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THEORETICAL AND EXPERIMENTAL DETERMINATION OF THE BOUNDARY CONDITIONS INFLUENCE ON GAS TURBINE BLADE VIBRATION CHARACTERISTICS

A description of the stand based on a digital speckle interferometer with a diffuse reference wave and separated branches is given, which allows determining the natural frequencies and vibration modes of objects in real time. In the frequency range 100...4000 Hz, an experimental study of the vibration characteristics of a turbine rotor blade of a gas turbine engine was carried out, with rigid fastening of the blade fir tree part, which was achieved by fixing the blade in the lock and then fixing it in the clamping device. In the frequency range from 100 to 4000 Hz, 9 blade vibration modes were identified. The object of the study is the turbine rotor blade of a gas turbine engine with a height along the trailing edge of 288 mm and a chord in the middle section of 88.5 mm. A solid-state geometric model of a rotor blade based on a faceted body obtained from 3D scanning has been created. Concerning the frequency range 100...4000 Hz, using the ANSYS Workbench software package, a series of calculations of the resonant frequencies of the blade by the finite element method was carried out. Many vibration modes have been obtained, and the data obtained from experiments and calculations have been compared. The analysis of the spectrum of the natural vibration frequencies of the blade showed that the root-mean-square value of the deviations between the results obtained is 5.5% for the same modes. To verify the software calculation, the values of the resonance frequencies were recalculated using a three-dimensional model of the blade fixed in the lock. To determine the influence of the boundary conditions for fixing a gas turbine blade on its vibration characteristics, a series of calculations of the resonance frequencies and vibration modes of the blade model with cutting off a part of the blade at different heights was carried out. It is shown that cutting off the fir tree part of the blade root when modeling the boundary conditions of fixing makes it possible to simplify the calculation process by simplifying the geometry of the three-dimensional model of the blade under study, with a minimum loss of calculation accuracy.

Keywords: *speckle interferometry; GTE blades; finite element method; resonance frequencies; vibration modes.*

Introduction

During the operation of a gas turbine engine, the rotor blades are exposed to time-varying gas-dynamic loads [1, 2]. Since the nature of the change in these forces in time is determined by the rotor speed and the number of structural elements located upstream, they are periodic in nature. The action of these forces causes the scapula to vibrate. When the frequency of the external action coincides with one of the natural frequencies of the blade, resonance occurs, accompanied by an increase in vibration amplitudes and a sharp increase in vibration stresses in the blade.

Resonant vibrations can result in the appearance of cracks, the development of which entails the possibility of blade breakage. The places of origin of fatigue cracks are determined by the lines of the greatest stresses (corresponding to the lines of the greatest curvature) of the oscillating blade [3, 4].

Thus, the determination of the forms and frequencies of natural vibrations allows:

– to determine the resonant modes of the blade;

– to determine the most dangerous places in terms of the appearance of cracks on the profile part of the blade;

– when working out the engine, take measures to detune from dangerous resonance modes.

Natural frequencies and vibration modes of GTE parts are traditionally determined by calculation and experimental methods.

Experimental methods for determining the vibration characteristics of GTE parts are rather conditionally divided into contact and non-contact.

Contact methods are based on the use of so-called «contact» sensors, which have a mechanical connection with the investigated object [5]. These devices are easy to implement, have a relatively low cost and acceptable accuracy. However, this method has significant drawbacks: a sensor fixed on a moving object is subject to mechanical, temperature and other negative influences, which leads to failures and failures in equipment condition monitoring systems; there is no possibility of measuring vibrations of high frequency and low amplitude due to the high inertia of the sensor, which leads to distortion of the signal shape. The indicated disadvantages are devoid of contactless measurement methods.

Non-contact methods are characterized by the absence of mechanical connection with the object, the distance to which or the movement of which they measure, significantly reducing the effect on the measured value [6, 7]. The most common methods for the non-contact determination of vibration characteristics of parts are optical methods.

Optical methods for measuring vibrations include the following: holographic, diffractive, Doppler and interference [6, 8]. Holographic methods have high resolution, but they require complex and expensive equipment. The disadvantage of the diffraction method, as well as the holographic method, is the need for a reference surface. Doppler methods involve the use of laser systems with frequency modulated radiation, which allows you to investigate mainly only polished surfaces and profiles of the correct shape.

The combination of high accuracy and sensitivity at a high measurement speed has led to the widespread use of interference methods, both in research laboratories and in industrial environments. The most common interference method for studying the vibration characteristics of gas turbine engine parts is speckle interferometry [9-14]. Its application allows real-time visualization of the dislocation of nodal lines, i.e. determine the forms and resonance frequencies of the blade vibrations, as well as the distribution of vibration amplitudes over its surface. However, due to the complex geometry of the object under study, a number of problems arise during the experiment:

– the complexity of the experimental reproduction of the boundary conditions for attaching a blade as part of a gas turbine engine, during operation;

– the need for special equipment for the experiment;

– a high amount of time and resources required to organize and conduct an experiment.

In view of the presented features of experimental studies, in the practice of engine building, a direction is intensively developing, focused on determining the vibration characteristics of gas turbine blades by calculation methods [15-20].

At present, the calculation of the vibration characteristics of turbine blades is mainly carried out numerically, using three-dimensional models, using the finite element method (FEM), implemented in modern software systems (ANSYS, SolidWorks, NASTRAN, COSMOS, etc.) [21-27]. The main idea is that the original structure is divided into a number of simple parts-elements, after which the equilibrium equations are described by a system of algebraic equations, which greatly simplifies the calculation procedure. The advantage of this method is that it makes it possible to take into account the geometry of the structure, working conditions, distribution and change in time of external loads, temperature factors, physical properties of structural materials.

At the same time, the accuracy of the calculated data (obtained by the FEM) directly depends on the compliance of the geometry of the investigated blade with the used calculation model, and significantly reduces it in the event of a discrepancy. As a result, to ensure the accuracy of the calculation, a geometric model is required, created by 3D scanning the dimensions of a real blade, which increases the complexity of developing a three-dimensional model.

1. Formulation of the problem

At the same time, the accuracy of the calculated data (obtained by the FEM) directly depends on the compliance of the geometry of the investigated blade with the used calculation model, and significantly reduces it in the event of a discrepancy. As a result, to ensure the accuracy of the calculation, a geometric model is required, created by 3D scanning the dimensions of a real blade, which increases the complexity of developing a three-dimensional model.

The aim of this work is to determine the influence of the boundary conditions for fixing the model of a gas turbine rotor blade to determine its vibration characteristics using a geometric solid-state parametric model created on the basis of 3D scanning of a real blade.

2. Methodology of experimental studies of oscillations of turbine blades

2.1. Description of the experimental stand

In the process of experimental determination of the vibration characteristics of the blade, an experimental stand was used, operating on the basis of the digital speckle interferometry method, with a diffuse reference wave and separate propagation channels of the reference and object beams (Fig. 1) [28, 29].

The source of coherent light is a diode-pumped solid-state laser 1 (DPSS) with a radiation power of 50 mW and a wavelength of $\lambda = 0.532$ μm. With the help of a microlens 2, the laser beam is expanded and divided by a beam splitter 3 into transmitted and reflected. The transmitted beam illuminates the surface of the blade 4, which is cantilevered in the clamping device 5, is scattered by its surface, and forms a diffuse object wave.

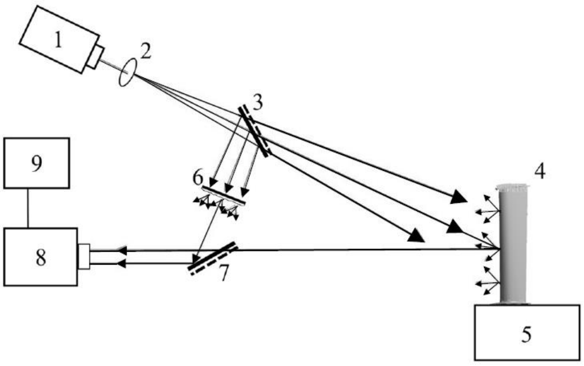


Fig. 1. Optical layout of the experimental stand:
1 – laser; 2 – micro lens; 3, 7 – beam splitters;
4 – the investigated blade; 5 – clamping device;
6 – transmissive diffuser; 8 – video camera;
9 – personal computer

Vibration excitation of the blade is carried out through the lock by a piezoceramic vibration transducer, to which a sinusoidal signal of the sound generator is fed, amplified by a low-frequency amplifier. The light beam reflected by the beam splitter 3 is scattered by the transmission diffuser 6 and creates a diffuse reference wave. The object and reference beams, combined by the beam splitter 7 and the camera lens 8, form the resulting speckle field - a specklogram on the light-sensitive matrix. With resonant vibration, it encodes an interferogram of the vibrational shape of the blade, which is decoded on a computer 9 using the method for determining the dynamic pattern of speckles [30].

A detailed description of the scheme of the experimental stand, as well as the method of obtaining and processing holograms, are presented in [28, 31].

2.2. Experimental boundary conditions

A turbine blade of a gas turbine engine was chosen as the object of research; blade dimensions: height along the trailing edge - 288 mm, chord in the middle section - 88.5 mm. The experimental determination of the vibration characteristics was carried out with a clamped of the blade fir tree part. For this, the blade was installed in the lock (Fig. 2, a), after which it was fixed in the clamping device along the outer surfaces of the lock body (Fig. 2, b).

2.3. Experimental determination of natural frequencies and vibration modes of a blade

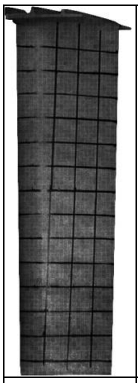
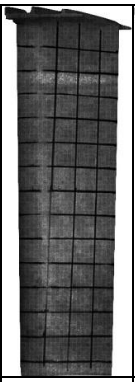
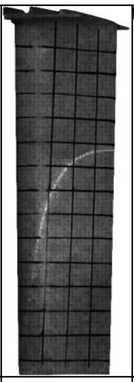
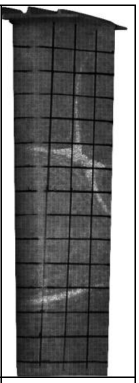
The resonant frequencies and vibration modes of the blade obtained experimentally are presented in table 1. The boundary conditions of the experiment are described in Section 2.2.

a b

Fig. 2. Scheme of placement and fastening of the blade:
a – the location of the blade in the lock; b – installation of the blade in the clamping device

Table 1

Some experimental forms and frequencies
of a cantilevered blade oscillations

			
165 Hz	805 Hz	1706 Hz	2844 Hz

2.4. Construction of the geometric model of the blade

To determine the vibration characteristics of a particular blade under study, its solid-state geometric model was created based on 3D scanning. On the basis of the faceted body obtained during scanning (Fig. 3, a), in the environment of the Siemens NX computer-aided design system, using the «Reverse engineering» functions, along sections (Fig. 3, b), a 3D model of the blade was developed (Fig. 3, c) [32].

3. Influence of the method of fixing the blade lock on its vibration characteristics

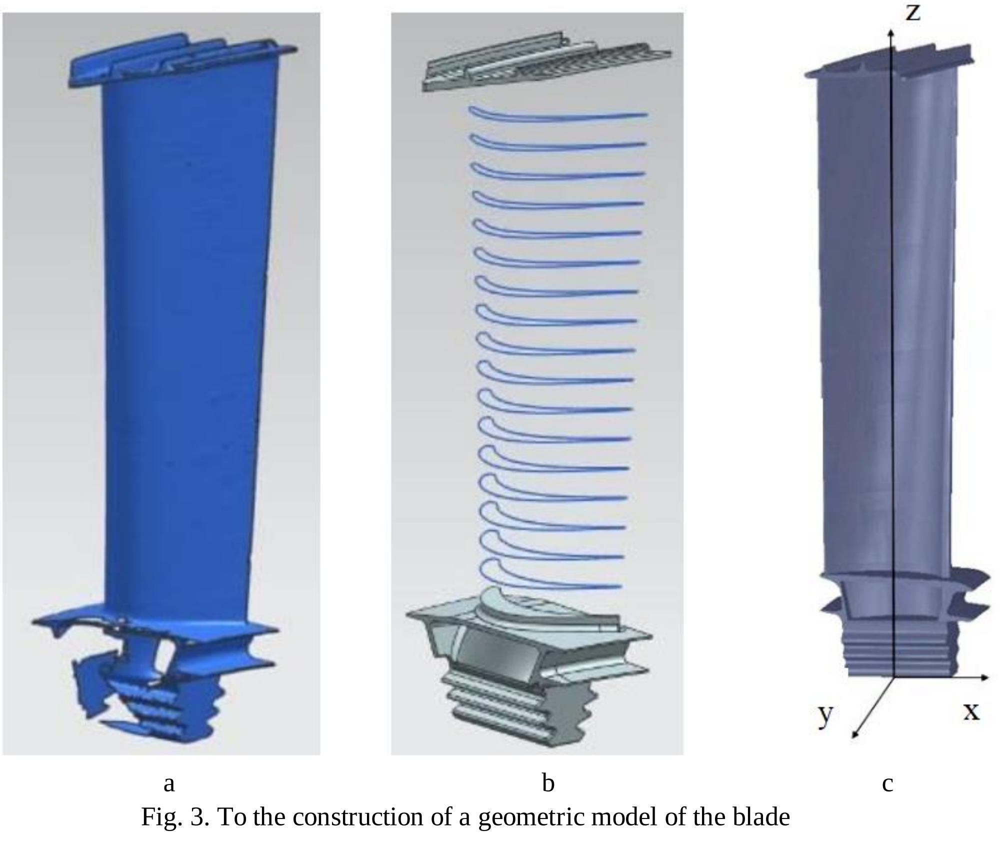
Resonant frequencies and vibration modes of the investigated blade model are obtained by the finite element method implemented in the ANSYS Workbench software package. The boundary conditions are cantilever fastening of the blade root part (Fig. 4a), which corresponds to the conditions of the blade fastening to the experimental stand described in Section 2.2.

The properties of the material are determined by achieving the minimum root-mean-square deviation of the calculated values of the resonant vibration frequencies of the blade from the experimental data under free boundary conditions: ρ - 7830 kg/m^3; μ - 0.3; E - 215 GPa [32].

In the course of the calculation, a finite element SOLID 187 (tetrahedron) was used, the element height was 0.6 mm. The number of elements was ~ 1.5 million (Fig. 4b). Calculations carried out with a twofold decrease in the finite element showed an insignificant deviation (less than 1%) of the obtained values of the resonant vibration frequencies for the studied blade model.

Some characteristic frequencies and vibration modes of the blade model are shown in Fig. 5.

A comparison of the values of the resonant frequencies of the investigated blade, obtained experimentally and by calculation, is given in Tabl. 2.



a b c

Fig. 3. To the construction of a geometric model of the blade

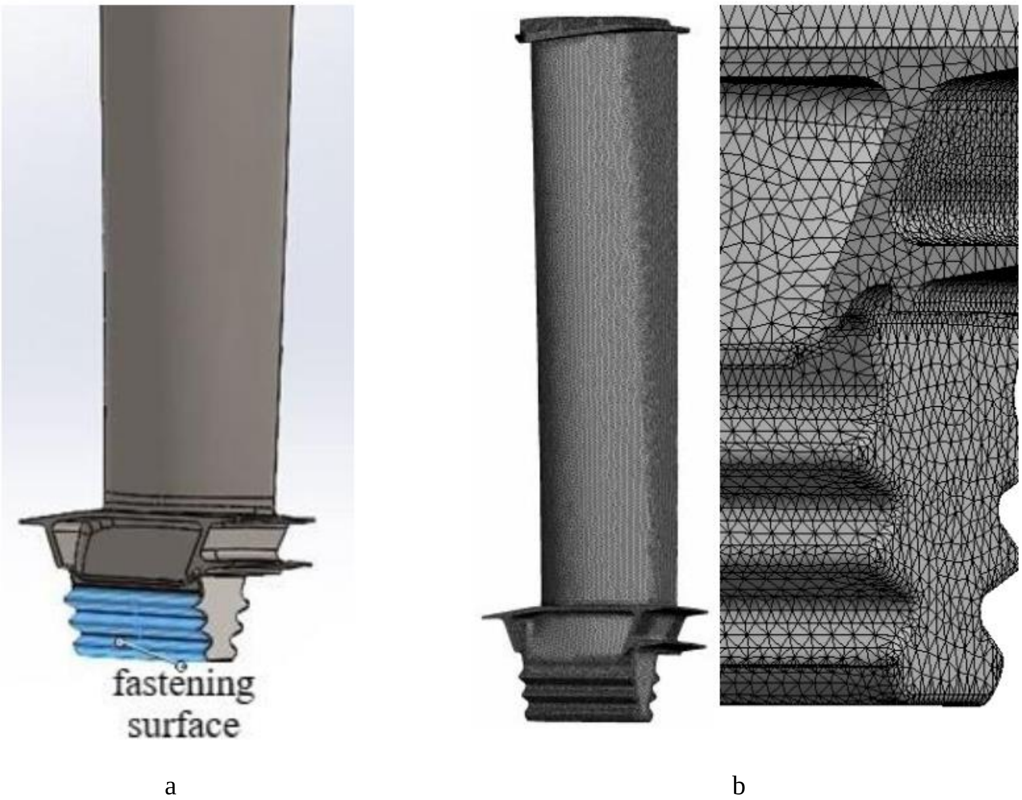


Fig. 4. To the calculation of the vibration characteristics of the blade:
a – the boundary conditions for the attachment of the blade;
b – scheme of splitting the blade model into tetrahedrons

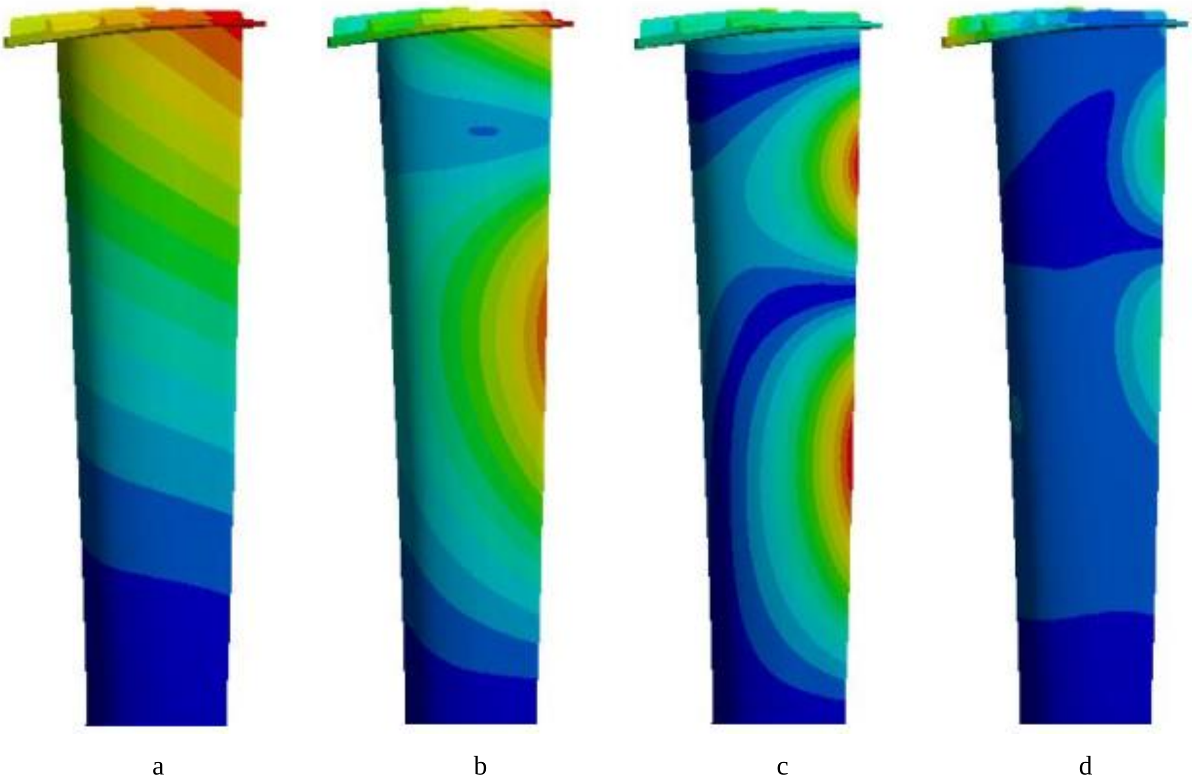


Fig. 5. Some calculated vibration modes and resonance frequencies of a cantilevered blade:
a – 179,66 Hz; b – 856,04 Hz; c – 1712,4 Hz; d – 2843,7 Hz

Table 2

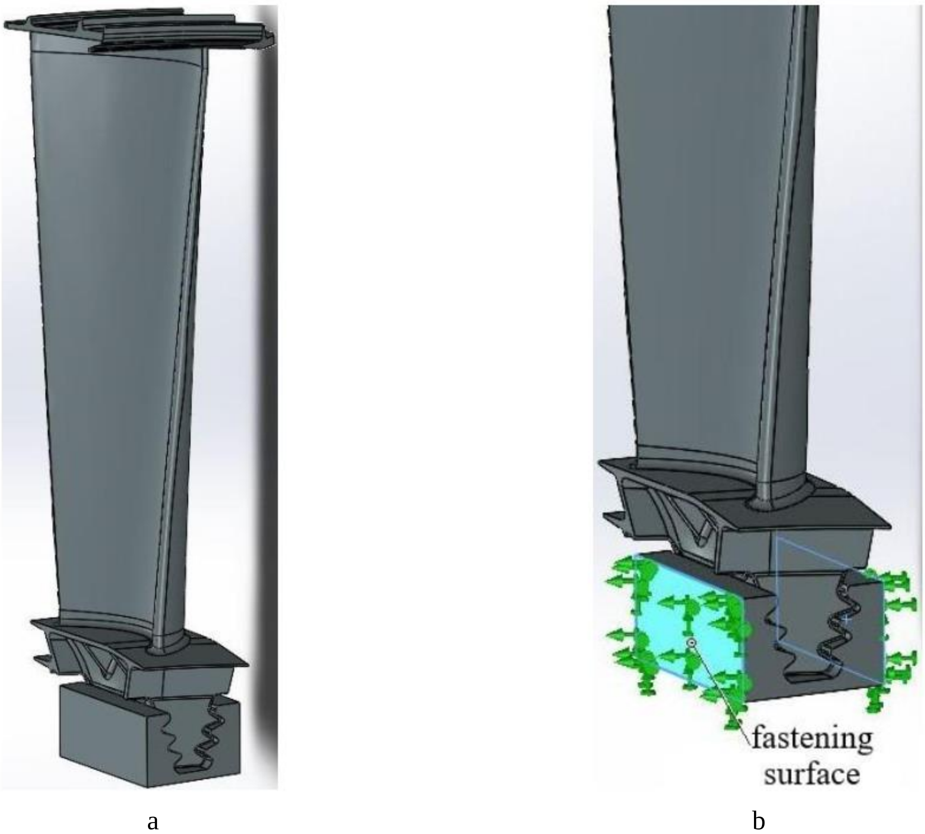
Comparison of the resonant frequencies of a blade fixed along the blade root part with experimental data

Form number	Resonance frequencies, Hz		Percent error, %
	Experiment	Calculation	
1	165	179.66	8.88
2	805	856.04	6.34
3	1310	1368.2	4.44
4	1706	1712.4	0.38
5	2033	2269.0	11.6
6	2844	2843.7	0.01
7	3321	3236.4	2.55
8	3384	3407.1	0.68
9	3999	3946.9	1.30
Mean square value, %			5.50

Since, when calculating the vibration characteristics of the blade, by the finite element method, the influence of the lock (Fig. 2, a), used when fixing the blade in the clamping device, was not taken into account, it became necessary to verify the calculated data. For this, the calculation of the values of the resonance frequencies was carried out using a three-dimensional model of the blade, combined with the lock. The surfaces of the blade attachment (Fig. 4, a) are mated with the inner surfaces of the lock model (Fig. 6, a). The 3D model of the lock was developed in accordance with the overall dimensions of the lock used in experimental research.

The calculation was carried out in conditions of rigid fixation of the outer surfaces of the lock body (Fig. 6b). To exclude the influence of the boundary conditions on the calculation results, the material properties, as well as the final element, remained unchanged.

The percent error of the resonant frequencies of the blade model fixed in the lock are given in Tab. 3.



a b

Fig. 6. 3D model of the blade in the lock:
a – 3D model of the blade, clamped in the lock; b – boundary conditions for fastening the lock

Table 3

Comparison of the resonant frequencies of the blade fixed in the lock with experimental data

Form number	Resonance frequencies, Hz		Percent error, %
	Experiment	Calculation (blade+lock)	
1	165	181	9.70
2	805	864	7.33
3	1310	1385	5.73
4	1706	1728	1.29
5	2033	2296	12.94
6	2844	2865	0.74
7	3321	3266	1.66
8	3384	3442	1.71
9	3999	3960	0.96
Mean square value, %			6.30

As follows from the data obtained, the magnitude of the deviations in the calculation of the resonance frequencies of the model of the blade clamped in the lock increased. The standard deviation was 6.3% (versus 5.5% when calculated without a clamping device). Thus, the calculation of the vibration characteristics of the blade model taking into account the lock is impractical.

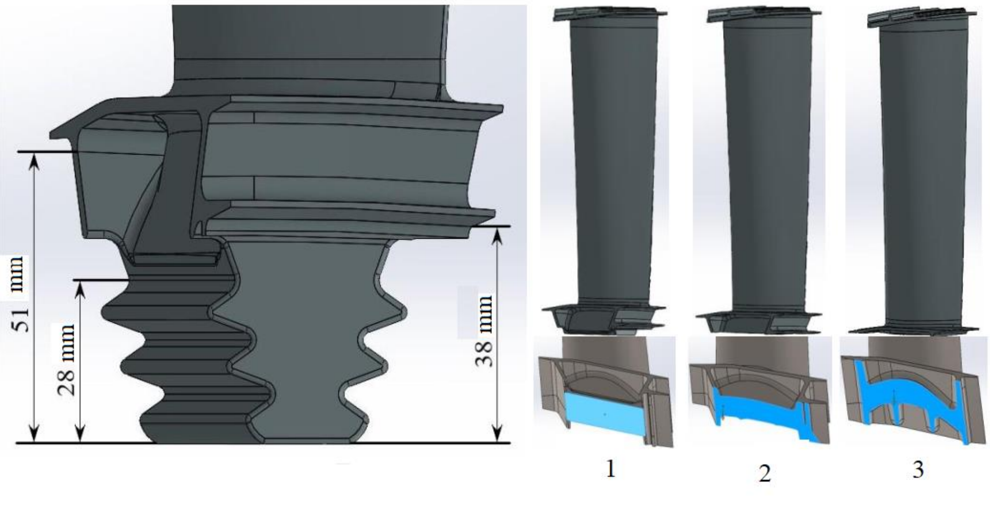
4. Methods for modeling the boundary conditions for fixing the blade to determine the vibration characteristics

In order to determine the influence of the boundary conditions of the fixing of the blade on its vibration characteristics, a series of calculations of the resonance frequencies and modes of vibration of the blade models with cutting off the part of the blade root was carried out (Fig. 7a). Three variants of the blade root were considered: fixing 1 - cut off 28 mm (this fixation meant cutting off the fir tree part of the blade root); fixing 2 - cut off 38 mm (cutting off the blade root part to the plane of the shroud platform); fixing 3 - cut off 51 mm (cut off to the beginning of the shroud platform).

The calculation was carried out while fixing the blade along the cut-off plane. The blade models used in the calculation, as well as their fixing surfaces, are shown in Fig. 7b.

It was revealed that with an increase in the cut-off part of the blade, the percent calculation error increased in comparison with the calculation of the blade model presented in Section 3.

It was revealed that with an increase in the cut-off part of the blade, the percent calculation error increased in comparison with the calculation of the blade model presented in Section 3. The value of the standard deviation was: for fixing type 1 - 1.49%; for fastening type 2 - 3.43%; for fastening type 3 - 5.56% (Fig. 8).



a b

Fig. 7. Dissection of the hinge part of the blade:
a – Scheme of dissection of the blade model; b – three-dimensional models, and the surface of the blade attachment

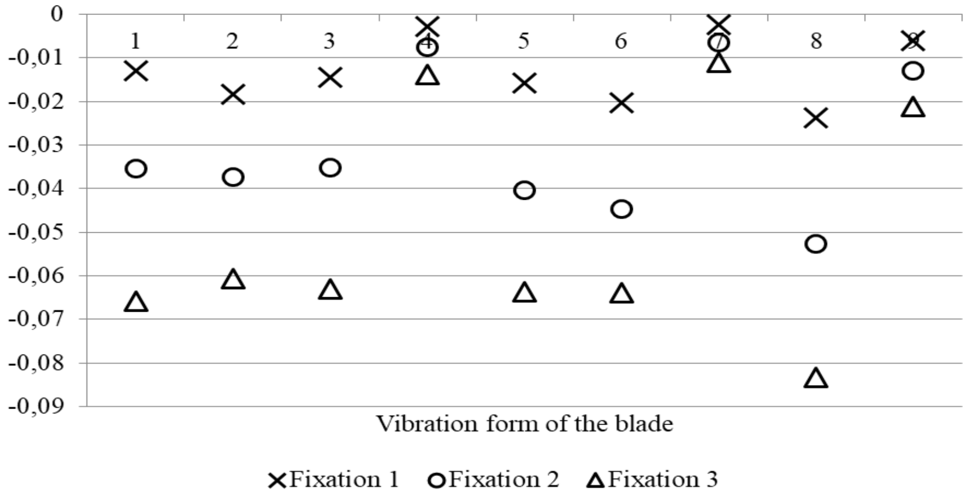


Fig. 8. Percent error of the calculated values of the resonance frequencies of the blade model with cutting off part of the lock

As follows from the results obtained, the minimum value of deviations, which was 1.49%, was achieved with the type of fixation 1. The use of this variant of the blade root part of the model when calculating the vibration characteristics will facilitate the calculation process by simplifying the geometry of the three-dimensional model of the studied blade, with a minimum loss of accuracy (~ 1.5%).

Conclusions

1. Using the method of real-time digital speckle interferometry, natural frequencies and modes of oscillations of the working turbine blade of a gas-turbine engine are determined. In the frequency range from 100 to 4000 Hz, 9 blade vibration modes were identified.

2. In the frequency range from 100 to 4000 Hz, using the finite element method, the resonant vibration frequencies of a three-dimensional model of a GTE rotor blade are determined. The standard deviation of the calculated and experimental data was about 5.5%.

3. The calculation of the values of resonance frequencies was carried out using a three-dimensional model of a blade fixed in the lock. It is shown that when calculating the vibration characteristics of a blade taking into account the clamping device, the deviation increases and amounts to 6.3%.

4. It is shown that cutting off the fir tree part of the blade root when modeling the boundary conditions of fixing makes it possible to simplify the calculation process by simplifying the geometry of the three-dimensional model of the blade under study, with a minimum loss of calculation accuracy (~ 1.5%).

5. The results obtained make it possible to significantly simplify the geometric model of the turbine blade in the course of further studies of its resonant under conditions of clamping along the lock and twisting on the shroud.

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ТЕОРЕТИЧНЕ ТА ЕКСПЕРИМЕНТАЛЬНЕ ВИЗНАЧЕННЯ ВПЛИВУ ГРАНИЧНИХ УМОВ НА ВІБРАЦІЙНІ ХАРАКТЕРИСТИКИ РОБОЧОЇ ЛОПАТКИ ГАЗОВОЇ ТУРБІНИ

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Дано опис стенду на основі цифрового спекл-інтерферометра з дифузною опорною хвилею та розділеними гілками, що дозволяє визначати власні частоти та форми коливань об'єктів у реальному часі. У діапазоні частот 100...4000 Гц проведено експериментальне дослідження вібраційних характеристик робочої лопатки турбіни газотурбінного двигуна, при жорсткому закріпленні замкової частини лопатки, яке досягалося шляхом закріплення лопатки в замку і наступної фіксації його в затискному пристрої. Як об'єкт дослідження розглянуто робочу лопатку турбіни газотурбінного двигуна з висотою по вихідній кромці 288 мм і хордою в середньому перерізі 88,5 мм. Створено твердотільну геометричну модель робочої лопатки на основі фасетного тіла, отриманого 3D скануванням. Що стосується діапазону частот 100…4000 Гц, з допомогою програмного комплексу ANSYS Workbench, проведено серію розрахунків резонансних частот лопатки методом кінцевих елементів. Властивості матеріалу визначені шляхом досягнення мінімального середньоквадратичного відхилення розрахункових значень резонансних частот коливань лопатки від експериментальних даних за вільних граничних умов. Отримано ряд форм коливань, проведено зіставлення даних, отриманих експериментальним і розрахунковим шляхом. Аналіз спектру частот власних коливань лопатки показав, що середньоквадратичне значення відхилень між отриманими результатами, становить 5,5% для тих самих мод. Для верифікації програмного розрахунку проведено перерахунок значень резонансних частот, використовуючи тривимірну модель лопатки, закріплену в замку. З метою визначення впливу граничних умов закріплення лопатки газової турбіни на її вібраційні характеристики проведена серія розрахунків резонансних частот та форм коливань моделі лопатки з відсіканням частини лопатки по різній висоті. Показано, що при розрахунку вібраційних характеристик лопатки з урахуванням затискного пристрою, відхилення збільшується і становить 6,3%. Показано, що відсічення замкової частини лопатки до плоскості "ножці" при моделюванні граничних умов закріплення, дозволяє полегшити процес розрахунку, шляхом спрощення геометричної форми трьохмірної моделі дослідженої лопатки, при мінімальній похибці розрахунку (~ 1,5%).

Ключові слова: спекл-інтерферометрія; лопатки ГТД; метод кінцевих елементів; резонансні частоти; моди коливань.

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