The use of the finite element calculations to assess the impact of prolonged use on strength reliability of the turbine disk aviation engine

N P Velikanova¹, P G Velikanov², A S Kiselev¹ and S I S Salih¹

¹Tupolev’s Kazan National Research Technical University, 10, Karl Marx St., Kazan, 420111, Russia
²Kazan Federal University, 35, Kremlyovskaya St., Kazan, 420008, Russia

E-mail: pvelikanov@mail.ru

Abstract. Based on the results of the calculation of the turbine disk by the finite element method and on the results of experimental tests of the disk samples from the heat-resistant deformable alloy under pulsing isothermal loading cycle, the effect of long-term operational life on the characteristics of the strength reliability of the disk is evaluated.

Based on the assessment of the stress-strain state and experimental study of low-cycle fatigue of samples from the disc material in the initial state and after long-term operation, the analysis of the effect of long-term operation on the characteristics of the strength reliability of the most loaded turbine disc of the engine TV3-117 is performed.

The object of the study is the first stage of the turbine drive of the TV3-117 for civil helicopter Ka-32. The disc material is a deformable heat-resistant alloy El698-VD Nickel-based.

As a characteristic of strength reliability the reserve on cyclic durability on the parameter of low-cycle fatigue (LCF) was used.

The stress-strain state of the disk was evaluated using the finite element complex "ANSYS", a geometric model for which was built in the system Unigraphics NX9. Twenty-node tetrahedral isoparametric finite elements were used to improve the quality and reliability of the calculation (figure 1-2).
In accordance with the initial data, the model was accompanied by the boundary conditions: the condition of cyclic symmetry of the disk sector in the polar coordinate system; the disk rotation frequency \( n = 19792 \text{ rpm} \) in the mode of cold exit to the maximum speed, the total centrifugal force of the blades (with shelves and legs) \( C = 738.6 \text{ kN} \) was applied on the disk rim; to exclude the case of hard disk movement, the disk was fixed in the hub zone from axial movements (figure 3-4).

As a result of the calculation, the stress-strain state of the disk was determined at the cold output at maximum speed. Figures 5-7 show the isolines of the distribution fields of equivalent elastic stresses by Mises, and figure 8 shows the isolines of the distribution of radial deformations of the disk [1].
The results were compared with the results of calculation by the method of integral equations, and a satisfactory agreement of the results of the calculated data was revealed. Some differences are explained by more detailed consideration of the disk geometry features in the three-dimensional formulation in the finite element calculation.

The results of the calculation were determined by the maximum operating stress $\sigma_{\text{max}} = 679.3 \text{ MPa}$ at a distance of $r = 0.0771 \text{ m}$ from the axis of rotation of the disk. To predict the durability of the turbine disks by the parameter of low-cycle fatigue, empirical dependences can be used, for example, the Manson equation [2] or experimental data on the tests on the LSF of specimens.

In both cases, data on the parameters of cyclic elastic-plastic deformation of the disk are required: maximum $\sigma_{\text{p max}}$ and minimum $\sigma_{\text{p min}}$ plastic stress in the loading cycle, average stress in the cycle $\sigma_{\text{m}}$ and the deformation magnitude $\Delta \varepsilon$.

To determine the parameters of elastic-plastic deformation, it is necessary to construct a schematic diagram of elastic-plastic deformation of the disk material. In this work, a similar chart was built on the recommendations of I. V. Demianushko and Y. M. Temis [3]. As a result, the parameters of the elastic-plastic deformation cycle of the disk material in the region of maximum stresses were obtained:

$$\sigma_{\text{p max}} = 646 \text{ MPa}; \sigma_{\text{p min}} = -57 \text{ MPa}; \sigma_{\text{m}} = 295 \text{ MPa}; \Delta \varepsilon = 0.309 \times 10^{-2}.$$ (1)

Based on the results obtained, it can be concluded that the disk loading cycle in the zone of maximum stresses is close to the pulsating one.

In this work, the results of experimental study of standard cylindrical samples from the alloy EI698-VD with a diameter of the working part of 5 mm were used. Tests were carried out before failure in accordance with GOST 25.502-79 “Methods of mechanical testing of metals” at “soft” axial cyclic loading and two temperature levels – $t_1 = 20^\circ \text{C}$ and $t_2 = 400^\circ \text{C}$ with a pulsating isothermal loading cycle at a frequency of $f = 0.25 \text{ Hz}$.

Statistical analysis of the results of the experimental study found:

- resistance of LCF of EI698-VD alloy is characterized by a set of values of durability Np (durability to crack LCF), satisfactorily approximated logarithmically normal law with different average values of Np depending on the level of stress and test temperature with a constant dispersion of 0.0087 at a temperature $t_1=20^\circ \text{C}$ and 0.061 at a temperature $t_2=400^\circ \text{C}$ at the same level of mechanical properties in the initial state of the material [4-7];

- the resistance of the disc material is influenced by the level of mechanical properties, test temperature and operating time; the characteristics of the cyclic durability dispersion depend only on the test temperature – with an increase in temperature from $t_1=20^\circ \text{C}$ to $t_2=400^\circ \text{C}$, the dispersion increases by 7 times; the average values of durability decrease with the increase in the test temperature, with a decrease in plasticity as the operating time increases, [4-7].
- with a decrease in the ductility characteristics (relative contraction $\psi$ as a percentage of 34%) of samples with an operating time of ~ 5000 loading cycles, the durability of $N_p$ is reduced by 25% [4-7].

According to the results of experimental study of LCF samples from EI698-VD alloy for the new material (without operating time), LCF curves were constructed with the probability of failure $P = 50\%$ for normal $t_1 = 20 \, ^\circ C$ and elevated temperature $t_2 = 400 \, ^\circ C$. Lines of equal probability are constructed by the least squares method and represent regression lines of the form:

$$\lg N_p = a \cdot \lg \sigma_{\text{max}} + \lg b$$

The resulting equations have the form:

$$t_1 = 20 \, ^\circ C \quad \lg N_p = -7.122 \cdot \lg \sigma_{\text{max}} + 25.557$$

$$t_2 = 400 \, ^\circ C \quad \lg N_p = -9.430 \cdot \lg \sigma_{\text{max}} + 31.640$$

According to the equations of the form (3), corrected for the operating temperature of the disk in the hazardous section $t_3 = 280 \, ^\circ C$, we obtain the number of cycles to the formation of a crack in the LCF $N_p \approx 140,000$ cycles for the new disk. When operating ~ 5000 loading cycles, the number of $N_p$ cycles is reduced by 25% and will be $N_p \approx 105000$ loading cycles.

It is known that in one hour of operation of the Ka-32 helicopter 18 loading cycles are realized. Consequently, 5000 loading cycles for the engine in question take place at 277 hours of operating time.

Table 1 provides information about loading and changing the margin of longevity for two levels of operational practices.

| Operating time | Maximum stress $\sigma_{\text{max}}$ MPa | Durability $N_p$ cycle | $K_N = \frac{N_p}{N}$ |
|----------------|------------------------------------------|------------------------|-----------------------|
| cycle          |                                          |                        |                       |
| 1800           | 646                                      | 140000                 | 77                    |
| 5000           | 646                                      | 105000                 | 21                    |

It follows from the above data that for the first 5000 operating times in the loading cycles, the reserve for the cyclic durability of this disk is reduced by 3.7 times.

**Conclusion**

The results of the study show that the design of the turbine disks of aviation GTE should take into account the reduction in the cyclic durability of the disk material as the engine operating time increases.

**References**

[1] Velikanova N P, Velikanov P G and Kiselev A S 2015 Analysis of the resource capabilities of the disk of aviation gas turbine engines for helicopters XX Anniversary international Congress of engine Manufacturers 2 227–231

[2] Menson S 1975 Temperature stresses and low-cycle fatigue (Moscow: Mashinostroenie) 344

[3] Demyanushko I V and Temis Y M 1982 Determination of cyclic durability in the design of rotors of aircraft GTE Problems of strength and dynamics in aircraft engine: SB. articles 2 24–38

[4] Velikanova N P 2009 Statistical analysis of the results of an experimental study of low cycle fatigue resistance of high-temperature alloy EI698-VD Izvestiya vuzov. Aviation equipment 25–28

[5] Velikanova N P 2010 Changing characteristics of reliability for disks of gas turbine during long
operation Aerospace technique and technology 77 (10) 123–125

[6] Velikanova N P, Velikanov P G and Kiselev A S 2012 Influence of operational developments on the short-term mechanical properties of heat-resistant alloys for turbine parts of aviation GTE Proceedings of the XVII international Congress of engine manufacturers. Bulletin of engine building 2 251–253

[7] Velikanova N P 2011 Assessment of the strength reliability of turbine parts of aviation GTE by the parameter of LCF Proceedings of the VI International scientific and technical conference " Problems and prospects of development of aviation, land transport and energy (ANTE-2011)". - Vol. I. 443–447