Thesis for the degree of Doctor of Philosophy

Multimethod aerodynamic research of engine-realistic turbine rear structures

Valentin Vikhorev

Department of Mechanics and Maritime Sciences
CHALMERS UNIVERSITY OF TECHNOLOGY
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VALENTIN VIKHOREV
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Department of Mechanics and Maritime Sciences
Chalmers University of Technology
SE–412 96 Göteborg, Sweden
Telephone + 46 (0) 31 – 772 1000

Cover: The TRS flow illustrated by data from hot-wire anemometry, PIV, oil visualization pattern, and total and static pressure contours.

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"An experiment is a question that science poses to nature, and a measurement is the recording of nature's answer"

- Max Planck

Abstract

Multimethod aerodynamic research of engine-realistic turbine rear structures

Thesis for the Degree of Doctor of Philosophy in Thermo and Fluid Dynamics
VALENTIN VIKHOREV
Department of Mechanics and Maritime Sciences
Division of Fluid Dynamics
Chalmers University of Technology

Despite the significant advancements in aircraft engine technology over the past years, the aerodynamics of engine-realistic turbine rear structures (TRS) remain largely unexplored. The TRS, a structural and aerodynamic component situated downstream of the low-pressure turbine (LPT), plays a pivotal role in engine aerodynamic performance, deswirling the LPT flow to maximize the engine thrust. However, there is a significant gap in available experimental aerodynamic data on state-of-the-art TRS configurations under engine-relevant conditions.

The thesis closes this critical knowledge gap and provides the first comprehensive aerodynamic analysis of the latest and most advanced TRS configurations. Prior studies on the TRS were limited to simplified models. In contrast, this thesis is focused on two TRS types used in all state-of-the-art turbofan engines: with radial and leaned outlet guide vanes (OGVs). For the first time, aerodynamic tests of engine-realistic TRSs have been carried out under engine-relevant Reynolds numbers and flow coefficients, facilitated by a unique annular 1.5 stage LPT-OGV facility at Chalmers University of Technology, established in 2015.

For the experimental investigation of the TRS flow, a multimethod approach was applied and involved an array of advanced measurement techniques to provide insights into various aspects of TRS flow. This included the use of pressure probes and static pressure taps for acquiring total and static pressure distributions, crucial for estimating pressure losses. The oil-film method was employed to capture flow-visualization patterns, serving to indicate laminar-turbulent transition and loss-generating structures. Moreover, for the first time in the context of TRS flow, hot-wire anemometry (HWA) and PIV techniques were employed to provide time-resolved and instantaneous velocity field data, effectively capturing the unsteady phenomena.

The central focus of this thesis is detailed examination of pressure loss mechanisms within TRS, focusing on the impact of different OGV designs and operating conditions on TRS aerodynamics. This involves an in-depth aerodynamic evaluation of multiple OGV types commonly found in real engines, such as regular OGVs, those with increased thickness, and OGVs with integrated engine mount recesses (bumps). For the first time, this study aerodynamically evaluated and compared two engine-realistic TRSs with simultaneously mounted OGVs of different types. The experimental data for the radial TRS was compared with preliminary CFD results, obtained using current industrial tools. The insights obtained from the PIV and HWA campaign were instrumental, allowing for a thorough examination of the structure and propagation of LPT rotor and stator wakes into TRS.

Keywords: turbine rear structure, turbine rear frame, turbine exhaust case, engine-realistic, outlet guide vanes, engine-mount recess, bump, vane lean, low-pressure turbine, experimental multimethod approach, multi-hole probe, pressure taps, oil-film visualization, hot-wire anemometry, particle image velocimetry, computational fluid dynamics.

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I am also immensely thankful to the team at GKN Aerospace for sharing their industry insights and perspectives. Their contributions have significantly enhanced my understanding of real-world applications and challenges in our field.

My experience in the laboratory has been truly rewarding, and for this, I owe a special thanks to all those involved in the lab projects. Their collaboration and camaraderie have made working in the lab an enriching and enjoyable experience.

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Lastly, I would like to express my profound appreciation to my family, friends and my girlfriend, who have been my unwavering support system. Their love, encouragement, and presence in my life have been a source of strength and happiness, helping me balance the demands of my academic pursuits with the joys of personal life. Their collective support has been a cornerstone of my journey, and I am deeply thankful to each one of them for their role in making this journey a success.

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List of Publications

This thesis is based on the following appended papers:

Paper 1. Vikhorev, V., Chernoray, V., Thulin, O., Deshpande, S., and Larsson, J. *Detailed experimental study of the flow in a turbine rear structure at engine realistic flow conditions.* Journal of Turbomachinery, 143(9). Paper No: TURBO-20-1372, 2021.

Paper 2. Vikhorev, V., and Chernoray, V. *Experimental flow analysis in a modern turbine rear structure with 3D polygonal shroud under realistic flow conditions.* 14th European Turbomachinery Conference on Turbomachinery Fluid Dynamics and Thermodynamics, Virtual conference, Paper No: ETC2021-539, 2021.

Paper 3. Vikhorev, V., Nylander, P., Chernoray, V., Larsson, J., and Thulin, O. *Experimental and numerical flow analysis of an engine-realistic state-of-the-art turbine rear structure.* Journal of Engineering for Gas Turbines and Power, 144(7). Paper No: GTP-22-1022, 2022.

Paper 4. Vikhorev, V., Jonsson, I., Tokarev, M., and Chernoray, V. *Experimental study on the low-pressure turbine wake interaction and development in the turbine rear structure.* 9th European Conference For Aeronautics and Space Sciences (EUCASS), 2022.

Paper 5. Vikhorev, V., Chernoray, V., Abdel Mallak, Z., and Larsson, J. *The influence of the vane lean on the flow in a turbine rear structure.* 33RD Congress of the International Council of the Aeronautical Sciences (ICAS), 2022.

Other publications:

Paper 6. Vikhorev, V., Chernoray, V., Thulin, O., Deshpande, S., and Larsson, J. *Detailed experimental study of the flow in a turbine rear structure at engine realistic flow conditions.* ASME Turbo Expo, Paper No: GT2020-15734, 2020.

Paper 7. Vikhorev, V., Chernoray, V., Thulin, O., Deshpande, S., and Larsson, J. *Aerodynamic Investigation of the Flow in a Turbine Rear Structure at Realistic Flow Conditions.* 3rd ECATS Conference, Making Aviation Environmentally Sustainable, 2020.

Paper 8. Vikhorev, V., Nylander, P., Chernoray, V., Larsson, J., and Thulin, O. *Experimental and numerical flow analysis of an engine-realistic state-of-the-art turbine rear structure.* ASME Turbo Expo, Paper No: GT2021-59224, 2021.

Paper 9. Rodriguez Acero, P.D., Jonsson, I., Xisto, C., and Vikhorev, V. *Experimental investigation of waste heat recovery concept in turbine rear structure for a Liquid Hydrogen Gas-Turbine.* International Symposium on Turbulence, Heat and Mass Transfer (THMT), 2023.

Paper 10. Deshpande, S., Ricchi, M., Larsson, J., Vikhorev, V., and Chernoray, V. *Impact Of lean on aerodynamic performance of a turbine rear structure.* Manuscript, 2024.

Paper 11. Vikhorev, V., Chernoray, V., Abdel Mallak, Z., and Larsson, J. *The influence of the vane lean on the flow in a turbine rear structure.* Manuscript, 2024.

Nomenclature

Acronyms

BPR	–	Bypass ratio
CAD	–	Computer aided design
CFD	–	Computational fluid dynamics
FPR	–	Fan pressure ratio
HPC	–	High-pressure compressor
HWA	–	Hot-wire anemometry
LPC	–	Low-pressure compressor
LPT	–	Low-pressure turbine
MHP	–	Multi-hole probe
NGV	–	Nozzle guide vane
OGV	–	Outlet guide vane
PIV	–	Particle imaging velocimetry
SAF	–	Sustainable aviation fuels
SLA	–	Stereolithography
TRS	–	Turbine rear structure

Contents

Part I

Introductory chapters

Chapter 1

Introduction

1.1 Transitioning to sustainable aviation: challenges and strategies

The escalating concerns related to the growth of global emissions necessitate immediate and effective actions to achieve the goals of the Paris agreement, established in 2015. While the aviation transport sector accounts for a relatively small percentage of global emissions—contributing 2.5% to carbon dioxide (CO_2) emissions—it poses substantial challenges in transitioning to carbon neutrality due to its complex operational requirements and industry structure [1].

CO_2 emissions have the potential to persist in the atmosphere for hundreds or thousands of years, and it is the aggregate emissions that are of crucial concern as they lead to elevated concentrations of CO_2 in the atmosphere. Even though the emissions from the aviation transport represent a small proportion of the total global emissions, the observed escalation in emissions both from this sector and on a global scale in recent years is noteworthy (refer to Figure 1.1).

In addition to CO_2 emissions, it is critical to emphasize the presence of other significant pollutants such as nitrogen oxides, soot particles, water vapour, and sulphate aerosols. These diverse emissions collectively change radiative forcing (disparity between the energy entering and leaving the atmosphere), which in turn intensifies global warming [3]. This underscores the urgent need for effective strategies to reduce emissions comprehensively. According to Daley [4], the strategies in the aviation transport sector can be divided into four main categories: implementations of specific regulations, operational improvements, technological advancements, and exploration of substitutes for kerosene-based fuels.

Regulatory approaches primarily involve the imposition of standards and sanctions on aviation emissions, coupled with certification processes. The strategies for operational improvements encompass advancements in aircraft maintenance and the optimization of air traffic management systems, minimizing time spent taxiing, and the adoption of more efficient flight route planning. Technological advancements in aviation are poised to propel the industry toward more sustainable practices and designs, with a focus on incremental improvements in both engine and airframe. Meanwhile, fuel strategies in aviation revolve around the systematic exploration and

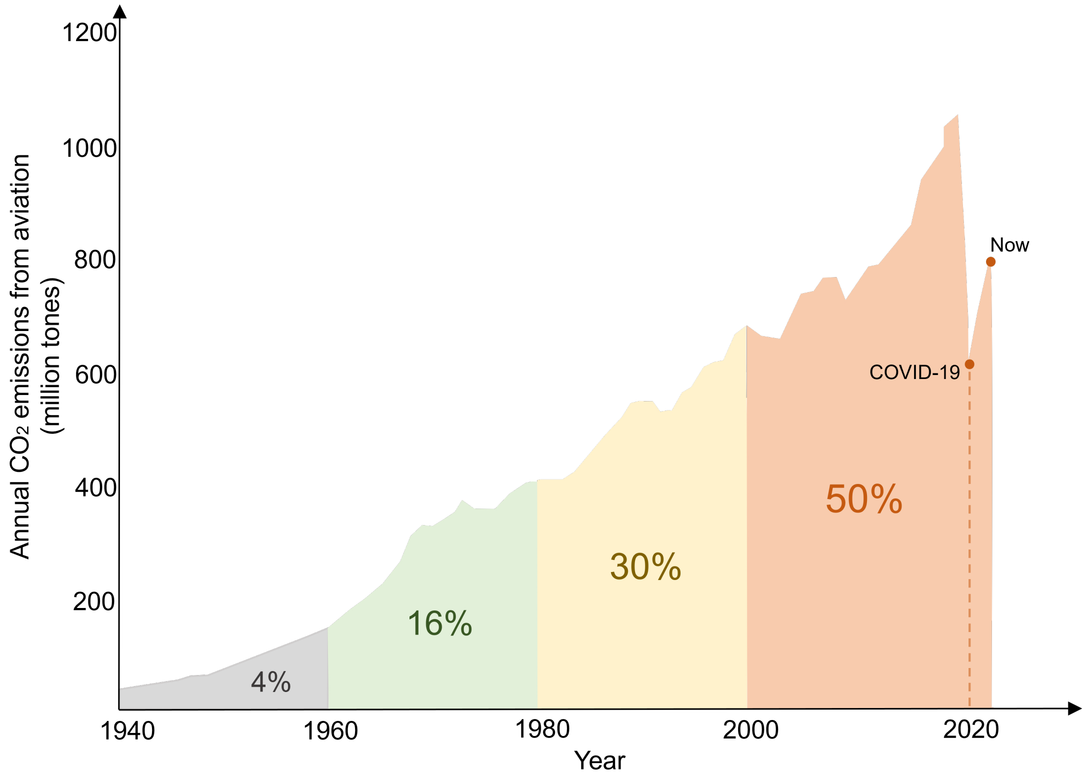

Figure 1.1: Annual global CO_2 emissions from aviation (1940-2023) with % of total cumulative emissions broken down into 20 year periods . Adapted from [2].

integration of alternative energy sources and fuel types, aiming to replace conventional jet fuels.

Within these fuel strategies and the ongoing advancements, there are several prominent fuel replacement methods currently being deliberated extensively within industry and academia. The envisioned shift to alternative fuel sources such as hydrogen [5, 6] requires extensive aircraft redesigns, new certification, and development of infrastructure to accommodate the novel fuel source. Electric propulsion is also attracting considerable interest, with innovations in both fully electric and hybrid-electric models being pursued [7]. Yet, the current limitations of battery technology restrict fully electric models to light aircraft capable of only short distances, rendering them impractical for commercial air travel [8]. Balancing the exploration of future fuel options with immediate advancements in current technologies is vital for a seamless transition to more sustainable aviation practices. In light of these concerns, the aviation sector is concurrently focusing on and considering the integration of drop-in sustainable aviation fuels (SAF) [9]. The integration of SAF offers a path that doesn't necessitate radical modifications but rather enables a series of incremental advancements in materials, aerodynamics and propulsion systems.

In conclusion, addressing environmental concerns in aviation necessitates innovations in operations, technology, and fuel alternatives. This pushes engineers and scientists to deeply explore and understand the physics behind these innovations, overcoming challenges to create new sustainable solutions.

1.2 Exploring paths in turbofan engine design

The Advisory Council for Aviation Research and Innovation in Europe (ACARE) has established ambitious emission reduction goals, targeting a 75% decrease in CO_2 emissions and a 90% reduction in NO_x emissions by 2050 relative to the levels of the year 2000, as outlined in [10]. To achieve these targets, significant enhancements in the overall efficiency of aircraft propulsion systems are necessary.

The designers of turbofan engines are currently focusing on two key areas: the implementation of new technologies and the optimization of existing designs to enhance both propulsive and thermal efficiencies [11]. With current trends towards lighter and compact turbofan engine designs, reducing the size of the engine core and increasing the bypass ratio (BPR) [12], the optimization of each component becomes crucial.

In a traditional two- or three-spool turbofan engine [13], a low-pressure shaft connects the low-pressure turbine (LPT) and fan. The larger fans of high-BPR turbofan engines require more power and lower rotational speeds, which also restricts LPT speeds due to the common shaft. However, a high rotational speed is preferred for the LPT that drives the fan to ensure optimal efficiency and high specific work. Therefore, to achieve the specified thrust with reduced LPT velocities and maintain equivalent energy for fan drive, the relatively large LPT core diameter and number of stages are required. To avoid the addition of new LPT stages, which would increase engine weight and complexity, it becomes crucial to increase turning within the final LPT stage. This approach allows for more efficient energy extraction at lower rotational speeds. However, this adaptation results in a significant increase in the load on the LPT and leads to increased swirl angles in the airflow exiting the last LPT rotor.

To overcome these challenges, Pratt and Whitney introduced and incorporated a gearbox in their PW1000G engine (Figure 1.2), a significant innovation in turbofan technology [14–16]. This allows both the LPT and the high-pressure turbine (HPT) to operate at their optimal speeds, facilitating efficient energy transfer to the low-pressure compressor (LPC), high-pressure compressor (HPC), and the fan. The incorporation of a gearbox also decouples the fan, allowing its speed to be optimized independently, thereby enhancing the engine's overall efficiency. This approach enables the engine core to achieve requisite thrust levels with a reduced number of compressor and turbine stages. The swirl angle from the last turbine rotor becomes less problematic. However, the off-design variations of the outlet swirl angle increase substantially.

Following this trend, Rolls Royce is also advancing with their upcoming Ultrafan technology [17, 18]. This technology represents Rolls Royce's commitment to the geared turbofan concept with enhanced efficiency (25% increase compared to first generation Trent engines) and full compatibility with drop-in SAF.

Although the geared turbofan engine offers advantages in terms of component efficiencies, the addition of a gearbox introduces new considerations in terms of weight, engineering complexity, and maintenance. Conversely, General Electric and Safran Aircraft Engines (CFM International) have chosen a different strategy, focusing more on improvements within ungeared engines [19, 20]. Despite not currently employing geared turbofan technology, General Electric has achieved a leading position in the market across various thrust classes. Moreover, there is a growing interest in exploring different open rotor technologies which can effectively increase bypass ratios, leading to significant fuel consumption savings [21]. Their approach demonstrates a different path in the evolution of turbofan engines, where the emphasis is placed on optimizing and enhancing existing ungeared designs while the potential adoption of geared technology remains a consideration for future developments.

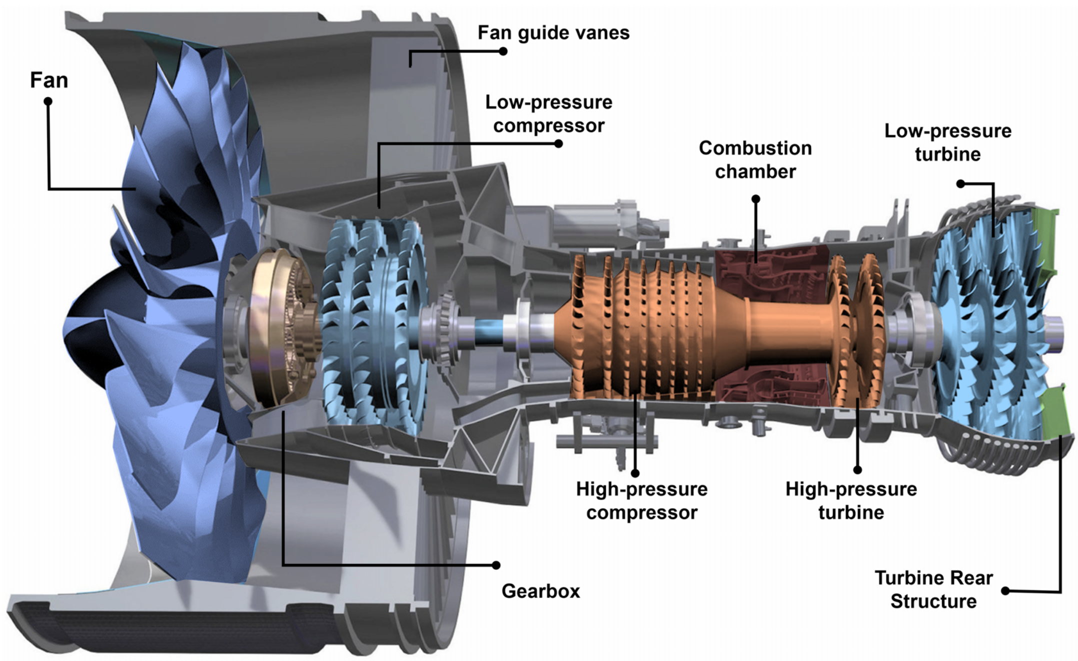

Figure 1.2: Schematic representation of the PW1100G's internal configuration. Adapted from [22].

Therefore, the choice between geared and ungeared turbofan engines hinges on balancing efficiency, complexity, and the specific performance requirements of different aircraft types, reflecting priorities of aircraft manufacturers and airlines. This diversity in engine design philosophies leads to different challenges in the design of turbine rear structure (TRS). Addressing the challenges posed by different turbofan engine designs necessitates optimization of TRS with detailed focus on thermal characteristics, material properties, mechanical integrity, and aerodynamics.

1.3 Turbine rear structures

The primary focus of the thesis centers on the TRS. Figure 1.3 shows a photograph of an aeroengine with highlighted TRS. From the structural point of view, TRS is a fundamental component positioned at the aft end of the engine, which provides essential mechanical support and alignment for the LPT stages. As the supporting structure, the TRS accommodates the rear bearing of the low-pressure spool, thus playing a major part in maintaining the clearances in the low-pressure turbine. Additionally, the rear engine mount is located on the TRS and the design of the

TRS is vital for engine attachment to the aircraft. The engine is typically attached to the pylon using a rear mount. With the mounting system and pylon, the TRS plays a pivotal role in efficiently transferring significant mechanical loads from the engine to the aircraft's frame.

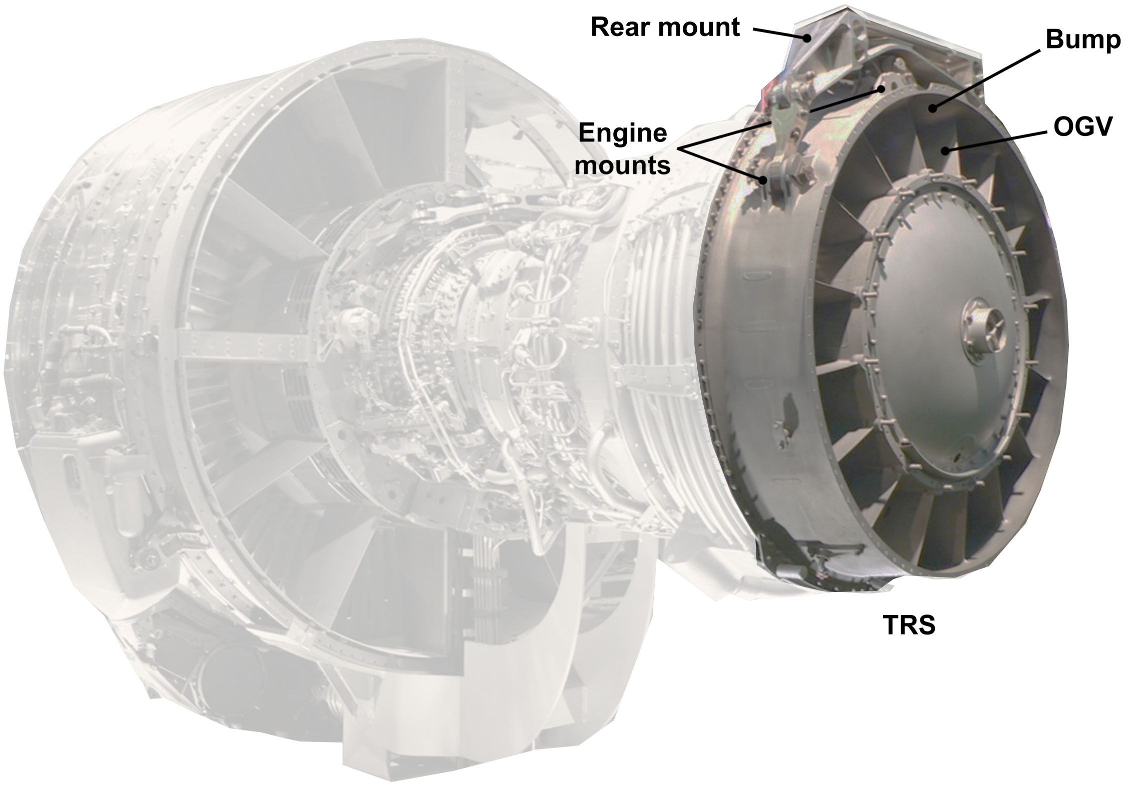

Figure 1.3: Rear view of a CFM56-5 aero engine. Adapted from [23].

The design of the TRS varies considerably across different engine designs. Typically, the TRS is composed of struts that connect the outer and inner casings, known respectively as the shroud and the hub. The design of these surfaces is adaptable, often featuring either a radial or a polygonal configuration [24]. Moreover, there is notable variability in the number of struts and its spatial alignment; they may be set up in a radial pattern or leaned at specific angles [25–27]. Finally, the structural design of the struts themselves is tailored to integrate features such as oil pipelines, crucial for the lubrication of the engine bearing, and modifications like engine-mount recess, so-called bumps. These bumps are specifically designed to minimize induced bending moments, addressing the challenges posed by the engine's attachment to the aircraft. All these design elements are dictated by requirements such as mechanical (thermal, structural, vibrational), aerodynamical, acoustical, weight and manufacturing.

The struts within the TRS are commonly termed as outlet guide vanes (OGVs). The name derives from their primary aerodynamic function: to deswirl the flow of exhaust gases emerging from the last stage of the LPT and subsequently direct this flow seamlessly into the nozzle. Such flow management significantly enhances aerodynamic efficiency and engine thrust. However, while OGVs offer improved flow guidance, their implementation can also introduce additional pressure losses which should be minimized. Therefore, along with the industry's push for more compact engines and stringent weight constraints, the task for TRS design is becoming more complex and challenging.

In developing the aerodynamic design of OGVs as shown in Figure 1.4, and considering their potential geometric variations as earlier outlined, achieving optimized aerodynamic performance requires the aerodesigner to focus on several key factors:

- Determining the TRS length, OGV number and lean angle.
- Optimizing hub and shroud geometries.
- Aerodesign of individual OGVs.
- Incorporating bumps.
- Taking into account influence of welds, tip leakage flow, purge flow and P-flange pocket flow.

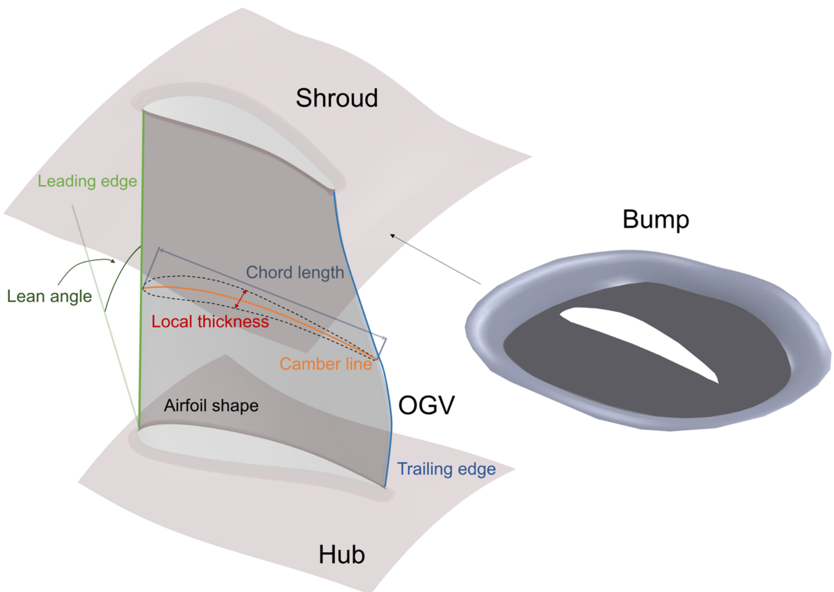

Figure 1.4: A 3D model of OGV with primary OGV nomenclature, hub, shroud and bump surfaces.

Using this foundational framework as a starting point, it is essential to customize and optimize the TRS design in conjunction with the preceding LPT stage and its specific outlet conditions. Therefore, conducting detailed aerodynamic research on TRS becomes crucial in order to provide invaluable insights and refinements for the design process. The next section describes previous investigations of the TRS aerodynamics.

1.4 Previous studies of TRS aerodynamics

The design of the TRS should be meticulously adapted to accommodate the specific outflow conditions from the LPT. This outflow is characterized by a high degree of unsteadiness, primarily due to the relative motion of blade surfaces. This motion instigates periodic interactions between the rotor and stator flows. Furthermore, the development of boundary layers on nozzle guide vanes (NGV), LPT rotor blades and casings results in the formation of wakes and secondary flows, which are crucial contributors to the aerodynamic loss. The phenomena of secondary and endwall flows within a turbine's blade or vane cascade have been thoroughly investigated and documented by numerous experts [28–32], with Langston [33] providing a comprehensive synthesis of these studies. Understanding the aerodynamics of the TRS involves dealing with complex inflow that further interacts with the casing and OGV boundary layers.

The first study on the aerodynamics of LPT OGVs was undertaken at Chalmers in a specially build linear cascade facility by Hjärne [34]. The linear cascade simplified complex aerodynamic interactions within the TRS, providing a manageable framework for experimental and numerical evaluations [35, 36] of the flow under different design conditions. Additionally, Hjarne et al. [37, 38] made a substantial contribution to the study of secondary flows and loss development within the LPT OGVs specifically highlighting the influential role of the inlet boundary layer thickness and free-stream turbulence. However, the linear cascade approach could not accurately simulate the annular geometry of actual turbines lacked the presence of radial pressure gradients, curvature effects, tip leakage flows and unsteady LPT wakes. To overcome these limitations, Schoenleitner et al. [39] employed advanced annular rig tests, providing a detailed comparison with traditional 2D linear cascade. Their research illuminated complex three-dimensional flow effects, such as rotor tip leakage and incoming wakes particularly evident in oil flow visualizations and pressure distributions. The authors also emphasized the need for broader rig tests, exploring an extended range of engine-realistic conditions.

In parallel to these developments, an advanced annular test facility was built at Chalmers University of Technology, Sweden [40]. This facility was designed to facilitate comprehensive experimental investigations, enabling more accurate simulations of complex TRS flow under a wide array of realistic operating conditions. Detailed information about this facility and its advantages is presented in Chapter 2.

In addition to the effort invested in designing this rig, Rojo [41] initiated the preliminary series of experimental measurements within TRS. Expanding upon the initial studies, Jonsson et al. [42] undertook an extensive aerothermal analysis with a comprehensive exploration of flow behavior, Jonsson et al. [43] particularly focused on the laminar-turbulent transition and Jonsson et al. [44] conducted thorough uncertainty analysis. Additionally, Jonsson et al. [45] conducted experimental studies to understand the impact of surface roughness on TRS flow, and Deshpande et al. [46] completed these findings by numerical analysis.

However, without undermining the significance of these foundational studies, it should be noted that these studies were conducted using a simplified TRS geometry.

The shift towards more advanced designs requires an in-depth exploration of state-of-the-art TRS configurations considering variations in the number of OGVs, their spatial arrangements, and engine-realistic OGV geometries.

This, in turn, underscores the necessity for extensive experimental investigations conducted for configurations similar to realistic TRS geometries of engine.

1.5 Research objectives of the thesis

This section outlines the specific research objectives set to fulfill gaps in the aerodynamics of the TRS:

- Initiate breakthrough testing in an environment that replicates engine-relevant conditions, utilizing the LPT-OGV facility detailed in Chapter 2.
- Investigate engine-realistic annular TRS concepts through the acquisition of trusted data, critical for improvement of current industrial design tools.
- Undertake a thorough analysis of diverse OGV designs, evaluating their individual effects on the aerodynamic performance of TRS.
- Identify and examine the unsteady inlet flow structures originating from the LPT and assess their subsequent development throughout the TRS.
- Examine in detail three specific TRS configurations, described in Chapter 2, emphasizing the aerodynamics changes associated with distinct geometric features.
- Employ a multimethod research approach (Chapter 3), providing both quantitative and qualitative techniques to capture a holistic view of the TRS flow dynamics.
- Provide an extensive database, serving as a substantial resource for numerical validation

Chapter 2

2. LPT-OGV Test Facility

This chapter provides an overview of the test facility, emphasizing its unique benefits and presents different concepts of TRS explored during this study. Each TRS is meticulously described, with particular attention paid to its key features.

2.1 General description

The research conducted for this thesis was performed at the Chalmers LPT-OGV test facility, a semi-closed loop setup equipped with 1.5 stages of LPT. This facility is designed for in-depth analysis of the aerothermal performance of TRS. The schematic representation of the facility is presented in Figure 2.1.

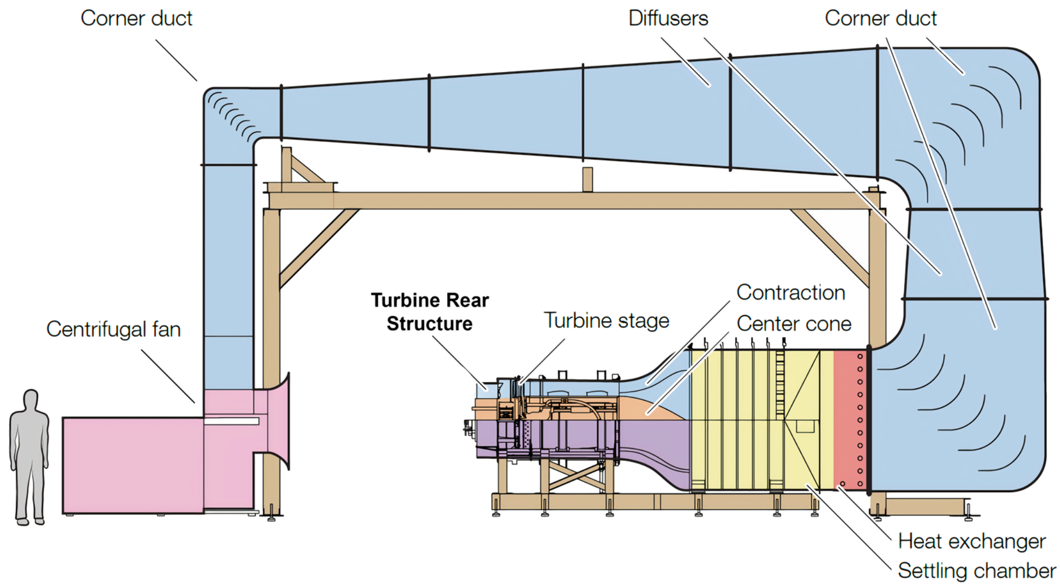

Figure 2.1: Chalmers LPT-OGV facility. Adapted from [45].

The flow in the facility is driven by a centrifugal fan, activated by an electric motor. Subsequent to this stage, the flow passes through a series of corner ducts and diffusers, culminating in a diffusion process within a 2×2 m^2 cross-sectional area.

The angle of flow diffusion is optimized to mitigate potential flow separations and unsteadiness. Following diffusion, the flow undergoes cooling to maintain constant operational temperature ensured by a heat exchanger, depicted in red on the facility schematic. The flow then proceeds to a settling chamber (yellow section), where it encounters a honeycomb structure and a series of five screens. This arrangement is instrumental in enhancing flow uniformity by tempering irregularities and turbulence. Upon exiting the settling chamber, the flow experiences acceleration as it enters the contraction section, eventually leading into the LPT stage. The LPT stage, a collaborative design effort between GKN Aerospace in Trollhättan, Sweden, and Chalmers University, features 60 nozzle guide vanes (NGVs) and 72 rotor blades. The turbine load and speed is controlled by a hydraulic system connected to the rotor's shaft. Passing the LPT stage, the flow enters the TRS module where the experimental measurements are done. The rotor blades, stator vanes (NGVs) as well as OGVs are shown schematically in Figure 2.2. Further details of the facility design can be found in [40].

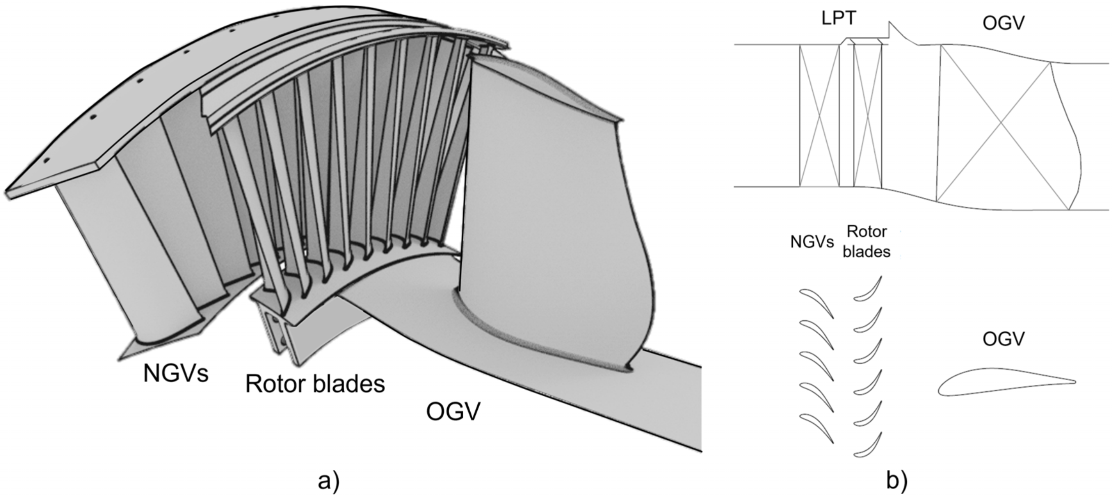

Figure 2.2: The schematic of LPT and TRS: (a) isometric view (b) meridional view with midspan profiles.

Having established the foundational aspects of the facility, it is crucial to highlight the unique attributes of this rig, which carve out a distinct niche for it in the realm of experimental setups:

- **Representative inlet flow to TRS**

It's pivotal for the facility to maintain aerodynamic conditions that mirror those of actual engines. The facility's operational scope, concerning Reynolds number and variations in LPT midspan swirl angle, is depicted in Figure 2.3. The measurement objectives were specifically tailored to investigate the flow in TRS under on- and off-design conditions similar to the cruise, take-off and climb phases of the flight mission. Furthermore, it is imperative for the LPT turbine output to exhibit characteristics true to actual engine conditions, encompassing representative wakes, secondary flows, swirl, mass flow and pressure distributions.

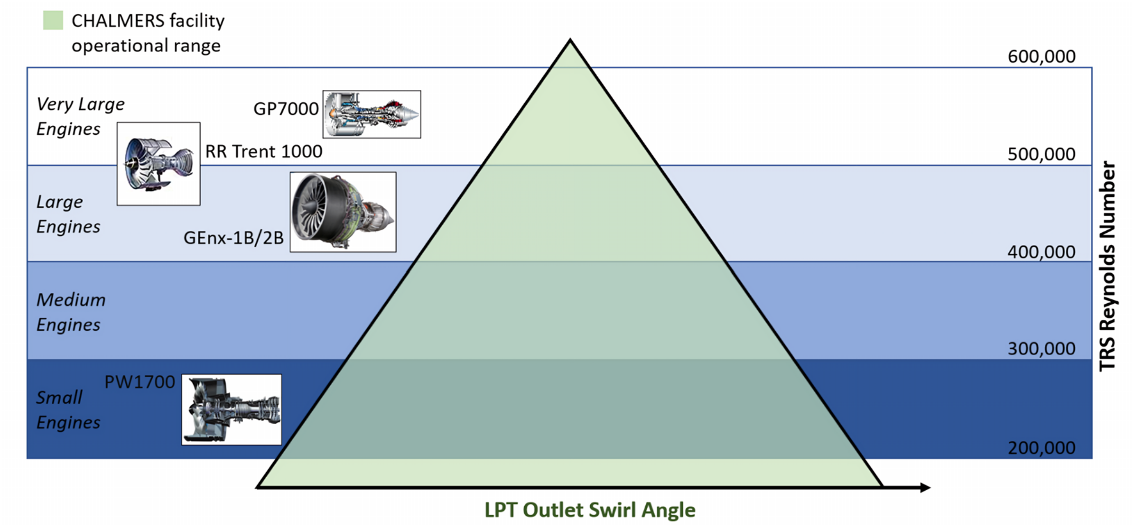

Figure 2.3: Chalmers LPT-OGV test facility operational space. Adapted from [44].

- **Assurance of Operational Stability and Repeatability**

The facility is designed to demand uniformity in flow conditions, encompassing velocity, pressure, and temperature, specifically targeting LPT and TRS sections. One of the defining strengths of the facility is its consistent performance, ensuring dependable and repeatable results under uniform experimental scenarios.

- **Measurement Accessibility**

The facility is adept at accommodating a variety of measurement techniques, prioritizing minimal disturbance to the flow conditions during these procedures. This equilibrium is maintained through advanced traversing systems and using non-intrusive techniques such as PIV.

- **Low-Cost Continuous Operation and Extensive Data Cataloging**

A distinctive advantage of the facility is its ability to operate continuously at a relatively low operational cost, presenting a cost-effective solution for extensive experimental campaigns. This efficiency is particularly beneficial for generating comprehensive data sets that serve both scientific exploration and practical industrial needs.

- **Flexibility of modular design**

The facility is characterized by its adaptable design, offering TRS components that can be easily interchanged, as it is shown in Figure 2.4. This modularity is essential for enabling comprehensive aerodynamic research across different TRS geometries.

The next section will go into detail about the different TRS designs tested in the LPT-OGV facility.

Figure 2.4: The disassembled LPT and TRS components, highlighting the modular design of the TRS.

2.2 TRS configurations

2.2.1 C1 configuration (Baseline configuration with interchangeable OGVs)

The C1 configuration is the baseline configuration and was designed by GKN Aerospace. The TRS has circular geometry of hub and shroud and 12 OGVs. Figure 2.5 represents a front view of C1 TRS CAD model.

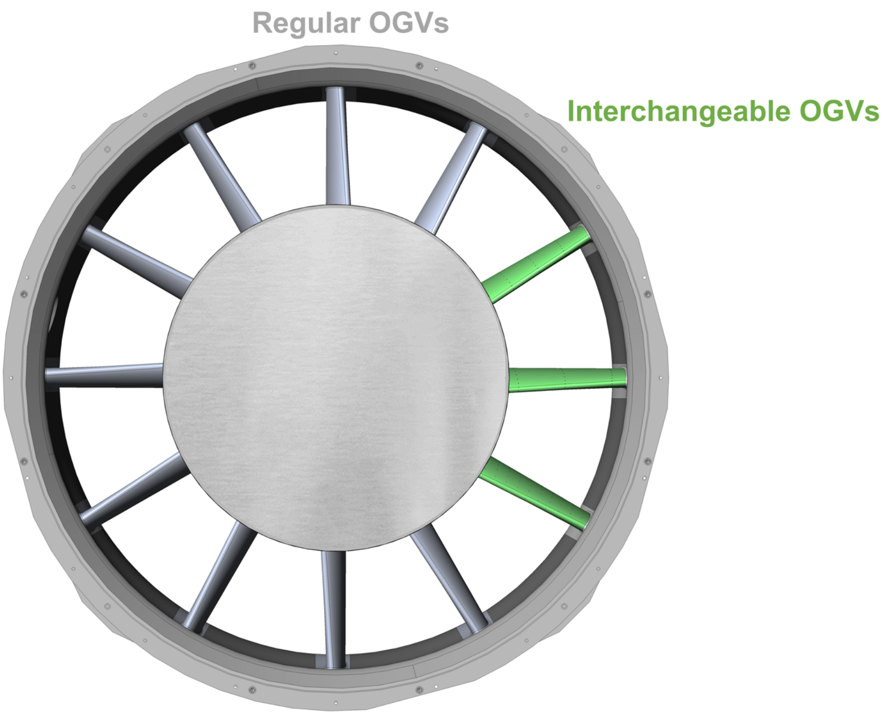

Figure 2.5: Baseline (C1) TRS configuration with instrumented interchangeable OGVs.

In the current configuration, attention was specifically given to the variation of three distinct interchangeable OGVs, aiming to capture the nuances of their performance. The remaining OGVs adhered to a baseline design, referred to as "regular" OGVs. Tests were done for three types of interchangeable OGV designs: regular, thick and ones equipped with an engine-mount bump. The measurements were performed on the mid-vane of interchangeable OGVs. The subsequent sections delve into the specific distinctions between the "thick" and "bump" OGVs in contrast to the standard "regular" design.

- **Thick vane**

In a turbofan engine, the lubrication system performs a crucial role: the lubrication and cooling of the rotor bearings, essential for the engine's safety and reliable functionality. To facilitate the delivery of oil, specific pipelines are necessary, which must pass through the OGVs. Consequently, this requires that certain OGVs be thickened to accommodate these tubes seamlessly. A dedicated thick OGV (research configuration) with enlarged thickness was designed by GKN Aerospace Engine Systems. The chord length distribution was not changed, while the thickness distribution was varied for each span. The midspan profile as well as 3D CAD geometry are presented in Figure 2.6.

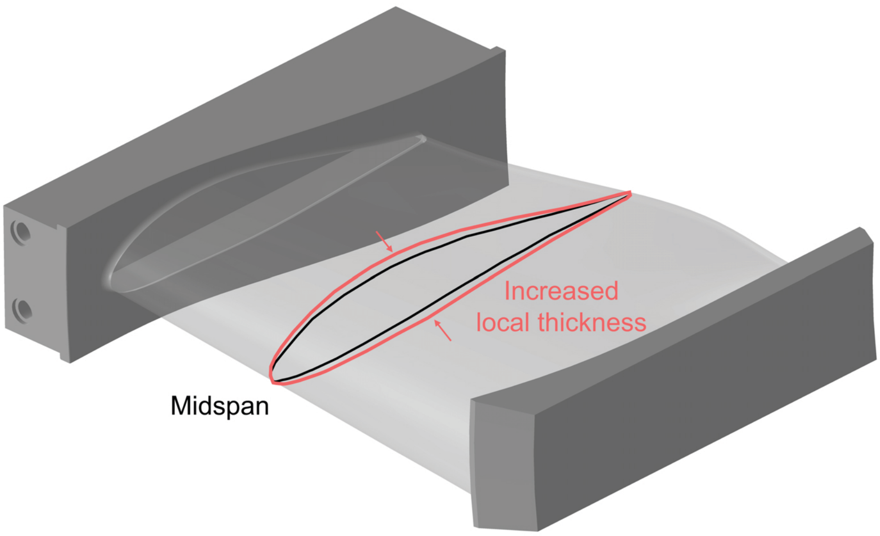

Figure 2.6: A 3D model of a thick OGV with midspan profile (solid red line) compared to regular vane midspan profile (solid black line)

- **Bump vane**

The structure of turbofan engines is such that the engine's attachment to the aircraft is facilitated through mounts that directly connect to the TRS (Figure 1.3). To minimize induced bending moments, a specific engine-mount recess is integrated into the TRS shroud. This OGV with bump was also designed by GKN Aerospace Engine Systems (Figure 2.7).

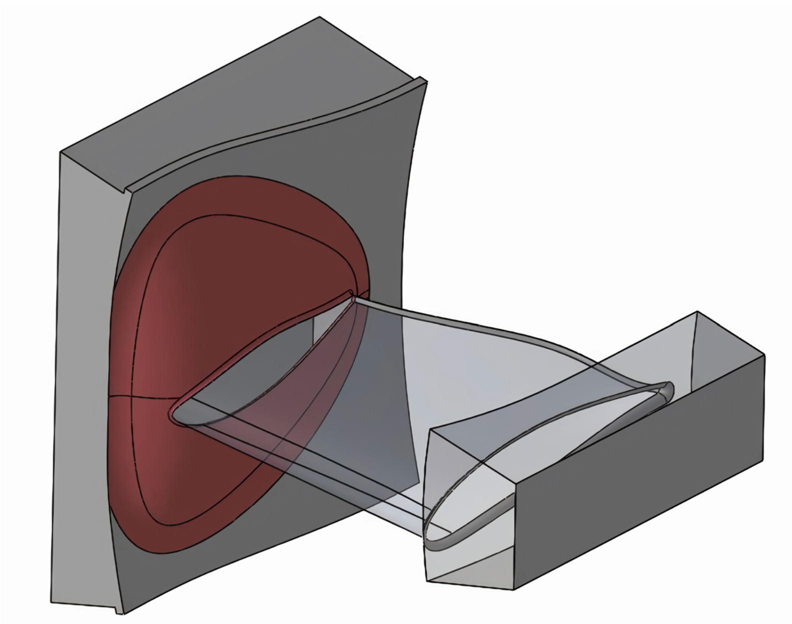

Figure 2.7: A 3D model of OGV with a mount bump marked with red.

2.2.2 C2 configuration (State-of-the-art with radial OGVs)

The C2 configuration represents the state-of-the-art in TRS technology, currently employed in modern turbofan engines. This version introduces a polygonal configuration, a shift driven by manufacturing and mechanical requirements. The hub shape is profiled to gradually narrow the flow path anticipating flow acceleration near the hub. This advanced setup involves the integration of 12 specialized OGVs, specifically comprising 3 thick, 3 bump and 6 regular OGVs, all concurrently assembled as depicted in Figure 2.8. The OGV design is also typical for state-of-the-art TRS. The aero-design was made by GKN Aerospace.

2.2.3 C3 configuration (State-of-the-art with leaned OGVs)

The C3 configuration represents another state-of-the-art TRS concept with a higher number of OGVs (increased from 12 to 18) and leaned orientation of OGVs. 'Lean' denotes the intentional angular deviation of OGV from its radial orientation as shown in Figure 2.9. For this particular geometry, the OGVs deflect in the circumferential direction, and the lean angle is +30 degrees. Positive lean angle is defined as the state wherein the pressure side is oriented toward the hub surface. In line with the configuration presented in the previous section, the current TRS features three distinct OGV typologies, all of which have been meticulously designed by GKN Aerospace and installed in LPT-OGV facility simultaneously as shown in Figure 2.9.

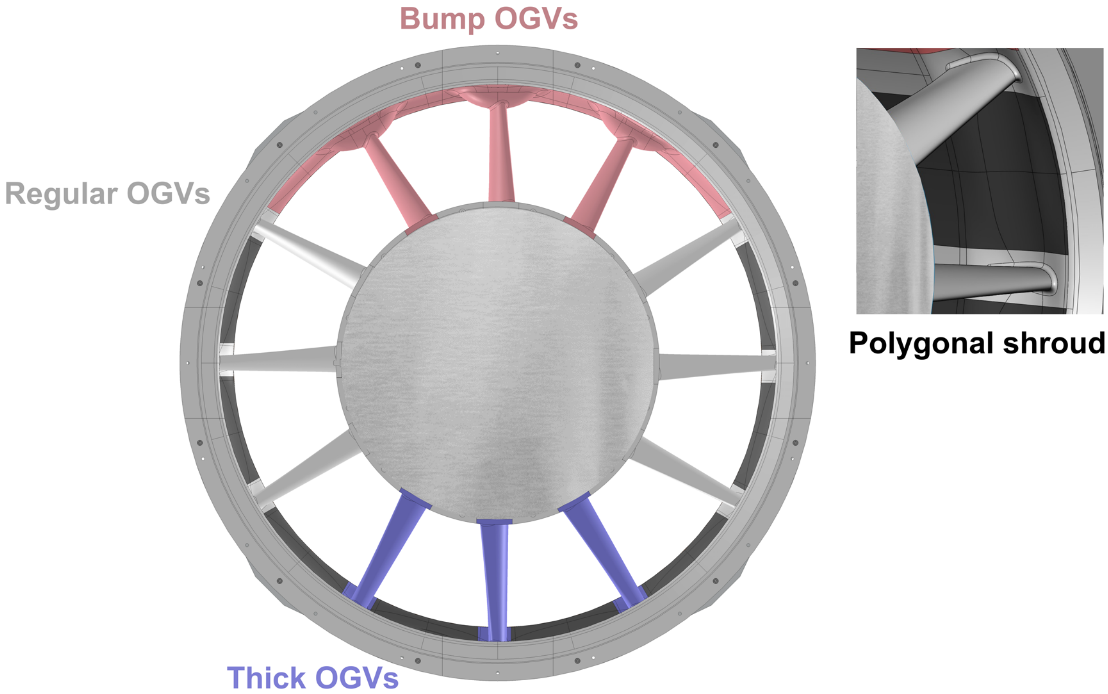

Figure 2.8: State-of-the-art TRS configuration with polygonal shroud and three types of OGVs: regular, thick and bump.

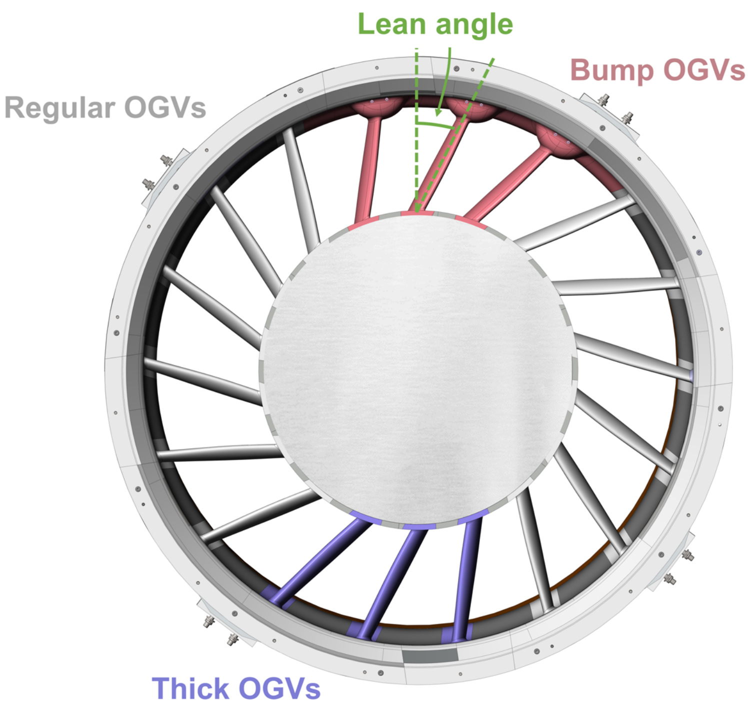

Figure 2.9: State-of-the-art TRS configuration with three types of leaned OGVs: regular, thick and bump.

Chapter 3

Instrumentation and measurement techniques

This chapter describes the instrumentation and measurement strategies implemented in appended papers, essential in establishing a multimethod approach. The incorporation of various techniques is crucial in obtaining both qualitative and quantitative data, thereby offering a comprehensive analysis of the investigative phenomena.

3.1 Pressure measurements

The experimental technique, established as the standard procedure for these investigative measurements, involved the utilization of five and seven-hole aero probes (Figure 3.1).

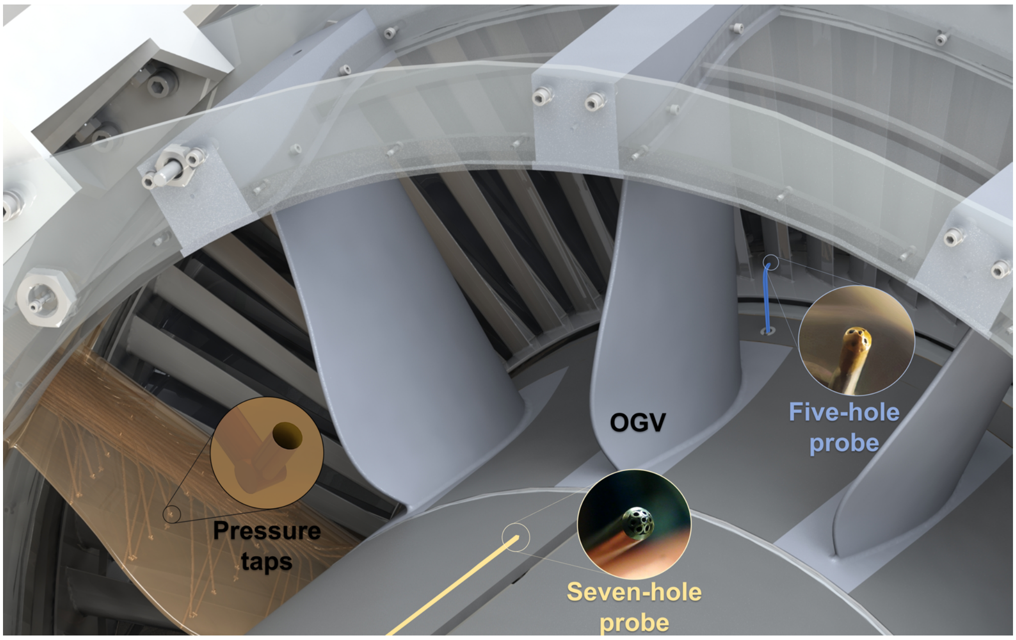

Figure 3.1: Isometric view of the test section with instrumented 5- and 7-hole aero probes and OGV with integrated pressure taps.

An L-shaped five-hole probe is located upstream of the OGVs at the inlet plane and turned about 20 degrees respective to the axial direction. A straight seven-hole probe is located downstream of the OGVs and positioned along the axial direction. The calibration procedure for these probes, along with an extensive uncertainty analysis, is comprehensively documented by Jonsson [44]. The static pressure distribution on the OGV surface was measured using static pressure taps incorporated into both the pressure and suction surfaces. The construction of pressure channels within the OGV was facilitated through automated Computer aided design (CAD) scripts, and the actualization of these designs was achieved with the high-resolution capabilities of stereolithography (SLA) printing technology.

The detailed acquisition of total and static pressure data from inlet and outlet probes serves as a fundamental approach to estimate pressure losses associated with different OGV designs. Furthermore, corresponding angles, including swirl distributions, provide information concerning the primary function of OGVs and their turning performance under on- and off-design conditions. The implementation of static pressure taps was motivated by the necessity to obtain a granular insight into the wall pressure variations and consequent pressure gradients. The wall pressure variation often indicate the presence of complex flow phenomena, including secondary flows, laminar separation bubbles or areas of flow separation, which can adversely impact aerodynamic performance of TRS.

3.2 Oil film method

The oil film method stands out as both an accessible and powerful tool for obtaining qualitative data in fluid dynamics, particularly employed to provide detailed surface flow visualization. This method involves applying a mixture of oil and powdered pigment to the test object, creating a sensitive layer capable of revealing fluid movement and behavior. Under the action of airflow, the oil flows on the surface, forming traces along surface streamlines and accumulating in the regions of low shear stress. In the conducted experimental campaign, digital cameras were employed to capture the flow patterns, resulting in a series of videos. The dynamic analysis of the flow visualization sequences in Papers 1-3 was performed manually, with careful tracing of particles. In Paper 5, the most recent contribution, a more advanced method was introduced. This method utilizes Sobel and Gaussian filters in conjunction with PIV algorithms to enhance the analysis further. This thorough process carried out using PIV software, is illustrated in Figure 3.2.

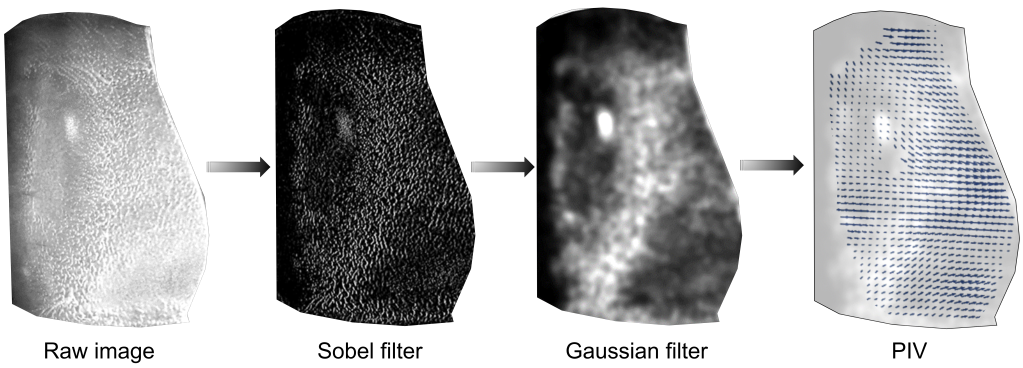

Figure 3.2: Sequential steps involved in the image processing procedure of oil film visualization.

3.3 Hot-wire anemometry

Hot-wire anemometry, a technique predicated on the principles of heat transfer, employs a sensor heated above the ambient temperature of the fluid medium. This sensor's interaction with the fluid facilitates the determination of flow velocity by monitoring the heat dissipated from the sensor to the moving fluid. Central to our investigation was the acquisition of time-resolved information, providing a comprehensive analysis of transient behavior of TRS flow. This time-sensitive data is crucial, providing insights into phenomena that are averaged out in pressure measurement technique.

Our research employed two distinct experimental setups, each tailored for distinct measurement domains and specific measurement objectives, as reflected in Figure 3.3. Calibrations for both setups were done before and after measurement using a calibration facility as detailed in previous work by Rojo [41].

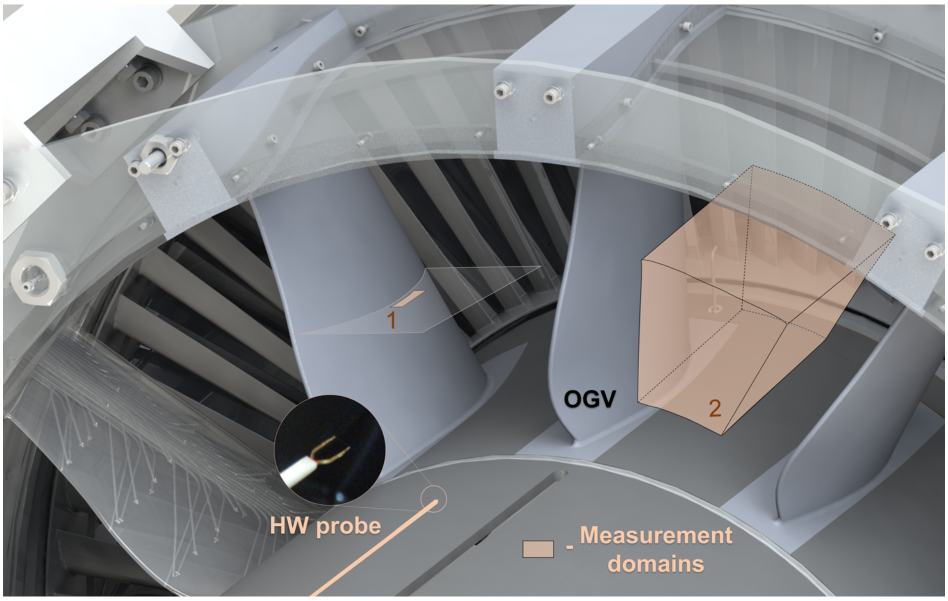

Figure 3.3: Isometric view of the test section with measurement domains for hot-wire measurements: 1 – boundary layer measurements; 2 – volume measurements between OGVs.

The first setup focused on boundary layer measurements. Here, the hot-wire probe was positioned to capture the boundary layer velocity profiles and intermittency factor, see Chernoray et al. [47] for details. The results obtained from the hot-wire boundary layer measurements performed by the author of this thesis, played a crucial role in characterization of laminar-turbulent transition and complementing the infrared measurements in Jonsson et al. [43]. Those results are not part of the current thesis but represent a significant contribution of mine to the study of TRS flow. The measurement results provided accurate determination of the specific location of the laminar-turbulent transition and boundary layer momentum thickness Reynolds number. The second setup aimed for volume measurements. This arrangement facilitated a broader spatial examination with comprehensive spatial analysis crucial for understanding of the development of wakes, particularly those emerging from the boundary layers of LPT and OGVs. This detailed approach illuminated the complex dynamics of stator and rotor interaction flows within the TRS.

3.4 Particle image velocimetry

Particle image velocimetry (PIV) is a non-intrusive optical technique used to measure and visualize fluid flow velocities. To facilitate the measurements, the method involves introducing particles into the fluid, known as seeding. These seeded particles are then illuminated using a laser, selected for its ability to produce short pulses of high-intensity light. The movement and displacement of these particles within the fluid is captured by cameras through the recording of two consecutive images and subsequently analyzed using a cross-correlation method. By leveraging the known time interval between the emitted laser pulses and particle displacement, the velocity field of the fluid flow can be reconstructed. More detailed theoretical and practical description of the method can be found in the papers by Adrian et al. [48] and Raffel et al. [49].

In our studies, 3C-2D (three-component velocity, two-dimensional) stereo PIV, was employed. The experiments were segmented into two separate configurations to capture different measurement areas (Figure 3.4). The locations of planes were chosen to facilitate intermethod validation, ensuring alignment of results with earlier presented methods. The first configuration delved into the downstream OGV wake dynamics, operating without any synchronization to the turbine's rotational speed. In contrast, the second configuration centered around the flow characteristics in the region upstream of the OGVs and downstream of the LPT. For this setup, the measurements were synchronized with the turbine rotation to capture phase-resolved flow patterns.

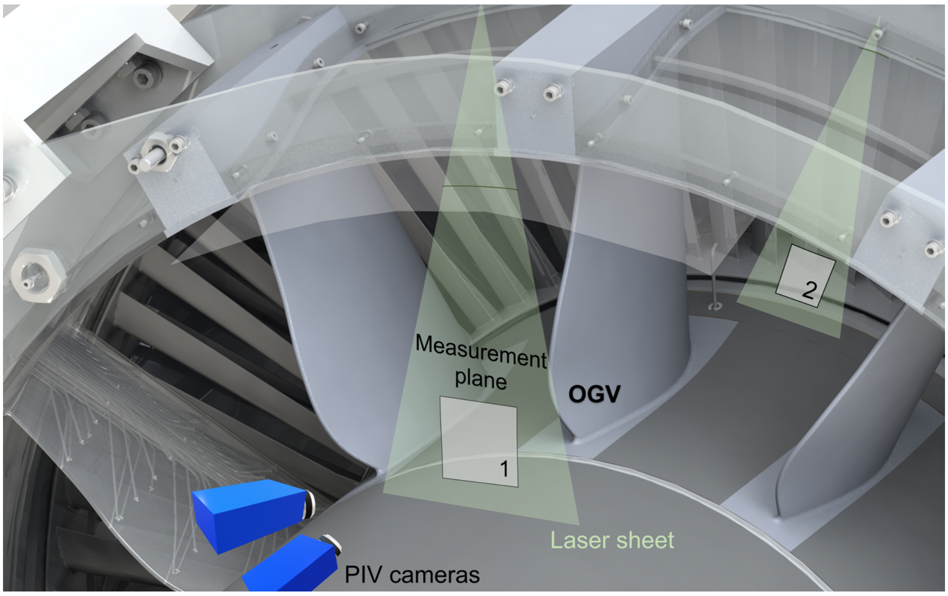

Figure 3.4: Isometric view of the test section with PIV cameras, measurement and laser planes: 1 – downstream plane in the OGV wake region; 2 -upstream plane.

Chapter 4

Summary of papers

4.1 Paper 1

Detailed experimental study of the flow in a turbine rear structure at engine realistic flow conditions, *Journal of Turbomachinery, 2020.* Valentin Vikhorev (VV), Valery Chernoray (VC), Oskar Thulin (OT), Srikanth Deshpande (SD), Jonas Larsson (JL).

4.1.1 Division of work

VV was the main author, performed pressure measurements and flow visualization, post-processed experimental data, and did the experimental analysis with further presentation of the paper at ASME Turbo Expo conference 2020. VC helped with instrumentation of TRS, data analysis, provided feedback on the paper, and supervised the work. JL gave aerodynamic analysis from the industrial perspective and provided feedback on the paper. OT coordinated the project and provided feedback on the paper. SD provided feedback on the paper.

4.1.2 Summary and discussion

This paper contributes by providing experimental data for the flow in an annular TRS (referred to as C1 in the thesis) equipped with three types of outlet guide vanes (OGVs) typical for a modern TRS design: regular vanes, thickened vanes, and bump vanes with engine-mount recess. Total and static pressure measurements together with oil-film visualizations were performed in the annular LPT-OGV rig at engine-representative inflow conditions. The measurements were performed at on-design and two off-design points varying ± 5 degrees from the on-design condition. The aerodynamic performance of each OGV geometry has been investigated in detail. Comparison of thickened and regular OGVs showed that mechanisms for the loss formation are similar for these two OGVs, although thickening of the OGV leads to higher pressure losses due to the increased blockage of the main flow and increased suction-side diffusion. The bump OGV design is shown to have noticeable influence on downstream losses in the hub and shroud regions, although the bump is shroud-located. As well, it was found that the bump OGV affects the inflow conditions by influencing the inlet total pressure and swirl.

4.1.3 Contribution

The paper presents the first aerodynamic study in an annular TRS module with investigation of different OGVs typical for a modern aeroengine. This study, through detailed pressure measurements and flow visualizations, offers significant contributions to the understanding of the effects of OGV thickness and incorporated engine-mount recesses (bumps) on TRS flow. These findings show that thickened OGV handles both on-design and off-design conditions effectively, without a substantial increase in total pressure losses or loss in turning performance. The investigation into bumps, typically considered only as structural features, uncovers their significant role in shaping OGV aerodynamics. This research highlights that shroud bumps, through their modification of wall pressure distribution and inlet conditions, indirectly contribute to notable pressure losses in the near-hub region of the TRS.

4.2 Paper 2

Experimental flow analysis in a modern turbine rear structure with 3D polygonal shroud under realistic flow conditions, *European Turbomachinery Conference on Turbomachinery Fluid Dynamics and Thermodynamics (ETC), 2021.* Valentin Vikhorev (VV), Valery Chernoray (VC).

4.2.1 Division of work

VV was the main author, performed TRS instrumentation, pressure measurements and flow visualization, post-processed experimental data, and did the experimental analysis with further presentation of the paper at the 14th European Conference on Turbomachinery Fluid Dynamics and Thermodynamics. VC helped with data analysis, provided feedback on findings, and supervised the work.

4.2.2 Summary and discussion

In this paper, aerodynamic analysis of an engine realistic state-of-the-art TRS with polygonal shroud (referred to as C2 in the thesis) was performed. The aerodynamic study of TRS with regular, thick and bump OGVs was undertaken for a fixed Reynolds number of 350,000 and three operation points. New design of the bump OGV led to blockage with extra adverse pressure gradient that influenced the flow in the shroud region and additional vorticity region for all design cases. Wake comparison for different OGVs shows that wake intensity does not significantly change for the on-design and low-loading conditions, while at the high-loading condition for the bump OGV the flow near the hub region becomes more diffusive. For the bump OGV, the oil-film visualizations indicate reversal flow and additional stagnation area in the shroud corner region. These two flow regions are the main suppliers of the additional pressure losses due to the bump.

4.2.3 Contribution

The present work provides an aerodynamic evaluation of state-of-the-art TRS with 3D polygonal shroud geometry. For the first time, a TRS with simultaneously mounted OGVs has been tested under operating conditions that closely replicate engine-realistic environments. Through this research, significant insights into the aerodynamics of different OGV configurations, particularly the impact of shroud bumps on TRS flow, are revealed. The results from this study demonstrate the importance of considering the combined effects of OGV and bump designs as a unified aerodynamic unit. Such an approach is crucial to minimize pressure losses and optimize TRS aerodynamics.

4.3 Paper 3

Experimental and numerical flow analysis of an engine-realistic state-of-the-art turbine rear structure, *Journal of Engineering for Gas Turbines and Power, 2022*. Valentin Vikhorev (VV), Pär Nylander (PN), Valery Chernoray (VC), Jonas Larsson (JL), Oskar Thulin (OT).

4.3.1 Division of work

VV was the main author, performed pressure measurements and flow visualization, post-processed and compared experimental and numerical data, with further presentation of the paper at ASME Turbo Expo conference 2021. PN performed CFD simulations, helped with numerical data analysis and writing. VC helped with experimental data analysis, provided feedback on the paper, and supervised the work. JL gave valuable analysis from the industrial perspective, provided feedback on the paper, and helped with writing. OT coordinated the project and provided feedback on writing.

4.3.2 Summary and discussion

This paper presents both experimental and numerical results for a state-of-the-art TRS with 3D polygonal shroud and simultaneously mounted regular, thick and bump vanes. The configuration is referred to as C2 in the thesis. The TRS performance was analyzed both at on- and off-design conditions. CFD was found to overpredict the intensity of the secondary flow near the hub on suction side and a vortex from a bump. Apart from this, CFD did not reveal a laminar separation bubble occurring at the on-design and high-load conditions. CFD showed good agreement with experiments for circumferentially averaged outlet profiles of the swirl angle, reflecting that the prediction of turning performance is very satisfactory.

4.3.3 Contribution

The paper provides detailed side-by-side comparison of numerical and experimental results for state-of-the-art TRS considering the wakes, blade loadings, and flow visualization patterns. From numerical simulations it can be concluded that current CFD can be used as a conservative evaluation tool of TRS aerodynamic performance. The investigation also showed that different OGV types have different upstream influences, which is crucial knowledge for accurate modeling of TRS aerodynamics. Provided experimental flow analysis has significant value from the validation point of view.

4.4 Paper 4

Experimental study on the low-pressure turbine wake interaction and development in the turbine rear structure, *European Conference For Aeronautics and Space Sciences (EUCASS), 2022.* Valentin Vikhorev (VV), Isak Jonsson (IJ), Mikhail Tokarev (MT), Valery Chernoray (VC).

4.4.1 Division of work

VV was the main author and executed both PIV and hot-wire measurements. VV also post-processed the experimental data, undertook a comprehensive inter-method analysis with further presentation of the paper at European Conference for Aeronautics and Space Sciences, 2022. MT contributed by assisting with the setup and calibration of the PIV equipment and provided invaluable practical guidance and insights throughout the research process. IJ aided by providing raw PIV data derived from a downstream plane of measurements. VC assisted with experimental data analysis, provided feedback on the paper, and supervised the work.

4.4.2 Summary and discussion

The present study offers a rigorous examination of the LPT wake interaction and its development in the TRS. Emphasis was placed on assessing the complex interaction between rotor wakes, stator wakes, and outlet guide vanes (OGVs). Comprehensive experimental investigations using PIV and hot-wire measurements revealed pronounced unsteady flow modulations at the TRS inlet, which subsequently developed throughout the TRS. The PIV results provide fundamentally crucial insights into the inflow structure, particularly highlighting rotor wakes modulated by small-scale vortices. As the flow propagates through the TRS, the level of fluctuations decreases, yielding a more smoothed-out pattern. Notably, due to swirl angle gradients, the rotor and stator wakes exhibit a leaning behavior, resulting in a staggered wake pattern.

4.4.3 Contribution

This research substantially advances the study of flow unsteadiness within TRS, unveiling previously unexplored aspects of the flow and complementing previous steady state measurements. It marks the first instance of employing both HW and PIV techniques in the context of TRS flow, providing comprehensive data on both time-resolved and instantaneous flow fields. The results offer invaluable insights into structure and propagation of LPT rotor and stator wakes. This new knowledge stands to significantly enhance future computational fluid dynamics ensuring the intricacies of flow unsteadiness are adequately addressed in upcoming TRS designs.

4.5 Paper 5

The influence of the vane lean on the flow in a turbine rear structure, *Congress of the International Council of the Aeronautical Sciences (ICAS), 2022.* Valentin Vikhorev (VV), Valery Chernoray (VC), Zuher Abdel Mallak (ZA), Jonas Larsson (JL).

4.5.1 Division of work

VV was the main author, performed pressure measurements, post-processed experimental data with further side-by-side comparison between state-of-the-art radial and lean TRS designs. These results were presented by VV at Congress of the International Council of the Aeronautical Sciences. VC provided feedback on the paper and supervised the work. JL gave valuable analysis from the industrial perspective, provided feedback on the paper. ZA provided feedback on writing.

4.5.2 Summary and discussion

This paper presents experimental results for state-of-the-art radial and leaned TRS configurations, referred to as C2 and C3 in the thesis. These tests were conducted under engine-representative Reynolds numbers and across three distinct LPT loads. Pressure distributions both upstream and downstream of the outlet guide vanes (OGV) were meticulously measured utilizing pressure probes. When compared, it was discerned that the positive lean angle of the OGV had a significant influence on the TRS flow. The OGV lean resulted in a redistribution of total pressure, attributed to both a reduced radial pressure gradient and diminished flow diffusion on the vane's suction side proximate to the hub. Consequently, wake regions showed decreased total pressure losses, particularly for highly loaded LPT. Furthermore, considering leaned OGVs with bump, losses near the shroud notably lessened, while those near the hub intensified.

4.5.3 Contribution

This paper contributes to the TRS research by conducting a comprehensive aerodynamic evaluation of a leaned state-of-the-art TRS configuration, tested under engine-representative flow conditions. For the first time, this study explores two state-of-the-art configurations, both engine-realistic with three OGV types, offering a detailed side-by-side comparison of experimental results. By focusing on the combined effects of straight lean and diverse OGV geometries on pressure losses, this research substantially advances understanding of TRS aerodynamics and provide valuable insights for future design enhancements.

Chapter 5

Concluding remarks

The integration of novel technology into aircraft engines is a lengthy and scrupulous process, essential for ensuring high standards of performance, reliability, and safety. It involves progression through nine technology readiness levels (TRLs), from investigation of basic principles to the actual application of the technology in its final form. Concerning TRS research, many studies have reached up to TRL 3, a stage involving laboratory studies to physically validate the analytical predictions of TRS separate elements. However, these studies were often constrained either by the lack of engine relevant conditions or relied on simplified models. This reflects a limited experimental database on TRS and highlights the need for comprehensive TRS validation.

The thesis serves as a significant milestone in closing this knowledge gap and elevating the level of TRS research to TRL 4 transitioning from the limited scope of laboratory investigations to detailed experimental analysis of the TRS flow conducted under engine-relevant flow conditions in state-of-the-art TRS designs.

For the first time, the experimental analysis focused on three modern TRS configurations: C1, C2 and C3 as named in the thesis. Each of these configurations features OGVs typical for state-of-the-art turbofan engines: regular, with increased thickness and with engine-mount recesses (bumps). Configurations C1 and C2 have radial OGVs, and C3 incorporates leaned OGVs. Configuration C1 has a circular shroud and two state-of-the-art TRS configurations C2 and C3 have polygonal shroud. Furthermore, configurations C2 and C3 have optimized OGV and hub geometries, and simultaneously installed OGVs of different types as in a real turbofan engine.

The research is conducted in an annular 1.5 stage LPT-OGV facility at Chalmers University of Technology, equipped with a realistic shrouded LPT. These tests, despite being at low Mach numbers, are highly relevant to engine conditions as the flow in an aeroengine LPT is fully subsonic, devoid of compressible effects such as shocks or shock-boundary layer interactions. For C1 configuration, the measurements were performed for Reynolds number of 235,000 and three flow coefficients with a swirl angle varying ±5 degrees from on-design point. For C2 and C3 configurations, the experiments were carried out at higher Reynolds number of 350,000 and three flow coefficients with swirl angles varying from -10 to +5 degrees from on-design point.

The pressure distributions for both radial C1 and C2 configuration obtained with pressure probes show that thickening of the OGV leads to minor additional pressure losses compared to the regular OGV due to its good aerodynamic design. Both regular and thick OGV designs are shown to handle on- and off-design conditions without deterioration of turning performance. The main contribution to the profile loss (a 2D loss) of regular and thick OGVs is shown to be due to the secondary flow formed in a region near the hub on the OGV suction side. The oil-film visualization indicates these loss-core structures at on- and off-design conditions with high loading. Moreover, these visualizations for most of the design cases also indicate laminar-separation bubbles that locate at 40% of the midspan chord for the lower Reynolds number and at 30% for the higher Reynolds number. However, based on wake analysis, the laminar-separation bubble does not contribute to pressure losses due to the further turbulent reattachment.

For the first time in the context of TRS flow, time-averaged pressure measurements for C1 configuration were complemented with detailed time-resolved and instantaneous velocity field data obtained from both HWA and PIV techniques. The PIV and hot-wire measurements in this study highlighted notable unsteady flow modulations at the TRS inlet that propagate into TRS. The HWA results specifically bring attention to the leaning of rotor and stator wakes, which leads to a staggered pattern in the wake arrangement. Furthermore, the PIV analysis provides detailed structure of the rotor wakes, modulated by small-scale vortices, each approximately 5 mm in size. These results are crucial for future high-fidelity CFD simulations.

The integration of a bump in OGV design significantly changes the pressure distribution and consequently, the pressure losses. For C1 configuration, the wake analysis shows more than double the increase of pressure losses in the hub region due to the indirect influence on LPT outlet conditions with increase in absolute swirl angle by approximately one degree and higher radial pressure gradient. For C2 configuration, the bump OGV pressure losses near the hub increase substantially only for the highly loaded case, reaching approximately up to 15% increase of wake depth. This can be attributed to improvements in the OGV design as well as the impact of a more convergent channel geometry with polygonal shroud design. However, this design has a more aggressive bump and the main contribution to the pressure losses is shown to be due to the secondary flow formed in a region of the shroud bump itself. The oil-film visualization patterns with axial vorticity distribution obtained for all design conditions have revealed reversal flow and additional vorticity region in the shroud corner region with twice higher vorticity magnitude compared to the wake core. This leads to over-turning of the flow in the shroud region by approximately two degrees compared to the regular and thick OGVs.

The state-of-the-art TRS with pressure-side leaned OGVs (C3) was evaluated and compared to a radial state-of-the-art design (C2) in terms of pressure losses. The alteration in the loss-core structures is primarily attributable to the changed radial pressure gradient and weakened flow diffusion on the suction side of OGV. Furthermore, the OGV bump significantly impacts the pressure losses near the hub across all design conditions, owing to the induced pressure gradient from bump itself. Despite the leaned vane design being developed under numerous constraints from multiple disciplines, it performs well in terms of pressure losses and turning performance, proving its good aerodynamic efficiency under different design conditions.

Regarding CFD results obtained for the radial C2 configuration, the wake analysis shows the good estimation of pressure losses in the midspan region, however, current CFD tools used by industry tend to overpredict secondary flow structures in the endwall regions. This leads to a substantial increase in pressure losses, which can be as much as double in the hub and shroud regions, particularly under high loading conditions. The experimental results from this work not only offer a valuable database for future CFD simulations but also underscore the need for continued refinement of current industrial CFD tools essential for development of aerodynamically efficient TRS designs.

Chapter 6

Ongoing and future work

As we continue to advance in our understanding and capabilities, this thesis identifies several promising directions for future research that build upon our current achievements. Many of these development areas are linked to already ongoing projects or those planned for future exploration.

- **Influence of welds**

The welding process used in the manufacturing of TRS with OGVs introduces surface welds, potentially impacting the development of OGV and endwall boundary layers, and, consequently, affecting pressure losses. Therefore, in order to investigate the influence of weld shape and size on TRS aerodynamics, I did an extensive experimental campaign for engine-realistic TRS involving 43 different cases. Despite the importance of these experimental data for CFD simulations, the scope of this research was limited to a singular weld type: radial weld on the OGV surface. Future research should include a comprehensive analysis of TRS aerodynamics with other weld types, extending to areas beyond OGV, such as the hub and shroud endwalls. Although the findings from these measurements are not included in the current scope of this thesis, their significance is sufficient to justify a dedicated publication.

- **Heat transfer study**

Despite the complete understanding of engine-realistic TRS aerodynamics, investigating thermal performance of TRS remains crucial. For this purpose, I carried out initial heat transfer measurements and will further expand upon these measurements for a thorough thermal analysis of TRS flow. The first part of heat transfer investigation was conducted on water heated OGV with increased thickness. These experiments were instrumental in obtaining surface heat transfer data for the OGV, hub and shroud endwalls. Additionally, the technique used in these experiments has been proved to be effective for identifying the laminar-turbulent transition. This has been supported by earlier work [43] that involved my hot-wire measurements of the OGV boundary layer and further calculations of intermittency factors to accurately determine the transition location. During the second part of the investigation, the endwall hub surface was externally heated by purge flow to assess the film effectiveness on the adiabatic wall. In the context of the TRS with purge flow, it was observed that aerodynamic characteristics have minor influence on engine-realistic TRS aerodynamics. However, recent investigations in both heat transfer studies indicated significant discrepancies between experimental results and numerical simulations underscoring the need for more detailed experimental measurements and refined computational tools. Therefore, for a comprehensive thermal study, it is crucial to enhance industrial CFD tools, validate existing heat transfer experimental data using alternative methods, and expand research with a specific emphasis on OGVs featuring bumps and welds.

- **Novel engine concepts**

As engine designs undergo rapid evolution, characterized by trends favoring compactness, lightweight structures, hybridization, and the integration of heat recuperation systems, the need to adjust and create new TRS designs to align with these technological shifts becomes essential. One of these innovative concepts aimed at enhancing heat recuperation has already been assessed within the Chalmers LPT-OGV facility, where I was involved, demonstrating satisfactory aerodynamic performance while concurrently exhibiting a notable 40% increase in heat transfer coefficient. Another example of future TRS design, performed in an ongoing EU project SWITCH, where I will be involved, is related to hybridization that requires using of thick cables for the hybrid-electric engine that pass through the OGVs. Therefore, it becomes essential to enlarge the thickness of OGVs to accommodate these changes. These and other novel concepts necessitate extensive experimental investigations to build a comprehensive database and gain new insights into TRS flow.

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