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TAXIING ABILITY OF AN AIRCRAFT ON EARTH

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The useability of an aircraft for flights from dirt strips is characterized primarily by its taxiing ability, i.e. its ability to start up from a stop using its engine, accelerate and separate from the ground within the limits of the runway. The track which the aircraft leaves must not be deeper than a certain permissible limit. Calculations of taxiing ability are required for selection and maintenance of dirt air strips and determination of the possibility of performing flights from the strips.

This article studies the influence of the characteristics of the aircraft and soil on taxiing ability and the method of calculating taxiing ability.

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13. ABSTRACT

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The useability of an aircraft for flights from dirt strips is characterized primarily by its taxiing ability, i.e. its ability to start up from a stop using its engine, accelerate and separate from the ground within the limits of the runway. The track which the aircraft leaves must not be deeper than a certain permissible limit. Calculations of taxiing ability are required for selection and maintenance of dirt air strips and determination of the possibility of performing flights from the strips.

We shall examine the case of a plane with wheeled landing gear and study how airplane and ground characteristics influence taxiing ability and how taxiing ability is calculated.

When an aircraft moves on the earth, the resistance to movement (in kg) is equal to the product of the coefficient of the ground's resistance to movement (f) times the weight of the aircraft. In turn, the value of f and the depth of the tracks left (in cm) (h) can be calculated using formulas

$$f = \frac{q_{rp}}{\xi\mu\sigma}; \tag{1}$$

$$h = \frac{q_{o k}^{2}}{\xi^{2}\mu\sigma}. \tag{2}$$

where σ is the strength of earth in kg/cm^2, i.e. the ability to resist deformation (for example, formation of tracks) under the influence of a load. It depends on the composition, condition and moisture content of the earth and is determined using the U-1 impact tester. Due to possible unevenness in the surface of the strip, the value of σ is taken as the arithmetic mean of the results of measurements in a number of spots on the runway.

The specific load factor of the main wheels ($q_{o\ k}$) and front wheels ($q_{\pi\ k}$) in kg/cm^2 is equal to the ratio of the load (G) resting on the wheel to the area measured by the product of its diameter (D, d) by its width (B, b) and is determined by the formulas

$$q_{o k} = \frac{K_{o k} G}{n_{o k} \cdot D B} \text{ and } q_{\pi k} = \frac{K_{\pi k} \cdot G}{n_{\pi k} d b}.$$

where $n_{o\ k}$, $n_{\pi\ k}$ are the number of main and front wheels.

The corrected specific load factor of a wheel ($q_{\pi p}$) will be: $q_{\pi\ p} = q_{o\ k}K_{o\ k} + q_{\pi\ k}K_{\pi\ k}$.

The system of wheels of an aircraft with varying specific loading is replaced by a system of wheels of equivalent resistance, each of which has identical specific loading, while $K_{o\ k}$, $K_{\pi\ k}$ represents a share of the weight of the aircraft attributable to the main and front landing gear uprights. For aircraft with three wheels, $K_{o\ k} = 0.85\text{-}0.9$ and $K_{\pi\ k} = 0.1\text{-}0.15$, for aircraft with bicycle landing gear $K_{o\ k} = 0.5\text{-}0.55$ and $K_{\pi\ k} = 0.45\text{-}0.5$.

Coefficient μ considers the influence of deformation of a normally inflated main wheel tire on the taxiing resistance and the depth of the track. When a track is formed, the tire is deformed and the actual radius of curvature in the sector where it contacts the ground becomes greater than the radius of the undeformed wheel. The track formed is therefore like that which would be formed by a rigid wheel of diameter $D_1 = \mu D$. Consequently, introducing coefficient μ, we replace the actual wheel of diameter D with a rigid wheel of diameter D_1, equivalent in operating conditions.

The value of μ depends only on the strength of the soil. For wheels in which the air pressure in the tires is selected so that the tire compression when parked on a hard surface is 0.07-0.075 times the diameter of the wheel, coefficient μ varies as follows:

σ, kg/cm^2	4 or less	6	8	12	14	16	18 or more
μ	1.0	1.12	1.3	1.53	1.88	2.23	2.5

If the compression of the tires when marked is more or less than 0.07-0.075 D_k, the rolling conditions of the wheels on the earth differ from those used in determining μ and therefore, correction ξ must be introduced to formulas (1), (2), considering the influence of this deviation from normal pressure.

For a fixed flying weight, the value of ξ depends on the strength of the earth and the pressure in the tires. It is determined from the graph of Figure 1, where we have introduced curves of the change of ξ as a function of ratio of measured pressure in the tires to normal pressure (P_t/P_{tN}), for various soil strengths σ.

An increase (decrease) in the weight of the aircraft corresponds to an increase (or decrease) of the compression of the tire. Consequently, it can be considered approximately that with unchanged value of P_t, the value of ξ depends on the ratio P_t/P_{tN}. Therefore, the approximate equality $P_t/P_{tN} \approx G_N/G$ must be understood as follows: if P_t changes with constant aircraft weight, the first ratio must be used to determine ξ, and if the weight changes with constant P_t -- the second ratio must be used.

With normal inflation of the tires and normal aircraft weight, coefficient ξ is equal to 1.0 for all values of soil strength. In other cases, the value of ξ must be determined from the graph as a function of the strength of the soil, pressure in the tires of the main wheels if the weight is constant, or ratio of weight if the tire pressure is constant. Normal values of tire pressure and aircraft weight are presented in descriptions and certification sheets.

The depth of the track depends on the weight of the aircraft and the strength of the earth and furthermore of the diameter of the main wheel. Since the main wheels make a deeper track than the nose wheels, calculation is performed only for the main wheels.

It requires more force to start an aircraft from a parked position than to continue motion once started, since even for a hard surface the force of friction at rest is greater than the force of friction in motion. This is even more true for earth, where the wheels sink to a greater depth when parked than when moving. It is assumed in the calculations that the thrust required to move the aircraft from a parked position is 1.4 times the resistance of the earth to movement of the aircraft, i.e. in the limiting case $P \geq 1.4F = 1.4f \cdot G$ or, using formula (1):

$$\sigma_{min} = \frac{1.4q_{\pi p}}{\xi \cdot \mu \cdot \overline{P}} , \qquad (3)$$

where $\overline{P} = P/G$ is the thrust of the aircraft; σ_{min} is the minimum soil strength for which the aircraft can start moving.

The possibility of using the runway for repeated flights is determined to a significant extent by the depth of the tracks left by an aircraft during takeoff and landing. For example, if there is a sod cover, it is possible to be sure that the depth of the track does not exceed the permissible limits, which may fluctuate between 4 and 10 cm depending on the thickness of this cover.

The permissible track depth is selected on the basis of the tasks at hand. With long term use of an airfield, it generally should not exceed 5-8 cm. The value of h_{per} from formula (2) can easily be used to determine the permissible soil strength σ_{per}.

Obviously, the surface of the runway will be well preserved if the condition $h < h_{per}$ or $\sigma > \sigma_{per}$ is fulfilled.

Since formulas (2) and (3) include the value of μ, which depends on σ (see Table), when σ_{min} and σ_{per} are determined, several sequential calculations must be performed.

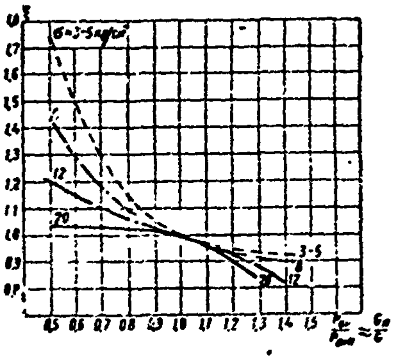

Figure 1.

For modern aircraft with a high thrust to weight ratio, the minimum soil strength, found from the condition of being able to start from a stop is generally less than the actual permissible soil strength. Thus, the condition limiting aircraft takeoff if it is not limited by the strip size, is conservation of the runway surface with repeated usage. Of course, when necessary individual takeoffs are possible with a soil strength σ_{min}, but then the tracks may be too deep and several such takeoffs will make the strip unuseable.

Determination of the takeoff run length on an earthen runway with otherwise standard conditions was studied in the article "Engineering Methods of Calculation of Takeoff and Landing Characteristics of Aircraft," published in *Vestnik Protivozdushnoy Oborony*, No 12, 1962.

In order to determine the possibility of takeoff of an aircraft from a strip, we must consider the influence of all operational factors on takeoff run length: atmospheric conditions, takeoff weight, wind, longitudinal inclination of the runway and operating mode of the engines in flight. Calculation of the required runway length for a new airfield should be performed for the most severe takeoff conditions. It must be kept in mind that random, slight deviations from the established takeoff procedure may always occur, as a result of pilot actions, such as failure to maintain precise angle and speed of separation, use of brakes, etc. Therefore, a correcting factor must be introduced to the calculation for random errors, i.e. the designed takeoff run length should be increased by K_{random} = 1-1.15.

As we know, one means of increasing the cross country ability of motor vehicles is to reduce the pressure in the tires. In principle, this measure is also possible for aircraft; with a tire pressure lower than normal, the taxiing ability is improved. However, the picture here is somewhat more complex. The problem is that the minimum pressure in the tires of aircraft wheels is limited by two factors: the permissible compression during taxiing and landing, as well as the critical speed of the wheel. If the tire pressure could be reduced with respect to the first condition, since the compression of the wheels is less due to deformation of the soil, the second limitation still may not allow this reduction. When the pressure is reduced, the rigidity of the wheel is decreased, as well as its ability to withstand centrifugal loads -- the critical speed is decreased, up to which the wheel can operate safely. Of course, the critical speed of a wheel must exceed the speed reached during takeoff and landing. A reduction in tire pressure may decrease the critical speed to below this permissible limit, causing the tire to blow out. Therefore, tire pressure must not be decreased to below the established limits.

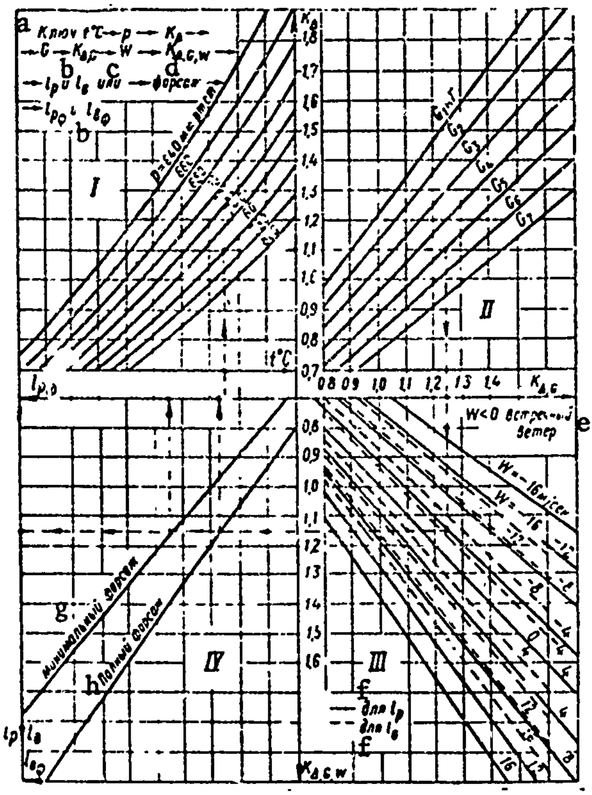

Figure 2.

Key: a, Key, b, and, c, or, d, afterburner, e, headwind, f, for, g, minimum afterburner, h, full afterburner.

The length of the landing run on an earthen landing strip generally does not exceed the length of the landing run on concrete. The reason for this is that the decreased effectiveness of the brakes is compensated for by the additional drag of the earth. However, it is important to observe the established landing speed, since an increase in landing speed by 1% causes an increase in landing run length by 2%.

Calculations of takeoff characteristics and taxiing ability over earth can be significantly facilitated and accelerated if nomograms similar to those shown on Figures 2 and 3 are constructed for each type of aircraft available in the unit.

The first nomogram (Figure 2) allows us to determine the takeoff run length and air sector of takeoff distance with changing atmospheric conditions and takeoff weight, with wind and for various operating modes of the engine on takeoff. It is constructed using the formulas which we studied earlier[1].

The graph has been remade in the fourth quadrant, in which the problem of determining the takeoff run length and length of the airborne sector of the takeoff distance during takeoff at maximum engine thrust, minimum and full after burner is solved. The graph is constructed in coordinates l_p (length of takeoff run without after burner) and $l_{p\cdot\phi}$ (with after burner), l_B and $l_{B\cdot\phi}$ (length of airborne sector of takeoff distance without and with afterburner). The straight lines marked "minimum afterburner" and "full afterburner" consider the change in thrust as the operating mode of the engine is changed, i.e. reflect the product $l_p K_p = l_{p\cdot\phi}$ (or $l_b K_p = l_{b\cdot\phi}$). The right vertical axis shows the overall conversion factor K; the values of l_p and l_B on the left vertical axis are calculated using the formulas $l_p = l_{p_0}\cdot K$ and $l_B = l_{B_0}\cdot K$, where l_{p_0} and l_{B_0} are the standard values of takeoff run length and airborne sector.

The graph in the third quadrant of the nomogram indicates the influence of wind on takeoff run length (solid lines) and length of airborne sector of takeoff distance (dotted lines). The key for performance of calculation is shown on the nomogram.

The nomogram shown on Figure 3 is designed for determination of the taxiing ability of a aircraft over soil and consideration of the influence of the longitudinal slump of the runway on the takeoff run length. Quadrant I allows us to calculate the value of coefficient K_f. In it, curves of the dependence of the wheel rolling resistance (f) on takeoff weight G are constructed (under the condition of constant tire pressure and various values of soil strength).

The graph in quadrant II is used to determine the conversion factor K for takeoff at the maximum operating mode, and in the modes of minimum and full after burner operation. Each of these curves is produced using formula (9)* for the corresponding values of mean thrust to weight ratio.

The curves in quadrant III are constructed according to the formula $K_{if} = K_i\cdot f$. The values of coefficient K_i are produced using formulas (11)*. This

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[1] Here and in the following, references are made to the article mentioned earlier, published in Vestnik Protivovozdushnoy Oborony, No 12, 1962.

graph allows us to find both the total conversion factor $K_{i,\ f}$, and coefficients K_i (where $K_f = 1.0$). Furthermore, the straight lines marked "maximal", "minimal afterburner", "full afterburner" and the lower horizontal scale of the graph are used to solve the problem of multiplication of conversion factors times standard values of takeoff run length during takeoff in these modes.

Quadrant IV shows a graph for determination of the depth of the track left with various values of takeoff weight and soil strength. Each of these curves is constructed using formula (2) for the constant value of σ marked on it.

The key for determination of the conversion factors and track depth is presented on the nomogram.

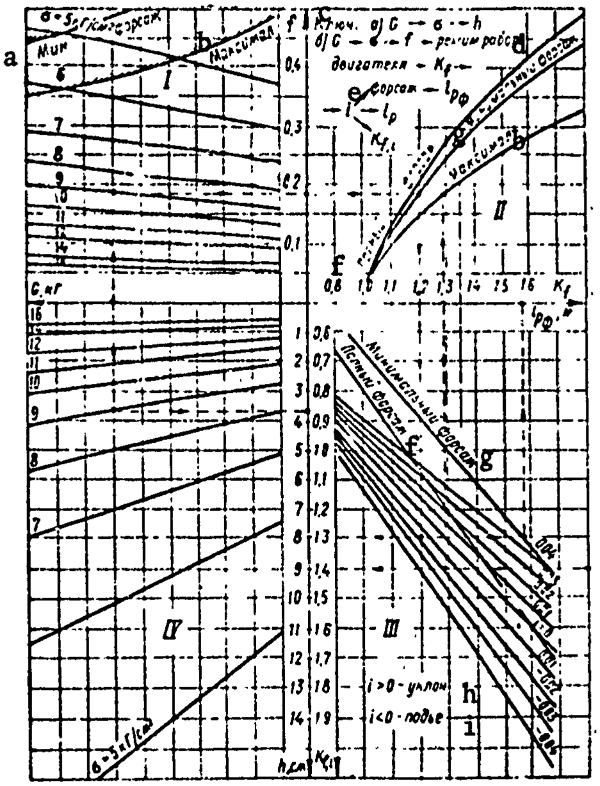

Figure 3.
Key: a, minimum afterburner, b, maximal, c, key, d, engine operating mode, e, after burner, f, full afterburner, g, minimum afterburner, h, downslope, i, upslope.

The nomogram also allows us to determine the possibility of starting an aircraft from the parked position. For this purpose, quadrant 1 carries the boundary lines marked "maximal" and "minimum afterburner," were used on the basis of formula (2) for the corresponding values of motor thrust. The aircraft can be started in this engine operating mode with values of f lying below the corresponding boundary line. If the takeoff weight is known, it is not difficult to determine the soil strength at which it is still possible to start the aircraft.

In addition to performing the corresponding calculations, these nomograms allow us to determine the takeoff run length under conditions when any number of operational factors change from among those reflected on them. To do this, multiply the conversion factors taken from the two nomograms and, laying out the product produced on the vertical axis K in quadrant IV of the nomogram (Figure 2), find the length of the run corresponding to the operating mode of the engine in takeoff.

The order of calculation of taxiing ability can be illustrated on the example of an aircraft for which: $G = 9{,}000$ kg, $G_N = 8{,}000$ kg, $P = 4{,}500$ kg, $\overline{P}_{cp_0} = 0.45$, $K_{otp} = 6$. The wheel data are: $n_{o.k} = 2$, $n_{n.k} = 1$, $K_{o.k} = 0.88$, $K_{\pi.k} = 0.12$, $D = 80$ cm, $B = 20$ cm, $d = 50$ cm, $b = 18$ cm. The takeoff run length under standard conditions $l_{cp_0} = 1{,}100$ m. The tire pressure is normal and constant. The taxiing ability of the aircraft must be determined for a runway 2,000 m in length with a soil strength $\sigma = 8$ kg/cm^2, when the track depth should be not over 6 cm.

1. Let us check the possibility of starting the aircraft from parked. The start up conditions are:

$$P:G > 1{,}4f;\quad P:G = 4500:9000 = 0{,}5;$$

$$q_{np} = K_{o.k}\cdot q_{o.k} + K_{n.k}\cdot q_{n.k} =$$

$$= \left(\frac{K_{o.k}^2}{n_{o.k}DB} + \frac{K_{n.k}^2}{n_{n.k}d\cdot b}\right)G =$$

$$= \left(\frac{0.88^2}{2\cdot 80\cdot 20} + \frac{0{,}12^2}{1\cdot 50\cdot 18}\right)\cdot 9000 = 2.32.$$

According to Figure 1 for $G/G_N = 9{,}000/8{,}000 = 0.89$, we determine $\xi = 1.03$, and from the Table -- $\mu = 1.3$. Then $f = q_{\pi p}$; $\xi\mu\sigma = 2.32:1.03\cdot 8 = 0.216$, while $1.4f = 0.303$. Consequently, it is quite possible to start the aircraft from the parked position.

2. Let us find the track depth left by wheels when the aircraft taxis:

$$h = q_{o.k}\cdot D\,\mu^{\text{[illegible]}}\sigma^{\text{[illegible]}} = 2.47\cdot 80\;1.3\times$$
$$\times 1{,}03^{\text{[illegible]}}\cdot 8^{\text{[illegible]}} = 5.5\ \text{cm}.$$

Therefore, the true track depth is less than the permissible depth.

3. Let us find the aircraft takeoff run length:

$$l_{pf} = l_{p_0} \cdot K_f.$$

$$K_f = \frac{\bar{P}_{cp_f} - 0.5\left(0{,}03 + \frac{1}{K_{отр}}\right)}{\bar{P}_{cp_0} - 0.5\left(f + \frac{1}{K_{отр}}\right)} = \frac{0{,}45 - 0{,}5\left(0{,}03 + \frac{1}{6}\right)}{0{,}45 - 0{,}5\left(0{,}215 + \frac{1}{6}\right)} = 1.36,$$

from which l_{pf} = 1,100·1.36 = 1,490 m. If we consider random deviations from technical flying conditions, takeoff run length $l_p = K_{random} \cdot l_{pf}$ = 1.15·1,490 = = 1,710 m, i.e. the runway can allow takeoff of the aircraft.

We note in conclusion that the calculations analyzed above seem too complex and cumbersome to some commanders and engineers. Therefore, they begin to do without them, using chance decisions. This is quite wrong, since maximum utilization of the capabilities of any equipment, including aviation equipment and its most effective application are possible only on the basis of precise calculations, considering the operating conditions.