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Optimization of the structure of turbine blades produced by methods of additive technologies

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Abstract. This study is devoted to the analysis of methods for optimizing the process of manufacturing turbine blades using additive technologies, taking into account the factors of external and internal influence on the finished product, determining the parameters for manufacturing the part, as well as the technical and technological aspects of additive manufacturing of the part. The validity of this integrated approach lies in the complexity of production and the extreme nature of the operation of the part itself, which makes it impossible to accurately estimate the duration of the operation period. But the ability to additively manufacture turbine blades with precise final characteristics will allow the production of a high-quality part with a predictable operational process. In view of these requirements, the authors give recommendations on the criterial and algorithmic support of the process of optimizing the manufacture of a gas turbine engine blade. As a result of the research, it was concluded that the main criterion for optimizing the shape of a gas turbine engine blade is to maintain a constant distance between the corresponding boundary points of the blade sections. Therefore, it will be more efficient and expedient to optimize not the shape of the blade, but the composite from which it is made.

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Оптимизация конструкции лопаток турбин при производстве методами аддитивных технологий

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Аннотация. Анализируются способы оптимизации процесса производства лопаток турбин методами аддитивных технологий с учетом факторов внешнего и внутреннего воздействия на готовое изделие, определяются параметры изготовления детали, а также технико-технологи-

Ключевые слова:
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ческие аспекты ее аддитивного изготовления. Обоснованность данного комплексного подхода заключается в сложности производства и экстремальности эксплуатации самой детали, что приводит к невозможности точно оценить продолжительность периода эксплуатации готового изделия. Цель работы – определение оптимальных характеристик процесса аддитивного производства лопатки газотурбинного двигателя. Возможность аддитивного производства лопаток турбин с точными конечными характеристиками позволит производить деталь высокого качества с прогнозируемым эксплуатационным процессом. Разработаны рекомендации по критериальному и алгоритмическому сопровождению процесса оптимизации изготовления лопатки газотурбинного двигателя. По результатам проведенных исследований сделан вывод о том, что в качестве основного критерия оптимизации формы лопатки газотурбинного двигателя необходимо принять сохранение постоянного расстояния между соответствующими граничными точками сечений лопаток. Следовательно, эффективнее и целесообразнее оптимизировать не форму лопатки, а композит, из которой она изготовлена.

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Introduction

Additive technologies are gaining more and more popularity in the production of parts that are subject to high quality control and durability requirements. The whole process of additive manufacturing should be monitored at each stage of material-production-post-processing-product to determine the most optimal parameters.

Turbine blades have a complex geometric shape, at the same time, high requirements are imposed on the quality of their manufacture, since a violation of the geometric shape can lead to a decrease in the efficiency of the turbine. Quality control of blades is a multi–stage process, which in the vast majority of cases is carried out manually, whereas at present methods of optimizing production processes and quality control of machine-building parts by mathematical modeling are becoming more and more relevant [1–4].

1. Statement of the research task

The purpose of the work is to determine the optimal characteristics of the additive manufacturing process of a gas turbine engine (GTE).

At the first stage of developing the technology of additive manufacturing of blades, it is necessary to develop criteria that must be met during the production of the part to achieve the maximum degree of quality. First, it is necessary to identify several control parameters of reliability. Since reliability is a time-varying parameter, the group of control parameters should be exclusively dynamic in nature and have the ability to transform, which can be tracked and recorded, while highlighting the influence of a specific factor on the product under study [5].

The first and most obvious control parameter is temperature. It should be noted that temperature parameters, in particular fluctuation fields, are quite difficult to measure and track at high temperatures. Therefore, one of the objectives of the study is to assess changes in the nature of the propagation of the temperature field during the life cycle of the part.

The next equally important parameter is the response to vibration – the vibration spectrum. Measuring this parameter is also a technically difficult operation, since this spectrum must be taken on a moving apparatus, the mounting of sensors of which does not meet the necessary reliability. Technically, the system includes a sensor equipped with a microwave element. The response to the vibration effect is formed inside the sensor itself, namely, by converting mechanical vibrations into high-frequency radio signals. This process consists of the following steps [6]:

– excitation of the sensor receiver when the blade moves;

– detection of mechanical vibration waves;

– translation of mechanical vibration into radio frequency vibrations.

As in the case of assessing the detail by temperature fluctuations, in this situation it is also necessary to identify diagnostic signs. In this case, it is recommended to consider by analogy not one parameter, but a pair: a spectrum describing the state of the blade under the influence of vibration and anomalies in the structure of this spectrum, which will indicate critical states of the blade that can lead to breakage. Any software product can be used for visualization and calculation, which will make the following assumptions [7]:

– replacement of metal elements with equivalent electric currents;

– excitation of the medium in the chamber volume by these currents;

– imposition of boundary conditions;

– splitting of conducting surfaces into elementary platforms, the length of which does not exceed $L = \lambda/8$, where λ is the wavelength of the electromagnetic field;

– compilation of systems of linear algebraic equations for these currents;

– solution of the obtained equations.

Such a significant number of assumptions, at first glance, complicates the calculation and modeling, but these assumptions allow us to move away from the practical development of the system, having a minimal set of initial data; simulate the remaining parameters, or immediately obtain oscillatory characteristics by setting only qualitative parameters of the blade. The proposed method makes it possible to simulate the oscillation spectrum fairly accurately and without the use of additional means [8].

In contrast to the simulation of vibration spectra, diagnostics using anomalies in the structure of the spectrum is a more analytical issue, requiring an understanding of the life cycle of the blade [9]. For the analytical evaluation of the data obtained, it is necessary to identify criteria in accordance with which anomalies should be compared and calculated. Due to the fact that we remove 2 wave characteristics – working (vibration) and radio frequency (converted by the sensor), then the criteria will be set for these measured values. It is also necessary to take into account that the operating characteristic has such a property as the cyclicity of responses, which must be taken into account when calculating and modeling more than one cycle. Then, according to [6], the frequency of the workflow is

$$F_{И} = \frac{F_r n}{60} = F_{\text{В}} n, \quad (1)$$

where F_r – the number of revolutions (rpm) of the rotor; $F_{\text{В}}$ – the rotation frequency of the rotor, Hz; n – the number of turbine rotor blades.

Let us consider the use of the spectrum of radio response sequences. The workflow with this spectrum modulates the radio frequency oscillation in the autodyne sensor (Figure 1). When studying the figure, it becomes obvious that the processes of vibration of the gas turbine engine during movement and the flow of the medium passing through the gas turbine engine contribute to each peak section. The graph shows that two characteristics of the read signals are displayed at once: the amplitude for the vibration effect and the frequency for the translated radio signal.

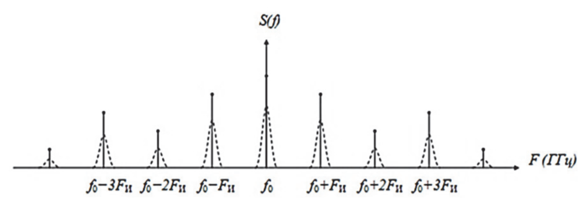

Figure 1. Radio frequency response spectrum, hHz

Since the spectral components in this case are of interest not only as an amplitude characteristic, but also as a true value modulo, it is necessary to develop a mathematically sound calculation method, according to which the main control parameters of reliability for any given blade will be calculated further. All calculations and algorithms will be further carried out within the $(-\theta_1, 0)$ half-wave segment of the cosine, where $[\cos\theta - \cos(\omega t)] = \cos\tau$, $\omega = 2\pi(F_{И}, t)$, τ are dimensionless [9].

The approximation of the symmetric branch of the cosine should be carried out taking into account the slow: $\rho\tau(\rho < 1)$ and fast oscillation phases: $q\tau < (q < 1)$ having an amplitude of $\mu << 1$.

Based on the above, we will make a system of equations:

$$\alpha(\tau) = \begin{cases} 0{,}5A(\cos\tau - \cos\theta_1), \tau \in (-\theta_1, 0); \\ 0{,}5A(\cos\theta_1 - \cos(\rho\tau) + \mu\cos(q\tau)), \tau \in (0, \theta_2). \end{cases} \quad (2)$$

Since there is a radio frequency characteristic in the spectral characteristic under consideration, the use of Fourier coefficients will be legitimate:

$$\gamma_n(\theta_{1,2}, p, q, \mu) = \frac{1}{\pi A}\int_{-\theta_1}^{0} a(\tau)\cos(n\tau)\, d\tau. \quad (3)$$

A significant advantage of the chosen approximation method is the simplicity and possibility of obtaining equations without composing systems and matrices, which not only simplifies calculations, but also reduces the probability of error. The main components of the study and approximation are the constant component (4) and the amplitude of the first harmonic (5):

$$\gamma_0(\theta_{1,2}, p, q, \mu) =$$
$$= \frac{1}{\pi}(\sin\theta_1 - \theta_1\cos\theta_1) +$$
$$+ \frac{1}{\pi p}(\sin\theta_2 - \theta_2\cos\theta_2) +$$
$$= \frac{\mu}{2\pi q}(\sin\theta_2 - \theta_2\cos\theta_2). \quad (4)$$

$$\gamma_1(\theta_{1,2}, p, q, \mu) =$$
$$= \frac{1}{\pi}\sin(2\theta_1) + \frac{1}{\pi p}(\sin(2\theta_2)) +$$
$$+ \frac{\mu}{2\pi q}\left[\frac{\sin(\theta_2(q+1))}{q+1} - \frac{\sin(\theta_2(q-1))}{q-1}\right]. \quad (5)$$

In the process of this study, the determination of the parameters of the working spectrum will allow not only to evaluate the characteristic parameters of the geometric and physico-chemical properties of the working blade, but also by the presence of a discrete component of the spectrum to determine additional effects from the entire unit of equipment on a single blade (Figure 2). This factor is often not taken into account in the workflow, while providing a huge impact on the durability of the blades [10].

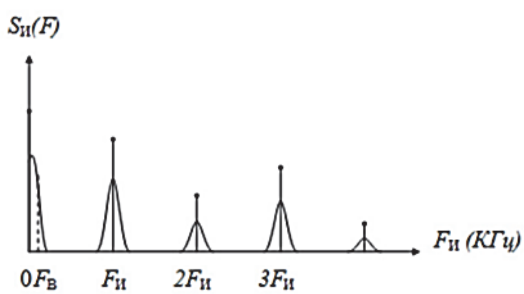

Figure 2. The working spectrum of the GTE blades, kHz

The main diagnostic parameter is the vibration spectrum. Let us consider in more detail its graphical arrangement (Figure 3), in which the initial indications of the movements of control points on the surface of the blade are translated into a spectrum by differentiation. Usually, this spectrum has a non-smooth envelope even in a safe situation, and nevertheless, it is it that is taken as a standard when compared with any real spectrum when evaluating performance characteristics.

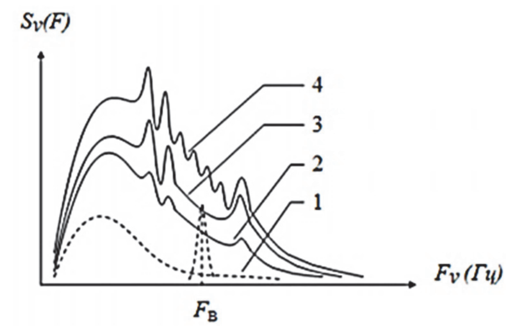

Figure 3. Vibration response spectra, Hz:
1 – reference; *2* – abnormal; *3* – critical; *4* – emergency

Table 1 shows the parameters used to control the reliability of blades, modeling, and calculations in the manufacture of blades, including using additive technologies.

Diagnostic responses and their causes

No.	Cause	Response
1	Shaft speed	Change the workflow interval
2	Shaft beat	Component $F_в$ on several of the impellers
3	Deformation of the blades	Change in the value of γ_n
4	Vibration of the blades	Blurring of spectral lines
5	Blade breakage	Failure of the blades of the $F_в$ component, but of smaller amplitude and observed on one of the impellers

The table shows the most significant criteria that can be used for work on the development of additive manufacturing technology parts. In practice, the assessment of the node's condition is based on a comparison of the readings of several sensors in the corresponding measuring channels. However, excessive complication by introducing additional parameters can lead to an increase in operating time, as well as to errors [7].

2. Choosing an optimization method

When choosing an optimization method, first of all, it is necessary to be guided by two important factors. Firstly, work is carried out on a product of a rather complex geometric shape, characterized by a significant set of requirements for physical and mechanical properties. Secondly, the optimization of the part must be carried out in the context of its manufacture using additive technology. Thus, restrictions will be set not only taking into account the operational properties of the part, but also the method of its manufacture [11].

Since the task is multifaceted, it is possible to use the Pareto principle or transform a multi-criteria design problem into a single-criteria problem. At the first stage, a vector model is created that will allow you to evaluate the shape of the part and make possible adjustments [12] (Figure 4).

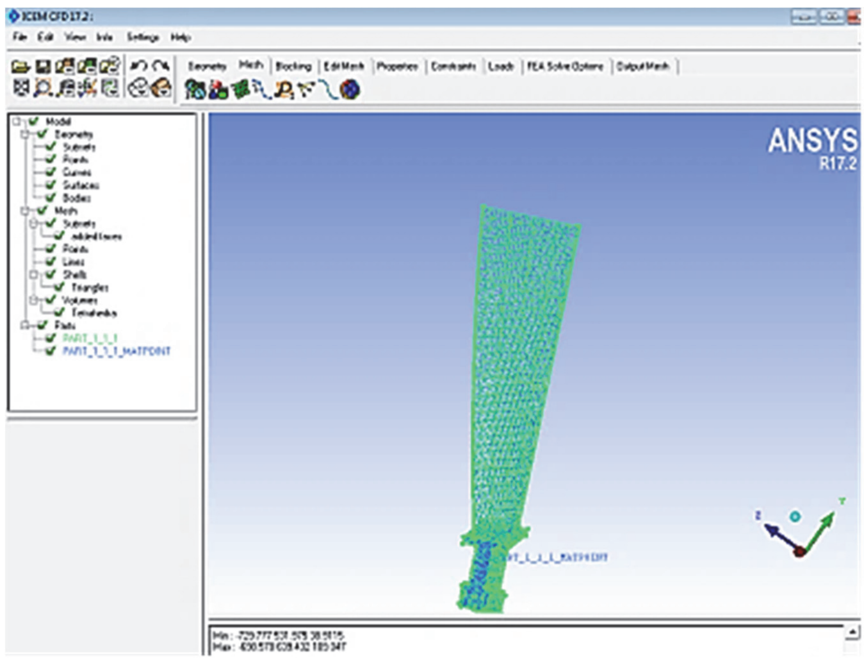

Figure 4. Creation of a vector model of a GTE blade

After building the model, focusing on the final goal, it is necessary to determine the optimization method, which depends on the method of setting parameters, the dimension of the parametric space, the smoothness of the goal functions and constraints, a constant and variable set of restrictions on iterations, etc. These operations are performed using various software modules, since it is quite difficult to manually account for all parameters, and, in addition, the software package allows you to save all iterations and results [13].

The choice of the software product is also determined by whether the optimization is local or global, the choice of the method and the limits of approximation of constructions and transformations will depend on this. Of course, software products that work with local parameters solve problems more quickly, but they are less loaded with source data [14].

Local approximation methods use current information about the point and, possibly, the results of previous iterations. Based on this information, the transition to the next point is carried out. If the problem has several local optima, then each of them will have its own area of attraction, which may be characterized by a complex structure. In this case, global approximation methods have some advantage, especially if the found approximation corresponds to the true functions of the goal and constraints. Despite the fact that the construction of a global approximation requires significantly more calculations of goal functions and constraints, finding several solutions or a Pareto set for a multi-criteria task will be carried out without additional calls to an external calculation program (Figure 5).

Methodically, the optimization of the blade design cannot be reduced to improving a specific parameter without studying the impact This parameter is used in a real system both in a static and dynamic state [15].

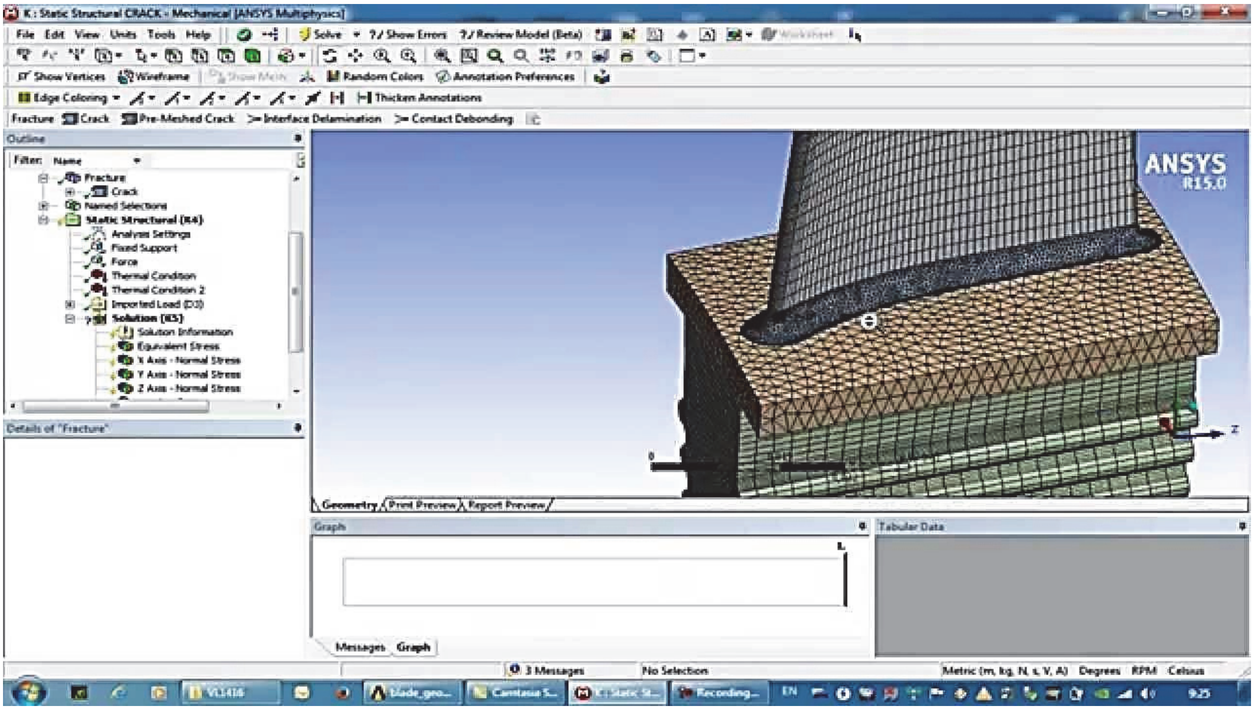

Figure 5. Selection of areas for local approximations

3. Discussion

In general, it is possible to describe and justify an algorithmic approach for the software optimization of a structural element – the blades of a gas turbine engine [16]. Like any modeling software package, this product must have a block or modular structure to divide the task into post-evaluated processes, the results of which in the final module are reduced to obtaining the desired characteristic. A special control program can be used to control the interaction between modules (Figure 6). For simplification, such software packages often use dialog boxes together with a graphical interface that reflects not only the final, but also intermediate results.

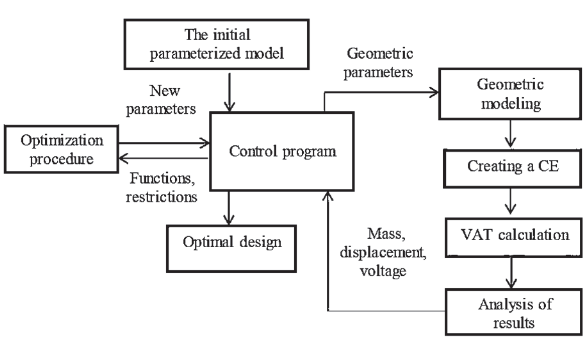

Figure 6. Structure of interaction between modules in the optimization problem

The calculation process itself can take place using the finite element method or the boundary element method [17].

When executing this command file, the following is produced [18]:

– building a geometric model;
– building a finite element grid;
– application loads;
– calculation of stress-strain states;
– output of results.

The algorithm of the program is always the same, so even a single change in parameters triggers the same data processing mechanism.

The study of practical data and equipment catalogs allowed us to conclude that the main approaches to optimizing the blades of the gas turbine engine are reduced to solving the problems of reducing the mass of the entire structure (Figure 7) and obtaining a stress-strain state in the blade and disk that meets the requirements and limitations on manufacturability and strength, which refers to the task of designing the shape of the part [19].

When developing a method for optimizing the blade design, it is necessary to solve not only the problem of geometric characteristics, but also to preserve or increase the reliability and wear resistance of the blade [20]. One of the key points of modeling is the evaluation of the aerodynamics of the part being developed. To conduct research, a part in a computer model is placed in a stream and the emerging pattern of vortex flows and flow around the blade is evaluated (Figure 8).

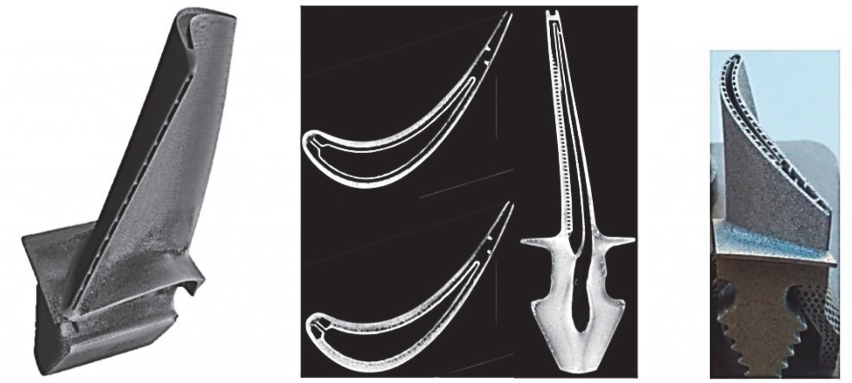

Figure 7. Reduction the mass of the structure due to the creation of hollow blades

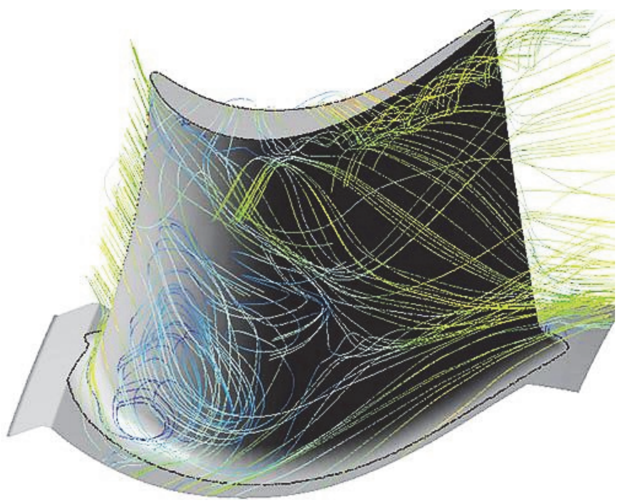

Figure 8. Aerodynamic evaluation of the model

The ultimate goal is to obtain a blade shape that will not overload the system with its mass but will remain strong enough and resistant to vibration loads, temperature fluctuations and will maintain the trajectory of movement in the flow. To fulfill these requirements, it is necessary to take as an optimization criterion the preservation of the constant distance between the corresponding boundary points of the blade sections, especially regarding to the sections on the input and output edges of the blade [21]. It means, it is necessary to optimize the shape of the blade itself so that it remains for a long period of operation [22]. Therefore, it will be more efficient and expedient to optimize not the shape of the blade, but the composite from which it will be made. Additive technologies provide such an opportunity. Taking into account the ability of additive technologies to work with almost any metals and alloys, the proposed optimization direction is extremely relevant [23].

Conclusion

Analysis of the effect of control parameters on the reliability characteristics of the blade of a gas turbine engine showed that as an optimization criterion, it is necessary to take a constant distance between the corresponding boundary points of the blade sections to preserve the shape of the blade over a long period of operation. In the process of the work, a conclusion was made about the effectiveness and expediency of optimizing not the shape of the blade, but the composition of the composite from which it will be made. A method for optimizing the shape of a GTD blade manufactured using additive technology is proposed.

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