Gas-Dynamic Methods to Reduce Gas Flow Nonuniformity from the Annular Frames of Gas Turbine Engines

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Abstract. Gas flow nonuniformity is one of the main sources of rotor blade vibrations in the gas turbine engines. Usually, the flow circumferential nonuniformity occurs near the annular frames, located in the flow channel of the engine. This leads to the increased dynamic stresses in blades and consequently to the blade damage. The goal of the research was to find an acceptable method of reducing the level of gas flow nonuniformity. Two different methods were investigated during this research. Thus, this study gives the ideas about methods of improving the flow structure in gas turbine engine. Based on existing conditions (under development or existing engine) it allows the selection of the most suitable method for reducing gas flow nonuniformity.

1. Introduction
Circumferential nonuniformity of gas flow is one of the main sources of turbomachinery rotor blades destruction [1-6]. Several approaches are implemented in practice to reduce the level of gas flow nonuniformity. The main idea of these methods is to eliminate the negative effect of nonuniformity. Firstly, it is possible to modify the design of turbomachinery by changing the axial clearance between the RW and GV or by changing the stagger angles and pitch of GV blades to non-uniform [7-9]. Secondly, the modifications can be implemented for the annular frame by changing the number of struts or using the inclined struts. However, it is difficult to use them for existing engines.

This article is dedicated to reducing the circumferential nonuniformity of gas flow appeared form the annular frame of axial compressor. The goal of this research was to find the ways of the flow nonuniformity reduction, which would lead to a decrease in the level of dynamic stresses in RW blades located in front of the annular frame, but would not require a fundamental engine design changing.

Both ways of reduction of flow nonuniformity including variations in design of compressor and frame were considered in the paper. The main advantage of this research is detailed consideration of the reasons of negative effects of flow nonuniformity and possible ways to reduce the nonuniformity.

2. Motivation of the research. Description of the compressor.
The motivation for this study was the real-life problem of the destruction of rotor blades of the fifth rotor wheel in intermediate pressure compressor (RW5 in the Figure 1). This compressor is part of a gas turbine engine NK-36ST, which has been designed and manufactured at JSC "Kuznetsov" [10].

The cause for the blade destruction is circumferential flow nonuniformity from the struts of the annular frame. The struts have different thickness and uninorm distribution (Figure 2). The struts cause the local areas of high pressure (Figure 3).
3. Method of calculation of the level of gas flow nonuniformity

Step 1. CFD simulation of the sector IPC model at the main GTE modes which consists of intermediate annular frame, all blade rows of IPC, middle annular frame, and HPC IGV domains. All blades were simulated as one blade passage with periodical boundary conditions; frames were simulated as a sector of one strut. To transfer flow parameters between the domains, the Mixing Plane interface averaging the flow parameters in the circumferential direction was used [11]. The aim was to determine the distribution of the flow parameters along the height of flow section (total pressure, total temperature and flow angle) behind the RW4. These parameters then were used as boundary conditions for subsequent calculations.

Step 2. Calculation of the "full circle" model. Full circle model is used to detect the flow circumferential unevenness, which arises from the annular frame struts. Full circle model consists of GV4, RW5 and GV5, the middle annular frame and HPC IGV. Gas dynamic load on the all blades and static pressure distribution along the circumference of the RW5 are determined in this calculation.

Finite volume mesh of the full circle model was created in AutoGrid5 [11]. Parameters of the mesh and configuration of computational models were chosen according to the recommendations from [12, 13]. Computational models have been verified [7, 14].

Total pressure, total temperature, flow direction at the inlet obtained from sector model and static pressure at the outlet of were set as boundary conditions for the full circle model. To transfer parameters between rotating and stationary domains of the full circle model, the interface Frozen Rotor was used. This interface transmits the flow parameters between domains without their averaging in the circumferential direction [15]. Thus, it can be used to calculate the circumferential flow nonuniformity.
4. Gas-dynamic methods to reduce gas flow nonuniformity

One of the methods of circumferential nonuniformity reduction is to use guide vanes with different circle pitch and different stagger angles in front of annular frame struts [8, 9]. This allows to redistribute the flow between the blade passages and to adjust the position of high pressure zones [16].

To implement the proposed method, a parametric model of IPC GV5 was created. Guide vanes were divided into 7 groups according to the location of 7 struts of the annular frame. Changes in the stagger angles and pitch were performed within each group. The minimum number of variable vanes was a key factor, since the production of many blades with different geometry greatly increases the charges.

The stagger angle of has not been changed for GV5 vanes located in the symmetry plane of the strut, the first and the last vane in the group. Changing the stagger angles was carried out according to the linear law. Vanes located on the opposite sides of symmetry plane of the strut were rotated in opposite directions (Figure 4). When the vanes are located closer to the strut, they were rotated by a larger angle. If the stagger angle increases, there is sign "+" before the angle. If the stagger angle decreases, there is sign "-" before the angle. Stagger angles were measured from the leading edge plane.

In case of the pitch change, the number of variable vanes was not restricted. Different pitch was set within -0.35...+0.35 of the initial pitch. The sign + (-) indicates that the pitch increase (decrease). The number indicates the maximum increase (decrease) in the pitch between the vanes in the group in relative values from the initial pitch with evenly spaced vanes. The position of extreme vanes in the groups has not been changed. The law of the pitch changing was also linear.

There were investigated 11 different configurations of GV5 with circumferentially different stagger angles and pitch. The variants with the greatest decrease of dynamic stresses are shown in the Table 1.

Ununiform stagger angles and pitch allow to achieve a significant reduction in gas flow nonuniformity. Flow structure becomes more uniform due to the redistribution of the flow (Figure 5). In addition, the values of pressure peaks behind the RW5 were reduced (Figure 6). These improvements lead to the decrease in dynamic stresses in rotor blades. That was confirmed in [17] with the help of calculation method proposed by researches A.I. Ermakov and A.O. Shklovets.

Implementation of this method leads to a complication of manufacturing technology, since it is necessary to produce the guide vanes using a new technology in this case.

![Figure 4. Scheme of GV vanes position change.](image1)

![Figure 5. Static pressure distribution of basic variant (a) and GU variant No. 9 (b).](image2)
Another method for reducing the circumferential nonuniformity is based on the results of [16]. It is
in distancing the leading edge of frame struts from the trailing edge of GV blades located upstream.
An important requirement is to maintain the internal cavities of frame struts the engine system.

Struts can be divided into three groups according to the maximum thickness of profile Cm: thick
(strut No. 1), medium (struts No. 2,4,5) and thin (struts No. 3,6,7) (Figure 2).

To implement the method of the nonuniformity reduction, the parametric models were developed
for each type of the strut. The models allow to adjust the position of the leading edge, maintaining the
thickness and the rest of the profile by specifying the desired value of shifting (Δb) (Figure 7). Parametric models consider the limitations related to the location of the engine systems in the struts.

**Figure 6.** Graphs of the relative static pressure behind RW5 of the basic (a) and GV variant No. 9 (b).

**Table 1.** The results of the parametric IPC model calculation.

| No | Parameter of stagger angles, maximum stagger angles (No. of blades) for groups: 2, 5, 6 | Parameter of alternating blade pitch for the groups: 1, 3, 7, 4 (3) | Number of variable blades | Dynamic stresses MPa |
|----|-----------------------------------------------------------------|-----------------------------------------------------------------|--------------------------|-----------------------|
| 4  | 3 (6)                                                           | 3 (6)                                                           | 3 (8)                    | 0.3                   |
| 9  | 6 (2)                                                           | 6 (2)                                                           | 6 (2)                    | 0                     |

**Figure 7.** The algorithm of shifting the leading edges of struts

**Figure 8.** Finite volume mesh for the elementary model with thick struts.

To analyze the effect of leading edge shifting on the circumferential nonuniformity of the gas flow,
the set of computational models of the compressor was created using the parametric models of the
struts. All of them were full circle models and consisted of GV4, RW5 and GV5, middle annular
frame, and IGV of HPC. The annular frame contained only two struts opposite each other with the
same thickness in each model (Figure 8). These elementary model were created to assess the
contribution of each type of strut in the total circumferential flow non-uniformity. In other words, they were used to calculate the pressure peaks occurring opposite each type of strut.

Moreover, leading edge shifting of struts with $\Delta b = 0$, $\Delta b = 0.2$, $\Delta b = 0.4$, $\Delta b = 0.6$, were set for each type of struts in different models. Thus, the total number of computational models was 12.

The calculation and analysis of the results were carried out in Ansys CFX using the supercomputer of SSAU “Sergei Korolev”.

The circumferential distributions of relative static pressure in the section behind the RW for each type of strut with all values of leading edge shifting were obtained. It should be noted that obtaining of the pressure distribution only for one model took a long time, both in terms of creation model, and the calculation process. The total time for testing of just one variant is approximately 12 hours. Computational models were verified in [7, 17] while assessing the level of vibrations in rotor blades. These distributions were averaged to obtain the so-called elementary peaks (Figure 9).

![Figure 9](image)

**Figure 9.** The distribution of the relative static pressure for thick strut with $\Delta b = 0$ (a), $\Delta b = 0.6$ (b).

Annular frame struts lead to the complex pressure peaks after the RW. The peaks have not only the maximum jump $h$ (positive upper part of the graph), but also it goes into the decline $h_1$ (Figure 9).

Maximal jump of pressure peaks $h$ decreases while the leading edge shift is increasing. Maximum drop of pressure peaks $h_1$ does not depend on the shift of the leading edge. Similar results were obtained for the other types of struts. To verify the adequacy of the dependences, the graph from the individual elementary peaks of each type of the struts was assembled and compared with the graph for the reference design of annular frame (Figure 10). In general, graphics derived from the elementary peak, describe the pressure distribution after the RW well.

Quadratic equations were derived for each type of strut using the regression analysis that describe the effect of the leading edge shift ($\Delta b$) on the pressure peak height ($h$). Equation 1 corresponds to the thick strut, Equation 2 to the medium struts and Equation 3 to the thin struts.

$$h = 0.001\Delta b^2 - 0.135 \Delta b + 7.5$$  \hspace{1cm} (1)

$$h = 0.001\Delta b^2 - 0.095 \Delta b + 4$$  \hspace{1cm} (2)

$$h = 2.64 \cdot 10^{-18} \Delta b^2 - 0.02 \Delta b + 2$$  \hspace{1cm} (3)

Application of leading edge shift of annular frame struts allows for not only quantitative changes in the values of pressure peak (Figure 11). The proposed method also provides better quality of flow structure: field becomes more uniform, high-pressure zone reduces.

The received regression equations were used for optimization of the location and shift of annular frame struts to reduce the dynamic stresses on the rotor blades [18].
Figure 10. Graph of relative static pressure after RW obtained by different methods.

Figure 11. Circumferential distribution of the relative static pressure for the reference design and frame with shifted leading edges.

5. Conclusion.
Several approaches to decrease the gas flow nonuniformity in the axial compressor because of the annular frame have been developed because of conducted research. Proposed approaches allows to reduce the level of pressure peaks after the RW of the last compressor stage. Firstly, it was suggested to modify the guide vanes of the last compressor stage. It was found that the different stagger angles and alternating pitch flatten the circumferential variation after the RW5. In addition, flow field becomes more uniform and periodic. Secondly, the circumferential unevenness of gas flow in the compressor can be reduced by distancing its source (the support rack) from the elements, experiencing the negative impact of circumferential unevenness of gas flow (rotor blades located upstream). This is accomplished by shifting the leading edges of the support racks. The advantage of the second method is that it makes possible to predict the pressure peak level behind the RW without the long process of preparation of the computation model, calculation and post-processing of the results by using surrogate models. This can accelerate the design process of new compressors and design refinement of existing units.

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