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TRANSLATION

FLIGHT-NAVIGATION INSTRUMENTS: INSTRUMENT FLYING (THE PILOTING OF A PLANE BY INSTRUMENTS)

By

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FOREIGN TECHNOLOGY
DIVISION

AIR FORCE SYSTEMS COMMAND

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V. G. Denisov and R. N. Lopatin

PILOTAZHNO-NAVIGATSIONNYYE PRIBORY
(o pilotirovanii samoleta po priboram)

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FLIGHT-NAVIGATIONAL INSTRUMENTS: INSTRUMENT FLYING

This book deals with the psychophysiological and technological aspects of instrument flying. The authors point out that the success of a flight depends not only on the skill of the pilot but also on the flight-navigation instruments and how they are combined and arranged on the instrument panel. The book also gives the requirements for new flight-navigation instruments and systems to ease the task of flying.

This book is intended for the flight and engineering-technical staff of all departments of aviation as well as for persons associated with the development and application of civilian and military aircraft instrumentation.

The book incorporates material from both the Soviet and the open foreign literature.

Introduction

Civil and military aviation utilizes aircraft of many types having diverse design and different power plants, turboprop and turbojet being the most widespread.

At the present time designers and inventors in many countries are working on the development of planes capable of vertical takeoffs and landings and also on rocket planes and space craft intended for orbital flights with return to the Earth. Return to the Earth from outer space with atmospheric entry and landing will rely on aerodynamic forces. Consequently, with respect to design and equipment, such flight craft will have much in common with the conventional airplane. Flight programs during the basic flight stages will be similar also.

In order for a flight to reach its objective safely, the plane must be controlled. The directed motion of a plane through space (determined from fixed coordinates, course, velocity and acceleration) are called the conditions of flight and are characterized by the magnitude of their parameters. Control (piloting) of the aircraft consists in changing the flight-regime parameters. Therefore, during flight the pilot must know the attitude of his plane with respect to the horizon, its altitude, and its position with respect to fixed points of reference. In addition he must have information concerning the motion of the aircraft with respect to the surrounding air.

We will consider all these parameters.

The airplane is a symmetrical object with the plane of symmetry passing lengthwise through the center of gravity. The spatial orientation of the aircraft is usually determined by means of three axes passing through its center of gravity (Fig. 1). The longitudinal axis lies in the plane of symmetry along the axis of the fuselage. The lateral axis is perpendicular to the longitudinal axis and extends along the wing. The normal axis is perpendicular to the plane formed by the longitudinal and lateral axes.

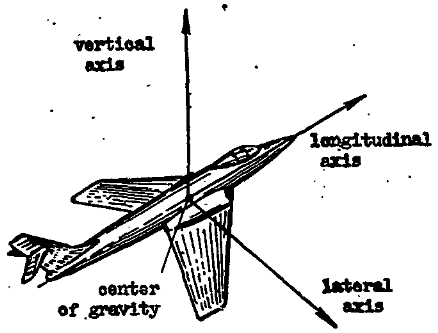

Fig. 1. System of coordinates associated with an aircraft.

Let us consider what angles (angular coordinates) determine a deviation of the plane from an initial straight-and-level flight.

When the plane is rotated about its lateral axis, the longitudinal axis forms an angle with the the plane of the horizon known as the pitch attitude (Fig. 2). The angle formed by the lateral axis and the horizon is called the bank attitude (Fig. 3). In this case rotation occurs about the longitudinal axis. Rotation of the plane in the horizontal plane about the normal (vertical) axis is called yaw. The angle of yaw is measured from some fixed line such as the direction of flight or a north-south line (Fig. 4). If the initial attitude of the plane is not horizontal, the angle of yaw is read from the projection of the longitudinal axis onto a horizontal plane.

During flight the center of gravity of the plane traverses a definite trajectory. A tangent to this trajectory at any point indicates the direction of true rate of motion (velocity vector). This speed is measured with respect to the surrounding air and is called the true air speed. The angle between the projection of the velocity vector onto the plane of symmetry and the longitudinal axis of the plane is called the angle of attack (Fig. 2). The lifting power of the wing is dependent on the size of this angle. At a so-called supercritical angle of attack the lifting force becomes less than the weight of the plane and the plane will stall.

The velocity vector forms, with the horizontal plane, the flight-path angle.

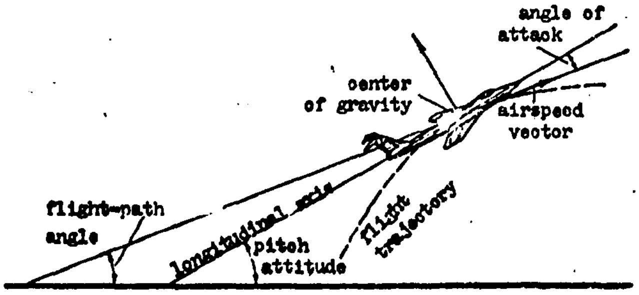

Fig. 2. Angle characterizing the attitude of an aircraft in the vertical plane.

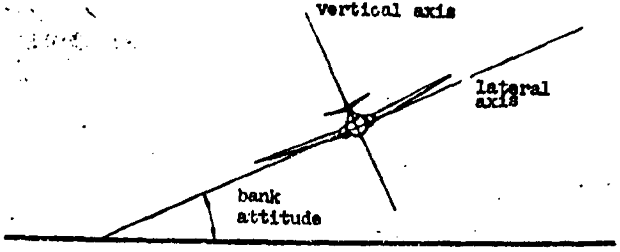

Fig. 3. Aircraft banking.

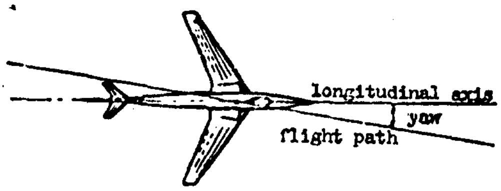

Fig. 4. Yaw.

If the velocity vector does not coincide with the plane of symmetry, a slip angle forms and the plane, in addition to its forward motion, has lateral motion — side-slip.

At speeds greater than 500 km/hr it is necessary to take into account the compressibility of the air which depends on flight speed and propagation rate of sound in air. The ratio of flight speed to the speed of sound at a given altitude is called the Mach number (M).

The position of the aircraft with repsect to the ground is determined from parameters which in air navigation are called navigational elements. Let us recall the most important of them.

The height of the plane above sea level is called the true altitude, above the level of the takeoff or landing field — the relative altitude, and above the surface of the ground over which the plane is flying — the absolute altitude (Fig. 5).

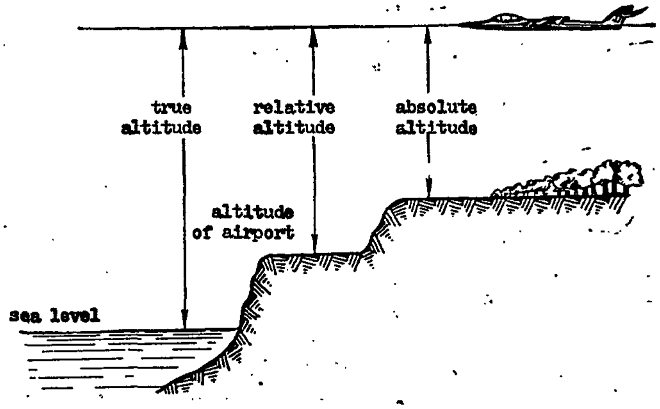

Fig. 5. Aircraft altitude.

The heading of the aircraft is the angle measured in a clockwise direction from north to its longitudinal axis (more accurately, to its airspeed vector). The heading will be either true or magnetic depending on whether it is taken from true or magnetic north (Fig. 6).

The direction over the ground from point A to point B is measured in terms of the angle between the meridian passing through point A and the orthodrome (another great circle) passing through points A and B (Fig. 7). This angle is called the azimuth or bearing.

The direction from the aircraft to a landmark is called the bearing of the landmark while the direction from the landmark to the aircraft is called the bearing of the aircraft (Fig. 8). The angle between the longitudinal axis of the aircraft and the direction to the landmark is called the landmark heading, and is equal to the algebraic sum of the aircraft heading and the landmark bearing.

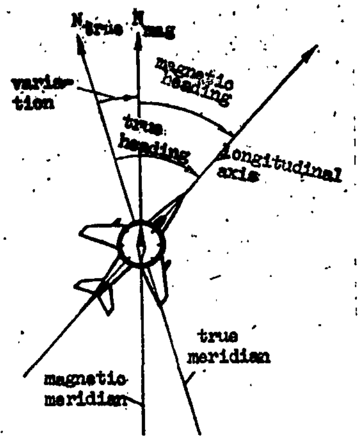

Fig. 6. Heading.

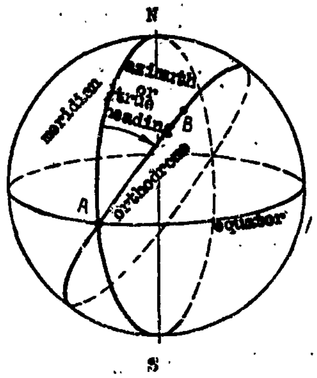

Fig. 7. Great circles on the Earth.

The velocity of the aircraft with respect to the ground is called ground speed and is equal to the geometric sum of the airspeed and windspeed vectors (Fig. 9). The ground speed is in the direction of the tangent to the track of the aircraft, i.e., to the projection of the flight path onto the ground. The direction of the track is determined from the actual track angle, which is measured clockwise from north. The difference between the actual track angle and the heading is equal to the drift angle, i.e., the angle between the longitudinal axis of the plane and the track.

The point on the ground over which the aircraft is located at a given moment is called the ground position of the aircraft.

In order to maintain constant conditions of flight the pilot must alter the parameters in an appropriate manner. The attitude of the plane may be changed by means of control surfaces whose position with respect to a flowing airstream may be altered. The dynamic air pressure on the control surfaces produces moments which cause the plane to turn about its center of gravity. Most aircraft have elevators, a rudder and ailerons (Fig. 10). The elevators and ailerons are deflected by longitudinal and lateral movements, respectively, of the stick (or by turning the wheel), while the rudder is controlled by foot pedals.

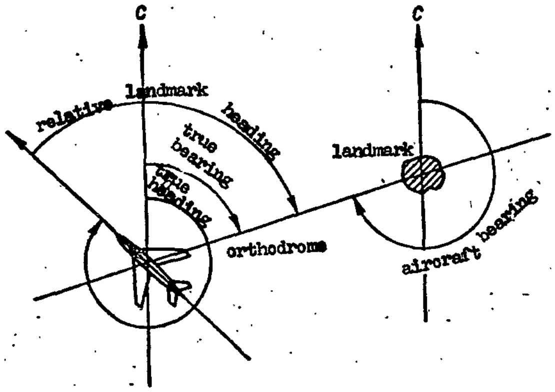

Fig. 8. Angles on the Earth's surface.

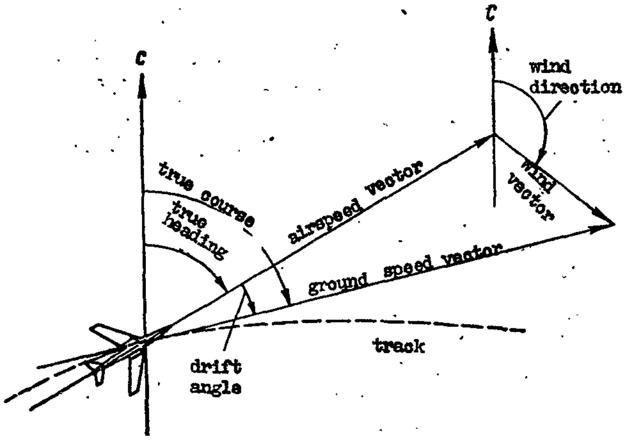

Fig. 9. Navigational velocity triangle.

Airspeed is altered by means of the throttle which changes the engine thrust. The speed may also be reduced by means of aerodynamic braking, e.g., by using special air brakes or by altering the angle of attack.

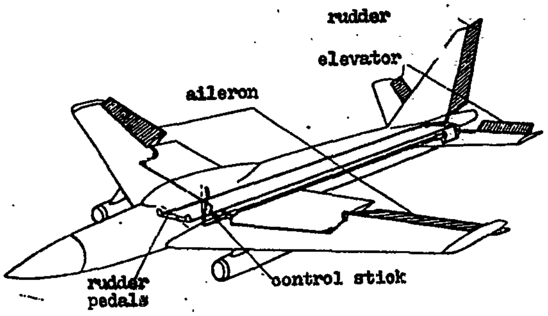

Fig. 10. Aerodynamic control surfaces.

Deflection of the elevators alters the angle of pitch, the angle of attack, and the height of the plane. Deflection of the ailerons alters the angle of bank, while deflection of the rudder alters the angle of yaw (heading). The changes in the angles of bank and yaw are interrelated, i.e., when the plane banks it also turns, and when it turns it also banks.

Aircraft stability and maneuverability are of great importance in flying. Stability refers to the ability of the plane to return to the original conditions of flight without altering the controls after disruption of equilibrium by brief random disturbances (e.g., a gust of wind). Aircraft stability makes flying easier since the pilot does not need to constantly eliminate random disturbances of the given conditions of flight.

The maneuverability of an aircraft depends on its ability to respond to displacements of the control surfaces. If when slight but clearly felt forces are applied to the control stick the plane alters its conditions of flight sufficiently fast, it is said to have good maneuverability.

Stability and maneuverability of modern aircraft are assured by the use of various means of aerodynamic compensation as well as automatic devices to eliminate undesirable vibrations of the plane. To alter the conditions of flight at high speeds it is necessary to apply to the control levers forces which are beyond the strength of the pilot. Therefore intermediate amplifying devices (usually hydraulic or electrical) called boosters are introduced into the control system. The booster provides the power required to move the control surface and the pilot has only to apply a normal force to control the booster. This however deprives the pilot of the sense of control of the aircraft. In order to restore this sense automatic devices are employed (such as springs) in order to artificially create a load on the control stick in relationship to the amount of deflection and to the flight speed (and altitude).

In addition to the basic controls (stick, rudder, and throttle) the pilot must manipulate many additional ones (levers, buttons, switches, and wheels) which actuate various elements of the wing mechanization (flaps, spoilers), means of aerodynamic compensation (trim tabs), engine controls systems, etc.

On many aircraft the elevators are replaced with a controllable stabilizer. Delta-wing aircraft in general do not have a horizontal stabilizer but instead incorporate elevons (control surfaces which function both as ailerons and elevators) to control the angles of pitch and bank.

High-speed and high-altitude flights will utilize compressed air and reactive controls, using the reaction from exhaust gases.

The pilot is able to judge the spatial orientation of the aircraft (with respect to the horizontal plane) from the relative position of the visible horizon and the various parts of the plane. By orienting himself with respect to the terrain, the pilot can determine his flight speed, altitude and direction. Even when the horizon is not visible it is possible to estimate the attitude and height of the aircraft from the characteristic location of various landmarks and their basic features.

When flying at night, in fog, or in clouds (i.e., when the horizon is not visible), as well as at high speeds and high altitudes visual orientation is markedly reduced or eliminated altogether. Under these conditions the pilot must rely on flight-navigational instruments. It is only during takeoff and landing that visual orientation retains its predominant significance.

The basic flight-navigational instruments are: attitude indicator which shows the angles of pitch and bank; the magnetic compass and directional gyro to indicate heading; airspeed indicator; altimeter; rate-of-climb indicator; turn-and-bank indicator; and Machmeter. In addition to the basic navigation instruments there are also a clock and a thermometer to measure the temperature of the surrounding air. To monitor the operation of the power plant, the pilot makes use of tachometers, thermometers, manometers, fuel gages, and flowmeters. He is also provided with other indicators (visual, audio, or mechanical) which inform him about the operation or malfunction of individual components (e.g., the position of the landing gear and flaps), or of entering into hazardous flight conditions (e.g., approach of the critical angle of attack), etc.

The pilot also makes use of navigational devices which indicate the geographical coordinates of his plane or his position with respect to a fixed course. Military aircraft have, in addition, fire control-systems. Finally, flight and navigation information reaches the pilot from radio and radar stations by means of appropriate instruments.

The number of different devices in the cabin has continually increased with the improvement of equipment and as a result of attempts to increase the accuracy and reliability of the information supplied to the pilot. The cabin has become so loaded with various devices, indicators, buttons and control levers that they no longer ease but instead complicate the work of the pilot.

In recent years a great deal of work has been carried out abroad on the fundamental improvement of methods of indicating the conditions of flight on the basis of theoretical and experimental data of engineering psychophysiology dealing with the questions of the most efficient combination of psychological and physiological capabilities of the man (pilot) and the technical capabilities of the machine (aircraft).

Like all control processes, the piloting of an aircraft is subject to the laws of cybernetics, the special science of control and communications systems in living organisms and machines.

Any cybernetic system which consists of individual elements (links) is a complete unit relatively isolated from its surroundings. At the same time this system is connected with the external world which has somehow an influence on it and the system in turn experiences this influence. That part of the system which perceives the influence of the external world is called the input while that part which presents the influence to another system is called the output. The elements which compose the given system may be considered as independent systems with their own inputs and outputs.

Each cybernetic system has its controlling and controlled parts (servo organs). Both of these parts are combined into a single closed self-controlled (automatic) system (Fig. 11). The system is closed by means of feedback, between the output of the controlled part and the input of the controlling part. By means of the feedback, any deviation in the behavior of the system from that specified is communicated to the input of the system. When the controlling part reduces this deviation (mismatch) the feedback is said to be negative. Positive feedback, on the other hand, heightens the mismatch which interrupts the stability of the system and even leads to its complete collapse. Consequently, cybernetic systems usually incorporate negative feedback.

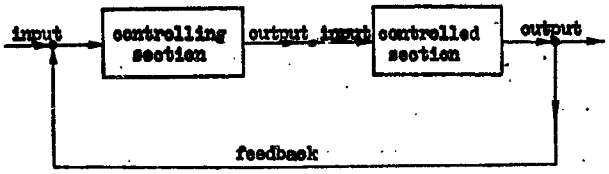

Fig. 11. Schematic of cybernetic system.

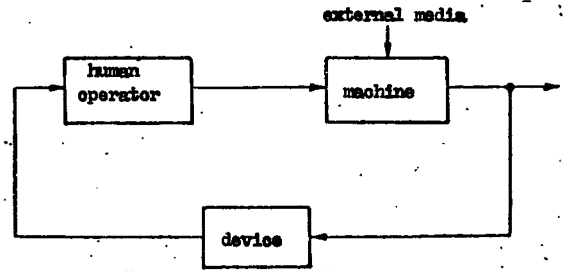

Fig. 12. "Man-machine" system.

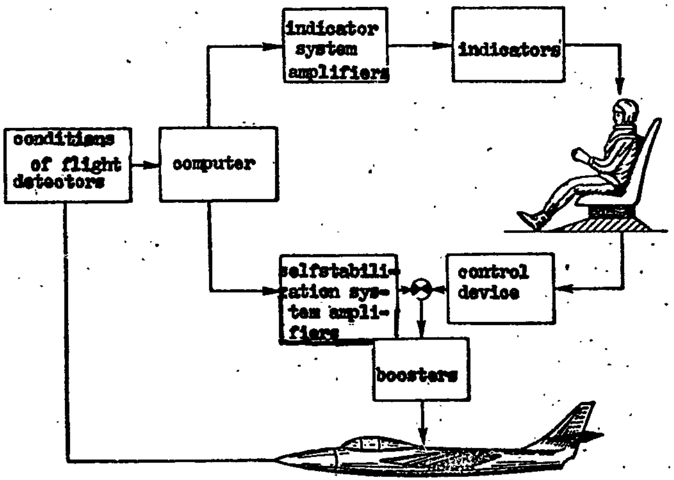

Fig. 13. "Pilot-aircraft" system.

All of the links of a cybernetic system are interconnected by information flow. Information refers to the communication of events taking place both in the medium surrounding the system and within the system itself. The actual information carrier is a signal which represents a change of some physical quantity such as electrical potential, air pressure, degree of illumination, mechanical force, etc.

In the "man (operator)-machine" cybernetic system the controlling portion is the man (Fig. 12). A special case of this type is the "pilot-aircraft" system (Fig. 13). In such a system the operation of the machine is conventionally expressed by readings of the controlling device. In order for the machine to properly accomplish its functions, the characteristics of its operation, as well as all of the changes in its operation must be reflected very accurately and rapidly by this device.

The indications of the device which are perceived by the man are basic for the stimulation of a response in him. In order for this reaction to be effective the information received from the device must be simple and easily understood.

Human response is the means by which any system of mechanical machine control is put into operation. The control of a machine must be directly associated with the basic operation of the machine in such a way that the control will be reflected in the operation of the machine and the operation of the machine will in turn be accurately reflected in variations of the instrument readings. These indications inform the man as to whether additional changes must be introduced into the control. In practice many functions of the basic mechanism are combined in a single unit to form a complex system of devices.

The man, in addition to information from the devices and interpretation of it, must have additional information about the surrounding medium, for example, and must combine these data with the information from the devices.

If the demands of the situation exceed the capabilities of the man for small intervals of time, then the result may be an improper combination of the information received and an improper response. In this case the response often consists of a complex group of actions which it is necessary to combine in order to obtain the desired alteration in operation of the mechanism as a whole. Here it is necessary to bring into play the organs of control, each of which carries out its own share of the work. The final result of this is the alteration of the total operation of the entire mechanism which in turn is reflected in the basic devices. The instrument readings must then be reinterpreted.

Thus in the process of control the man continuously receives and combines information from numerous sources. Sometimes because of the peculiarity of the human organism the information which reaches the man during the process of control is discrete, i.e., not continuous but in separate portions.

The task of piloting an aircraft involves deliberately maintaining or altering its position in space while maintaining stability and control. By manipulating the controls of the aircraft, the pilot maintains or alters its coordinate angles (bank, pitch, yaw), that is he stabilizes (or alters) the position of the plane with respect to its center of gravity. By means of the control surfaces the pilot either maintains or alters the altitude, direction of flight, and speed of the plane, thus controlling the position of the center of gravity of the plane with respect to a fixed flight trajectory.

Thus flying an aircraft is primarily a tracking or control process, i.e., the magnitude of a given parameter is maintained or else deliberately altered. Thus for instance, during takeoff the pilot maintains a selected direction, eliminating with the control surface deviations which arise. When landing he lowers the plane to the ground, proportioning the deflection of the control surfaces to the rate of descent. During level flight, constant altitude, speed, and heading are maintained, and in formation flying the distance, interval, and relative height are maintained. In all these cases a visual signal — more precisely, the deviation of the actual value from the prescribed value (mismatch) noted by the eye — is used as a signal to operate the controls.

As a result of action on the control devices, parameters other than those enumerated are also altered:

- velocity pressure, i.e., the dynamic pressure of air, the minimum value of which is limited by lift and the maximum value by the stability characteristics of the structural elements of the aircraft;
- Mach number, at definite values of which the stability and maneuverability of the aircraft deteriorate severely;
- pressure drop in a pressurized cabin;
- acceleration, the highest value of which is limited by the physiological characteristics of man and the stability characteristics of the plane;
- slip of the plane.

The question arises: Is it necessary to include a pilot in an aircraft control system since automatic devices and systems (for instance pilotless flight equipment) have been built which completely replace the human pilot in the flight control system? Apparently he is needed since the automatic systems in use at the present time for the control of aircraft flight in certain cases yield in quality to systems in which control is affected by a person.

For example, an experienced pilot who is well trained and familiar with the technique of flying a certain type aircraft, i.e., the neuropsychophysiological activity of his body being adapted to the dynamic properties of the aircraft, controls the plane so as to avoid significant deviation of the stabilized coordinates from predetermined values.

The activity of the pilot in this case is analogous (with respect to the quality of the control) to the action of a nonlinear link of a system of automatic control which alters its parameters in relation to the complex of information reaching it from without. Common automatic pilot systems do not contain in their closed circuit links possessing similar properties.

A control system with a pilot is more reliable and universal than a completely automatic one since the human organism is the most reliable link and is able to adjust to various flight conditions including those not anticipated in the design of an automatic system.

Many of the operations involved in controlling an aircraft are accomplished with equal success by both the man and the automatic device. Certain activities are too difficult for the pilot and must be done automatically. Thus, of basic importance in the development of a control system incorporating a man is the optimum combination of human capabilities having natural limitations, with the ever increasing capability of automatic devices.

The capability of a human is limited; he may make errors especially when fatigued. This must be kept in mind when designing a device which the pilot must control at extreme speeds and altitudes. Any attempt to construct a mechanism without taking into account the capabilities of the man will not only reduce its usefulness but may even lead to grave consequences. Certain of the capabilities of a human are obvious. For example, it is always possible to predict whether or not he will be able to operate a certain lever, to raise a load of a specific weight, etc.

The transmission of a light stimulus from the eye to the brain and the associated reflex action resulting from the interpretation of the transmitted signal is a relatively lengthy process which might influence the success of the control of an aircraft especially when landing, attacking a target, encountering an obstacle, etc. The period of action of a light stimulus on the eye and the transmission of the appropriate nerve impulse to the brain takes from 0.03 to 0.3 seconds. When the nerve impulse has been transmitted to the brain, the man is cognizant only of the fact that there is something in his field of vision. It takes him up to 0.5 seconds or more to define concretely his perception.

After identifying the information it is necessary to evaluate and explain it and then decide what action to take. The time required for reaching a decision amounts to from one to several seconds. After reaching a decision a response takes place which continues for no more than several tenths of a second.

When controlling an aircraft the perception and response times of the pilot are just the beginning of a whole series of actions by the pilot and behavior of the plane. Here it is necessary to take into account:

— the delay in transferring response to the control devices;

- the time required for the plane to deviate from a fixed trajectory or from a given position with respect to its center of gravity after the control devices have been put into action;
- the delay in indication of measuring devices which respond to the deviation of corresponding measured parameters.

For example, it takes on an average 0.5 seconds for an aircraft to assume a given bank attitude after the ailerons have been deflected and it takes several seconds for the aircraft to attain a different speed after the engine power has been changed, etc.

Accomplishing any aircraft control task requires attention to the capabilities of the pilot and composite flight conditions (demanded by the situation). As long as the capabilities of the pilot exceed the demands of the situation he is completely capable of controlling the plane, but if the flight conditions become more complex or the capabilities of the pilot become reduced it might happen that he cannot control the aircraft under the conditions so created.

The capabilities of the pilot usually decrease at high altitudes, under the influence of acceleration, as the result of fatigue (on long flights) due to great physical and mental strain, restraint of movements by clothing and special equipment, etc.

In order to successfully control an aircraft it is very important that the pilot be able to see what is going on around the plane and to accurately understand and evaluate the situation. All of the control actions of the pilot must be rapid and accurate.

By observing the ground, landmarks, and the horizon, the pilot obtains certain information concerning the position of the aircraft with respect to the earth, the speed and direction of flight. This information reaches the central nervous system, is properly comprehended and the pilot comes to a conclusion about manipulating the controls so as to correct the position of the plane and the parameters of its motion in accordance with a given flight plan.

When going from visual to instrument flying the time for making decisions is curtailed since an extra link is added to the control circuit. In this case the pilot does not view the flight directly but only after obtaining various information from a large number of control points (instruments, indicators, sights), after the information has been generalized and reduced.

The time from the start of the survey of the information to the start of control action is the total of the time for perceiving and generalizing the information and the reaction time of the pilot. Rapidity of reaction is usually obtained by individual selection and pilot training. The time of accumulation and generalization of data from information sources depends on the number of different control points, their relative position, and the form of the information retained.

The number of control points may be reduced by combining the readings of individual devices within a single housing. It must be kept in view however that a simple mechanical combining may not reduce the perceiving time and may even significantly increase it if definite limits are not taken into consideration.

Efficient placement of the instruments on the panel as well as the nature of the information provided by the instruments is of great significance in reducing the time of gathering information and making decisions.

Depending on the nature of the information being provided, aviation instruments are divided into control-measuring devices, instruments which indicate the deviation of variable quantities from their prescribed values, and command and integral devices. In addition the aircraft is fitted with indicating devices.

I. AIRCRAFT INSTRUMENTS

Measuring Instruments

The six basic flight-navigation instruments (attitude indicator, compass, altimeter, rate-of-climb indicator, speed indicator, and turn indicator), most of the instruments of the radio system, astronomical devices, and devices controlling the power unit are the simplest measurers of the various flight parameters.

Measuring devices simply indicate the magnitude of some parameter and the remaining processes (evaluation, generalization and analysis of the indications) must be performed by the pilot. As a result measuring devices do not assure complete reliability and accuracy of flight in cases where it is necessary to obtain information relative to a large number of devices and to generalize their indications (especially when time is limited as during landing, or when attacking an airborne or land target). Nonetheless, measuring devices are widely used on modern aircraft when flying without a visible horizon or landmarks.

The form and dimensions of the scales of these devices and the order of reading the measured parameters have a substantial effect on the control process of an aircraft.

Instruments with circular stationary scales and revolving indicators are the most widely used. The indicators are usually arranged to turn in a clockwise direction as the value of the parameter being measured increases, and vice versa.

Recently in connection with the increased number of aircraft instruments and the limited area of the instrument panel, instruments with vertical and horizonal scales are coming into use abroad. This kind of instrument takes up little space on the instrument panel and their scales are convenient for reading certain parameters. For example, it is very easy to read altitude from a vertical scale, it being especially graphic for perceiving descent of the aircraft or a gain in altitude. Horizonal scales are especially convenient for reading distance to target, flight speed, etc.

With devices haveing stationary circular horizonal and vertical scales, the dimensions of the scales are limited by design considerations and this significantly reduces the accuracy of reading parameters with a very wide range of values (e.g., altitude, flight speed, etc.). To improve reading accuracy it is possible to design devices with several needles, barrel indicators, or moving tape scales.

Altimeters and speed indicators with two or three needles are often used. In this case readings on the same scale have different values.

According to the foreign press, multi-needle devices which increase the accuracy of reading have one disadvantage, namely, the percentage of errors in reading is significantly greater than with single-needle devices especially in cases where the parameter being measured changes rapidly. Barrel indicators with extended scales have the same disadvantage. The latter fact is explained by the fact that the pilot using a clock-type instrument is able to determine both the magnitude of the measured parameter and the nature of its change, the first and even the second derivative of this varying parameter. This of course gives additional information concerning the given parameter which cannot be obtained from a barrel indicator which gives factual discrete (discontinuous) information about the magnitude of the parameter only.

In addition the clock-type indicator is easily seen peripherally.

Instruments with a moving tape scale have a stationary index for reading the changing quantity and the scale is a long continuous tape. One such instrument which was developed in the USA is pictured in Fig. 14.

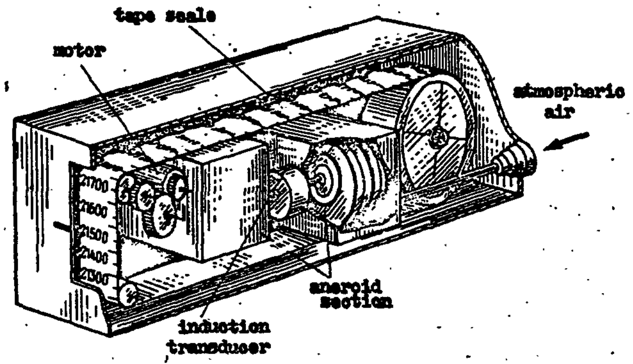

Fig. 14. Tape-scale altimeter.

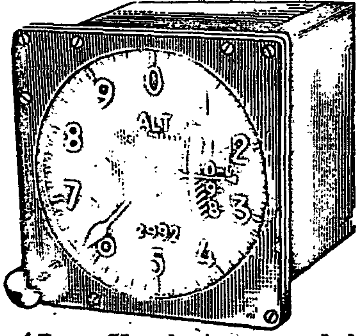

Fig. 15. Clock-type and barrel instrument combination.

Some modern instruments incorporate both a clock-type indicator and a barrel type. The altimeter-speed indicator shown in Fig. 15 is an example of such a device.

The scale of a measuring device may be either linear or nonlinear with equal scale divisions. Linear scales are more widely used. However, some instruments have nonlinear scales: tapering (logarithmic), expanding, scales with "depressed" zero, etc. The nature of the scale is dependent on the range of the parameter being measured, the operating (basic) range of the measurement, the required accuracy of measurement of the parameter in one or another range. For example, for an airspeed indicator it is most important to have a scale with smaller scale divisions in the range of landing speeds and with larger scale divisions over the remainder of the scale. The same applies to the altimeter where it it also desirable to have smaller division values in the range of low landing altitudes. In individual devices as for instance in radio altimeters scale division values are altered by switching scale multiples.

The indicating characteristics of aircraft measuring instruments directly influence the rapidity, accuracy and completeness of the pilot's perception of the information and consequently his evaluation of the situation and his decision.

There exist measuring devices which provide symbolic (arbitrary) indications, as well as descriptive (pictorial, graphic) indications.

Measuring devices with symbolic indication include all instruments in which an arrow moves, symbolically indicating the variations derived from an object or from some measured parameter of the object (aircraft). The indications of these devices are far from ideal and it takes practice and training to read them.

The ideal instrument with descriptive indication would be one which simulates the picture seen from a flying aircraft.

Instruments with relatively descriptive indications include the attitude indicator and the so-called systematic instruments (e.g., compass, heading indicator, automatic direction finder, etc.). These instruments are capable of representing two kinds of simulations: the view of the plane from the ground and the view of the ground from the plane. So far it has not been settled as to which is better. Pilots and navigators feel that flight instruments should simulate the view of the plane from the ground while navigation instruments should show the view from the plane to the ground.

The representation of flight conditions by certain attitude indicators, in some cases does not coincide with what is observed by the pilot when he wants to establish the position of his plane with respect to the horizon.

When during visual flight the plane starts to gain altitude the horizon appears to the pilot to drop below the nose of the aircraft while during a dive it appears that the horizon is rising. The attitude indicator, however, shows the motion of a miniature airplane with respect to a stationary horizon or the motion of the line of the horizon on the other side of an image of an airplane.

When developing the form of indication one must bear in mind that the basic purpose of the device which informs the pilot of the position of his plane with respect to the plane of the horizon when the ground is not visible is to help the pilot determine the spatial attitude of the aircraft and it is not necessary to present him with a pseudo-visual presentation.

Attempts to produce conditions of visual orientation on an attitude indicator have psychological limitations due to the fact that since he is located at the vertex of an angle, the pilot is not able to measure the angle. Thus at a steep pitch attitude, for example when climbing at an angle of 60°, the pilot who is oriented with respect to an attitude indicator feels uncertain.

It would be better to create an instrument to show pitch attitude as seen from the side. However, adherents of descriptive indicators feel that the instrument indication must imitate the picture observed by the pilot through his canopy in order for him to easily make the transition from flying by instrument to visual orientation (e.g., when breaking through clouds) otherwise, in their opinion, there arises the danger of confusin the pilot when leaving a cloud unexpectedly. This fear however is groundless. If the pilot accurately visualizes tha tttitude of the plane no confusion will arise since visual perception will not contradict the mental image.

A pitch attitude indicator (in combination with a rate-of-climb indicator) which has a needle that rotates a full 360° (Fig. 16) permits the pilot to determine the attitude of his aircraft with respect to the horizon even when performing a loop.

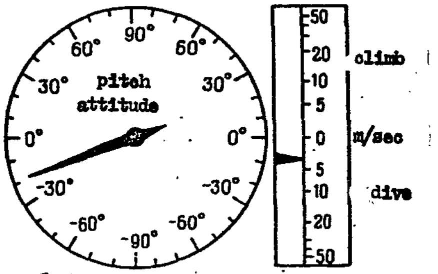

Fig. 16. Pitch attitude indicator in combination with rate-of-climb indicator.

At high attack angles (i.e., at low speeds) the aircraft may lose altitude but the instrument will indicate a positive angle of pitch. In order to control this a rate-of-climb indicator is placed beside the pitch attitude indicator. The rate-of-climb indicator may also be used to correct the gyroscope of the pitch attitude indicator just as the directional gyro is reset from a magnetic compass. The pitch attitude indicator will then show true angle of inclination of the flight trajectory and these readings will be completely independent of the attack angle. Since in most cases flight is carried out within a range of pitch angles of ±30°, the scale may be made logarithmic to increase the accuracy of the indication at small angles (e.g., during a landing approach).

Some attitude indicators use a so-called screen to indicate the bank and pitch attitudes. The line of the horizon rather than the usual silhouette of an airplane is depicted on the instrument. The Earth is indicated by a black segment and the sky by a white segment. When the plane alters its position with respect to the lateral axis the ratio between the white and black segments varies correspondingly (Fig. 17).

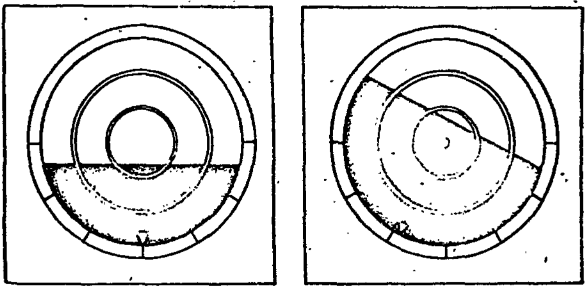

Fig. 17. Screen attitude indicator: left) climb; right) descent with left bank.

Information concerning the attitude of the plane with respect to the tru horizon may be obtained separately from the bank and pitch attitudes (Fig. 18). In this case a device located in front of the pilot serves to indicate bank attitude and two devices at the sides of the cabin indicate pitch attitude. These devices free the pilot from having to constantly refer to the instrument panel.

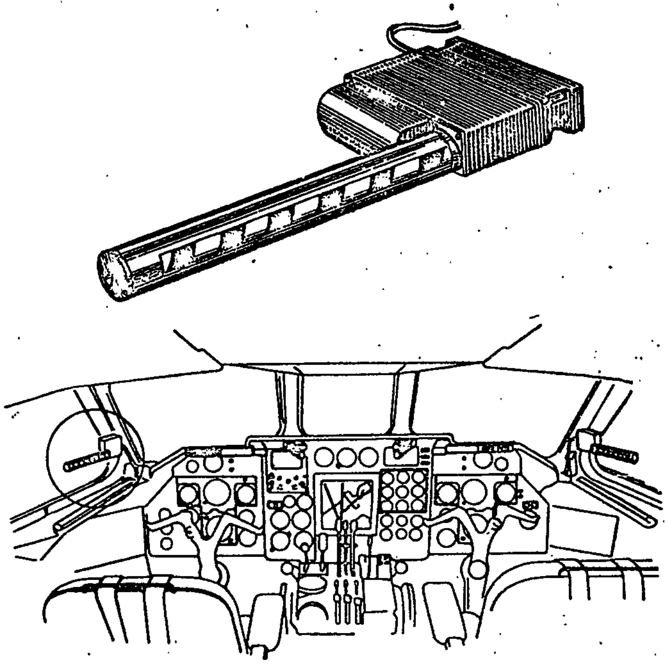

Fig. 18. Separate pitch and bank indicators (by English firm of Smith).

These instruments use a cylinder covered with a black and white spiral stripe as a means of indication. When the cylinder is stationary, stationary black and white rhombuses are visible. When the cylinder rotates, the spiral stripes seem to travel along a slot and quickly attract the pilot's attention. The direction of movement of the stripes depends on the direction of rotation of the cylinder. If the stripes on the bank attitude indicator move toward the right then the pilot does a right bank until they stop. Forward motion of the stripes on the pitch attitude indicator is stopped by moving the control stick forward.

This device has been tested during takeoffs and landings and even when the pilot shifted his gaze 45° from the line of flight he accurately maintained a landing trajectory by referring to these instruments.

Both forms of simulation of flight conditions are possible in fixed heading devices also.

If during a right turn the aircraft alters its heading then its previous heading and consequently the direction of flight will be found after a turn to the left. From this point of view it would be expedient to have as an indicator of course a stationary silhouette of a plane and a stationary heading scale to simulate the stationary landmarks..

However the controlled object for the pilot is the aircraft responding to his action on the control stick. The pilot is well trained (attached time link) to the fact that if he presses the right rudder forward and the stick to the right then the plane will turn to the right. The pilot expects to see on the device a motion of the heading indicator in the direction of the rudder. Therefore it is preferable to accept a stationary heading scale with a moving indicator to simulate the plane.

Therefore, if the heading indicator must indicate which direction the plane turns to, then it must simulate the view of the plane from the ground and if it must indicate the cardinal points of the compass it should show the view from the plane to the ground.

It is claimed that primary attention should be given to the question of combining both forms of simulation on a single panel, on one combined instrument and on the same controlled parameter (the latter is especially important when going from one aircraft to another). At first glance it seems obvious that only one type of simulation should be used on the same instrument panel and more importantly on the same instrument since mixing them will confuse the pilot in controlled events. However, when solving certain specific problems combination of both types of simulation of flight conditions is not only possible but also necessary.

The methods of instrument simulation of flight conditions considered above provide a practical solution as to the operation of controls when there is a deviation of the moving index which represents the plane or a landmark (horizon). It is possible to return the aircraft to a given flight path (program) by moving the control stick in the direction of deflection of the instrument needle or in the opposite direction. In the second instance the needle will return to the original position provided by the flight program in the direction of the motion of the plane to the given trajectory.

Foreign radar, optical and infrared sights have both symbolic and image indications. For example, in the clock-type radar sighting instrument information concerning distance to the target and the angular displacement of the target with respect to the fighter may be superimposed on the information from the attitude indicator. This makes it possible to attack an invisible target just as a visible one.

It is very important to make it possible for the pilot not to be distracted by monitoring the instruments on the panel and thereby free him from the possibility of eye fatigue. Indications from the basic instrument, the attitude indicator, could be observed as if through the windshield by means of reflectors and lenses. The lines and arrows on the instrument scales could be transferred without distortion so as to appear to be located outside the aircraft.

The type of information given to the pilot depends on functions performed by the pilot in controlling the aircraft. Information which does not facilitate performing these functions is considered useless or even dangerous to the system which includes a pilot.

Functions performed by the pilot in modern systems of aircraft control are divided into two categories: functions within the systems and functions outside of the system.

As an internal element of the system the pilot performs functions of tracking and control. If the functions of the pilot were limited to these problems alone then he would require information only as to what control surfaces should be started, when this should be done, and to what degree.

As an external element of the system the pilot performs the function of a control and of an executive organ striving to complete a scheduled flight taking into consideration unanticipated emergencies which cannot be taken into account by the elements of the system even when the system is to some extent automated. Here the pilot is irreplaceable; he alone can perform these functions.

Usually two types of information are taken into account: "end point" information and "position" information.

1) <u>"End-point" information</u> (EPI). This information permits the pilot to select action for reaching some final target which may be either a geographical location (rendezvous point, turning point, etc.) or some determined flight condition (e.g., line of flight). EPI indicates the final position of the aircraft and the necessary action (error indication) for reaching that target.

In order to obtain EPI it is necessary for the system to be given:

- the desired end point or condition;
- the desired program trajectory for attaining the end point;
- the performance of the system at any moment of time with with respect to the points indicated above, i.e., error.

By means of EPI, the following are achieved:

- an increase in the number of actions which the pilot can simultaneously accomplish (combination of parameters in one indication);
- a large number of response actions;
- reduction of the training time;
- limitation of the possibility of choice.

"End-point" information is usually provided by director instruments.

However, such information does not permit orientation under actual flight conditions and the selection of some other direction.

2) "Position" information (PI). This information gives an idea as to the relative position of the aircraft and the end point and also of the actual flight conditions, thus making it possible not only to obtain information about the deviations, but also makes it possible to find out about events taking place which are necessary for conscious control of the aircraft.

Positional information is usually provided by the measuring and deviation instruments described earlier.

Both types of information (EPI and PI) may be presented by a single combined instrument for efficiency in aircraft control.

In order to simplify the perception (comprehension) of all information two techniques are utilized in the instrumentation:

- the technique of relieving which frees the pilot from having to make complex logic operations concerning the interpretation and calculations by using preliminary reduction of information by means of a computer;
- the technique of acceleration through which the pilot obtains information immediately after manipulating the control stick.

Instruments Indicating Deviation from Fixed Parameter Values

In addition to the basic measuring instruments, aircraft are equipped with instruments used to determine variations of parameters from fixed values. Instruments of this kind consist of a sensor for the parameter to be measured, a reference, a comparator, and an indicator (Fig. 19).

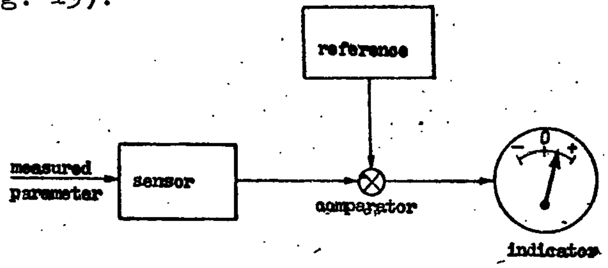

Fig. 19. Block diagram of a device for measuring deviation of a parameter from a fixed value.

A deviation instrument might indicate the magnitude of deviation of the current value of a parameter from a fixed value or both the current and fixed value of a given parameter (if there is no comparator). In the first case in order to complete a flight program the pilot must keep the moving needle in coincidence with a stationary scale and in the second case he must keep two scales, indicating current and fixed values of the parameter, in coincidence. In both cases, the scales of the indicators are graduated in units of the measured parameter.

The given value of a parameter at any stage of flight may be completely determined and constant or it may vary according to a predetermined program provided either manually by the pilot or else automatically.

An example of a device which indicates the magnitude of deviation of the current value of a parameter from a predetermined value is the gyromagnetic compass.

In this instrument the measuring device is turned to various angles by means of a special pinion mechanism. In order to maintain some fixed heading (when flying a course or during landing) the pilot, by rotating the mechanism of the indicator, sets a special index (usually on the upper portion of the scale) to the required course and then turns the aircraft so that the true heading which is represented by the silhouette of an airplane coincides with the predetermined heading.

Instruments which indicate current and given values of a parameter are, for the most part, an ordinary gage (e.g., altimeter, Machmeter, speed indicator, rate-of-climb indicator, heading indicator) with a device which indicates on the same scale the predetermined value of the parameter established as desired by the pilot or automatically in accordance with the flight plan.

Abroad most such devices are used to guide fighter planes to an aerial target by means of a ground command.

The same devices could be used for flying a course, when landing and taking off, i.e., when performing the programmed stages of a flight.

Combined Instruments

The number of instruments needed to control an aircraft has grown rapidly. In order to mount them on an instrument panel, several measuring systems are combined within a single standard housing.

In addition, combining instruments reduces the time needed to read the indications.

During normal flight conditions the instrument needles are usually set up in an easily-remembered configuration (cross, letter T, inverse T, horizontal line, vertical line, etc.). When the parameters deviate from the norm, the usual and easily-remembered arrangement of the needles is upset and immediately attracts the attention of the pilot.

As a rule, two, three, and sometimes even four clock-type instruments are combined. It has been established that it is expedient to combine in a single housing devices designated for the monitoring of parameters which refer to a single controlled object (e.g., one of the engines) and which are used together when carrying out a flight or separate stages of the flight, as well as for monitoring similar parameters.

Two systems of combination are used to monitor the engine operation. One system combines the instruments for monitoring the various parameters of a single engine in the same housing. These parameters usually include those which must be monitored within certain permissible limits (e.g., oil pressure, fuel pressure, oil temperature). These parameters need not be read accurately when the system is operating normally. Therefore these combined instruments are usually designed for rapid and easy determination of deviations of the parameter from the norm.

The second system combines within the same housing instruments for monitoring identical parameters of all the engines. These parameters usually require an accurate adjustment and equilization of the individual engines. Instruments of this type include, for example, double (but not doubleOneedled) tachometers, thrust meters, etc. The task of the pilot when using these instruments is to "align" one needle over the other, equalizing the parameters of the individual engines.

Flight instruments are usually combined according to the principle of simultaneous application. For example, one housing may contain indicators for true airspeed and angle of attack; a barometric altimeter and a radio altimeter; a rate-of-climb indicator and an indicator to show the rate of turn about the vertical axis; a pitch and yaw indicator with a slip indicator; indicators of course, heading angle and radio station bearing, etc.

Combination of true airspeed and angle of attack indicators makes it possible to determine a more accurate value for critical flight speed. Actually, reading critical speed according to the true airspeed indicator holds true only for a specific aircraft weight without any overloading which would lead to a rise in critical speed. Critical speed (without consideration of the compressibility of air) depends on the angle of attack.

If there is an angle of attack indicator which informs the pilot of the reserve of lift force in any flight condition it is possible to perform landings with greater safety, making sharper turns. At all flight altitudes this attack angle indicator (with correction for the effects of compressibility) indicates the reserve of lift force during turning.

The combined true airspeed and angle of attack indicator must have the scales for both parameters located side by side so that when approaching critical speed i.e., when true airspeed is decreasing the pilot may more frequently make use of the angle of attack indicator (Fig. 20). The angle of attack scale is numbered in decreasing fashion with respect to the speed scale since its basic purpose is to indicate the reserve of lift force (the values of angle of attack not yet used), and the smallest values of reserve are more conveniently placed at the lowest point of the scale. The critical value of angle of attack is located opposite the average value of critical speed corresponding to level flight at sea level for a given aircraft weight.

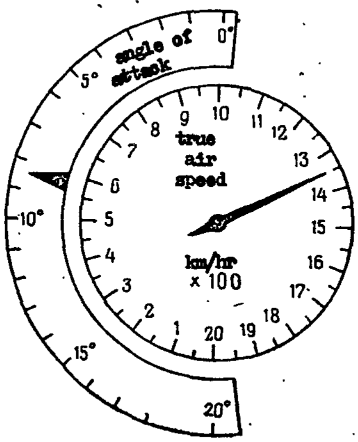

Fig. 20. Combined true-airspeed and angle-of-attack indicator.

When bank attitude and angle of sideslip indicators are combined the angular rate of turn indicator is best replaced with a turn-radius indicator. The angular rate is of interest only to aerodynamics specialists while for the pilot turn radius is of primary interest. The radius of turn is a function of true airspeed and overload and therefore may be obtained from the data provided by instruments to measure these parameters. In the case of a turn with gain or loss in altitude, a device is needed which will take into account the inclination of the plane of the turn to the horizontal.

A combined instrument to indicate heading, bank attitude, angle of sideslip, and radius of turn is shown in Fig. 21. The last three indicators are arranged together with a card compass. The sideslip angle indicator is located in the upper part of the scale so the pilot can establish at once if he is accomplishing the turn with or without sideslip. The bank indicator which is similar to that used in an attitude indicator (but with a moving airplane silhouette and a stationary horizon line), is located in the center of the scale. Below this is mounted the turn-rate indicator which has a logarithmic scale.

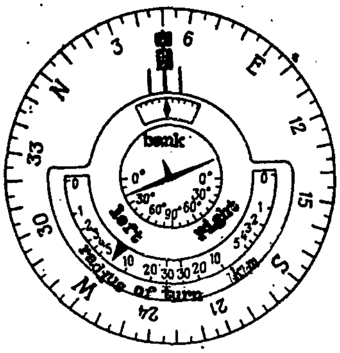

Fig. 21. Combined indicator of heading, sideslip, bank attitude, and radius of turn.

In addition to the mechanical combination of various instruments within a single housing, in some cases instruments are organically united for joint operation.

An example of such organic combination is a barometric altimeter which is discretely corrected by a radio altimeter (USA).

It is known that a barometric altimeter, actually measuring the air pressure, gives a steady indication of altitude independent of the relief of the flight locale. But in order to accurately measure the flight altitude with such an instrument it is necessary to know the actual ground-level temperature and atmospheric pressure of the flight locale as well as its relief (above the air base) which is not always possible to do in flight. The radio altimeter in contrast to the pressure altimeter does not require additional information from outside in order to determine absolute altitude but the readings are unsteady dur to a change in the relief of the locale.

It is considered that the combination of these two instruments with the application of special connecting devices (filters) makes it possible to obtain "hybrid" devices with stable and accurate indications of flight altitude at those points on the course where this is especially important (e.g., when approaching a bombing target).

Directing (Command) Devices

As the missions to be accomplished by airplanes increase, control-measuring devices and devices to measure the deviation of parameters from fixed values cease to satisfy new and increasing requirements. This is especially noticeable during flights along a fixed trajectory as for example along the radio beam of an instrument landing system. As is well known, this system utilizes directional antennas to generate narrow radio beams (equisignal zones).which indicate the direction of approach and glide slope to the runway. The aircraft is equipped with a receiver for signals from the course and glide-slope markers; this receiver has a cross-point indicator which indicates deviation of the aircraft from the equisignal zone.

To approach the course and glide-slope beam the pilot must read, analyze, and generalize the information from the measuring instruments and make a decision concerning the control of the aircraft. These operations cannot always be accurately and rapidly accomplished by the pilot when the time is limited and when there is, of necessity, a high rate of change in the flight situation; this often leads to unexpected and frequently serious consequences.

Let us consider the action of the pilot when utilizing the indications of various instruments to bring the aircraft to the trajectory given by the equisignal zone of the course marker.

If the aircraft has left the equisignal zone then in order to reenter it the pilot must execute a double turn; first in the direction of the zone and then back again so as to smoothly enter the required flight trajectory.

Optimum entry into the trajectory (i.e., without crossing over it or else protracting the entry) depends on an accurate selection at each point of the actual trajectory of the turn rate when making the double turn.

To complete this maneuver accurately, the pilot must gather, compare and reduce information from at least three instruments: bank indicator (one of the scales of the attitude indicator) an indicator of the deviation of the actual course of the aircraft from the one prescribed (according to a compass scale especially set up by means of a rack) and an indicator of the deviation of the center of gravity of the aircraft from the given trajectory (Fig. 22).

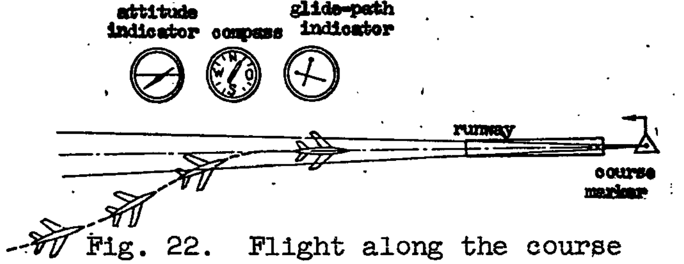

Fig. 22. Flight along the course marker beam.

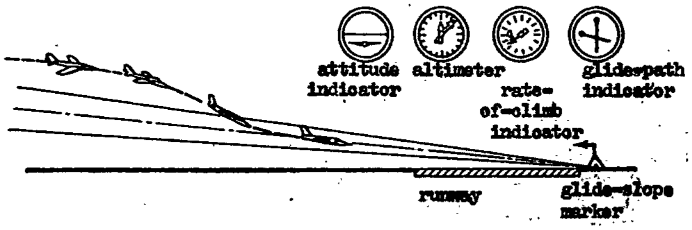

Fig. 23. Flight along the glide-slope marker beam.

As the given trajectory is approached, the indications of the instruments change: the greater the bank executed by the aircraft the more rapidly will the course be altered and the closer the plane will approach the given trajectory. Proper proportioning of the bank and accurate determination of the moment of altering the bank depend mainly on the training of the pilot and are determined by his individual abilities.

When bringing the aircraft into the equisignal zone of the glide-slope marker normal forces required for a double turn in the vertical plane are created by the elevator. In order to accomplish an accurate maneuver of the aircraft in the vertical plane the pilot must make use of three and sometimes four instruments: glide-slope indicator, the pitch attitude indicator, rate-of-climb indicator and altimeter (Fig. 23).

Comparison of the varying indications of these instruments when approaching the glide slope, the reduction of the entire flow of information from these instruments, the development and adoption of a decision by the pilot requires a great deal of time, consequently inaccurate approach and following of the glide slope occurs very frequently. Flight along the glide slope is further complicated by the fact that the pilot must operate the throttle to maintain a definite forward speed (required speeds at various points of the slope trajectory are different).

In order to simplify control of the aircraft when approaching a prescribed trajectory and when following this trajectory, so-called directing or command flight-navigation instruments are being used abroad (Fig. 24).

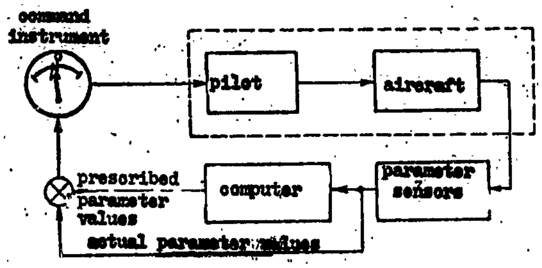

Fig. 24. Functional diagram of a command device.

These instruments provide the pilot with information in an already reduced and generalized form indicating how to direct the aircraft: up or down, right or left.

It is no longer necessary to compare the indications of the instruments mentioned earlier. All he must do is carry out the command (direction) of the new instrument by operation of the aileron (to approach the trajectory in the horizontal plane) and the elevator (to approach the trajectory in the vertical plane).

Generalization of the information received from various sensors and development of a signal as control commands are accomplished in director devices with special computers (calculators). The pilot need not perform complex mathematical or logic operations. It is as if he stopped controlling the aircraft and began to control only the pointer of the director device, holding it on zero. Deviation of the command indicator is proportional to the total value of the signals of bank, deviation from the prescribed course heading, and deviation from the equisignal zone of the course marker. The pilot, banking the aircraft, holds the command indicator on zero, while the bank attitude is changed so that the aircraft performs a double turn with an accurate approach to the equisignal zone. This is achieved by the selection of the ratios of the combined signals. The position of the indicator of the command instrument on zero indicates that the actual bank executed by the pilot coincides with the required bank (so as to enter the required trajectory accurately and on time) which is determined by the command computer according to the magnitude of the deviation of the aircraft from the trajectory and according to the difference between the actual and prescribed headings of the aircraft.

Entry into the equisignal zone of the glide-slope marker may also be accomplished by means of a special command device in which are accumulated signals which are proportional to the pitch attitude, vertical speed, and deviation from the glide slope. The command indicator is maintained on zero by operating the elevator. In this way the pitch attitude is made to coincide with that required as determined by the computer according to the magnitude of the vertical speed of the aircraft and deviation of the aircraft from the glide slope.

It has been noted in the press that directive devices which simplify the approach of an aircraft to a given trajectory and hold it on a trajectory are not completely satisfactory for the pilot because they do not indicate the position of the aircraft with respect to the horizon and the given trajectory. Holding the command indicators on zero the pilot may also not know if the aircraft is located on the trajectory since the null reading of the indicators attests only to the fact that the aircraft is accurately approaching the trajectory (or is located on it). Therefore in addition to the directing device, indications from the usual measuring instruemnts must be used.

Usually the command instrument is made with two mutually perpendicular pointers. Maintaining the vertical pointer on zero ensures holding the given trajectory in the horizontal plane while the horizontal indicator is used for holding in the vertical plane. The command index may be a single indicator in which case its average position would indicate correct accomplishment of the command by the pilot with respect to approach of the trajectory in both the vertical and the horizontal planes.

The command indication may be accomplished in the form of a system arbitrarily called a "question-answer" system. For instance, as a command instrument to determine correct approach to the trajectory in the horizontal plane one may use a single stationary lateral bank scale with two independently moving indicators to show the prescribed bank (determined by the computer) and the actual bank of the aircraft. This makes it possible to combine command and measurement functions within the same instrument.

The task of the pilot in accomplishing the command is to put the two indicators in coincidence with one another.

Director devices may be employed for piloting aircraft along trajectories determined by systems of distant and near guidance, for flight at a fixed altitude, (for example when echeloning aircraft vertically in the same flight route), when photographing the ground, etc. These systems use as commands signals which correspond to deviations from the direction to an objective or from a predetermined altitude.

Integrated Instruments

Integrated instruments are instruments which combine the indications of usual measuring instruments for the purpose of obtaining a single generalized picture which directly informs the pilot of the conditions of flight. Usually entire integral instrument systems are developed. Signals from individual sensors are fed to a computer where they are reduced and compared in appropriate ways with prescribed parameter values. Output signals from the computer are transmitted to indicators from which the pilot may determine at once what position the aircraft is in and what action he must take to carry out the prescribed flight plan.

An example of an integrated instrument is the navigation instrument which provides the pilot information concerning the magnetic heading, the bearing of the radio station as well as the prescribed direction of flight and the magnitude of deviation of the aircraft from this direction (Fig. 25).

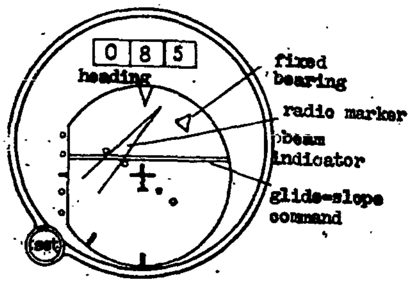

Fig. 25. Integral navigation instrument (USA).

Another integrated instrument provides correlation for the control of engines.

Engine operation is characterized by a definite combination of parameters (power or thrust, thermal and mechanical strain, efficiency, acceleration characteristics) which may be associated by a single functional dependence, the regime function. It may be simulated by a computer. It is easier for the pilot to evaluate the operation of an engine from a single instrument which gives an over-all evaluation of its operation than from several individual parameters read from a number of instruments. Moreover, an integrated instrument which controls the operation of the engine can be calibrated in definite ratings, for example: no-load condition, cruising rating, nominal rating, take-off rating, maximum reheat rating, etc.

The integrated instrument which controls the fuel system of an aircraft is a gage of the available flight range. This instrument frees the pilot from calculations of the available flight range according to data from separate instruments (fuel reserve and per hour consumption, true flight speed, windspeed and direction, flight altitude and air density, reduction of gross weight with fuel consumption or dropping of load). Information from the sensors of these devices as well as information from predicting devices (prediction of the reduction of gross weight and variation of height of flight with windspeed and direction), is fed to a special computer in the integrated instrument and is reduced in accordance with an algorithm established in the computer (with specifications, sequence of action on one or another quantity, etc.). As a result the instrument at any moment indicates the available flight range.

Indicating Devices

There are instruments being used on aircraft which do not adequately indicate dangerous deviation of controlled parameters from standard value. Therefore various indicating devices have been placed on the instrument panel which are actuated when one or another flight parameter deviates from some allowed level. The indicator is a simulator which arouses an appropriate reflex in the pilot aiding him to perceive any new event in time. According to the nature of their action on the pilot, indicators may be attracting (when a light comes on near an instrument or apparatus), warning (when the lighted lamp warns that a parameter is approaching a critical value) guiding (when the signal accentuates the pilot's attention to a specific group of instruments or to a certain lever), informing (when the signal gives information concerning events taking place) and command (for instance in the form of a legend like "Reduce Throttle" or "Lower Landing Gear").

Most indicators are noise or light (lamp or glowing legend) indicators. Indicators which demand rapid action by the pilot, i.e., which warn him of an emergency condition are usually in the form of a tableau with a lighted inscription. The inscription does not shine constantly but flashes so as to rapidly attract the pilot's attention and inform him of the approach of an emergency condition. Under normal conditions these inscriptions are not visible.

Indicators used during landing are combined in a flight-landing indicator. It may include signals concerning the condition of the landing gear and the landing flaps ("Down," "Up").

Red, green, yellow and white lights are used as indicators. A red light usually indicates an emergency condition and a green light the normal condition of a controlled system or controlled parameter.

Mechanical indicators are sometimes used whose action is perceived either visually (signal flags which flash onto the instrument face) or mechanically (e.g., trembling of the control stick when approaching a condition of critical flight speed).

Arrangement of Instruments and Components upon the Instrument Panel

Instruments and indicators must be arranged upon the instrument panel in such a way that it will be possible to rapidly perceive and comprehend the information presented by the instruments and indicators and so that when the pilot performs the most labor consuming stages of instrument flight (landing, homing on a target) he will expend a minimum of energy (small and infrequent turning of the head, etc.). In addition, the arrangement of instruments used during landing must be such that the pilot may rapidly convert from instrument to visual flight orientation.

The most important instruments must be placed as far as possible in the central field of vision of the pilot and instruments which serve for occasional in-flight checking and for reference may be arranged within the field of peripheral vision.

In order to arrange the instruments and indicators properly when constructing experimental aircraft, pilots, engineers and flight surgeons (physiologists and psychologists) are carrying out a great deal of work in evaluating the work activity of the pilot at each phase of flight. Many specialists formerly held that the arrangement of instruments (at least those most needed by the pilot).could be standardized for all aircraft types. This would make it much easier to train a pilot for instrument flying and to assure him of mastering the new physical aspects.

Such standardization was not introduced however. This is explained by the fact that in connection with the expansion of the problems which confront each new type of aircraft the number of instruments and combinations of them grows continuously and it does not do to arrange these numerous instruments in standard racks.

Escape from this difficult situation was found. An arrangement of instruments which is not standard but is typical was developed and introduced.

Instruments are grouped according to their importance. A special section of the instrument panel is set aside for each group and for each new type of aircraft the arrangement of instruments may be altered to some extent within the limits of these sections, i.e., obsolete instruments may be replaced with new ones.

The most easily observed portions of the instrument panel, the left and central sections, are reserved for the basic flight-navigation instruments. Instruments especially required for instrument landings must be arranged on the left side of the instrument panel. This arrangement is the most successful for conversion from instrument to visual landing.

The right side of the instrument panel is usually set aside for devices which control the operation of the engines, the cruising conditions and the fuel system.

Instruments which control the pilot's life-support system as well as other auxiliary systems are located in the lower portion of the instrument panel.

Examples of instrument panel groupings will be considered in subsequent descriptions of developed and proposed systems of instrumentation.

II. INSTRUMENT FLYING

Peculiarities of Flight Beyond the Visibility of the Ground and Horizon

The main difference in the functioning of a pilot when flying under good and bad weather conditions is in the way he obtains information concerning the position and motion of the aircraft in space.

Under good weather conditions the spatial location and motion of the aircraft is determined directly by means of visual reference points (horizon, objects below). Flight-navigation instruments are used in this case only to increase accuracy in holding and controlling the conditions of flight and when doing maneuvers.

When the horizon is not visible and when weather is bad it is possible to fly only by using an entire system of instruments, i.e., indirectly by sensing the indications of various instruments which, when evaluated, provide the pilot with complete and accurate information concerning the position and motion of the aircraft.

In accordance with the indications of the instruments, the pilot establishes, maintains, and alters the conditions of flight.

Such a system of indirect orientation is not only difficult for the pilot but also requires more time than direct orientation.

As is known, a person orients himself in space as the result of the interaction of the various organs of sense with sight playing the lead role. By using his sight a person determines the position of his body with respect to other visible objects. This type of orientation takes place almost instantaneously.

For clarity let us consider a simple example. In order to discern such a development of the aircraft as descent the pilot has simply to look outside. According to the relative position of the nose of the plane and the line of the horizon and the nature of the shifting of ground objects he is able to determine if the plane is descending. In practice this kind of direct perception functions very rapidly.

When indirectly evaluating the same development the pilot must determine the position of a silhouette of a plane with respect to an arbitrary horizon line on the attitude indicator, establish the loss of altitude from an altimeter, determine the rate of descent from the rate-of-climb indicator, etc. And only by comparing the indications of these instruments does the pilot obtain an idea about the spatial orientation and motion of the aircraft.

As is known, the pilot during flight works at a demanding pace. This is associated with the fact that he must constantly react to rapidly changing conditions. His work pace will depend on how many operations he must perform in a given period of time or when accomplishing a given element of flight and how he must see objects and instruemnts and operate the pedals.

Much additional perception and activity takes place in instrument flying. It is necessary to constantly watch a large number of instruments, to frequently make use of radio aids, special equipment etc. This means that the work pace will be more intense when performing a given element of flight by instrument than it would be visually.

If in flight the instrument indications are watched continuously it is relatively easy to detect and evaluate their constantly changing indications. Various deviations in the flight which must be eliminated by the intervention of the pilot can then be detected in time.

In order to successfully fly by instrument the pilot must learn to apportion and shift his attention properly.

The need to shift one's attention during instrument flight results from the fact that it is not physically possible for the pilot to accurately evaluate the indications of a number of instruments at the same time.

More demanding conditions develop when the pilot, flying visually, must suddenly switch over to instrument flight. This frequently happens when there is a sudden worsening of flight conditions when the possibility of perceiving the true horizon or other reference points outside of the aircraft is eliminated. For example, if the plane enters a cloud the pilot must complete the pattern, using only the instrument indications for orientation. The same situation arises when firing on a lighted target at night, since after leaving the attack the true horizon is not visible and flight may be carried out only by instrument. These examples graphically show why it is inadmissible to be distracted from the instrument indications especially when descending to land.

When it is necessary to convert to instrument flight each pilot behaves differently. One will do it all at once, i.e., when he still knows the position of the plane and the flight situation. Observing by instrument the subsequent change in flight parameters and attitude of the aircraft, he creates for himself a condition much like that of continuous flight by instrument.

Another pilot, when no longer able to continue visual flight, attempts for a time to discover some reference (horizon, runway lights, etc.). Meanwhile the position of the aircraft in space is changing continuously. Not knowing how the position of the plane has changed, the pilot has difficulty in converting to instrument flight. In this case he can only determine his position indirectly by reading the indications of almost all of the flight instruments.

When flying beyond view of the horizon or landmarks, the pilot experiences false sensations (illusions) about the position of his aircraft.

Illusions contribute to a situation which distracts the pilot's attention from the instruments when an acceleration is acting on him.

Most frequently the pilot observes illusions of banking, gliding, pitching and even the sensation of reverse bank when slipping and the sensation of reverse turning.

The frequency of illusions is proportional to the degree of complexity of managing spatial and navigational orientation. Illusions most frequently occur at night in turbulent air (during storm activity and severe bumping) and also when flying in clouds which have varying illumination or density and which draw the pilot's attention away from his instruments. Less frequently illusions occur when flying through regions with heavy fog, during unexpected entry into cloudiness, significant slipping, abrupt entry into a curved flight and exit from it, sudden increase of speed, and decelerating.

The false impression of the position of the aircraft will be especially severe for a pilot with little training in instrument flying. As a result the pilot ceases to believe in the instrument indications, flies the plane according to his false sensations and as a result permits incorrect action of the control surfaces; this inevitably leads to gross deviations in the flight which do not assure the safety of the flight.

The number of false sensations which the pilot gets decreases with his experience at instrument flying and the flight-navigation instruments will replace for him visual orientation with respect to the true horizon and visible ground objects.

Flight in clouds with modernly equipped aircraft and with sufficient ground aids to navigation presents no difficulties. Air crews which know how to fly by instrument are completely free to carry out flight tasks both in clear weather and when it is cloudy or when there is rain, snow, fog, etc.

Flying in clouds differs from good-weather flying and even from instrument flying in a closed cabin in the fact that neither the horizon nor the ground are visible and the plane is subject to the action of atmospheric phenomena associated with a sojourn in a clouc layer.

The experienced pilot when entering clouds responds calmly and confidently continues to fly along the given course. When entering clouds for the first time a pilot begins to be disturbed and loses faith in his ability to direct the plane by instrument. If a pilot is trained in instrument flying but has never flown in clouds and his cabin is covered with a hood then he will direct the plane as well inside a cloud as he will out of it. But as soon as the cabin is uncovered and he sees that he is in a cloud, the quality of his flying may be impaired.

This may be explained by the fact that in a closed cabin the pilot's attention is concentrated on the instruments but when flying in clouds his attention is drawn to the visible parts of the plane, the varying density and brilliance of the clouds, to snow, rain, and ice formation. Thus the developed degree of distribution and transfer of attention is disturbed and the quality of flying skill decreases.

Flying in clouds is accompanied by bumping especially when entering the cloud from below and when flying just under it at a low altitude. Bumping makes maintaining flight conditions more difficult while the need to maintain them accurately increases.

At night it is much more difficult than in the daytime to determine the distance to the ground, the height for leveling out and for flare out which leads to certain difficulties in landing.

Illumination of the cabin during night flight has an adverse effect on the adaptability of the organs of sight to the observation of objects outside. The conditions of night flight as compared with day-time conditions arouse certain psychological tensions in the pilot which may be reflected in the quality of instrument flight.

Takeoff

Takeoff refers to the stage of flight from the moment the plane starts its takeoff until it reaches a height of 25 meters after leaving the ground. For the pilot takeoff is one of the most demanding and complex tasks of flying.

When taking off the pilot must accurately determine and maintain the acceleration of the plane, attain the proper takeoff speed, maintain the heading and attitude of the plane with respect to the axis of the runway extended, establish and maintain the rate of separation from the runway and the climb rate. In doing this the pilot must keep in mind the aircraft's takeoff distance, the length of the runway, the nature of its surface, the weight of the aircraft, wind velocity and direction, air temperature and pressure, and a number of other points which determine the takeoff characteristics of the plane. If bad weather conditions are added to this then it becomes apparently impossible to systematically train a pilot in takeoffs or to use instrumentation in this stage of flight.

Let us consider some instrument systems developed abroad for controlling takeoffs.

The airborne equipment of the first system includes an accelerometer to measure the takeoff acceleration of the aircraft, and a dynamic airpressure meter. In this system a special instrument in the cabin indicates the magnitude of acceleration and provides a warning signal (Fig. 26).

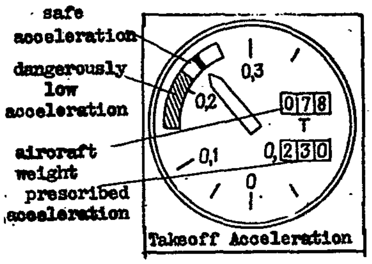

Fig. 26. Takeoff control instrument.

The pilot must set into the instrument the weight of the aircraft and a prescribed acceleration as determined by slide-rule or nomograph on the basis of information concerning the type of aircraft, surrounding temperature, pressure, runway slope, and engine rating. This system does not require the pilot to make any manipulations at the start of takeoff. On some aircraft however it may be necessary to compensate for small variations in pitch attitude brought about by various locations of the center of gravity since when the accelerometer leaves the original horizontal position acceleration on the takeoff run will be measured inaccurately as the result of the effect of acceleration on the force of gravity. Calculations have shown that altering the pitch attitude of heavy jet aircraft by 1° may lead to an error of almost 10% in linear acceleration measurement. Such an error means the difference between normal and inadmissible takeoff conditions. It may be compensated for by using a correction signal for pitching from the vertical gyroscope.

During the ground run the indicator informs the pilot of the plane's acceleration: normal, high, low. The cross-hatched portion of the scale indicates dangerously low acceleration.

The acceleration of a jet aircraft with constant thrust decreases somewhat with increased speed in the ground run because of increased drag. In order to compensate for this normal reduction in acceleration a combined signal from the accelerometer and the dynamic pressure detector is used. The sum of these signals remains constant throughout a proper takeoff and is independent of wind thus eliminating the need to introduce wind datd into the system by hand.

The airborne equipment of the second system to control takeoffs continuously measures the distance covered by the aircraft along the runway and determines its ground speed. At a specific distance the actual ground speed is compared with the prescribed value which the plane should have reached at this point.

The prescribed values of ground speed (determined by slide-rule) and the control distance are entered by the pilot on the panel (comparator) which is located in the cabin (Fig. 27). Also located there is a digital indicator of elapsed distance and a signal light.

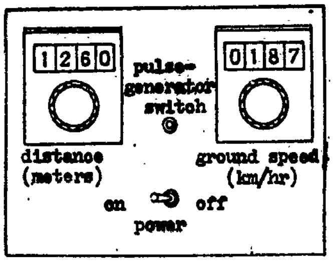

Fig. 27. Take-off control system panel.

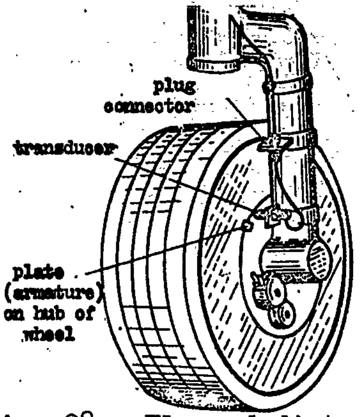

Fig. 28. Elapsed distance indicator for take-off control system.

A miniature pulse generator mounted on the main landing gear is used to measure the distance (Fig. 28). This generator consists of an induction transducer mounted on the landing gear strut and an iron plate (armature) on the hub of the wheel. Each rotation of the wheel produces a pulse in the transducer circuit and the number of these pulses is proportional to the distance covered. Differentiation with respect to time yields a signal which is proportional to ground speed. When the aircraft reaches a certain control point on the runway this signal is compared (in the comparator) with a voltage which corresponds to some velocity. A flashing green light indicates an acceptable takeoff speed and a flashing red light indicates that the speed is too low.

The system described permits the pilot to check its operational ability in two ways before takeoff. The first method requires pressing the "Taxi" button to verify the operation of the distance transducer and certain other circuits during taxiing. The second method of checking the system requires pushing the "Test" button several times. Each time this button is pressed a signal is fed to the comparator which corresponds to one revolution of the main landing gear. Having pressed the button a certain number of times it is possible to verify if the counter indication corresponds to the elapsed distance.

Before starting the takeoff run the pilot must press the "Takeoff" button. This operation could be made automatic.

A third system for controlling takeoff measures the ground speed, computes acceleration and compares it with a norm value.

An acceleration indicator in the cabin (Fig. 29) provides the pilot with continuous information about the relative magnitude of the actual acceleration of the aircraft during takeoff. This system requires no preliminary calculation from graphs or with a slide rule. All that is required is setting up the runway length and windspeed on the indicator. Variations in atmospheric pressure are compensated for automatically by an aneroid unit connected to the aircraft's pitot system.

In the simplest variation of the system the maximum takeoff weight of the aircraft is calibrated. In a more accurate variation the takeoff weight must be introduced into the system as an initial parameter. Compensation for the reduction of acceleration with increase in speed is provided for in the system. The indicator operates on the command principle of "YES-NO" without a numerical scale.

The heading of the aircraft during takeoff is determined from standard airborne instruments — the gyromagnetic compass or the directional gyroscope.

The linear deviation of the aircraft from the axis of the runway as yet cannot be measured by any simple means. However, it may be assumed that if the aircraft is accurately pointed along the axis of the runway at the outset and the takeoff heading is maintained, then it will be practically on the axis of the runway at lift-off.

Level Flight

An aircraft levels off (usually from a climb or descent regime) at an altitude 50-100 m below (during climb) or above (during descent) the assigned altitude. The control stick is used to keep the attitude indicator and the rate-of-climb indicator on zero and the compass needle on a fixed heading. It must be borne in mind that the silhouette in the attitude indicator does not usually rest on zero during level flight if the rate-of-climb indicator reads zero, i.e., it does not coincide with the bar which simulates the horizon due to the fact that the aircraft possesses a certain pitch attitude. Therefore to make it easier the pilot centers the reference "airplane" with the horizon bar.

The prescribed flight speed as shown by the speed indicator is adjusted by varying the thrust of the engine(s).

Level flight is maintained when the indications of these instruments mentioned remain constant.

Any external disturbance (gusts of wind, variation in drag, etc.) as well as voluntary movement of the control stick by the pilot may alter the conditions of level flight. This will first be reflected in the attitude indicator and the rate-of-climb indicator and then by the altimeter and the compass.

If the airplane silhouette in the attitude indicator rises above the horizon bar the pilot brings them together again by moving the stick forward and then pulls it back slightly to fix the silhouette in the place corresponding to level flight. Meanwhile the rate-of-climb indicator must remain on zero. When the longitudinal attitude deviation is in the opposite direction the pilot must operate the control stick in a reverse manner.

If the aircraft deviates in a lateral direction and the established course begins to change as indicated by the attitude indicator, turn indicator and compass, then by coordinated movements of the controls (stick and rudder) the tendency to turn is removed and the attitude indicator (with respect to lateral deviation) and the turn indicators return to zero and the compass is returned to the previous heading.

When eliminating deviations from level flight, control operation must be appropriate to the magnitude and rate of deviation of the attitude indicator readings. The faster and greater the indications change the more energetic and farther must the controls be moved.

When there is no bumping, attention to the instruments for the purpose of maintaining level flight may be in the following order: attitude indicator — rate-of-climb indicator; attitude indicator — speed indicator; attitude indicator — compass — altimeter; attitude indicator — turn-and-bank indicator.

Periodically the pilot must turn to the engine controls.

When there is bumping and rate-of-climb indicator operation is unstable, the pilot, who is trying to maintain a given heading and altitude, must frequently refer to the attitude indicator. If level flight is being carried out at low altitude additional attention must be given to the barometric altimeter and the radio altimeter for altitude control.

Climb

An aircraft may be brought into a climb either from a level flight condition or from a descent.

When converting from level flight the pilot establishes a nominal power setting and increases the flight speed suitable for a climb. Then by pulling the stick back he establishes the pitch attitude at which the aircraft's true airspeed remains practically constant and controls it using the attitude indicator. The rate-of-climb indicator must show a constant value. The pilot then adjusts engine thrust (according to the tachometer), increasing or decreasing the rpm to maintain a fixed speed.

When converting from a descent to a climb the pilot sets engine rpm to correspond with a given flight speed and smoothly pulls the stick back to bring the aircraft into level flight being guided by the attitude indicator, speed indicator, compass, and rate-of-climb indicator. The transition to a climb is then carried out as described above.

Correcting for deviations in climb from a predetermined or selected rate is carried out in the same sequence as correcting in level flight with the exceptions that the "airplane" in the attitude indicator does not coincide with the horizon bar but remains in a position which corresponds to the given climb condition and the rate-of-climb indicator maintains a positive value.

To maintain a climb attention may be directed to the instruments in the following order: attitude indicator — rate-of-climb indicator — speed indicator; attitude indicator — rate-of-climb indicator — compass; attitude indicator — rate of climb indicator; attitude indicator — turn-and-bank indicator — altimeter.

The pilot must periodically turn to the engine controls.

Flight Along a Route

In flight along a route with accurate stabilization of the aircraft with respect to the Earth, with accurate approach to a predetermined trajectory and with retention of that trajectory, orientation must be maintained.

Navigation is knowledge of the location of the aircraft with an accuracy required for continuing flight. Flight navigation requires a systematic determination of the location of the aircraft and comparison of the actual direction of the aircraft with the predetermined one.

When the ground and landmarks are visible the location of the aircraft is most easily determined visually. As a rule visual orientation is combined with the use of various technical means of air navigation. When the ground is not visible navigation is carried out completely by airborne and ground navigational aids.

When preparing for a blind flight the route is usually marked off into a minumum number of legs. This simplifies the flight and increases the accuracy of following a given path. In addition, the route is selected so that the flight will be provided with radio and light navigation aids.

Instrument flying on a route is assured by various technical means of air navigation (navigational systems) which may or may not be automatic. Automatic systems are mounted on the aircraft and require no ground equipment for their operation. In nonautomatic systems the airborne equipment receives signals from ground (usually radio) equipment.

Navigational systems are divided into three groups according to the measurements required to determine the location of the aircraft:

- positional systems which directly determine the coordinates of the location of the aircraft;
- dead-reckoning systems which measure the speed according to which the position of the aircraft can be determined by single integration;
- inertial systems which measure the acceleration and the position of the aircraft is measured by double integration.

The systems of the first group may be automatic (e.g., celestial navigation) and nonautomatic. Systems of the other two groups are all automatic. Automatic navigational systems are especially needed in military aviation since secrecy of operation and the ability to navigate in regions deprived of ground equipment are assured.

Positional Air Navigation Systems

In positional systems the measurement of each parameter (angular or linear coordinates) makes it possible to obtain on the surface of the Earth (reckon on a regional map) the line of position (LOP) on which the aircraft is located at the moment of measurement.

The point of intersection of two LOP's for the same moment of time will be the location of the aircraft. The measured parameters most frequently used are bearing (θ) and distance to a landmark (R). Therefore positional systems may be angle-measuring, angle-and-distance-measuring, distance-and-distance-difference-measuring, or hyperbolic (Fig. 30) systems.

In <u>angle-measuring</u> systems the LOP will be a straight line (orthodrome) passing through a given landmark. The error in measuring depends on the distance to the landmark (about 1.5 kilometer for each 100 kilometers distance). The location of the aircraft according to the bearing of two landmarks is also determined with an error which depends on the angle formed by the LOP's (it will be minimum at an angle of 90°). The angle-measuring system is therefore used for short-range navigation.

The angle-measuring system makes it possible to use one LOP for the purpose of air navigation. If the landmark is the end point of the course then its bearing will coincide with the prescribed flight heading and may be used to guide the plane to that object (for instance a radio marker beacon). In this case the accuracy of the bearing measurement is not important. Even when deviating from the given heading the aircraft will eventually reach the beacon.

An automatic direction finder (ADF) aboard the plane and a ground radio beacon or a ground radio beacon and a radio receiver on the aircraft are both examples of an angle-measuring system.

<u>Automatic Direction Finder</u> (ADF). The automatic direction finder, often simply called a radio compass, consists of an airborne radio receiver with a directional (loop) antenna. The strength of the received signal is minimum when the plane of the loop is perpendicular to the direction to the station.

The ADF has the advantage that it does not require any special ground transmitters. The ADF may be used with any radio transmitter operating within the frequency range of the ADF receiver. Special airfield radio beacons are used to direct the plane to the field by ADF. The ADF indicator shows the relative bearing of the radio station measured from the longitudinal axis of the aircraft extended, to the direction to the station. To fly toward the station the pilot simply maintains a null reading on the bearing indicator.

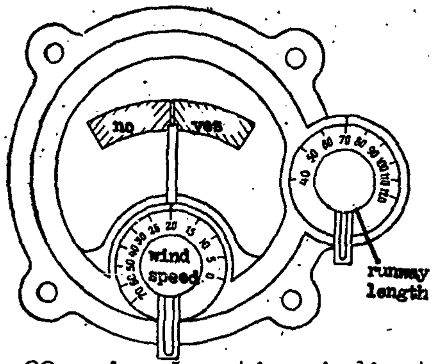

Fig. 29. Acceleration indicator for takeoff control system.

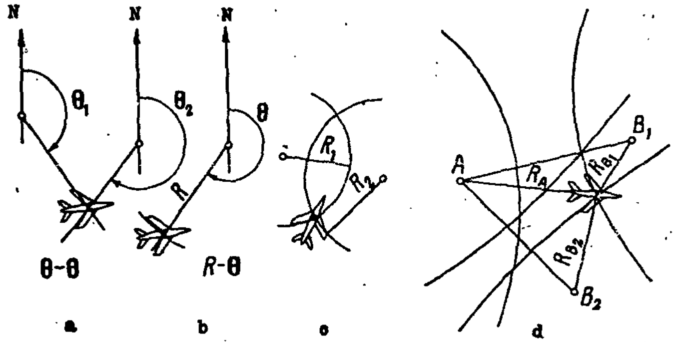

Fig. 30. Position determination: a) angle measuring; b) angle-distance measuring; c) distance measuring; d) distance difference measuring (hyperbolic).

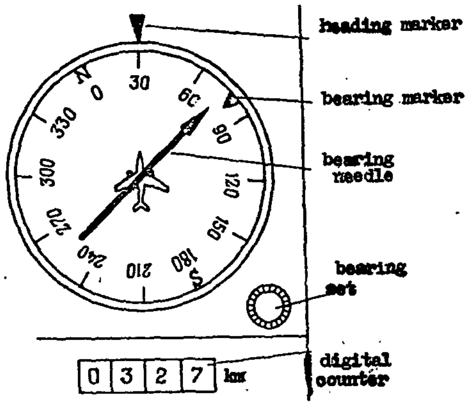

Fig. 31. Heading-bearing indicator.

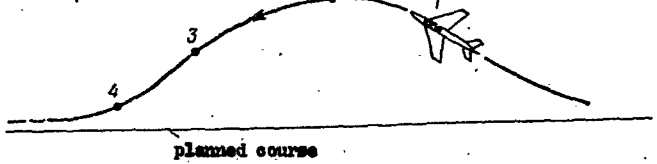

Fig. 32. Flight along a planned course: 1, 2, 3, 4) positions of aircraft on the true track.

Radio Beacon. The radio beacon is a special ground-located radio transmitter with directional radiation providing usually two or four beams.

UHF Omnirange (VOR) radio beacons make it possible to determine the direction to the station from any point with angular measurements accurate within 3-4°. VOR operation is limited to a distance of about 300 kilometers since vhf signals are limited to line of sight use.

The signal from the radio beacon is picked up in the aircraft by a receiver and then presented aurally or with a null indicator.

In distance measuring systems the LOP is a circle with the landmark at its center. The accuracy of measuring the distance to the landmark is independent of the distance. One LOP alone does not give complete navigational information. In order to determine a fix a second parameter is needed, namely the bearing or distance of another landmark.

The two LOPs (circles) intersect in two points; therefore in order to determine which one the plane is located at, additional information is required. The accuracy of the fix depends on the angle of intersection of the circles.

The most widespread distance measuring system is the celestial navigation system which uses LOPs which are circles of equal elevation. The geographic position of a star is the center of a circle of equal elevation. This angle is called the elevation of the star and is measured with an aircraft sextant. Having measured the elevation of two stars and determined the coordinates of their geographic locations from a special table, it is possible to chart the corresponding circles of equal elevation and determine a fix from their point of intersection.

The accuracy of celestial navigation methods is increased significantly by the use of sextants which are stabilized with respect to the plane of the horizon, automatic photographic servomechanisms, and digital computers to speed necessary calculations.

In angle-distance measuring systems the bearing and distance of a single landmark are measured at the same time. The accuracy of this system depends primarily on the accuracy of bearing measurements and is therefore best suited for short-range navigation.

The American short-range navigational system Tacan is an angle-distance measuring system. Tacan uses an SHF ground beacon in combination with radio-distance equipment. Bearing accuracy is 1°. Distance is determined from airborne interrogation by measuring the time interval between the transmission of the pulse from the aircraft and the reception of the reply pulse from the ground station. Distance measurement is accurate to about 150 meters.

The hyperbolic radio navigational system includes at least three ground stations which are plotted on special charts together with hyperbolic curves of equal distance from two of the stations. This system is used both for short- and long-range navigation and determines aircraft location with great accuracy. Its main disadvantages are the need of special charts showing time-difference hyperbolas and of complex indicating equipment, and the difficulty of obtaining information concerning a specific line of flight.

Moreover, each determination of a line of position requires a certain amount of time. If a fix is determined from two LOPs then obviously in order to determine their point of intersection the line determined first must be displaced parallel to itself along the actual ground path by an amount equal to the distance covered by the aircraft during the time interval between the determinations of the two LOPs. Since the actual ground path and ground speed are not usually known with sufficient accuracy, the fix will only be approximate. The error obtained will be directly dependent on the length of time between measurements and on the flight speed.

For modern high-speed aircraft only navigational systems in which the LOPs can be obtained simultaneously or in which sufficient information may be obtained without determining the location of the aircraft are of use.

Dead Reckoning

If an aircraft flies in a known direction at a know speed from the starting point of a route at which the coordinates are known then its subsequent location may be determined by multiplying the speed by the flight time. More precisely, the distance covered is equal to the integral of velocity with respect to time. The error in determining the location of the plane is proportional to the distance and reaches a maximum near the termination of the route.

Of late, means for determining ground speed and drift angle have been inadequate; thus dead-reckoning (navigational) systems have played a secondary role in case of failure or more accurate means, and have been periodically corrected by using those means.

The present use of accurate computing devices and radar doppler measurements of ground speed and drift angle has significantly increased the accuracy of the dead-reckoning system. It is believed that doppler radar may be used even when there is a need for secrecy in military operations since it radiates energy in a narrow beam at a large angle to the surface of the Earth and consequently may only be detected in a small area for a short period of time. A part of the energy reflected from the ground below is returned to the aircraft. By changes in the frequency of the transmitted and reflected signals it is possible to determine the speed of the plane with respect to the reflecting terrain, i.e., the ground speed, with an accuracy of 0.5-1%. If two beams are used the drift angle may be determined with accuracy of 0.5°.

Heading in a navigational system is determined from a compass which is either magnetic, gyroscopic, or astronomical. Heading systems are based on either a distance-reading gyromagnetic compass or a distance-reading flux-gate compass in which the axis of the gyroscope is maintained in a fixed direction by means of a flux gate which measures the Earth's magnetic field. At high latitudes these compasses are switched to directional compass operation, i.e., without magnetic correction. Magnetic compasses are used mainly as support instruments since they are not very accurate and cannot be used in polar regions.

Despite all improvements, compass accuracy does not exceed 0.75° or about 1.3%. This error limits the accuracy of all systems of dead reckoning.

Inertial Navigation Systems

The idea of inertial navigation is very simple and has been known for a long time. The position of the aircraft is determined in the same way as in dead reckoning but the measured parameter is acceleration, which is integrated twice with respect to time.

The acceleration of an aircraft may be measured with great accuracy. However the practical realization of an inertial navigation system involves several technical difficulties. An accelerometer located within the gravitational field of the Earth is not able to distinguish airplane acceleration from gravitational acceleration; hence the accelerometer must be accurately maintained in a horizontal plane so as not to detect the force of gravity or in a vertical position to make compensation for the force of gravity as easy as possible. In either case it is necessary to accurately determine the vertical. For this reason the so-called Schuler pendulum is used in inertial systems rather than the common pendulum (which deviates from true vertical under the influence of a horizontal acceleration). The Schuler pendulum is a pendulum which has a length equal to the radius of the Earth and its mass located at the Earth's center. Such a pendulum is not subject to the influence of acceleration and always remains vertical. Its period is equal to 84.4 minutes.

In the aircraft the Schuler pendulum is produced in the form of a platform with accelerometers which, by means of a servomechanism, swings at an angle which corresponds to the distance covered by the aircraft. As a result of the inaccuracy in measuring the vertical, it begins to oscillate with respect to the horizontal plane with a period of 84.4 minutes. Thus the error acquires an oscillatory character and will be cumulative with time.

The platform with the accelerometers is stabilized by gyroscopes which are oriented with respect to stationary stars. The accuracy of these gyroscopes determines the accuracy of operation of the entire inertial navigation system. It is pointed out in the literature that only in recent years have gyroscopes been produced which can satisfy the requirements of an inertial navigation system. At present there are gyroscopes available with drift rates (deviation of the main axis from an initial direction) of the order of 0.01 degrees per hour. Drift of the gyroscopes yields an error which is cumulative with time. Consequently, purely inertial systems are frequently combined with astronomical aids (astrogyro-orienter) and doppler radar, which periodically regulates the operation of the inertial system.

Indication of Navigation Parameters

The pilot or navigator is not required to understand how information is reduced in the computer. His job is to rapidly understand and make use of the information provided in order to control the aircraft. Above all he must know what to do at any moment in order to arrive on target and then know what the position of the plane is with respect to the terminal point of the course.

The extent to which any navigation system answers to these needs depends on the information which it provides and on the way it is presented to the pilot. Digital readout is now being used on most navigation instruments with the exception of direction indicators, which are clock-type or have a moving scale.

Output data from the navigation system most frequently indlude: bearing and distance of a landmark (intermediate or terminal point of a course); distance covered over a given line of flight and the linear lateral deviation from it; and the location of the aircraft on a map of the terrain being flown over. Heading and true track angle are also indicated.

If the pilot is set the task of flying to a predetermined point (target) in the shortest distance, then it would be of value to him to obtain information concerning its bearing and distance.

Bearing is indicated by an arrow which is concentrically mounted with respect to a rotating heading scale (track angle). Heading is read from the scale divisions opposite the heading marker which is located at the top of the instrument (at the 12 o'clock position) and bearing is read from the needle and the divisions on the scale (Fig. 31). To arrive at a given landmark the aircraft is turned until the bearing needle coincides with the heading marker without the pilot having to estimate the true bearing. The distance is registered on a digital counter.

Using such an instrument it is possible to approach a PAR (precision approach radar) station from any desired angle by manually setting the proper bearing on the instrument.

If the aircraft has deviated and it is necessary to bring it onto a given course, then the distance along this line and the lateral deviation may serve as the navigation parameters. These parameters however do not indicate to the pilot what direction to fly and thus are usually supplemented with a heading command signal. The computer forms this signal from 2 components: 1) the difference between the predetermined and the actual track; 2) the lateral deviation from the given track. Oriented by the final command signal, the pilot may direct his plane along a smooth curve to the prescribed track (Fig. 32). At point 1 the aircraft is flying off course to the right. Both error signals require a turn to the left. At point 2 the plane is flying parallel to the planned course, and the track-angle error signal is zero while the left-turn command signal is determined by the signal of lateral deviation. Beyond point 2 the track-angle signal calls for a right turn, i.e., counteracts the lateral deviation signal. At point 3 these signals cancel and the command signal becomes zero.

A right-turn signal then begins to predominate and the aircraft smoothly enters the planned course.

Figure 33 shows a typical indicator for this type of navigational system.

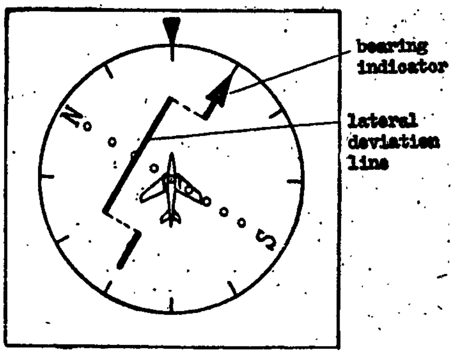

Fig. 33. Integrated navigation instrument.

Heading and bearing to the ground marker is read the same as from the instrument shown in Fig. 31. The bearing to the ground marker (the angle between the heading mark and the bearing indicator) serves as a measure of course-line deviation.

Lateral deviation is indicated by a segment from the center of the bearing indicator which moves perpendicular to it. When the aircraft is on the planned course this line segment coincides with the rest of the bearing indicator, which in turn points to the heading mark. If the aircraft is not on the planned course then it must be turned to bring the lateral deviation line into coincidence with the heading line (between the heading mark and the "airplane" in the center of the instrument). Figure 33 shows the instrument, indicating the position of the aircraft as at point 4 in Fig. 32. If the lateral deviation segment is thought of as the planned course then it can be seen from the instrument (looking at the aircraft position indicator) where the aircraft is located (to the right of the planned course and approaching it at an angle of 30°).

Automatic indication of the aircraft's position on a map is used mainly for special purposes. This method has the disadvantage that the map must be small so that it can be unfolded inside the cabin. Consequently it will be a map of a very small area or of inadequate small scale. A map can, however, be used to indicate a tactical situation showing the positions of several planes at once and is the only means of visual indication that can be used with hyperbolic navigation systems. For this purpose rolled maps which are wound along on rollers as the plane progresses are used. Maps are convenient for use in search and rescue operations, especially if the course is plotted.

Descent

When descending from level flight at a predetermined altitude and at a predetermined speed it is necessary to adjust the engine rpm and with a smooth action push the stick forward so that the "airplane" in the attitude indicator comes below the horizon line by the amount of the required pitch attitude appropriate to the forward speed and the rate-of-climb indicator reads the required value. To reduce the rate of descent by pulling the stick back it is necessary to establish the rated value of vertical speed and simultaneously increase engine speed to that required.

In this case the angle of pitch is reduced.

Deviation from given descent conditions is prevented in the same way as deviation from level flight conditions, but the "airplane" in the attitude indicator remains in a position which corresponds to the descent conditions rather than coinciding with the horizon line, and the rate-of-climb indicator shows the required vertical speed.

The order of reading instruments during descent is as follows: attitude indicator — rate-of-climb indicator — speed indicator; attitude indicator — rate-of-climb indicator — compass; attitude indicator — rate-of-climb indicator; attitude indicator — turn-and-bank indicator — altimeter.

The pilot must turn his attention periodically to the engine controls.

Allotment of attention to instruments during descent depends on the altitude of the aircraft. When descending from high altitudes attention is centered on the attitude indicator, speed indicator, and rate-of-climb indicator, and as the ground is approached attention is directed to the attitude indicator and the altimeter (while maintaining a fixed rate of descent and fixed heading).

Flying an aircraft equipped with loading mechanisms in the control system has one special feature. In some of these systems lowering the landing gear switches on the takeoff-land loading mechanism which results in a reduction of stick pressure and control becomes easier, which makes it more difficult to maintain the conditions of descent.

Landing

The main tasks in landing are bringing the aircraft into an approach heading, safe descent, and touch-down on the runway. The most important and difficult of these is descent prior to touch-down.

Landing is accomplished either by means of instruments which utilize signals from a ground radio facility or which operate automatically, or by means of command signals from the ground (in which case the pilot uses automatic airborne equipment).

In order to land successfully and to land in bad weather every pilot must be well acquainted with the special features of instrument flying.

The essence of landing from clouds with the use of standard airborne equipment, ground stationed localizer transmitters, and marker beacons is as follows: the pilot, being in clouds, guides his aircraft to the outer marker (located about 4 kilometers out along the axis of the runway extended) by following indications of heading from one of the beacons (outer marker) or using a bearing indicator to that station. He then completes a maneuver to bring him on a course opposite to the landing course, the pilot being informed of the direction of the landing course from the ground by means of radio direction finder indications. A heading opposite to the direction of landing is maintained for a distance (determined by timing) which will ensure downward penetration of the clouds and emergence below the clouds at a height of 200 meters and at a 30 second flight distance from the localizer transmitter. In accordance with the passage of the estimated time, the plane is turned to the landing heading and begins to penetrate the clouds in the direction of the outer marker.

When the outer marker is reached (this is indicated by a siren or triggered by the marker receiver) the pilot switches the automatic direction finder to the inner marker which is located 1 kilometer from the end of the runway and continues to descend along the approach heading.

The marker receiver is again triggered as the plane reaches the inner marker (the aircraft at this point is at a height of 50-70 meters). After passing the inner marker the pilot converts from instrument to visual flight and sets down visually. At the moment of touchdown the bank of the aircraft must be zero and the longitudinal axis must coincide with the axis of the runway.

When there is a cross-wind the pilot must turn the longitudinal axis of the aircraft to compensate for the drift angle. In this case, in order to avoid objectionable lateral loads on the landing gear it is necessary, before touching down to turn the aircraft (deliberately having banked or turned) so that the longitudinal axis will be parallel with the axis of the runway.

Landing requires a great deal of effort on the part of the pilot and he must continually direct his attention to a number of instruments or a number of groups of instruments at the same time. Even during descent prior to touching down he must watch the compass, attitude indicator, speed indicator, altimeter, and other instruments.

Investigators of the higher nervous system of the human being have established that when carrying out a number of activities, one of them remains dominant. The person's attention is thus concentrated on this one thing and digresses from the other activities. In flying practice this phenomenon may be observed when, for example, flaring out to land. For some pilots under conditions of this nature perception of indications on the compass becomes dominant while at the same time variations in the indications of the altimeter, speed indicator and other instruments go unnoticed.

Being aware of these special features every pilot must with conscious, determined effort direct his attention to carrying out all required activities even at moments when they seem secondary.

In bad weather when the cloud ceiling is less than 400 meters and horizontal visibility 4 kilometers or less one of the following maneuvers is required in order to approach the runway after flying over the outer marker: standard turn, circle above the marker, or standard rate turn.

Standard Turn. In order to land using a standard turn it is necessary to guide the aircraft to the outer marker at a height of 200 to 300 meters above the clouds by means of the radio compass. At the moment of entering the marker, the time is noted with a stopwatch, the plane is turned to a heading opposite to the direction of landing and this heading is maintained for the period required to penetrate down into the cloud. A standard turn is made in the required time and the aircraft is brought into a final approach heading.

A standard turn is performed at a bank angle of 15 or 30° as follows: within a predetermined time the aircraft is turned 80° to the right, then put into a left bank and held there until the relative bearing of the radio station is zero and the magnetic heading is the same as the approach heading.

When the standard turn has been completed the landing gear are lowered, the flaps dropped 20° and the speed brakes operated. The radio altimeter is then switched to low altitude operation, the aircraft is balanced at a speed established for cloud penetration, and descent begun.

Circle Above the Marker. Individual aircraft as well as formations, if they arrive at the outer marker at an angle of ±45° or greater to the approach heading fly a circle over the outer marker.

Having determined from the automatic direction finder (ADF) the moment of passage over the outer marker, the pilot puts the aircraft into a turn at a 30° bank. As soon as the aircraft again begins to intersect the landing direction at the outer marker, i.e., when the station bearing has turned 270° to the left (90° to the right) the angle of bank must be reduced to 15° and the turn continued. In this case the ADF indicator is held to the station bearing equal to 270° (or 90°) by decreasing or increasing the bank angle until the aircraft is on a heading opposite to the approach heading. Roll-out from the turn must begin about 5 to 10° before reaching this heading.

With a heading opposite to the landing heading, the pilot continues flight for a specified period of time after which he does a 180° turn in the same direction as that over the outer marker with a bank angle of 30°, coming on to the approach heading in the direction of the outer beacon.

The direction of heading over the outer beacon is determined from the side of approach to the outer beacon with respect to the direction of the approach heading. When approaching the outer beacon from the right it is necessary to turn to the right and vice versa.

Standard Rate Turn. The standard rate turn is the basic method of accurately coming onto an approach heading. It is distinguished by its simplicity and the minimum time required for its completion. A standard rate turn is accomplished when an aircraft (formation) approaches the outer marker on a heading which differs less than ±45° from that opposite to the approach heading.

The essence of turning to land with a standard rate turn is found in the fact that after flying over the outer beacon the aircraft is turned by a prescribed angle, and during a predetermined period of time with a specific forward speed leaves the plane of the runway (final approach heading) to a distance equal to twice the radius of turn of the aircraft at an angle of bank of 15 or 30°.

The size of the standard rate turn depends on the flight altitude, the bank attitude, horizontal flight speed, and rate of descent.

During a preset period of time the plane turns, banking 15 or 30°, by an amount equal to the angle of turn plus 180°, and the ADF and compass indicate that the aircraft is on a final approach heading.

Bombers, transport, civil and certain other aircraft complete the final stage before landing (descent along the final approach) by means of heading and glide-slope beacons and airborne instruments to measure the deviation from the heading and glide-slope zones. The use of heading and glide-slope beacons permits relatively accurate final approach.

The instrument that measures deviation from the heading-glide-slope zone (ILS indicator) determines only the direction in which the center of gravity of the aircraft has deviated from the glide path and to some extent the angular magnitude of the deviation. Consequently, as compared to flight according to a directing instrument, ILS flight in the glide-slope zone requires greater effort and can be performed only by an experienced and sufficiently trained pilot.

The needles of the ILS indicator move to the center of the scale only when the aircraft is on the glide path. The rate of displacement of the needles is proportional to speed with which the aircraft approaches the glide path. The pilot must judge for himself when to turn so as to intercept the glide path. When there is an indeterminate cross-wind this may be very difficult to decide and the aircraft may either overshoot the glide path or else intercept it very slowly.

It is considered that much better results in intercepting and maintaining the glide slope are obtained by the use of a director (command) instrument which receives information from the ILS indicator, the track-deviation indicator, and the bank indicator.

The method of landing by command from the ground by means of airborne equipment consists of the following: commands which aid the pilot, who is controlling the flight by means of automatic airborne equipment, are received by radio from the airport and help him guide the aircraft to the required final landing approach.

To generate these control commands from the ground, radar stations are usually set up at the airport; these make it possible to determine the error between the actual and the required position of the aircraft on the landing approach.

In order to simplify flying in this case, either manual control according to a director instrument receiving information from the ground or automatic control, whereby ground command could control the autopilot directly, might be used. The required commands could be developed by a computer on the ground and automatically transmitted to the aircraft.

III. INSTRUMENT FLYING UNDER SPECIAL CONDITIONS

Consideration has been given above to some of the peculiarities of instrument flying during various stages of flight. The determining stage of a combat flight is the accomplishment of the objective set: bombing, attack of an air target, etc.

Detailed consideration of the military application of aviation is beyond the scope of this book. Therefore we will consider only certain cases which are of interest from the point fo view of the application of flight-navigation instruments and the special features of flight during combat maneuvers.

Low-Altitude Bombing

Unlike horizontal and dive bombing, in low-altitude bombing the bomb is thrown off as the aircraft climbs. This method permits the aircraft time to escape the blast zone, thus assuring the safety of the plane and its crew.

There are three methods of bombing from low altitudes;* bombing from a sharp climb with the bomb cast at an angle of 45-60° (Fig. 34a), "over-the-shoulder" bombing (Fig. 34b) and bombing from a vertical

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*Aviation Week, Vol. 66, Nos. 3 and 22, 1957; Flug Revue, No. 3, 1958; Interavia Review, No. 3, 1959.

climb (Fig. 34c).

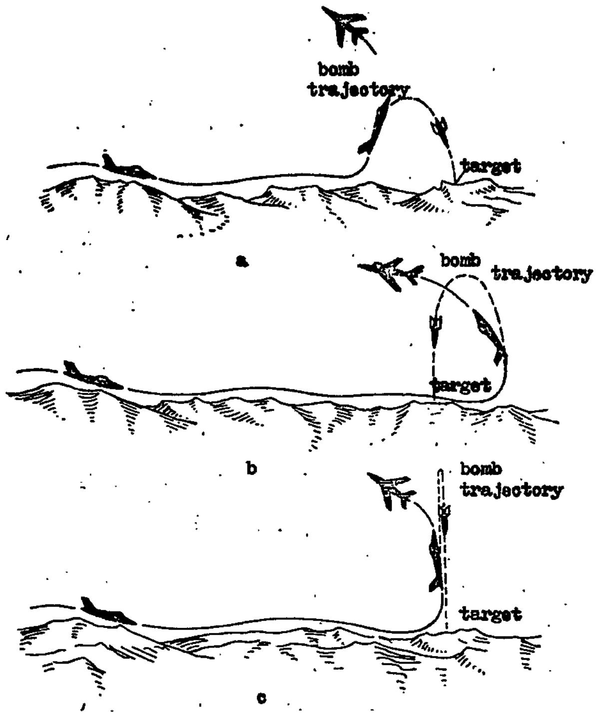

Fig. 34. Low-altitude bombing: a) lob; b) "over-the-shoulder"; c) vertical.

The first method does not require the aircraft to fly over the target, making surprise attack possible.

A landmark serves as a starting point for calculating the time up to the beginning of the bombing maneuver: a half-loop with a turn about the longitudinal axis. The bomb is released at a predetermined angle to the horizon. The exact angle depends on the distance from the target, speed of the aircraft, and the ballistic characteristics of the bomb.

When bombing from a pullup the pilot determines from special tables the time required to reach the required pitch attitude after the beginning of the maneuver, taking into account the combat load. Then, proceeding from this time he determines the moment when after passing the starting point it is necessary to begin the half-loop.

"Over-the-shoulder" bombing is used when the visibility is bad or when the nature of the locality requires the crew of the plane to pass right over the target in order to identify it.

This method uses the target itself as the starting point. Just as in the previous method the aircraft does a half-loop but the bomb is released when the pitch attitude is greater than 90° so as to describe a trajectory which intersects the trajectory of the aircraft at the point of departure from the half-loop.

The magnitude of the pitch angle at the moment of release of the bomb depends on the speed of the plane and the ballistic characteristics of the bomb.

Bombing from a vertical climb (pitch angle of 90°) is used for attacking targets whose exact locations are not known and which must be first identified.

Individual instruments (bank, pitch, heading, and indicators) or combined instruments can be used for low-altitude bombing.

A typical US combined instrument (Fig. 35) incorporates both flight and bombing parameters and indicates heading, pitch and bank attitude, command signals for performing the bombing maneuver, as well as actual and predetermined values of vertical g-forces. The indicator system and gyroscopic detectors (heading gyro and vertical gyro of the instrument) rotate freely about all three axes.

Another indicator has been developed in the US (Fig. 36) which serves as a flight-directing instrument and is suitable for use in military and civil aircraft as a combined flight-navigation instrument. It is equipped with a pair of intersecting bars for indicating signals from a radio navigation system and with a small pointer on the left side to indicate the position of the aircraft with respect to the glide path. A turn-and-bank indicator is mounted below the main spherical indicator.

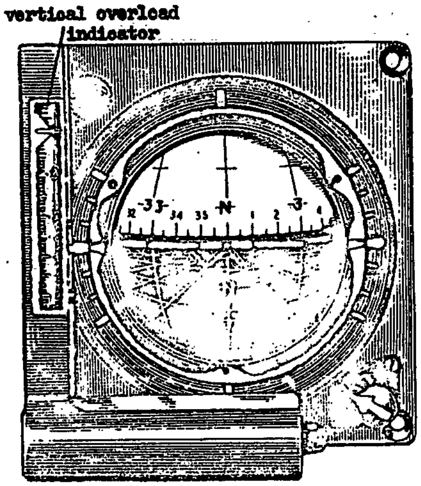

Fig. 35. Combined instrument for low-altitude bombing.

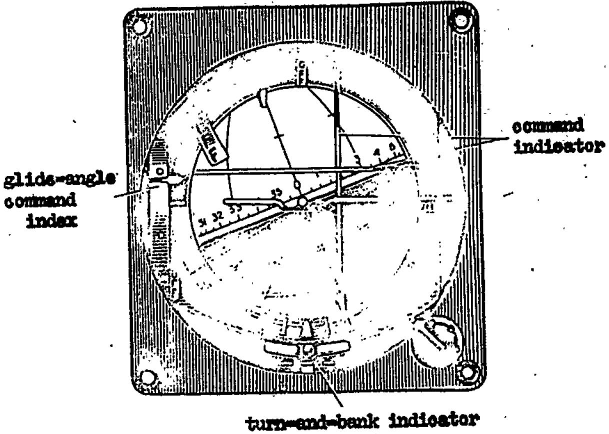

Fig. 36. Director instrument for low-altitude bombing.

The indicator contains a spherical scale 102 mm in diameter, within which there are two small-scale servomechanisms which correct the position of the sphere for azimuth and pitch attitude. A flat disk which separates the sphere into two parts is supported at two points for free rotation about the plane of bank.

This provides the spherical indicator with three degrees of rotational freedom and it, in effect, floats inside the instrument housing.

In order to create the illusion of visual flight, the upper half of the sphere is given the blue color of sky while the lower half is given a dark color and is provided with light-colored lines of perspective to give the impression of depth (perspective).

The heading scale is marked off along the equatorial line with divisions of 5°, and in the region of large positive and negative pitch angles, division lines are laid out at 30°.

The bank scale is marked out on the rim of the indicator. The range of measurement is 30° on either side of zero, each division being equal to 10°.

The special feature of the instrument shows up at pitch attitudes exceeding $\pm 70^{\circ}$. Under these flight conditions the bank angle scale divisions automatically disappear from the rim of the instrument so that the pilot must control the ailerons according to changes in heading and not bank angle. As soon as the pitch attitude returns to $\pm 70^{\circ}$ the bank angle divisions again appear on the scale.

It is pointed out that such a three-dimensional system of indicating the flight parameters is more in keeping with the psychophysiological capabilities of the pilot.

For night operation this instrument is equipped with a special lighting system. The semitransparent spherical scale and the plastic rim with the bank scale are illuminated by a red light.

Let us consider a low altitude bombing sequence (first and second methods) with the use of the combined indicator after the aircraft has entered the target area (Fig. 37):

1) the pilot brings the aircraft onto an attack heading (in the direction of the target);
2) at the check point the pilot presses a button on the control stick which readies the bombing systems and starts an intervalometer;
3) with the elapse of a predetermined interval of time the intervalometer provides an attack maneuver command at which time a signal is heard in the pilot's headset, an indicator lights, and a command index on the vertical accelerometer (on the scale of the combined indicator) is displaced downward under the influence of the timing mechanism;
4) pulling back on the stick, the pilot maintains a pitch attitude at which the ball of the vertical accelerometer, which indicates the actual g-forces, remains opposite the command index (triangle); at the same time the pilot, so as not to deviate from the heading, maintains zero bank;

5) when the required pitch attitude is attained the bomb is released automatically, and the signal light on the accelerometer goes out, indicating that the bomb has been cast off;

6) the pilot completes a Nesterov half-loop and heads for home.

Attacking an Airborne Target

Using fire-control systems, attack of targets in the air may be accomplished either along a curved path or on collision and intercept courses.

Basic diagrams of foreign fire-control systems for one- and two-seat fighters are shown in Fig. 38.

Before the fighter begins attack of a target in the air it is necessary to bring it into the area of the target (distant guidance) is such a way that the relative positions of the fighter and target will allow successful accomplishment of the subsequent stage of flight — attack (close-range guidance). Command from the ground is usually used to bring the fighter within range of target detection by the airborne radar.

Formerly, commands from the ground were radioed to the pilot. Flying by this means of communication was unsatisfactory. During a turn to accomplish a ground command manual flight entailed dynamic errors in heading (20-30°) and great delay (10-30 sec). In addition, with a too-slow command transmission (each 20-30 sec), in the intervals between commands bank attitude changes constantly from maximum to 0°. As a consequence, the plane does not follow a smooth curve but moves along a trajectory which has straight portions. As a result, the turn is protracted and the intercept point shifts. It is assumed that guidance would be improved if the heading commands from the ground were received more frequently (e.g., every 10 to 15 sec) and an additional bank command were added.

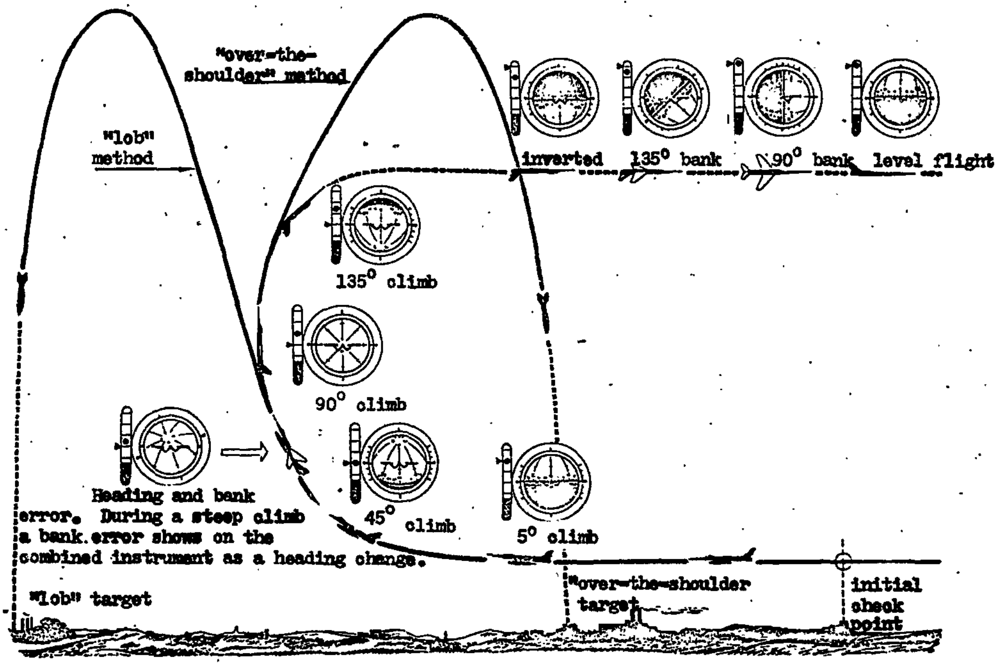

Fig. 37. Low-altitude bombing systems.

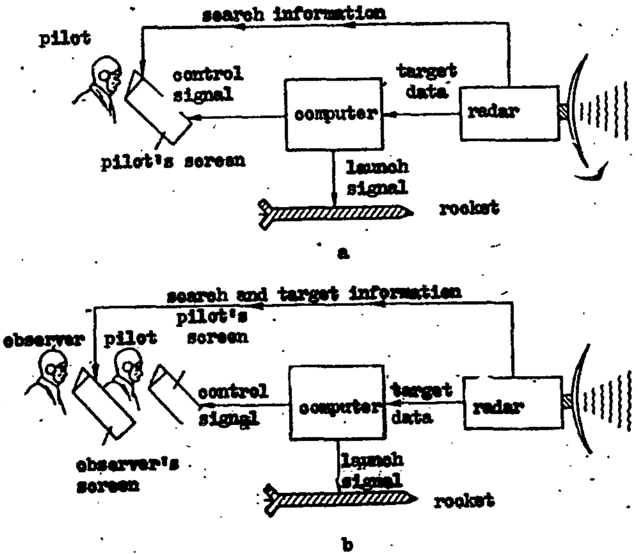

Fig. 38. Functional diagram of fire control systems for fighter aircraft: a) one-seat; b) two-seat.

The accuracy of carrying out commands from the ground might be increased by using a system to automatically transmit them directly to an airborne indicator. These commands are processed by a special ground-stationed computer, the input of which is provided with information concerning the coordinates and parameters of motion of the target and of the fighter from ground radar surveying the air situation. Output information concerning the required heading, bank attitude, and air speed of the fighter, as well as the difference between altitude of the target and the fighter, is transmitted to the fighter over a radio communication channel in a coded form. Here the signal is decoded and fed to visual indicators. The indicators as a rule are ordinary instruments — heading indicator, altimeter, speed indicator — containing a built-in system of reducing the received commands and a corresponding pointer or adjustment index. Commands from the ground are received at the indicator in discrete form rather than continuously and the frequency of transmission of commands depends on the rate of rotation of the ground radar antenna, the load of the radio link, and the flight characteristic of the target (with or without maneuvers).

Observing the instruments, the pilot can fly the fighter in such a manner that at any moment of controlling, the current values of speed and heading coincide with the command values, and the difference in altitude of the target and fighter approaches zero.

Bank attitude commands cannot be introduced directly onto the attitude indicator but are shown on a special illuminated panel. In some systems the distance to the target is also presented on a parallel panel.

When interception of a target is being controlled from a distance, director instruments may also be used. In this case a null-indicator with a scale intersected in the middle with index pointers may be used as the indicator of the required flight trajectory of the fighter.

When the fighter has reached the area of target detection a system of near control with an airborne radar is put into operation (the fire-control system). Let us consider attack with rockets.

Theoretically, an attack can be made from any direction if fighter and target are at the same altitude; the best angle for attack is one close to 90°. In this case, the target image is more distinct on the radar.

In the middle of the instrument panel before the pilot is a radar screen (Fig. 39). During search operation the radar antenna slowly moves from right to left and simultaneously a sector survey is made in the vertical direction and synchronous with it a vertical bright line sweeps the indicator screen. Superimposed on this image are lines similar to the attitude indicator indices, which permit the pilot to fly according to the screen while only occasionally looking at the speed indicator and other instruments. When climbing, the pilot looks past the screen. At the same time the ground-control station operator informs him when he should expect to get a target indication. At a distance of about 40 km from the target an echo from the target in the form of a spot appears on the indicator screen. Distance and azimuth of the target are determined from the position of the spot on the screen, the vertical deviation of the marker corresponding to the distance to the target and the horizontal displacement (to the left or right) corresponding to azimuth. Having identified the target, the pilot stops the antenna horizontal sweep mechanism, manually places the vertical line on the target marker and presses the "lock-on" button on the stick. The target marker begins to grow larger and the radar begins to automatically track the target.

When the radar is switched from search to track operation, a sighting circle and a sighting point appear on the screen. At first the sighting circle has a large diameter. A gap in its circumference, which corresponds to a point on the circular scale located on the perimeter of the screen, indicates the speed with which the fighter is approaching the target.

The pilot maneuvers so that the target point coincides with the center of the sighting circle. This indicates that the aircraft is following an attack course. If, for example, the sighting point is located to the right above the center of the screen then the pilot must turn the fighter to the right and climb.

When the distance between the fighter and the target reduces to 20 seconds before open fire, the sighting circle begins to decrease to the dimension of the sighting point. From this moment on the pilot must direct the aircraft accurately since the moment of firing is approaching. At 4 seconds to firing a signal appears on the screen which requires pressing the firing button. The pilot must beforehand determine the number of rockets to be released. In response to the signal from a calculating device, the rockets are released automatically and a cross appears on the screen to signal withdrawal from the attack. If the pilot is not able to accurately direct the fighter to an attack position then a cross also appears on the screen but the rockets are not released (the attack is scrubbed).

The rockets approach the target with a much greater speed than the fighter and so the pilot may, after the salvo, continue in straight flight at the previous altitude without fear of collision with the bomber.

A frontal attack will certainly entail abrupt changes in course or sharp increases in altitude either automatically or manually by the pilot.

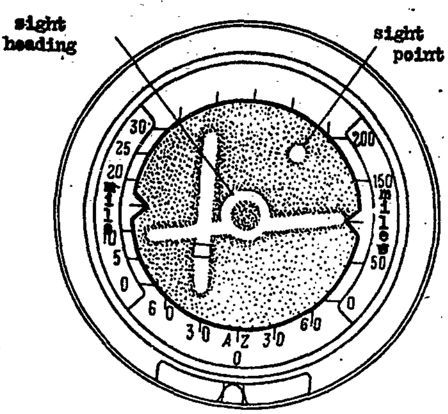

Fig. 39. Radar sighting indicator on the pilot's instrument panel (USA).

The conventional representation of the relative position of the target and the fighter on the screen of a radar sight may be different. In particular, for a more qualitative manual flight of the aircraft during near guidance of the fighter to the target, director (command) markers may be supplied on the screen (the control system would require a special computer for this).

The stages of near guidance, attack and departure from the attack might be made completely automatic on a piloted aircraft. In this case the pilot would have simply to fly by instrument and the aiming screen to accomplish the required attack program correctly.

Departure from a Complex Situation

When flying by instrument beyond the visibility of the horizon or of landmarks, the pilot may be confronted with conditions when he will be unable to clearly determine the position of his aircraft in space. In such cases the pilot, taking into account the circumstances (especially the flight altitude), must decide whether to continue the flight at a normal attitude or to alter it).

In order to bring the aircraft out of a complex situation it is necessary to act in the following sequence. First determine the attitude of the aircraft from the attitude indicator, the turn-and-bank indicator, the rate-of-climb indicator, altimeter, and speed indicator. Then with coordinated motion of the stick in the direction opposite to the deflection of the turn indicator, bring the plane into straight flight, having eliminated turning and banking of the aircraft. After this, bring the aircraft into level flight as was explained above.

The distribution and shift of attention to instruments depends on the situation created (on the speed, altitude, pitch attitude, and bank attitude).

Flight Using Support Instruments

Under instrument flight conditions one or another instrument or group of instruments might, for some reason, become inoperative. For example, after completing some advanced maneuver the attitude indicator may be "dislodged" or else refuse to operate at all. When the air pressure detector lines are frozen or obstructed, the speed indicator and Machmeter fail to operate. When there are defects in the static line the altimeter and rate-of-climb indicators (as well as the speed and Machmeters) fail to operate. Under certain conditions the gyrocompass (due to power failure, power-matching system failure, etc.) and the radio compass (electrification of the aircraft, etc.) may fail to operate.

The pilot must first of all be trained to rapidly and in time determine what instrument or group of instruments are inoperative, and after detecting failure to know how to convert to other flight-navigation instruments which support the inoperative ones.

Determination of the moment of failure of the attitude indicator is one of the most difficult things to do in instrument flying, especially when flying in clouds or turbulence when the turn-and-bank indicator is unstable.

Failure of the attitude indicator or its inaccurate indications (with respect to banking) may be detected by comparing the attitude indicator indications with those of the turn-and-bank indicator. Thus, if the pilot maintains zero bank in level flight according to an improperly operating attitude indicator, the aircraft will actually be turning and begin to leave the given heading which will be noticed on the turn indicator and the compass. When turning, an inoperative attitude indicator results in turn indicator readings and a rate of heading change on the compass which do not correspond with the bank value.

When the attitude indicator is not accurately indicating pitch, readings on the rate-of-climb indicator, airspeed indicator, and altimeters will not be in agreement.

Thus in case of attitude indicator failure, the aircraft may be flown according to the turn-and-bank indicator, compass, rate-of-climb indicator, airspeed indicator, and altimeter.

Level flight, climb and descent can be maintained using these instruments without the attitude indicator. In particular, the lateral equilibrium of the aircraft can be maintained according to the turn-and-bank indicator (zero needle reading, ball at scale center). In this case the plane will have zero bank attitude.

Longitudinal equilibrium of the plane may be maintained using the rate-of-climb indicator (its indications must correspond to conditions of vertical speed) when the forward speed is constant as controlled by the airspeed indicator and variation of altitude is in accordance with the predetermined condition (according to the altimeter).

In order to maintain the longitudinal equilibrium in any condition of flight the motions of the wheel (elevator) must be brief and double. This is necessary because when the angle of attack is altered the airspeed indicator deviates somewhat from the flight speed of the aircraft. Attempts on the part of the pilot to restore the given speed by deflecting the wheel during a single procedure leads to an abrupt movement of the controls which gives rise to significant deviations from the given speed and to longitudinal oscillation of the aircraft.

Heading equilibrium is maintained using the compass (to keep a fixed heading).

When there is failure of the airspeed indicator and the Machmeter as the result of malfunction in the pitot static system, the sensitivity of the instruments to variations in flight conditions drops and their indications frequently drop to zero. Therefore, in order to determine failure of these instruments it is necessary to alter the conditions of flight and control it according to the attitude indicator, rate-of-climb indicator, and altimeter.

When there is failure of the airspeed indicator, level flight, climbing, descending and turning may be accomplished using pitch indications on the attitude indicator and engine rpm corresponding to the required conditions of flight. The required conditions in this case are controlled using the rate-of-climb indicator, altimeter, compass and turn indicator.

The most complex element of failure of the airspeed indicator is descent at low altitudes. The complexity arises from the fact that as the flight altitude is reduced it is necessary to gradually reduce the vertical speed and consequently to change the angle of attack also. In order to maintain a given forward speed during descent it is necessary to increase the engine rpm appropriately for these changes and this requires careful attention to the instrument indications and makes the pilot's task more complex. In addition, the pilot must know accurate values of pitch angle and the corresponding engine rpm for all conditions, which of course is very difficult.

Failure in the operation of the altimeter and the rate-of-climb indicator as a result of disorder in the pitot static system (which puts the airspeed indicator and Machmeter out of order) is usually determined from the behavior of the needles of these instruments. In level flight the airspeed indicator, altimeter and rate-of-climb indicator needles are stationary. During a climb the airspeed indicator needle is displaced in the direction of reduced indication (and during a long climb goes to zero) the altimeter needle remains stationary and the rate-of-climb needle drops sharply to zero. During descent the airspeed indicator gradually increases its indication while the altimeter and the rate-of-climb indicator act the same as during a climb.

When these instruments fail the aircraft is flown using the attitude indicator and tachometer. A great deal of attention must also be given to altitude control using the radio altimeter and altitude indicator in a pressurized cabin. It is also possible to ask for the results of altitude measurement from ground radar stations

Compass and automatic-direction-finder failure results in constant heading indications when there is an actual change in heading of the aircraft. These instruments may be supported by ground direction-finder and radar stations.

IV. NEW TYPES OF AIRCRAFT INSTRUMENTATION

The trend toward easing the pilot's task when flying modern aircraft by instrument has caused many engineers and designers to produce new, more complete instruments and instrument systems, and to arrange the instrument panel and distribute the equipment in the cabin of the aircraft differently. Samples of these instruments and systems are already being used in serial production aircraft, others are still in the stage of experimental development, while still others remain as interesting proposals and plans.

Here we will consider a few examples of new types of aircraft instrumentation, information about which has been published in the foreign literature.

Integrated Systems of Flight-Navigation Instruments

The English Aviation Institute has developed an instrument panel with the basic flight-navigation instruments which obtain information from two centralized pickups: the aerodynamic-parameters central and the gyro central.

The aerodynamic parameters central has two flexible sensing elements by means of which the static and dynamic pressure of a counter flow of air are measured. The pressure signal is fed to a computer which works out equivalent air speed (proportional to the dynamic head, without taking into account variations in the air density and compressibility), barometric altitude (proportional to static air pressure), vertical speed and Mach number as well as true air speed.

The gyro central consists of a vertical gyroscope and directional gyro and provides pitch and bank angle signals as well as magnetic heading (with corrections from a sensor of the Earth's magnetic field).

In addition the navigation indicator may receive signals from the radio navigation system: the angle-distance system Tacan and ILS.

Located in the center of the instrument panel (Fig. 40) is the command attitude indicator; to the right of this, the navigation indicator; to the left, the altimeter and rate-of-climb indicator; above, a horizontal tape indicator of speed and Mach number and in the upper right, a distance and marker-bearing digital counter (Tacan system).

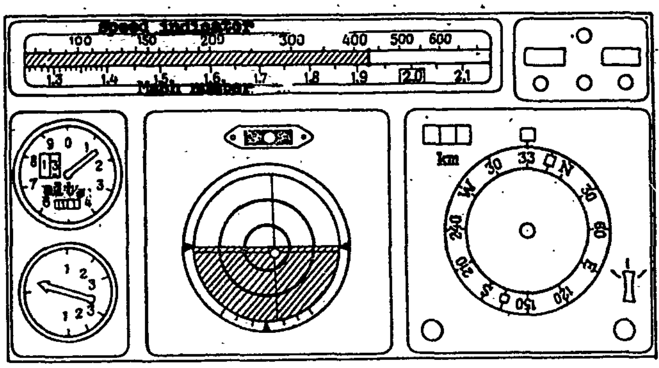

Fig. 40. English system of flight-navigation instruments.

The attitude indicator is an instrument with a screen scale which makes it possible to measure pitch and bank angles even when the aircraft is in an almost vertical position (±3° from vertical). A horizontal line bisects the screen scale into two parts: white (sky) and black (ground). As the pitch attitude changes the screen in the instrument window is displaced upward or downward so that by the predominance of black or white color it is easy to judge whether the pitch attitude is positive or negative and the magnitude of the angle is determined from marks on the face glass. The screen moves in a frame which (together with the screen) turns to the left or right depending on the bank signals. The magnitude of the bank angle is indicated by a scale on the lower rim of the instrument. Zenith and nadir marks (the points vertically above and below the aircraft) are also indicated on the screen, making it easier to determine bank angles at a pitch attitude near 90°.

The pilot receives command signals on the attitude indicator by means of a small circular indicator suspended by thin, almost invisible threads. Displacement of this indicator with respect to the face glass indicates to the pilot how to fly the aircraft.

The altimeter is a single-needle instrument with a drum counter. The needle of the instrument describes a full circle every 1000 feet (305 meters). Scale divisions equal 50 feet (15 meters). The counter indicates thousands of feet. The upper limit of the instrument is 100,000 feet (30,500 meters).

The tape airspeed indicator and Machmeter are placed horizontally so as to better aid the pilot in perceiving changes in these parameters. The airspeed scale is stationary while the Mach number scale automatically moves in accordance with changes in altitude, thus making it possible to take readings from both scales using the same moving index. For greater accuracy in the range of landing speeds, the scale is not linear.

The combined navigation indicator, like the attitude indicator, is provided with a screen scale divided crosswise into three sections corresponding to three different conditions of flight established by means of a switch, namely: flight according to an automatic direction finder, according to an angle-distance measuring radio navigation system, and flight according to a glide-slope instrument landing system. For all conditions the screen scale remains within a rotating compass scale from which the magnetic heading is reckoned with respect to a stationary heading mark at the top. The use of a rotating compass scale corresponds to the principle of reading "from the aircraft to the ground" which is used in this system for the attitude indicator. This kind of indication is more graphic than a stationary heading scale with a moving needle in which case for headings close to 180° the needle points downward, i.e., opposite, as it were, to the direction of the aircraft. The end of the required-heading needle (with a square index) is set manually or automatically, taking into account the drift angle, and remains visible in all conditions.

In the condition of flight by compass, the portion of the screen visible on the instrument remains empty excepting for a small circle in the center which corresponds to the location of the aircraft (Fig. 40).

When flying according to a Tacan system of angle-distance measuring (near-navigation system), the scale of the navigation indicator appears as in Fig. 41a. The central circle, as before, represents the aircraft while the screen is located above or below, depending on where the radio beacon is located: in front or behind. The distance to the radio beacon is approximated from concentric circles drawn on the screen and in addition is indicated with an accuracy of

1 km on a digital counter at the upper left of the instrument. A frame with the screen rotates with respect to the compass scale in such a way that a line passing through the index of the radio beacon indicates on this scale the bearing of the radio beacon or the aircraft. (In Fig. 41a the bearing of the radio station is 280° and the bearing of the aircraft is 100°. In order to approach the beacon the plane must turn to the left 40° since the heading is now 320°. The screen would then turn to the right and the bearing line coincide with the heading mark. In flight the screen will move downward until the radio beacon index coincides with the central circle indicating the moment of passage over the station. After this the screen rotates 180° and indicates a heading away from the beacon.)

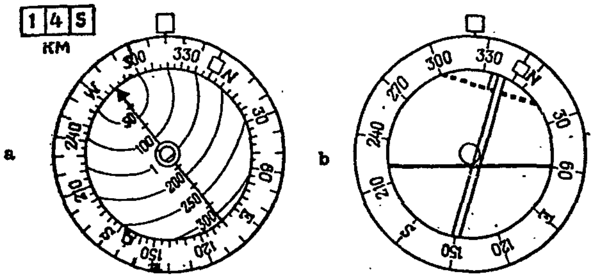

Fig. 41. Navigation indicator: a) flight toward an angle-distance system radio beacon; b) flight according to a glide-slope blind-approach landing system.

The appearance of the navigation indicator during blind approach landing is shown in Fig. 41b.

The index of the heading beacon beam appears as two parallel lines directed toward the azimuth of the heading beam. This index is drawn on the screen and turns with it, moving to the right or left in accordance with the linear lateral deviation of the aircraft from the heading beam. The azimuth of the runway and the lateral deviation is read from a scale attached to the frame carrying the screen and seen through a transparent portion of the screen. A single horizontal line corresponds to the slope marker beam and is operated by a separate servomechanism. The position of the aircraft with respect to the glide slope is indicated by a central circle (Fig. 41b shows the aircraft above and to the left of the glide slope).

The azimuth of the runway is set up with the same knob as the prescribed course (to set the heading it must be pressed in and to set the azimuth it is pulled out).

Reception of the heading and slope marker signals is indicated by the lighting of lamps in labeled windows below the navigation indicator.

At the present time in America serially produced supersonic military aircraft are also being equipped with new instrument panels and integrated flight-navigation instruments. Two basic requirements were stipulated in the development of these instrument panels:

1) all information provided the pilot by the flight-navigation instruments must indicate directly what action is required in controlling the aircraft;

2) the motions of the pilot in controlling the aircraft must correspond to variations of the flight regime parameters indicated by the instruments.

To facilitate the pilot's perception of the commands transmitted to the aircraft by radio from a ground control station the integrated flight-navigation instruments are located on the instrument panel so that when the required flight conditions are attained the indices of all the instruments are arranged along horizontal and vertical reference lines (Fig. 42).

The horizontal reference line corresponds to parameters which vary during longitudinal control of the aircraft, i.e., when the control stick is moved forward and back and when controlling the engine thrust. These parameters include: pitch attitude, air speed, Mach number, vertical speed, altitude, angle of attack and acceleration.

The vertical reference line corresponds to parameters which vary when the control stick is moved to the left or right (bank angle, heading, rate-of-turn) as well as parameters of navigation and tactical conditions.

In the center of the instrument panel is located a command combined attitude indicator with a spherical scale (Fig. 43) divided into light and dark portions by a horizontal line. Lines of perspective are drawn to this horizontal line to simulate the view from the aircraft to the ground. The horizon line moves with respect to a stationary airplane silhouette according to the principle of indication "from the plane to the ground." The pitch attitude is read from a vertical scale above (nose up) and below (nose down) the horizon line every 5°. To permit reading greater pitch angles when the horizon line passes off the face of the instrument an additional horizon strip is connected with the Cardan pitch frame and is always in view of the pilot. Bank angle is read from the end of this strip along a scale on the upper rim of the instrument. An ordinary turn-and-bank indicator is located in the lower part of the instrument.

A command indication is made in this attitude indicator in the following way. On the left is a vertical scale indicating deviation from the required landing glide slope. A command mark moves along this scale in accordance with signals from the slope marker. When the proper glide angle is maintained this mark coincides with the center of the scale (opposite the airplane silhouette and along the horizontal reference line of the instrument panel). The required pitch attitude is established by the pilot with a knob located in the lower right corner of the instrument and is indicated by a horizontal strip.

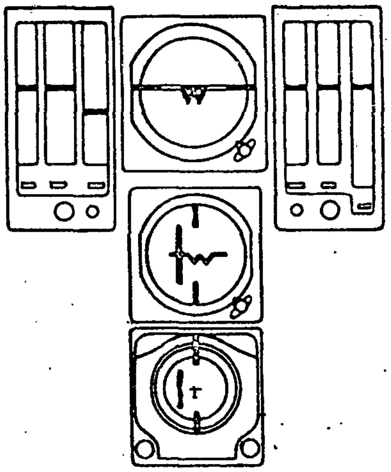

Fig. 42. Principle of horizontal and vertical reference lines on an integrated instrument panel.

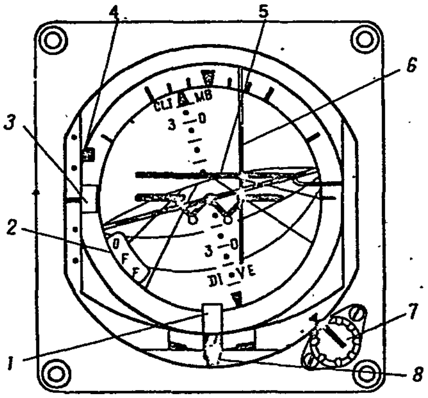

Fig. 43. Command combined attitude indicator: 1) wrong heading-marker channel signal; 2) no-input signal; 3) wrong slope-channel signal; 4) deviation-from-required-slope index; 5) pitch command strip; 6) bank command strip; 7) pitch knob; 8) turn indicator needle.

The vertical strip is called the command bank strip since its deviation from the reference line indicates that the aircraft is banking and consequently is deviating from the required direction of flight. It is moved to the right or left by means of signals from a radio navigation system (e.g., the heading marker of a landing system).

If the required direction of flight is maintained then the vertical strip coincides with the vertical reference line.

To the left of the attitude indicator is a combined tape instrument with vertical scales showing angle of attack, acceleration, Mach number, and airspeed (Fig. 44).

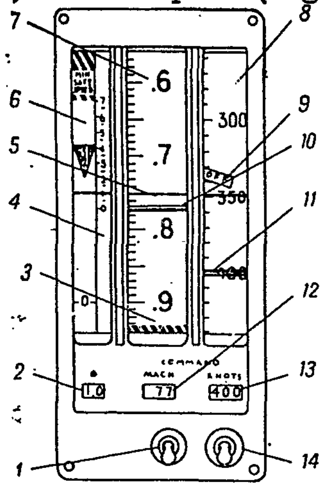

Fig. 44. Combined tape instrument for measuring angle of attack, acceleration, Mach number and airspeed: 1) Mach number control switch; 2) digital acceleration indicator; 3) maximum allowable Mach number indicator; 4) acceleration tape; 5) horizontal reference line; 6) angle of attack tape; 7) Mach number tape; 8) speed tape; 9) power-off signal; 10) Mach number command index; 11) speed command index; 12) required Mach number digital indicator; 13) required speed digital indicator; 14) speed control switch.

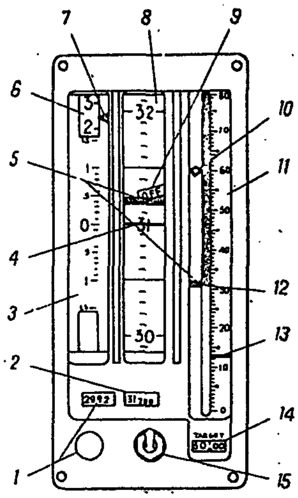

Fig. 45. Combined altimeter—rate-of-climb indicator: 1) barometric pressure set and digital indicator; 2) required altitude digital indicator; 3) stationary vertical speed scale; 4) horizontal reference line; 5) altitude command index; 6) vertical speed barrel indicator; 7) vertical speed arrow; 8) speed tape indicator; 9) power-off signal; 10) target altitude indicator; 11) vertical scale of generalized altimeter; 12) actual flight altitude; 13) "altitude" in the cabin; 14) target altitude digital indicator; 15) altimeter control switch.

A horizontal reference line to which all readings are referred, passes through all of the scales. The left edge of the scale is used to indicate angle of attack by means of a triangular index with the vertex turned downward. Absolute values of angle of attack (in degrees) are not shown. Coincidence of the vertex of the triangle with the reference line indicates an angle of attack corresponding to the best rate of descent for landing. Thus the pilot does not have to compute the required rate of descent with regard to the weight of the aircraft. The base of the triangle indicates the angle of attack at the levelling-out stage. Above the triangle index there is a cross-hatched area which indicates minimum safe airspeed.

Vertical acceleration is read from a tape scale and is also given in the window of a digital indicator below the scale. Mach number is measured from the middle tape scale according to which the pilot, using an adjust knob, may move the command index to the predetermined Mach number. The same Mach number value will then appear in the digital indicator window.

In a similar manner airspeed is measured from the scale at the far right. The required airspeed is also set up with an adjustment knob according to a digital indicator and the command index. The numbering of the speed and Mach-number scales increase from top to bottom, i.e., the values of these parameters increases as the tape moves upward. Thus in order to increase the flight speed the pilot must push forward the control stick or the throttle control, causing the tape of the indicator to move upward.

To the right of the attitude indicator is a combined altimeter—rate-of-climb indicator (Fig. 45). The middle, stationary portion of the vertical scale of the rate-of-climb indicator has a zero which coincides with the general horizontal reference line. Vertical speeds from +10 to -10 m/sec are measured by a moving needle. A vertical speed greater than 10 m/sec is registered in a special window in which a moving tape with a scale up to 200 m/sec is visible.

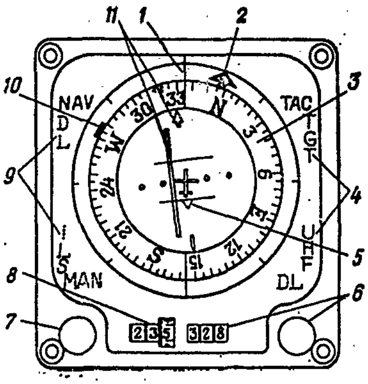

Fig. 46. Command navigation indicator: 1) heading mark; 2) bearing arrow; 3) compass scale; 4) regimes of operation of bearing indicator; 5) direction of flight indicator; 6) azimuth set knob; 7) heading set knob; 8) distance to marker; 9) mode of operation of navigation indicator; 10) heading command index; 11) azimuth arrow and bar.

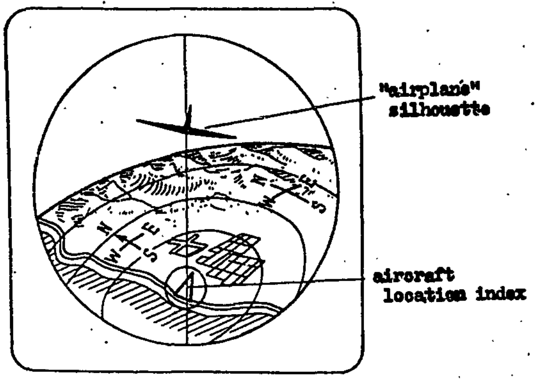

Fig. 47. Optical-mechanical visual flight analog indicator.

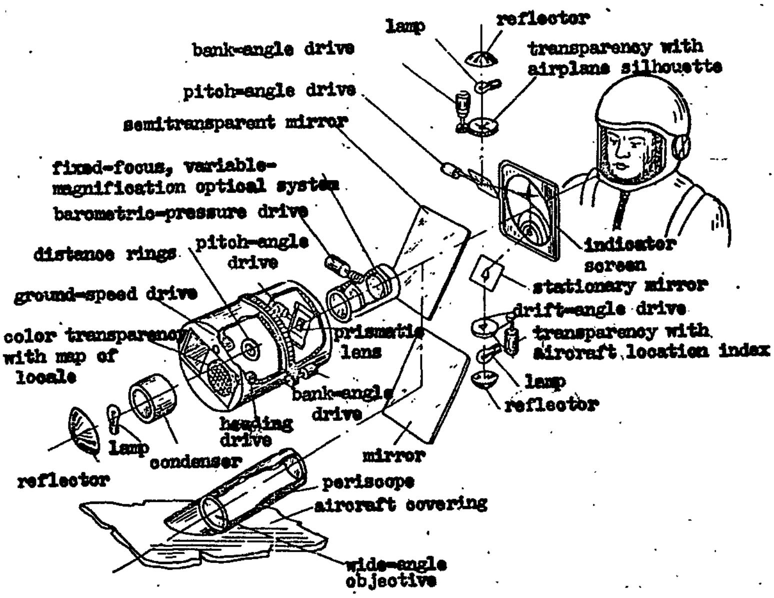

Fig. 48. Optical-mechanical visual visual flight analog — exploded view.

The altimeter is located in the center of the instrument and has a tape scale. With an increase in altitude this scale moves downward so that the altitude reading, taken at the horizontal reference line, increases. The required altitude may be set with a command index and on a barrel counter by means of a set knob. On the right side of the instrument is located an additional small stationary-scale altimeter with a range from zero to 24,000 meters on which is indicated the actual and the required flight altitude, the altitude corresponding to the pressure in the cabin, and also the altitude of the target (obtained from other sources). Also mounted on the face of the instrument is a scale and knob for setting barometric pressure.

Directly below the attitude indicator is the command navigation indicator (Fig. 46). Heading is read from a rotating compass scale by means of a heading mark located on the same vertical as the stationary "airplane" in the center of the scale. The predetermined heading is indicated by a command index which is set manually by a control knob. Along the outer circumference of the scale a bearing needle moves toward a marker, the distance between them being shown in the window of a digital counter. The central portion of the instrument has an arrow which is set by a knob located on the right-hand side and which indicates the direction (bearing, azimuth) of a reference line such as the beam of a radio marker or the line of flight of another aircraft. The central portion of this arrow (predetermined direction strip) may be moved to the left or right of the arrow. The azimuth of the predetermined line is indicated along the compass scale and in the window of a digital indicator. When flight is in the set direction the arrow and strip lie along the vertical reference line together with the vertical command strip of the attitude indicator.

Visual Flight Analogs

The development of aircraft instruments is proceeding also in the direction of imitation or simulation of conditions of visual navigation even though visual navigation does not always meet the demands of flying. For instance, when flying at low altitudes the ground passes under the aircraft with such rapidity that the pilot is not able to distinguish and identify landmarks. The quality of flight-navigation information during visual flying is often very low. Pitch and bank attitudes are not accurately evaluated visually especially when the aircraft is significantly displaced from level flight. Altitude and heading are determined poorly. The location of the aircraft can be established only when the pilot is well acquainted with the flight locale or when there are characteristic landmarks.

Instruments which simulate the conditions of visual navigation are usually called visual flight analogs. Electrical, optical, optical-mechanical and electronic-optical (television) devices are used in their construction.

Visual flight analogs may be made in the form of a complex instrument which provides indications of all of the flight-navigation parameters, or in the form of individual instruments providing flight and navigation parameters separately.

An example of an optical-mechanical visual flight analog is a system developed by the American Convair Co. The indicator of this system (Fig. 47) presents a view forward and somewhat downward from the cabin with an "airplane" added to the picture as a visual reference to facilitate spatial orientation. From the figure it is clear that the plane is banked to the right at an angle of about 20° and has a positive pitch angle of about 10°. Below the airplane on the surface of the Earth is a triangle index signifying its location. The tilt of the triangle indicates drift angle. The "airplane" and its location marker are located on a single stationary vertical line passing through the center of the indicator and corresponding to the actual line of flight.

The image of the locale which appears on the indicator is almost undistorted close to the aircraft location mark and is foreshortened in the direction of the horizon. The distance of various points of the locale from the location of the aircraft may be estimated using concentric distance rings. Heading is determined from compass roses (directions to the cardinal points) which are periodically visible on the locale image. Images of cities are simplified, all unimportant details being eliminated.

The flight speed may be estimated from the rate of motion of the locale under the aircraft location index. The flight altitude is determined from the scale of the locale near the aircraft location and the curvature of the horizon line. The relief of the locale is indicated by color which conventionally shows the minimum allowable flight altitude.

The optical-mechanical analog of visual flight operates as follows (Fig. 48). A light source illuminates a positive transparency showing a map of the locale. According to heading and ground speed signals obtained from navigation means, the transparency may be rotated and translated in accordance with the motion of the aircraft. Beyond the transparency with the map is located a transparency with distance rings and beyond them a prismatic lens which foreshortens the scale of the locale image in the direction of the horizon and also distorts the horizon line. The position of the horizon line is controlled by two servosystems in accordance with signals from pitch-and-bank sensor. The image then passes through an optical system with fixed focus and variable magnification controlled by an altitude signal and is then focused on the screen of the indicator.

The "airplane" silhouette and the aircraft location index are projected onto the same screen through separate optical systems from the corresponding transparencies.

An aerialphoto transparency may substitue for the map transparency. For flight over water or an unknown locale a coordinate grid is superimposed on these transparencies.

The visual flight analog indicator also serves for visual orientation with respect to the actual locale, observed through a periscope with a wide-angle objective and projected on the screen by a system of mirrors. Transition from the actual picture to the artificial one depending on visibility is performed automatically.

Radar images of the locale, target marks, etc., may also be projected on the screen.

The electromechanical visual flight analog (flight indicator) of the Waldorf Co., USA, is 180 mm in diameter and 280 mm long. The basic elements of its indicator are two semitransparent spheres placed one inside the other. The outer sphere consists of two hemispheres, above and below, which turn independent of each other. On the upper hemisphere are pictured clouds in a number of horizontal layers. The lower hemisphere has horizontal lines to indicate speed.

In order to indicate deviation from the predetermined course the inside lower hemisphere has black lines which converge on a single point. The combination of these lines provides a conventional image which corresponds to the picture seen by the pilot during visual flight.

Special motors turn both spheres clockwise or counterclockwise in agreement with change in bank. Variation in pitch attitude is indicated by rotation of both spheres in one direction or another.

Turning of the lower inside hemisphere about the vertical axis in accordance with compass signals indicates deviation of the aircraft from the prescribed course.

Flight speed is indicated by rotation of the lower half of the outer sphere in accordance with airspeed or ground speed signals. A lowering of the horizontal lines on the hemisphere, as if moving from the horizon toward the pilot, imitates forward motion of the aircraft.

A wedge-shaped indicator placed directly in front of the spherical surfaces serves for maintaining fixed conditions of flight. It may be moved up and down, left and right, and turned some angular amount according to signals from a radio navigation system or from a fire control system in the plane.

The pilot observes the image of the spherical surfaces through an optical system with Fresnel lenses, i.e., he sees an image as if in space (Fig. 49). The indicator shows the location of the aircraft with respect to the location of the destination or target, the target being registered as an illuminated triangle for greater clarity. The azimuth of the target is read from an external ring and the distance to the target (or to the base) and the flight time from a barrel counter.

Television is considered the most complete analog of visual flight. As opposed to the electromechanical analog, it has a more universal indicator which permits the addition of information such as radar information at different stages of the flight and yields a more graphic image, a visual indication of flight altitude, etc.

In the flight indicator of a television analog of visual flight the basic information is projected from the surfaces of two thin aluminum hemispheres, one marked off with a grid, the other smooth. If parts of the hemispheres are imaged on a cathode ray tube by means of television cameras, the picture produced will be similar to that seen by the pilot flying over a field divided into square plots. On the indicator screen will be seen a grid of lines converging at a point on the horizon (Fig. 50). The nature of the image is similar to the image obtained on the electromechanical visual flight analog indicator.

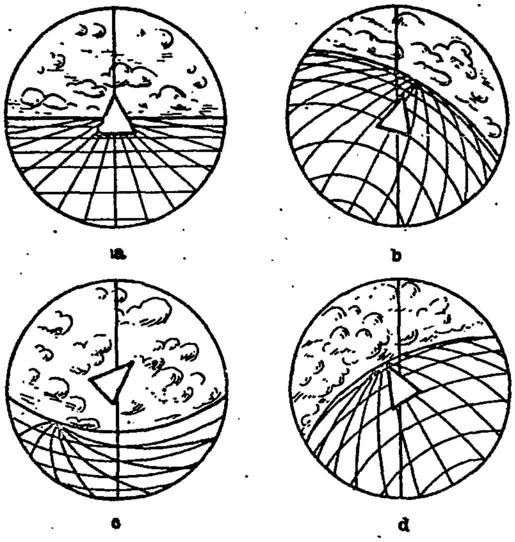

Fig. 49. Indicator of an electromechanical visual flight analog: a) level flight along a fixed trajectory; b) descent with left turn and bank (the plane is located above and to the right of the prescribed trajectory); c) climb with right turn (plane located above and to the right of the prescribed trajectory); d) plane has right bank and is above the prescribed trajectory.

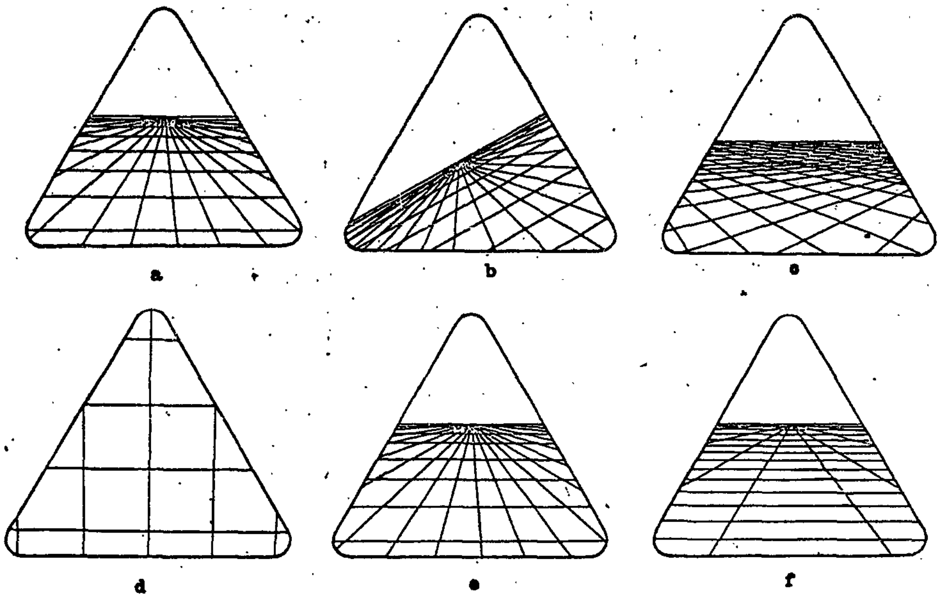

Fig. 50. Indication of aircraft position on the indicator of a television visual-flight analog: a) level flight in required heading; b) right bank; c) level flight at an angle to the prescribed heading; d) vertical dive; e) high-altitude flight; f) low-altitude flight.

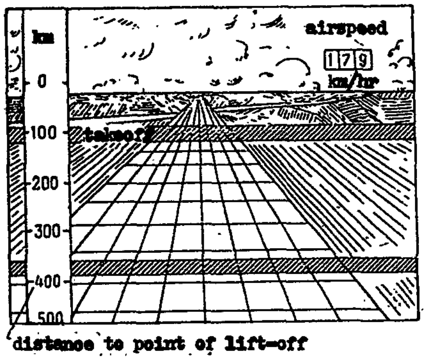

Fig. 51. View of indicator of an electronic-optical visual flight analog during takeoff (numbers at the left indicate distance to point of lift-off, numbers at upper right show aircraft speed).

Variation in heading and pitch is achieved by motion of the sphere with respect to a stationary cathode ray tube. The sphere is supported by a double-axis bearing and is rotated by means of a servosystem using signals from the appropriate sensors.

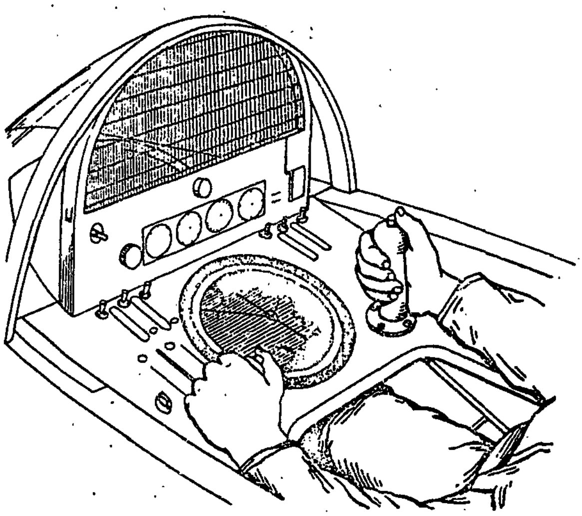

Fig. 52. Instrument panel with indicators on flat television tubes.

The indicator uses a spherical hinged optical system which transmits information to the indicator device. The transmitting system receives information concerning the position of the sphere and modifies it in accordance with the altitude, speed and bank of the aircraft.

The transmitting system includes a beam scanning system and photomultipliers. The raster of the cathode ray tube of the system with beam scanning forms a uniform luminous square on the surface of the sphere. The difference in the level of light reflected from the white lines and black surface is converted by 3 photomultipliers into video impulses, which are amplified by a video amplifier and formed into an input signal.

The scan of the tube is synchronized with the scan of the indicator by a sync generator. The beam deflection system in the CRT rotates in coincidence with bank attitude signals.

Sometimes, in addition to the usual grid of lines which represent an image of the surface of the Earth projected on the screen of the indicator of a television visual flight analog, the trajectory of the aircraft in the form of its "road in the sky" is imitated. This kind of presentation makes it easier for the pilot to orient during instrument flight. If the plane is exactly on course then an image appears on the screen which resembles a road going off into the distance. If the image is seen from the side, above, or below it means that the aircraft has deviated from the predetermined heading and altitude.

A navigation indicator of the television analog shows a map of the flight locale and also provides information concerning distance and flight time.

The television visual flight analog being considered employs a special computer-resolver which processes information obtained from primary flight and navigation sensors. It not only processes information about the position of the aircraft and the conditions of flight but also computes the optimum altitude and speed required for flight over maximum distance depending on the fuel consumption, determines the maximum flight distance in any direction taking into account wind, flight time, estimated time of arrival at a specified point on the route, etc.

One American firm makes an electro-optical visual flight analog with a flight-navigation indicator which yields a visual integrated presentation of the conditions of flight. This system is intended for installation on supersonic aircraft which have a limited field of vision from the cabin.

On a large indicator screen the pilot may see a colored image of the locale obtained from visual, radar, and infrared means, information concerning the use of armament, navigation parameters and data concerning takeoff and landing.

The basic element of the indicator is a modified optical viewfinder with two optical systems, one with a wide (80°) and the other a narrow field of vision. It is used on aircraft for visual observation of the Earth's surface and the viewing of space in the forward hemisphere.

The flat Fresnel lens of this viewer provides a 279 × 330 mm visual image at infinity which can be seen with little turning of the head. With an increase in dimension of the image it would be possible to produce a complete illusion of observation of the outside through a glassed-in cabin.

On account of the relatively small increase in the dimensions and weight of the instrument and also the complexity of its system, the information from radar and infrared systems which is fed to the screen of the CRT (one of instrument's components) may be optically combined or superimposed on the visual picture of the locale. For example, by combining images in infrared light and light in the visible range, the pilot may see thermal targets such as power stations and factories. At the same time the image of a navigation chart could be placed on the indicator for direct comparison with the visual picture of the flight locale.

The pilot may select and view on the indicator information corresponding to any phase of flight. Obtaining information from various sources on the same indicator, the pilot will not have to watch a number of instruments at the same time.

By means of a similar indicator it is possible: to control takeoff by superimposing on an image of the runway a marker to indicate the distance to the point of lift-off or the discontinuance of the run (Fig. 51); to superimpose information concerning the spatial position of the aircraft on a visual image of the ground or airspace before the aircraft with simultaneous indication on the edge of the indicator of the angle of attack and the airspeed; to select during flight along a route a visual or radar image of the locale, an image of an air navigation chart, or a combination of these images; for target recognition, to combine the data from infrared receivers (during bombing — sighting check marks from the bombsight-computer signals) into a visual or radar image. During the landing approach, and when landing, the position of the heading and glide-slope beams are presented graphically and superiomosed on a picture of the visual conditions with an indication of the angle of attack and airspeed on the edge of the indicator.

In other American flight-navigation indicators a modulated image of visual landmarks is projected on the screen by means of reflection from a transparent glass screen. This screen does not alter the form and color of the locale observed through it and at the same time reflects well, under almost any illumination conditions, the image (projected onto it from the screen of a CRT) which is obtained from the signals of a generator which simulates visual orientation.

A so-called trichroic combiner is used as the screen. It consists of a glass lens with a multilayer optical coating which reflects pure green light and transmits the other colors. The green light from the leaves of grass, from dyes, and signal lights contains significant amounts of blue and yellow. It has been shown that the human eye has the ability to adjust rapidly to the absence of green light and restore its range of colors in visual images devoid of these rays. At the same time collimation of the image (removal to infinity) plays a significant role.

The simulated picture of visible flight landmarks is reproduced on the screen of the CRT in green light; almost any picture and instrument reading can be projected. In addition, the image may be seen at a large angle to the screen.

It is pointed out that apparently there are no real limits to the visual angle of the image; the main difficulties in constructing an optical analog are found in the application of uniform high quality trichroic coatings on large areas and in the construction of a unique projection optics.

Investigations now being carried out abroad give every reason to believe that future use of tetrachroic and pentachroic combiners will make possible the projection of two- and three-color images.

It is believed that the projection method of producing a simulated picture of a visible landmark, in which a CRT and a projection optics system are mounted behind the pilot and a simple collimator screen in front of him would be simpler than the method using a flat television tube.

An instrument panel with two indicators in the form of flat television tube screens from which the pilot obtains all the necessary flight and navigation information has been developed in the USA (Fig. 52).

One of the screens is located vertically in front of the pilot. It is covered with a thin, nearly transparent layer of phosphor and in clear weather the pilot sees, as through a window, the area ahead of the plane. Under conditions of poor visibility this "window" becomes a flat television screen on which is visible an image of the same area but with the aid of a special video scanning system. Simultaneously, information concerning speed, bank, and altitude of the aircraft is presented on the screen. The screen measures 20 × 8 cm and has a 2,000 line definition.

On the upper part of the panel there is a selector with which the pilot selects the basic regime of control during takeoff, landing, course flying, etc.

Horizontally in front of the pilot is located a second television screen with a diameter of about 20 cm on which an image of the locale passes slowly. Glancing at it the pilot visualizes the area below the aircraft from the flight altitude.

The picture of the locale beneath the aircraft is obtained by means of a television camera which has before its objective a map of the locale which corresponds to the selected flight route. This map moves with respect to the objective in accordance with data produced by navigational means.

A point in the center of the screen indicates the position of the aircraft at a given moment, the perimeter of the screen is used for indicating azimuth (from an outer circle), distance to the control point or destination (according to the navigation system), engine rpm, fuel reserve, maximum distance the aircraft can fly at the present rate of fuel consumption taking into account wind, etc.

At the beginning of a flight the maximum range corresponds to the radius of the portion of the map shown on the screen. Then a circle appears on the screen and it gradually contracts to a point in accordance with the consumption of fuel, taking into account the actual conditions of flight and the wind vector.

Modern aviation is equipped with first-class flight-navigation equipment which assures control of flight at various heights, at high speeds, and in any weather, day or night.

One of the most important marks of a highly trained pilot is the ability to fly by instruments in bad weather. This ability is acquired by detailed study of flight-navigational devices, only from a great effort on the part of the pilot and his instructor. Instrument flying requires strict discipline, attention, stamina, and fast reflexes.

The tendency to lighten the pilot's task, to assure the safety of flight and accuracy of accomplishing a given mission has set scientists, designers and inventors to developing even more modern forms of flight-navigation instrumentation.

The Twenty-Second Congress of the Communist Party of the Soviet Union has set a course of wide technical progress in all areas of industry and transportation including aviation. Automation, cybernetics, electronic computer-resolvers and control mechanisms will be developed at an accelerated pace.

Automation will become more and more rooted in aircraft control systems but the pilot, as before, will retain the role of commander, making the final decisions.

Therefore, with further development of flight-navigation instruments consideration must be given not only to technical but also to psychological and physiological factors governing pilot participation in aircraft control.

REFERENCES

1. N. A. Efimov, et al. Osnovy teoriy poleta samoleta. Voyenizdat, 1957.

2. K. K. Platonov. Psikhologiya letnogo truda. Voyenizdat, 1960.

3. I. A. Poletayev. Signal, M., "Sovetskoye radio," 1958.

4. Spravochnik aviyatsionnogo shturmana. Voyenizdat, 1957.

5. Aviation Week, Vol. 66, No. 3, 16, 18, and 22. 1957; Vol. 68, Nos. 8 and 25, Vol. 69, No. 4, 1958; Vol. 71, No. 1, 1959; Vol. 73, Nos. 2 and 4, 1960.

6. Aviation Age, No. 1, 1956.

7. Canadian Aeronautical Journal, No. 1, 1960.

8. Control Engineering, No. 1, 1957.

9. Flight, Vol. 72, No. 2438, 1955; Vol. 73, Nos. 2452 and 2496, 1956; Vol. 77, No. 2674, 1960.

10. Flug Revue, No. 3, 1958.

11. Interavia Review, No. 3, 1959; Nos. 3 and 7, 1960; No. 3, 1961.

12. J. Inst. Nav., Vol. 13, No. 4, 1960; Vol. 14, No. 3, 1961.

13. Naval Aviation News, No. 1, 1958.

14. Popular Science, No. 6, 1955.

15. Proc. IRE, Vol. 47, No. 1, 1959.

16. Skyways, Vol. 16, No. 12, 1957; Vol. 17, No. 5, 1958.

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