

Upstream Forcing Due to Turbine Rear Structure Vanes on Low Pressure Turbine of an Aero-engine

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ABSTRACT

In axial turbomachines, blade rows are subjected to aerodynamic forcing from both upstream and downstream components, including entropy, vortical, and acoustic disturbances. Assessing the impact of these disturbances on performance and stability is essential. This study focuses on the upstream forcing from outlet guide vanes (OGVs) in turbine rear structure (TRS) of a typical jet engine. The OGVs are designed to de-swirl the flow exiting the low-pressure turbine (LPT) and align the flow axially.

A key concern is the upstream forcing exerted by the OGVs on the LPT rotor. This phenomenon is influenced primarily by two factors: the thickness of the OGVs and their axial distance from the rotor. OGV thickness is driven by structural requirements and its function to accommodate lead-throughs like oil pipes. Thicker vanes generally require larger axial spacing to reduce their aerodynamic impact. However, reducing this distance could enable more compact engine designs, leading to improved fuel efficiency.

A two-step approach to study upstream forcing is used in this work. First, static pressure measurements are conducted at multiple axial locations upstream of the OGV using a turbine test rig. The experimental setup includes different vane types-regular, thick, and mount-vanes to represent realistic engine configurations. This step provides an indication of forcing function from OGVs. Second, transient numerical simulations are performed to evaluate impact of unsteady pressure fluctuations on the LPT rotor.

Results show that pressure disturbances from the OGV propagate upstream and decay with increasing distance from leading edge. The findings indicate that thicker vanes lead to stronger pressure fluctuations, highlighting the importance of vane design and axial positioning in minimizing upstream forcing effects.

Keywords: Upstream forcing; Pressure waves; turbine rear structure; low pressure turbine

NOMENCLATURE

ADP	Aerodynamic Design Point
CFD	Computational Fluid Dynamics
CTH	Chalmers Technical University
FC	Flow Co-efficient
LE	Leading Edge
LPT	Low Pressure Turbine
NGV	Nozzle Guide Vane
OGV	Outlet Guide Vane
RANS	Reynolds-averaged Navier-Stokes
SST	Shear Stress Transport
TRS	Turbine Rear Structure

Symbols

C_p	Non-dimensional static pressure coefficient $(P_S - P_{S,ref}) / (P_{T,ref} - P_{S,ref})$
P_S	Static pressure
$P_{S,ref}$	Inlet midspan average static pressure
$P_{T,ref}$	Inlet midspan average total pressure
v_t	Circumferential velocity component
v_x	Axial velocity component
v_r	Radial velocity component

1.0 INTRODUCTION

In axial turbomachines, a blade-row must sustain the aerodynamic forcing from upstream and downstream structures viz. entropy and vortical disturbances from upstream and acoustic disturbance from both upstream and downstream blade-rows⁰⁰. It is imperative to check the impact on performance and stability of the blade-row experiencing the flow disturbances from upstream and downstream vanes. The blade-row of interest in this work comprises of vanes in turbine-rear-structure of a typical commercial jet-engine.

A Turbine Rear Structure (TRS) is a component at the aft of a low-pressure-turbine (LPT) in a jet engine. TRS has Outlet Guide Vanes (OGVs) that de-swirl the LPT outlet flow and makes the flow as axial as possible. This paper investigates the upstream forcing effects induced by the OGVs on LPT rotor blades. Two main factors contribute to the upstream forcing phenomenon: the characteristic high thickness of the OGVs and axial distance of OGVs from the LPT rotor. The thickness of outlet guide vane is driven by the structural load that guide vanes must carry and the size of oil pipes that the vanes must accommodate. The thicker the vane, the farther away from LPT should the OGV location be to minimize impact of upstream forcing on LPT rotor.

Understanding the impact of OGV thickness on upstream forcing on the LPT rotor blade helps to explore more compact turbine designs by reducing the axial distance between the leading edge of the OGV and the LPT rotor. Such reduction in axial distance can be important to shorten the engine length, which has beneficial impact on the engine's specific fuel consumption.

Miller et al [3][4] performed experimental and numerical studies to assess the impact of vane wakes and potential field on high-pressure-turbine rotor. Fast response pressure sensors were used to experimentally capture the unsteady pressure effects on rotor profile due to upstream and downstream vanes. Power spectrum studies performed show interaction of blade-passing frequencies from upstream and downstream vanes. In the context of current work, it is important to note that potential field from a downstream vane has significant impact on unsteady pressure on the upstream rotor. Also highlighted is the fact that unsteady pressure on a rotor is a function of blade-passing frequency of surrounding vanes and axial distances between blade-rows.

Impact of vanes on rotor in an axial compressor environment was studied by Ben et al [5]. Rotor wake oscillations, rotor wake skewing and rotor exit flow angle fluctuations are mechanisms addressed in the study. It is shown that potential field from downstream stator cause oscillations of rotor wakes. Interaction between rotor and stator is studied by varying axial distances. Consistent with expected turbomachinery behaviour, rotor-stator interaction is shown to reduce with increase in axial distance between blade-rows.

With a goal to explore the possibilities of reducing overall engine length, the study on upstream forcing due to OGVs on LPT rotor is initiated. Following sections describe the steps followed in understanding impact of OGV on LPT rotor.

2.0 APPROACH

In the present work, a two-step approach is adopted to study the impact of upstream travelling pressure waves on the LPT rotor due to OGVs. The first step is to experimentally measure the static pressures at different axial locations between LPT rotor trailing edge and OGV leading edge. These measurements indicate the forcing function due to potential field by OGVs. In the second step, impact of forcing function on a mid-span section of LPT rotor is assessed.

The first step consisted of conducting experimental static pressure measurements at several axial locations upstream of the OGV. These measurements were performed using the low-pressure LPT-OGV turbine rig at Chalmers University of Technology in Gothenburg. The aerodynamic design of LPT and OGV were carried out at GKN Aerospace, Sweden. Figure 2-1 shows a cross-section of the rig, depicting the different blade rows and associated instrumentation. Also shown in Figure 2-1 are the three axial planes upstream of outlet-guide-vane where static pressures were measured.

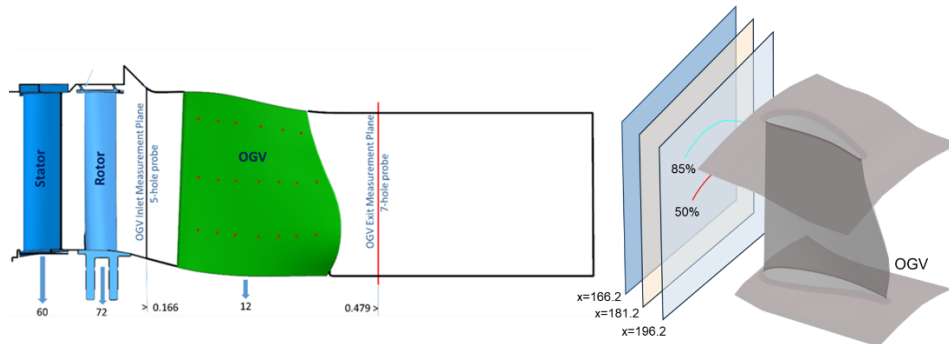


Figure 2-1 Meridional view of blade-rows in test-rig and axial locations for measurement

The test object used in the present test campaign is shown in Figure 2-2. The test object has three different kinds of OGVs at different circumferential position, viz., regular-vane, thick-vane and mount-vane. Regular-vane and mount-vane have same strut thickness. Thick-vane is thicker compared to regular-vane by 25%. The three mount-vanes have engine mount recess at the outer-case. An engine mount recess is a protrusion inside the flow-path as shown in Figure 2-2. The engine mount recess is used to attach the TRS to the engine structure in a real engine. In this test campaign, static pressure measurements are carried out at three axial planes in front of all three kinds of OGVs providing broad understanding of the physical phenomenon of upstream forcing in an engine-realistic configuration.

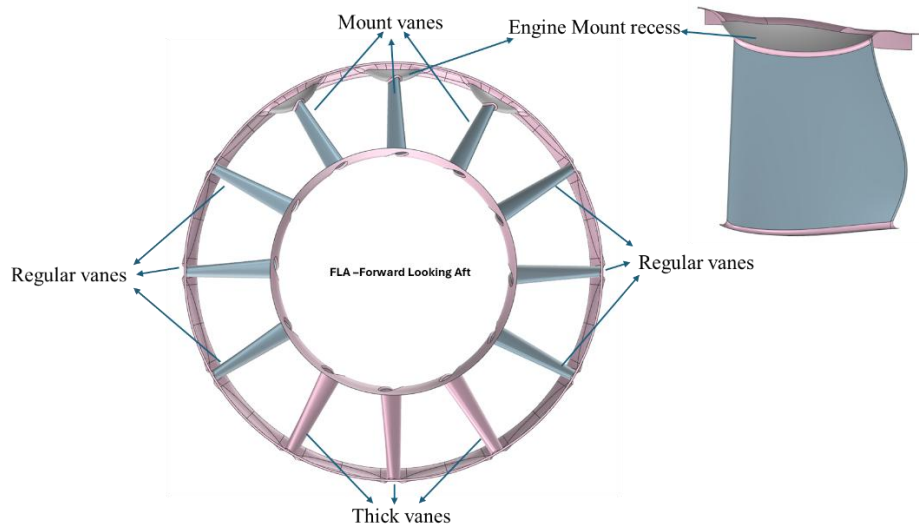


Figure 2-2 Test Object

The second step was to perform transient numerical simulations for an initial study of upstream forcing impact on LPT rotor. The unsteady pressures on mid-span section of LPT rotor are monitored to assess the impact of outlet-guide vanes on the rotor. Impact of thickness of vanes and axial locations of vanes are explored. Unsteady pressure fluctuations are presented for four cases, viz., without outlet-guide vane, with regular, thick and mount-vanes. The unsteady pressures presented herein are influenced by both the upstream LPT NGV and the downstream OGV.

3.0 FORCING FUNCTION

The potential field due to vane in TRS applies force on the upstream rotor. To measure this forcing function, experiments were conducted in LPT-OGV rig at Chalmers university of technology. Potential field was measured upstream of all three different kinds of vanes in TRS. Data was extracted at two spanwise location 50% and 85 %. Decay of potential field away from vane LE is also captured in measurements by static pressure measured at three axial planes. Details of the experiments and instrumentation is covered in the following section.

3.1 Experimental Details

The experiments were conducted in the 1.5-stage LPT-OGV facility at Chalmers University of Technology, developed under GKN supervision. The rig provides well-controlled and repeatable inlet conditions, with Reynolds numbers ranging from 100,000 to 600,000 based on channel height and axial velocity at the TRS inlet. The flow coefficient (FC), defined as the ratio of axial velocity to turbine blade speed, was adjusted via a hydraulic brake on the rotor shaft. All measurements were performed at low Mach numbers ($M \approx 0.1$). The rig consists of a shrouded LPT stage with 72 rotor blades and 60 stator vanes, designed by GKN Aerospace. The upstream rotating stage enables realistic wake generation, providing engine-representative flow conditions in a cold-air test rig. Further details on the facility are available in the publication by Rojo et al [7].

Static pressure measurements were conducted using a custom-made static pressure probe shown in Figure 3-1. The probe was manufactured in-house from two circular disks, each with a thickness of 0.5 mm and a diameter of 15 mm, incorporating pressure taps of 0.2 mm diameter, which were bonded together to form a double-sided configuration. The probe was calibrated prior to the measurements and aligned with the flow direction to minimize errors associated with flow angularity. The probe was positioned using a traversing system with positioning accuracies of 0.01° in the circumferential direction and 0.075 mm in both radial and axial directions. Measurements were acquired at three axial locations and at two radial spans, corresponding to 50% and 85% of the span. Pressure data were acquired with a PSI-9116 system at 500 Hz with a sampling time of

2.5 s. Two independent pressure channels enabled cross-verification of the data, and the reported values correspond to the average signal.

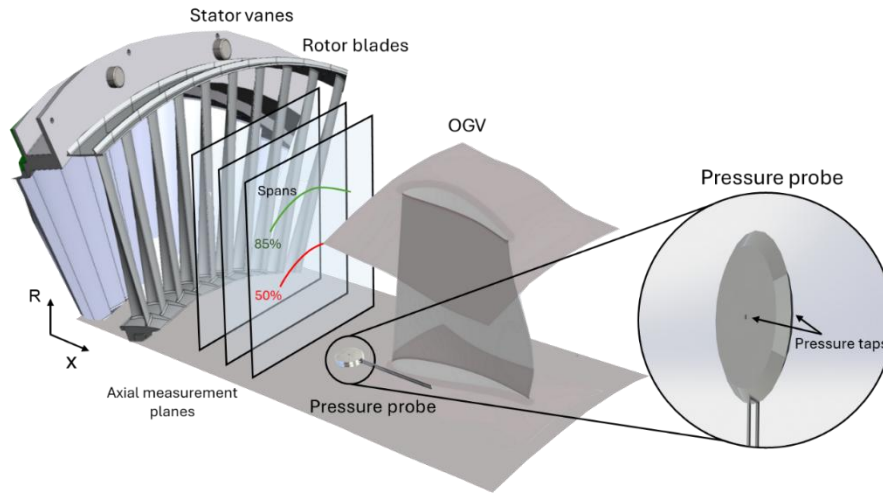


Figure 3-1 Schematic of LPT and TRS with measurement planes and instrumentation

3.2 Numerical Details

Numerical simulations of the TRS (only) using experimental data as boundary conditions were performed using commercial software FLUENT. Three-dimensional CFD using steady-state RANS equations were carried out. A two-dimensional total-pressure contour of data extracted from 5-hole probe at TRS inlet along with flow direction are applied at TRS inlet. Typical TRS inlet boundary conditions are shown in Figure 3-2. Swirl angle is defined as $\tan^{-1}(v_r/v_x)$ and yaw angle is defined as $\tan^{-1}(v_r/v_x)$. Static pressure profile, also from measurements is used as exit boundary condition at TRS outlet. The $k\omega$ -SST turbulence model with transition was used for closure of RANS equations. Simulations were performed as a validation effort for another test-campaign. Simulations were carried out by Nylander et al [8]. This publication can be referred for further numerical details.

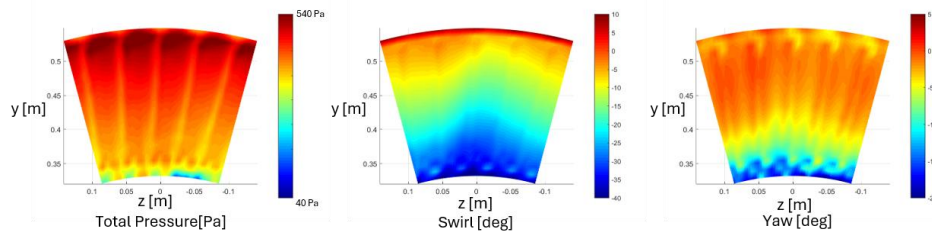


Figure 3-2 Inlet Boundary conditions from experiments

3.3 Results

Experimental data that are available to assess forcing function are static pressure measurements at three axial locations and two spanwise locations. These data are available for all three kinds of vanes. Also, data is available to study impact of Reynolds number and change in operating conditions. Experimental results from the test campaign to determine the forcing function of the TRS vane on the LPT are compared with bespoke data extracted from numerical simulations. Firstly, the impact of type of vane on the forcing function at a given Reynolds number is discussed. Then the discussion on impact of Reynolds number on forcing function in a thick-vane sector is picked up. Lastly, impact of inlet swirl on upstream forcing for a thick-vane section is presented.

3.3.1 Impact of Vane-type

To discuss the impact of vane type on upstream forcing, aerodynamic design point (ADP) condition corresponding to FC of 0.622 is considered.

In Figure 3-3, experimental results of static pressure measurements at different planes and numerical results are shown. Three columns are for mount-vane, regular-vane and thick-vane. First row of Figure 3-3 corresponds to measurements done at 50% span and second row corresponds to measurements done at 85% span. Data captured at three axial-plane locations are shown for each image.

The TRS vanes create a potential field propagating upstream. The potential field so formed has high intensity close to LE of vane that is causing the potential field. This effect of high potential field close to LE can be observed from the measurements. The static pressure distribution has high gradients close to LE of vane and the distribution flattens out further away from LE.

Since thick-vanes are thicker by 25%, the potential field developed by thick-vanes have higher gradients. In Figure 3-3, this trend for thick-vanes can be seen. Peak pressures for each type of vane at 50% span and on closest plane to LE are mentioned. For thick-vane the peak pressure is 211 Pa (gauge pressure) compared to 185 Pa for regular-vane and 187 Pa for mount vane. The impact of thicker vanes penetrates axially closer to LPT rotor.

In mount-vane, due to engine mount recess at the outer-case, upstream forcing at higher span is higher when compared to regular and thick-vanes. Potential field distribution for a regular-vane and a thick-vane looks similar for 50% span and 85 % span. But for mount-vane, the impact of engine mount recess can be clearly seen. At 85 % span for mount-vane, number of measurement points are limited due to less spatial access for pressure probes.

The upstream forcing curves extracted from numerical simulations are also shown in Figure 3-3. The peaks and gradients of upstream forcing curves are captured satisfactorily in CFD. Since the upstream forcing curves being compared are not near wall curves, a generic, industry standard mesh was able to capture the static pressure distributions upstream of TRS vanes. It is important to note that to match the clocking positions of OGVs in experiments and CFD is extremely difficult. At upper spans for Mount-vane, the flow is very complex with tip-leakage flow interacting with flow deflection due to engine-mount recess. Minor differences can be seen between experiments and CFD values. But the overall trends are captured satisfactorily by CFD.

From these results it can be concluded that, due to different kinds of vanes placed circumferentially in a TRS, LPT rotors experience potential field that is circumferentially non-uniform. LPT rotors should be designed robust enough and stiff enough to withstand this circumferentially varying pressure field. More the LPT rotor can withstand, the closer the TRS vanes can be placed to LPT rotor and hence affect the overall engine length.

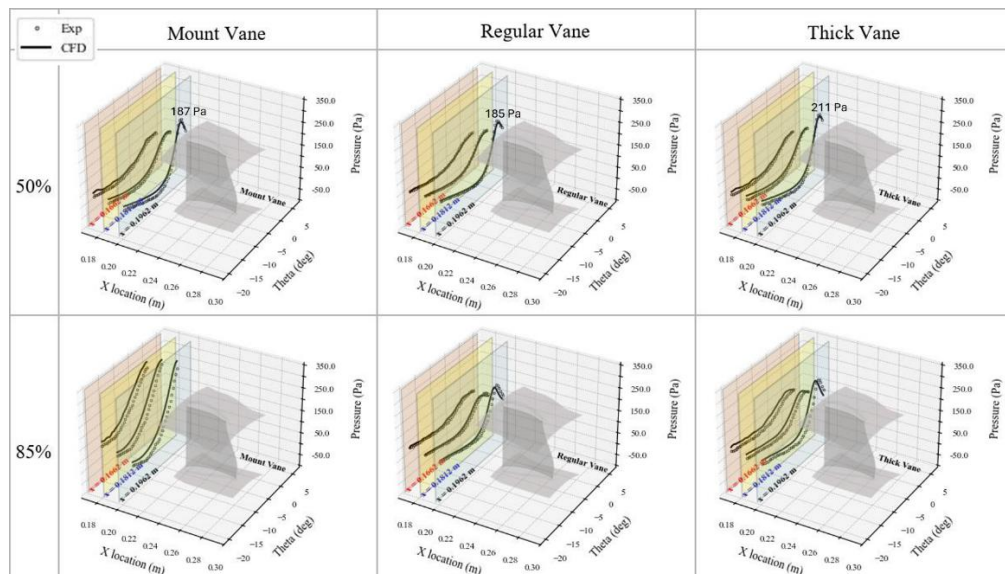


Figure 3-3 Impact of vane-type on forcing function

3.3.2 Impact of Reynolds number

Reynolds number for the LPT-OGV setup is calculated based on channel height at OGV inlet. Two Reynolds numbers 350k and 465k are considered to study the impact of Reynolds number on upstream forcing due to TRS vanes. To study the impact of Reynolds number, thick-vane sector was considered for measurements and simulations at ADP flow conditions (FC of 0.622). Upstream propagating pressure curves are shown in Figure 3-4. It can be observed, both at 50% span and 85% span, upstream forcing is stronger with higher Reynolds number. This indicates that higher the Reynolds number, greater will be the impact of OGVs on the LPT rotor.

Numerical results compare satisfactorily with measured data capturing the effect of Reynolds number.

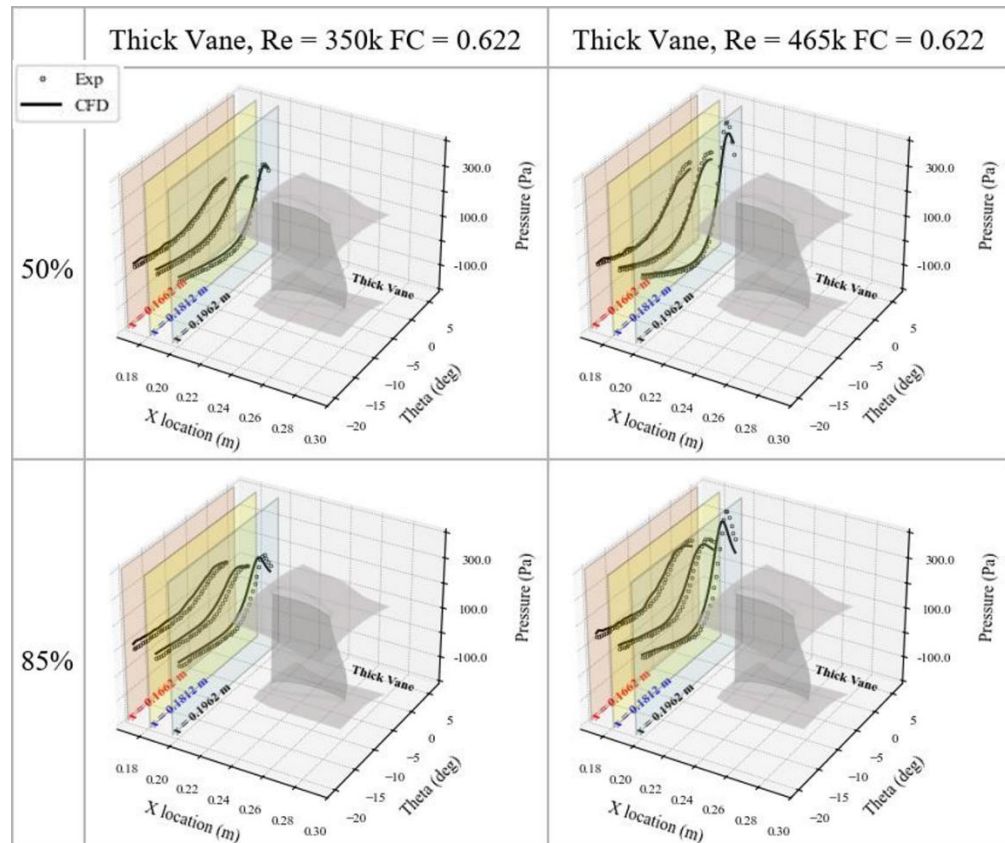


Figure 3-4 Impact of Reynolds number on Upstream forcing

3.3.3 Impact of Inlet Swirl

Experiments were conducted at two flow coefficients FC 0.622 and 0.657 which correspond to two inlet swirls on vanes as shown in Figure 3-5. Difference in inlet swirl angle is 5 degrees. For this difference in incidence, upstream forcing is measured and shown in Figure 3-6.



Figure 3-5 Schematic showing change in incidence angle due to flow coefficient

Figure 3-6 shows the impact of flow-coefficient on upstream potential field. Left-hand side column shows the pressure variations for flow-coefficient of 0.622 and right-hand side column shows the same for flow-coefficient of 0.657. Since it is difficult to spot the differences, curves from experiments are compared for both flow-coefficients in a two-dimensional plot in the centre of Figure 3-6. With 5 degree change in inlet swirl, measured data shows around 0.5 degree shift in peak points on upstream propagating pressure curves. The peak in static pressure curve for FC 0.657 shifts away from LE towards the flow direction. Similar trend is seen both at 50% span and 85 % span. Though the shift in peak position is not affected significantly, a noticeable change in depths of pressure variation is seen hence increasing the gradients of pressure curves with increase in flow-coefficient.

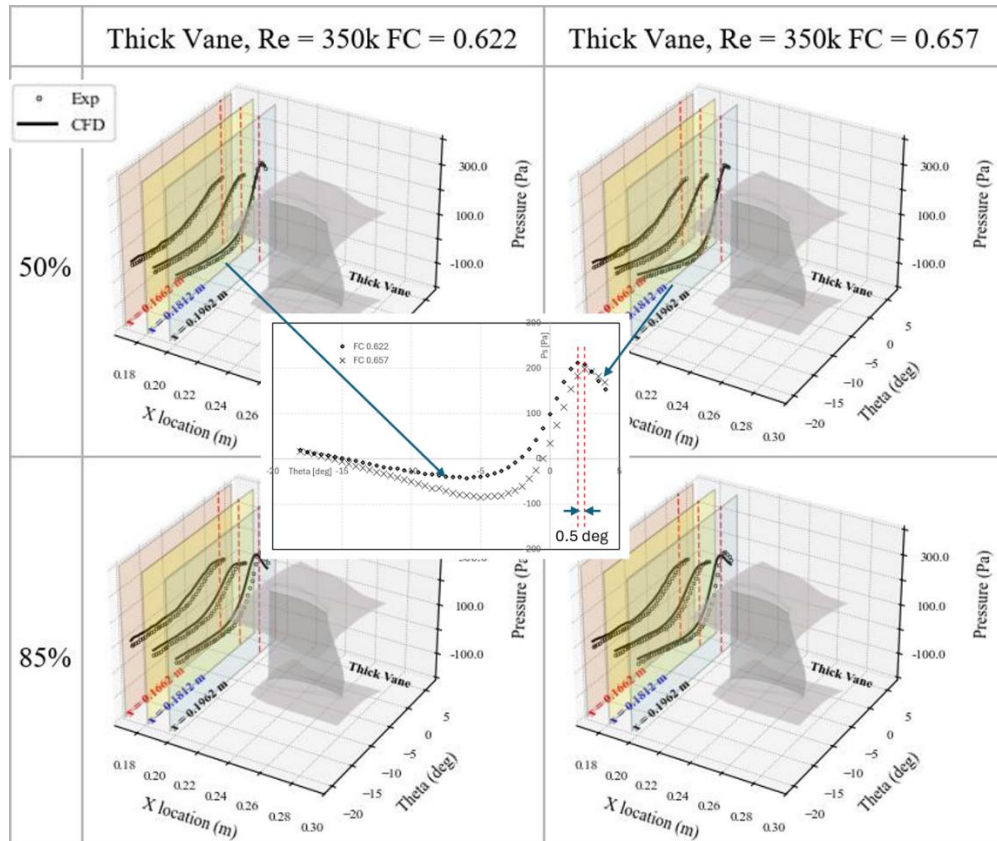


Figure 3-6 Impact of flow-coefficient on Upstream Forcing

4.0 IMPACT OF FORCING ON ROTOR

To study the impact of potential field of OGVs on LPT rotor, unsteady numerical simulations are performed. Numerical domain comprising of 5 LPT stators, 6 LPT rotors and 1 OGV vane is analysed. Number of stators, rotors and OGVs in analyses result in pitch ratio of unity between blade rows since there are 60 stators, 72 rotors and 12 OGVs in 360-degree test setup. Blade-rows in the numerical domain are shown in Figure 4-1. Purpose of the analyses was to setup an initial process to study the impact of potential field on LPT rotor. Mesh details for each domain are provided in Table 1.

Table 1
Mesh details

	Mesh size for the domain
NGV/Stator	1 million
Rotor	2.5 million
OGV	0.5 million

The mesh resolution employed in the present study is based on prior experience, and a formal mesh independence assessment has not been conducted at this stage. This is considered acceptable, as the primary objective of the initial investigation is to establish a process to examine the transient behavior of static pressure at the rotor mid-span section, rather than to establish grid convergence.

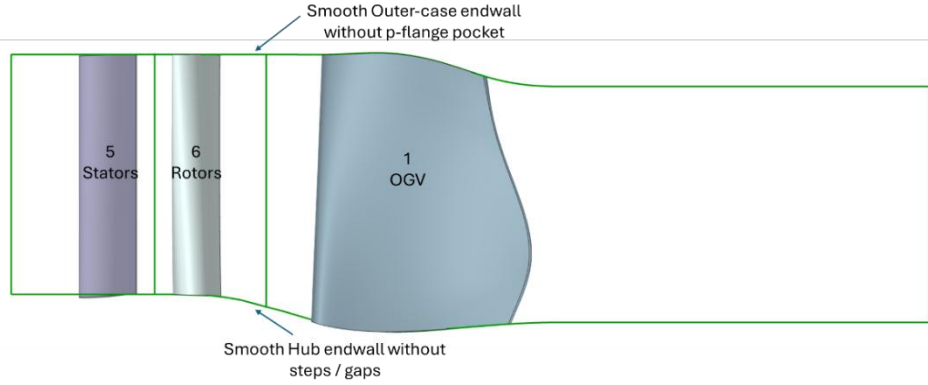


Figure 4-1 Blade-rows in numerical domain for transient simulation

Analyses are performed using commercial tool Ansys CFX 2023r1. Only ADP (flow-coefficient 0.622) is analysed with rotor speed of 820 rpm and mass flow of 17.8 kg/s. Turbulence intensity of 1 % is assumed at inlet of NGV (stator). The boundary conditions were prescribed as mass flow at the inlet and static pressure at the outlet, consistent with the available test data. This approach facilitates direct comparison with experimental measurements and ensures that the flow field within the test rig is accurately represented. For transient simulation, total time of analysis is 0.024 seconds. One rotor blade covers four passages of OGV in 0.024 seconds. The rotor blade takes 100 steps to cover one OGV passage. With the same simulation setup, four cases with different OGV domains are analysed.

1. No OGV vane downstream of LPT
2. Regular-vane sector downstream of LPT
3. Thick-vane sector downstream of LPT
4. Mount-vane sector downstream of LPT

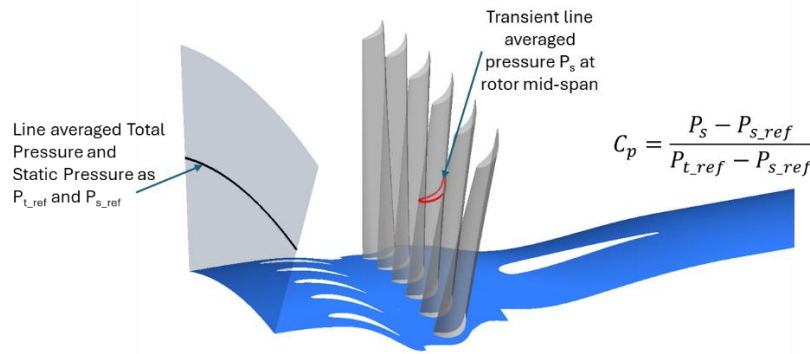


Figure 4-2 Unsteady simulation - geometry and data of interest

For post-processing of numerical simulation, in present study, length-averaged pressure value at mid-span profile (P_s) of rotor is extracted. The rotor cross-section of interest is shown in Figure 4-2. For normalization of P_s , reference total pressure and static pressures are picked at stator inlet mid-span that is also shown in Figure 4-2. Equation to calculate coefficient of pressure is given by

$$C_p = \frac{P_s - P_{s_{ref}}}{P_{t_{ref}} - P_{s_{ref}}}$$

Figure 4-3 shows C_p values for each of the four cases as the rotor passes upstream of OGVs. For a no-OGV vane case (No-Vane), the change in C_p value reflects the impact of stator wakes on rotor mid-span profile. When rotor passes in front of regular-vane, the C_p value deviates from No-vane case. This is the impact of potential field due to the presence of regular-vane. Since the vane thickness is higher in thick-vane when compared to regular-vane, the C_p distribution against time further distorts from No-Vane case for thick-vane case. Maximum deflection of C_p curve is seen in mount-vane case. This is because of decreased blade height in mount-vane due to engine-mount recess (refer Figure 2-2). Moreover, the simulation with mount-vane assumes adjacent vane to be mount-vane hence increasing blockage and Mach number.

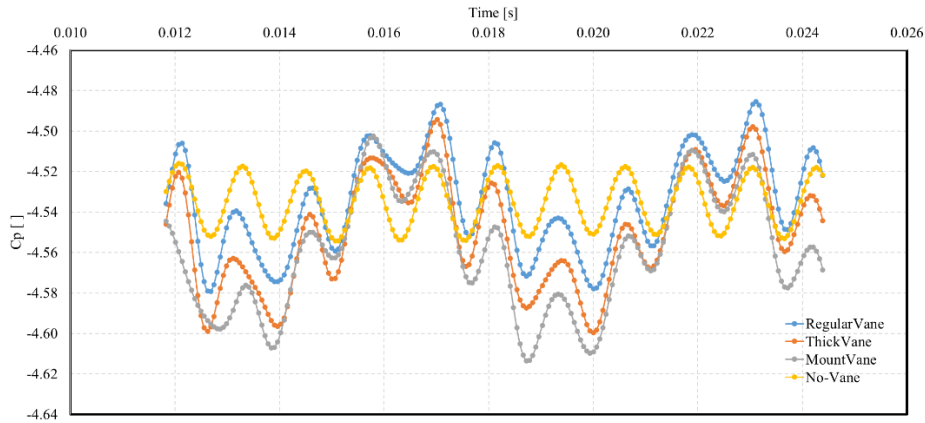


Figure 4-3 Length averaged C_p at mid-span rotor section

In reality, the rotor sees impact of regular-vane, thick-vane and mount-vane in 360 degrees when rotor goes through one revolution. This implies that rotor sees potential field corresponding to engine order 12 (number of OGVs) super-imposed on No-vane case. This is a complex pressure field for rotor to endure.

These distributions shown are for single section on rotor. However, the data needs to be expanded and assessed for all the points on the rotor surface for impact of potential field of OGVs. The unsteady pressure on entire rotor surface serves as input to forced response analyses of LPT rotor. This package of impact of OGV potential field on entire rotor surface and forced response analyses will be considered for future studies.

One of the reasons to study impact of potential field of OGV on rotor is to explore the possibility of moving OGV towards LPT rotor and hence reducing overall engine length. As a preliminary numerical check, regular-vane was moved upstream by 10 mm and the impact on rotor mid-span profile was studied.

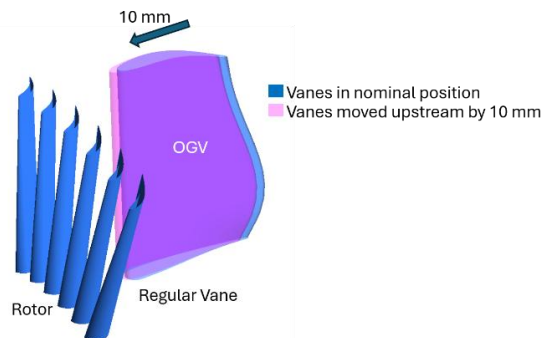


Figure 4-4 Regular Vane moved upstream by 10 mm

While doing so, all the remaining geometric parameters and flow parameters are retained. Figure 4-5 shows C_p distribution for Regular-Vane compared to Regular-Vane moved

upstream by 10 mm. Only minor changes can be seen in C_p distribution when regular-vane is moved upstream by 10 mm.

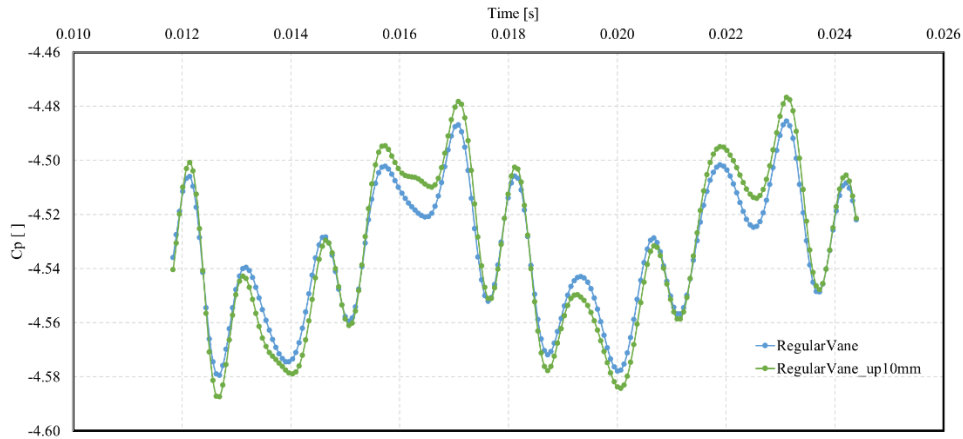


Figure 4-5 Impact of moving Regular-vane upstream by 10 mm

Though the result may look promising, a caveat with this result of no impact on forcing due to axial movement of regular-vane by 10 mm should be mentioned here. Impact is shown only at the midspan profile. To have a complete picture, unsteady pressure on the entire rotor surface must be studied. Methodology to resolve the pressures on entire blade surface is ongoing. Another caveat is that the flow conditions are for very low Mach number (around 0.1). The impact of moving regular-vane by 10 mm is to be assessed for engine realistic Mach numbers. It is in the interest of GKN to study the impact of TRS vanes on rotor to design better and shorter turbine-rear-structures. This study is work in progress as the learning continues.

5.0 CONCLUSIONS

To study the impact of OGV potential field on rotor, an approach to measure forcing function and numerically study impact of forcing on LPT rotor are presented.

Forcing function could be established from the experiments conducted at Chalmers University of Technology. Numerical analyses also showed satisfactory agreement with experimental results in predicting the forcing function. It was reconfirmed that potential effect of vanes is higher at locations closer to LE of vanes. The intensity of pressure field reduces with increasing distance from LE. Upstream forcing for a thick-vane was higher than regular-vane or mount-vane at 50% span which was due to 25% increased thickness in a thick-vane. At 85 % span, mount-vane, due to engine mount recess had higher upstream propagating pressure waves.

Two other concurrent studies to see the impact of inlet swirl and inlet Reynolds numbers were initiated in the test campaign. Upstream forcing was observed to be higher with high Reynolds number. With change in inlet swirl of 5 degree, a shift in pressure peak of 0.5 degree was seen.

A process to assess the transient impact of potential field numerically on the rotor is initiated. Going further, the intention is to build on this process and understanding. A better understanding will support in exploring possibilities to reduce engine length.

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