirable that the center of gravity be in the middle of the section

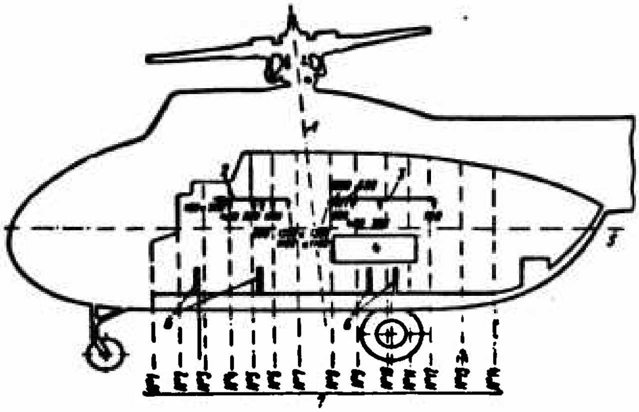

Fig. 105. Diagram of marking of the cargo cabin of the Mi-4 helicopter: 1 — rotor axis; 2 — blue arrows; 3 — red arrows; 4 — inscription "Attention! Arrange center of gravity of cargo between the blue and red arrows corresponding to the given load;" 5 — horizontal datum line; 6 — white bands indicating the position of axes of wheels of the transported equipment; 7 — numbers of frames of the fuselage.

limited by the indicated arrows. With such arrangement of cargo centering will not fall outside the limits permissible with any variant of servicing of the fuel.

If it is necessary to determine the exact centering with any variant of loading of the transport version of the Mi-4 helicopter, then it is necessary to use the centering graph (Fig. 106). The centering graph has an upper grid, corresponding to the weight and centering of an empty helicopter, and lower grid, corresponding to takeoff or landing weight and centering of the helicopter, and also a number of scales corresponding to the arranged loading. Arrows on the scales show where the center of gravity of the helicopter moves during distribution of the load on the corresponding place of this scale, and the figure by the arrow — the value of the scale division.

To determine the centering it is necessary to know the weight

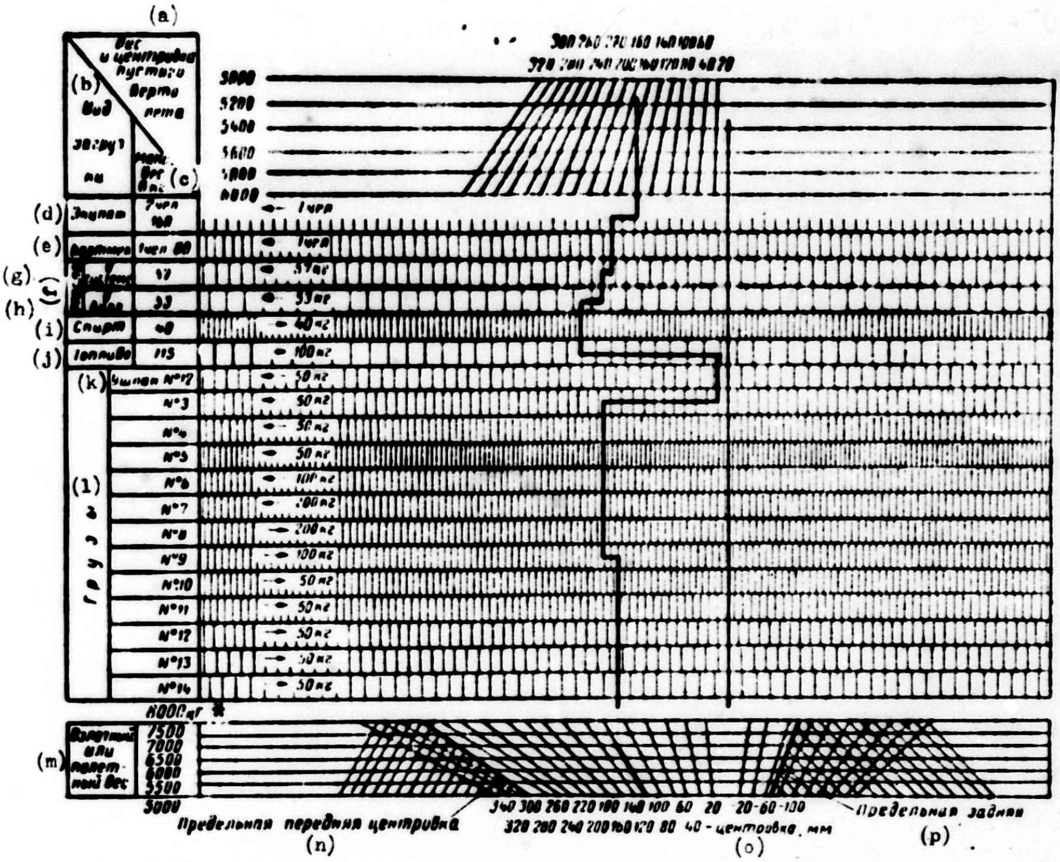

Fig. 106. Centering graph of the Mi-4 helicopter in the transport version.
KEY: (a) Weight and centering of an empty helicopter; (b) Type of loading; (c) Maximum weight in kg; (d) Crew; (e) Flight engineer; (f) Oil; (g) In system; (h) In tank; (i) Alcohol; (j) Fuel; (k) Frame; (l) Loads; (m) Takeoff or flying weight; (n) Maximum forward centering (o) Centering, mm; (p) Maximum rear centering.
*sic кГ = kgf].
Designations: кг = kg; цел = person

of the empty helicopter, its centering, magnitude and position of the placed load, and also servicing by fuels and lubricants. The weight of the empty helicopter and its centering must be taken from the logbook of the helicopter.

Example: The weight of an empty helicopter is 5190 kg, centering of an empty helicopter – 139 mm, crew of 2 persons – 160 kg, oil in system – 57 kg, oil in the tank – 53 kg, fuel – 715 kg, load at the third frame – 600 kg, load at the ninth frame – 200 kg. Takeoff weight is calculated and it will be equal to 5190 + 160 + 57 + 53 + + 715 + 600 + 200 = 6975 kg. On the upper grid we find the point corresponding to the weight of an empty helicopter of 5190 kg and centering, 139 mm. From this point we drop a perpendicular on the "crew" scale and draw a horizontal line in the direction of the arrow on two divisions. After that we drop a perpendicular on the scale "Oil in the system" and plot along the horizontal one division in the direction of the arrow. Further reading is also produced, only omitting scales on which there are no loads. Finally we drop a perpendicular on the lower grid to the horizontal line, corresponding to the takeoff weight of 6975 kg. From the obtained point we draw a line in parallel with the slanted line and read the centering. It will be equal to 120 mm. The centering does not fall outside the permissible limit of centerings. If centering falls outside the permissible limits, it is necessary to transfer the loads to another frame and repeatedly determine the centering.

To determine centering in landing, it is necessary to plot on the "Fuel" scale divisions corresponding to the remaining fuel at the moment of landing and also consider the weight on other scales, if loading will be transfered at the moment of landing. Then also drop a perpendicular on the lower grid to the horizontal line corresponding to the landing weight of the helicopter, and then read the centering.

The additional capacity for fuel, a tank of 500 ℓ, is set so that its center of gravity almost coincides with the center of gravity of the empty helicopter, and with any servicing the centering of the helicopter in practice almost does not change, and therefore during calculation of the centering this capacity is not taken into account; only the weight of the drum and fuel is introduced, which enters into the flying weight of the helicopter.

Along the lateral axis of the helicopter loads must be placed symmetrically. If, however, the load is asymmetric, then it is desirable to place its center of gravity to the left side of the longitudinal axis for obtaining great reserve of deflection of control stick to the left.

If passengers are transported in a helicopter of transport version on folding seats, then the centering of the helicopter is determined by this graph, but in this case it is necessary to consider places of the passengers by numbers of the frames corresponding to the number of the seat, according to Table 6 and Fig. 107.

Table 6.

Number of seat	1 and 16	2 and 15	3 and 14	4 and 13	5 and 12	6 and 11	7	8	9 and 10
Number of frame	2	4	5	7	8	9	10	12	13

Note: The moving of one person from the front section of the cargo cabin to the rear part (door of the cargo cabin) displaces the centering back 35 mm.

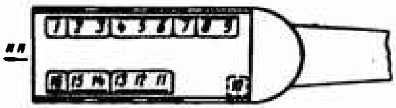

Fig. 107. Distribution of seats in the cargo cabin of the Mi-4 transport helicopter.

To determine the centering when transporting cargo on the external suspension, it is necessary to use the centering graph, shown in Fig. 106. With this it is necessary to consider that the load on the external suspension is located strictly along the axis of the rotor shaft, which is plotted on the centering graph by a vertical line through the whole graph.

The Mi-4 helicopters in the passenger version are made in 10-, 11- and 13-seat versions. For each of these helicopters separate centering graphs are developed. Figure 108 gives a centering graph for an 11-seat Mi-4 passenger helicopter. The centering graph for the passenger version is constructed on the same principle as the graph for the transport version, only scales are shown for numbers of the seats. Centering by this graph is determined by the same method as by the graph for the transport helicopter, but with taking into account the location of seats in the passenger compartment (Fig. 109).

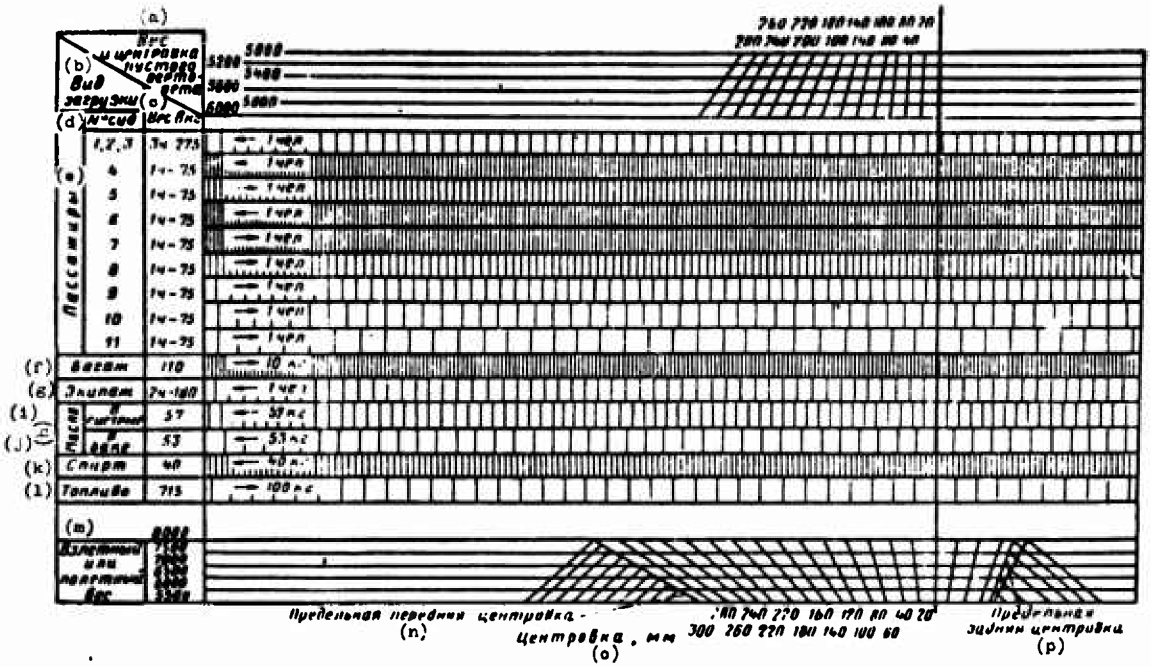

Fig. 108. Centering graph of the Mi-4 passenger helicopter (11-seat versions).
KEY: (a) Weight and centering of the empty helicopter; (b) Type of loading; (c) Weight in kg; (d) No. of seat; (e) Passengers; (f) Luggage; (g) Crew; (h) Oil; (i) In system; (j) In tank; (k) alcohol; (l) Fuel; (m) Takeoff or flying weight; (n) Maximum forward centering (o) Centering, mm; (p) Maximum rear centering.
Designations: кг = kg; цел = person.

When transporting passengers less than the maximum, it is necessary to place them in the front seats, leaving the rear seats free.

Finally centering can be determined in conditions of hovering both by the position of the control stick in a longitudinal relation and by readings of longitudinal and lateral trim tabs. Centering will not fall outside the limits of that permissible, if when hovering with a headwind and with completely removed pressure from the control stick the deflection by indicators of the longitudinal trim tab does not exceed 0.5-1.5 of the division forward, and of the lateral, 0-0.5 of the division to the right. But for every Mi-4 helicopter these readings can be different.

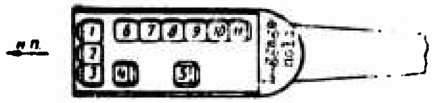

Fig. 109. Location seats in the passenger cabin of the Mi-4 helicopter (11-seat version).

3. Lateral Balancing

Transverse and directional balancing of the helicopter are closely connected with each other and comprise lateral balancing of the helicopters. On a single-rotor helicopter lateral balancing can be carried out without slip with a right bank or without a bank but with left slip.

Let us consider separately both cases of lateral balancing.

Lateral balancing without slip. Flight without slip can be performed only in the case when the lateral component of the aerodynamic force Z_B, acting to the right in powered flight, is equal to the thrust of the tail rotor $T_{X.B}$, which acts to the left. The aerodynamic force of the rotor R should be deflected from the axis of the hub by angle b_1 (coefficient of flapping motion, Fig. 110). For lateral balancing of the helicopter the following equality of moments should be observed:

$$Z_B h_1 + M_{x_{BT}} = T_{X.B} h_2 \quad \text{or} \quad R \cdot Z_1 + M_{x_{BT}} = T_{X.B} h_2.$$

Such an equality of moments can only occur with a right bank since arms h_1 and h_2 are almost equal in value, but to the right the inertial moment of the hub acts owing to spacing of the flapping hinges – $M_{X_{BT}}$. A bank will cause the component of weight G_2 equal to G sin γ. Only now the equality of lateral forces along lateral axis will be observed:

$$T_{X.B} = Z_B + G_2.$$

As is already known, in conditions of hovering the cone of rotation of the rotor and its aerodynamic force R are not independently deflected to the right, and therefore it is necessary to deflect them by the plate of the cyclic pitch control with the help of the control stick, which the pilot does. Then the lateral force Z_B and component of weight G_2 will appear, which will balance the thrust of the tail rotor.

With an increase in flight speed the cone of rotation and aerodynamic force of the rotor, due to flapping motions and the presence of the flapping control, are deflected to the right, and the lateral force is increased at the same position of the plate and control stick as that when hovering. Now, in order that lateral forces Z_B and G_2 do not exceed the thrust of the tail rotor $T_{X.B}$, the lateral force Z_B must be decreased with the help of the plate of the cyclic pitch control and the control stick, deflecting them from right position to the left.

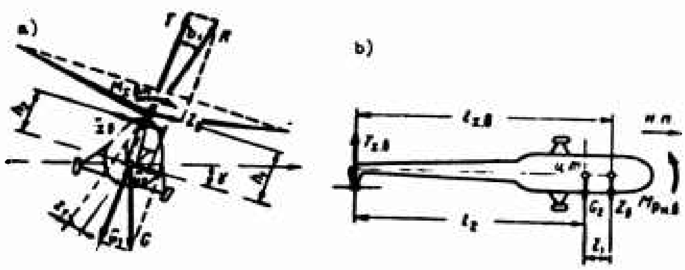

Fig. 110. Lateral balancing of the helicopter without slip: a) lateral balance; b) directional balancing.

Consequently, for lateral balancing of the helicopter at various speeds of powered flight a different position of the plate of the cyclic pitch control and control stick in a lateral relation is required. For lateral balancing of the helicopter in all flight conditions for the Mi-4 helicopter movement of the plate of the cyclic pitch control is set in a lateral relation at the following: to the right, 4°, and to the left, 4° 20'.

Figure 111 gives balancing curves of the necessary deflection of the plate of the cyclic pitch control η° in a lateral relation from the speed of flight V in the rate of climb and in autorotation (broken) with three centerings x_T = -20 mm, x_T = 25 mm, and x_T = 180 mm for the Mi-4 helicopter. According to the balancing curves, it is clear that a high flight speed great deflection of the plate of the cyclic pitch control to the left is required. The influence of centering on the necessary deflection of the plate of the cyclic pitch control in a lateral relation for powered flights is insignificant, and there they are not considered here.

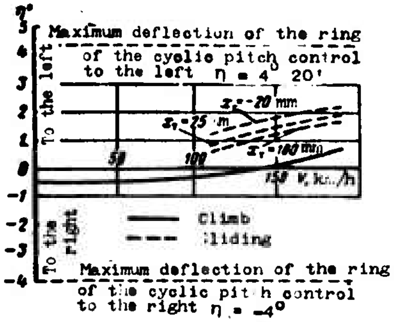

Fig. 111. Necessary deflections of the cyclic pitch control in a lateral direction as a function of speed at various centerings for the Mi-4 helicopter.

In autorotation the thrust of the tail rotor is directed to the right. Therefore, for its balancing it is required to direct the lateral component of the aerodynamic force Z_B to the left. In connection with this it is necessary to deflect the cone of rotation of the rotor and aerodynamic force R to the left with the help of the cyclic pitch control. In Fig. 111 it is clear that in autorotation greater deflection of the plate is required to the left than that for powered flight.

Figure 112 gives a curve of the interconnection of the deflection of the plate of the cyclic pitch control and control stick in a lateral direction for the Mi-4 helicopter. As can be seen from the curve, with a neutral position of the control stick in a lateral position the plate of the cyclic pitch control is deflected to the left 20'. Such a deflection of the plate is attained upon adjustment of the lateral control. It is necessary that at various limiting deflections of the plate in a lateral position (4° 20' and 4°) the control stick should have an identical movement. An increase in the movement of the plate of the cyclic pitch control to the left by 20' is provided for obtaining a sufficient reserve of deflection of control vanes in autorotation of the rotor, especially for landing in these conditions with a left wind and with maximum rear centering

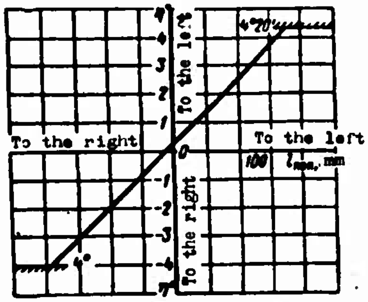

Fig. 112. Interconnection of the deflection of the plate of the cyclic pitch control η° and movement of control stick in a lateral direction for the Mi-4 helicopter.

of the helicopter (see Fig. 111).

In hovering the bank γ consists of about 2°, with an increase in speed up to the economic; for example, in horizontal flight the bank decreases because of a decrease in lateral moment of the hub $M_{x_{BT}}$. This occurs because the required power and reactive moment decrease, and therefore the necessary thrust of the tail rotor decreases, and this means the deflection of the cone of rotation of the rotor to the right (Fig. 113, position 1).

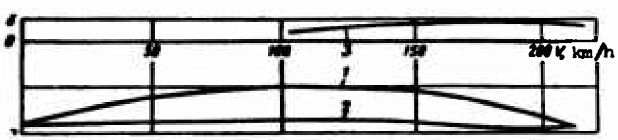

Fig. 113. Dependence of the angle of the angle of bank of the helicopter on the speed of flight: 1 — horizontal flight; 2 — climb; 3 — autorotation.

At the economic speed the bank consists of about 1°. With a further increase in speed the band is again increased, since the required power increases. With this the reactive moment of the rotor is increased, the necessary thrust of the tail rotor increases, and for its balancing great deflection of the cone of rotation of the rotor is required to the right for obtaining great lateral force Z_B. This leads to an increase in the moment of the hub owing to the spacing of the flapping hinges $M_{x_{BT}}$, which increases the bank.

On conditions of autorotation the helicopter has a small left bank, since the cone of rotor rotation is deflected to the left, and the lateral moment of the hub due to spacing of the flapping hinges is directed to the left (Fig. 113, position 3).

Directional balancing of the helicopter during flight without slip is provided by the equality of moments acting around the vertical axis (see Fig. 110b):

$$M_{p_{H.B}} = T_{X.B} l_2 + Z_B l_1$$

or

$$M_{p_{H.B}} = T_{X.B}(l_2 + l_1) = T_{X.B} l_{X.B},$$

since the thrust of the tail rotor $T_{X.B}$ can be approximately equated to the lateral force Z_B in view of small value of the component of weight G_2. Here the equality of the moments is given with the location of the center of gravity of the helicopter behind the axis of the rotor shaft (rear centering). During location of center of gravity ahead of the axis of the shaft (forward centering), the force Z_B creates a moment in the direction of the reactive moment of the rotor $M_{p_{H.B}}$.

In various flight conditions and at various speeds different power for flight is required, and, consequently, a difference reactive moment of the rotor is obtained. Therefore, with a constant arm of the thrust of the tail rotor for directional balancing a different thrust of the tail rotor will be required:

$$M_{p_{H.B}} = T_{X.B} l_{X.B};\ T_{X.B} = \frac{M_{p_{H.B}}}{l_{X.B}};\ M_{p_{H.B}} = \frac{716.2N}{n_{H.B}};\ T_{X.B} = \frac{716.2N}{l_{X.B} n_{H.B}}.$$

To ensure directional balancing in all flight conditions by means of creating sufficient thrust of the tail rotor, the range of pitch to the tail rotor is set. For the tail rotor of the Mi-4 helicopter, for example, the type V-531-Kh3, the setting angles on the radius equal to 1 m are maximum, 20° 15', and minimum, 8° 15'.

In conditions of hovering the pilot deflects the right pedal forward for creating great pitch to the tail rotor. With an increase in speed of flight the required power decreases, and in connection with this the reactive moment decreases. This means less thrust of the tail rotor will be required, and therefore with an increase in speed of flight the right pedal should be moved back from the front position, and at speeds close to being economic the pedals should occupy a neutral position. With a further increase in speed although the required power is increased the left pedal moves forward, since the slanting airflow of the tail rotor continues to increase its thrust. Only at speeds close to the maximum is it already necessary to increase again the pitch to the tail rotor, in view of the drop in its thrust and increase in reactive moment of the rotor.

In autorotation the thrust of the tail rotor should be directed to the right, and therefore for directional balancing negative setting angles are necessary to blades of the tail rotor, which is done by deflection of the left pedal forward. Figure 114 shows curves of the necessary angle of setting of blades to the tail rotor as a function of flight speed in the rate of climb (full throttle) and in autorotation. In intermediate flight conditions between gliding and climb with full throttle there will be intermediate required setting angles of blades of the tail rotor.

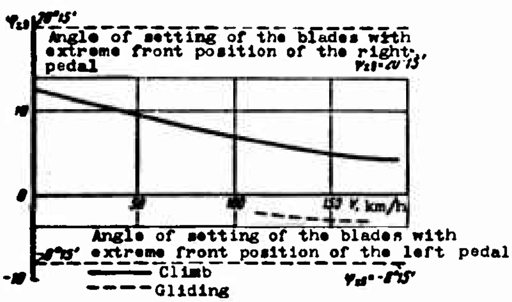

Fig. 114. Change in the required angle of setting of blades of the tail rotor as a function of flight speed.

Flight without slip with a right bank is the most rational, since for such a flight less power is required, the aerodynamic drift angle [US_{aer}] ($yC_{aэp}$) is absent, and therefore there is not required additional its calculation upon calculating the flight course. But it is rather complicated to fulfill practically such a flight, since it is impossible to hold the needed bank for a given flight speed. The pilot usually tries to accomplish flight without a bank, but then it is obtained with a left slip.

Lateral balancing with slip and drift angle. Lateral balancing with a left slip provides for flight of the helicopter without a right bank. In this case to ensure lateral balancing, moments around longitudinal axis should be balanced in the absence of a bank (Fig. 115a):

$$Z_{в}h_1 + M_{x_{вт}} = T_{х.в}h_2 \text{ or } R\cdot Z_{т} + M_{x_{вт}} = T_{х.в}h_2.$$

If one were to consider that arms h_1 and h_2 are almost equal, then the sum of moments $Z_{в}h_1 + M_{x_{вт}}$ is more than moment $T_{х.в}h_2$. Therefore, in order that there is no bank, and the moments are equal, it is necessary that the lateral force Z_B is less than the thrust of the tail rotor $T_{X.B}$. This means that during flight without a bank lateral forces $T_{X.B}$ and Z_B remain unbalanced, i.e., the thrust of the tail rotor is greater than the lateral force Z_B. Consequently, there will appear a left slip at which the helicopter will be flowed past by airflow in front and on the left with an angle of slip β (Fig. 115b).

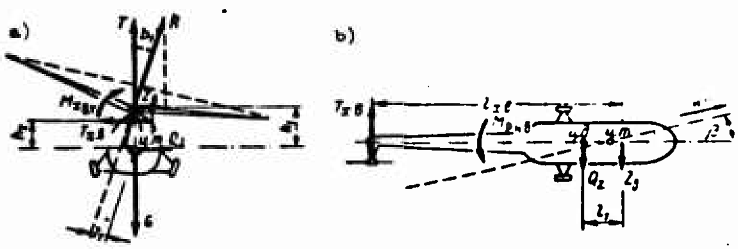

Fig. 115. Lateral balancing of the helicopter with a left slip without a bank: a) lateral balance; b) directional balancing.

In steady flight there should be an equality of moments around the longitudinal and lateral axes. Lateral airflow of the helicopter on the left generates a lateral force on the fuselage Q_z, which balances the unbalanced forces:

$$T_{х.в} = Z_{в} + Q_z.$$

With this the lateral force Q_z is applied almost to the center of gravity and does not create an additional moment. With an increase in the speed of flight the lateral force Q_z will be increased, and then for the observance of lateral balancing the angle of slip should decrease, which will lead to a decrease in lateral force Q_z, i.e., it will be maintained constant.

Directional balancing without a bank with left slip is provided by the equality of moments:

$$T_{x.v} l_{x.v} = M_{p_{n.v}} + Q_z l_1, \quad \text{hence} \quad T_{x.v} = \frac{M_{p_{n.v}} + Q_z l_1}{l_{x.v}}.$$

From this it is clear that the tail rotor should balance not only the reactive moment of the rotor but also the moment of the lateral force Q_z. On this basis thrust of the tail rotor during flight with slip must be greater than during a flight without slip. Consequently, an increase in thrust of the tail rotor will be required by moving the right pedal forward, especially at low speeds when the slip is great. Furthermore, during flight with a slip to the left greater deflection of the plate of the cyclic pitch control to the left is required, and a left slip will lead to an increase in deflection of the cone of rotation of the rotor to the right. On this basis greater deflection of control stick to the left is required. For balancing the additional drag Q_z and creating great thrust of the tail rotor $T_{X.B}$, high power will be required and the fuel consumption will be increased.

Flight without a right bank with a slip carries the helicopter from the assigned flight course by the magnitude of the angle of slip β, which is called the drift angle US_{aer}. With an increase in speed of flight the aerodynamic drift angle decreases, since the lateral force Q_z is increased (see Fig. 115). An increase in this force leads to the necessity of greater deflection of the cone of rotation of the rotor to the right by the control stick; here the lateral force Z_B increases in the absence of a bank, and the slip to the left decreases. The change in aerodynamic drift angle from the flight speed is shown in Fig. 116.

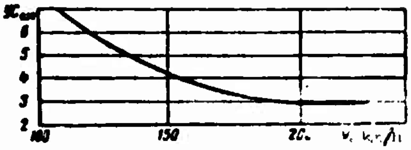

Fig. 116. Change in aerodynamic drift angle from the flight speed for the Mi-4 helicopter.

With the fulfillment of navigational calculations for increasing the accuracy of helicopter piloting, especially during flights above an area without landmarks or poor landmarks and during flights at night, it is possible to consider the aerodynamic drift angle with a minus sign. But in practice it is rather difficult and almost impossible to fly accurately without a bank with such small angles of slip, as it was impossible to fly without slip with small bank angles. The pilot ordinarily flies first without a bank, then with a right bank without slip, and then with a right bank greater than that shown, giving a right slip or with a left bank, giving a drift angle greater than that during flight without a bank. All of this leads, naturally, to additional errors in the flight course, which are obtained for other reasons.

Consequently, flight with a left slip requires great power and great reserve of deflection of the control vanes, requires calculation of the aerodynamic drift angle, and in practice it is difficult to execute. It can be accurately carried out only by flight tests with the application of special accurate instruments. Calculation of the drift angle with such a flight, although it theoretically increases the accuracy of helicopter piloting, is practically of no value in view of its small magnitude and the impossibility to fly the helicopter accurately without a bank. Therefore, upon the fulfillment of navigational calculations both for visual flights so for instrument flights it is inexpedient to consider it.

In flight, by determining the drift angle depending upon wind for controlling the flight course by the visual method or with the help of electronic means, the aerodynamic drift angle, if it was owing to the balancing of the helicopter, will enter into the magnitude of the general drift angle by the magnitude of which the flight course is corrected.

For aircraft there is also aerodynamic drift angle owing to the reactive moment of the propulsion systems, but in practice it is not considered in view of the small value.

§ 2. Controllability

Controllability of the helicopter is called the ability of it to revolve around three axes and to change the other attitudes with the help of the appropriate control levers, i.e., the ability to change flight conditions by will of the pilot.

According to the three axes of rotation the helicopter has three forms of controllability: longitudinal, lateral, and directional. All the indicated forms of controllability of a single-rotor helicopter were examined earlier. In this section effectivness, sensitivity, delay and independence of control are examined, as well as forces transmitted to the control levers.

1. Control Effectiveness

By control effectiveness it is necessary to understand as the appearance of moments revolving the helicopter around the axes upon deflection of the appropriate control levers. The greater these moments are in value, the greater the effectiveness of the control. With the deflection of the cone of rotation of the rotor and direction of action of its aerodynamic force aerodynamic moment around the center of gravity of the helicopter appears, which forces the helicopter to revolve around the corresponding axis. In addition to the aerodynamic moment the mass moment of the rotor hub will also act owing to the action of centrifugal forces of the blades and the presence of spacing of the flapping hinges.

The greater the distance from the rotor to the center of gravity of the helicopter and the greater the spacing of the flapping hinges, the greater the effectiveness of the controlling, and this means better controllability by the helicopter, which allows increasing the range of permissible centerings or decreasing the necessary deflection of the plate of the cyclic pitch control and movement of the control stick.

Numerically the control effectiveness is determined by the degree of effectiveness of control μ_δ, which is determined by the ratio of the moment acting around the center of gravity to the angle of deflection of the plate of the cyclic pitch control or to the magnitude of movement of the cyclical pitch lever. Thus, for example, for single-rotor helicopter the degree of control effectiveness is determined:

$$M\delta = \frac{M_{откл}}{\delta},$$

where $M_{откл}$ — effective moment acting around the center of gravity; δ — deflection of the plate of the cyclic pitch control.

For the Mi-4 helicopter the degree of control effectiveness is about 450 kg-m. Consequently, the degree of control effectiveness is the number showing how much the effective moment will be changed with deflection of the plate of the cyclic pitch control of 1°. With respect to the magnitude of the degree of control effectiveness the conclusion can be made that controllability of a helicopter is no worse, if is not better than the controllability of an aircraft.

2. Control Sensitivity

By control sensitivity one should understand as the ability of a helicopter to revolve around its axes with definite angular velocity upon deflection of the corresponding controls.

Sensitivity is proportional to control effectiveness: the more the effectiveness, the higher the control sensitivity. Sensitivity is numerically estimated by the magnitude of maximum angular velocity of the rotation of the helicopter around its axes upon the deflection of the plate of the cyclic pitch control or pitch of the main and tail rotors by 1°, or movement of the lever and pedals by 1 mm. Therefore, sensitivity of the control ω_δ is determined by the division of angular velocity of rotation of the helicopter by the angle of deflection, for example, the plate of the cyclic pitch control with action by the control stick

$$\omega_\delta = \frac{\omega}{\delta},$$

where ω – angular velocity of rotation.

Control sensitivity depends not only on effectiveness but also on the degree of damping: the less the damping, the higher the sensitivity of controlling and conversely. Light helicopters possess high sensitivity, since they have little damping, which creates a definite inconvenience in control. For the Mi-4 helicopter the sensitivity is moderate, which creates especially great convenience in the control.

3. Delay of Control

As is known, for an aircraft there is no delay in control, or it is insignificant. Such a position is explained by the fact that the control vanes for an aircraft are at a great distance from the center of gravity and therefore the insignificant change of aerodynamic forces on the control vanes is caused by the great moments, which without delay revolve aircraft around the corresponding axes.

In the control of the rotor, especially heavy helicopters, a delay of control exists, since moments are created because of the small arms by great forces. Therefore, in order to change the direction and magnitude of the great forces, it is necessary to surmount the mass inertia of the rotor and its gyroscopic effect, and also change the direction and speed of the large mass of air passing through the rotor, which requires a definite time.

In view of the presence of the delay of control and because of the inadequate stability, it is necessary to control the helicopter by repeated advanced motions of the control stick: the control stick deflected in a fixed direction and, not waiting for the helicopter to occupy a new position, the control stick returns to the opposite direction, but at a smaller magnitude than it was deflected before this. Motions by the control stick at the same time should be short.

4. Independence of Control

A distinctive peculiarity of the control of a single-rotor helicopter in comparison with an aircraft or a coaxial helicopter is that for the creation of any new flight conditions it is necessary to actuate all control levers, since with the deflection of any lever the helicopter is unbalanced and revolves around three axes. Thus, for example, in order to pass from hovering to vertical climb along a strictly vertical trajectory with a constant direction, it is necessary to lift the "pitch-throttle" lever upwards. The helicopter will start climb but simultaneously will start to turn to the left because of the increasing reactive moment of the rotor. In order to prevent the turn, it is necessary to deflect the right pedal forward. Then the thrust of the tail rotor will become larger than the lateral force, and the helicopter will start move to the left, i.e., in the direction of action of thrust of the tail rotor. To prevent this movement it is necessary to deflect the control stick to the right in order to increase the lateral force.

Another example. To increase the speed of horizontal flight up to the economic it is not enough just to deflect the control stick forward and to change the power: it is necessary, furthermore, to change the position of the pedals and also the position of the control stick in a transverse relation. With such acceleration of speed a decrease in power will lead to a decrease in reactive moment, and this will require motion of the left pedal forward. An increase in deflection of the cone of rotation of the rotor to the right in connection with an increase in speed and a decrease in thrust of the tail rotor will cause a right slip, and to preventing it will require moving the control stick to the left. The same coordinated motions by all control levers should be in all transient flight conditions of a single-rotor helicopter, which is the reason of the more complicated control of this helicopter as compared to control of an aircraft or a coaxial helicopter.

Consequently, in the control of a helicopter the full dependence of one form of control on the other forms exists, which is a considerable deficiency of it.

5. Forces on Control Levers

It is known that to control levers of an aircraft aerodynamic loads are transmitted from control surfaces. These loads change with respect to speed, and therefore the pilot senses the speed according to the change in pressure transmitted to the control levers. For high-speed and heavy aircraft to decrease the pressure on control levers, hydraulic and other systems are provided.

On the helicopter the "pitch-throttle" lever and control stick are united with the cyclic pitch control, and the pedals are connected with the pitch control system of the tail rotor.

The "pitch-throttle" lever is united with a slider and receives forces from blades of the rotor, which try to decrease the setting angles and to lower the slider downwards. The control stick is united with the plate of the cyclic pitch control through an external ring of the universal joint with the help of two rockers and rods of longitudinal and lateral control and receives forces from blades, which try to change the setting angles. Additionally in forward flight the blade advancing on the flow will induce pressure on the plate of the cyclic pitch control and control stick more than the blade retreating from the flow; and this will elicit driving of the control stick.

Forces on all control levers are very great, especially for heavy helicopters. Therefore, in the control of a helicopter special systems are applied which completely or partially remove these forces. The systems make it possible with the help of all control levers to hold the blades of the main and tail rotors with the necessary setting angles, and this allows maintaining the definite general and cyclical pitch.

Provided on the Mi-4 helicopter is an irreversible hydraulic system, which removes completely all forces from all the control levers.

For Mi-4 helicopters which do not have an automatic pilot in the circuit of longitudinal, lateral and foot control, three BU-10P boosters hydraulic control (booster) are connected, and in the general pitch control circuit the BU-10Sh booster is connected. All these boosters have identical characteristics: working movement of the actuating rod, 50 mm (on 25 mm on both sides of the neutral position), full movement of this rod is 54 mm, the distributive valve has a movement of 2.3-2.6 mm, and at the place of its connection with the rocker of the control circuit, not more than 1.2 mm; at maximum pressure in the hydraulic system of 65 kgf/cm^2 on the actuating rod a maximum force of 1100 kgf is developed. The BU-10Sh booster develops a maximum force of 1250 kgf on the actuating rod.

If the helicopter is supplied with an automatic pilot, then in the circuit of longitudinal, lateral and directional control instead of boosters RA-10 control aggregates are connected. With a disconnected autopilot the control aggregates fulfill the role of the boosters. Characteristics of RA-10 control aggregates are precisely the same as those of BU-10P boosters. With the failure of the hydraulic system the actuating rods of control aggregates and hydraulic boosters operate as rigid rods in a control system, and therefore there is a certain possibility of controlling the main and tail rotors.

So that the pilot will sense flight of helicopter by forces transmitted to the control levers, i.e., to let him judge the necessary direction of action by the control levers, in the system of longitudinal, transverse and directional control spring loading mechanisms are included. To remove forces from control levers from these loading springs in any steady flight electrical mechanisms MP-100L (trim tabs) are provided. Loading mechanisms in combination with the MP-100L electrical mechanisms and the electrical control system comprise the so-called system of automatic trimming — autotrimming.

Figure 117a shows the dependence of forces on the control stick in a longitudinal direction from the angle of deflection of the plate of the cyclic pitch control χ, and this means movements of the control stick with a neutral position of the trim tab and with extreme position of it forward and back. As can be seen from the figure, it is possible to remove the force from the control stick down to zero in a longitudinal direction in a great range of deflection of the plate of the cyclic pitch control from 3° (back) to -2° 20' (forward), i.e., almost in the whole range of the necessary movement of the plate of the cyclic pitch control and in the whole speed range of the helicopter and permissible limit of longitudinal centering.

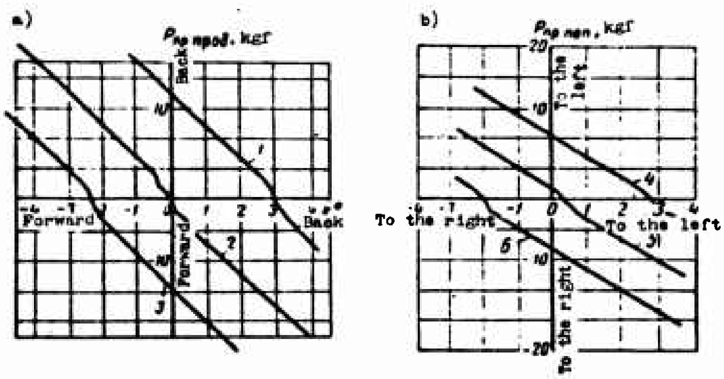

Fig. 117. Dependence of forces on the control stick of the rotor appearing from loading springs $P_{\text{пр}}$ upon its deflection: a) in a longitudinal direction; b) in a lateral direction; 1 — extreme position back; 2 — neutral position; 3 — extreme position forward; 4 — extreme position to the left; 5 — neutral position; 6 — extreme position to the right.

Figure 117b shows such a characteristic of the mechanism of loading only in the circuit of lateral control (deflection of the plate of the cyclic pitch control, η).

The "pitch-throttle" lever and throttle control do not have similar devices for loading, since special mechanisms of locking in any assigned position are provided for them.

§ 3. Stability

1. General Determinations

Stability of the helicopter is called its ability independently to restore the disturbed equilibrium after cessation of the action of force causing this disturbance. For an analysis of the stability of the helicopter, just as with aircraft, the stability is subdivided into static and dynamic.

By static stability it is necessary to understand the ability of the helicopter to return to the initial position after the action of the force causing the disturbance of equilibrium is ceased. The helicopter is considered statically stable if it tries to return to the initial state after cessation of the action of force causing the disturbance of equilibrium around axes or the change in speed, direction, and appearance of slip. The helicopter is considered statically unstable if it tries to depart from the assigned position around its axes or change the assigned speed, and direction, and enter into a slip. The helicopter is considered neutral (indifferent) if it remains in the assigned position with respect to the axes of rotation or speed direction and without slip. Consequently, stability is the stability of the position of the helicopter.

Dynamic stability examines the character of oscillations of the aircraft or helicopter around the three axes, which they accomplish relative to the former position from which they were brought out by some method. The helicopter is considered dynamically stable if after disturbance of the equilibrium relative to any axis the amplitude of oscillations decreases (fades) with time. The helicopter is considered dynamically unstable if the amplitude of oscillations increases with time.

This means that the dynamic stability characterizes the behavior of the helicopter during the whole time of the perturbed motion, i.e., this is stability of motion.

Static and dynamic stability appear and act simultaneously, sometimes causing one another.

The Mi-4 helicopter is given a certain static stability; however, the dynamic stability is too insufficient, and this does not permit accomplishing flight, even short-term, with an abandoned control.

According to the three axes of rotation three forms of stability exist: longitudinal, lateral, and directional. Transverse and directional stability comprise lateral stability.

2. Longitudinal Stability

Longitudinal stability is the ability of the helicopter independently to restore longitudinal equilibrium after cessation of the action of force causing the disturbance of equilibrium. The longitudinal stability is influenced by the character of the change in moment of the rotor, fuselage, hub and stabilizer with disturbance of the longitudinal equilibrium. The basic influence on longitudinal stability of the helicopter is caused by moments of the rotor and stabilizer.

Static stability of the helicopter is subdivided into stability with respect to speed and angle of attack (overload) because with a steady state of flight the disturbance of it by external forces or by the pilot himself will lead to a change in the speed or angle of attack of the rotor, and the change in angle of attack – to a change in overload.

The aircraft is usually stable in speed, since the change in speed of an outside force leads to a change in lift in proportion to the speed, the aircraft passes to climb or descent and the speed is therefore restored.

The rotor also gives stability to the helicopter with respect to speed: with an increase in flight speed of the helicopter for some reason the deflection of the cone of rotation and of its aerodynamic force back is increased, which leads to the creation of a pitching moment decreasing the speed of flight; with a decrease in speed the deflection of the cone of rotation of the rotor decreases, the diving moment is created, and there occurs a tendency of the helicopter to increase its speed. Furthermore, a change in the deflection of the cone of rotation owing to the change in speed because of the change in flapping motions also leads to a change in the moment of the hub because of the spacing of the flapping hinges in the same direction, which improves the static longitudinal stability of the helicopter.

As flight tests showed, the Mi-4 helicopter possesses insignificant longitudinal stability with respect to speed, and in climb in normal rating of the engine operation it is even neutral with respect to speed.

An aircraft is usually stable with respect to the angle of attack, since the change in the angle of wing setting and stabilizer leads to a great change in the moment of the stabilizer as compared to the moment of the wing and therefore the former angle of attack (overload) is restored. The rotor of the helicopter makes the helicopter unstable with respect to the angle of attack (overload). An increase in the angle of attack of the rotor leads to an increase in aerodynamic force, and in connection with this flapping motions of the blades are increased, which lead to great deflection of the cone of rotation of the rotor and of the direction of action of its aerodynamic force back. This, in turn, increases the pitching moment, which leads to an even greater increase in the angle of attack of the rotor. With a decrease in angle of attack (overload) of the outside force a reverse phenomenon will occur: the angle of attack of the rotor will approach a further decrease.

In hovering and forward flight the longitudinal stability is partially ensured owing to the appearance of restoring moments in the process of the actual disturbance of equilibrium — damping.

<u>The essence of damping</u> consists in the following. With the influence of an outside force on the helicopter (gust of wind), the cone of rotation of the rotor and the direction of action of its aerodynamic force are not deflected the first time in view of

inertness and gyroscopic properties of the rotor (axis of rotation maintains the dir ction), i.e., the helicopter is like a pendulum suspended to the rotor. In connection with the influence of the outside force between the direction of the aerodynamic force and center of gravity of the helicopter arm a will appear (Fig. 118a), and therefore there will appear the moment restoring the equilibrium. The rotor hub is banked together with the helicopter, and then owing to the spacing of the flapping hinges from centrifugal forces of blades the mass moment of the hub ($F_{цб}h$) will appear, which will also restore the equilibrium of the helicopter. With this it is necessary to consider that such moments will act only with short-term action of the force on the helicopter,which will lead it out of the state of equilibrium. If, however, the external forces act on the fuselage of the helicopter for a long time, then the deflected fuselage will lead beyond the rotor and its aerodynamic force, since together with the body of the helicopter the cyclic pitch-control mechanism will be deflected with respect to the cone of rotation of the rotor. Such a position will lead to the beginning of flapping motions (if helicopter is in hovering) or to their change (if the helicopter is in forward flight) and, together with this, to the deflection of the cone of rotation of the rotor and direction of action of the aerodynamic force of the rotor beyond the fuselage of the helicopter. Then the aerodynamic force will continue the disturbance of equilibrium in the same direction, which is the outside force.

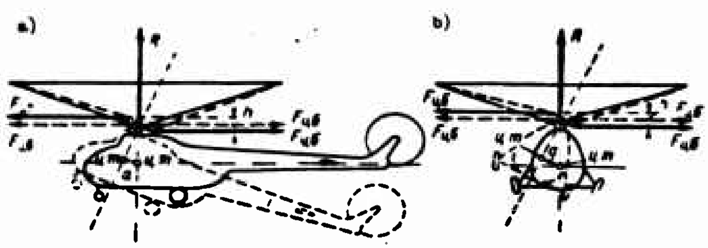

Fig. 118. Damping moments of the rotor:
a) longitudinal; b) lateral.

From this conclusion follows that the cyclic pitch-control mechanism gives instability to the helicopter. But if one were to consider that the process of deflection of the cone of rotation of the rotor and direction of action of the aerodynamic force beyond the fuselage occurs not at once but with a certain delay, then the body of the helicopter succeeds in restoring the equilibrium. In connection with this damping will appear, which will give a certain longitudinal and lateral stability, since the described effect appears in all directions. The magnitude of the damping moment will depend on the centering of helicopter along the vertical axis (y_T see Fig. 100) and on the magnitude of spacing of the flapping hinges: the low center of gravity of the helicopter is located from plane of rotation of the rotor and the greater the spacing of the flapping hinges, the greater the damping moments.

The stabilizer of the helicopter, especially in forward flight, is a powerful means ensuring the static longitudinal stability both with respect to speed and angle of attack, since the change of the latter leads to a change in the moment of the stabilizer restoring the disturbed equilibrium.

The fuselage of the helicopter gives instability in a longitudinal relation with respect to speed. This occurs because its moment in flight, taking into account airflow by the rotor and approach flow, is diving, and therefore the change in speed in any direction leads to a change in the moment of the fuselage in an unnecessary direction — to further disturbance of the equilibrium.

The tail rotor in practice does not affect longitudinal stability. Such neutral equilibrium occurs due to the fact that with an increase in flight speed its reactive pitching moment decreases, and because of the increase in longitudinal force of the tail rotor this moment is increased.

On the whole there is longitudinal stability of a single-rotor helicopter, but as compared to the stability of an aircraft it is still insufficient. Therefore, the pilot must hold the helicopter in a longitudinal relation almost by continuous, although insignificant, motions of the control stick.

3. Lateral Stability

Lateral stability is the ability of the helicopter to restore independently lateral equilibrium after cessation of the action of the force causing this disturbance.

The helicopter possesses lateral stability for these reasons: because of the same damping of the rotor, which appeared in a longitudinal relation (see Fig. 118b), and also owing to the action of the tail rotor and the obtaining of slip.

Lateral stability because of damping will depend, just as the longitudinal, on the magnitude of centering along the vertical axis (y_T – see Fig. 100) and the spacing of the flapping hinges: the more the centering and the greater the spacing of the flapping hinges, the higher the stability and conversely (see Fig. 118b).

As is known, the tail rotor is elevated above the tail boom. This is done in order to remove the tail rotor from land, to decrease right bank because of the action of lateral force in hovering and in forward flight, and also in order to carry it out of the flow proceeding from the rotor. But at the same time such an arrangement of the tail rotor leads to the fact that with the appearance of a left bank the tail rotor obtains an additional direct airflow on the left, which leads to a decrease in angles of attack of the blades and its thrust. In connection with this the moment of lateral force around the longitudinal axis will be greater than the moment of the tail rotor, and the helicopter will obtain a restoring moment. With the appearance of a right bank the phenomenon will be the reverse: the thrust of the tail rotor, acting to the left, will be increased, and also to the left the restoring moment will appear.

With the disturbance of the lateral equilibrium both in hovering and in forward flight, the helicopter will obtain a slip to the side of a bank. As a result of this slip, the cone of rotation of the rotor and direction of the action of its aerodynamic force are deflected to the opposite side of the slip, and the appearing moment restores the equilibrium.

On the whole the lateral stability of the single-rotor helicopter, just as the longitudinal, as compared to the stability of an aircraft is insufficient and requires its improvement.

4. Directional Stability

Directional stability of the helicopter is the ability to restore independently directional equilibrium after cessation of the action of the force causing this disturbance.

Directional stability in forward flight forward for a single-rotor helicopter is good and ensured by the tail rotor. The tail rotor serves not only for balancing of the reactive moment of the rotor and for realization of directional control, but it is a powerful lever of directional stability. Furthermore, the stability is provided because of the feathering properties of the helicopter.

With the appearance, for example, of a left slip the angles of attack of blades of the tail rotor decrease, the thrust of it also decreases, and the helicopter restores the equilibrium owing to the reactive moment of the rotor (Fig. 119a).

With the appearance of a right slip the angles of attack of the tail rotor and its blades are increased, the thrust increases, and the helicopter restores the disturbed equilibrium because of the increasing yawing moment of the tail rotor.

In flight the pilot senses the good directional stability, since the helicopter independently holds the selected direction and there is no need to depress the pedals.

In conditions of hovering in a calm the helicopter has indifferent directional equilibrium in view of the absence of additional airflow of the tail rotor, fuselage and tail boom.

When flying backwards and when hovering with a tailwind the tail rotor and fuselage with a tail boom create instability of the flight path (Fig. 119b). In this case with deflection, for example,

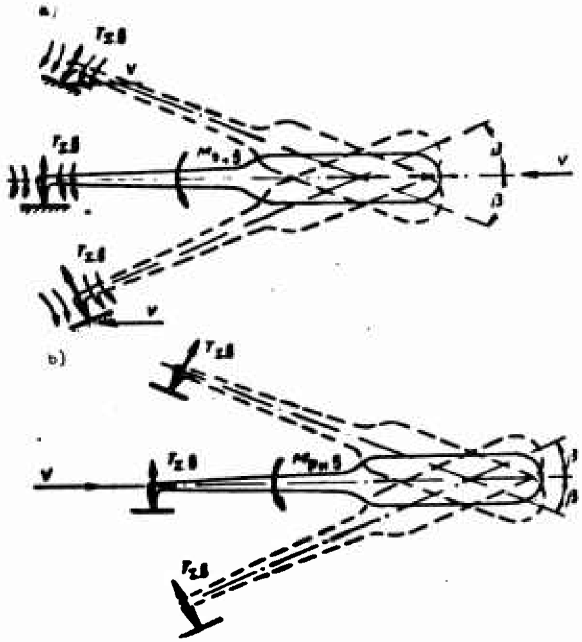

Fig. 119. Directional stability of the helicopter: a) during flight forward; b) during flight back or in hovering with a tailwind.

of the tail of the helicopter to the right, owing to the airflow from behind, the tractive force of the tail rotor decreases and the reactive moment of the rotor will continue the turn of the helicopter to the left, trying to set its nose into the flow. The turn will also be promoted by lateral pressure on the fuselage and tail boom. With deflection of the tail to the left, the increasing the thrust of the tail rotor and lateral pressure on the fuselage and tail boom will turn the helicopter to the right.

In view of the absence of directional stability of the Mi-4 flights backwards with a speed of more than 10 km/h and turns in hovering upwind at an angle of more than 90° with a wind over 5 m/s are forbidden.

APPENDIX

ACCEPTED MAIN ABBREVIATIONS AND SYMBOLS

Abbreviations

ГШ – flapping hinge;
ВШ – drag hinge;
ОШ – feathering hinge;
ц. т. – center of gravity;
ц. д. – center of pressure;
ц. ж. – center of rigidity;
КПД – efficiency
НВ – rotor
ХВ – tail rotor
$I_{р.в}$ $II_{р.в}$ – first and second rated altitudes of the engine
НП – direction of flight
$Н.В_р$ – direction of rotation

Characteristics of the Rotor

D – diameter of screw
d – minimum diameter of stream under the rotor (zones of reverse flow around)
R – radius of rotor
r – radius of element of blade
$F_{ом}$ – disk area
$F_{эф}$ – effective disk area
S – area of blade

H – geometric rotor pitch

H_a – rotor advance ratio

C – slip of rotor

A – angle of attack of rotor

α – angle of attack of wing and element of rotor blade

ϕ – setting angle of the element of blade (collective pitch) of rotor

$\phi_{х.в}$ – setting angle of tail rotor

ψ – azimuthal position of blade of rotor

β – flapping angle of blade of rotor

a_0 – angle of conicity of rotor

c – relative thickness of profile of blade

r – relative radius

b – chord of blade

Δ_ϕ – twist of blade

μ – characteristic of operating conditions of rotor

$r_{ц.т}$ – radius of center of gravity of blade

σ_1 – angle of regulator of stroke

K – characteristic of flapping control

Characteristics of the Helicopter

Θ – angle of descent (gliding) or climb

γ – angle of bank

ϑ – pitch angle

x_T – distance from center of gravity of helicopter to axis of rotor shaft along longitudinal axis (centering of helicopter)

y_T – distance from center of gravity of helicopter to plane of rotation along vertical axis

ω_δ – sensitivity of control

$yc_{аэр}$ – aerodynamic drift angle

δ – deflection of plate of cyclic pitch control

κ – deflection of plate of cyclic pitch control in a longitudinal direction

η – deflection of plate of cyclic pitch control in lateral direction

$H_{п.в}$ – ceiling of hovering of helicopter

Forces

$F_{р.з}$ – force of reaction of earth

$F_{тр}$ – frictional force of wheels against earth

R – full aerodynamic force of rotor

T – thrust of rotor

T_y – component of thrust of rotor perpendicular to flight path

T_x – component of thrust of rotor along flight path

T_z – lateral component of thrust of rotor in hovering conditions

Y – lift

Q – drag

$Q_в$ – longitudinal force of rotor (drag of rotor)

$Q_{окр}$ – circumferential force (drag to rotation of blade)

$R_л$ – resultant all forces acting on blade

ΔR – full aerodynamic force of element of blade

ΔY – lift of element of blade

ΔQ – drag of element of blade

ΔT – thrust of element of blade

$\Delta Q_{окр}$ – circumferential force of element of blade

$Q_{в_x}$ $Q_{в_y}$ – components of longitudinal force in continuous system of coordinates

$Z_в$ – lateral component of force $R_{нв}$ in coupled system of coordinates

$T_{х.в}$ – thrust of tail rotor

Z – distorting force on turn

$F_{цб}$ – centrifugal force

$F_{ин}$ – force of inertia

$F_к$ – coriolis force

$Z_{х.в}$ – lateral force of tail rotor

$Q_{х.в}$ – longitudinal force (resisting force) of tail rotor

Q_z – force of lateral drag

$Q_{ф}$ – drag of fuselage

Moments

$M_{кр}$ – torque

$M_{p_{н.в}}$ – reactive moment of rotor

$M_{p_{х.в}}$ – reactive moment of tail rotor

$M_{x_{пр}}$ – moment of average profile drag of blades of rotor

$M_{х.в}$ – moment of tail rotor

$M_{y_{х.в}}$ – yawing moment of tail rotor

$M_{x_{х.в}}$ – lateral moment of tail rotor

$M_{z_{ф}}$ – longitudinal moment of fuselage

$M_{x_{ф}}$ – lateral moment of fuselage

$M_{z_{х.в}}$ – longitudinal moment of tail rotor

$M_{z_{вт}}$ – longitudinal moment of hub owing to spacing of flapping hinge

$M_{x_{вт}}$ – transverse moment of hub owing to spacing of flapping hinge

$M_{откл}$ – effective moment

M_y – bending moment acting on blade from lift

M_x – bending moment acting on blade from drag

Coefficients and General Parameters

$m_{кр}$ – coefficient of torque

c_T – thrust coefficient of rotor

c_y – coefficient of lift

c_R – coefficient of full aerodynamic force

σ – rotor solidity

λ — coefficient of leakage

c_x — coefficient of drag

a_1, b_1 — coefficient of flapping motions of blades of rotor

a_B — coefficient of Vel'ner [Translator's Note: Name is not verified, could be Wellner].

ξ — utilization factor of engine power

η_B — efficiency of rotor

η_0 — relative efficiency of rotor

c_z — coefficient of lateral force of rotor

c_Q — coefficient of longitudinal force of rotor

$\frac{\rho_0}{\rho_H}$ — height power factor

M_δ — degree of effectiveness of control

α_T — coefficient of tractor propeller

Powers

N_e — effective power of engine

$N_{H.B}$ — power of engine transmitted to rotor hub

$N_{охл}$ — power expended for cooling of engine

$N_{тр}$ — power expended for surmounting of friction

$N_{X.B}$ — power transmitted to tail rotor

$N_{ид}$ — power of ideal rotor

$N_{потр}$ — required power for flight of helicopter

$N_{потр_0}$ — power necessary on land

$N_{потр_H}$ — power necessary at altitude

$N_{инд}$ — inductive power

$N_{пр}$ — profile power

$N_{дв}$ — power of motion

ΔN — surplus of power

$N_{потр_{вис}}$ — required power for hovering

$N_{расп_{вис}}$ — available power in hovering

$N_{потр_{набор}}$ — required power for climb

$N_{ном}$ — nominal power

$N_{взл}$ — takeoff power

Speed

V — speed of flight

$V_{кр}$ — critical speed of flight (flow around)

W — true approach stream velocity

ω — angular velocity

u — peripheral velocity

$V_{отн}$ — relative speed

a — speed of sound

V_y — vertical speed of helicopter

$V_{взм}$ — speed of flapping of blade

v — induced speed

Parameters of Engine

$r_к$ — air pressure after supercharger

C_h — consumption of fuel per hour

$C_к$ — fuel consumption per kilometer

$n_{дв}$ — number of revolutions of crankshaft of engine

C_e — specific consumption of fuel

General Symbols

ρ — air density

m — mass

Δ — relative air density

H — altitude
n — overload
G — weight