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Natural Vibrations of a Turbine Blade During Milling

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Abstract. The main problems in processing the surfaces of turbine blades are deformation and oscillatory processes directly during their processing. The same processes further determine both the product life and the noise intensity generated by devices using turbines, including aircraft engines. The aim of the work was to study the regularities of changes in the frequency of natural vibrations of a turbine blade throughout the entire technological cycle from design, manufacture of a workpiece, milling and fixing in the turbine disk. The article developed an approach to the analysis of this problem based on digital models. Computer modeling and determination of natural frequencies of turbine blade vibrations are consistently carried out for a stamped blank, during its milling with fixing in fixtures along the base and apex, as well as in the dovetail of the turbine disk lock. The distribution of stresses and deflections in milling conditions is determined. It is concluded that the natural vibrations of the blade airfoil during milling shift to the region of lower frequencies when the machining allowance is removed. However, for the first two lower vibration modes, technological heredity is preserved. Therefore, at the stage of designing the technological process of processing, it is necessary to determine the natural vibration frequencies and maximum deviations of the blade airfoil in order to avoid the occurrence of resonance vibrations when the processing conditions change and to carry out processing within the tolerance.

Keywords: Turbine blade · Free mode · Mechanical processing · Deviation · Aircraft noise

1 Introduction

The existing programs “Europe-Horizon” in the development of green energy and transport provide, in addition to reducing emissions of carbon dioxide, nitrogen oxides and particulate matter to zero, also the development of programs to reduce aircraft noise [1]. The solution to the problems is planned to be obtained at the expense of the energy of hydrogen, wind, and water. Almost all of the listed energy conversion processes use various turbines and devices containing blades. These blades work in a wide variety of conditions. Aircraft engines that use hydrogen as fuel are of particular interest. In this

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case, the emissions of water and steam create new problems in the atmosphere, and the turbine from a truly gas-dynamic one turns into a hybrid or steam one. Consequently, traditional technologies for the manufacture of steam turbine blades must be considered from the point of view of their use in aircraft engines. Moreover, since the noise of aircraft engines is closely related to the frequency and amplitude of natural oscillations of the turbine blades, scientific interest is formed, in particular, from consideration of the processing conditions of the blades and their influence on the subsequent number of blades. noise. The aforementioned problems give rise to increased interest in the problems of manufacturing turbine blades. The most important step in blade technology is milling, as this removes the maximum layer of stock. However, the determination of the spectrum of natural vibrations of products is carried out only after polishing and often varies greatly, despite the seemingly identical processing conditions. Therefore, it is relevant to consider the peculiarities of the distribution of the natural frequencies of the blade vibrations during the milling operation and the arising deviations of the console from the cutting forces in order to maintain the processing accuracy, as well as a preliminary assessment. the influence of the technology of manufacturing the blade apparatus on the noise level.

An analysis of modern studies of fluctuations shows that the main efforts are directed in two directions. The first is the forced vibrations of the machine part system, which are characteristic of an intermittent milling process. Secondly, there are various types of blade oscillations under conditions of gas-dynamic flow and rotation. Very little is paid to the process of forming and changing the spectrum of natural vibrations of blades at various successive stages of manufacturing technology. Thus, the aim of this study is to fill this research gap.

2 Literature Review

In predicting accuracy and stability during parts' machining, accurate knowledge and information about the dynamics of the machine-tool-part is very important. It was an article [2] performed a Modal Frequency Study of Carbon Steel and Cast-Iron End Mills Using Impact Excitation in order to potentially assess the risk of resonance phenomena during machining since vibrations affect the quality of the workpiece. The experiments were conducted with a carbon steel and cast-iron end mill and workpiece to study modal frequencies using a frequency response function (FRF). Tool, part and cutting tool modeling were investigated using FEA.

As is well known the dynamics of a part is an important factor when planning a machining strategy [3]. On the basis of the analysis which revealed that, typically, the structural dynamic parameters of a part are obtained by experimental modal analysis (EMA) [4]. However, the dynamics of thin-walled workpieces changes due to material removal and tool-to-workpiece adhesion. Online modal analysis (OMA) provides a way to evaluate structural dynamic parameters during operation, but the input excitation of the milling system is mainly periodic milling force, which violates the OMA premise. In article [4] it was requested to the modal identification method only for the derivation of the dynamic parameters of a thin-walled workpiece. The milling force has been analyzed by authors [4] and the analysis results were shown that the milling force contains white noise for OMA. In research [5] it was developed a dynamic model to study the stability of the thin floor milling process by comprehensively considering the flexibility of both static bending defects and dynamic reactions. In paper [6] the authors studied deformations and vibrations arising from side milling of thin-walled parts. The explores deformation and vibration caused by force have been considered.

The examines the effect of radial engagement and milling direction on the stability of thin-walled milling is presented in the paper [7]. The dynamics of the processes of milling thin-walled parts, in particular of face milling operations, in this research is described by a matrix of directivity coefficients, which is compressed to a single coefficient, the average value of which unambiguously depends on the engagement limits and the ratio of the radial-tangential cutting force [7].

The modified Nyquist method to study the effects of spindle speed, depth of cut and structural damping factor on vibration frequencies was used in the works [8, 9]. It was important to note, however, that for more convenient and accurate control of the milling process [10], and adaptable single-point control method based on one acceleration sensor can be used. For increasing resistance to vibration during end milling the development of a holder with damping of a limited layer has been devoted paper [11]. These authors found the dynamic stiffness is proportional to the damping coefficient and static stiffness of the holder, while the natural frequency is proportional to the specific stiffness of the tool materials [11]. On the basis of analysis of the literature researches, it was observed that composite damping materials have been used in the tool-holder clamping industry to suppress vibration [12, 13]. The authors [14] claim that composite materials, widely used in CNC machine beds, have a huge impact on the efficiency and accuracy of a part's processing. In addition, has been noted that the optimization of the parameters of the processing of thin-walled parts is generally carried out on the basis of finite element modeling of oscillations of the workpiece [3, 15]. In paper [15] it was noted that in practice, it is necessary to take into account the change in natural frequencies due to the removal of the allowance and change in the position of the cutter during processing thin-walled parts. Currently, further progress in high-speed machining efficiency is mainly limited by vibrations of the machine and part system, which limits productivity, accuracy, and part quality. The problem becomes critical during finishing. thin-walled parts with tightly limited accuracy. In thin-walled milling, the proposed method of stability petals cannot be applied directly due to dynamic changes during processing [15, 16]. The natural frequencies of the workpiece change in the process of stock removal, which reduces the weight and rigidity of the workpiece. The solution to this problem in research [15] was proposed to study the processing of a part in small zones. In work [16] authors have addressed the prediction of stability boundaries during milling taking into account changes in dynamic parameters and specific coefficients of cutting force. In research [17] the issues address the gap in the variety of the thin-walled parts computer-aided machining parameters calculation solutions that have been addressed. The research [18] touched upon issues related to the pre-scheduling of the feedrate before the start of motion control, which has no constraints on the number of analyzed blocks and the scheduling execution. In this context, it is also important to indicate that the topic of vibration and noise in aviation is constantly in the spotlight [19]. Moreover, since the noise of aircraft engines is closely related to the frequency and amplitude of natural vibrations of turbine blades, scientific interest is formed, among other things, from consideration of the conditions for machining the blades and their influence on the subsequent magnitude of aircraft engine noise. Most significantly, the noise has recently gained relevance due to the new stringent ICAO requirements for noise and pollution at the airport at the level of Chapter 4 requirements according to 7 EPNdB [19, 20]. The most comprehensive overview of reliable aviation research is currently presented in work [21]. In particular, emphasis was placed on aviation applications for noise reduction in aircraft and aircraft propulsion systems. It was noted that the most prominent sources of noise in modern aircraft are associated with aircraft engines.

A generalized European view of aircraft noise is detailed in the source [22]. It should be noted that for a turbofan engine with a by-pass degree of 3 and higher, the turbine noise becomes significant, and research is needed to suppress it.

There are theoretical and empirical models for estimating turbine noise, taking into account various correlation parameters. However, the results of theoretical results of experimental studies show that one of the proposed methods is imperfect and further experimental and analytical studies are needed to study the correlation parameters, which are more related to the physical methods of generation, propagation and emission of noise. Developing a robust model that can predict turbine noise during the design phase is still a valid test.

Analysis of the state of affairs has shown that the role of forced vibrations of the blades in the milling process is being intensively studied. At the same time, attention is paid to reducing the vibrations of the machine bed, holder, tool, forced vibrations in the cutting zone. The relevance of the role of natural and forced oscillations of blades in the composition of turbines is obvious. However, the question of the influence of successive stages of processing, including milling, on the amplitude of natural vibrations of the blades requires further study. The purpose of this article is to fill this gap to some extent.

3 Research Methodology

As well know, the noise range is in the frequency range from 0 to 20,000 Hz. Oscillations in this range can be roughly divided into two groups. Oscillations associated with the rotational frequencies of the rotors are characterized by a frequency range 70… 200 Hz, and blade frequencies 200… 20.0 kHz.

The need to calculate the natural frequencies and the corresponding vibration modes arises when analyzing the dynamic behavior of the blades under the action of variable loads. The most typical situation is when at the design stage it is necessary to check the likelihood of product resonance under operating conditions. Resonance phenomena are observed at frequencies close to the natural frequencies of the blades. Therefore, if during the design of the product it is possible to assess the spectrum of natural frequencies of the blades, then it is possible with a significant degree of probability to predict the risk of resonance phenomena in the known frequency range of external influences. Therefore, the research methodology includes the stages of design, modeling and experimental research. At the first stage, digital 3D models of the blade workpiece and the blade model after the milling process using the SolidWorks computer program were created. Curved blade airfoil surfaces were described using NURBS. At the next stage, the study of the natural oscillation frequencies of the workpiece and blade after milling using the CAE SolidWorks Simulation software and the CAE ANSYS MODAL program with the finite element method was carried out. Duplication of studies, on the one hand, made it possible to exclude random errors in the results, and on the other hand, to expand the possibilities of research. A further step, the study of the natural oscillation frequencies of the processed blade when it is fixed in the turbine disk, a herringbone dovetail lock in order to determine the natural frequencies responsible for creating noise was carried out. The next phase was the modeling of blade deformation during processing, which had been implemented in the CAE ANSYS system using the finite element method. At the final phase, the milling of the blade on a CNC machine, with regard to results-based, was carried out. Thus, the presented study covers the full end-to-end cycle of "design-manufacture" of a blade using its digital model at all phases.

Online calculator Kennametal [23] was used to calculate the tangential cutting force, moment and power.

For research, a blade made of stainless steel AISI 304/X5CrNi18-10 (DIN 1/4301) was chosen. Blade length - 625 mm. Workpiece type - blanking. The allowance for the blade airfoil processing was 3 mm.

Basic material properties: elstic moduls – 2e+11 N/m^2, poisson's ratio – 0.28 N/A, shear modulus – 7.9e+10 N/m^2, mass density – 7900 kg/m^3, tensile strength – 600 000 000 N/m^2, yield strength – 400 000 000 N/m^2, hardness – 170 MPa.

4 Results

The study of the distribution of natural oscillation frequency was carried out in the range of up to 80 modes, which corresponds to the natural oscillation frequency of $2.05 \times 10^{+4}$ Hz. However, the most dangerous frequencies are in the low-frequency region and therefore were considered in more detail. The allocation of natural frequencies for the workpiece is shown in Table 1 and Fig. 1. It was found that the most dangerous are modes 1, 2, 4 and 10. Natural frequencies 585.77, 1202.1 and 1685.2 are characteristic of lateral modes in the directions of the X and Y axes. Based on the research results the mode of frequency 10 is dangerous along the Z axis.

Table 1. Distribution of workpiece's natural frequencies

Mode number	Frequency (Hertz)	X direction	Y direction	Z direction
1	585.77	0.13911	0.19454	4.7461e−06
2	1202.1	0.10385	0.099792	3.4503e−05
4	1685.6	0.10042	0.052854	9.6407e−05
10	4880.2	9.1375e−05	1.8388e−06	0.44696

Beginning with a frequency of 5000 Hz, the vibration amplitudes along all axes become more equiprobable. This was confirmed by the distribution of the value of the cumulative vibration mass of the workpiece (Fig. 2). The construction design of the blade provides for fixing it in the turbine disk with one end, and the other in the shroud ring.

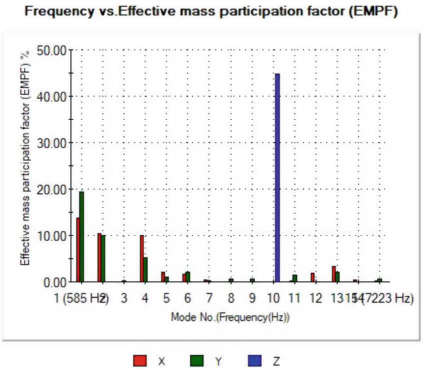


Fig. 1. Distribution of the effective mass depending on the mode of the workpiece

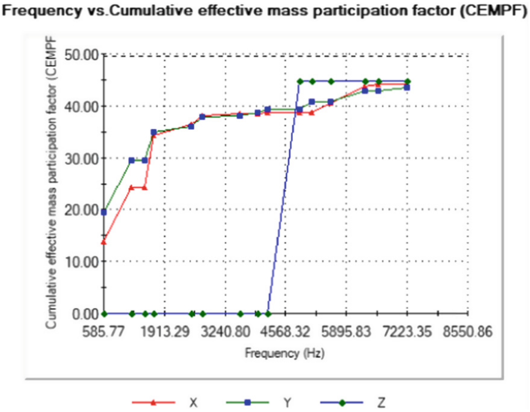


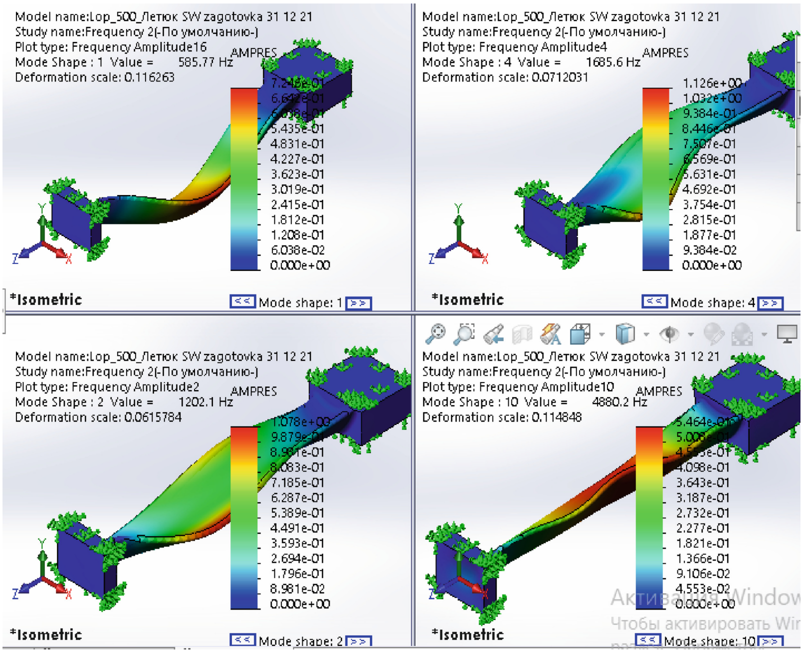
Fig. 2. Distribution of the cumulative effective mass for the workpiece depending on natural frequency of vibration

Therefore, in simulating the processing of a blade, the workpiece was fixed at both ends in accordance with the processing scheme in the metal-cutting machine tool (Fig. 3). Here, the shape and distribution of the amplitude of natural frequencies along the workpiece aerofoil was also presented. The maximum local deviations are 0.72 mm at 585.77 Hz, 1.078 mm at 1202.1 Hz, 1.126 at 1685.6 Hz and 0.54 mm at 4880.2 Hz. After removing the 3 mm allowance from the workpiece, the following results were obtained. The 1, 2 and 4 modes of lateral oscillation have been preserved. However, the natural frequency of the first mode decreased by 23%, the second - by 19%, and the fourth - by 12% (Table 2).

Table 2. The distribution of the detail's natural frequencies after removing the allowance of 3 mm

Mode number	Frequency (Hertz)	X direction	Y direction	Z direction
1	475.27	0.12032	0.20281	1.3239e−06
2	1010.2	0.099691	0.087818	8.4636e−05
4	1493.6	0.10434	0.052689	7.9674e−05
10	3873.5	0.002094	0.012815	8.4446e−05
13	4859.9	4.0549e−05	0.00029477	0.40914

Oscillations in the longitudinal direction Z were replaced from mode 10 to mode 13 (Fig. 4), but the natural frequency of oscillations decreased by only 0.4%.


Model name:Lop_500_Летюк SW zagotovka 31 12 21
Study name:Frequency 2(-По умолчанию-)
Plot type: Frequency Amplitude16
Mode Shape : 1 Value = 585.77 Hz
Deformation scale: 0.116263

Model name:Lop_500_Летюк SW zagotovka 31 12 21
Study name:Frequency 2(-По умолчанию-)
Plot type: Frequency Amplitude4
Mode Shape : 4 Value = 1685.6 Hz
Deformation scale: 0.0712031

Model name:Lop_500_Летюк SW zagotovka 31 12 21
Study name:Frequency 2(-По умолчанию-)
Plot type: Frequency Amplitude2
Mode Shape : 2 Value = 1202.1 Hz
Deformation scale: 0.0615784

Model name:Lop_500_Летюк SW zagotovka 31 12 21
Study name:Frequency 2(-По умолчанию-)
Plot type: Frequency Amplitude10
Mode Shape : 10 Value = 4880.2 Hz
Deformation scale: 0.114848

Fig. 3. The shape and distribution of the amplitude of natural frequencies along the workpiece airfoil

This can be explained by the fact that the reduction in the blade stiffness when removing the allowance occurs in the transverse direction, i.e. in the XY plane. Longitudinal stiffness changes insignificantly. This is also confirmed by changes in the distribution of the cumulative effective mass (Fig. 5).

In Fig. 6 was shown a diagram of fastening a blade to a herringbone lock and side flat surfaces in accordance with the processing scheme in the machine-tool fixture. It is important to point out that the shape of the distribution of natural frequencies of the blade airfoil after the end of milling processing is similar to the distribution for the workpiece. However, the amplitude of the natural frequencies increases significantly.

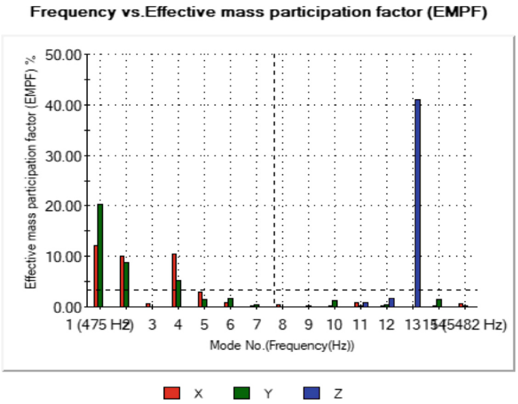


Fig. 4. Distribution of the effective mass depending on the mode of the airfoil

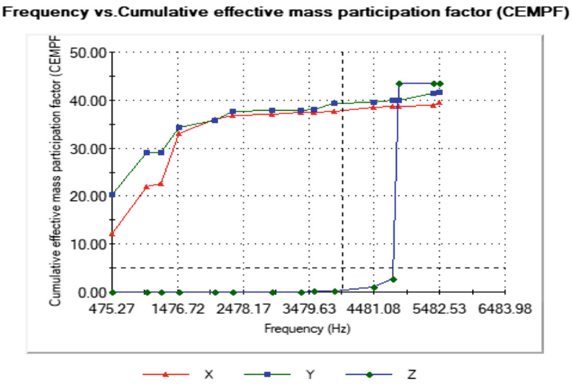
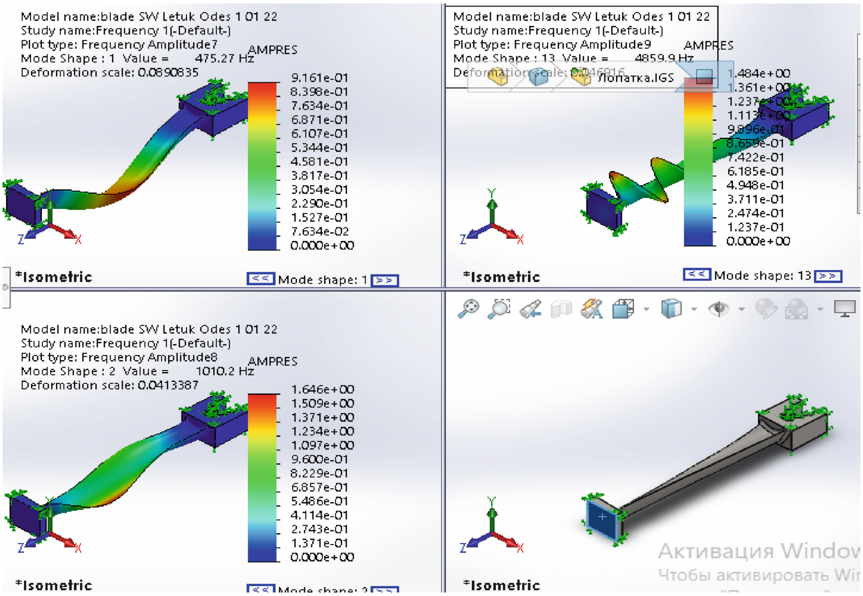


Fig. 5. Distribution of the cumulative effective mass for the airfoil depending on natural frequency of vibration

So, the maximum amplitude of the first mode increases from 0.72 mm to 0.91 mm (26%), and the second mode increases from 1.078 mm to 1.64 mm (52%). This may be an indication that considering only the maximum amplitudes is mandatory in the analysis of machining operation, but not entirely sufficient. It is necessary to coordinate the tool-path in the real form of the distribution of natural frequencies along the blade of the airfoil. For this purpose, an analysis of the stress-strain state of the blade, simulating the loading process during milling, was performed. Since we were interested in precisely the maximum possible deviations, to simplify the calculations, a static load distributed along three axes with a predominance of the tangential load was applied to the blade airfoil (Fig. 7). As a result of modeling, the area of the greatest deformations of the blade airfoil was determined (Fig. 8). From the obtained simulation results, it becomes obvious that the shape of the distribution of the blade natural frequencies oscillations (Fig. 6) is correlated with the shape of the distribution of deformations (Fig. 8). It also became apparent that the processing conditions in this local area needed to be changed. To consider this from the standpoint of natural frequencies, the modal analysis of the workpiece was carried out and the distribution of the isolines of the workpiece deformations along the airfoil blade workpiece, depending on the natural frequency before the start of processing, was obtained (Fig. 9).

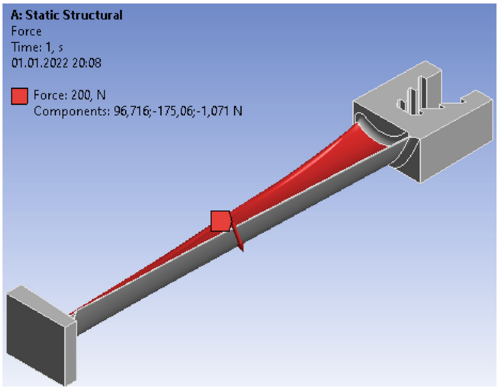


Model name:blade SW Letuk Odes 1 01 22
Study name:Frequency 1(-Default-)
Plot type: Frequency Amplitude7 AMPRES
Mode Shape : 1 Value = 475.27 Hz
Deformation scale: 0.0890835

Model name:blade SW Letuk Odes 1 01 22
Study name:Frequency 1(-Default-)
Plot type: Frequency Amplitude9 AMPRES
Mode Shape : 13 Value = 4859.9 Hz
Deformation scale: 0.046916

Model name:blade SW Letuk Odes 1 01 22
Study name:Frequency 1(-Default-)
Plot type: Frequency Amplitude8 AMPRES
Mode Shape : 2 Value = 1010.2 Hz
Deformation scale: 0.0413387

Fig. 6. Distribution of the amplitude and mode of the blade airfoil natural frequency



A: Static Structural
Force
Time: 1, s
01.01.2022 20:08

Fig. 7. Local loading of the blade airfoil

Isolines clearly delineate the hazardous and adjacent areas. If we take into account the fact that the change in the natural vibration frequency of the first and second modes during the transition from the workpiece to the blade changes by an average of 20%, then this dangerous local area should also be increased by 20%.

The experimental processing of the blade on a multi-axis CNC machine was performed (Fig. 10).

The following processing parameters were used: Ø 32 mm trident cutter with 12 mm replaceable inserts, spindle speed 1250 rpm, cutting depth 3 mm, cutter attack angle 20°.

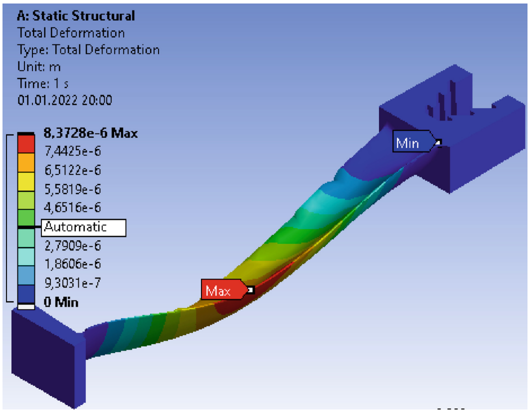


Fig. 8. Type of total blade deformation in the first natural frequency mode

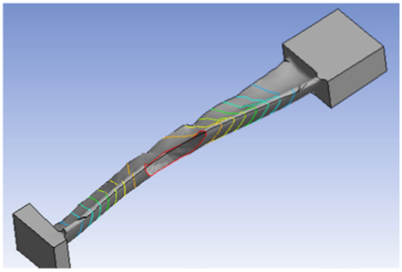


Fig. 9. Distribution of isolines of oscillation natural frequencies of the workpiece (directional deformation - Y Axis, frequency - 590.32 Hz)

In non-hazardous areas, the feed per minute corresponded to 1200 mm/min. In dangerous areas, the feed per minute was changed programmatically. Since the surface was described with Nurbs, justification for retaining the smoothing machining the S-Shape feedrate scheduling method was used [18]. As a result of this approach, the entire blade surface had a uniform roughness of 0.1 mm while maintaining accuracy.

The distribution of natural frequencies of the blade in the turbine disk in working condition is shown in Fig. 11. It should be noted that the error in finding natural frequencies in the SolidWorks and ANSYS programs does not exceed 1%.

Fig. 10. Experimental blade treatment

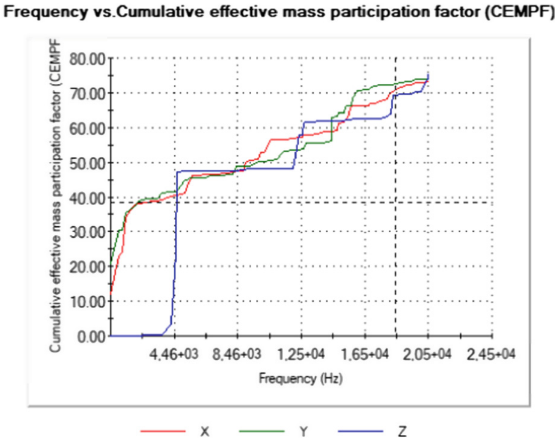


Fig. 11. The distribution of natural frequencies of the blade in the turbine disk in working condition

In the range of more than 5000 Hz, the presence of natural high-frequency oscillations was found. These frequencies will undoubtedly also contribute to turbine noise and are of interest in the high-speed milling field.

5 Conclusions

A detailed study of the change in the distribution of natural frequencies of parts during machining allows to take a new look at the machining process itself, to significantly expand the understanding of the problems that arise and how to eliminate them. The distribution of natural frequencies over the surface of the blade has extrema that correlate with the distribution of deformations. Thus, in contrast to the existing processing strategies, a new strategy based on the processing of local dangerous areas of the blade airfoil using isolines of equal strain and natural frequencies has been proposed.

A technique for computer prediction of the behavior of natural frequencies for both the machining area and the appearance of the noise spectrum is proposed. This approach makes it possible to find dangerous areas without experimental studies with the imposition of forced vibrations and makes it possible to make adjustments to the blade model at the design stage.

It has been established that for the 1st, 2nd and 4th blade modes, the frequency technological heredity will be preserved. These modes carry the most important information in successive stages of processing. To avoid the possibility of resonances, it is necessary that the main part of the low natural frequencies of the structure does not lie in the frequency range of external influences.

However, the traditional method of shifting the frequency of forced oscillations of the tool relative to the natural oscillation frequency by a constant value may be ineffective, since the real distribution of natural frequencies over the surface of the blade airfoil has a complex and non-single-frequency character. This is also important for the formation of the noise spectrum when an aerodynamic aerodynamical flows around it in various areas. As a result, in addition to the fundamental frequencies, white noise components may appear in the spectrum.

To optimize the natural frequency spectrum of a structure, it is first necessary to evaluate these frequencies at the product design stage.

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