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AN ESTIMATE OF THE INFLUENCE OF THE COMPRESSOR STABILITY MARGIN ON THE PICK-UP TIME OF A TURBOJET ENGINE

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The relations are derived enabling to estimate the acceleration time of the turbojet engine rotor set. The terms are established allowing for the determination of the effect of individual operational and structural engine parameters upon the time needed for acceleration of the rotor system. Influence of the economic and optimum ranges of operation upon that time is also analyzed.

1. Introduction

One of the more important parameters of operation of a turbojet engine is the acceleration time pick-up [11], adaptation time. This time, which is necessary for an engine to pass from one steady speed to another steady speed, is usually defined as that of passage from idling to 95% of the maximum speed and is decisive for the safety in case of unsuccessful landing approach, on an aircraft carrier, in particular [18], or in formation flight, during refuelling in flight or air combat and in any case of necessity of precise control of the thrust vector (for aeroplanes with improved manoeuvrability). The pick-up time of a turbojet engine is contained (depending on the structural features of the engine) within the interval of 6...15 s [11], lower values being those for engines with adjustable air duct and higher – for engines with an afterburner. As an example let us mention the JT9D-70 Pratt and Whitney engine. The companies occupied with the design of a digital system for automatic control of that engine (Boeing, Pratt and Whitney, Hamilton Standard and Bendix) were required to devise a control program to ensure an acceleration time of the order of 5 s. This was achieved by, among other means, appropriate selection of the idling speed in flight [10] and by control of the main duct of the engine (air bleeding, the use of controlled nozzle blades and a propelling nozzle with variable cross-section).

The pick-up time is decided upon by structural factors, such as the polar moment of inertia of the rotor, the magnitude of the tip clearances of the compressor and turbine blades and their variation in the course of the pick-up process [17], the presence of mechanical control devices in the main duct of the engine, or air bleeding to ensure air supply to the cockpit, for instance, or operational factors such as erosion of compressor blade profiles, variation in the Reynolds number due to varying flight conditions, humidity of the air, non-uniformity of pressure, speed and temperature in the inlet section of the engine, thermal state of the engine, the flying speed and altitude [1, 2, 4, 5, 7, 8, 9, 12, 14] or the degree of pollution of the surface of all the elements located in the main duct of the engine. Correct assessment of all the conditions influencing the pick-up time is necessary to make an engine with good dynamic properties and, therefore, to obtain the required operational characteristics for the aeroplane.

2. The computation model

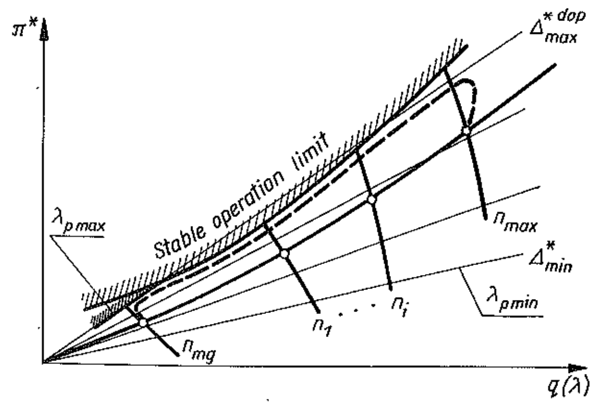

FIG. 1. Example of characteristic of an axial compressor. $q(\lambda)$ – relative density of the stream, Δ^* – degree of preheating of the stream, $\lambda_{p_{max}}$ – limit value of the coefficient of mixture composition mixture ratio, —— control program of the engine during the acceleration process of the rotor assembly.

Figure 1 represents the characteristics of a compressor, showing also the program of regulation of the engine to prevent the limit proportion of the air-fuel mixture (within the range of low rotor speeds) as well as the limit of stable operation of the compressor and the admissible temperature of the combustion gases before the turbine from being exceeded during the acceleration process.

In its general form the equation of motion of the rotor assembly of a jet engine is as follows

$$J\left(\frac{\pi}{30}\right)^2 n\,\frac{dn}{dt} = \delta P + P_{\mathrm{agr}}, \tag{2.1}$$

where J is the polar moment of inertia of the rotor assembly, n – r.p.m., t – time, δP – excess of the available power P_T of the turbine over the power

P_S necessary for driving the compressor:

$$\delta P = P_T - P_S, \tag{2.1'}$$

P_{agr} – the power necessary for driving the accesories (connected with the propelling assembly and the board installations of the aeroplane), which will be disregarded in further considerations, its value being small with reference to the power of the compressor, for instance.

Let us introduce the following dimensionless parameters

$$\bar{n} = \frac{n}{n_{\max}}, \qquad \bar{n}_p = \frac{n_p}{n_{\max}}, \qquad \bar{n}_k = \frac{n_k}{n_{\max}}, \qquad \overline{\delta P} = \frac{\delta P}{P_{T_{\max}}}, \tag{2.2}$$

with the indices p – initial, k – final, max – maximum, the symbol $P_{T_{\max}}$ denoting the maximum power of the turbine in steady state.

On substituting this into Eq. (2.1) we obtain, after some manipulation, the folowing expression of the acceleration time

$$t = K_T \int_{\bar{n}_p}^{\bar{n}_k} \frac{\bar{n}}{\overline{\delta P}}\, d\bar{n}, \tag{2.3}$$

where K_T is the coefficient of dynamic properties of the engine [15]

$$K_T = J\left(\frac{\pi}{30}\right)^2 \frac{n_{\max}^2}{P_{T_{\max}}}. \tag{2.4}$$

Figure 2 shows some values of the coefficient of dynamic properties of a single-rotor turbojet engine depending on the compression ratio. All the parameters involved in Eq. (2.4) result from the computation values assumed

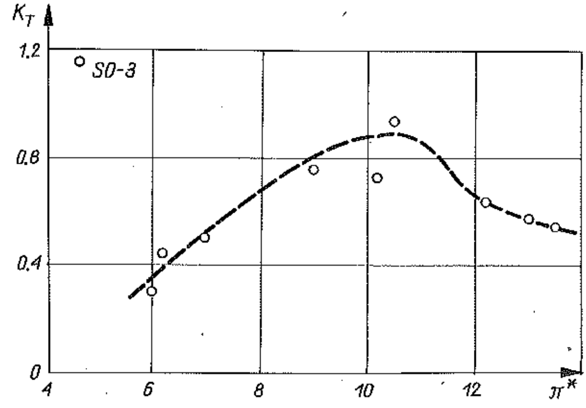

FIG. 2. Values of the coefficient of dynamic properties of the engine for various values of the compression ratio [15].

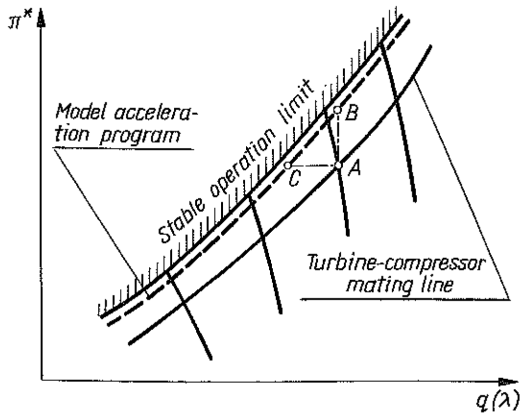

FIG. 3. Simplified characteristic of an axial compressor indicating the computation model: $A - B$ – acceleration with $\dot{m}$ = const, $A - C$ – acceleration with π^* = const, according to [15].

for the engine. The polar moment of inertia of the rotor assembly may be assessed on the ground of the data of [15].

In further considerations it will be assumed that power of the turbine in the course of the acceleration process is equal to the power which would be absorbed by the compressor if its compression ratio approached the value corresponding to the limit of stable operation as determined by the value of the degree of preheating of the air stream (Fig.3). This means that the pick-up of the rotor assembly proceeds according to the control program $\Delta^* =$ const. It is also assumed that, for the lines of constant rotational speed under consideration, the relative density of the stream is constant for a steady and a transient state, which is represented by the line segment $A - B$. Such an assumption seems to be better justified for an axial compressor with medium and high degree of compression than the assumption made in [15] and illustrated by the segment $A - C$, that is the assumption of constant compression ratio during the pick-up process of the engine for a prescribed rotation speed (Fig.3).

Bearing in mind the simplifying assumptions which have been made, the relations describing the power of the turbine in a transient state and the power absorbed by the compressor in a steady state have the form

$$\begin{aligned} P_T &= P_{Sp} = \dot{m}_p c_p T_1^* (\pi_p^{*\frac{k-1}{k}} - 1)\frac{1}{\eta_s^*}, \\ P_{Su} &= \dot{m}_u c_p T_1^* (\pi_u^{*\frac{k-1}{k}} - 1)\frac{1}{\eta_s^*}, \qquad (2.5) \\ \dot{m}_p &= \dot{m}_u \qquad \text{by assumption,} \end{aligned}$$

where T_1^* is the temperature of the air in the inlet cross-section of the compressor, c_p – specific heat of air, η_s^* – efficiency of the compressor, π compression ratio, $\dot{m}$ – air flow intensity and k – isentropic exponent, with the indices u – steady state, p – engine acceleration.

On substituting Eq. (2.5) into Eq. (2.1′) and transforming, we find

$$\delta P = \dot{m} c_p T_1^* \frac{1}{\eta_s^*} \pi_u^{*\frac{k-1}{k}} \left[\left(\frac{\pi_p^*}{\pi_u^*} \right)^{\frac{k-1}{k}} - 1 \right]. \tag{2.6}$$

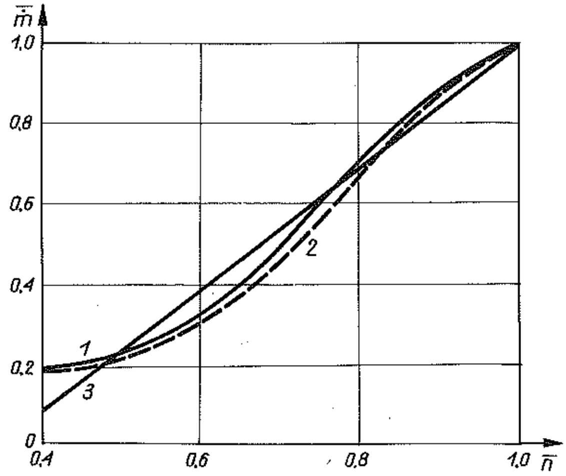

FIG. 4. Dependence of the compression ratio and air flow intensity on the engine speed under test bed conditions in steady states (solid line) and transient states.

Without committing in our model considerations any major error (Fig.4), it may be assumed that the air flow intensity through the engine depends linearly on its rotary speed and may be described by the expression

$$\dot{m} = \dot{m}_0 \bar{n},$$

where $\dot{m}_0$ is the flow intensity under the computation conditions.

On substituting the above relation into Eq. (2.6) and bearing in mind (2.2) we obtain the following expression describing the excess of turbine power

$$\overline{\delta P} = K_P \pi_u^{*\frac{k-1}{k}} \bar{n} \left[\left(\frac{\pi_p^*}{\pi_u^*} \right)^{\frac{k-1}{k}} - 1 \right], \tag{2.7}$$

where K_P is the power coefficient

$$K_P = \frac{\dot{m}_0 c_p T_1^*}{\eta_s^* P_{T_{\max}}}. \tag{2.8}$$

The ratio of the compression ratio during the acceleration process of the engine to its value under steady-state conditions can be found by making use of the continuity equation of the air stream under the conditions of co-operation between the compressor and the nozzle ring of the turbine [6]

$$jA_1q_1(\lambda)\frac{p_1^*}{\sqrt{T_1^*}} = j'A_{WD}\,q_{WD}(\lambda)\sigma_{WD}\frac{p_3^*}{\sqrt{T_3^*}},$$

where j is the gas-dynamic parameter ($'$ – for the combustion gases)

$$j = \sqrt{\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}\frac{k}{R}},$$

A_1, A_{WD} – the cross-sectional area of the inlet to the compressor and the nozzle ring of the turbine, respectively, $q_1(\lambda)$, $q_{WD}(\lambda)$ – relative density of the stream at the inlet to the compressor and the nozzle ring of the turbine, respectively

$$q(\lambda) = \sqrt{\frac{2}{k-1}\left(\frac{k+1}{2}\right)^{\frac{k+1}{k-1}}}\sqrt{\left(\frac{1}{\pi^*}\right)^{\frac{2}{k}} - \left(\frac{1}{\pi^*}\right)^{\frac{k+1}{k}}},$$

σ_{WD} – pressure losses in the nozzle ring of the turbine, π^* pressure ratio.

On transforming the continuity condition and assuming that the pressure losses in the combustion chamber are negligibly small ($p_3^* = p_2^*$), we obtain

$$\pi = \mathrm{const}\sqrt{\frac{T_3^*}{T_1^*}}\,q_1(\lambda). \tag{2.9}$$

By introducing the notion of stability margin of the compressor (cf. Eq. (2.1)) and making use of the simplifying assumptions which have been made (Fig.4) we obtain the expressions

$$\begin{aligned}\Delta Z_u &= \frac{\pi_{\mathrm{gr}}^*}{\pi_u^*} - 1,\\ \Delta Z_p &= \frac{\pi_{\mathrm{gr}}^*}{\pi_p^*} - 1.\end{aligned} \tag{2.10}$$

On substituting Eq. (2.9) and transforming, we find

$$\begin{aligned}\Delta Z_u &= \sqrt{\frac{T_{3\mathrm{gr}}^*}{T_{3u}^*}} - 1 = Z_u - 1,\\ \Delta Z_p &= \sqrt{\frac{T_{3\mathrm{gr}}^*}{T_{3p}^*}} - 1 = Z_p - 1.\end{aligned} \tag{2.10'}$$

By confronting Eq. (2.10) with Eq. (2.10′) the compression ratio involved in Eq. (2.7) can be determined from the relations

$$\frac{\pi_p^*}{\pi_u^*} = \frac{Z_u}{Z_p} = \sqrt{\frac{T_{3p}^*}{T_{3u}^*}}$$

therefore the relation (2.7) takes the form

$$\overline{\delta P} = K_P \pi_u^{*\frac{k-1}{k}} \bar{n} \left[\left(\frac{Z_u}{Z_p} \right)^{\frac{k-1}{k}} - 1 \right]. \tag{2.11}$$

For steady-state conditions the compression ratio has been assumed to depend on the square of the rotary speed (cf. Fig. 4), that is

$$\pi_u^* = \pi_0^* \bar{n}.$$

On substituting this into (2.11) we find

$$\overline{\delta P} = K_P \pi_0^{*\frac{k-1}{k}} \bar{n}^{\frac{3k-2}{k}} \left[\left(\frac{Z_u}{Z_p} \right)^{\frac{k-1}{k}} - 1 \right]. \tag{2.11′}$$

Now, on substituting Eq. (2.11′) into Eq. (2.3) we find the following relation for the acceleration time of the engine

$$t = \frac{K_T}{K_P} \int_{\bar{n}_p}^{\bar{n}_k} \left[\left(\frac{Z_u}{Z_p} \right)^{\frac{k-1}{k}} - 1 \right]^{-1} \bar{n}^{\frac{2(1-k)}{k}} d\bar{n}, \tag{2.12}$$

where the coefficient of power K_P has been corrected to become

$$K_P = \frac{1}{\eta_{so}^*} \frac{\pi_0^{*\frac{k-1}{k}}}{\pi_0^{*\frac{k-1}{k}} - 1}. \tag{2.13}$$

Assuming, for the model conditions, that $Z_p = \text{const}$ and $Z_u = \text{const}$ and integrating the expression (2.12), the acceleration time of the engine can be evaluated from the relation

$$t = \frac{K_T K_Z}{K_P} \frac{k}{2-k} \left[\bar{n}_k^{\frac{2-k}{k}} - \bar{n}_p^{\frac{2-k}{k}} \right], \tag{2.14}$$

where K_Z is the relative stability coefficient:

$$K_Z = \left[\left(\frac{Z_u}{Z_p} \right)^{\frac{k-1}{k}} - 1 \right]^{-1}. \tag{2.15}$$

From the discussion of the relation obtained it follows that the acceleration time of the rotor assembly is longer for a higher value of the coefficient of dynamic properties K_T , a higher value of the relative stability coefficient K_Z and a lower value of the power coefficient K_P.

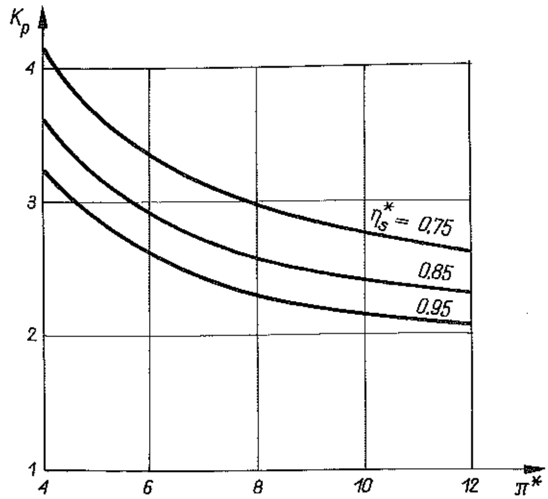

FIG. 5. Dependence of the power coefficient on the compression ratio for various values of the compressor efficiency.

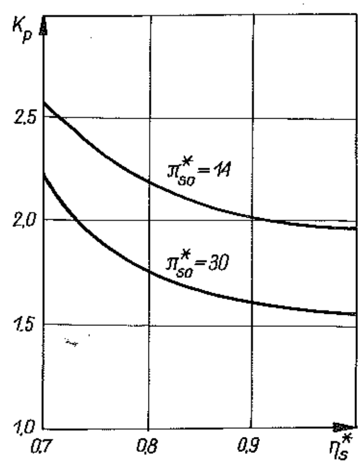

FIG. 6. Dependence of the power coefficient on the efficiency of the compressor for various assumed compression ratios.

The power coefficient K_P depends on the assumed operation parameters of the compressor. Its value is higher, if the efficiency of the compressor is lower. Figure 5 shows the dependence of the power coefficient on the assumed compression ratio for various values of the compressor efficiency. For compressors of medium and high compression ratio ($\pi^* > 8$) the coefficient of power is practically constant for a given compressor efficiency. Thus, for instance, an increase in compression ratio by 60% (for $\eta_s^* = \text{const}$) results in a reduction in the power coefficient by no more than 14%.

Figure 6 shows the dependence of the power coefficient on the compressor efficiency for various values of the computational compression ratio. In practice, an efficiency $\eta_s^* = 0.85,\ldots,0.9$ is a limit of the influence of that parameter on the acceleration time of the engine.

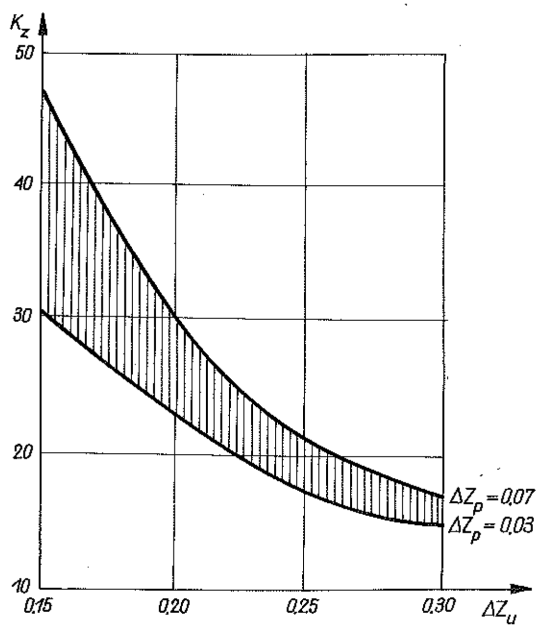

FIG. 7. Dependence of the relative coefficient of stability on the stability margin under steady-state conditions, for various values of the stability margin during the acceleration process of the engine.

The relative stability coefficient K_Z – the value of this coefficient depends on the ratio of the stability margin for steady-state operation to the stability margin for a pick-up process. In modern turbojet engines the stability margin reaches during pick-up value $\Delta Z_p = 0.05,\ldots,0.07$ [16].

Under steady-state conditions the stability margin of the compressor reaches a value $\Delta Z_u = 0.15,\ldots,0.25$ [2,3] and its variation as a function of the rotary speed depends on the structural form of the engine. Figure 7 shows the dependence of the relative stability coefficient on the stability margin of steady state operation for various values of the stability margin during a pick-up process of the engine. The form of the curve shows that,

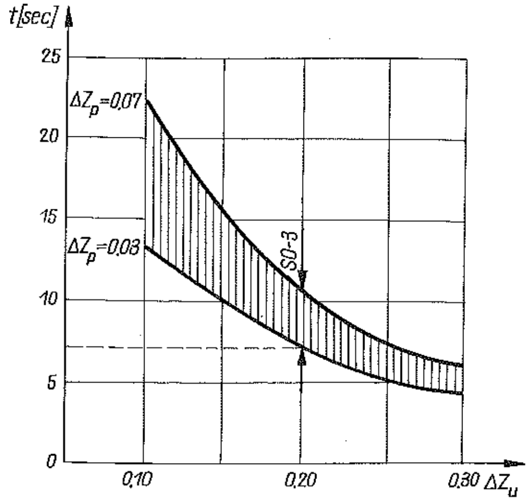

FIG. 8. Dependence of the acceleration time of the engine on the stability margin under steady-state conditions, for various values of the stability margin during the acceleration process.

beginning from $\Delta Z_u > 0.25$ the intensity of reduction of the relative stability coefficient is low. This means that, in military aircraft in particular, the stability margin under steady-state conditions should be contained within the interval $\Delta Z_u = 0.25,\ldots,0.30$.

Figure 8 shows an example of dependence of the acceleration time of the SO-3 engine on the stability margin of the compressor in steady state for various values of the stability margin during a pick-up process. The diagram shows also an estimated acceleration time of the engine assuming, on the basis of the characteristic of the compressor, that $\Delta Z_u = 0.20$. By virtue of Eq. (2.14) and assuming two limiting values of ΔZ_p it has been found that $t = 7.6,\ldots,9.5$ s. By confronting this result with the data contained in the technical conditions for tests of the SO-3 engine, in which the required time was $t = 8,\ldots,14.5$ s, it is found that the relation obtained seems to enable us to estimate the acceleration time of the engine with sufficient accuracy. (The result was obtained by assuming that $\Delta Z_u = \text{const}$ and $\Delta Z_p = \text{const}$).

3. THE INFLUENCE OF THE OPTIMUM RANGE AND THE ECONOMIC RANGE OF OPERATION OF A TURBOJET ENGINE ON THE ACCELERATION TIME

The form of the curves in Fig. 2 and 5 shows that for the computational compression ratio $\pi^* > 10$ the coefficient of dynamic properties and that of power are both approximately constant. Hence, for the purposes of modelling, it is assumed that

$$K_T = \text{const}, \qquad K_P = \text{const}.$$

With such assumptions, to estimate the influence of the stability margin of the compressor (for the economic and optimum operation range) on the acceleration time, the following relations should be used

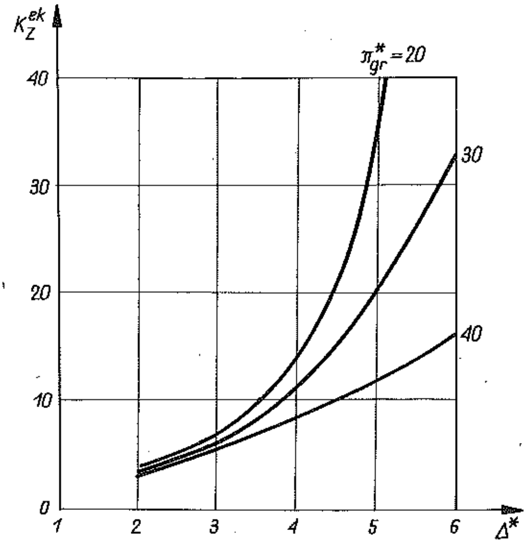

FIG. 9. Dependence of the relative coefficient of stability for economic values of the compression ratio on the degree of preheating of the air stream and various values of the limit compression ratio.

$$(3.1) \qquad \begin{aligned} K_Z^{\text{ek}} &= \left[\left(\frac{Z_{\text{ek}}}{Z_p}\right)^{\frac{k-1}{k}} - 1\right]^{-1}, \\ K_Z^{\text{opt}} &= \left[\left(\frac{Z_{\text{opt}}}{Z_p}\right)^{\frac{k-1}{k}} - 1\right]^{-1}. \end{aligned}$$

To this aim, making use of the following relations taken from [13]

$$Z_{\text{opt}} = \frac{q_{\text{opt}}(\lambda)}{q_{\text{gr}}(\lambda)} \frac{\left(1 + \frac{k-1}{2} Ma^2\right)^{0.5} \pi_{\text{gr}}^{*\,\frac{k-1}{2k}}}{(\Delta^* \eta_r \eta_s a)^{0.25}},$$

$$Z_{\text{ek}} = \frac{q_{\text{ek}}(\lambda)}{q_{\text{gr}}(\lambda)} \frac{\pi_{\text{gr}}^{*\,\frac{k-1}{2k}}}{\left\{\left[\Delta^* - \left(\frac{1}{\eta_s} - 1\right)\right] \eta_s\right\}^{0.5}} \left(\frac{2}{a\eta_r} - 1\right)^{0.5},$$

and substituting them into Eq. (3.1), we find the relation sought for.

Figure 9 shows the dependence of the relative coefficient of stability K_Z^{ek}, in the case of economic compression ratio, on the degree of preheating of the stream Δ^* , for various values of the limit compression ratio. From the form of the curves it follows that its value is lower for a higher value of the limit compression ratio.

The difference between the values of $K_Z^* = f(\pi_{gr}^*)$ becomes essential at the degree of preheating of the stream within the range of $\Delta^* = 4,\ldots,4.5,$. This is caused by a rapid reduction of the stability coefficient within the economic range of engine operation.

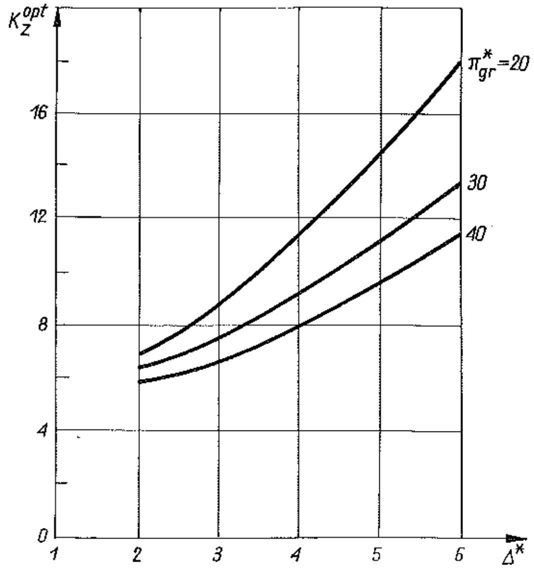

FIG. 10. Dependence of the relative stability, for optimum values of the compression ratio on the degre of preheating of the stream and various values of the limit compression ratio.

Figure 10 illustrates the dependence of the relative coefficient of stability, in the case of optimum compression ratio, on the degree of preheating of the stream, for various values of the limit compression ratio. From the form of the curves and by confrontation with Fig. 9 it is seen that under optimum conditions the value of the relative coefficient of stability is low over the entire range of preheating of the stream. This is a consequence of moderate variation of the stability coefficient under the optimum conditions, with variable degree of preheating of the stream. On the basis of (3.1) and making use of (2.14), the relative pick-up time has been determined for the economic compression ratio. From the form of the curves in Fig. 11 it is

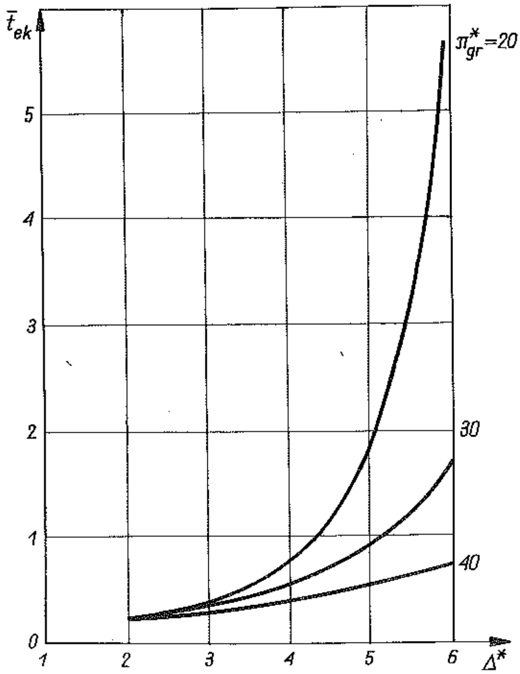

FIG. 11. Dependence of the relative acceleration time of the rotor assembly, for the economic compression ratio, on the degree of preheating for various limit values of the compression ratio.

seen that it is only for moderate values that the pick-up time of the engine can be reduced with reference to the value obtained by computation for a stability margin $\Delta Z = 0.2$. For high limiting values of the compression ratio $\pi^*_{gr} = 40$ this time is by nearly 60% shorter than the initial time for $\Delta^* = 4$.

Figure 12 illustrates the dependence of the relative acceleration time of the engine, for the optimum compression ratio, on the degree of preheating of the stream. In the case of this operation range of the compressor it is seen that, independently of the limit value of the compression ratio, the acceleration time of the engine is always shorter than the reference time. Similarly to Fig. 11 for $\Delta^* = 4$ this time is shorter than the reference time for $\pi^*_{gr} = 40$ by about 60%. This agreement of results is a consequence of the equality of the stability margins for the condition of economic and optimum compression ratio, if $\Delta^* = 4$. From the above analysis it follows that the acceleration time of an engine can be shortened by controlling the operation of the compressor within the range of π^*_{ek} and π^*_{opt} . It is only in the case when the compressor of a moderate compression ratio is controlled within

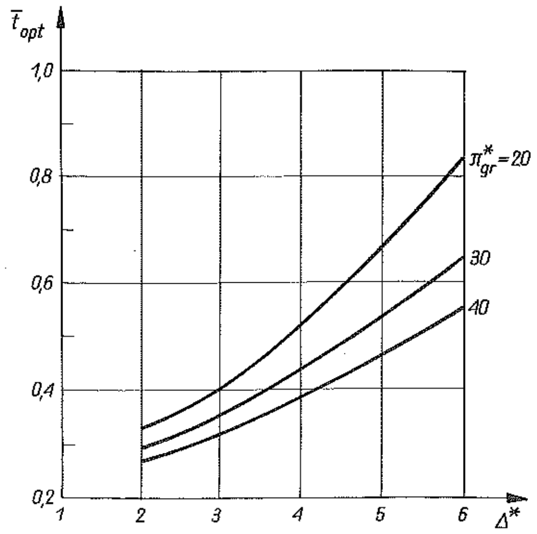

FIG. 12. Dependence of the relative acceleration time of the engine, for the optimum compression ratio, on the degree of preheating for various limit values of the compression ratio.

the π^*_{ek} range, that the acceleration time of the engine may be increased. For the limiting values of $\pi^*_{gr} < 30$ an insignificant deviation from the prescribed value of the degree of preheating Δ^* may produce considerable changes in the dynamics of the engine, if it operates according to the criterion of economic compression ratio.

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STRESZCZENIE

OCENA WPŁYWU ZAPASU STATECZNOŚCI SPRĘŻARKI NA CZAS ROZPĘDZANIA ZESPOŁU WIRNIKOWEGO TURBINOWEGO SILNIKA ODRZUTOWEGO

Wyprowadzono zależność pozwalającą na obliczenie czasu rozpędzania zespołu wirnikowego turbinowego silnika odrzutowego. W otrzymanej zależności wyróżniono współczynniki pozwalające na ocenę wpływu parametrów konstrukcyjnych silnika i parametrów eksploatacyjnych na czas rozpędzania zespołu wirnikowego. Przeprowadzono również ocenę wpływu zakresu pracy silnika ekonomicznego i optymalnego na ten czas.

Резюме

ОЦЕНКА ВЛИЯНИЯ ЗАПАСА УСТОЙЧИВОСТИ КОМПРЕССОРА НА ВРЕМЯ РАЗГОНА РОТОРНОГО ТУРБИННОГО АГРЕГАТА РЕАКТИВНОГО ДВИГАТЕЛЯ

Выведена зависимость, позволяющая рассчитывать время разгона роторного турбинного агрегата реактивного двигателя. В полученной зависимости выделены коэффициенты, позволяющие оценить влияние конструкционных параметров двигателя и эксплуатационных параметров на время разгона роторного агрегата. Проведена тоже оценка влияния диапазона работы экономического и оптимального двигателя на это время.

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