Forecasting the Durability of the Free Turbine Disk of a Ground-Based Gas Turbine Engines for Gas Pumping Aggregate on a Probabilistic Approach

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Abstract. The method is based on the analysis of the stress-strain state of the free (power) turbine (FT) disk and its change during long-term operation in accordance with the characteristics of the operation of a ground-based gas turbine engines (GTE) for gas pumping aggregate (GPA). In addition, the paper examines statistical data on the mechanical characteristics and durability of the material disk of a FT — a heat-resistant nickel-based alloy EI698-VD. It takes into account the change in the characteristics of the material during the long-term operation of the ground-based GTE for GPA. The durability of the FT disk is predicted based on changes in statistical strength reserves during operation. The object of the study is the FT disk of the NK-16ST, which is currently widely used and has an established assigned resource of 150,000 hours.

1 Page layout

Currently, aviation gas turbine engines, which have spent their flight life, are used to drive gas pumping aggregate, electric generators, gas jet installations, devices for cleaning quarries, snow plows, etc. [1, 2]. Such use of aircraft engines, which have retained the ability for further use, allows you to save materialized labour in science-intensive high-tech products, as well as save expensive materials. At the same time, most of the parts and components of the basic aircraft engine are preserved. These details include disks. Turbine disks of gas turbine engines, both aviation and ground-based, are the most important parts,

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largely determining the possibility of obtaining high operating parameters, service life and safety. The destruction of turbine disks, both in flight and at gas pumping stations, leads, as a rule, to significant destruction inside the power plant. Therefore, the problem of accurately predicting the durability of disks, minimizing the probability of destruction, has always been and remains relevant at all stages of the creation, refinement and operation of engines.

During long-term operation, due to degradation changes (erosion and corrosion of blades, development of seals, contamination and changes in the size of the engine flow), the main parameters of engine operation change, in particular, rotor speeds and gas temperatures in the turbine, which determine the stress-strain state of turbine rotor parts.

Structural materials used in mechanical engineering, including for parts of aviation gas turbine engines, have a scattering of mechanical properties and durability characteristics, both in the initial state and after long-term operation.

The initial characteristics of the scattering of mechanical properties and durability of materials of turbine parts under the influence of deformation and temperature aging occurring during the operation of the engine tend to change, which must be taken into account for the successful solution of the problem of forecasting durability. These arguments determine the need to apply the methods of probability theory and mathematical statistics to assess and predict the durability of critical parts, such as disks.

The object of research in this work is the FT disk of serial single-circuit two-shaft ground-based GTE NK-16ST for the GPA, developed on the basis of converted aircraft engines of the NK-8 family designed by N.D. Kuznetsov. The experience of creating drive units based on an aircraft engine shows that up to about 75% of the components and parts of the base engine can be preserved [1, 2]. Changes are carried out in the nodes associated with the new purpose of the product, the change of the type of fuel used and the appearance of the converted engine FT, which is being created anew.

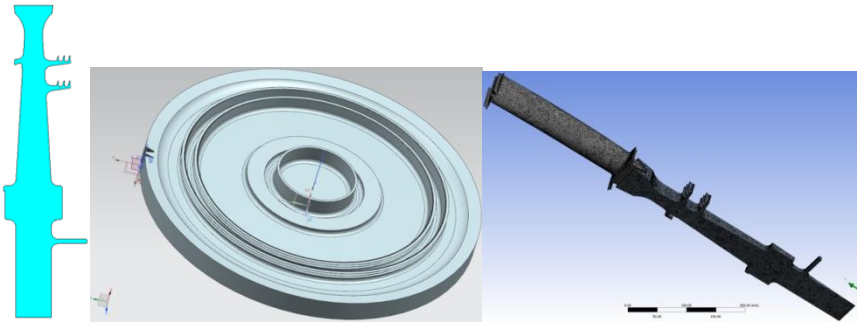
The material of the FT disk, as well as the gas generator turbines, is a heat–resistant nickel-based alloy EI698-VD.

The calculation of the static strength of the FT disk of the NK-16ST engine was carried out using the integral equations method (IEM) and using the finite element method (FEM) in two-dimensional and three-dimensional formulations. The compliance of the results of the calculated study of the stress-strain state of the FT disk with their real load was confirmed by the data of the metallurgical study of the disks after prolonged operation.

For the long-term static loading characteristic of the disks of the engine under consideration, a two-dimensional probabilistic criterion of destruction proposed by I.A. Birger was used.

2 Setting and solving problems

The FT disk, like the rest of the gas generator turbine disks (Fig. 1) of the NK-16ST engine, are made of a deformable heat-resistant nickel-based alloy EI698-VD, belonging to the group of dispersion-hardened alloys.



a) b) c)

Fig. 1. Geometric model of the FT disk: a) a flat model of the FT disk; b) a spatial model of the FT disk; c) a finite element model of the assembly of the FT impeller sector.

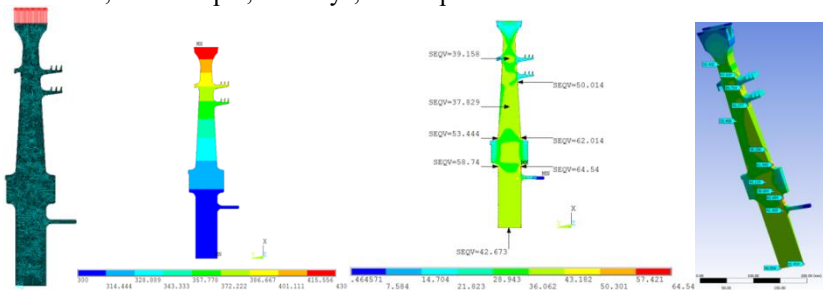
The calculation of the FT disk was carried out for a resource of 200,000 hours with 100% of its use per resource. For calculations, a mode with minimal safety margins is selected.

The calculation of the stress-strain state of FT disk was performed using the integral equations method (IEM) [3, 4] and using the FEM in the Ansys program [5] in two-dimensional (Ansys APDL) and three-dimensional (Ansys Workbench) formulations. The tasks were solved in an elastic-plastic formulation. Isoparametric finite elements (FE) with linear and quadratic approximations of the displacement field within the FE were used to discretize the FT disk region.

Figure 2 shows the results of calculation using FEM in Ansys in two-dimensional (Ansys APDL) and three-dimensional (Ansys Workbench) statements. Table 1 shows the results of calculations using IEM and FEM.

Analysis of the calculations of the FT disk with two methods (IEM and FEM) showed that the qualitative nature of the stress distribution along each section is the same. Quantitatively, the total stresses determined using FEM are higher than the stresses obtained by IEM.

The difference in the calculation results is explained by a more complete account of the operating loads and the complexity of the geometric model in the FEM, which is implemented, for example, in Ansys, in comparison with the IEM.



a) b) c) d)

Fig. 2. a) the FE model of the FT disk with applied loads and fixing; b) The temperature distribution in the FT disk (0C); The intensity of stresses according to the criterion of strength of the Mises-Huber-Genka in the FT disk: c) the FT disk in a two-dimensional formulation (10 MPa); d) the FT disk in a three-dimensional setting (10 MPa).

Table 1. Stresses ($\sigma_r^{max}, \sigma_\varphi^{max}, \sigma_i^{max}$ - radial, circumferential and intensity respectively), strength reserves for local stresses (k_M^{min}) and bearing capacity (k_{b1}^{min}, k_{b2}^{min}) in the FT disk.

Engine	σ_r^{max}	σ_φ^{max}	σ_i^{max}	$k_M^{min}/k_{b1}^{min}/k_{b2}^{min}$

	MPa			-
NK-16ST	436	436	410	2.36/1.7/1.6 ($k_M^{min}/k_{b1}^{min}/k_{b2}^{min}$, IEM)
	737.2	507.3	645.4	1.5 (k_M^{min}, 2D FEM)
	715	644	639	1.52 (k_M^{min}, 2D FEM)*
	718.7	490.2	626.8	1.55 (k_M^{min}, 3D FEM)

*Refined two-dimensional calculation

The correspondence of the results of the calculated study of the stress-strain state of disks with their real load is confirmed by the data of the metallurgical study of disks after prolonged operation [6, 7, 8].

Using regression analysis methods, approximating empirical dependences of the average values of the mechanical properties characteristics on the operating time were obtained for the FT disk.

3 Probabilistic methods for estimating the durability of FT disks

The proposed method for predicting the durability of the FT disk of the NK-16ST engine by the long-term strength parameter is based on statistical information on changes in the loading and resistance characteristics of the FT disk material to prolonged static loading during long-term operation.

For the long-term static loading characteristic of turbine disks, I.A.Birger in [9] proposed a two-dimensional probabilistic criterion of failure:

Pf=ver(σr<σq,τr<τq), (1)

where σr= σlt is the limit of the long–term strength of the disk material; σq= σi is the intensity of the disk stress; τr=τd is the durability of the disk material in hours; τq is the time of loading the disk in operation in hours.

Convert expression (1) to the form:

Pf=ver(σlt/σi<1,τd/τq<1)=ver(K_M^*<1, K_τ^*<1), (2)

where K_M^* and K_τ^* are statistical reserves of strength and durability calculated from statistically extreme values of parameters.

For the FT disk, the expressions for statistical strength and durability reserves are functions of one-sided tolerance coefficients KS1,...,KS4 [10, 11] for the normal distribution, the selected significance levels α and the confidence probability Pc, as well as the sample volume n1,...,n4 and the desired durability value τ:

$$K_M^* = K_M^*(\alpha, P_c, n, \tau) = \frac{\sigma_{lt\min}(\tau)}{\sigma_{i\max}(\tau)} = \frac{\overline{\sigma_{lt\tau}} - K_{S1}(\alpha, P_c, n_1) S_{\sigma_{B\tau}}}{\overline{\sigma_i} + K_{S2}(\alpha, P_c, n_2) S_{\sigma_{i\tau}}}; \quad (3)$$

$$K_\tau^* = K_\tau^*(\alpha, P_c, n, \tau) = \frac{\tau_{d\min}(\tau)}{\tau_{q\max}(\tau)} = \frac{\overline{\tau_{d\tau}} - K_{S3}(\alpha, P_c, n_3) S_{\tau_{d\tau}}}{\overline{\tau_q} + K_{S4}(\alpha, P_c, n_4) S_{\tau_{q\tau}}}, \quad (4)$$

where $\overline{\sigma_{lt\tau}}$, $\overline{\sigma_i}$, $\overline{\tau_{d\tau}}$, $\overline{\tau_q}$ are the average values (limit of long-term strength, equivalent stress, time to failure, loading time, respectively) of the parameters under consideration; $S_{\sigma_{B\tau}}$, $S_{\sigma_{i\tau}}$, $S_{\tau_{d\tau}}$, $S_{\tau_{q\tau}}$ are the average square deviations (limit of long-term strength,

equivalent stress, time to failure, loading time, respectively) of the parameters under consideration.

Then the conditions of destruction in accordance with criteria (3) and (4) can be represented as:

$$K_M^* = \varphi_1(\alpha, P_c, n_1, n_2, \tau) = 1; \quad (5)$$

$$K_\tau^* = \varphi_2(\alpha, P_c, n_3, n_4, \tau) = 1. \quad (6)$$

From the solution of equations (5) and (6) with respect to τ, we obtain two values of durability in hours, from which we take the minimum value.

As a result of the conducted research, the estimated durability of the FT disk from the NK-16ST engine was determined, which turned out to be equal to 204460 hours.

Currently, the NK-16ST gas turbine engine has a resource of 150,000 hours for the GPA. The results obtained in the article indicate the possibility of a significant increase in the resource of this engine.

The proposed method for predicting the durability of turbine parts by the long-term strength parameter based on a probabilistic approach makes it possible to determine the durability of disks of aircraft engines and a gas generator of a ground-based GTE for GPA at any level of operational operating time. The method is applicable to the assessment of an individual resource during operation according to the technical condition [12 – 16].

4 Conclusion

The calculation of the static strength of the FT disk of the NK-16ST engine according to the IEM and using the FEM (in two-dimensional and three-dimensional formulations) was performed. The data of the metallurgical study of disks after long-term operation confirmed the compliance of the results of the calculated study of the stress-strain state of the disk with their real load.

For the long-term static loading characteristic of disks, a two-dimensional probabilistic criterion of destruction proposed by I.A. Birger was used.

As a result of the conducted research, the durability of the FT disk of the NK-16ST engine was determined.

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