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EFFECT OF BLADE MATERIAL OF STEAM TURBINE ROTOR ON AEROELASTIC CHARACTERISTICS

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Elements of powerful steam turbines are subjected to significant unsteady loads, in particular the rotor blades of the last stages. These loads, in some cases, can cause self-excited oscillations, which are extremely dangerous and have a negative impact on the efficiency and service life of the blade cascade. Therefore, when designing new or modernizing existing steam turbine stages, it is recommended to study the aeroelastic characteristics of the blades. The conditions for the occurrence of self-excited oscillations are influenced by both the geometric characteristics and the alloy from which the blade is made. To determine the effect of the blade material on the aeroelastic behaviour, a numerical analysis of the aeroelastic characteristics of the last stage blades made of steel and titanium alloy was performed. For the analysis, the method of simultaneous modeling of unsteady gas flow through the blade cascades and elastic vibrations of the blades (coupled problem) was used, which allows obtaining the amplitude-frequency spectrum of the interaction of unsteady loads and blade vibrations. The paper presents the results of numerical analysis for harmonic oscillations with a given amplitude and a given inter-blade phase angle, as well as for the regime of coupled vibration of blades under the action of unsteady aerodynamic forces. The dependences of the aerodamping coefficient on the inter-blade phase angle and the distribution of the coefficient along the blade are presented. The results of modeling the coupled vibration of the blades for the first six natural forms are presented in the form of a time-evolving displacement of the blade peripheral section, as well as forces and moments acting on the peripheral section. The corresponding amplitude-frequency spectra of displacements and loads in the peripheral section are also presented. The analysis of the results showed an insignificant difference in the characteristics of the proposed blade materials. For the first natural form of blade oscillations, the possibility of self-excited oscillations was found, and for the second form, there are conditions for the appearance of stable self-oscillations.

Keywords: *aeroelasticity, flutter, steam turbine, modal method, CFD, fluid-structure interaction.*

Introduction

Turbine blades, regardless of their purpose, are subjected to significant unsteady aerodynamic loads over the entire range of operating conditions. These loads can be caused by non-uniformity of the inlet flow, unsteady flow in the blade channels, and the interaction of blade vibrations and flow. Under certain conditions, self-excited blade oscillations can occur even if the natural frequencies of the blade and flow oscillations do not match. This phenomenon of interaction between flow and blade oscillations in turbomachinery is dangerous and can cause damage, largely affecting the last stages of steam turbines [1–4]. Similar aeroelastic phenomena appear in other blade devices, in particular, in wind turbines [5], fans [6–10], compressors [11–14], etc.

Modeling of aeroelasticity consists in solving the problem of interaction between two physical media (liquid and elastic), i.e., simultaneous integration of the equations of motion of a fluid and an elastic solid. The fastest method is to solve the problem in the frequency domain [15-17]. This method requires linearization of the nonstationary equations of motion of the fluid, so it is effective for cases of small amplitudes of excitations in flows where nonlinearity does not appear (without separation, close to the flow of an inviscid fluid). To take into account the nonlinear effects of the interaction between the fluid and the blade, it is necessary to simultaneously solve the full Navier-Stokes equations of turbulent fluid motion and blade motion with the exchange of data on the boundaries [18–20].

Modern problems of studying aeroelasticity require the development of methods that allow modeling in a wide range of turbomachinery operating conditions. The most promising method for studying the aeroelastic behavior of turbomachinery blades is modeling three-dimensional unsteady flow and modeling blade motion by modal method (coupled aeroelastic problem) [21–22]. This method allows modeling both forced oscillations and self-excited oscillations of the blades, and also makes it possible to identify the conditions for the occurrence of increasing blade oscillations, which can lead to the occurrence of a flutter.

In this work, a mathematical model of viscous gas flow described by a system of unsteady Navier-Stokes equations averaged over Reynolds is used, complemented by the SST turbulence model by Menter [23]. The unsteady motion of the blades is described by a system of differential equations using a modal approach. Numerical modeling was performed using the ANSYS Fluent Academic Edition 19R3 software package with additional in-house developed program modules.

Problem formulation

The described numerical method was used to analyze the aeroelastic behavior of the rotor blade cascade of the last stage of the low-pressure unit of a 1000 MW steam turbine. The rotor blades were studied after improvement using the state-of-the-art method [24], the length of the improved blades increased from 1200 to 1650 mm. A partial study of the aeroelastic characteristics of this rotor has already been conducted, which did not reveal the threat of self-excited oscillations [25]. This study was conducted using the already proven method [26], which is widely used to analyze aeroelasticity in turbomachines.

In the described method, as in [26], the integration of the equations of viscous gas flow (Reynolds-averaged Navier-Stokes equations) and the equations of blade oscillations under the action of unsteady loads (modal method) is performed sequentially at each time step. The study was carried out for the nominal operating mode of the turbine rotor blade with a rotation speed of n=1500 rpm. The primary criterion for blade resistance to flutter is the result of analyzing the characteristics of blade vibration damping under given harmonic vibrations at different inter-blade phase angles.

Fig. 1 shows fragments of the computation mesh in the meridional plane (Fig. 1, a), the tangential plane (root section of the blade, Fig. 1, b, peripheral section of the blade, Fig. 1, c). Each of the segments of the computational domain is discretized using a hybrid deformable H-O mesh.

The operation mode of the turbine blade cascade is characterized by the following distribution of gas-dynamic parameters:

– variable along the radius total pressure and total temperature of the flow at the inlet P_0=14708...19101 Pa; T_0=325...333 K;

– the flow angles in the circumferential (α) and radial (γ) directions are given;

– static pressure behind the cascade variable along the radius P_2=3824...3826 Pa.

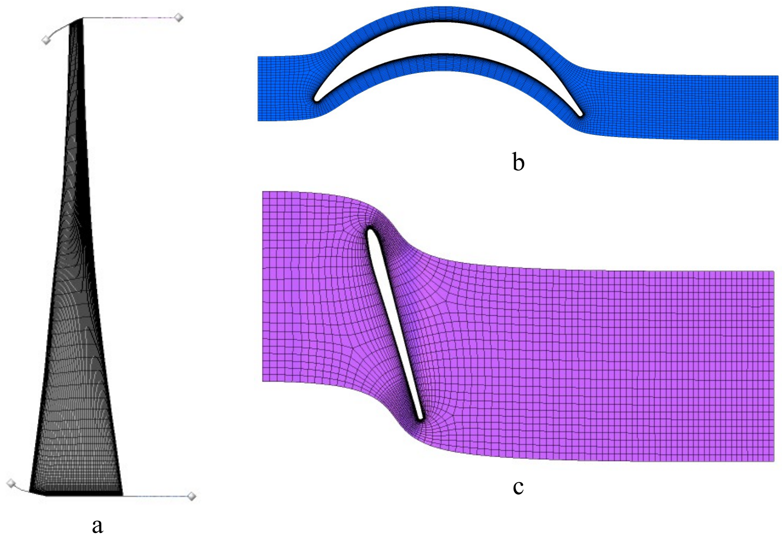


Fig. 1. Fragments of computation mesh:
a – meridional section of computation mesh; b – root section of computation mesh; c – peripheral section of computation mesh

Table 1. Natural frequencies of blade oscillations

Form number	1	2	3	4	5	6
ν_i, Hz, steel	48.04	76.80	158.58	197.93	221.07	290.29
ν_i, Hz, titanium	48.14	76.99	159.07	198.59	219.16	290.90

The natural oscillation forms of the rotor blades were determined using the Pre-Stress Modal algorithm from the ANSYS package. Two variants of blade material were considered: instrumental steel (Young's modulus E=2×10^{11} Pa, Poisson's ratio ν=0.3, and density ρ=7850 kg/m^3) and titanium alloy (Young's modulus E=1.138×10^{11} Pa, Poisson's ratio ν=0.3399, and density ρ=4429 kg/m^3). To model the blade motion using the modal method, the first six natural oscillation modes were taken into account. The values of the blades' natural frequencies are given in Table 1. The difference in the natural frequencies does not exceed 0.8%, and in the natural forms – no more than 1%, depending on the blade material.

Results of numerical analysis

The first task of the study was to determine the aeroelastic characteristics of the rotor according to a given blade vibration law. In this case, the blades perform harmonic oscillations in each of their natural forms separately with a constant inter-blade phase angle (IBPA) δ=0°; 180°; ±90°. A measure of the stability of oscillations to the flutter is the aerodamping coefficient *D*, which is equal to the work of aerodynamic forces with the opposite sign. Positive values of the coefficient correspond to damping of oscillations, and negative values correspond to possible excitation.

Figs. and 3 show the distribution by blade height of the dimensionless aero-damping coefficient *D* for four values of the IBPA for steel and titanium blades, respectively.

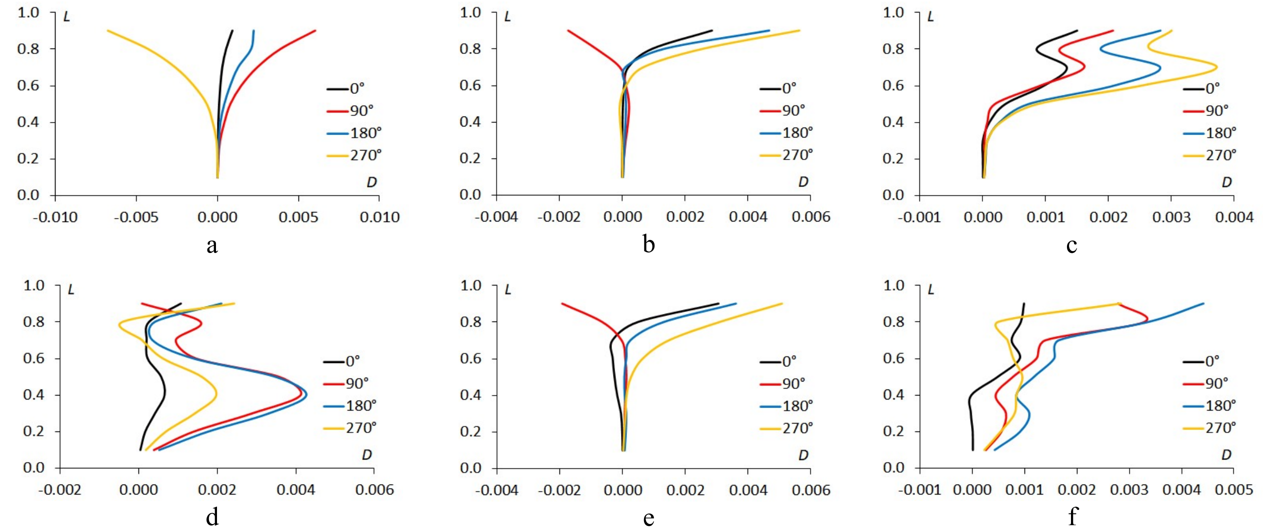


Fig. 2. Variation of aerodamping coefficient by steel blade height for IBPA=0°, 90°, 180°, 270°:
a – 1st form; b – 2nd form; c – 3rd form; d – 4th form; e – 5th form; f – 6th form

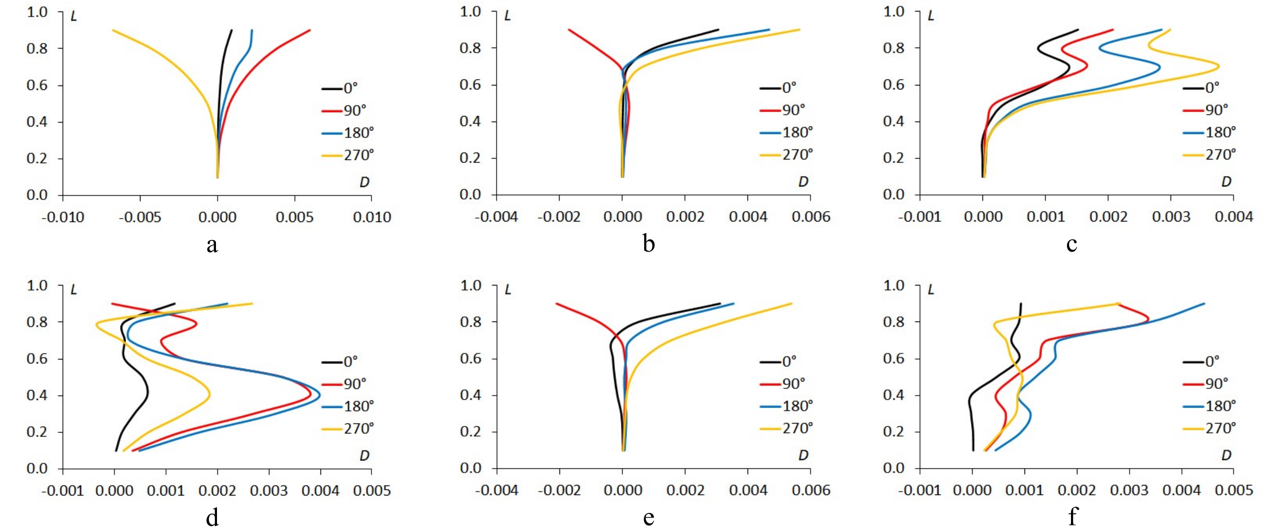


Fig. 3. Variation of aerodamping coefficient by titanium blade height for IBPA = 0°, 90°, 180°, 270°:
a – 1st form; b – 2nd form; c – 3rd form; d – 4th form; e – 5th form; f – 6th form

In most cases, positive values of the aerodamping coefficient are observed, with the exception of form 1 and IBPA=270°, form 2 and IBPA=90°, and form 5 and IBPA=90°. The distribution of work by blade height for steel and titanium is almost the same, as shown in Fig. 4, which shows the dependence of the aerodamping coefficient *D* on the IBPA for the two blade materials simultaneously. These graphs confirm that oscillation damping is mainly observed, with the exception of form 1 and IBPA=270°, form 2 and IBPA=90°, and form 5 and IBPA=90°.

The pattern and values of the aero-damping coefficients are practically the same for steel and titanium. The maximum deviation does not exceed 7% (4th natural form, IBPA=90°, Fig. 4, d).

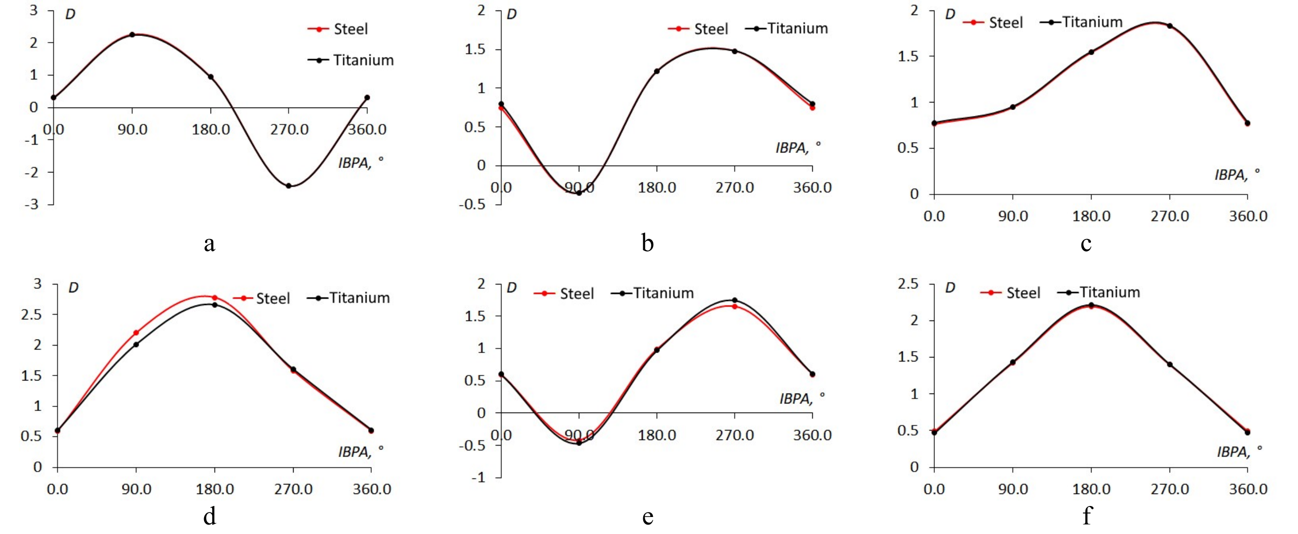


Fig. 4. Comparison of the dependence of the blade height-averaged aerodamping coefficient on the IBPA for steel and titanium blades:
a – 1st form; b – 2nd form; c – 3rd form; d – 4th form; e – 5th form; f – 6th form

The next task of the study was to simulate the coupled oscillations of the blades of the rotor, which takes into account the influence of aerodynamic forces on oscillations and vice versa. The simulation was carried out for a period of 0.4 s, which corresponds to 10 rotor revolutions, with the amplitudes and inter-blade phase angle set at the start, for a titanium blade. To demonstrate the results, three modes were chosen: for the first natural frequency and angles of 90° and 270° (at these angles, the maximum and minimum values of the aero-damping coefficient are observed), and for the second natural frequency and angle of 90°, at which there is a potential probability of self-excited oscillations.

Fig. 5 shows the motion of the blade's peripheral section oscillating according to the first shape and phase angle of 270° and its spectra, and Fig. 6 shows the aerodynamic forces acting on the blade's peripheral section.

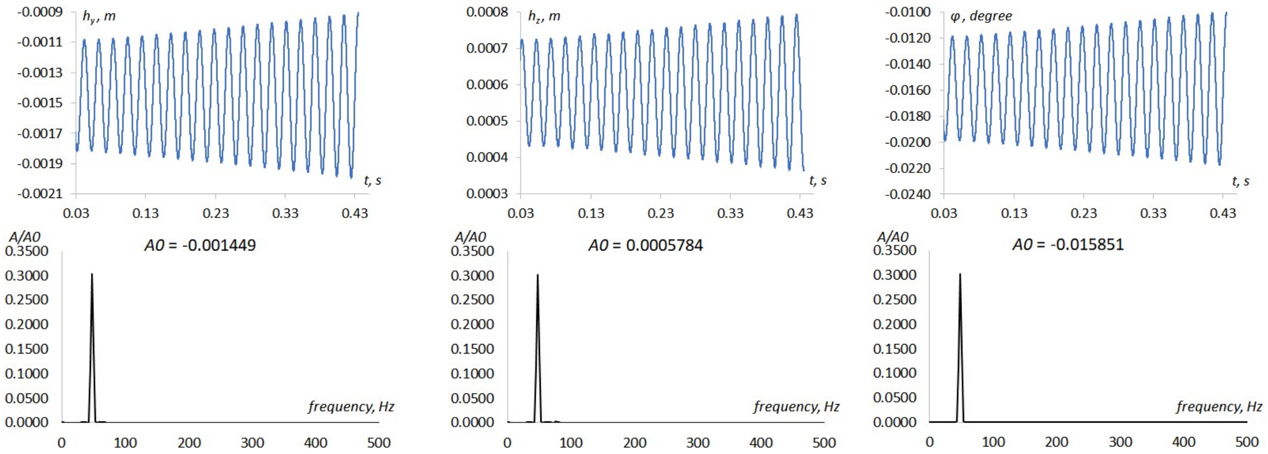
The graphs clearly show an increase in the amplitude of blade oscillations and aerodynamic forces; the first natural frequency dominates the oscillation spectrum, and the first natural frequency and its harmonics dominate the spectrum of forces.

Fig. 7 shows the motion of the peripheral section of the blade oscillating according to the first form and phase angle of 90°, and its spectra, Fig. 8 – the aerodynamic forces acting on the blade's peripheral section during motion.

In this mode, the amplitude of blade oscillations and aerodynamic forces are damped, the first natural frequency dominates the oscillation spectrum, the first natural frequency and its harmonics dominate the force spectrum, and the second natural frequency is also present.

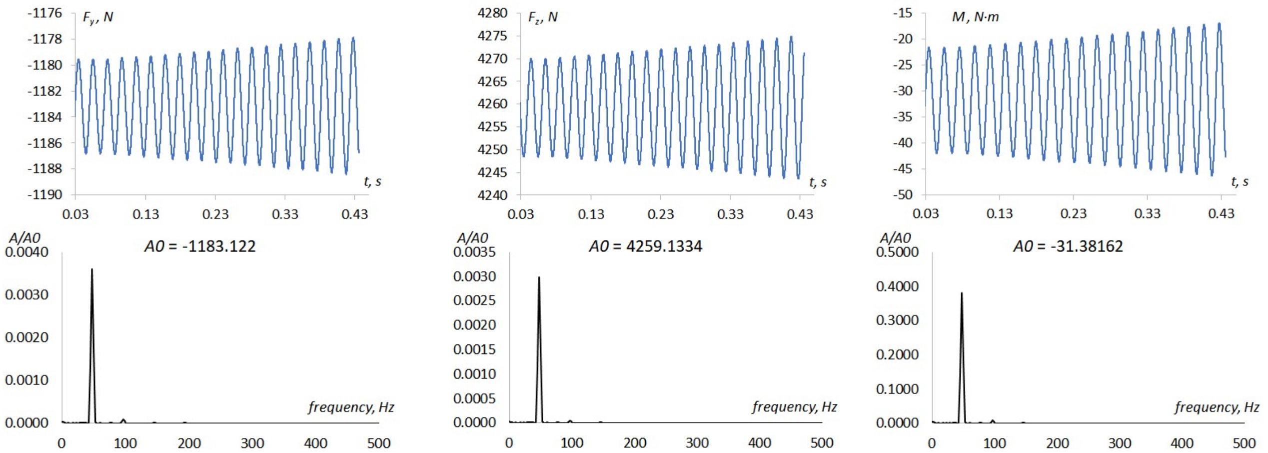
Fig. 9 shows the motion of the peripheral section of the blade oscillating according to the second form and phase angle of 90°, and its spectra, Fig. 10 – the aerodynamic forces acting on the blade's peripheral section.

This mode is characterized by the presence of blade oscillations of constant amplitude; the spectra are dominated by the second natural frequency, but the influence of the first natural frequency and their harmonics is also visible.



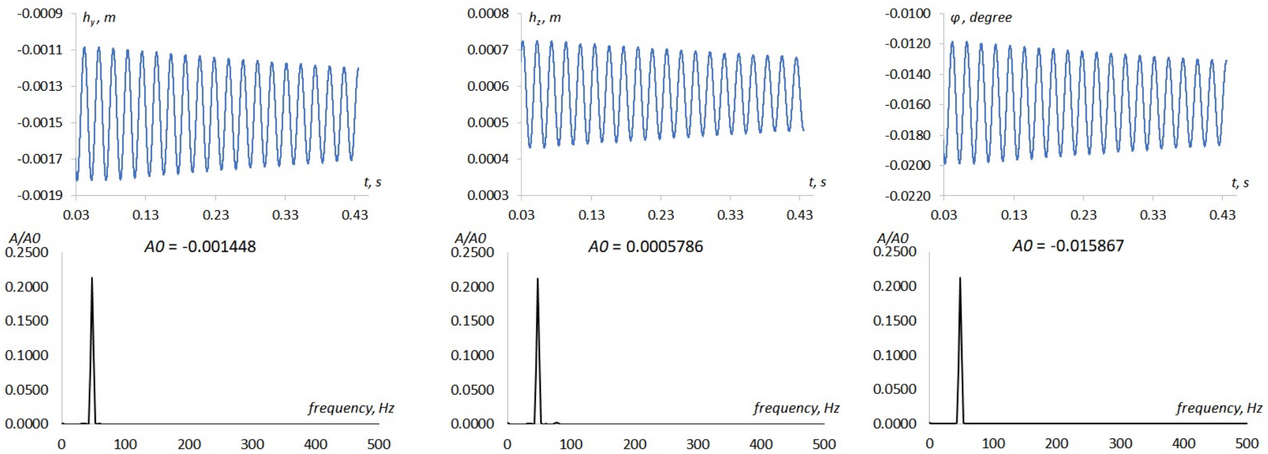
a b c

Fig. 5. Displacement of the peripheral section of the blade in time and its spectra (1st form, IBPA=270°):
a – in the circumferential direction; b – in the axial direction; c – rotation relative to the center of gravity



a b c

Fig. 6. Forces acting on the peripheral section of the blade in time and its spectra (1st form, IBPA=270°):
a – in the circumferential direction; b – in the axial direction; c – moment relative to the center of gravity



a b c

Fig. 7. Displacement of the peripheral section of the blade in time and its spectra (1st form, IBPA=90°):
a – in the circumferential direction; b – in the axial direction; c – rotation relative to the center of gravity

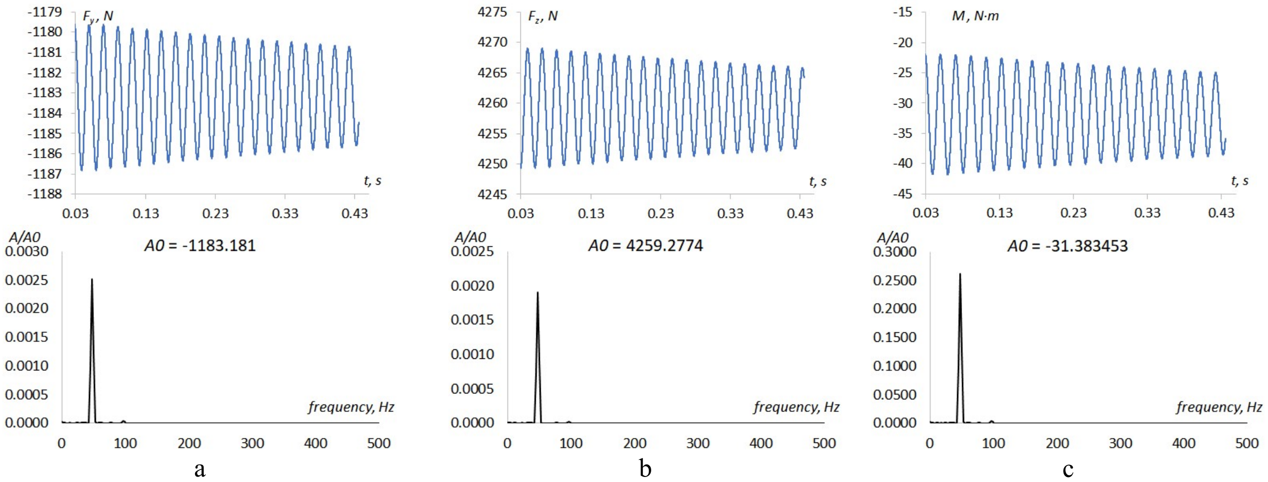


Fig. 8. Forces acting on the peripheral section of the blade in time and its spectra (1st form, IBPA=90°):
a – in the circumferential direction; b – in the axial direction; c – moment relative to the center of gravity

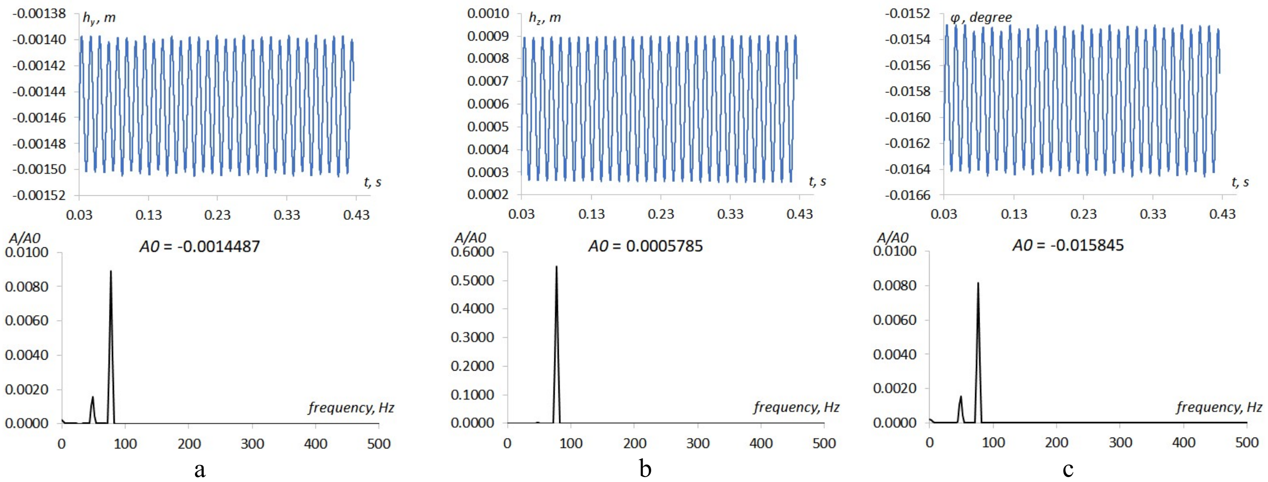


Fig. 9. Displacement of the peripheral section of the blade in time and its spectra (2nd form, IBPA=90°):
a – in the circumferential direction; b – in the axial direction; c – rotation relative to the center of gravity

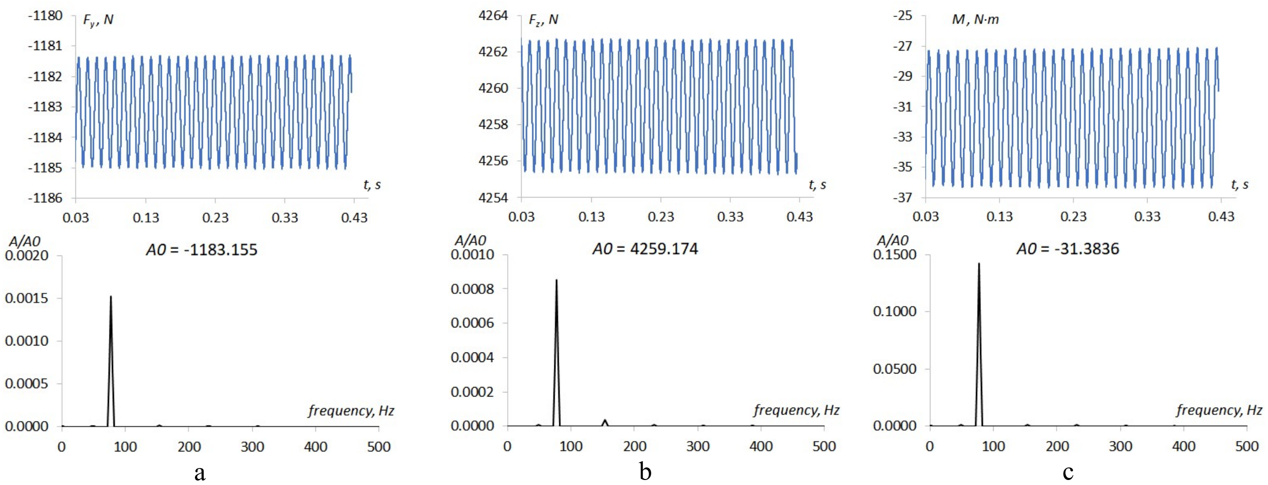


Fig. 10. Forces acting on the peripheral section of the blade in time and its spectra (2nd form, IBPA=90°):
a – in the circumferential direction; b – in the axial direction; c – moment relative to the center of gravity

Thus, for almost all modes of rotor blade oscillations, aerodynamic damping of oscillations was detected, except for the first natural frequency and phase angle of 270°, where an increase in the amplitude of oscillations is observed, and the second natural frequency and phase angle of 90°, where self-oscillations with a constant amplitude are observed. These modes are potentially dangerous during turbine operation, so additional measures should be taken to reduce the oscillations. The measures may include the installation of bandages, tuning of blade natural frequencies, change of blade material, etc.

Conclusions

A numerical study of the influence of blade material on the aeroelastic characteristics of the advanced rotor of the last stage of a powerful 1000 MW steam turbine was carried out. Previous studies for the blades of this turbine made of steel did not reveal the threat of blade flutter. The analysis used a numerical method based on the simultaneous modeling of viscous flow in the turbomachinery cascades and modeling blade vibrations with modal method. The numerical study was performed using the ANSYS Fluent software package. The modeling was performed for the given and coupled oscillations of the blades in a viscous steam flow. The results of the calculations confirmed the damping of blade vibrations in most modes, except for vibrations with the first form and phase angle of 270° and the second form and phase angle of 90°. Comparison of the results for blades made of steel and titanium alloy did not reveal any significant differences that could affect the conditions for the occurrence of self-excited vibrations. To eliminate the modes identified in the analysis, which can excite blade oscillations, it is necessary to improve the blade design, select a different blade material, or adjust the turbine operation mode.

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Вплив матеріалу лопаток ротора парової турбіни на аеропружні характеристики

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Елементи потужних парових турбін, зокрема, лопатки ротора останніх ступенів, зазнають значних нестаціонарних навантажень, які в деяких випадках можуть викликати вкрай небезпечні самозбудні коливання, що негативно впливають на ефективність і ресурс лопаткового апарату. З огляду на це при розробці нових чи модернізації існуючих ступенів парових турбін рекомендовано досліджувати аеропружні характеристики робочих лопаток. На умови виникнення самозбудних коливань впливають як геометричні характеристики, так і сплав, з якого виготовлено лопатку. Для визначення впливу матеріалу лопаток на аеропружну поведінку було проведено числовий аналіз аеропружних характеристик робочих лопаток останнього ступеня, виготовлених із сталевого й титанового сплаву. Для аналізу використано метод одночасного моделювання нестаціонарної течії газу через лопаткові вінці й пружних коливань лопаток (зв'язана задача), який дозволяє отримати амплітудно-частотний спектр взаємодії нестаціонарних навантажень і коливань лопаток. У роботі представлено результати числового аналізу для гармонійних коливань із заданими амплітудою й міжлопатковим фазовим кутом, а також для режиму зв'язаних коливань лопаток під дією нестаціонарних аеродинамічних сил. Наведено залежності коефіцієнта аеродемпфування від міжлопаткового фазового кута і розподіл коефіцієнта вздовж лопатки. Результати моделювання зв'язаних коливань лопаток для шести перших власних форм представлено у вигляді зміни за часом переміщення периферійного перетину лопатки, а також сил і моментів, що діють на периферійний перетин. Наведено відповідні амплітудно-частотні спектри переміщень і навантажень у периферійному перетині. Аналіз результатів показав несуттєву відмінність характеристик від запропонованих матеріалів лопатки. Для першої власної форми коливань лопатки виявлена можливість виникнення самозбудних коливань, для другої форми є умови для появи стійких автоколивань.

***Ключові слова**: аеропружність, флатер, парова турбіна, модальний метод, числова аеродинаміка, взаємодія рідини зі структурою.*

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