Impact of dust erosion on the reduction of axial compressor efficiency of a turboshaft engine and on the stability of its operation

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Abstract. This paper aimed to solve the impact of operational abrasive wear on the rotor blades of the axial compressor of the turboshaft engine on the decrease in its total compression efficiency η_{Ct} and its transition into unstable work mode (surge). This process is analyzed based on the obtained data by operating TV3-117 helicopter turboshaft engines in high dust atmosphere conditions. Abrasive wear of the rotor blades of axial compressors causes mechanical damage to the blades, reducing their strength, changing their geometry, and aerodynamic properties, reducing the life of the whole compressor and thus the entire engine. Destruction of the compressor of a turboshaft engine may occur suddenly as a result of unstable compressor operation caused by damaged axial compressor blades due to their damage by the abrasive effect of dust.

1 Introduction

The first research on the dust erosion impacts was carried out in Germany already in 1930. These studies were based on a theoretical analysis of the influence of erosion on various materials based on elaborated models for registration of the volume of worn material, deformation and abrasive wear, particle motion, etc. A great scientific contribution to the creation of erosive wear models was brought by I. Finnie, J. G. Bitter, J. Neilson, A. Gilchrist, W. Tabakoff, G. Grant, and others. In the Russian Federation, scientists from many universities and organizations (CIAM, UGATU, SGAU, IAIA, VIVA, and others) have made a major contribution to experimental and numerical research of the influence of operational factors on the characteristics of aircraft turbo-compressor engine (ATCE) (CIAM, UGATU, CGAU, MAI, VVIA, and others). [2, 3, 4].

The basic wear mechanism is a complex function of the physical properties of the damaged material, a composition of abrasive particles, their dimensions, the angle of a collision (interaction), and the collision velocity. This mechanism has been investigated by many scientists and it has resulted in a definition of an experimental correlation between the

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material wear level as a function of erosion parameters. [5] J. Goodwin and others have found that the erosion level practically directly depends on the percentage of quartz in the dust. [6] This is due to the fact that quartz is one of the most present dust components. At the same time, they have shown that the degree of erosion at the given interaction velocity increases with a growing dust particle diameter. The dust particle size is one of the important factors determining the level and nature of erosive wear. Particles with dimensions of less than 70 micrometres are classified as dust.

The results of further research illustrate that the level of wear increases with growing particle size. [7] In the case of high dust levels, the turboshaft turbo compressor engine (TsTCE) shows equal wear and tear on the first stage blades and increased wear on the peripheral parts of the last stage blades. With a moderate dust content in the air, the blade's wear is local in nature and depends on the specificity of the flow, which causes a local increase in particle concentration and their velocity with regard to the compressor blades. The wear of the compressor blades results in a change in the shape of the blade's aerodynamic profile and an increase in the blade surface roughness. Due to decreasing the total efficiency of the compressor η_{Ct}, the total compression rate π_{Ct}, the mass flow rate Q_{Air}, the gas-dynamic stability of each stage of the compressor, and the compressor as a whole of K_y decreases, resulting in unstable operation of the TsTCE and combustion turbine (CT) compressors. [8]

2 TV3-117 turboshaft helicopter engine

To analyze the influence of the erosive wear of the rotor blades of the axial compressor of a turboshaft engine on the unstable work of the axial compressor, one of the most widely used turboshaft helicopter engines at present, the TV3-117, was selected. Its selection was also influenced by the fact that the mentioned turboshaft engine was and still is massively used in the conditions of countries with atmosphere with considerable dust content (Afghanistan, Iraq, Iran, Syria, Egypt, Algeria and others). The advantage of this selection is that statistical data of individual parameters are available and usable from the operation of these turboshaft engines in the above conditions.

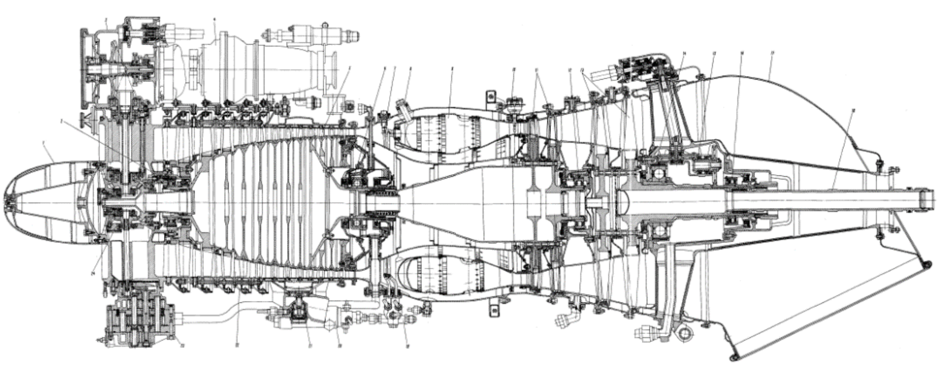

Fig. 1. TV3-117 turboshaft helicopter engine section. [6]

The TV3-117 is a turboshaft engine with an axial inlet, a twelve-stage axial compressor with rotary vane blades and two air bleed valves, an annular combustion chamber, a two-stage axial, cooled gas turbine compressor, a two-stage axial, free gas turbine, and an outlet

system with the outlet tube rotated at an angle of 60° to the right or left with respect to the engine [11].
Two TV3-117 3rd series turboshaft engines are used to drive the Mi-24D and Mi-24DU helicopters, two TV3-117V engines of the Mi-24V drive the helicopter, and two TV3-117MT engines drive the medium transport Mi-17 helicopter [11].

Table 1. Modes of the turboshaft engine TV3-117, 3rd series.

Mode	**P_e kW**	**c_e kg.kW^{-1}.h^{-1}**	**T_{3t} K**	**n_{TC} %**	**n_{MR} %**	**Operating time (min.)**	
						Continuously	**3x for TL**
Take off	1628	0,314	1248	97,6	98±1	6	≤ 5 %
Nominal	1427	0,342	1208	94,7	98±1	60	≤ 40 %
1. Travel	1244	0,369	1173	93,5	100±2	Unlimited	Unlimited
2. Travel	1098	0,396	1143	91,5	100±2	Unlimited	Unlimited
Idle	879	≤ 155 kg.h^{-1}	1103	73+1	65	20	-

The TV3-117 turboshaft engine compressor is an axial, single-shaft, twelve-stage compressor with adjustable guide vanes on the first four stages of the compressor stator. The adjustment of the guide vanes is carried out automatically in the range from $\alpha_{GV} = 27°$ to $\alpha_{GV} = 0°$, depending on the calculated rotor speed of the turbo-compressor. To ensure the stable operation of the compressor, two air release valves are also used downstream of the seventh compressor stage.

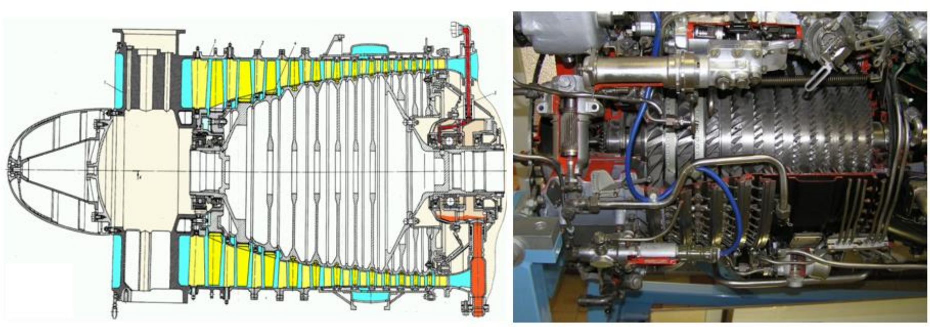

Fig. 2. Compressor section of the turboshaft helicopter engine TV3-117.

To protect against the occurrence of unstable compressor operation, the compressor uses adjustable stator vanes (variable stator vanes) of the first four stages and the inlet rectifier, which are set to a given position according to the specified program $\alpha_{GV} = f(n_{C,calc.})$. A deviation from the program of 1,5 ° to the opening side results in a reduction of the K_y compressor's steady-state operating margin of 1,5 % to 2,0 %. A deviation of 1° to the closing side results in a reduction of 66 kW in engine power. Control of the compressor vane rotation mechanism is provided by two hydraulic slave cylinders, which are supplied with pressurised fuel from the NR-3A pump-regulator.
Two blow-off valves, which discharge part of the air outside the compressor depending on the recalculated speed of the turbo-compressor rotor according to a program controlled by the pump-controller NR-3A, also provide an increase in the supply of stable operation of the engine compressor on the transient modes.

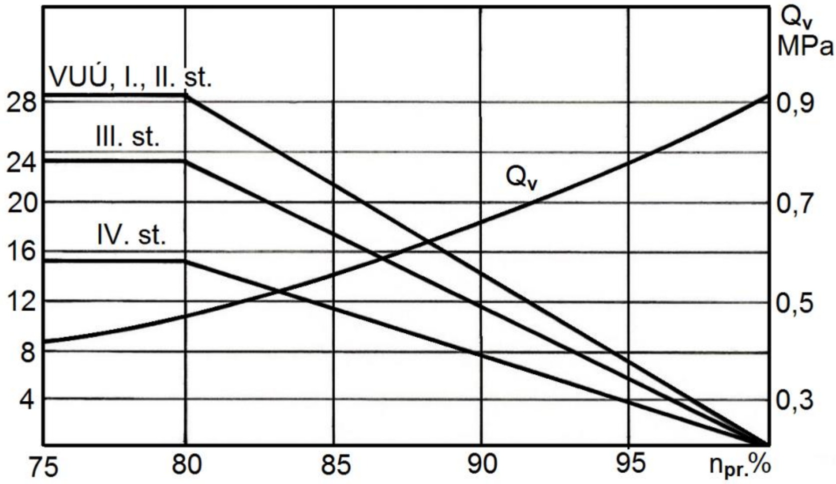

Fig. 3. Control program for the adjustable guide vanes of the inlet rectifier and the first four stages of the compressor stator of the TV3-117 engine.

Table 2. Gas-dynamic parameters of the compressor of the turboshaft engine TV3-117 in take-off mode

Parameter	**Compressor stage**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
T_{2t} (K)	312	340	370	398	427	456	484	511	533	564	589	613
ΔT_t (K)	24	28	30	29	29	29	28	27	27	26	25	24
π_{Cc} (1)	1,289	1,314	1,298	1,271	1,246	1,228	1,205	1,192	1,175	1,159	1,146	1,28
η_{Cc} (1)	0,889	0,899	0,904	0,907	0,902	0,904	0,904	0,904	0,901	0,896	0,823	0,857
z_{stator}	60	60	60	60	80	84	84	86	88	90	90	114
z_{rotor}	37	43	59	67	73	81	89	89	89	89	89	89

Where:
T_{2t} – temperature at the outlet of the stage;
ΔT_t – heating the air to v degree;
π_{Ct} – the overall degree of compression of the grade;
η_{Ct} – overall degree efficiency;
The total efficiency of the compressor is η_{Ct} = 0,86**.**

3 Effect of dust erosion on the characteristics of a turboshaft engine axial compressor

The disturbance of the stable work of the axial compressor of a turboshaft helicopter engine, caused by the loss of gas-dynamic stability, is one of its most dangerous failures. For this reason, operation on modes, where the working point in the compressor characteristic is close to the limit of unstable work, i.e. where the stock of stable work is small, is inadmissible.

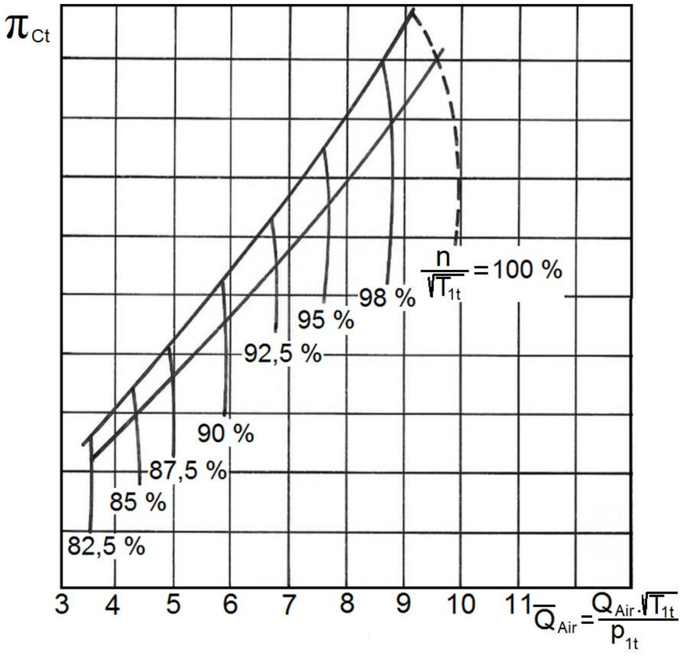

Fig. 4. Characteristics of TV3-117 turboshaft engine axial compressor.

The steady-state workload of an axial compressor can be expressed by the equation

$$\Delta K_y = \left[\frac{\left(\frac{\pi_{Ct}}{Q_{Air}}\right)_{SL}}{\left(\frac{\pi_{Ct}}{Q_{Air}}\right)_{WP}} - 1 \right] . 100\ \% \qquad (1)$$

Where:
$\pi_{Ct,SL}$ – the overall degree of compression at the limit of unstable work (on surge line),
$Q_{Air,SL}$ – air mass flow rate at the limit of unstable work (on surge line),
$\pi_{Ct,WP}$ – the total degree of air compression at the working point,
$Q_{Air,WP}$ – air mass flow rate at the working point.

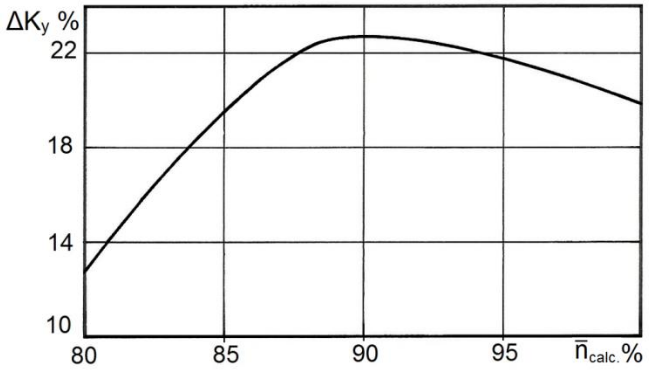

Fig. 5. Dependence of the steady-state work reserve of the axial compressor of the TV3-117 turboshaft engine on the engine operation mode.

When the compressor is tested above the calculation mode, the compressor's steady-state operating margin reaches $K_y = 2 - 5$ %.

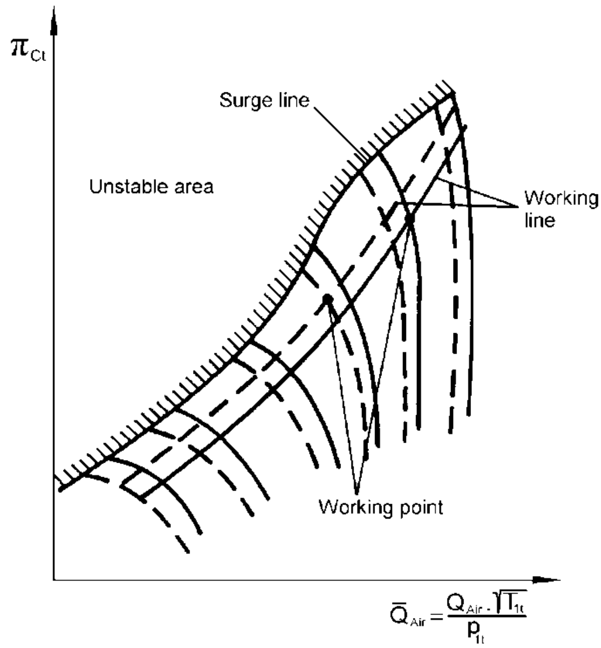

Fig. 6. Characteristics of a compressor with intact rotor blades and blades damaged by dust erosion.

Statistical analysis of the measurement results of the blades of different stages of the axial compressor of the TV3-117 engine, which were subjected to abrasive action of dust in operation, showed that the shortening of the blade bowstring was manifested only in the peripheral part of the blades, at the level of the upper third of the blade (Fig. 5). The analysis of the blade leaf wear values in the individual stages of the axial compressor allowed to detect the regularities caused by the design peculiarities of the compressor of the TV3-117 engine. It was confirmed that there are close correlations between the value of blade wear of the second to the twelfth stage of the compressor, which is due to the homogeneity of the processes that lead to blade wear. Maximum wear occurs in the first and sixth stage blades of an axial compressor. However, the nature of the wear is different. The rotor blades of the first stage show signs of damage mainly on the leading edge and on the front face, which is the result of contact with the largest abrasive particles that are fragmented in other parts of the axial compressor. The rotor blades of stages one to four had basic wear at the leading edges and in the blade trough. Rotor blades of the fifth to twelfth stages had wear at the inlet and outlet edges and the trailing edge of the blade. The above wear patterns can be explained by the fact that large dispersive abrasive particles encounter the leading edges of the rotor blades of the first stage of the axial compressor, fragment and move with the air stream towards the next stages. As the rotor blades of the first stage encounter relatively large particles, these blades are the most damaged. Already in the second stage, the shortening of the bowstring due to wear is considerably less, but it is of an increasing character up to the sixth (seventh) stage of the compressor. This effect is due to the fact that the rotor blades of the subsequent stage have a smaller profile thickness compared to the previous blade, but the volume of abrasive particles acting on it remains constant. At the same time, the rotor blades of each successive stage operate at a higher temperature (Table 2) resulting in a reduced ability of the material to resist wear.

The blades from the eighth to the twelfth stage have considerably less, approximately equal wear when compared to the sixth and seventh stages. This is due to the air intake chamber to the blow-off valves located after the seventh stage (Fig. 6).

When the engine is running at low speed (idle, right correction) on the ground, under dusty conditions, some of the dust (sand) along with the air escapes through the blow-off valves to the atmosphere. As a result, less abrasive particles reach the next stages, resulting in less blade wear.

Change in overall adiabatic compressor efficiency $\eta_{Ct,ad}$. as a function of the engine operating mode is shown in Fig. 7.

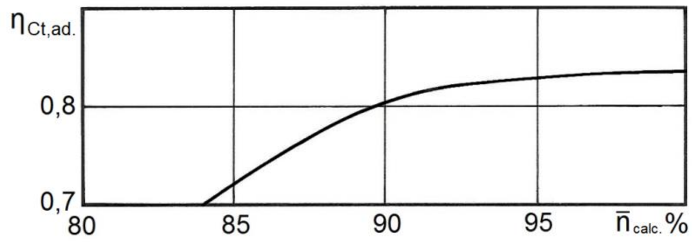

Fig. 7. Change in the total adiabatic efficiency of the axial compressor of the TV3-117 turboshaft engine $\eta_{Ct,ad}$. as a function of the engine operating mode.

The research results in the change of the TV3-117 compressor condition as a function of the number of hours worked in dusty atmosphere conditions, which with the increase of the leaf erosion intensity leads to a shift of the whole compressor characteristic (Fig. 8), as a result of which the overall compressor compression ratio π_{Ct} and the overall compression efficiency η_{Ct} decreases.

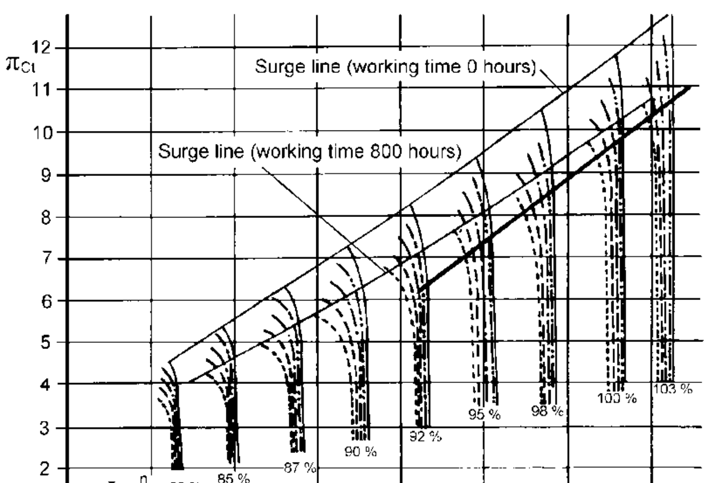

Fig. 8. Characteristics of TV3-117 turboshaft engine compressor with marked changes after working different number of hours in dusty environment.

_____ 0 working hours, _ _ _ _ 200 working hours, _ . _ . _ . _ 400 working hours, _ .. _ .. _ 600 working hours, - - - - - - - 800 working hours

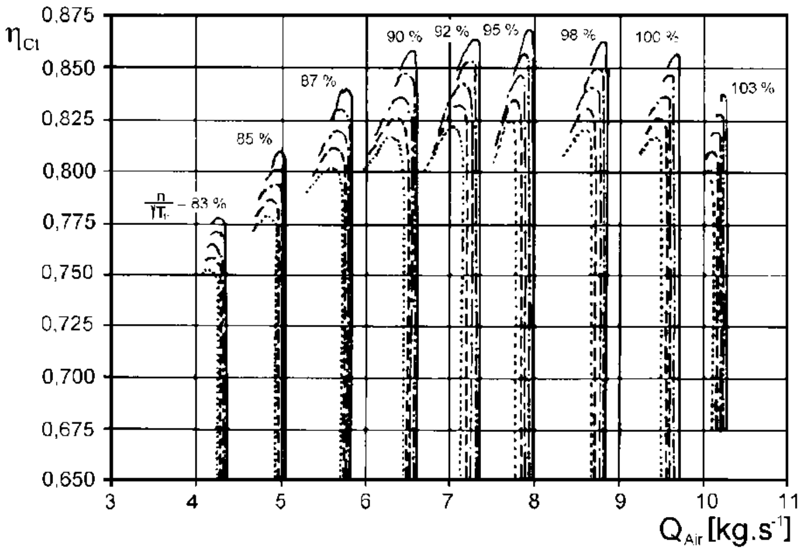

Fig. 9. Characteristics of TV3-117 turboshaft engine compressor with marked changes total compressor efficiencies after working different number of hours in dusty environment. _____ 0 working hours, _ _ _ _ 200 working hours, _ . _ . _ . _ 400 working hours, _ .. _ .. _ 600 working hours, - - - - - - - 800 working hours

It is known that a 15 % reduction in the gasodynamic stability margin of an axial compressor induces the development of unstable compressor operation in bench tests of the TV3-117 turboshaft engine.

Table 3. Change in the gasodynamic stability reserve of the compressor after working different periods of operation

Earned time (hours)	$\frac{n}{\sqrt{T_{1c}}} = 95\ \%$	$\frac{n}{\sqrt{T_{1c}}} = 98\ \%$	$\frac{n}{\sqrt{T_{1c}}} = 100\ \%$	$\frac{n}{\sqrt{T_{1c}}} = 103\ \%$
0	25,25 %	22,14 %	20,58 %	19,10 %
200	21,30 %	18,32 %	16,52 %	15,13 %
400	17,35 %	14,51 %	12,46 %	11,16 %
600	13,39 %	10,69 %	8,39 %	7,18 %
800	9,44 %	6,87 %	4,33 %	3,21 %

In addition to the influence of flow section erosion, damage, erosion, pollution, frost and others, the characteristic of the TV3-117 engine compressor is affected by the angle of adjustment of the engine compressor guide gear. The compressor motor alignment gear enables better coordination of the operation of the individual stages and the achievement of high values of the overall compression efficiency η_{Ct} and the stock of stable work of the axial compressor. Such research requires technical personnel to periodically check the characteristics of the directing gear and achieve their nominal values through control.
For a helicopter turboshaft helicopter turbo-compressor engine operated in dusty atmosphere conditions, one of the current challenges is to evaluate the effect of compressor blade erosion on its gasodynamic characteristics. Its solution, simultaneously with the evaluation of the influence of blade erosion on the vibro frequency characteristics, allows to elaborate recommendations in terms of the compressor blade boundary condition.

To evaluate the influence of dust erosion on the change of the compressor's gasodynamic characteristics, calculations of the air velocity and pressure in the flow section for the nominal (initial) blade geometry, as well as the geometry corresponding to the operating time of the engine in operation during 200, 400, 600 and 800 hours, were carried out. [1]
The results of calculations of the compressor characteristics (Fig. 8., 9.) π_{Kc}, $\eta_{Kc} = f(Q_v)$ from the operating time in dusty atmosphere showed that with the increase of the blade erosion intensity, the overall compression ratio in the compressor and its overall compression efficiency decreases. This implies that the limit of stable operation decreases, while at the same time the stable work margin of turboshaft engine ΔK_y decreases. The steady-state work reserve of the turboshaft engine was calculated according to the relation (1).
The results of the calculation are shown in Table 3.
It is known that a reduction of the compressor's gasodynamic stability margin below 15 % causes the compressor to develop unstable compressor operation (pumping) during bench tests of turboshaft engine TV3-117.
The analysis of the obtained results shows that the investigated compressor reaches its limit state when working in conditions of dusty atmosphere for 730 to 750 hours. The analysis of the absolute current velocity in the peripheral region of the flow area of the compressor with blades having different degree of wear, as well as the absolute current velocity fields at the height of 90 % from the compressor blade root, showed that due to the erosive wear in the peripheral region of the blades 6. Up to the 9th stage of the compressor develops air stream tear-off, which induces the development of unstable compressor operation. The cause of the phenomenon was the reduction of the rotor blade chord and the increase of the radial gap above the blades.

4 Conclusion

Maximum wear of the rotor blades of the axial compressor of the TV3-117 turboshaft engine due to dust erosion occurs at the first and sixth rotor blade stages.
From the point of view of the gas-dynamic stability of the axial compressor of the TV3-117 turboshaft engine, the erosive wear of the rotor blades of the sixth stage of the axial compressor is limiting, which can cause the jet to break off and cause the axial compressor to work unstably. When the bowstring in the peripheral part of the rotor blades is shortened by 6.19 mm, the stock of stable work of the axial compressor decreases by ΔK_y = 15 % to 17 %.
Determination of the limit value of permissible erosive wear of rotor blades of all stages of the TV3-117 turboshaft engine is possible on the basis of the required level of gas-dynamic stability.

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