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INFLUENCE OF MANUFACTURING DEVIATIONS ON NATURAL FREQUENCIES AND MODE SHAPES OF TURBINE BLISKS

Purpose. *To establish the vibration characteristics of cast turbine blisks (monowheels) and to determine the influence of inevitable manufacturing deviations on their natural frequencies and mode shapes by combining computational and experimental methods.*

Research methods*. A comprehensive computational-experimental approach was applied. The computational part included finite element modal analysis of two models: 1) an idealized cyclically symmetric model with nominal geometry, and 2) a full model reproducing the actual geometry of the manufactured product, obtained via high-precision 3D scanning. The experimental part consisted of two stages: preliminary determination of the amplitude-frequency spectrum using the impact excitation method (tap testing) and a detailed investigation of natural frequencies and mode shapes using a piezo-probe.*

Results. *It was confirmed that manufacturing deviations cause significant changes in the dynamic behavior of the blisk. Frequency spectrum splitting and asymmetry of mode shapes, which are not predicted by nominal geometry models, were established. The computational model built from 3D scanning data demonstrates significantly better correlation with experimental data. A shift in nodal diameters relative to the axis of symmetry was experimentally recorded, which is direct proof of the influence of asymmetry caused by manufacturing tolerances.*

Scientific novelty. *For the first time, an approach to blisk quality control has been proposed and tested, based not on static geometric comparison, but on the analysis of the product's integral dynamic “signature” – its natural frequencies and mode shapes. It has been proven that the discrepancies between the nominal geometry calculation and the experiment are not an error, but a quantitative measure of the manufacturing deviations' impact on the structure's dynamic behavior.*

Practical value. *A rationale for a new non-destructive testing (NDT) method has been developed, which allows for objective decisions regarding the serviceability of both new and in-service blisks. The creation of a “reference” vibrational passport is proposed for the objective quality assessment of series-produced products and for diagnosing component degradation during inter-repair maintenance, thereby increasing the reliability and safety of aircraft engine operation.*

Key words: *turbine blisk, natural frequencies, mode shapes, manufacturing deviations, computational-experimental method, 3D scanning, non-destructive testing, blisk asymmetry.*

Introduction

The competitiveness of modern aircraft gas turbine engines is determined not only by the perfection of thermodynamic parameters, such as the compressor pressure ratio, turbine inlet gas temperature, and specific fuel consumption, but also by the economic efficiency of production. In the struggle for sales markets, the cost of the finished pro-

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duct becomes critical, prompting designers to search for innovative technological solutions. One such solution is the transition from traditional assembled structures, consisting of a disk and separate blades, to compressor and turbine blisks (bladed disks) manufactured as a single unit [1, 2].

However, the introduction of blisks imposes a qualitatively new level of requirements for production and quality control. Unlike assembled structures, where a defective blade can be replaced, any deviation or defect in a blisk leads to the rejection of the entire product or the need for expensive repairs. This problem is particularly acute for turbine blisks manufactured by investment casting. Unlike compressor blisks, which are machined on high-precision five-axis machines, cast turbine blisks are characterized by significantly larger manufacturing deviations in geometric parameters.

Manufacturing deviations lead to blade mistuning within the blisk, which directly affects its dynamic characteristics and operability [3–5]. The presence of even slight asymmetry can cause splitting of the natural frequency spectrum, changes in mode shapes, and the appearance of resonant regimes in the operating speed range. This creates an increased risk of fatigue failures during operation [6], especially under conditions of unsteady thermal states and significant centrifugal loads.

Existing blisk quality control practices, which include frequency testing of individual blades, geometric dimension measurements, and defect detection, do not allow for a full assessment of the combined influence of manufacturing deviations on the dynamic behavior of the blisk as an integral oscillating system. Modern 3D scanning methods open new possibilities for detailed modeling of the actual geometry of products; however, there is a lack of methodology for a comprehensive computational-experimental study of the influence of manufacturing deviations on the natural frequencies and mode shapes of turbine blisks.

The purpose of this work is to establish the vibration features of turbine blisks and determine the influence of manufacturing deviations on their dynamic characteristics through the comprehensive application of 3D scanning, finite element modeling, and experimental studies. The developed methodology will increase the objectivity of blisk quality assessment and decision-making regarding their serviceability.

Literature Review

The problem of mistuning in turbomachinery blisks has attracted the attention of researchers for over five decades. Early fundamental works by Dye and Henry (1969) [7], El-Bayoumy and Srinivasan (1975) [8], and Ewins (1969, 1973, 1984) [9–11] laid the foundations for understanding the impact of discrepancies in the mechanical properties of blades on the dynamic behavior of bladed disks. It is well known that inevitable variations in mechanical properties from blade to blade, referred to as mistuning, can cause frequency splitting and a significant increase in forced vibration amplitudes compared to a tuned structure with identical blades [12].

At the current stage of research in this field, several main directions can be distinguished. It has been established that vibrations of blades with lower inter-blade coupling, such as torsional modes or modes with a large number of nodal diameters, are characterized by increased sensitivity to mistuning. The obtained results allowed for the formulation of criteria for evaluating the level of mode localization depending on the parameters of real high-pressure compressor systems.

Particular attention is paid to the issues of experimental identification of mistuning. One modern approach is the method of individual blade excitation using a miniature impact tool followed by non-contact vibration velocity measurement using laser Doppler vibrometry, which ensures high accuracy in determining frequency characteristics [13]. At the same time, traditional methods require collecting modal information from many points around the disk or isolating individual blades, which complicates experiments [14].

One of the key research directions is the application of intentional mistuning as an effective method for reducing vibration levels. It was found that this approach can weaken the coupling between blades by separating their frequencies. It is proposed that the mistuning pattern should be designed to primarily separate the frequencies of those blades that demonstrate the strongest coupling [15].

A separate group consists of works on the identification of mistuning caused by defects. In work [16], experimental and numerical studies of cracks in blades were conducted, comparing the natural frequencies and mode shapes of defective and defect-free blades to identify the main differences in modal behavior. These studies are important for understanding the mechanisms of the influence of operational damage on the dynamic characteristics of blisks.

A revolutionary aspect in production quality control has been the introduction of 3D scanning technologies. Modern 3D scanning systems, especially those using blue light, provide high-precision measurements, reducing errors and guaranteeing strict compliance with design specifications, significantly reducing inspection time compared to traditional methods. The implementation of automated 3D scanning systems has reduced the inspection time for blisks from 18 hours using a coordinate measuring machine (CMM) to approximately 45 minutes, achieving test repeatability below five microns [17]. Laser scanning can create CAD data for legacy blades that lack documentation, allowing for reverse engineering or data usage to review specific characteristics [18].

However, despite significant achievements in understanding the mistuning phenomenon and the development of geometry control methods, there is a substantial gap in the comprehensive computational-experimental study of the influence of manufacturing deviations on the natural frequencies and mode shapes of turbine blisks. Specifically, the following aspects remain unsolved:

- Methodology of comprehensive analysis: There is no systematic approach combining 3D scanning of actual

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geometry, finite element modeling taking into account all manufacturing deviations, and experimental verification of results for turbine blisks.

- Specifics of cast blisks: Most studies focus on compressor blisks manufactured on high-precision machine tools. Turbine blisks made by casting are characterized by a fundamentally different nature and magnitude of deviations, the influence of which on dynamic characteristics has not been sufficiently studied.

- Criteria for serviceability assessment: Existing control methods (frequency control of individual blades, 3D scanning, defect detection) do not allow for an objective assessment of the serviceability of a blisk with manufacturing deviations based on a comprehensive analysis of its dynamic characteristics.

- Comparison of models of varying accuracy: There is a lack of systematic studies comparing the results of calculations for cyclically symmetric models with nominal geometry, full models with actual geometry, and experimental data to establish the degree of adequacy of simplified approaches

Purpose

To establish the vibration characteristics of cast turbine blisks (monowheels) and to determine the influence of inevitable manufacturing deviations on their natural frequencies and mode shapes by combining computational and experimental methods.

Materials and Methods

The object of the study is an aircraft gas turbine engine turbine blisk manufactured by investment casting with subsequent machining of the attachment points. The blisk consists of three main elements: the hub, the flange for attachment to the shaft, and the blade rim. A feature of this design is the inseparable connection of the disk and blades, which leads to increased requirements for production quality, as deviations in the geometric parameters of individual blades affect the dynamic characteristics of the entire blisk.

To conduct strength calculations and determine natural frequencies and mode shapes, a three-dimensional nominal model of the turbine blisk was built using the Unigraphics NX system. The model corresponds to the design geometry without taking into account manufacturing tolerances and deviations.

In the first stage of calculations, a cyclically symmetric model consisting of one sector with a single blade was used (Figure 1).

This model contained 845874 nodes and 319783 second-order elements. The application of the cyclically symmetric approach is based on the assumption of mathematically strict symmetry of the structure, where all blades have identical geometry. An isotropic material model was used for the calculations.

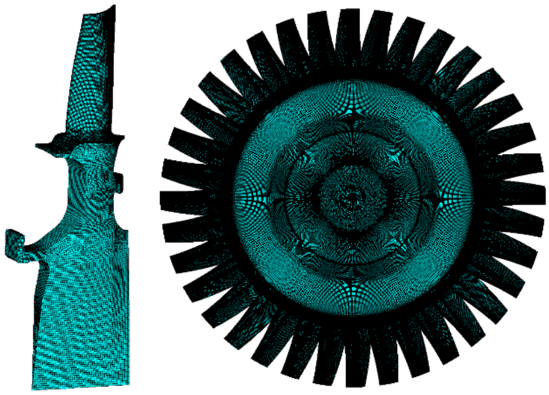

Figure 1. Cyclically symmetric computational model of the blisk

To determine the real influence of manufacturing deviations on the dynamic characteristics of the blisk, a 3D scan of the manufactured wheel was performed using an Atos Core 300 scanner. This control method allows obtaining complete geometric information about the part, including individual deviations of each blade. The obtained file in .stl format was loaded into the Unigraphics NX system, after which the actual geometry of the blisk was reconstructed. The modeled geometry corresponded to the actual one with an accuracy of up to 0.03 mm. The error is due to the shadowing effect of certain areas of the blisk during the scanning process, which makes complete scanning of some parts of the structure impossible.

Based on the 3D scanning data, a full computational model of the turbine wheel was built, which takes into account all manufacturing deviations, including geometric variations of each individual blade. The model contained 794784 nodes and 380485 second-order elements (Figure 2). Using the full model instead of the cyclically symmetric one allows accounting for the real asymmetry of the structure arising from the technological manufacturing process.

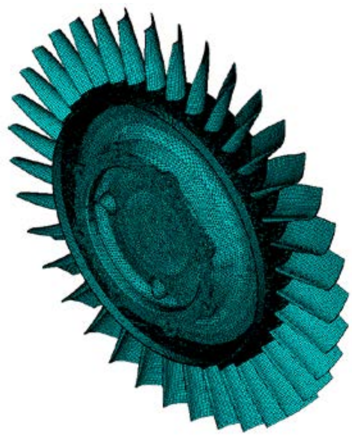

Figure 2. Full computational model of the turbine wheelи

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The determination of natural frequencies and mode shapes was carried out using the finite element method. For both models (nominal cyclically symmetric and full with deviations), modal calculations were performed in a specified frequency range. The results were presented in the form of frequency diagrams and visualizations of mode shapes (Figures 3, 4).

In the first stage of experimental research, the amplitude-frequency spectrum of the investigated blisk was obtained. To ensure free vibration conditions, the blisk was suspended between two stands on a cable passed through one of the through-holes in the hub. This mounting scheme minimizes the influence of additional stiffnesses and added masses on the natural frequencies and mode shapes. Excitation of natural frequencies and mode shapes was performed by striking the web on the outlet side of the blisk with a rubber mallet. The signal was registered using a microphone located near the rim part on the outlet side. The signal was recorded on a portable computer with subsequent processing to obtain the frequency spectrum (Figure 5).

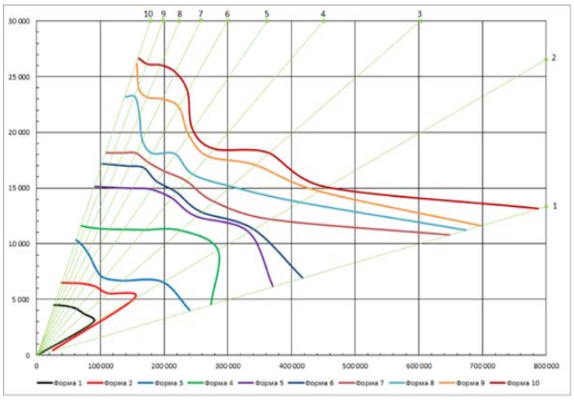

Figure 3. Resonance frequency diagram of the turbine wheel

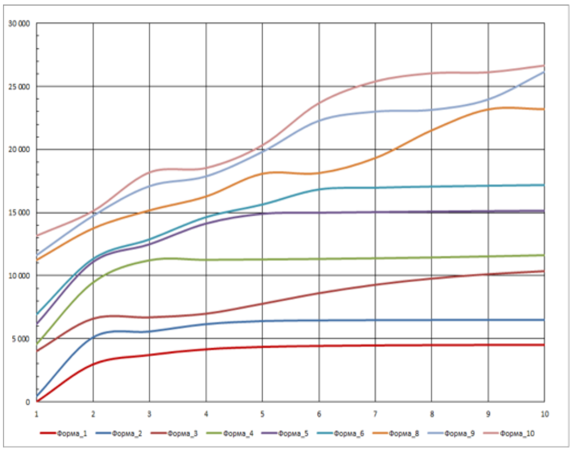

Figure 4. Frequency function of the turbine wheel

In the second stage, taking into account the previously obtained frequency spectrum, an equipment setup was assembled for a detailed study of natural frequencies and mode shapes. The setup included: a signal generator for excitation; oscilloscopes for signal visualization; a frequency counter for precise frequency measurement; a microphone for non-contact vibration registration; and a piezo-probe for contact investigation (Figure 6).

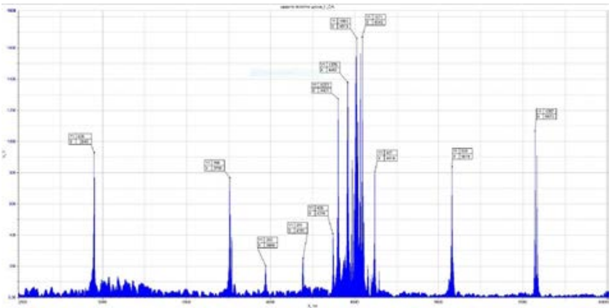

Figure 5. Spectrum of natural frequencies and mode shapes

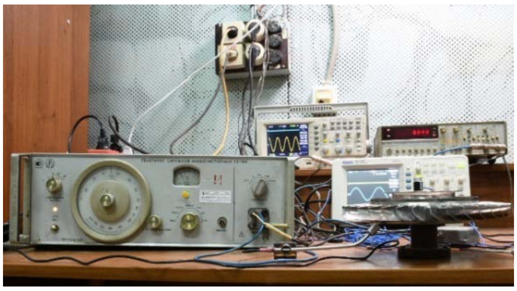

Figure 6. Equipment setup for investigating natural frequencies and mode shapes

The laboratory research methodology provided for the possibility of free movement of the blisk during resonant vibrations and the exclusion of the influence of any additional stiffnesses and added masses. The blisk was placed with its hub part under its own weight on a textolite stand. The use of a textolite stand ensured minimal influence on the intrinsic characteristics of the test object due to the low stiffness of the material.

Vibration excitation was provided by a vibration transducer installed through one of the holes in the flange using a threaded connection. The vibration transducer allowed ensuring a constant excitation level in the frequency range f = 0...25 kHz. For the research, a frequency range of f = 2500...6000 Hz was established, covering the most intense mode shapes of the blisk. The first six most intense mode shapes were investigated.

The determination of resonant mode shapes was carried out by a combined method using a piezo-probe and a microphone. The piezo-probe allowed determining local vibration amplitudes at various points of the structure, while the microphone provided non-contact registration of the overall vibration picture. The excitation frequency was smoothly changed manually using the generator in the selected range to tune precisely to the peaks of resonant vibration frequencies. To determine the vibration phases at resonant modes, the generator's output reference signal with a

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constant sign was used. This allowed identifying the location of nodes and antinodes, as well as determining the number of nodal diameters and circles for each mode shape.

For a comprehensive assessment, a comparative analysis of the obtained results by three methods was applied:

- Calculation of the cyclically symmetric nominal model (ideal geometry).
- Calculation of the full model taking into account manufacturing deviations.
- Experimental determination of natural frequencies and mode shapes.

Comparisons were made both by natural frequency values and by the configuration of mode shapes , with special attention paid to the effect of blade spectrum splitting and general blisk asymmetry.

Results

The calculation of the cyclically symmetric nominal model allowed determining the natural frequencies for the idealized geometry. The results show a regular arrangement of natural frequencies corresponding to the mathematically strict symmetry of the structure. The following natural frequencies were determined: 2916 Hz, 3846 Hz, 4641 Hz, and 5127 Hz (Table 1).

Table 1 – Natural frequencies of the blisk

№	Nominal model of the blisk, Hz	Model of the manufactured blisk, Hz	Experiment, Hz
1	2916	2877	2940
2	3846	3847	3754
3			3966
4		4400	4192
5	4641	5011	5079
6	5127	5489	5574

For the nominal model, clear frequency separation without spectrum splitting is observed.

The calculation of the full model, built from 3D scanning results, revealed significant differences. The determined natural frequencies were: 2877 Hz, 3847 Hz, 4400 Hz, 5011 Hz, and 5489 Hz. The most significant features were:

-Natural frequency shift: both a decrease (for the first mode from 2916 Hz to 2877 Hz) and an increase (for the fifth mode from 4641 Hz to 5011 Hz, and for the sixth mode from 5127 Hz to 5489 Hz) in natural frequencies relative to nominal values were observed.

- Spectrum splitting: Mistuning of blades caused by individual geometric deviations is present. The frequencies of the working blades for the first bending mode are located in the range f = 4375...4651 Hz.
- Mode shape asymmetry: Arbitrary asymmetry in mode shapes was detected.
- Appearance of additional modes: The real geometry model revealed a mode at 4400 Hz (first bending, blade-disk), which was not observed in the nominal model.
- Nodal diameter shift: A shift in the location of nodal diameters relative to the center of the symmetry axis is characteristic, explained by the inevitable asymmetry of the blisk itself.

Experimental research registered six most intense mode shapes in the range f = 2500...6000 Hz. The measured frequencies were: 2940 Hz, 3754 Hz, 3966 Hz, 4192 Hz, 5079 Hz, and 5574 Hz. The grouping area of intense mode shapes of working blades (first bending mode) was observed in the range f = 4370...4619 Hz, which is consistent with the calculation data on spectrum splitting.

The following characteristic mode shapes were determined:

- Vibrations with two nodal diameters (fan-like vibrations) at 2940 Hz.
- Vibrations with one nodal circle at 3754, 3966, and 4192 Hz.
- Vibrations with multiple nodal diameters and a circle (complex shapes) at 5079 Hz and 5574 Hz.

A key feature is the passage of nodal diameters with a shift relative to the center of the symmetry axis, confirming the presence of inevitable asymmetry in the cast blisk. Qualitative analysis (Table 2) showed satisfactory correspondence between calculation and experiment.

Discrepancies are attributed to: neglecting real material properties (anisotropy), 3D scanning accuracy limits (0.03 mm), mass distribution differences due to crystallization, and FE model discretization . However, the model with manufacturing deviations showed significantly better convergence with experimental data than the nominal model.

Discussion

The results demonstrate a fundamental difference between the dynamic characteristics of cast turbine blisks and theoretical characteristics for nominal geometry. Unlike compressor blisks, the influence of manufacturing deviations on turbine blisks is significantly greater.

Analysis of existing control methods revealed their limitations. Traditional methods (frequency control of individual blades, 3D scanning) do not allow for an objective assessment of serviceability without analyzing natural frequencies and mode shapes. Based on the results, a methodology for comprehensive control is proposed:

- Creation of a reference sample: Using the spectrum of a blisk that meets technical. requirements and matches calculation data.
- Periodic sampling control: Comparing the spectrum signature of new blisks with the reference to detect systematic deviations.
- Serviceability assessment criteria: Decision-making based on geometry, spectrum, frequencies, and mode shapes (at least six intense forms).
- Control of in-service blisks: Applying this control during inter-resource repair for Auxiliary Power Units (APU), where harsh operating conditions (high static stress, thermal gradients) can lead to geometry changes.

This approach allows for a more objective decision on further operation without destructive testing. Future research should focus on automating the spectrum acquisition process and applying laser holography .

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Table 2 – Experimentally determined and numerically calculated natural vibration mode shapes

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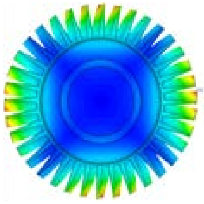
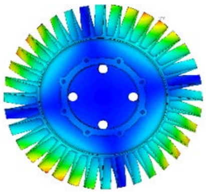
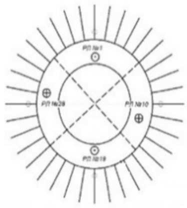
<tr><td>1</td><td>
f =2916 Hz</td><td>
f =2877 Hz</td><td>
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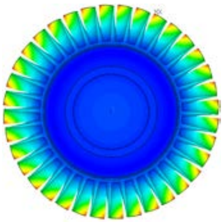
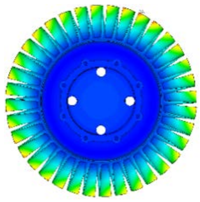
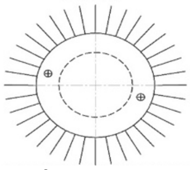
<tr><td>2</td><td rowspan="3">
f =3846 Hz</td><td rowspan="2">
f =3847 Hz</td><td>
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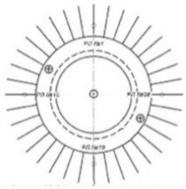
<tr><td>3</td><td>
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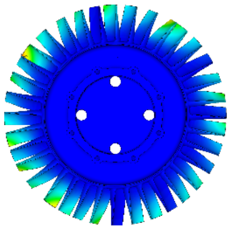
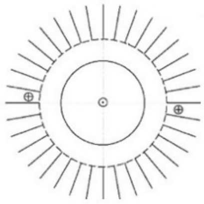
<tr><td>4</td><td>
f =4400 Hz</td><td>
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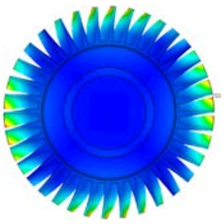
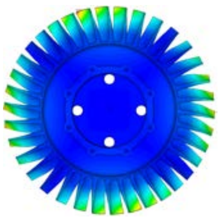
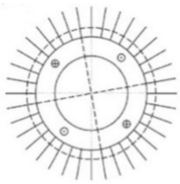
<tr><td>5</td><td>
f =4641 Hz</td><td>
f =5011 Hz</td><td>
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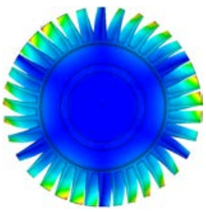
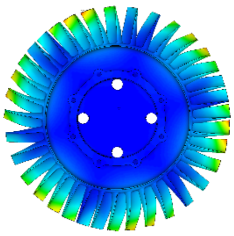
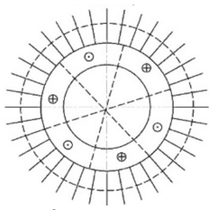
<tr><td>6</td><td>
f =5127 Hz</td><td>
f =5489 Hz</td><td>
f =5574 Hz</td></tr>
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Conclusions

Based on the conducted computational-experimental study of the influence of deviations allowed during the production of turbine blisks on their natural frequencies and mode shapes, the following has been established:

- Characteristic features of cast turbine blisk vibrations were identified, including mode shape asymmetry with a shift of nodal diameters relative to the axis of symmetry and the presence of complex mode shapes with multiple nodal diameters and circles.

- A significant influence of manufacturing deviations on dynamic characteristics was confirmed.

- The six most intense mode shapes of the investigated blisk were determined.

- The necessity of improving the turbine blisk quality control system was substantiated. It was found that traditional control methods (frequency control of individual blades, 3D scanning, defect detection, determination of actual geometric dimensions) without investigating natural frequencies and mode shapes and comparing calculation data with actual data do not allow for an objective assessment of the blisk's serviceability.

- A methodology for periodic control of turbine blisk natural frequencies and mode shapes using the spectrum and a computational-research method was proposed. The methodology involves: creating a reference sample with confirmed compliance with technical requirements and calculation data; periodic comparative analysis of the spectrum signature of sample blisks from a new batch; and decision-making on serviceability based on a set of criteria (geometry, spectrum, natural frequencies, and mode shapes) for at least six intense mode shapes .

- It is recommended to apply the proposed methodology for blisks in operation on auxiliary power units during inter-resource repair. This allows for a more objective decision on further operation without destructive testing, taking into account possible changes in geometry and stiffness under the influence of static, thermal, and dynamic loads.

Directions for further research have been defined:

- Automation of the process of acquiring amplitude-frequency characteristics and obtaining the natural frequency spectrum with the elimination of the human factor.

- Application of laser holography to determine mode shapes for a wide range of investigated parts.

- Investigation of the influence of material anisotropy and temperature fields on the dynamic characteristics of blisks.

- Study of changes in dynamic characteristics during long-term operation to establish criteria for residual life.

Practical significance of the work lies in the development of a methodology for comprehensive quality assessment of turbine blisks, which allows increasing the objectivity of decision-making regarding installation on an engine or rejection of both newly manufactured and in-service blisks. Ultimately, this increases the reliability of aircraft gas turbine engines and reduces the risks of operational failures.

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ВПЛИВ ВИРОБНИЧИХ ВІДХИЛЕНЬ НА ВЛАСНІ ЧАСТОТИ ТА ФОРМИ КОЛИВАНЬ МОНОКОЛІС ТУРБІН

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Мета роботи. *Встановлення особливостей коливань моноколіс турбіни, виготовлених методом лиття, та визначення впливу неминучих виробничих відхилень на їхні власні частоти і форми коливань шляхом поєднання розрахункових та експериментальних методів.*

Методи дослідження. *Застосовано комплексний розрахунково-експериментальний підхід. Розрахункова частина включала модальний аналіз методом скінченних елементів двох моделей: 1) ідеалізованої циклосиметричної моделі з номінальною геометрією та 2) повної моделі, що відтворює фактичну геометрію виготовленого виробу, отриману за допомогою високоточного 3D-сканування. Експериментальна частина складалася з двох етапів: попереднього визначення амплітудно-частотного спектра методом ударного збудження та детального дослідження власних частот і форм коливань з використанням п'єзощупа.*

Отримані результати. *Підтверджено, що виробничі відхилення спричиняють значні зміни в динамічній поведінці моноколеса. Встановлено розшарування частотного спектра та асиметрію форм коливань, що не прогнозуються моделями з номінальною геометрією. Розрахункова модель, побудована за даними 3D-сканування, демонструє значно кращу кореляцію з експериментальними даними. Експериментально зафіксовано зміщення вузлових діаметрів відносно осі симетрії, що є прямим доказом впливу асиметрії, спричиненої виробничими допусками.*

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Наукова новизна. *Вперше запропоновано та апробовано підхід до контролю якості моноколіс, що базується не на статичному геометричному порівнянні, а на аналізі інтегральної динамічної «сигнатури» виробу – його власних частот та форм коливань. Доведено, що розбіжності між розрахунком для номінальної геометрії та експериментом є не похибкою, а кількісною мірою впливу виробничих відхилень на динамічну поведінку конструкції.*

Практична цінність. *Розроблено обґрунтування для нового методу неруйнівного контролю, що дозволяє приймати об'єктивні рішення про придатність до експлуатації моноколіс. Запропоновано створення «еталонного» вібраційного паспорта для об'єктивної оцінки якості серійних виробів та діагностики деградації компонентів під час міжремонтного обслуговування, що підвищує надійність та безпеку експлуатації авіаційних двигунів.*

Ключові слова: *моноколесо турбіни, власні частоти, форми коливань, виробничі відхилення, розрахунково-експериментальний метод, 3D-сканування, неруйнівний контроль, асиметрія моноколеса.*

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