COMPARISON OF LABYRINTH SEAL CALCULATION AND REAL AIRCRAFT TURBINE ENGINE MEASUREMENT

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Abstract
This paper describes comparison between 3D CFD calculation of labyrinth seal of a turbine engine and measurement of actual advanced turbine engine in test facility. The goal is to verify capability of the 3D CFD modelling and obtain more insight into air flow path in the labyrinth seal. The total temperature was revealed not being a constant value through the labyrinth seal, thus driving design and even service trend monitoring consequences.

Keywords: Labyrinth Seal, Aircraft Turbine Engine, CFD, Test

1. Introduction
The labyrinth seal of aircraft turbine engine is an important part of air flow path in the engine. The air flow path consists of two vital branches [1]. Primary stream consists of compressor air flow, combustor contribution and turbine work stage(s) in a standard turbine engine architecture. Secondary air flow is used for cooling hot parts, bounded between rotating parts and stator counterparts (e.g. between shaft and stator where the shaft has very high rotational speed). Typical labyrinth seal scheme is shown in Figure 1. The labyrinth seal is produced as a part of shaft or within stator parts. Presented paper is focused on the shaft configuration.

The first research of labyrinth seals was started with steam turbines where the labyrinth seals were located to the tip of blades [2]. The purpose of labyrinth seal is eliminating mass flow passing through the seals [3], because air flow leaked through the seal does not produce work in primary branch of flow. Reduction of the detrimental leakage mass flow is enabled by a circumferential swirl, created in cavities between the teeth.

Most of the research conducted on labyrinth seals was associated with steam turbines. However, there are differences in boundary conditions between steam turbine and aircraft turbine engine: the key difference lies in rotation speed where the speed is greater in turbine engines, in turn influencing the strength of swirl and the resulting mass flow though the seal [6].

With the development of CFD increased number of reliable numerical simulations of labyrinth seals appears in the literature, e.g. [7].

At first instance, radial clearance, i.e. space located between rotating part (teeth) and non-rotating part (it is straight shape) [8], can be studied. Presented configuration is using the rotating teeth [5]. Such a flow path was simulated in the CFD software. The goal of this article is verification of the CFD results by comparison with reduced data measure in the test facility. Research was also aimed at investigation of possible changes of total temperature. Knowledge of the total temperature values and its development in labyrinth seal is important for designers of turbine engines. They can better specify e.g. material of rotating parts and manufacturing process. A better selection of material properties can be successfully pursued. Labyrinth seal in an aircraft turbine engine is specific by radial clearance. Clearance is smaller than in the steam turbines and rotational speed is higher.

2. CFD Calculation
Computational domain of the 3D CFD calculation consisted of three volumes. This configuration has been chosen because it enables a better description of air flow through the labyrinth seal. It is helpful in capturing the properties of a circumferential swirl.

Figure 1: Scheme of typical labyrinth seal [1]
The domain consists of:
- Inlet control volume
- Labyrinth seal volume
- Exit control volume

Inlet control volume has shape of 5deg annular segment (Figure 2). The volume does not rotate for better control of the air flow. The maximal vertical profile of an air flow is the same as the labyrinth seal without the teeth. Exit control volume (Figure 2) does have the same characteristics as the inlet control volume. Labyrinth seal volume features a different configuration setting manageable during evaluation process. Walls with labyrinth seal geometry rotate at constant circumferential speed. Opposite wall – stator wall – does not rotate. This setting correctly simulates the real machine. Labyrinth seal volume is displayed in Figure 3.

Calculations were performed with three different values of the radial clearance.

The computational mesh was prepared in ANSYS Meshing solver. Labyrinth seal volume was calculated with an inflation in rotor and stator walls in a structured mesh. Inflation is important for proper description and understanding the air flow in the vicinity of these walls. Critical flow path is considered the radial clearance between tip of teeth and stator. There are 14 rows of elements in order to ensure good resolution of the air flow in this critical part (Figure 4). The rows correspond of influence in air flow path – see Figure 5. Inlet and outlet control volumes was meshed by a difference steps, because there is not a critical part before stator and rotor walls (see seal mesh in Figure 4). Total number of elements is 2.4 million. Maximum Y+ value of rotating part is 4.

The boundary conditions of the calculation are fixed to the constant total pressure inlet, constant static pressure outlet and constant rotational speed. The only variable value is the radial clearance between the stator and rotor walls. On the side walls the rotationally periodic conditions were set, because of the usage of a 5deg cylindrical segment. Periodic conditions were applied at all volumes of the model (i.e. inlet control volume, labyrinth seal volume and exit control volume). All boundary conditions of the model are shown in Figure 6. Values of boundary conditions are listed in Table. 1.

Figure 2: Inlet and outlet control volumes
Figure 3: Labyrinth seal volume
Figure 5: Mesh in radial clearance
Figure 4: Labyrinth seal volume mesh
Figure 6: Boundary conditions of the calculation
Table. 1: Boundary Conditions

<table>
<thead>
<tr>
<th>Inlet Total Pressure [kPa]</th>
<th>Outlet Static Pressure [kPa]</th>
<th>Inlet Total Temperature [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>665</td>
<td>317</td>
<td>542</td>
</tr>
</tbody>
</table>

CFX v.18 was used as the calculation solver. The air as an ideal gas was set as medium. In all volumes there was set the k-\(\varepsilon\) turbulent model (see [9]) with scalable wall function for capturing the air flow properties close to the walls (similar results are in [10]) and Total Energy head transfer model. k-\(\varepsilon\) model was set because it uses equivalent kinetic energy and dissipation rate equation. In the air flow inlet condition, there was set the total pressure and total temperature. Static pressure was set in air flow outlet. By the aforementioned definition, in rotating part there was set the rotating speed.

The solver was converged after 1000 iterations. Residuals were converged in the 1.0E-04 values. Mass flow convergence through the domain is listening in Figure 7 (constant values in inlet and outlet 0.00081 kg/s).

The evaluation of the calculated data was based on following non-dimensional formulas (1), (2), (3), (4) and (5):

1. Radial Clearance
   \[
   RC_{CORR} = \frac{RC}{RC_{REF}} \quad (1)
   \]

2. Total temperature
   \[
   T_{CCORR} = \frac{T_C}{T_{CREF}} \quad (2)
   \]

3. Static enthalpy
   \[
   h_{SCORR} = \frac{h_C}{h_{CREF}} \quad (3)
   \]

4. Rotational speed
   \[
   n_{CORR} = \frac{n}{n_{REF}} \quad (4)
   \]

5. Kinetic energy
   \[
   E_{kCORR} = \frac{E_k}{E_{kREF}} \quad (5)
   \]

Reference conditions correspond to values of standard operation of the aircraft turbine engine.

A selection of 3 sets of operating conditions was made with take-off conditions of engine rotational speed– RC_{CORR}=0.02, 0.04 and 0.06. This setting was chosen for a better understanding the air flow in the labyrinth seal cavities during the different radial clearance. These situations are important for standard operation of the aircraft turbine engine.

Before post-process analysis there were plotted velocity vectors in periodic wall for initial evaluation of the results – see figure 8 to Figure 10.
Along with velocity vectors there were analyzed total temperature distribution for all radial clearances – see Figure 11 to Figure 13.

Figure 9: Velocity vectors with $RC_{CORR}=0.04$

Figure 10: Velocity vectors with $RC_{CORR}=0.06$

Figure 11: Total temperature distribution with $RC_{CORR}=0.02$

Figure 12: Total temperature distribution with $RC_{CORR}=0.04$
It can be observed from velocity vectors, that the maximal velocity occurs in the area of the last tooth. This is because the flow is exposed to maximal expansion to the exit conditions. Next, there was evaluated static enthalpy (Figure 14) and total temperature (Figure 15) through the teeth. Results from the trendlines of static enthalpy is that the total temperature is increased through the teeth and with decreasing radial clearance. Trendlines of total temperature deserves our attention. It can be seen from the picture that the relative total temperature change between inlet and exit with minimal radial clearance is approx. 0.19, static enthalpy change is approx. 0.2 and kinetic energy change is approx. 0.14.

Answer for question “why the total temperature, static enthalpy and kinetic energy change is worth attention” can be found in fact that the subject of the study is a case of reference circumferential speed being maximal, thus the circumferential swirl is well developed. To explore the field further we used the
model for $RC_{\text{CORR}}=0.04$ and calculated for a set of different speeds—see Figure 16, Figure 17 and Figure 18 (5 speeds in total). It can be seen from the charts that the rotational swirl has a dominant influence for appropriate function of the labyrinth seals of the aircraft turbine engine.

The trendlines of kinetic energy and static enthalpy change with different speeds are shown in Figure 19. Trendlines of total temperature is shown in Figure 20. From the total temperature change dependency, it can be seen, that the maximum value is in high speed. At higher speeds circumferential swirl is fully developed. This trend does not correspond with experience from steam turbines labyrinth seals, where the total temperature remains constant. It means that the temperature does not change through the seal. It is stated in [3] that the typical rotational speed of steam turbine is approx. 8% of typical aircraft turbine engine.

Figure 18: Total temperature through the clearance gaps at different speeds

Figure 19: Static enthalpy and kinetic energy with different speed

Figure 20: Total temperature with different speed
3. Data evaluation in test facility turbine engine

Center of Aviation and Space Research operates a test facility of aircraft turbine engine where the results presented in previous paragraphs could be verified. A test engine with a typical labyrinth consists of 4 teeth with constant radial clearance is installed in the test facility.

Following total temperature stations were measured:
- Labyrinth seal inlet (blue line in Figure 21)
- Labyrinth seal exit (orange line in Figure 21)

Total temperature was measured by nickel-alloy thermocouples in labyrinth seal inlet and exit with ±4degK accuracy. There were two thermocouples around the perimeter. The setup and process were the same as in typical aircraft engine.

There were measured 11 steady-state test points. The stabilization in the steady speed was minimum 3 minutes for representative data measured. The measurement procedure consisted of following steps:
- Start the engine and stabilize the speed in the idle in 5 minutes
- Move to steady state point and stabilize for 3 minutes (the process was repeated for all steady state points)
- Return to the idle speed, stabilize for 5 minutes and engine shut down

From the measured data it is visible that the total temperature is different before and after the labyrinth seal – see Figure 21. It was seen that the maximal total temperature change is approx. 0.06. It is not identical value compared with the CFD analysis, but general trend of total temperature rise in the studied part of aircraft turbine engine is captured.

4. Results and discussion

Result of 3D CFD calculation of labyrinth seal were presented in the paragraph 2. The results from calculation demonstrate that the total temperature change (i.e. delta between inlet and exit of labyrinth seal) is not zero value across the labyrinth sections (Figure 15 - constant speed and different clearance and Figure 18 - different speed and constant clearance). Circumferential swirl was identified to form a dominant factor in labyrinth seal. The effect of the swirl strength can be seen in higher rotational speeds. It cannot be traced in steam turbines, where the setup works in comparatively smaller speeds.

After 3D CFD calculation a measurement of the labyrinth seal in test facility turbine engine in Center of Aviation and Space Research (see paragraph 3) was carried out. Analysis of the measured data yields the same trend of total temperature.

In the next step a more detailed test layout shall be pursued.

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