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Experimental Evaluation of the Flow-Field in a State of the Art Linear Cascade with Boundary-Layer Suction

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ABSTRACT

This paper presents a detailed experimental evaluation of the flow field in a state of the art linear cascade with boundary-layer suction. The linear cascade was designed using a new design-process as described by Hjärne et al. [1]. From the measurements presented in this paper it can be concluded that all of the features of the test-rig work as expected. Hence the measurements validate the design process presented by Hjärne et al. in [1].

The intention with the test facility is to provide high quality benchmark cases for the flow field around aggressive designs of Low Pressure Turbine/Outlet Guide Vanes (LPT/OGV's) to be used for validation of numerical codes. The flow quality is assessed by measuring inlet uniformity, boundary-layer heights, periodicity of the static pressure distribution around the OGV's and uniformity of the outlet flow.

Keywords: Linear Cascade, Outlet Guide Vanes, CFD validation, Low Pressure Turbine

1 INTRODUCTION

Cost and weight requirements on modern jet engines often lead to more highly loaded turbines with fewer stages. In un-geared two and three shaft engines this gives higher swirl angles into the Low Pressure Turbine/Outlet Guide Vanes (LPT/OGV's) [2]. This, of course, makes the aerodynamic design of the OGV's more difficult and in recent LPT/OGV designs structural requirements often lead to non-cylindrical shrouds with complex three-dimensional polygonal shapes and sunken engine-mount bumps. This has sparked a renewed interest in design methods and validation cases for turbine OGV flows, in addition a literature survey shows that very few, if any, measurements of realistic OGV flow-cases are publicly available.

A new subsonic linear cascade has been designed at Chalmers University of Technology to investigate flows around LPT/OGV's. To create a flow field as representative as possible for real OGV flows, properties like boundary-layer heights and turbulence intensities need to have the same importance in the rig, as in a real engine. Therefore, boundary-layer bleeds, both on end- and side-walls, was included to create a boundary-layer height comparable to that in a real aero engine.

In the design process of the test facility, CFD was used extensively as described by Hjärne et al. [1]. Areas such as the contraction and the design of the boundary-layer suction system were very much based on the results of numerical calculations. The CFD analysis of the whole cascade was valuable in the design process since it provides the possibility to investigate the full flow field in the test-facility before building it. Issues such as the periodicity of the flow can easily be addressed and methods of how to improve it can be developed. Some noteworthy features with the current cascade are:

- Large scale and low speed for detailed measurements
- High Reynolds number, up to Re_c=500000

- Big span in variation of incidence angles (0-52 degrees)
- A wide range of measuring techniques are applicable, both intrusive and non-intrusive (such as PIV and LDA)
- Controlled boundary-layer suction

NOMENCLATURE

A	Area ratio between the diffuser outlet and inlet
CR	Contraction ratio
Ps	Static pressure
Ptot	Total pressure
Q	Dynamic pressure based on inlet velocity
Re_c	Reynolds number based on inlet conditions and chord length
Tu	Free stream turbulence
U_0	Free stream velocity in the x-direction
U	Local velocity in the x-direction
V	Local velocity in the y-direction
W	Local velocity in the z-direction
X	Contraction match point
x	x-coordinate
y	y-coordinate
z	z-coordinate

Greek Symbols

α	Incidence angle

Subscripts

0	Free stream
1	Upstream
2	Downstream
c	chord
max	maximum local value of the property

Acronyms

LDA	Laser Doppler Anemometry
LPT	Low Pressure Turbine
OGV	Outlet Guide Vane
PIV	Particle Image Velocimetry

2 THE TEST-FACILITY

The current subsonic linear cascade at Chalmers University of Technology is designed for investigations of the flow field around highly loaded LPT/OGV's. The facility is a low-speed blow-down linear cascade consisting of a wide angle diffuser with A = 4, a settling chamber, a three dimensional contraction designed of match cubic curves with CR=5 and the match point at X=0.5, according to Morel [3], an inlet-section and a test section with boundary-layer suction, see Fig. 1. The air-supply is a 30kW radial fan, delivering 9m^3/s air at a pressure of 2.2kPa.

The test section is designed out of two pairs of parallel discs where the inner discs constitute the side-walls of seven OGV's and the upper and lower end-walls. The end-walls are adjustable with the turning of the test section, i.e. as the test section rotates the end-walls moves towards each other so the mass-flow into the test section is controlled, see Fig 2. By turning the test section, the inlet-angles can be varied continuously from 0 to 52 degrees, making it possible to cover both on- and off-design conditions for OGV flows. To make it easy to exchange vanes and end-walls, the vanes are mounted in a cassette. With this design it is possible to introduce contoured end-walls with engine-mount bumps or cassette walls of hard glass for the use of LDA (Laser Doppler Anemometry) or PIV (Particle Image Velocimetry).

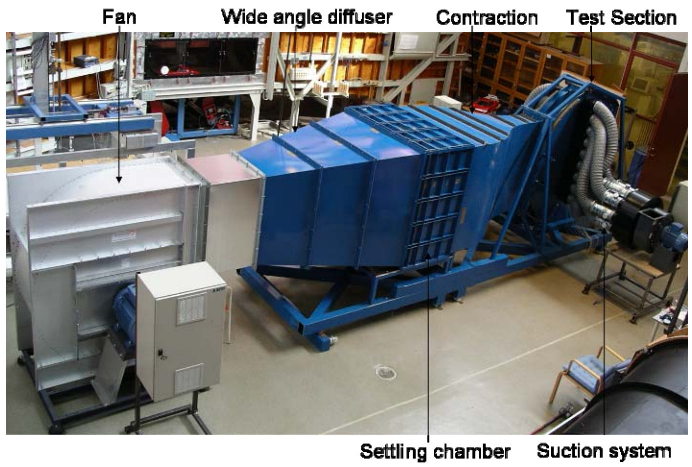

Figure 1 The test-facility

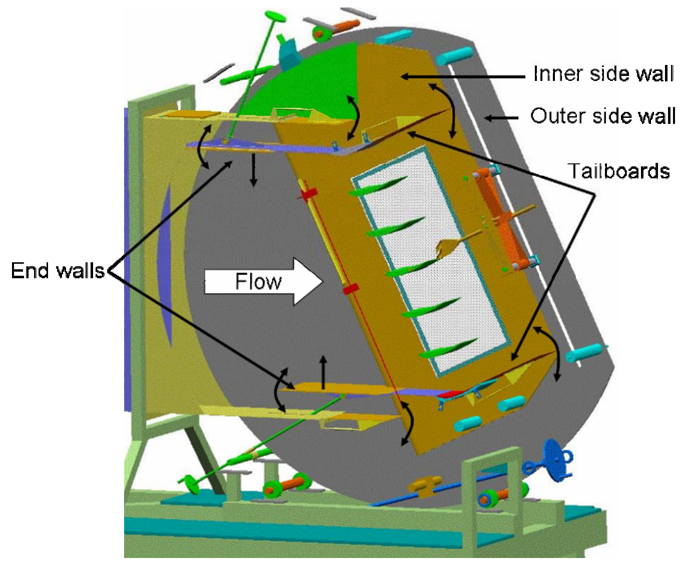

Figure 2 The test section showing the possibilities to control the flow with adjustable end-walls and tailboards

Since this experimental setup is designed for validation of CFD methods intended for investigations of LPT/OGV flows it is important to have well defined inlet conditions and as representative as possible for real OGV flows to capture the same physics. The linear cascade will not be able to account for effects from rotor-vane interactions and a radial variation in the inlet condition but the influence of these phenomena can be covered with a CFD method validated with the data from the cascade. Another issue of interest is the Mach numbers which are much lower compared to a real engine and there will be no compressible effects. However, Hjärne [4] confirmed with CFD simulations that compressibility effects are small for typical OGV flows.

2.1 THE BOUNDARY-LAYER SUCTION SYSTEM

Properties like boundary-layer heights need to have the same importance in the rig, as in a real engine. To accomplish this, boundary-layer bleeds, both on end- and side-walls are used to remove the boundary layers created upstream in the test facility. On the side-walls the bleeds are connected to two independent fans of 7.5 kW making it possible to remove the boundary-layers by suction. Since the suction systems are independent of each other it is also possible to adjust the suction on both sides.

Removing boundary-layers is a sensitive process and the operation of this has to be controlled. To accomplish this static pressure taps are located on the inner side discs to evaluate if the suction works symmetrically or if an increase or decrease of the rate of suction is necessary. The suction system connected to the suction slot is designed with nine suction tubes going out from the suction chamber, see Fig. 3. On each of the nine tubes mass flow controllers and valves are positioned to have the possibility to control the suction through each and every suction tube and by that adjust the suction over the slot.

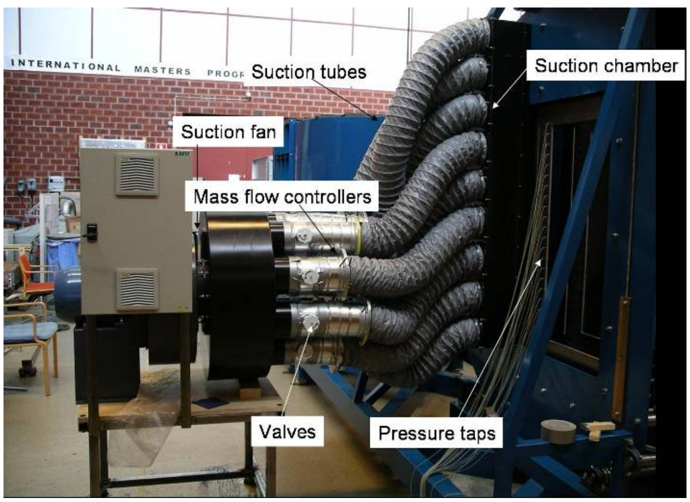

Figure 3 The boundary-layer suction system

When the test section is rotated to obtain the desired incidence angle it is important to have proper adjusting possibilities for the boundary-layer suction system. The rotation of the test section creates an asymmetric flow field in the suction slot where more air is sucked in through the upper parts. This flow is then deflected downwards by the suction chamber and obstructs the flow in the lower part of the suction slot. To counteract this effect the suction system must be adjusted for each new inlet angle, by closing the upper valves and suck more air through the lower valves as shown in Fig. 4. When the flow in the suction slot is blocked it does not only accelerate the flow field into the test section but it also changes the incidence angle (pitch angle). For the three different angles tested it was however quite easy to adjust the suction system. Running with all valves open gave a quite good velocity profile for all three cases, so this was a good starting point. When tuning the inlet properties for higher incidence angles the conditions improved when some of the upper valves were closed.

From the CFD analysis it was also noticed that inserting a porous wall, or a mesh, into the suction chamber made it much easier to adjust the velocity profile in the suction slot. The experimental results showed the same fact, without the mesh in the suction chamber, it was already at small inclination angles (10 degrees) very hard to control the suction system and a great velocity gradient was seen in the test section. The mesh even out the velocity in the suction slot and after this was included the problem reduced significantly.

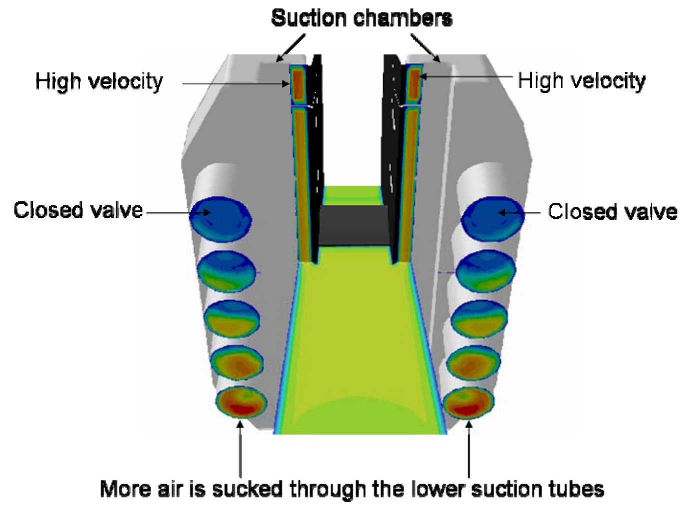

Figure 4 Picture of the CFD model showing that more air has to be sucked out of the lower tubes to get an even velocity profile going into the test section, see Hjärne et al. [1]

The adjusting possibilities for the flow going into the test section are:

- Suction rate through the boundary-layer suction system
- Opening or blocking the valves on the nine suction tubes
- Adjusting the angle of the end-walls, see Fig. 2
- Control of the mass flow going out above or beneath the end-walls, see Fig. 2

By adjusting these different parameters a good periodic and two-dimensional flow field through the inlet can be created.

3 MEASUREMENTS

Both upstream and downstream of the cascade there are traversing systems which can be equipped with both pressure probes and hot wires depending on the property to be measured. To control that the velocity going into the test section not is being accelerated, by blocked suction slots, a Pitot tube is placed in the inlet section (upstream of the test section) to assure that the velocity in the inlet and the test section are the same.

The boundary layers are sucked out two chord lengths upstream of the cascade and this affects the flow implying that it is important to remove a correct amount of air through the different sides of the test section. As already mentioned the mass flow rate can be measured through the mass flow controllers placed at the suction tubes to verify that the same amount of air is removed from both sides. In addition the pressure taps on the inner side-walls can be connected to a multi manometer or a scanning valve system so the static pressure distribution on the side-walls can be compared easily.

The measurements conducted to investigate the quality of the flow field in the linear cascade are made for three different angles of attacks 25°, 30° and 35°. This is a typical operating range for an engine LPT/OGV and also gives a good assessment of different working conditions for the facility.

Inlet measurements

The following inlet measurements were made with the upstream traversing system:

- Velocity and inlet velocity angles
- Pressure variation
- Free stream turbulence

The inlet conditions are crucial for reliable measurements in the test and at the outlet section [5] and therefore great effort have been made to verify these conditions. All of these measurements were made with a five-hole aerodynamic probe except for the free stream turbulence which was measured with hotwires. Considering the free stream turbulence it was measured to be around 0.4 % this is a low value and confirms a good quality of the flow field but not representative for real engine flows; however turbulence generating grids will later be used to increase the free stream turbulence significantly, around 7-10% if passive grids are used and even higher if active grids are used.

Measurements in the test section

When the inlet flow conditions showed satisfactory results measurements in the test section were conducted and the periodicity around the OGV's and the boundary-layer height on the side walls were determined.

The periodicity around the OGV's are measured with static pressure taps placed both on the mid span and on 25% and 75 % of the span. In total there are 77 pressure taps on each blade, see Fig 5. In order to tune the periodicity in the test section the end OGV's are equipped with tailboards which can be adjusted while running the experiment. When measuring the static pressure on the OGV's a scanning valve system connected to a Furness manometer was used.

When measuring the boundary-layers the downstream traversing system was equipped with an extension arm going in between OGV2 and OGV3 to measure the boundary-layer height developed until just upstream of the leading edges of the OGV's, see Fig . 6. The boundary-layers were measured with hot wires at the exact same position on both of the side-walls to see that they had a similar development on both sides.

Outlet measurements

For the measurements in the outlet the downstream traversing system was used together with the five hole pressure probe. The measurements were conducted one chord length downstream of the OGV's and the measured properties were velocity, velocity angles and pressure variations.

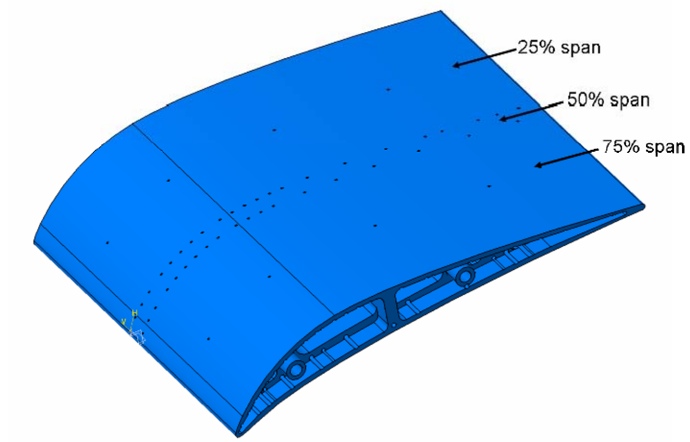

Figure 5 Picture of the OGV and the location of the pressure taps

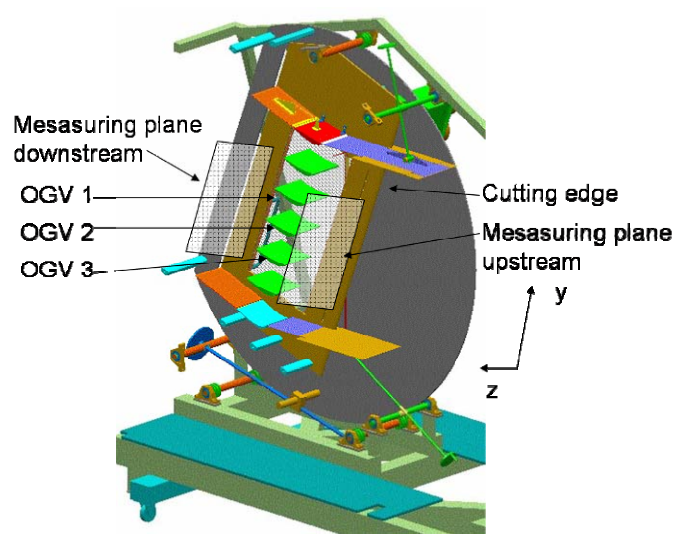

Figure 6 Picture of the measuring planes upstream and downstream of the cascade.

Operating conditions

The operating conditions for the measurements presented in this paper are presented in table 1:

Table 1 Operating conditions

c	220 mm
Pitch	200 mm
Span	200 mm
U_0	19.6 m/s
α	25, 30 and 35 degrees
Tu	0.4%

4 MEASUREMENT UNCERTAINTIES

The measurements with the five-hole probe were monitored by five Furness Control manometers, which have typical accuracy of less than 1% of reading. The five hole probe was calibrated between -20° and 20° in pitch direction and in roll direction between 0° and 175°. From the calibration the estimated total uncertainty of the angle measurements was 0.5°.

Boundary-layer measurements were performed by hot wires these were calibrated in the free-stream versus a Pitot-static tube. Typically, the calibration resulted in an error of the measured velocity of less than 0.5% for all points in the calibration range.

The traversing mechanism for the probes (both hot wires and pressure probes) are computer controlled and can be completely automated for long experimental runs through definition of a geometrical mesh of measurement points. Equipped with stepper-motors it can sustain an absolute coordinate system with an accuracy of 12.5, 1.6, 1.9, 0.5 μm, correspondingly in y_1, z_1, y_2, z_2 directions. The acquisition system is the 14-bit, 8 channel Instrunet module and the software used to control the sampling and saving of data files is linked into a program for automated flow measurements using the traversing system and a pre-defined mesh of sampling points.

After the data was collected, post processing was carried out in the software package Matlab (Matrix Laboratory, USA) .

5 RESULTS

Inlet conditions

The upstream measurements are made directly after the cutting edges in order to investigate if the flow going into the cascade is well aligned with the inlet section (pitch angle close to zero) as well as symmetric (yaw angle close to zero). The measuring plane is three pitches in the y-direction (from half a pitch above OGV1 to half a pitch below OGV3) and in the z-direction 95% of the span is measured, se fig. 5. 300 points were measured in this plane which gives a good picture of the inlet flow field.

Angle of attack 30 degrees (design point for the OGV's)

In Fig. 7 the velocity distribution, scaled with U_{max}, measured with the upstream traversing system is presented as a contour plot. Excluding the flow closest to the walls, which is of course highly affected by the cutting edge from the suction system, the velocity varies less than 2 percent in the inlet section. Keeping in mind that these measurements are made directly downstream of the cutting edges where the disturbances are large, the results are good. Typically, the velocity variation for the three different angles of attack varied between 1.8 and 2%.

Also shown in Fig. 7 is that no accelerating flow is visible around the edges. This confirms that a correct amount of air is removed with the suction systems.

Considering the inlet pitch angle the aim is to have a horizontal inlet flow field with a constant pitch angle. In Fig. 8 the variation of the inlet pitch angle is presented and as can be seen the inlet angle in the main flow varies between 0 and -0.5 degrees. Since these measurements are made very close to the cutting edges a bigger variation is seen near the edges.

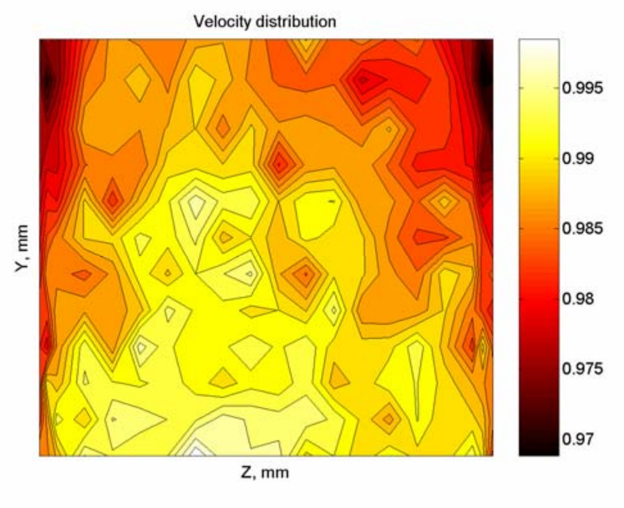

Figure 7 Scaled velocity distribution in the upstream measuring plane showing U/U_{max} in percent

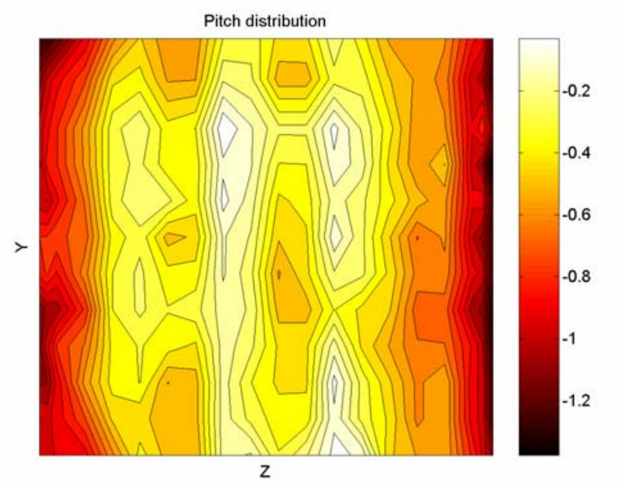

Figure 8 Inlet pitch angle variation in the upstream measuring plane

The inlet yaw angle is an important parameter when determining the symmetry of the inlet flow field and here the presence of the cutting edges and the suction system is even worse due to the amount of air sucked out from the two suction systems. Of course the yaw angle varies more close to the cutting edges but as can be seen in Fig. 9 the main flow yaw angle variation is only between -0.2 and 0.3 degrees. As also is evident in fig. 9 the yaw angle is positive on one side and negative on the other side this means that the flow is going towards the center of the test section which is an effect of the suction system. The important issue here is that the distribution of the yaw angle is symmetric which Fig. 9 shows.

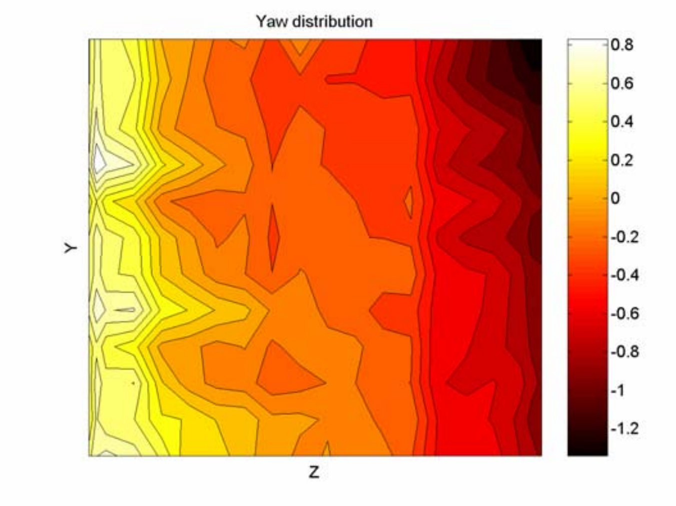

Figure 9 Yaw angle distribution in the upstream measuring plane

Periodicity

As previously shown the inlet pitch, yaw and velocity variations are minimal but a good periodicity is also an essential requirement for a cascade test. In Fig. 10, 11 and 12 the periodicity is plotted for the three mid OGV's in the cascade (OGV1, OGV2 and OGV3) for the three different incidence angles tested. Also shown is the result from a numerical solution of the pressure distribution conducted in Fluent [6] and as can be seen the experimental results fits the numerical results very well. The small disturbance seen on the suction side in all three cases (at x/c =0.5) is most likely an error in the measurement in one pressure tap since the error occurs at the exact same position in all three figures. This is also confirmed by fig. 13 where the pressure distribution on the suction side on 25% and 75% span are plotted against the pressure distribution around mid span for OGV2 when the angle of attack is 30 degrees.

As can bee seen the periodicity is very good for all three inlet angles. This confirms good inlet quality flow since the numerical calculations are made with a horizontal and symmetric inlet flow field.

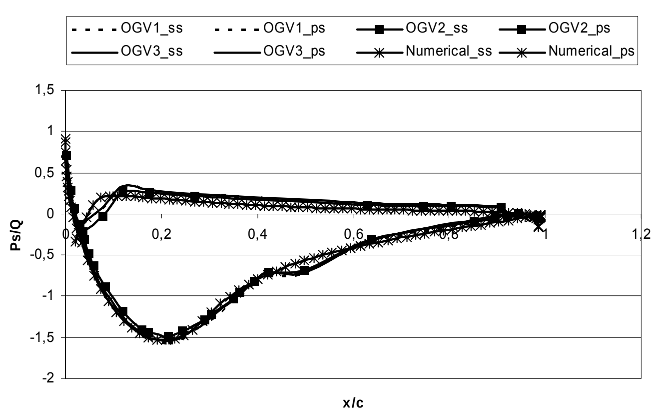

Figure 10 Periodicity around OGV1, OGV2 and OGV3 for an angle of attack of 25 degrees

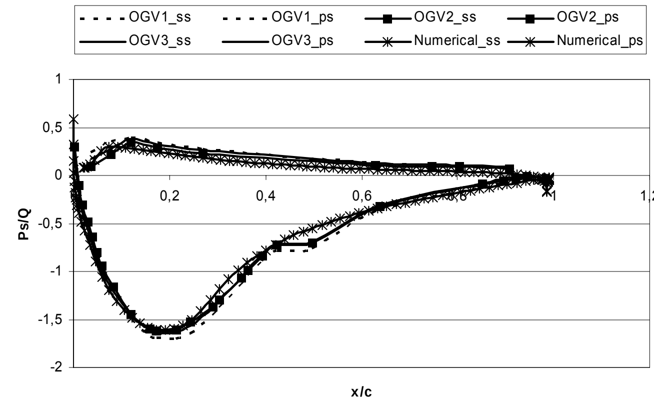

Figure 11 Periodicity around OGV1, OGV2 and OGV3 for an angle of attack of 30 degrees

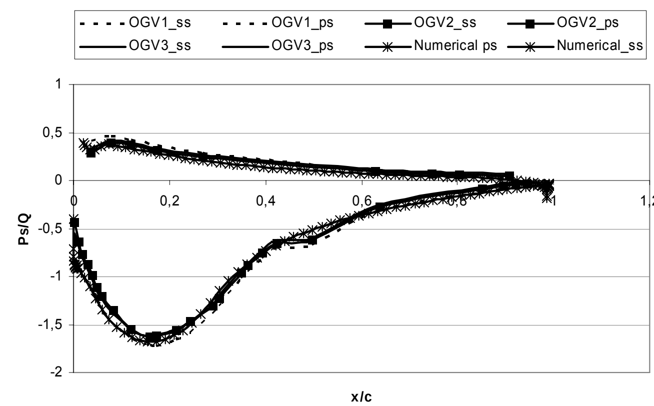

Figure 12 Periodicity around OGV1, OGV2 and OGV3 for an angle of attack of 35 degrees

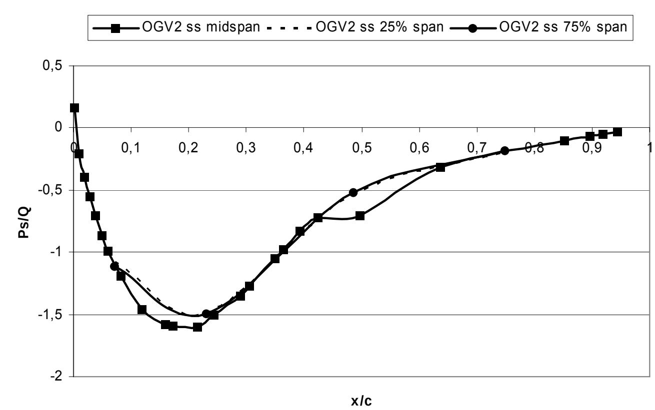

Figure 13 Suction side of OGV2 at mid span, 25% span and 75% span for an angle of attack of 30 degrees

Boundary-layer measurements

The aerodynamic function of the LPT/OGV's is to turn the swirling flow out from the last low-pressure turbine rotor into an axial direction. This de-swirling gives a diffusive flow with growing boundary layers, strong secondary flows, and risk for separation on the OGV's as well as on the end-walls. Non-cylindrical end-walls and engine mount bumps in the gas-channel further increases the risk of end-wall related separations and losses. Therefore a boundary-layer height which is representative for a real engine is very important if prediction of separation is to be investigated. This cascade is special in the sense that both two- and three-dimensional flows can be investigated. The flow is very two-dimensional along the mid span of the OGV's and therefore two-dimensional validations can be made for static pressure distribution, profile losses and flow turning. In addition three-dimensional validations such as separations and secondary flows can be made close to the sidewalls and on the OGV's because of similar boundary-layer heights compared to a real engine

In a real engine the total turbulent boundary-layer height (adding the boundary layers at hub and shroud) can be as high as 10% of the height of the gas channel, from Fig. 14 it can be seen that the total turbulent boundary-layer height in this facility is somewhere around 7% (adding the boundary layers on both sides). This value is a little bit lower than that in a real engine but with trip wires on the sidewalls the boundary-layer height can reach levels of 10%.

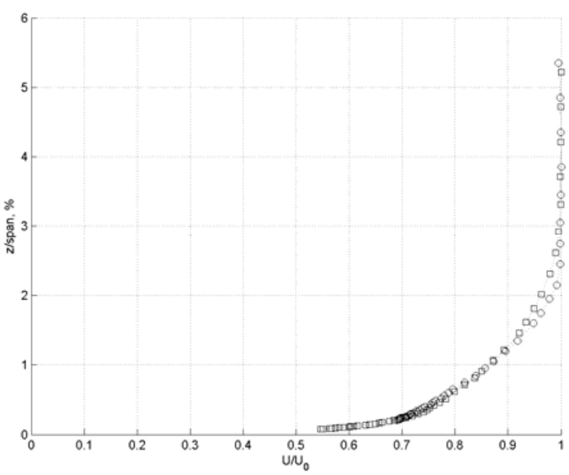

Figure 14 Boundary-layer distribution on the side-walls just ahead of OGV2 (o and □ represents the two different side-walls)

Outlet conditions

The outlet conditions are measured one chord length downstream of the cascade, as shown in Fig. 6, using a similar traversing plane as in the upstream measurements but with a finer mesh (600 measuring points) to resolve the wakes for a more thorough analysis.

The outlet conditions are the most interesting results for the investigation of how well the OGV's work. From the outlet conditions secondary flow patterns can be identified and losses can be calculated. Important in the outlet is to have a good periodicity of the wakes in the ptichwise direction but also a good uniformity of the flow field in the spanwise directions. The scaled total pressure distribution in Fig. 15 show that the wakes behind the cascade are very periodic, both in pitch and span direction, it is also shown that the wakes are bigger closer to the wall witch is an effect of the three-dimensional boundary layers created in the corner between the side-walls and the OGV's.

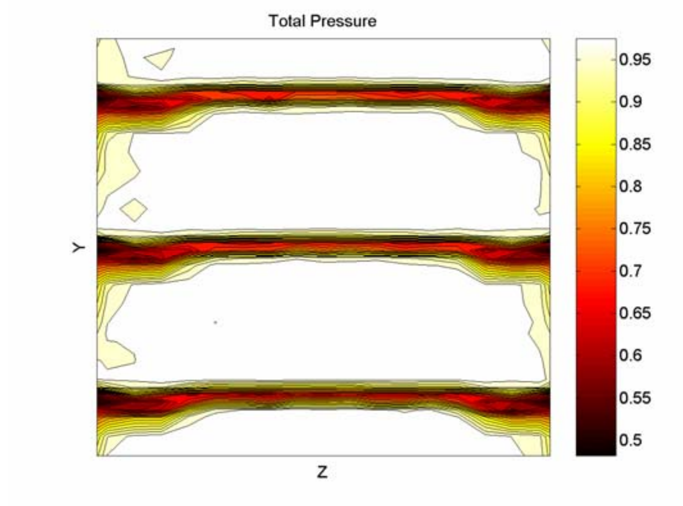

Figure 15 Scaled total pressure variation in the downstream measuring plane showing $Ptot/Ptot,_{max}$ in %

The downstream pitch angle is interesting to investigate as a measurement of how good the OGV's are. In Fig. 16 the downstream pitch distribution is shown. The pitch distribution is not as symmetric as the velocity variation but the variations in angles between the wakes are very small.

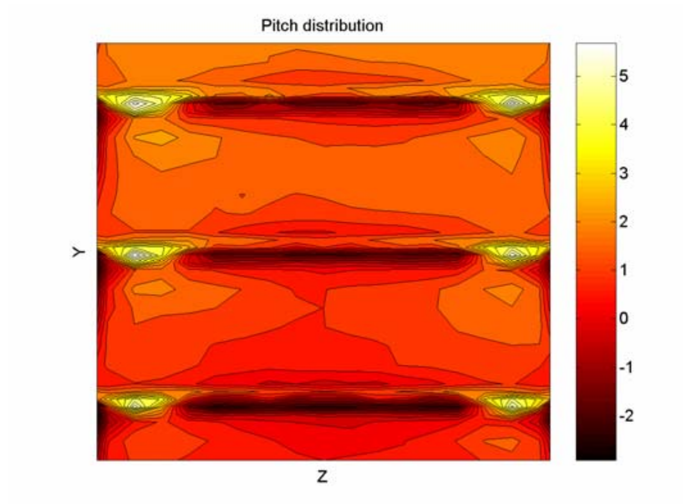

Figure 16 Outlet pitch angle variation in the downstream measuring plane

In Fig. 17 the V and W components for the velocity are presented. From this figure it is easy to see the secondary flow patterns created around trailing edges close to the side-walls. The secondary flows are also both symmetric and periodic. These flows are very important for investigations of corner flow separation.

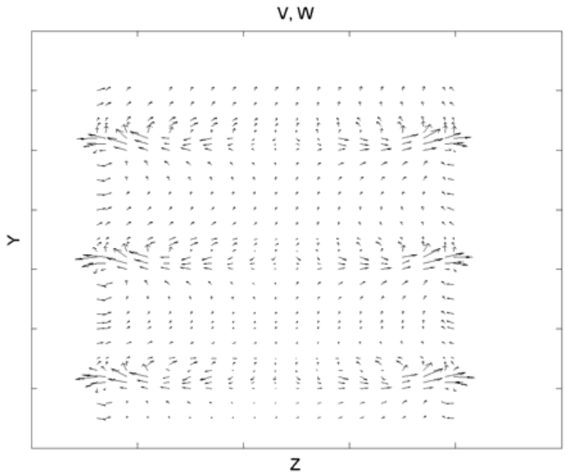

Figure 17 The V and W components plotted in the downstream measurement plane

6 CONCLUSIONS

This paper presents an experimental evaluation of a new test-facility for the investigation of highly loaded LPT/OGV's. The linear cascade was developed with a new design process based on modern CFD techniques combined with classical analytical approaches and experimental expertise as described by Hjärne et al. [1]. The CFD analysis of the whole cascade was very valuable in the design process, especially when it comes to the design of the boundary-layer suction system. In the experiments it was found that with the knowledge from the CFD analysis it was easier to control and understand how to operate this system.

The main conclusions drawn from this paper are the following:

- The design of the boundary-layer suction system works in accordance with the results from the CFD-calculations presented by Hjärne et al. in [1].
- The variation in the velocity, pitch and yaw angles where very small and a well defined two-dimensional flow is entering the test section.
- The periodicity of the static pressure distribution of the OGV's showed good agreement with the numerical results which also confirms good inlet conditions. In addition the periodicity at mid span compared to 25% and 75% span showed similar results which verifies a two-dimensional flow over the OGV's.
- The periodicity of the outlet wakes also showed a remarkably good periodicity in pitch direction and also symmetric distribution in the span direction. In the outlet the secondary flow field was also both symmetric and periodic.
- Finally, this experimental evaluation of the test-facility shows that this test facility will be able to provide high quality benchmark cases for both two- and three-dimensional numerical validation.

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REFERENCES

[1] Hjärne, J., Larsson, J. and Löfdahl, L., 2003, "Design of a Modern Test-Facility for LPT/OGV flows," ASME Turbo Expo

[2] Vazquez, R., Cadrecha, D., Torre, D., and Morales, M., 2001, "Low Pressure Turbines with High Stage Loading," Proceedings of the ISOABE, Bangalore

[3] Morel, T., 1975, "Comprehensive Design of Axisymmetric Wind Tunnel Contractions," ASME Journal of Fluids Engineering, pp. 225-233

[4] Hjärne, J., 2001, "Aerodynamic Analysis of Outlet Guide Vane Flows," Diploma thesis, Chalmers University of Technology, Göteborg, pp. 35-36

[5] Gostelow, J.P., 1984, *Cascade Aerodynamics*, Pergamon, Oxford

[6] FLUENT 6, 2001, Users manual, Fluent Incorporated, Lebanon, NH, USA

