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Исследование влияния расстройки параметров на прочностные характеристики элементов турбомашин

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Аннотация. Актуальность исследования обусловлена необходимостью повышения надежности и долговечности паровых турбин, широко используемых в энергетической отрасли. Одним из критических факторов, влияющих на эксплуатационные характеристики турбин, является возникновение и развитие трещин в рабочих лопатках, что может привести к их разрушению и аварийным ситуациям. Дефекты такого рода способны значительно изменить динамические характеристики конструкции, снижая ее ресурс и увеличивая вероятность выхода из строя. Поэтому анализ влияния трещин на вибрационные параметры и прочность лопаток является важной задачей для прогнозирования их надежности и разработки методов диагностики.

В данной статье исследуется влияние трещины на динамические и прочностные характеристики рабочих лопаток паровых турбин. Для исследования выбрано модельное рабочее колесо паровой турбины. Для анализа использовалась конечно-элементная модель в среде ANSYS Workbench. Исследованы собственные частоты и формы колебаний лопаток при различных угловых скоростях вращения, а также влияние трещины различной длины на динамические характеристики конструкции. Результаты анализа показывают, что наличие дефекта приводит к снижению собственных частот колебаний, особенно для низкочастотных форм изгибных колебаний. Кроме того, изучено влияние роста трещины на долговечность лопаток и всего рабочего колеса. Установлено, что увеличение длины трещины значительно сокращает ресурс лопаток, а долговечность рабочего колеса в целом снижается более медленно за счёт взаимодействия лопаток между собой. Полученные результаты могут быть использованы при разработке методик диагностики и прогнозирования ресурса турбомашин, а также для оптимизации их конструкции с целью повышения эксплуатационной надежности.

Ключевые слова: долговечность, рабочие лопатки, турбомашины, трещина, частота собственных колебаний, расстройка параметров.

Investigation of the effect of parameter mistuning on the strength characteristics of turbine elements

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Abstract. The relevance of the study is due to the need to improve the reliability and durability of steam turbines, which are widely used in the energy industry. One of the critical factors affecting the performance of turbines is the occurrence and development of cracks in the blades, which can lead to their destruction and emergency situations. This type of defects can significantly change the dynamic characteristics of a structure, reducing its life and increasing the likelihood of failure. Therefore, analyzing the effect of cracks on the vibration parameters and strength of blades is an important task for predicting their reliability and developing diagnostic methods.

This article examines the effect of cracks on the dynamic and strength characteristics of steam turbine blades. The object of the study is a working wheel made of 304 stainless steel. The finite element model in the ANSYS Workbench environment was used for the analysis. The natural frequencies and vibration mode of the blades at different angular speeds of rotation, as well as the effect of cracks of various lengths on the dynamic characteristics of the structure, are investigated. The analysis results show that the presence of a defect leads to a decrease in natural oscillation frequencies, especially for low-frequency forms of bending vibrations. In addition, the effect of crack growth on the durability of the blades and the entire working wheel has been studied. It has been found that increasing the crack length significantly reduces the life of the blades, and the durability of the working wheel decreases more slowly due to the interaction of the blades with each other. The obtained results can be used in the development of methods for diagnosing and predicting the life of turbomachines, as well as to optimize their design in order to increase operational reliability.

Keywords: durability, working blades, turbomachines, crack, natural frequency, mistuning parameters.

Introduction

Steam turbines are key elements of power plants, providing conversion of thermal energy into mechanical energy. High efficiency and reliability of turbomachinery operation directly depend on the condition of their structural elements, in particular working blades. In the process of operation blades are subjected to significant mechanical loads, as well as to high temperatures and cyclic stresses, which can lead to their damage. One of the most common types of blade damage is the formation of cracks arising under the influence of fatigue loads, erosion and other operational factors. The development of such defects can significantly change the dynamic characteristics of the structure, leading to changes in natural frequencies and vibration forms, as well as to an increase in the probability of accidents. Therefore, the study of the influence of cracks and other damages on the strength and vibration properties of blades is an important task to improve the operational reliability of turbomachines [1; 2].

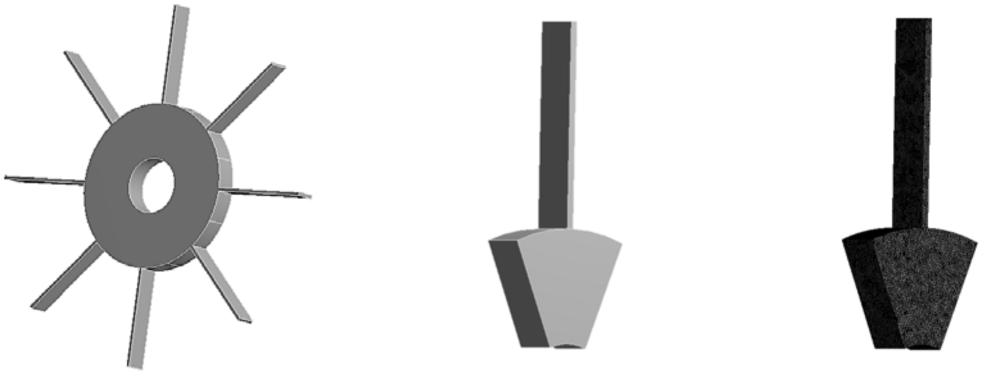
The problem of blade durability and reliability is relevant not only for traditional power engineering, but also for the rocket and space industry. Gas turbine and rocket engines operating under extreme conditions of high temperatures and loads are also subject to fatigue crack development in critical structural elements. The analysis of dynamic characteristics of blades allows to develop more reliable methods of damage prediction, which is especially important for aircraft and space engines, where sudden failure of turbomachinery elements can lead to catastrophic consequences [3; 4].

Modern methods of diagnostics and forecasting of the service life of working blades are based on numerical methods of analysis, among which the finite element method (FEM) occupies one of the leading places. With its help, it is possible to study in detail the stress-strain state (SSS) of a structure, identify critical zones and predict the influence of defects on the dynamic behaviour of blades and their service life [5; 6].

In this paper the influence of cracks of different lengths on dynamic and strength characteristics of steam turbine working blades is investigated. Finite element modelling in ANSYS Workbench environment was used for the analysis, which allows estimating the influence of defects on frequency characteristics and durability of the structure. The results of this study can be used in the development of methods of damage diagnostics and prediction of turbomachinery life, which contributes to the improvement of their operational reliability, life extension and reduction of risks of emergency failures both in power engineering and in rocket-space engineering [7–9].

Problem statement

The object of research of the present work is an impeller blade of a steam turbine. The impeller is made of stainless steel with the following mechanical characteristics: Young's modulus – $1.93 \cdot 10^5$ MPa; density – 7900 kg/m^3; Poisson's ratio – 0.25; tensile strength – 600 MPa, yield strength - 310 MPa, hardness – 170 HB. As a finite element model of this work is used finite element TET10 of commercial programme ANSYS WORKBENCH with 3 degrees of freedom in node and total number of finite elements - 117888 and 176499 nodal points. The number of degrees of freedom is 529497. The three-dimensional model of the impeller and the FEM sector are shown in Fig. 1 [10].



а *б* *в*

Рис. 1. Рабочее колесо модели паровой турбины с 8-ю лопатками:
а – общий вид; *б* – вид одного сектора; *в* – конечно-элементная модель сектора

Fig. 1. The working wheel of a steam turbine model with 8 blades:
а – general view; *б* – view of one sector; *в* – finite element model of the sector

When studying the free oscillation characteristics of the wheel, it is assumed that the wheel has a fixed support in the centre to avoid axial movements during simulation. During the study of dynamic and life characteristics, it is found that the working blades are affected by centrifugal and aerodynamic forces due to rotation and gas pressure. The rotation frequency is 314.159 rad/s and the angular velocity is applied in the axial direction along the hub. A sinusoidal load due to gas pressure acts on the blade surfaces [11]:

$$P = P_0 + P_a \cos(\Omega t), \tag{1}$$

where $P_0 = P_a = 0,05$ (MPa); $\Omega = 314,159$ rad/s. This load $\{F_{dyn}\}$ from equation (4) is modelled additionally and entered into the calculation using ANSYS software.

The static SSS of the structure is determined by the formula [1]:

$$([K_E]+[K_G]+[K_R]).\{\delta\} = \{F_\Omega\}+\{F_T\}+\{F_G\}. \tag{2}$$

The natural frequencies and vibration waveforms of the structure are calculated from equation [1]

$$[M]\{\ddot{\delta}\}+[C]\{\dot{\delta}\}+([K_E]+[K_G]+[K_R]).\{\delta\} = 0. \tag{3}$$

The dynamic response of the structure can be obtained from the expression [1]

$$[M]\{\ddot{\delta}\}+[C]\{\dot{\delta}\}+([K_E]+[K_G]+[K_R])\{\delta\} = \{F_{dyn}\}, \tag{4}$$

where $[K_E]$ and $[M]$ are the main stiffness and mass matrices of the structure; $[K_G]$ is the geometric stiffness matrix; $[K_R]$ is the additional stiffness matrix resulting from rotation; $\{F_\Omega\},\{F_T\},\{F_G\}$ are the vectors corresponding to the forces from rotation, temperature and gas pressure, respectively; $\{C\}$ is the damping matrix; $\{\ddot{\delta}\}$ is the acceleration of nodal points; $\{\dot{\delta}\}$ is the velocity of nodal points; $\{\delta\}$ is the displacement vector; $\{F_{dyn}\}$ is the vector of excitation forces.

The following main numerical methods are used to solve the system of matrix equations: Gauss exclusion method (static SSS); Jacobi method (calculation of natural vibrations); method of mode superposition (calculation of forced vibrations). For the task of predicting the service life of turbomachine impellers, the developed algorithms were combined on the basis of FEM [12-15]. The 'rain method' is used for damage summation, and the fatigue line is formed on the basis of the Palmgren-Miner hypothesis [1].

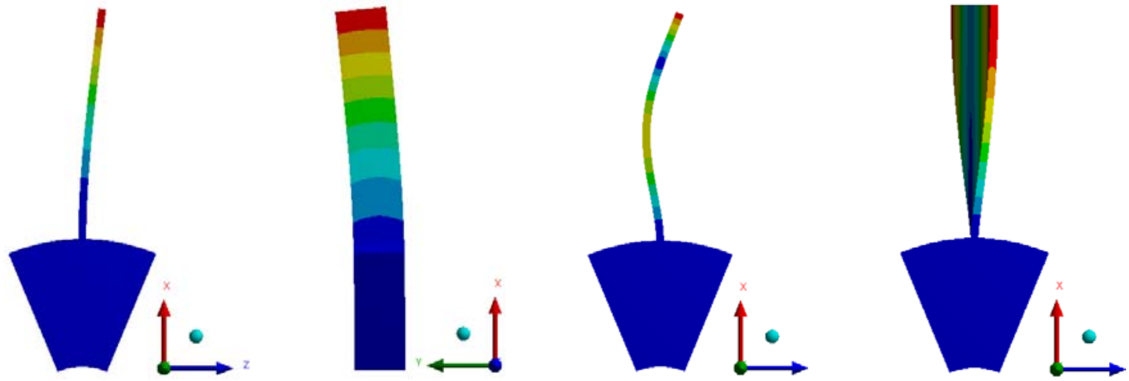
Simulation results

At the first stage, the natural frequencies and modes of vibration of a single blade of the rotor wheel were studied. Fig. 2 shows the modes of vibration of a blade of the turbine rotor wheel. Eight different modes are presented: longitudinal-bending, transverse-bending and torsional. Longitudinal-bending vibrations are manifested in modes 1, 3, 5 and 7, transverse-bending – in modes 2 and 6, and torsional – in modes 4 and 8. These modes of vibration are important for the analysis of the dynamic characteristics of the blade and the assessment of its reliability under operating conditions.

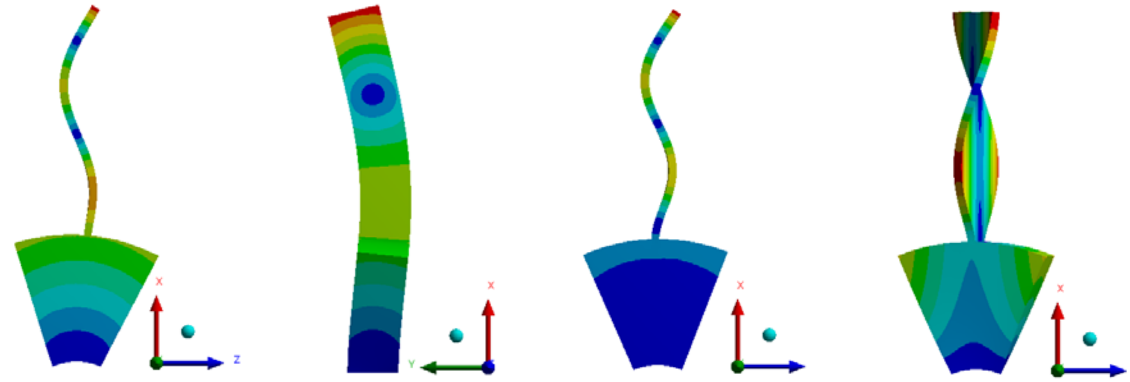
The study of natural frequencies of impeller oscillations at different angular speeds of rotation allows us to identify the effect of rotation on the dynamic behavior of the structure. The results obtained are presented in Table 1. The analysis of the data shows that a change in the rotation speed leads to different effects depending on the oscillation mode. Thus, the frequencies of 1, 3, 5 and 7 oscillation modes remain almost unchanged with an increase in the rotation speed. This indicates a weak dependence of longitudinal-flexural oscillations on centrifugal forces and gyroscopic effects. In modes 2 and 6, characterized by transverse-flexural oscillations, a decrease in frequency is observed. This may be due to a decrease in the rigidity of the structure during transverse bending under the action of centrifugal forces.

Unlike the previous group, some vibration modes demonstrate an increase in frequency with increasing rotation speed. For example, the frequency of mode 4 increases from 2585.7 (at rest) to 4766.6 rad/s at a speed of 1000 rad/s, and mode 8 – from 10216 to 11034 rad/s. This indicates that centrifugal forces significantly increase the effective rigidity of the structure during torsion.

Next, the effect of a crack defect on the natural frequencies of the turbine working blade oscillations was investigated. The location and dimensions of the crack are shown in Fig. 3. Three variants with different crack lengths were considered in the study: variant 1 with a crack length b = 10% a, variant 2 with a crack length b = 20% a, and variant 3 with a crack length b = 30% a, where a is the blade width. In this case, the crack opening width c = 1 mm remains unchanged. The crack is located at a distance of 102 mm from the center of rotation of the disk with blades.



Форма 1 Mode 1 | Форма 2 Mode 2 | Форма 3 Mode 3 | Форма 4 Mode4



Форма 5 Mode 5 | Форма 6 Mode 6 | Форма 7 Mode 7 | Форма 8 Mode 8

Рис. 2. Формы колебаний лопатки рабочего колеса турбины

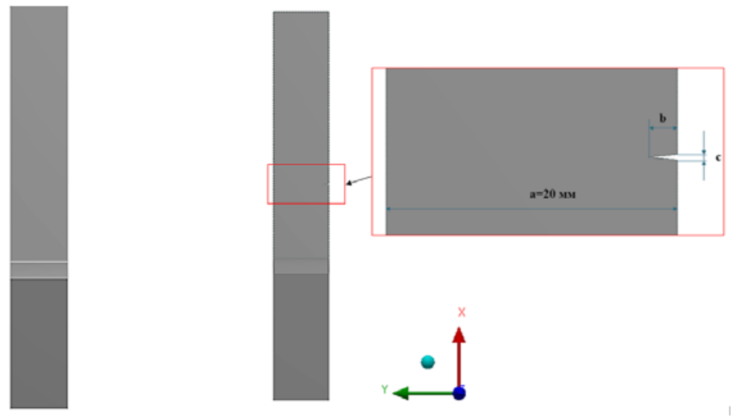
Fig. 2. Vibration mode shapes of the turbine working blade

Table 1

Results of the analysis of natural frequencies of vibrations of a single wheel blade taking into account rotation

Vibration mode	Without rotation	100 rad/s	500 rad/s	1000 rad/s
1	303.1	303.1	303.15	303.15
2	1889.1	1876.3	1438.1	1017.8
3	1918.4	1889.1	1889.1	1889.1
4	2585.7	2643.3	3435.5	4766.6
5	5258.1	5258.1	5258.1	5258.1
6	7915.4	7907.5	7742.0	7425.4
7	10124.0	10136.0	10216.0	10216.0
8	10216.0	10216.0	10392.0	11034.0

The results of the analysis of the natural frequencies of the single blade of the impeller taking into account the presence of a crack are given in Table 2. For all vibration modes, a decrease in frequencies is observed as the crack length increases, which is explained by a decrease in the rigidity of the structure due to a defect. The crack has the greatest effect on low-frequency vibration modes: the first two modes show a significant decrease in frequencies (by 9–10 %). This indicates a high sensitivity of bending vibrations at low frequencies to the presence of a crack. For higher-frequency forms, for example, the sixth and eighth, the decrease in frequencies is less pronounced and is about 1–4 %. This may be due to the fact that with such vibration modes, the zones of greatest stress affect the area of the crack to a lesser extent.



а *б*

Рис. 3. Вид и размер трещины на лопатке:
а – лопатка без трещины; *б* – лопатка с трещиной

Fig. 3. Type and size of the crack on the blade:
а – blade without a crack; *б* – blade with a crack

Table 2

Results of the analysis of the natural vibration frequencies of one wheel blade, taking into account the crack

Vibration mode	Without rotation	Variant 1	Variant 2	Variant 3
1	303.1	300.1	291.64	275.6
2	1889.1	1887.2	1816.8	1698.2
3	1918.4	1892.2	1881.7	1871.8
4	2585.7	2578.8	2552.9	2504.7
5	5258.1	5237.9	5188.1	5113.9
6	7915.4	7912.1	7896.9	7872.4
7	10124.0	10076.0	9933.2	9694.5
8	10216.0	10198.0	10146.0	10048.0

At the next stage of the study, the influence of geometric distortion on the performance characteristics of the impeller blades was examined. To verify the developed and applied FEM and numerical methods, a case of reducing the length of two adjacent blades by 1 mm was analyzed (Fig. 4). The results of the impeller's durability calculation, obtained by the authors using the ANSYS software suite, were compared with results from the ABAQUS software environment, as well as with the analytical solution from Tshwane University of Technology (TUT) [10]. For the analytical assessment of the impeller's durability, the Brown–Miller strain-life equation was used [11]:

$$\frac{\Delta\gamma_{\max}}{2}+\frac{\Delta\varepsilon_n}{2}=1.65\frac{\sigma'_f}{E}(2N_f)^b+1.75\varepsilon'_f(2N_f)^c, \qquad (5)$$

where N_f is the number of cycles to failure; $\Delta\varepsilon_n$ is the nominal stress range for the cycle; $\Delta\gamma_{\max}$ is the maximum range or amplitude of shear strain for the given cycle, $\sigma'_f = 1057$ MPa is the fatigue strength coefficient; b = –0.0385 is the fatigue strength index; ε'_f is the fatigue ductility coefficient; c is the fatigue ductility index (based on the fatigue properties of grade 304 stainless steel).

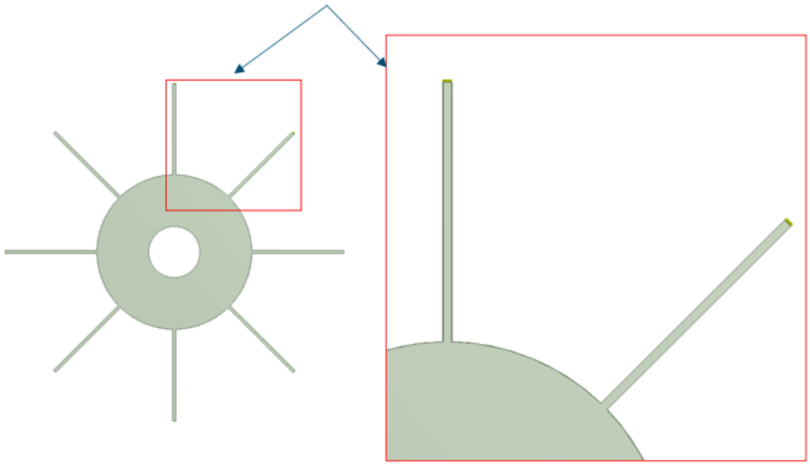


Рис. 4. Геометрия рабочего колеса с уменьшением длины двух соседних лопаток (–1 мм)

Fig. 4. Geometry of the working bladed disc with decreasing length of two adjacent blades (–1 mm)

As the data in Table 3 show, the results of the numerical analysis performed using the authors' approach and ANSYS are in good agreement with the data obtained by other researchers. This agreement confirms the adequacy of the FEM used for calculating the service life of structures and indicates the reliability of the proposed analysis methodology.

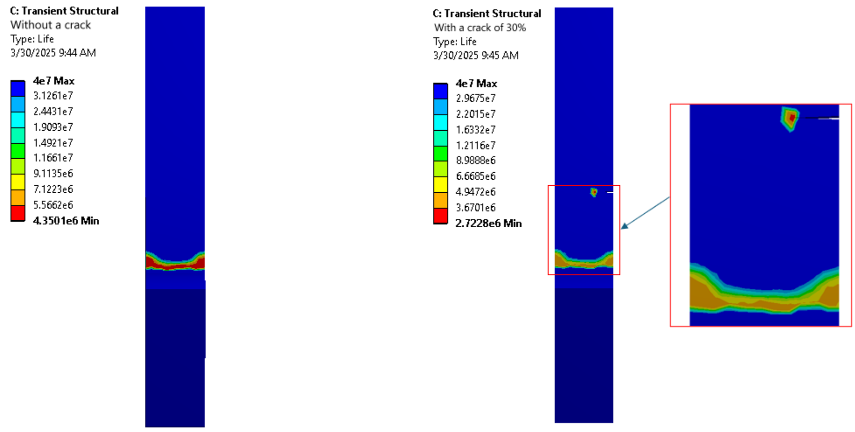
Table 3

Comparison of durability calculation results with numerical data

Type of analysis	Blade disk durability (×10^6 cycles)		
	(ANSYS)	ABAQUS (TUT)	Analitical solution
Perfect structure	4.551	4.587	4.435
Reducing the length of two adjacent blades (by 1 mm)	4.457	4.574	4.357

Based on the verification results of the developed and applied finite element models and numerical methods, the authors extended their application to study the influence of cracks on the service life characteristics of impeller blades. Fig. 5 shows the results of calculating the durability of a single blade without a crack and with a crack of 30 % of the blade width. It is evident that the service life of the working blade significantly decreases when a defect is present. In a blade without a defect, failure occurs at the root, whereas with a crack, the failure zone shifts towards the crack tip. This indicates a redistribution of stresses in the material, where the crack becomes a stress concentration point and the initiation point of failure.

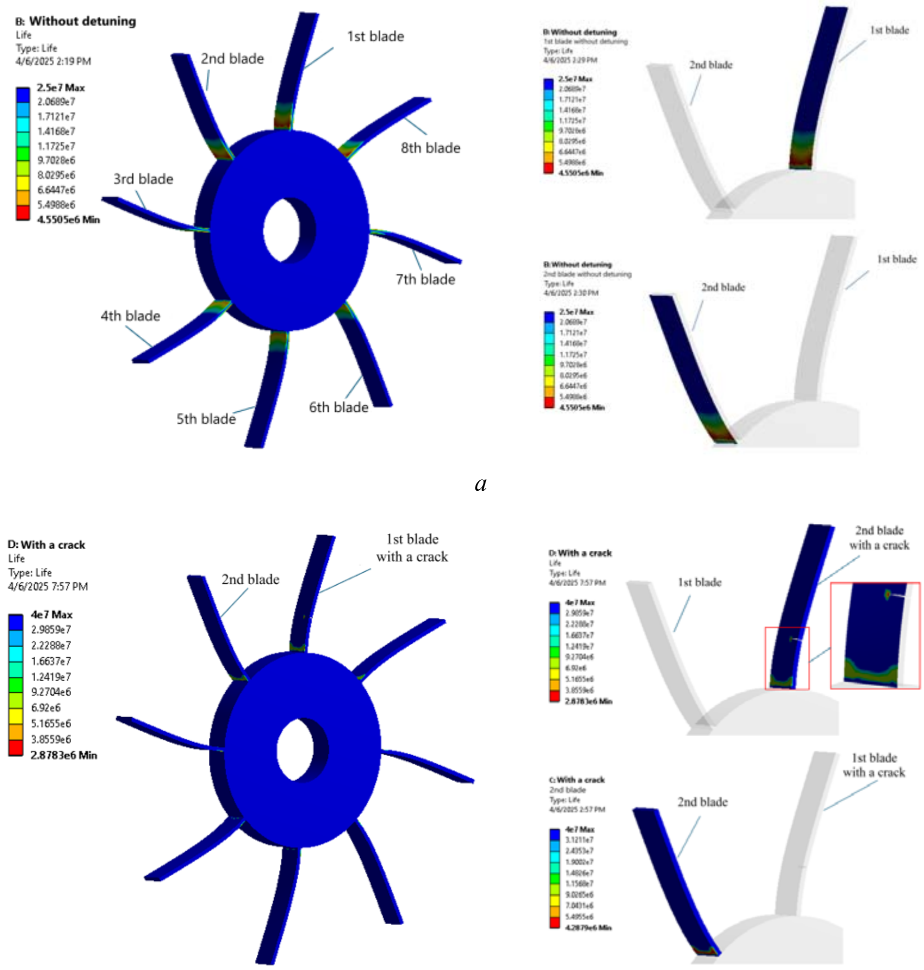
To more fully understand the impact of the crack on the structural performance, the durability indicators of the entire impeller with eight blades were considered, both in the absence of a crack and with a crack on one of the blades. The calculation results are presented in Fig. 6. As can be seen, in the absence of a crack, the durability of all blades is the same, amounting to 4.551 (x10^6 cycles). When a crack is present, the durability of the damaged blade decreases to 2.878 (x10^6 cycles), and it is this blade that fails first. Furthermore, the presence of a crack leads to a slight decrease in the durability of the other blades – within 7–8 %.



а *б*

Рис. 5. Долговечность одной лопатки:
а – лопатка без трещины; *б* – лопатка с трещиной

Fig. 5. Durability of one blade:
a – blade without crack; *б* – blade with crack



а

б

Рис. 6. Долговечность рабочего колеса:
а – колесо без трещины; *б* – колесо с трещиной на одной из лопаток

Fig. 6. Durability of the working wheel:
a – a wheel without a crack; *б* – a wheel with a crack on one of the blades

Next, the influence of crack growth on the service life characteristics of the blades and the impeller was studied. Three variants of crack length changes were considered, as mentioned above, and calculations were performed not only for a single blade but also for the entire impeller structure. The results of the numerical study are presented in Table 4. A comparison of the calculation results for a single blade and the entire impeller structure showed that the durability of the impeller is always higher than that of an individual blade. This is explained by the interaction between the blades and the damping properties of the structure through the disk, which can reduce the dynamic stresses acting on each blade.

Table 4

Durability analysis results for turbine impeller considering crack

Durability of one blade (x10^6 cycles)				Impeller durability (x10^6 cycles)			
Without cracks	Variant 1	Variant 2	Variant 3	Without cracks	Variant 1	Variant 2	Variant 3
4.350	4.175	3.683	2.723	4.551	4.148	3.929	2.878

Data analysis also shows that the durability of both the individual blade and the impeller as a whole decreases with increasing crack length. Moreover, the reduction in the durability of the impeller decreases faster with an increase in the crack, especially when its length is more than 20 % of the blade width. This indicates a high sensitivity of the system to crack growth, which requires early diagnosis and possible replacement of the blades before reaching a critical state.

Conclusion

In the course of the study, the calculations of the fatigue life of highly loaded turbomachine elements were verified and the influence of cracks of various lengths on the dynamic and strength characteristics of the working blades of steam turbines was studied. The numerical simulation using the finite element method allowed us to analyze in detail the changes in the frequency characteristics of the structure depending on the crack length. It was found that the presence of defects leads to a decrease in the natural frequencies of oscillations, especially for bending forms, which can contribute to resonance phenomena and accelerated destruction of the blades.

It was also found that increasing crack length significantly reduces the service life of individual blades, while the durability of the entire rotor decreases less intensively due to the interaction between blades. This highlights the need for timely defect detection and corrective measures.

The obtained results can be used in developing diagnostic techniques and predicting the service life of turbomachinery, which is particularly important for the energy and aerospace industries. In gas turbine and rocket engines operating under high-load conditions, the effect of fatigue damage on structural dynamics plays a key role in ensuring operational safety and reliability. The developed approaches may contribute to improving methods for extending the operational life of turbomachinery, especially when using block models of parameter variation [16].

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