Management Engineering Projects of Turbomachinery Bladed Disk Mistuning for Sustainable Energy and Transport Development

Repetckii O. V. [a]
Irkutsk State Agrarian University named after A.A. Ezhevsky, Molodezhny, Irkutsk district, Irkutsk region, Russia
repetckii@igsha.ru

Keywords: Vibration, Frequencies, Intentional mistuning, Forced response, Bladed disk, Finite element model, Block models.

Abstract: The paper analyses possible types of mathematical modelling of the effect of intentional mistuning for axial and radial impellers in order to increase their resource characteristics. The value of the maximum forced response of the rotor blades of turbomachines with parameter mistuning is usually much greater than that of tuned rotors. An increase in the detuning level of this critical value actually leads to a decrease in the amplitude increase coefficient. Thus, an urgent task is to introduce some degree of intentional mistuning into the design of the system to achieve these goals.

All previously known variants of intentional blade mistuning are associated with a change in the rotor blades. However, it is possible to introduce dynamic disturbances of the rotor blades by changing the aerodynamic load acting on them by making minor changes to the geometry or location of the stator blades.

As such changes in the geometry of the stator blades, changes in the initial profile of the stator blades, the rule of the location of the blades along the rim of the disk, the thickness or height of the stator blades, changes in the profile of the stator blades, the angle of installation of the pen profile and other options can be proposed.

The task of deliberately detuning the parameters of the rotor blades due to changes in the stator blades is to calculate how the load and stresses on the rotor blades change if the stator blades alternate according to a certain rule, for example, the 1st blade is straight, the 2nd is curved, the 3rd is straight, the 4th is curved, 9th straight, 10th curved. There may be dozens of such models and all of them will have an impact on the dynamic and strength characteristics of turbomachines.

It is safe to assume that the numerical and experimental study of the durability of axial and radial impellers of turbomachines can significantly reduce the time of creation and refinement of structures, the required computer resources and expensive experiment in the design of new turbomachines for aircraft, chemical, transport and power engineering, as well as correctly evaluate and increase the resource of already working turbomachine designs. In this paper, we study the types of intentional mistuning for axial and radial disks at the design and fine-tuning stage of power and transport turbomachines.

1 INTRODUCTION

The mistuning in the designs of axial and radial bladed discs occurs when there is a slight difference between the blades in weight, geometry, material and other factors that violate the cyclic symmetry of the impellers. Also, the reasons for the mistuning of the parameters are caused by the inevitable technological tolerances for their manufacture, the heterogeneity of the material, the different fit in the locks and the effect of various operational factors. Currently, there are quite a large number of options for deliberate mistuning, each of which can either be used on real structures, or serve as a kind of model that allows you to find certain patterns of the influence of certain changes on the static and dynamic characteristics of industrial turbomachines. The latter include, for example, the introduction of some concentrated masses at certain points on the surface of the blade area. Other parameters can be used for deliberate mistuning of real impellers, since they do not significantly affect the aerodynamics of the working stages of turbomachines. These types include: a slight change in the thickness and degree of twisting of the blades, for example, in violation of the technological

[a] https://orcid.org/0000-0003-2560-2721

processes of manufacturing these structures; the presence of small nicks or cracks during the operation of products, drilling holes in the blade pen, the use of various materials for blades, rounding or cutting the corners of the blade on its periphery, grinding of individual parts of the blade, heterogeneity of the blade material and many other changes (Repetckii, 2022).

2 RESEARCH METHODOLOGY

Turbomachine blade discs are nominally designed to be cyclically symmetrical (tuned system). But the actual vibration characteristics of all the blades on the disc are slightly different due to manufacturing tolerances, deviations in material properties and wear during operation. These small changes violate cyclic symmetry, violate pairs of eigenvalues, and affect the durability of turbomachine impellers.

The values of the mistuning parameters of the blades are determined by the formula (Beirow, Kühhorn, Figaschewsky, Bornhorn, Repetckii, 2018)

$$\Delta f_i = \frac{f_{j,i} - \overline{f}_j}{\overline{f}_j}, \qquad (1)$$

where $f_{j,i}$ - is the value of the frequency of the j-th shape of the vibration of the blades, $i = 1,\ldots,N$ (N is the number of blades), $\overline{f}_j$ - is the arithmetic mean of the fundamental frequencies.

The degree of mistuning is taken into account by the coefficient (Repetski, Rygikov, 2008 and Repetski, Zainchkovski, 1997):

$$S_k = \frac{1}{\overline{f}_j}\sqrt{\frac{1}{N}\sum_1^N \left(f_{i,j} - \overline{f}_j\right)^2}. \qquad (2)$$

Many researchers suggest that incorrect tuning has an undesirable effect on the dynamic response. It causes a self-excited vibration on the discs with blades. Also, gas turbines often operate at high loads from rotation and temperatures. In order to meet the new requirements for the efficiency, performance and durability of turbines, it is necessary to ensure that new system designs do not fail during the planned design life. There are three types of blade defects for the reasons of their occurrence: structural (for example, the presence of stress concentrators), technological (caused, as a rule, by the deviation of the blade from the optimal production process), and operational (corrosion and erosion processes, deviations from the nominal mode, etc.). According to statistics (Godovsky, 2006 and Repetski, Rygikov, Springer, 1999), 29% of defects they are structural, 17% and 11% are technological and operational, respectively, and the remaining 43% of defects are caused by a combination of these factors. However, a number of researchers still consider operational defects (often erosion of the blades) to be the main cause of deviations from the design modes and failures of gas turbine facilities (GTF). The development of certain defects will largely depend on the GTF scheme, the degree of refinement of the design solution and operating conditions.

There are several types of reasons for the failure of the axial or radial compressor blades (Godovsky, 2006 and Repetckii, 2022):

- Pore the surface of the part as a result of mechanical exposure by extraneous objects that fall into the running part. The shoulder blades of the axial compressor always work under the influence of quickly air flow. Any solid material captured by air will cause damage as a result of erosion or blow, and the all -in -ness of the appearance of a dent in the form of a small smooth depression with rounded edges and angles. These dents become stress concentrators and reduce vibrational strength and reduces the operational reliability and safety of working blades. The desire to make the edges of the blades thinner in order to reduce losses and increase the fuel efficiency of the turbine, makes the problem of damage to the blades by foreign objects even more relevant.
- Destruction of the shoulder blade is a type of fatigue caused by large plastic deformations with some number of load cycles before destruction. Strength destruction are divided into two types: low -cyclic fatigue and high -cycle fatigue. The most important causes of low -cyclic fatigue are transition temperatures. The most clearly they appear during launches and stops due to differences in heating and cooling of various sections of the aerodynamic profile. And high-cyclic fatigue is the result of a high vibrational stress during a forced reaction. A forced response usually occurs in conditions of a heterogeneous field of flow, when the frequency of excitation from non -stationary aerodynamic load coincides with the natural frequency of any blades.
- Continuous deformation of the part when operating at high temperatures and (or) centrifugal loads will cause creep in the hot part of the engine (turbine) and in the last blade steps of high -pressure compressors. When working on these conditions, the shoulder blades are lengthening towards the surrounding casing of the bandage. To increase the

engine efficiency, the gap between the shoulder blades and the housing should be as low as possible. When severe operating conditions cause a strong lengthening of the blades, then the tips of the shoulder blades rub against motionless covers, with the possibility of damage.

- Slow deterioration of the surface of the part or its coating as a result of a chemical or electrochemical reaction with atmospheric or hot gas pollution in the working environment. Details of aluminium and high - Strength alloys, as well as some stainless steels, can be corroded when stretching stresses are exposed to them.
- Flows from manufacturing technology lead to a violation of the frequency characteristics of the shoulder blades, both the rotor and the stator, which leads to the expansion of the range of resonant modes of the blades and can cause cracks for the formation of cracks.

In this work, some aspects of the analysis of the effectiveness of mathematical modelling and introducing intension mistuning at the stage of design and operation of axial and radial turbomachines (Fig. 1-12) reflected in well-known work are investigated (Repetckii, 2022):

Figure 1: Drilling holes.

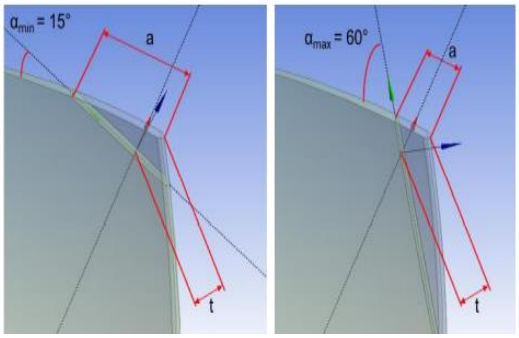


Figure 2: Cutting the shoulder blade.

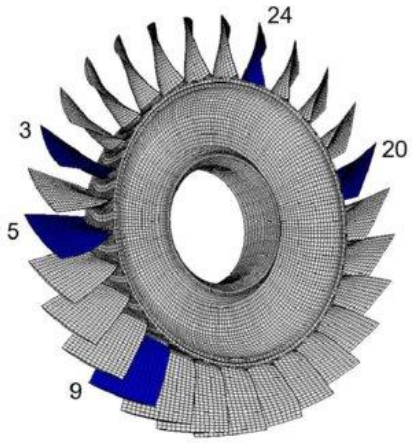


Figure 3: FEM with a geometric blades mistuning 3, 5, 9, 20 and 24.

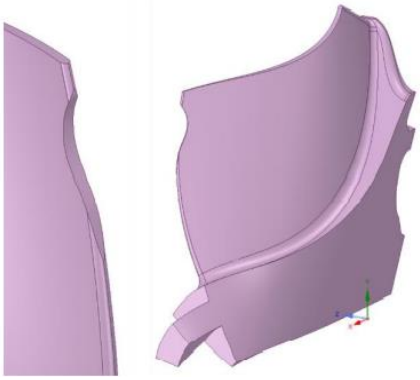


Figure 4: Processed edge.

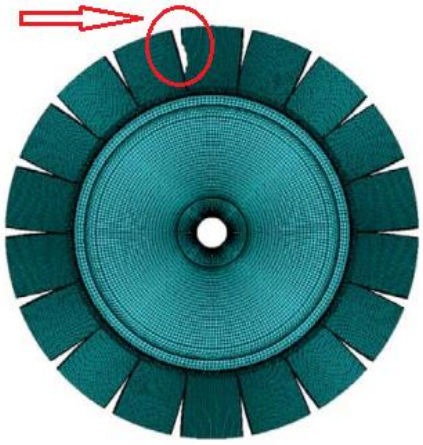


Figure 5: Mistuning with one blade in the block model.

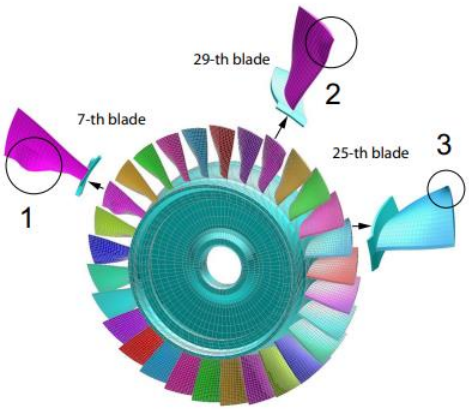


Figure 6: Changes in the geometry of three arbitrarily selected blades.

Figure 7: Turbine wheel of a turbocharger with additional masses on the shoulder blades.

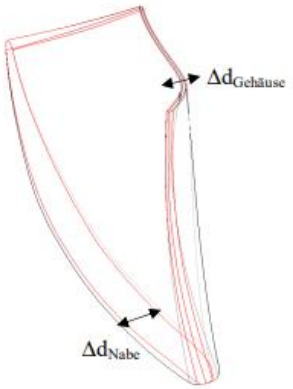


Figure 8: Change in the geometry of the radial blade in height.

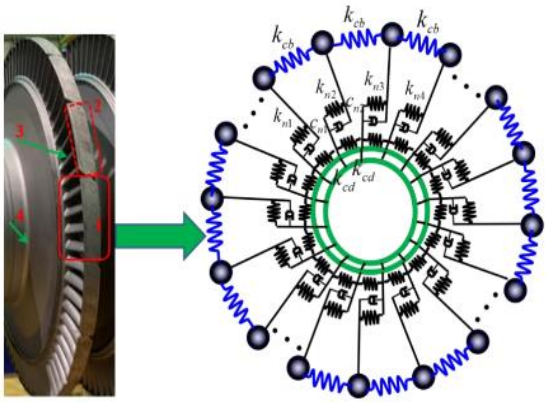


Figure 9: Model of the multi-packet disk (1-package, 2-band, 3-blade, 4-disk.

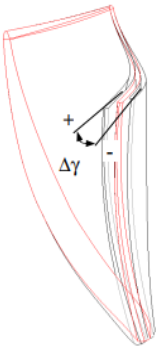


Figure 10: Change in the geometry of the radial blade by twist.

(a) Bladed disk featuring 2 mistuned blades

(b) Bladed disk featuring 3 mistuned blades

Figure 11: Bladed disk with 2 mistuned blades, (b) a bladed disk with 3 mistuned blades.

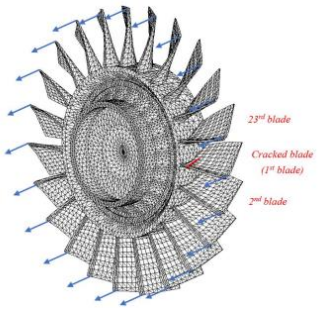


Figure 12: The finite element model of a mistuned blade disk with a cracked blade.

3 RESULTS OF RESEARCH

Such modelling of intentional mistuning parameters has been analysed in computational and partially experimental studies of both academic and real designs of gas turbine facilities and engines.

A similar analysis was performed using the example of a computational experiment for an academic impeller (Repetckii, Nguyen, Beirow, 2023) with 10 blades (Fig. 13).

Next, a numerical analysis of the conduct of intentional mistuning and its effect on the durability of this design was performed (Repetckii, 1995). The analysis of Table 1 shows that when the radius of transition of the blade to the disc changes at R = 1 mm, the durability of the academic wheel with intentional mistuning increases by 19.4% for second block model (it is the model in which there are alternating 3 blocks with 3 identical blades in the block and one single blade No. 10).

In the case of a cut of the output edge of the blade (t = 15mm), we obtain a decrease in the durability of the academic wheel in comparison with the original wheel by -4.2% (the second block model). The use of these results in the creation of GTF makes it possible to increase the efficiency and reliability of new structures at the design stage, fine-tuning and operation of elements of turbomachine impellers.

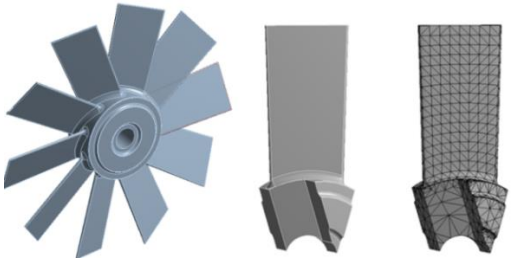


Figure 13: General view and FEM of the academic impeller.

Table 1: Durability calculation.

Case of geometric or mechanical change	Durability (in cycles)
R5-R1	$1.7065 \cdot 10^6$
R5-R3	$1.4577 \cdot 10^6$
R5-R7	$1.4205 \cdot 10^6$
$H_1 = 1.1 * H_0$	$1.4327 \cdot 10^6$
$H_2 = 0.9 * H_0$	$1.5601 \cdot 10^6$
Cutting (t=30мм, $\alpha = 8°$)	$1.4859 \cdot 10^6$
Cutting (t=15мм, $\alpha = 60°$)	$1.3680 \cdot 10^6$
4 holes on the left side of the blade	$1.4859 \cdot 10^6$
4 holes on the right side of the blade	$1.5528 \cdot 10^6$
Material: Steel - Titanium	$1.6722 \cdot 10^6$
Material: Steel - Titanium	$1.6611 \cdot 10^6$
Material: Steel - Titanium	$1.5552 \cdot 10^6$

Currently, there are quite a large number of variants of intentional mistuning caused by geometric or mechanical changes, each of which can be used both on real structures and serve as a kind of academic model (see above), which allows us to find certain patterns of the influence of certain changes on the static and dynamic characteristics of industrial turbomachines. Some geometric parameters can be used for intentional mistuning of real impellers, since they do not significantly change the aerodynamic characteristics of the stages of turbomachines.

4 DISCUSSION OF THE RESULTS

All previously known variants of intentional blade mistuning are associated with a change in the rotor blades. However, it seems possible to introduce such dynamic disturbances of the rotor blades by changing the aerodynamic load acting on them by making minor changes to the geometry of the stator blades.
Such changes in the geometry of the stator blades can be a change in the initial profile of the stator blades (Fig. 14); the rules of the location of the blades along the rim of the disk (Fig. 15); the thickness or height of the stator blades; changes in the profile of the stator blades (Fig. 16), the angle of installation of the pen profile (Fig. 17), etc. the intentional mistuning of parameters due to changes in the stator blades is to calculate how the load and stresses on the rotor blades

change if the stator blades alternate according to a certain rules, for example, the 1st blade is straight (Fig. 16), the 2nd is curved (Fig. 17), 3rd straight, 4th curved,... 9th straight, 10th curved. The next model may have a different rules of the arrangement of the blades (1-5 blades are straight, 6-10 blades are curved). The same can be done by changing the angle of the flow exit from the guide blade of the stator in the middle section (Fig. 18). There may be dozens of such models.

Many researchers suggest that intentional mistuning has an undesirable effect on the dynamic response of the rotor blades. It can cause self-excited vibration on disks with axial and radial blades. The turbines also operate at high centrifugal and gas loads and temperatures. In order to meet the new requirements for the efficiency, performance and durability of turbines, it is necessary to ensure that new designs do not fail, and intentional mistuning would increase resource characteristics.

The above section describes the simulation of intentional mistuning of rotor blades due to the mistuning of the stator blades, and as a result, a slight change in the aerodynamic load on the rotor blades, and consequently changes in the resource characteristics of turbomachines.

Figure 14: The initial profile of the stator.

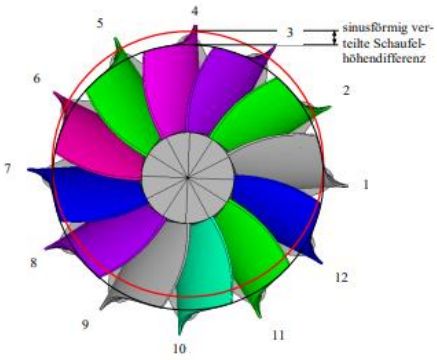


Figure 15: Change in the rules of installation of guide blades (GB) along the rim of the disk.

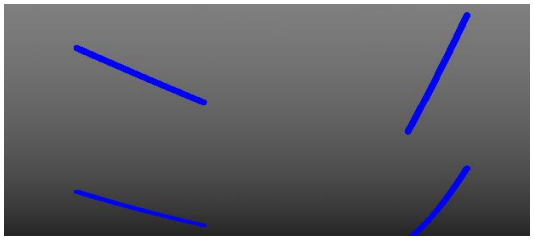


Figure 16: GB with a rectangular profile.

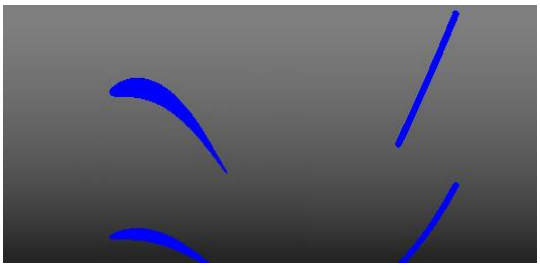
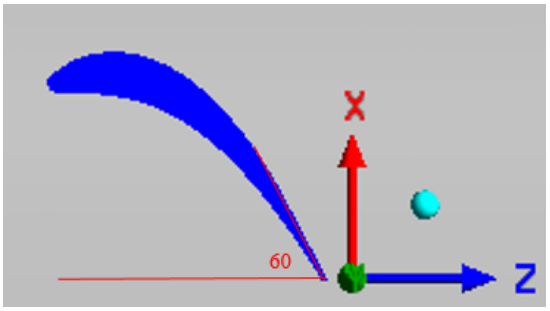


Figure 17: GB with a curved profile.



$\alpha_1 = 60^\circ$

Figure 18: Changing the angle of the flow exit from the guide blade of the stator.

The analysis of the effect of intentional mistuning on the fatigue strength of academic blade structures is also carried out. These results of studies of various types of intentional mistuning can be used to design and fine-tune the blades of the impellers of axial and radial turbomachines in order to create structures of increased service life or prolong it in operation (Repetckii, Ryzhikov, Nguyen, 2018).

REFERENCES

Beirow B., Kühhorn A., Figaschewsky F., Bornhorn A., Repetckii O.V., 2018. Forced response reduction of a blisk by means of intentional mistuning. In *Proceedings of the ASME Turbo Expo. Turbomachinery Technical Conference and Exposition, Cep. "ASME Turbo Expo:*

Turbomachinery Technical Conference and Exposition", GT 2018-76584.

Godovsky D. A., 2006. Defects of elements of gas turbine installations. In *Oil and gas business, Volume 4, No. 1, P. 201-206.*

Repetski O., Rygikov I., Springer H., 1999. Numerical analysis of rotating flexible blade-disk shaft Systems. In *Proceedings of the ASME Turbo Expo, P. 317*

Repetckii O.V., 2022. Mathematical modeling of types of deliberate detuning of axial and radial impellers of turbomachines. In *Climate, ecology, agriculture of Eurasia. Materials of the XI International Scientific and Practical Conference. Irkutsk, p. 318-327.*

Repetski O., Rygikov I., 2008. Modeling and simulation of dynamic processes with the help of program package BLADIS+. In *Innovations and Advanced Techniques in Systems, Computing Sciences and Software Engineering, p. 219-220.*

Repetckii O.V., Nguyen V. V., Beirow B., 2023. Sensitivity analysis regarding the impact of intentional mistuning on blisk vibrations. In *Proceedings of the 10th International Conference on Wave Mechanics and Vibrations (WMVC 2022), p. 408 – 415.*

Repetsky O.V., Nguyen T.Q., Ryzhikov I.N., 2017. Investigation of vibration and fatigue life of mistuned bladed disks. *In Proceedings of the international conference actual issues of mechanical engineering (AIME 2017), p. 702-707.*

Repetski, O., Zainchkovski, K., 1997. In The Sensitivity Analysis for Life Estimation of Turbine Blades. In *Proceedings of the 1997 ASME ASIA Congress & Exhibition, p. 136.*

Repetckii, O., Ryzhikov, I., Nguyen, T.Q., 2018. Dynamics analysis in the design of turbomachinery using sensitivity coefficients. In *Journal of Physics: Conference Series, p. 012096.*

Repetckii, O., 1995. Development of Mathematical Models for Assessment of Damage Accumulation and Predictions of Life for Turbomachine Blade. In *Proceedings of Higher educational institutions. Machine building 1-3, p. 45-53.*