NUMERICAL AND EXPERIMENTAL RESEARCH OF THE CIRCUMFERENTIAL GROOVES CASING TREATMENT INFLUENCING ON PERFORMANCE OF THE FIRST HIGH-LOADED COMPRESSOR STAGE

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This work numerically and experimentally studies the typical first high-loaded compressor Stage A-1 in two configurations: with smooth walls and with circumferential grooves casing treatments above the rotor blade. Characteristics of the high-pressure compressor are strongly dependant on fineness of its first high-loaded stage. Therefore, designing and testing of an individual stage is an important task. The casing treatments lead to an increase in gas dynamic parameters of Stage A-1 and a decrease in its pulsations. This can be explained by the fact that grooves generate additional vortices, interacting with the main tip leakage vortex. This non-stationary interaction leads to a weaker tip leakage vortex and an improvement of flow in the Stage.

Keywords: compressor, tip leakage, casing treatment.

1. Introduction

Casing treatments are of great interest, because it is possible to achieve various improvements in HPC stage performance by changing CT parameters (types, shapes, locations, sizes, etc.). A complex mechanism of interactions between CT and flow in the compressor stage calls for careful consideration for any new component. The advantage of the labyrinth-type CTs over other types is relative simplicity of their manufacturing.

Prospects for this technology are confirmed by numerous published works on this subject. Work [2] shows that a labyrinth CT can reduce mass flow through the tip clearance and change a trajectory of leakage vortex, thereby positively effecting on stall margins.

The complexity of CT effect correct modeling and tracking these effects in tests is demonstrated in [2]. The authors use the LES approach to simulate unsteady flow in the compressor; SPIV measurements are used to visualize flow found in tests. It is shown that, in spite of small sizes of grooves, a considerable part of total flow (1.5%) passes through grooves resulting in higher rotor tip loading. In [3], the authors show that the labyrinth-type CT can reduce the sensitivity of stage parameters to an increase in the tip clearance.

Located directly above the tip clearance, the labyrinth-type CT interacts with leakage vortex and suppresses its strength [4]. In work [5], it is shown by calculations that the labyrinth CT can provide a positive effect on stall margins. The positive effect of grooves on stall margins is also found in [6-8] - it is underlined that the labyrinth-type CT results in a considerable decrease in a blockage area at the rotor tip, as well as a weaker vortex rolling up in the tip clearance.
Work [9] focuses on the effect of geometric parameters of one groove and its position relative to the rotor blade on characteristics of the stage. It is shown that in order to increase the stall margin of the stage, the groove should be triangular and located at the leading edge of the rotor blade; to increase the stall margin, the groove should be trapezoidal and located at the trailing edge. It is also noted that these effects are independent, and they can be combined.

An important parameter in CT designing is the tip clearance, since the amount of air flowing through the clearance and, consequently, the CT effect, depends on its sizes. The CT effect is studied in work [10] at design and increased tip clearance values. It is shown that flow behavior considerably changes and the CT effect is lost as a result of an increase in the tip clearance. The authors point out that an important parameter is the axial location of the groove.

Work [11] studies the displacement of the total labyrinth-type CT consisting of 6 rectangular grooves - upstream and downstream relative to the rotor blade. It is shown that in those cases where the grooves are not above the rotor, they become inefficient, and max. increase in the stall margin (by 10.3%) is observed where all grooves are in the area above the rotor.

In [12], the authors study the effect of the labyrinth-type CT on flow with rotor blade sweep at the tip. It is shown that blade sweep can enhance the effect of CT and additionally increase the stall margin.

In [13], a combined CT consisting of two types (a labyrinth-type and a slot-type) is studied. The first CT is located in the region of the leading edge, and the second - in the region of the trailing edge. As a result of numerical and experimental studies, it is shown that both types of CT exert an impact on flow. It is noted that the impact on stall margins is associated with changes in the leakage vortex trajectory, and losses of efficiency are interrelated both with an increase in entropy in casing grooves and slots as well as losses caused by flow induced by casing slots.

2. Test component

Stage A-1 – the standard HPC high-loaded stage - provides the following parameters: corrected air flow - \( \dot{G}_{\text{air,cor.}} = 24.4 \text{ kg/s} \); total pressure ratio - \( \pi^* = 2.28 \); flow angle at the rotor inlet - \( \alpha_1 = 89^\circ \); flow angle at the stator outlet - \( \alpha_4 = 69^\circ \); rotor inlet outer diameter - \( D_1 = 0.55567 \text{ m} \); relative hub diameter at the rotor inlet - \( d_1 = 0.6623 \); design value of corrected tip speed - \( U_{c,\text{cor}} = 421.23 \text{ m/s} \); design value of theoretical work factor - \( \dot{H}_T = 0.507 \).

The stage consists of three blade rows: IGV (Z=37, \( \overline{h} = 2.42 \)), Rotor – blisk (Z=29, \( \overline{h} = 0.81 \)), and Stator (Z=58, \( \overline{h} = 1.11 \)). IGV and Stator vanes are variable (\( \Delta \delta_{\text{IGV}} = -33^\circ \pm 3 \) and \( \Delta \delta_{\text{S}} = -15^\circ \pm 3^\circ \)).

Fig. 1 shows the Stage A-1 flow passage and Sections from 0-0 to V-V for installation of measuring instrumentation.

The test component with a smooth flow passage (without CT) is assembled with the following clearances between stationary and rotating parts: rotor blade tip clearance along a talc surface is 0.65–0.7 mm (\( \overline{s} = 0.7 \pm 0.75\% \)); tip clearance between rotor blade tips and the hub at the design value of the stator vane angle is 0.6 – 0.75 mm for the leading edge and 1.0 – 1.5 mm for the trailing edge. Figure 2 shows the rotor blisk.

To study the clocking effect, Stage A-1 is assembled with the above-listed clearances (w/o CT) but with the reduced number of IGV vanes (Z=29).
Figure 1: Layout of Stage A

Air flow is measured by Ø320-mm inlet measuring orifice.

Seventy pitot tubes forming 7 total pressure rakes (10 pickup tubes in a rake) located in 7 radii are installed in Section IV–IV. Six tubes (3 tubes at the tip and 3 tubes at the hub) are installed on walls of the flow passage for static pressure measurements in this section. Single-arc rake, three-arc rake and seven-arc rake thermocouples are installed in Section V-V: total number of thermocouples is 28 in 7 arcs (4 temperature pickups in the rake arc).

Additionally, total pressure and temperature pickups for measurements of flow parameters at the rotor outlet are installed at the stator vane leading edges. The 1st, 3rd, 5th and 7th total pressure pickups are installed on one stator vane and the 2nd, 4th and 6th pressure pickups are installed on the next but one stator vane.

Table 1. Installation of total pressure pickup tubes in Section IV - IV

<table>
<thead>
<tr>
<th>Rake No.</th>
<th>R, mm</th>
<th>α°, relative to the axis</th>
<th>Tube No.</th>
<th>Spacing, t, mm</th>
<th>h from the tip</th>
<th>h from the hub</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>264.9</td>
<td>31</td>
<td>1-10</td>
<td>5.78</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>259.5</td>
<td>29</td>
<td>11-20</td>
<td>5.66</td>
<td>8.9</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>253.5</td>
<td>28</td>
<td>21-30</td>
<td>5.53</td>
<td>14.9</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>247.5</td>
<td>28</td>
<td>31-40</td>
<td>5.4</td>
<td>20.90</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>241.5</td>
<td>27</td>
<td>41-50</td>
<td>5.27</td>
<td>26.9</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>235.5</td>
<td>26</td>
<td>51-60</td>
<td>5.14</td>
<td>32.9</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>230.1</td>
<td>26</td>
<td>61-70</td>
<td>5.02</td>
<td>3.5</td>
<td></td>
</tr>
</tbody>
</table>

The static pressure pickups are installed in the same sections as total pressure pickups.

The measurement accuracy in tests at the test facility is shown in Table 2.

Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement range</th>
<th>Measuring device</th>
<th>Measurement error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque</td>
<td>0÷70 kg*m</td>
<td>Torque meter</td>
<td>±0.5% of measured value</td>
</tr>
<tr>
<td>Pressure</td>
<td>-50÷+150 KPa</td>
<td>IKD-27DF</td>
<td>±0.3% of measured value</td>
</tr>
<tr>
<td>Temperature</td>
<td>-20÷+100°C</td>
<td>Chromel-copel thermocouples</td>
<td>±2.5°</td>
</tr>
<tr>
<td>Rotational speed</td>
<td>2000÷20000 rpm</td>
<td>ELURA</td>
<td>±0.2% of measured value</td>
</tr>
<tr>
<td>Air flow</td>
<td>7÷12 kg/s</td>
<td>Flow meter (RMK, Ø320 mm)</td>
<td>±0.5% of measured value</td>
</tr>
<tr>
<td>Pressure pulsation</td>
<td>0÷100 kHz</td>
<td>Fast-response «Kulite» sensors</td>
<td>10% of measured value</td>
</tr>
</tbody>
</table>
3. Numerical model

The NUMECA FINE TURBO 11.1 software package for solution of Reynolds-averaged steady and non-steady state 3D Navier-Stokes equations is used for numerical flow simulation. The computational domain consists of IGV, Rotor and Stator (Figure 3).

The SST two-parameter turbulent viscosity model with wall functions is used as a turbulence model to study the effect of the grid and the labyrinth-type casing treatments. Solutions are found using the Jameson’s finite-difference scheme [12, 13] for the second-order approximation in space and time. The “mixing plane” approximation is used in simulation of rotor-stator interactions to find steady distributions of flow parameters; the NLH procedure is used to find unsteady flow fields.

The block-structured grid is built using the Numeca Autogrid 5 (Figure 4) grid generator. The computational domain consists of 27 blocks in blade channels (3,380,007 cells) and 5 blocks in the casing treatment (512,000 cells). \(y^+\sim 1\). The tip clearance above the rotor is taken equal to 0.4 mm; it covers 17 cells of the computational grid.

![Figure 3: General view of the computational domain](image1)

![Figure 4: Finite-difference grid](image2)

Viscous flow is calculated for the following corrected parameters at the inlet: \(T=288.15\) K, \(P=101325\) Pa at \(n=100\%\) corresponding to 14478 rpm. Conditions of radial flow equilibrium and constant static pressure at the tip are used in the outlet section. Conditions of adhesion and absence of heat transfer are specified on solid surfaces.

The labyrinth-type CT (Fig. 9) consists of 5 identical grooves. The grooves are located above the center of the rotor blade chord projection and blade leading edge. The grid blocks corresponding to circumferential grooves have a periodicity equal to periodicity of the rotor blade channels.

![Figure 5: Labyrinth-type casing treatment under study](image3)

4. Comparison of calculated and experimental data

The calculated and experimental integral characteristics for Stage A-1 with a smooth flow passage at \(n = 100\%\) are shown in Figure 6. As can be seen, there is a difference between calculated and experimental values of flow rate (by 0.5 kg/s); additionally, calculated flow values of the stage
with the CT are shifted more to the right (by 0.3 kg/s). Calculated efficiency is lower than test results by 2-4%; the same is true for the stage margin. Characteristics of the stage with CT calculated in different formulations (Mixing plane and NLH) are almost identical, while the stage without CT shows sensitivity to the calculation procedure. Max. efficiency of the stage without CT in the NLH formulation is 1% higher than in the Mixing Plane formulation.

Figure 6: Integral characteristics of Stage A-1

For comparison, Fig. 7 and Fig. 8 show flow fields in Stage A-1 at the tip (95% of the channel height) at the same back pressure (p = 190 kPa) for the stage with a smooth flow passage and with CT having 5 grooves that are calculated by two different approaches (Mixing plane and NLH). Max. blockage is observed in Figure 7a. When approaching the stall line, a wide area with low Mach numbers is generated at the tip of the stage as a result of tip leakage. Data calculated by two different procedures (Mixing plane and NLH) differ noticeably only for the stage with a smooth flow passage. In the Mixing plane formulation, the blockage at the rotor tip is higher, flow rate is lower (by 0.5 kg/s) and efficiency is also lower (by 0.8%). The CT causes shift of a shock inside blade-to-blade channel in both formulations, while increasing the flow rate in the stage with an increase in efficiency. The results of two formulations for the stage with the labyrinth-type CT are almost identical.

Figure 7: Relative Mach number distribution at the tip of Stage A-1, Mixing plane.

\[ a) \text{ without CT; } G=23.16 \text{ kg/s, } \pi^*=2.26, \eta_{ad}^*=0.861. \ b) \text{ 5 grooves; } G=24.22 \text{ kg/s, } \pi^*=2.29, \eta_{ad}^*=0.88. \]
a) without CT; G=23.63 kg/s, $\pi^* = 2.27$, $\eta_{\text{ad}}^* = 0.869$. b) 5 grooves; G=24.21 kg/s, $\pi^* = 2.29$, $\eta_{\text{ad}}^* = 0.877$.

Figure 8: Relative Mach number distribution at the tip of Stage A-1, NLH.

Figure 9 shows entropy distributions at the tip of Stage A-1 at the point with the same back pressure as calculated by the NLH method. An increase in entropy is clearly visible for a smooth flow passage due to presence of a leakage vortex in the tip clearance. The vortex trajectory tends to the pressure side of the next blade. Application of the CT changes the trajectory of the leakage vortex by directing it closer to the suction side of the initial blade. Max. entropy is located downstream, with an increase in entropy in the area between 3-rd and 4-th grooves, that is the evidence of active interaction between the main leakage vortex and additional vortices generated by the grooves.

a) without CT; G=23.63 kg/s, $\pi^* = 2.27$, $\eta_{\text{ad}}^* = 0.869$. b) 5 grooves; G=24.21 kg/s, $\pi^* = 2.29$, $\eta_{\text{ad}}^* = 0.877$.

Figure 9: Entropy distribution at the tip of Stage A-1, NLH.

5. Conclusions

1. Based on the 3D viscous flow calculations, an algorithm and a mathematical model are developed for numerical simulation of 3D effects in a typical HPC first high-loaded stage with labyrinth-type casing treatments.
2. 3D viscous turbulent flows in Stage A-1 with a smooth flow passage and with a labyrinth-type CT are calculated. It is shown that the CT can increase efficiency of the stage by 1% at $n = 100\%$ in the NLH formulation.
3. The Stage A-1 with a smooth flow passage and with a labyrinth-type CT is experimentally studied in different operating conditions. It is found that the labyrinth-type CT has a positive effect on flow in the stage - efficiency increases at $n = 100\%$ by 0.5%, stall margin - by 5%.
4. Experimental and calculated data of the stage with a smooth flow passage and with a labyrinth-type CT are compared at $n=100\%$. Both approaches (Mixing plane and NLH) using the SST
turbulence model are not in full compliance with test results. Characteristics calculated by the NLH method are closer to the experimental data.

5. The steady and unsteady flow fields in blade channels of Stage A-1 with a smooth flow passage and with a labyrinth-type CT are calculated.

6. It is shown that the labyrinth-type CT interacts with leakage vortex in the tip clearance, changes its trajectory, and noticeably decreases blockage at the rotor tip.

7. It is recommended to derive a more accurate turbulence model and continue studies the effect of the labyrinth-type CT on the Stage A-1 performance, namely, locations of grooves directly above the tip leakage vortex core.

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