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VIBRATION FEATURES OF TITANIUM ALLOY BLADES WITH EROSIIVE DAMAGES

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This paper deals with erosive damage influence on the vibration features of the working blades of the fifth-stage of the low pressure cylinder (LPC) of a K-1000-60/3000 steam turbine for a nuclear power plant (NPP). The blades are made of the TS5 titanium alloy and have a length of 1,200 mm. Notable erosive damages were observed in the fifth-stage LPC blades after more than 180,000 hours of operation at the Khmelnytska NPP, the greatest danger arising due to the formation of craters and slit-type damages. Such damage causes stress concentration, which leads to a decrease in fatigue and residual life. The radius of the erosive damage front mouth is noticeably larger than that of a fatigue crack. With such damages to the edge-to-edge contact, no damages can be observed. In the course of research, there was developed a finite-element model of a blade having a more condensed grid in the damage area, but a less condensed one in the main volume of the blade. There have been performed multivariate numerical oscillation studies of blades with different numbers of damages, which are located in different places along the blade length in the stress localization zone arising due to the features of vibration forms. There have been revealed the features of stress distribution in damage zones. It has been shown that an increase in the number of damages leads to an increase in the area of increased stresses but does not increase their concentration. There have been considered vibrations of the blades under the load of a conditional value, which made it possible to determine the real vibration stress concentration factors in the damage zones. This allows one to use the experience of analyzing the vibrations of damaged titanium alloy compressor blades. The degree of reduction of the endurance limit of damaged titanium alloy blades has been revealed. Recommendations on preventing damaged K-1000-60/3000 turbine blades from being used have been developed.

Keywords: erosive damage, vibration, blade, resource, titanium alloy.

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Introduction

The blade system of modern turbines is their most responsible and stressed part. Its working blades are under intensive static and dynamic loads. The main danger for a turbine blade system is blade vibrations, which are studied in [1–6]. Damaged blade vibrations, which are of particular interest, are investigated in [1–4].

Erosive damage influence on the vibration features of the working blades of the fifth-degree stage of the low pressure cylinder (LPC) of a K-1000-60/3000 steam turbine for a nuclear power plant (NPP) is considered.

Blades are made of the TS5 titanium alloy and have a length of 1200 mm. During long-term use of the last stages of steam turbines in the wet-steam environment, which is especially characteristic of those in NPP turbines, a noticeable erosion can be observed in the blades. Such erosive damage was observed in the fifth-stage LPC blades after more than 180 thousand hours of operation at SS "Khmelnyska NPP". The greatest danger arises due to the formation of craters and slit-type damages, usually in the upper third parts of the blade leading edges. It is this kind of damages that has been observed on the turbine LPC fifth stage blades. The most intensive dust-like damages along the entire thickness of the blade leading edge have been observed in the working blade No. 74 of the LPC fifth right-flow stage that is part of the turbine used in the power unit No.1 of SS "Khmelnyska NPP". Such damages cause stress concentration, which leads to a decrease in fatigue and residual life. Fortunately, stress concentration in erosive damages is different from that in fatigue cracks. This is due to the fact that the radius in the mouth of the erosive damage front is noticeably larger than that of a fatigue crack. The main danger for damaged blades is vibrations.

Problem Formulation

The blade, whose vibrations are under consideration, is made of the TS5 titanium alloy and has a length of 1200 mm. The G. S. Pisarenko Institute for Problems of Strength of NASU performed a morphological and fractographic analysis of the properties of the titanium alloy of blade in the erosion zone after more than 180 thousand hours of operation.

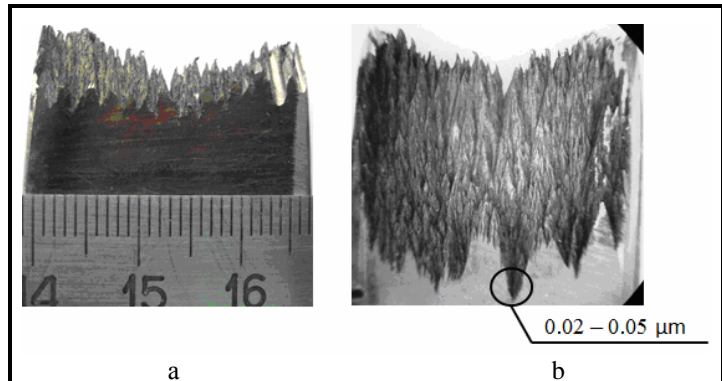


Fig. 1. General view of erosive damage on turbine blade feather sides:

a – rear (left); b – front (right)

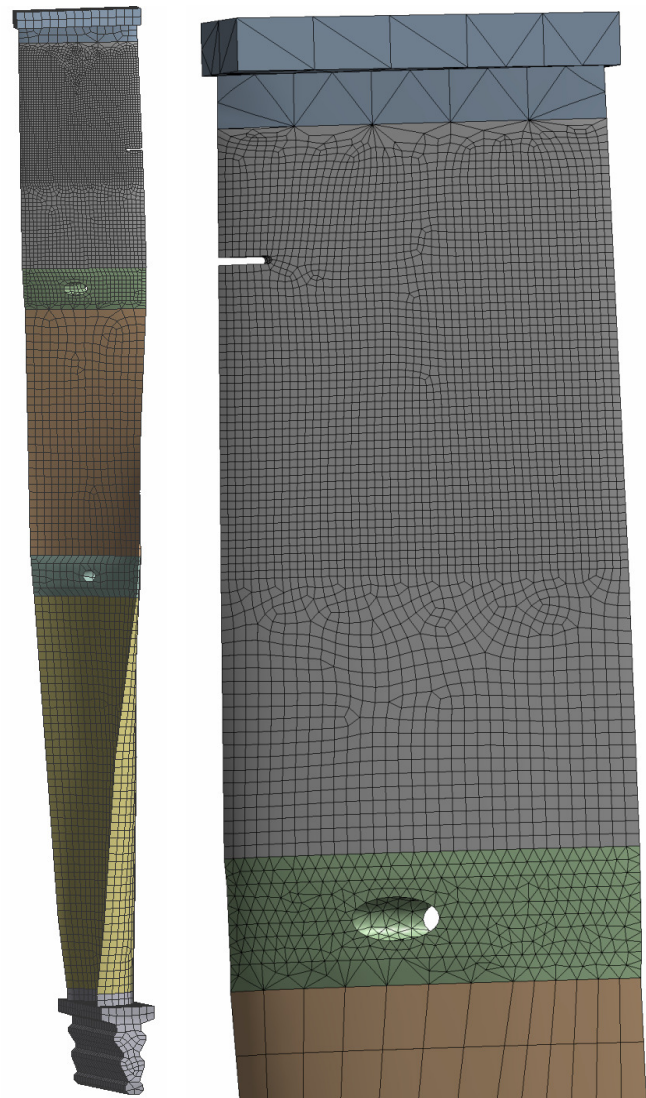


Fig. 2. Finite-element model of a working blade with a more condensed grid in the damage zone

The morphology of erosive damage to the blade contains deep cavities with arrow-like edges in the form of pyramidal elements. In the mouth of the damage, the distances between them are 400–700 microns and the radius of each of them is 0.02–0.05 μm . Under these circumstances, in the erosion zone of one of the blades (No. 74) one could observe originating micro-cracks with a length of 1–2 microns and a thickness of 1 micron. In the mouth of the cavity on another blade (No. 73), no microcracks were observed. Apparently, this is due to the fact that during the long-term operation plastic deformations are localized and microcracks are hampered [7, 8]. The main erosive damages are dust-like (Fig. 1).

With such damages to the edge-to-edge contact, no damages can be observed.

The morphological and fractographic analysis showed that the mechanical properties of the TS5 titanium alloy in the erosion zone in general meet the TR requirements [10]. No degradations of the blade material mechanical properties after 180,000 hours of operation, which should be taken into account in blade models, were not observed. However, erosive damage causes the appearance of stress localization and concentration zones. These damages lead to a change in the material fatigue and residual life.

According to the available data, the damages to the blade body in the mouth of the damage are modeled with blade final-element grid cutouts with a depth of 1–3 mm, width of 1–2 mm, and radius of 0.02–0.05 mm (Fig. 1).

Therefore, there has been developed a blade finite-element model, having a more condensed grid in the damage area, but a less condensed one in the rest of the area (Fig. 2). These changes practically do not affect the forms of stress displacement and distribution in the main volume of the blade, where there are no damages. But in the damage area, the stress distribution has been clarified especially around the mouth of the damage.

Using this model, there have been studied vibrations of the blades with a different number of damages and in different places along the length of the blades in the stress localization zone due to the features of the vibration forms.

Numerical Studies

The frequency variation for the cases with one and two damages has been studied. Table 1 shows frequency variations under the influence of centrifugal forces and in the event of an increase in the number of damages.

Table 1. Blade natural frequency variation taking into account the rotational frequency Ω and the number of damages

No. of vibration form	Rotational frequency of a blade without damages, Hz		Rotational frequency of a blade with damages, Hz	
	$\Omega=0$	$\Omega=50$ Hz	1 damage $\Omega=50$ Hz	2 damages $\Omega=50$ Hz
1	19.06	72.23	70.44	70.43
2	41.13	113.39	111.89	111.87
3	102.89	183.43	182.38	181.89
4	152.26	222.50	220.04	219.95
5	174.37	271.06	267.85	261.66
6	233.04	375.55	372.92	372.35

It should be noted that the blade natural frequency is much more influenced by the action of centrifugal forces than by the change in the number of damages.

Of much more interest is the distribution of vibration stresses as a result of damages. Multivariate numerical vibrational investigations of the blades with a different number of damages, located in different places along the blade length, have been fulfilled.

A series of calculations was carried out to locate damages in the stress localization zone under different vibration forms. The greatest stress localization is observed for the third and sixth forms of vibrations. Thus, Figs. 3 and 4 show vibration forms and how vibration stresses are distributed in the forms with one damage.

In these examples, the stress concentration in the case of damages is located in the stress localization zones under various vibration forms. But real erosive damages are located in groups near each other, so later, the study of blade vibrations was carried out when the blades had different numbers of damages located near each other in the stress localization zone.

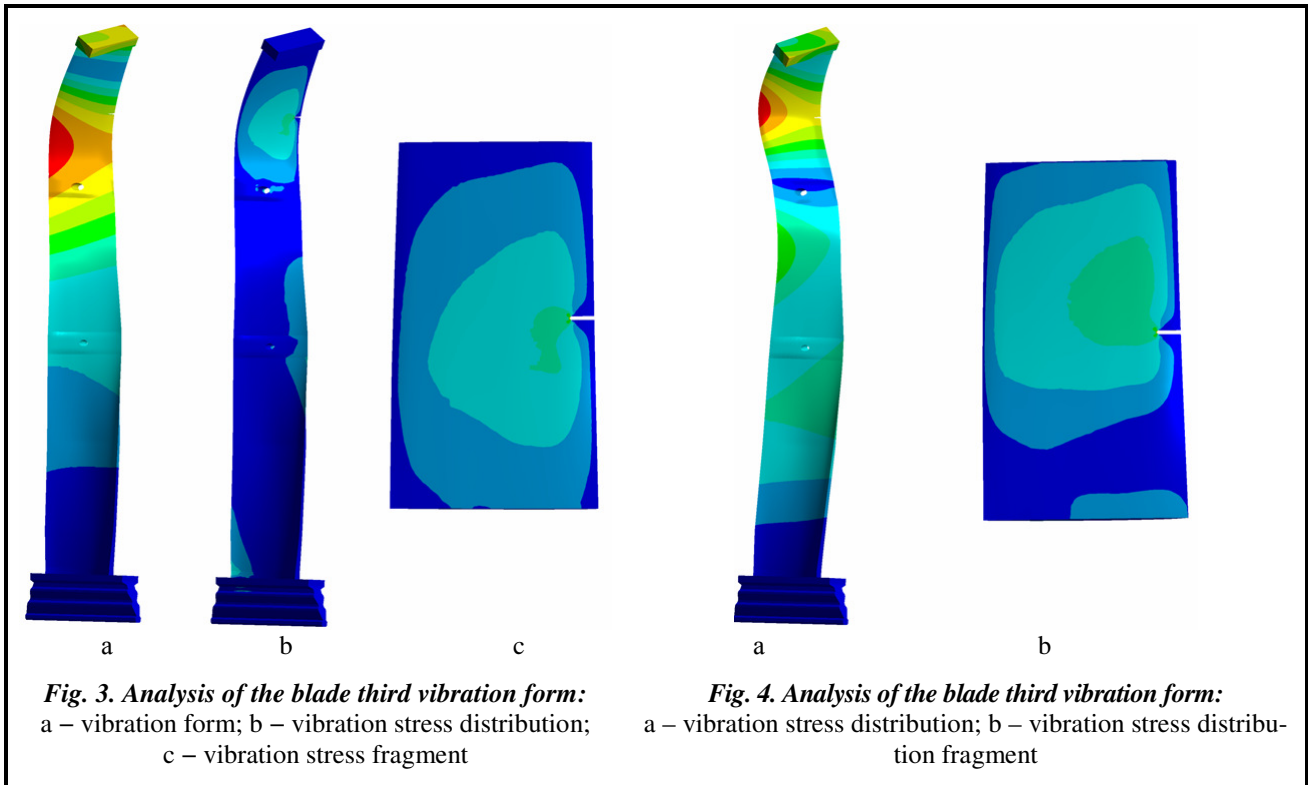


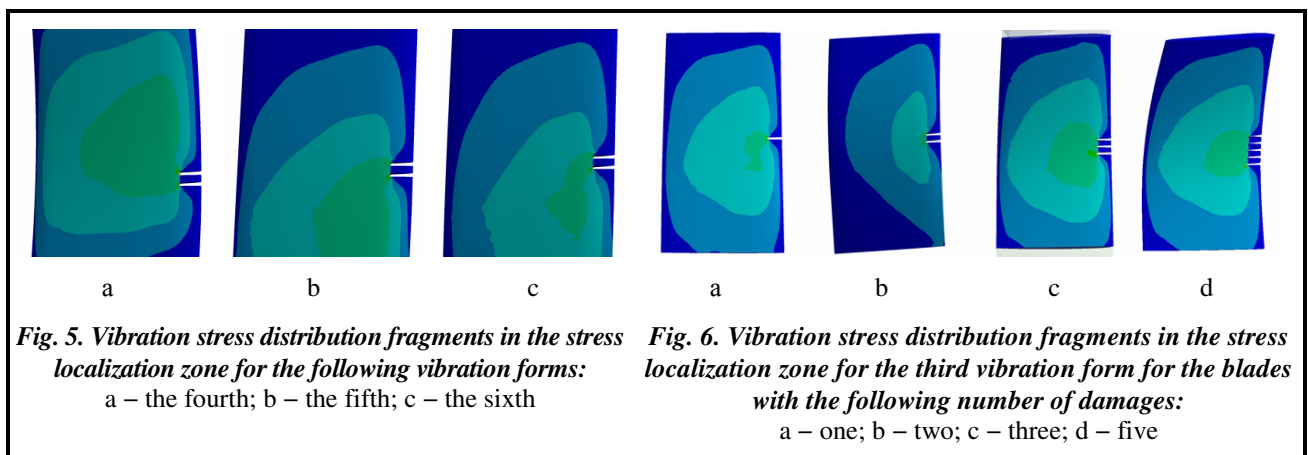
Fig. 5 shows vibration stress distribution for various vibration forms.

Fig. 6 shows the vibration stress distribution for the third vibration form with a different number of damages.

The vibrational investigations of the blades with a different number of damages shows that the increase in their number leads to an increase in the size of the zone of increased stresses in these areas, but does not cause greater stress concentration.

Multivariate vibrational calculations of the blades with different numbers of damages allowed us to obtain a qualitative idea about the regularities of stress concentration in the blades having different vibration forms. But in order to consider the real stress concentration factors, it is necessary to have the forced vibrational blade calculations at least under conditional loads.

Due to the lack of input data during the analysis of forced vibrations, there can be used a conditional load level that acts on the blade when flow fluctuations exist. The impeller blades are under the action of a constant component of the gas-dynamic flow strength and a variable component, which causes blade vibration.



The variable component can be expanded into a harmonic series [3, 4]

$$P(z, t) = \sum_{k=1}^k P_k(z) \sin(k\Omega t + \varphi_k),$$

where $P_k(z)$ are the amplitudes of harmonic components; k is the harmonic component multiplicity factor; Ω is the blade rotational frequency; φ_k is the harmonic component phase.

The amplitudes of the harmonic components of these forces are unknown. They can be estimated only on the basis of available input data. The frequencies of the harmonics that are dangerous can be determined. In the operating mode, there always exists a disturbing force whose frequency is $n=3000$ rpm, which corresponds to the frequency $\Omega=50$ Hz. In addition, the harmonic caused by the guide vanes, has a frequency of nz , where z is the number of guide blades. The frequency of this harmonic is $\omega_z=50 \cdot 42=2,100$ Hz. The amplitude of the harmonic component with the frequency $\omega_1=50$ Hz is taken as a distributed load acting on the blade pressure surface $P_1=1.25 \cdot 10^{-3}$ MPa. The amplitude of the harmonic component with a frequency of $\omega_z=2100$ Hz is taken as the distributed load $P_z=2.47 \cdot 10^{-3}$ MPa.

These loads are conditional, they are taken in order to estimate the ratio of vibration stresses in the blades with and without damages. Vibrational investigations of the blades with one, two and three damages located near the stress localization zone during the action of the harmonic component with frequencies of 50 and 2,100 Hz have been performed. Thus, Figs. 7 and 8 show the location of the vibration stresses in the blades with two damages.

The comparison of the results of studying the blades with different numbers of damages in the area of maximum stresses during the action of the harmonic component at frequencies of 50 and 2100 Hz with the results for the blade without damages indicates that the stress concentration coefficients lie in the range of 1.2 to 3.1.

Based on literature data, there can be determined a reduction in the endurance limit of titanium alloy blades, depending on the relative sizes of the dents and nature of the kinetic curve [7–9]. According to the results of calculations, it is possible to estimate the reduction of the fatigue limit of a titanium alloy blade with erosive damage. If this limit is 450 MPa, then, if the blade has erosive damage, it can drop to 210 MPa. Approximately the same reduction in the fatigue limit is noted in [9].

As a result, the residual life of a blade can be estimated on the basis of the existing assumptions about the stress level in blades [9]. If the maximum vibration stresses do not exceed the fatigue limit, taking into account the damage, then the number of the residual life cycles can be taken to be $N=10^7$.

On the other hand, based on the known data on titanium alloy blade endurance limit [9], an appropriate value of the material endurance limit is selected. Then an estimation of the largest vibration stresses is used. At the same time, there can be taken into account the endurance limit change due to the mechanical treatment of the blade surface. The residual life in such conditions is consistent with the above [9].

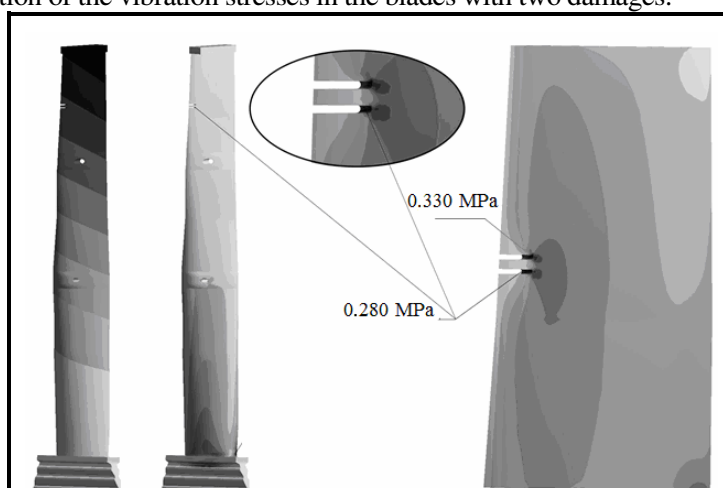


Fig. 7. Distribution of displacements and vibration stresses during the action of the harmonic component with a frequency of 50 Hz

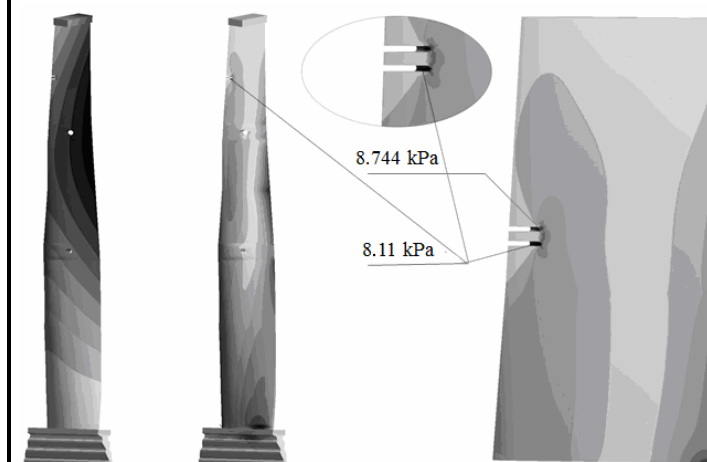


Fig. 8. Distribution of displacements and vibration stresses during the action of the harmonic component with a frequency of 2100 Hz

The results of the vibrational analysis of blades under conditional loads, namely, the determination of the stress concentration factor values within the limits of 1.2 to 3.1, makes it possible to predict the reduction of the margin of blade endurance to 210–240 MPa, which, in turn, limits the residual life of the blades to the number of cycles $N=10^7$.

With erosive damage to the titanium blades, the radius in the mouth of the dent is usually about 0.02–0.05 mm, which also causes stress concentration, but not as large as that resulted from fatigue crack initiation. Under such conditions, the nature of the damage is close to small dents and dust erosion. These types of damages are investigated for titanium alloy compressor blades in more detail in [9]. This makes it possible to use the results of analyzing the influence of damages to the titanium alloy compressor blades on the reduction in the titanium alloy endurance (Table 2).

Table 2. Endurance limit change in the case of damages to titanium alloy blades [9]

Alloy	Dent depth, μm	Endurance limit σ_{-1} , MPa		Endurance limit reduction degree
		original	when blades are damaged	
VTZ-1	300 – 800	320 – 350	140 – 200	1.75 – 2.27
VT8	300 – 500	450 – 520	220 – 238	1.98 – 2.63
VT9	500	520	253	2.05

Similar studies have allowed us to get an idea of the endurance limit change, which, in turn, affects the change in the residual life of titanium alloy blades, depending on the term of use.

According to the results of these studies, it can be assumed that, in order for the blade residual life to reach 107–108 cycles, the stress amplitudes σ_a should not exceed certain values. Such allowable vibration stress amplitudes for compressor blades made of different titanium alloys [9] are: for VTZ-1 $\sigma_a=300$ –350 MPa, for VT8 $\sigma_a=450$ –500 MPa, for VT9 $\sigma_a=500$ –520 MPa.

Common for the fatigue curves for titanium alloy compressor blades is the absence of inflection points up to the number of cycles $N=10^8$. In [9], there are given fatigue curves for VTZ-1, VT8 and VT9 titanium alloy compressor blades for different turbine stages and engines. At the same time, the endurance limit and residual life changes significantly depend on the type of alloys and treatment of surfaces, prone to erosion prior to further exploitation.

One of the types of mechanical treatment is smoothing the damage zone by turning and milling. Even more effective is subsequent grinding and polishing. Table 3 shows data on increase in fatigue limit, providing a residual life of $N=10^8$ cycles during the mechanical treatment of the erosive damage zone for the VT3-1 alloy.

Such an increase in fatigue is observed for alloys with relatively low fatigue values. This is typical of the VT3-1 alloy, which is most vulnerable to fatigue reduction in the case of erosive damage. Even for this alloy, after mechanically treating the damage zone, the fatigue limit rises to 360–450 MPa, which provides a residual life of $N=10^8$ cycles [9].

Table 3. Increase in the fatigue limit σ_{-1} due to the mechanical treatment of the erosive damage zone for the VT3-1 alloy [9]

Fatigue limit σ_{-1} after damage, MPa	Fatigue limit σ_{-1} after damage zone treatment, MPa	Type of mechanical treatment
140 – 200	300 – 310	Turning and milling
	360 – 370	Same + grinding
	450 – 470	Same + polishing, folding or hydroprocessing

The TS5 titanium alloy belongs to pseudo α -alloys. Such alloys have good technological properties, rather high corrosion and erosion resistance. They are also part of a group of alloys with low density and thermal conductivity, and high specific strength. The alloy is also prone to high deformation hardening [7, 8]. Therefore, it has been chosen for the blades of the NPP turbine last stages operating in the wet steam environment.

In the E. O. Paton Electric Welding Institute of NASU there have been taken material samples directly near the damage area of the blade after 180 thousand hours of operation. Those samples have been subjected to static and fatigue tests, using an MTS 810 machine under load amplitudes of 350 MPa. The results of those tests are shown in Table 4.

Table 4. Mechanical properties of the blade material (TS5 alloy) near the damage zone

Nos. of samples	Yield stress $\sigma_{0.2}$, MPa	Ultimate tensile strength σ_b , MPa	Fatigue limit σ_{-1} , MPa	Residual life
1–3	832 – 838	911 – 920	–	–
4–6	–	–	350 – 450	$N > 10^7$

According to the results of the fatigue tests, it was found that for specified load amplitudes after the number of load cycles reached the value of 10^7 , no destruction of samples 4–6 was observed, which means that the fatigue limit $\sigma_{-1} > 350$ MPa. For the purpose of conducting fractographic studies, sample number 6 was destroyed after $N = 6 \cdot 10^7$ load cycles.

Signs of destruction were found after the number of load cycles reached $N > 10^7$. Therefore, even after 180 thousand hours of operation blades have a residual life of $N = 10^7$ cycles, which was also detected as a result of numerical calculations. Thus, different approaches to the assessment of the blade material fatigue limit reduction after the damage, as well as the residual life give the same results.

If after 180 thousand hours of operation turbines are stopped for a preventive inspection, then it is advisable to repair the blades with erosive damage by milling, grinding and subsequent polishing their damage zones.

There can be recommended the following measures to prevent dangerous vibration stresses in the K-1000-60/3000 turbine last stage blades:

- periodic checks of blade and rotor vibration frequencies are to be performed, and in the case of the frequencies deviating from the reference ones by 8–10%, the turbine is to be stopped and the blades are to be required;
- if possible, a check of the evenness of the tension of shroud ties on the rotor periphery is to be performed;
- a check of the quality and possible damages to the rotor damping wire ties is to be performed;
- with over 500 μm deep damages, there is to be performed the damage zone smoothing by milling, grinding and subsequent polishing;
- if possible, the replacement of the set of damaged rotor blades is recommended.

Conclusions

On the basis of the developed three-dimensional blade and rotor models, there has been conducted multivariate vibration studies of blades with different numbers of damages located in different places along their lengths.

1. A finite-element model of the blade having a more condensed grid in the damage area has been developed, and the convergence of results has been checked during the growth of the number of grid nodes, which ensures a greater efficiency of multi-variational numerical calculations.

2. It has been shown that an increase in the number of damages does not lead to an increase in stress localization, but leads only to the expansion of the damage zone.

3. Blade vibrations under the loads of conditional magnitudes have been considered, making it possible to reveal the real vibration stress concentration factors in the places of damage.

The damage and concentration factors have been found to be close to those observed in the case of dust erosion of titanium alloy compressor blades. This makes it possible to use the experience of analyzing the vibrations of titanium alloy compressor blades with damages. A degree of reduction in the endurance limit of titanium alloy blades with damages has been revealed.

4. In the E. O. Paton Electric Welding Institute of NASU on the basis of experimental studies of the material samples of the blades with damages for fatigue endurance at load amplitudes with stresses of 350 MPa, it has been revealed that the blade material residual life is not less than $N = 10^7$ cycles. This confirms the conclusions made on the basis of experience in operating titanium alloy compressor blades with damages.

5. There have been developed recommendations to prevent dangerous operating modes of K-1000-60/3000 turbine blades with damages due to checking the vibration frequencies of blades with possible damages and the mechanical treatment of the damage zone.

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Особливості коливань лопаток з титанового сплаву з ерозійними пошкодженнями

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Розглядається вплив ерозійних пошкоджень на особливості коливань робочих лопаток п'ятого ступеня циліндра низького тиску (ЦНТ) парової турбіни К-1000-60/3000 для атомної електростанції (АЕС). Лопатки виготовлені з титанового сплаву ТС5 і мають довжину 1200 мм. Помітні ерозійні пошкодження спостерігалися в лопатках п'ятого ступеня ЦНТ після відпрацювання понад 180 тис. годин на ВП «Хмельницька АЕС». Найбільша небезпека виникає за рахунок утворення кратерів і щілиноподібних пошкоджень. Такі пошкодження викликають концентрацію напружень, що веде до зниження межі втоми і залишкового ресурсу. Радіус в усті (фронті) ерозійного пошкодження помітно більше, ніж для утомної тріщини. За таких пошкоджень контакту берегів пошкоджень не спостерігається. В процесі досліджень була розроблена скінченноелементна модель лопатки, що має більш густу сітку в області пошкоджень, але менш густу в основному об'ємі лопатки. Виконано багатоваріантні чисельні дослідження коливань лопаток з різною кількістю пошкоджень, які розташовані в різних місцях по довжині лопатки в зоні локалізації напружень, що виникає за рахунок особливостей форм коливань. Виявлено особливості розподілу напружень в зонах пошкоджень. Показано, що збільшення кількості пошкоджень призводить до зростання зони підвищених напружень, але не викликає більшої їх концентрації. Розглянуто коливання лопаток під час дії навантажень умовної величини, що дозволило виявити реальні коефіцієнти концентрації вібраційних напружень в місцях пошкоджень. Це дає можливість використати досвід аналізу коливань компресорних лопаток з титанових сплавів з пошкодженнями. Виявлено ступінь зниження межі витривалості лопаток з титанових сплавів з пошкодженнями. Розроблено рекомендації щодо запобігання небезпечним режимам роботи лопаток турбін К-1000-60/3000 з пошкодженнями.

Ключові слова: ерозійні пошкодження, коливання, лопатка, ресурс, титановий сплав.

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