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To cite this version:
Thorben Aufderheide, Udo Stark, Philip Frantzheld, Jens Friedrichs. Experimental and numerical investigations of a linear turbine cascade with sweep and dihedral. 17th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery (ISROMAC2017), Dec 2017, Maui, United States. hal-02397941

HAL Id: hal-02397941
https://hal.archives-ouvertes.fr/hal-02397941
Submitted on 6 Dec 2019

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Experimental and numerical investigations of a linear turbine cascade with sweep and dihedral

Thorben Aufderheide1*, Udo Stark2, Philip Frantzheld1, Jens Friedrichs1

Abstract
The present investigation has been initiated to further increase the understanding of sweep and dihedral effects in turbine cascades and turbines. For that purpose experimental and numerical investigations were performed on either side of a linear turbine cascade with \( \varphi = \pm 26.5^\circ \) true sweep and \( \nu = \pm 14.5^\circ \) dihedral (true lean) combining to \( \sigma = \pm 30^\circ \) axial sweep without tangential lean. The upper sign is for the upstream side of the cascade, and the lower one for the downstream side. An analysis of the results led to the conclusion, that the present cascade flow can be regarded as a superposition of an irrotational 3D primary flow and a rotational secondary flow. A special feature of the flow is, that primary and secondary flow are of opposite direction on the upstream side of the cascade and unidirectional on the downstream side. In addition, considerable sweep and dihedral effects on the blade pressure distributions (loadings) contribute to highly complex 3D flows on both sides of the cascade with different secondary flows and losses.

Keywords
turbine cascade — sweep effects — dihedral effects

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INTRODUCTION

The development of modern LP turbines leads to highly flared annulus walls and hence to high sweep and dihedral angles in radially stacked blade rows, cf. Figure 1. This unavoidable feature of axial flow turbine design causes complicated 3D flows, which were previously investigated, among others, by Hill and Lewis [1], Gotthardt [2], Potts [3] and Pullan and Harvey [4] using linear turbine cascades as an accepted model for fundamental research. A comparison between experimental and numerical results may be found in [2] and [5], including a comparison of the corresponding endwall flows on either side (upstream and downstream side) of the cascade. Similar investigations were performed on compressors and compressor cascades, among others, by Smith and Yeh [6], Weingold et al. [7], Place [8], Sasaki and Breugelmans [9], Friedrichs et al. [10], Gallimore et al., Part I [11] and II [12], and Clemen et al. [13]. An interesting discussion to [9] has been provided by Place and Cumpsty [14] using a lifting line representation of the blades to explain the non-viscous effects of sweep and dihedral on the flow close to the endwalls. The purpose of the present paper is to further increase the understanding of sweep and dihedral effects in turbine cascades and turbines. To this end, experimental and numerical investigations were performed on either side of a linear turbine cascade with \( \varphi = \pm 26.5^\circ \) true sweep and \( \nu = \pm 14.5^\circ \) dihedral (true lean) combining to \( \sigma = \pm 30^\circ \) axial sweep without tangential lean. The upper sign is for the upstream side of the cascade, and the lower one for the downstream side.

Figure 1. Definition of sweep \( \varphi \), dihedral \( \nu \) and axial sweep \( \sigma \)
1. EXPERIMENTAL SETUP

The experimental investigations were carried out in a low-speed cascade wind tunnel at the Institute of Jet Propulsion and Turbomachinery of the Technische Universität Braunschweig, cf. Figure 2. The horizontal test section width (blade span) of the wind tunnel is \( h = 200 \) mm, its vertical height varies between \( H = 170 \) and 360 mm depending on inlet angle \( \beta_1 \), space/chord ratio \( t/l \) and blade number. The cascade consists of six blades plus two additional ones (tailboards) over and below the outermost blades.

The cascade used in the present investigation models a stator vane in a flared annulus and is shown in Figure 3 together with two cross sections, one section (AA) parallel to the endwalls, and the other one (section BB) perpendicular to the blades. The angle \( \sigma \) between section AA and BB typifies axial sweep at zero tangential lean in the sense of Pullan and Harvey in [4] and [5]. The cross section BB represents the 2D geometry of the datum cascade (Index N) from which the axial swept cascade, including true sweep and dihedral, has been derived. The blade sections (chord length \( l_N = 60 \) mm) have max. thickness and max. meanline ordinate of 10 and 8% respectively. The stagger angle is \( \lambda = -30^\circ \), the space/chord ratio \( t_N/l_N = 1.0 \) and the aspect ratio \( h/l_N = 3.333 \). The design inlet and outlet angle, \( \beta_{1N} \) and \( \beta_{2N} \), are 0° and -40° respectively.

The relationship between \( \varphi, \nu \) and \( \sigma \) is given by

\[
\sin \varphi = \frac{\tan \sigma}{\sqrt{1 + \tan^2 \lambda_N + \tan^2 \sigma}}
\]

and

\[
\sin \nu = \frac{\tan \lambda_N}{\sqrt{1 + \tan^2 \lambda_N}} \cdot \sin \sigma
\]

as shown by Gotthardt in [2].

A combined total and static pressure probe (Prandtl probe), 300\% chord upstream of the cascade at \( z/(h/2) = -1.00 \) was used to control the inlet flow conditions and the theoretical outlet velocity of \( W_{2th} = 50m/sec \) representing a theoretical blade chord Reynolds number of \( Re_{2th} = 2.0 \cdot 10^5 \) and a theoretical Mach number of about \( Ma_{2th} = 0.15 \). The artificially increased freestream turbulence intensity was \( Tu_1 = 3\% \). Axial sweep \( \sigma \) and Reynolds number \( Re_{2th} \) are engine like (cf. Hourmouziadis[15]), \( Ma_{2th} \) only insofar as the real Mach number is also subsonic. Blade pressure distributions were measured and evaluated for one plus 12 spanwise locations at \( z/(h/2) = 0.00, \pm 0.30, \pm 0.60, \pm 0.75, \pm 0.84, \pm 0.90 \) and \( \pm 0.96 \). Wake measurements were carried out 40\% chord downstream the trailing edge plane using a calibrated five-hole probe. The
measured pressure differences were subsequently evaluated to obtain pitch averaged results of exit and yaw angle, static pressure difference and total pressure loss. The inlet endwall boundary layers were measured with a flattened Pitot probe on both endwalls at the same x-position, approximately 200% chord upstream of the cascade at $z/(h/2) = 0.00$.

2. NUMERICAL SETUP
All simulations in the present paper were done with the parallel 3D RANS solver TRACE. This solver has been developed specially for turbomachinery flow simulations at the Institute of Propulsion Technology, DLR Cologne, cf. Marciniak et al. [16] and Becker et al. [17]. Preliminary simulations were performed with different turbulence and transition models, along with a grid sensitivity analysis. The shear stress transport (SST) $k$-$\omega$ turbulence model [18] in combination with the $\gamma$-$Re_{\Theta}$ transition model [19] turned out to be best suited for this investigation. The computational domain covered one blade passage between periodic boundaries on the top and bottom and two additional boundaries at 100% true chord upstream and 200% true chord downstream of the cascade, measured on the upstream and downstream side endwall respectively. Computational grids of increasing number of cells were generated using the commercial grid generator
AutoGrid 5 by Numeca. The following sensitivity analysis showed that at least 1 million cells were required to achieve i) a high resolution of the boundary layers with $y^+ \approx 1$, and ii) the overall performance parameters accurately. The solution was assumed to have converged when the different RMS residuals reached a stable level less than $10^{-4}$, and the relative difference of in- and outlet mass flow was less than $10^{-4}$. The inlet boundary conditions for the computational domain were prescribed from the experimental measurements ($T_{i1} = 295 \text{ K}$, $p_{i1} = 101000 \text{ Pa}$, $\beta_1 = 0^\circ$ and $T_{u1} = 3\%$). The outlet boundary condition was set as uniform atmospheric pressure. In addition, the inlet boundary layer profiles on both endwalls were measured to complete the total pressure profile at inlet.

3. RESULTS

Blade Pressure Distributions Figure 4 presents experimental and numerical pressure distributions for both sides of the cascade at the following spanwise positions $z/(h/2) = 0.00$, ±0.75, ±0.84, ±0.90 and ±0.96. The midspan pressure distribution, a nearly infinite span distribution with vanishing endwall effects, has been included for comparison purposes. Clearly to be seen, that positive sweep ($+26.5^\circ$) of the upstream side of the cascade, combined with negative lean ($-14.5^\circ$), leading to a gradual reduction of the effective incidence and leading edge loading with decreasing endwall distance. This is typical for backward swept wings. For negative sweep ($-26.5^\circ$) and positive lean ($+14.5^\circ$) of the downstream side of the cascade, Figure 4 shows an increasing incidence and leading edge loading with decreasing endwall distance, which is typical for forward swept wings. The lean effects, already included in the results, may be shown to add to the sweep effects on the downstream side of the cascade, while the exact opposite occurs on the upstream side. The added endwall effects on the downstream side of the cascade tend to create very high incidence angles, so that leading edge separation is likely to occur for blade sections close to the endwall, cf. Figure 4c and d. The corresponding loading distributions are shown in Figure 5 for $z/(h/2) = \pm 0.96$.

Skin-Friction Lines and Contours The variations in blade pressure distributions close to midspan ($z/(h/2) = \pm 0.30$) were found to be negligibly small. This allowed a simple calculation of suction and pressure side streamlines assuming

![Figure 6. Boundary layer edge (non-viscous) and blade surface (viscous) streamlines on the blade suction and pressure side](image)

![Figure 7. Superposition of primary and secondary flow in the trailing edge plane, upstream view from behind in negative x-direction, a sketch](image)

![Figure 5. Experimental and numerical loading distributions for both sides of the cascade](image)
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Figure 8. Skin-friction lines (wall streamlines) and skin-friction contours for the suction side surface and endwall, upstream side of the cascade

Figure 9. Skin-friction lines (wall streamlines) and skin-friction contours for the suction side surface and endwall, downstream side of the cascade

Infinite-span, non-viscous flow (superimposing a constant spanwise velocity on a 2D velocity distribution). The resulting pressure and suction side streamlines are shown in Figure 6 together with the corresponding viscous streamlines (skin friction or wall streamlines). The non-viscous streamlines reveal spanwise velocity components towards and away from the upstream side endwall on the blade suction and pressure side respectively. The exact opposite occurs on the downstream side of the cascade. An analysis of these results led to the conclusion that the present cascade flow is a superposition of a non-viscous, irrotational 3D primary flow and a classical secondary flow (viscous, rotational), as was first suggested by Goßhardt [2], and more recently by Pullan and Harvey [5]. Figure 7 shows a simplified sketch of these findings for the trailing edge plane when looking upstream from behind in negative x-direction. The spanwise motion of the primary flow is marked by red arrows. Two more arrows were added on the vertical endwalls for reasons of continuity. Blue arrows represent the classical secondary flows. When all arrows were placed, the two endwall regions turned out to be of particular interest. There is i) the upstream side endwall with the primary flow in opposite direction to the secondary flow and ii) the downstream side endwall with the primary and secondary flow in the same direction. These differences, in combination with those discussed above regarding the leading edge loading, were expected to have strong effects on the secondary flow development and loss generation.

Skin-friction lines or wall streamlines have been used to analyse the surface flow on endwalls and blades. This is justified by the fact, that both, skin-friction lines and streamlines close to the wall, have nearly the same direction. Numerical skin-friction lines and contours are shown in Figures 8 and 9 for upstream and downstream side endwalls including parts of the adjacent suction side surface respectively. The streamline patterns in both figures display a saddle point in front of every blade. A saddle point is a point where two wall streamlines intersect. The first one is an attachment line, the
second one a separation line. The last one consists of two legs, a pressure and a suction side leg, forming the base of the so-called horse-shoe vortex.

For well-known reasons, the endwall boundary layers are overturned as shown in Figures 8 and 9 for the cascade upstream and downstream side respectively. A comparison reveals an overturning that is weaker in Figure 8 than in Figure 9, or stronger in Figure 9 than in Figure 8. The weaker overturning in Figure 8 is caused by a greatly reduced leading edge loading close to the endwall, cf. Figure 5, in combination with a 3D primary flow moving opposite the secondary flows, cf. Figure 7. On the downstream side of the cascade, the stronger overturning in Figure 9 is due to a considerably increased leading edge loading close to the wall, cf. Figure 5, and a 3D primary flow that is at this time moving in the same direction as the secondary flow, cf. Figure 7. The interaction of the cross-passage endwall flow with the suction side boundary layer of an adjacent blade leads on both sides of the cascade to highly complicated and completely different corner flows including 3D separation phenomena.

So-called corner-separation is shown in Figure 8 and 9 over the last 20% and first 15% of the endwall-suction side corner in Figure 8 and 9 respectively. However, the rather complicated corner separation close to the leading edge in Figure 9 seems to be more than a conventional corner separation because part of the adjacent leading edge flow is also involved.
The leading edge region in Figure 9 has been greatly enlarged and is shown in Figure 10 including separation (SL) and attachment (AL) lines together with several singular points (S, HS, N, HN, F). The highly increased effective incidence caused by a combination of negative sweep ($\varphi = -26.5^\circ$) and positive dihedral ($\nu = +14.5^\circ$) on the downstream side of the cascade is clearly shown.

The skin-friction contours in Figures 8 and 9 are mostly parallel to the leading and trailing edge for most of the span, $z/(h/2) = \pm 0.8$. For sections within these limits, the skin-friction distributions have a minimum at about 50% meridional chord ($x/b = 0.5$) and a downstream maximum at about 70% ($x/b = 0.7$). This may be best seen in Figure 11 with three shear stress curves for $z/(h/2) = 0$ and $z/(h/2) = \pm 0.75$, corresponding to $z/(h/2) = 0.00$ and $z/(h/2) = \pm 0.75$. The three distributions are quite similar and indicate a boundary layer transition that was experimentally tested.

The velocity distribution inside a boundary layer undergoes large changes during transition. This has been utilized for the determination of the transition region. A Pitot tube was moved parallel to the blade surface at a distance close to the maximum difference between the velocities in the laminar and turbulent regimes. On being moved downstream across the transition region, the tube showed a fairly sudden increase in total pressure. Using a measured surface pressure distribution, the measured total pressures were transformed into dynamic pressures as shown in Figure 12 for the three blade sections mentioned above. The physical content of Figure 11 and 12 is principally the same. This allows a comparison with respect to length and location of the transition region, showing very good agreement for the midspan section and fairly good agreement for the sections at $z/(h/2) = \pm 0.75$.

**Distributed Losses** The total pressure profiles of the incoming endwall boundary layers, obtained at the upstream traverse plan, were used to complete the computational inlet conditions. The corresponding velocity profiles were also obtained. They are shown in Figure 13 together with two power law profiles. The integral parameter of the measured velocity profiles are given in Table 1.

<table>
<thead>
<tr>
<th>$\delta$ [mm]</th>
<th>$\Theta$ [mm]</th>
<th>$H_{12}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>upstream side</td>
<td>5.2</td>
<td>0.555</td>
</tr>
<tr>
<td>downstream side</td>
<td>6.6</td>
<td>0.825</td>
</tr>
</tbody>
</table>

These results show that the upstream endwall boundary layers are turbulent with a shape factor of $H = 1.28$.

Contour plots of the numerical and experimental total pressure losses are presented in Figures 14 and 15 respectively.

![Figure 13. Inlet endwall boundary layers on up- and downstream side of the cascade](image)

The spanwise extent of these plots is restricted to one quarter span on both sides of the cascade, and the circumferential extent is one pitch. The narrow white strip in both frames of Figure 15 indicates a region not traversed by the probe. The total pressure losses were measured $\Delta x = 24$ mm (40% chord) downstream of the trailing edge plane, subsequently non-dimensionalized ($\zeta_{v2} = (p_{11} - p_{12})/q_{2h}$) and finally projected on to the outlet plane of the computational domain, where experimental and numerical results were compared.

According to Sieverding [20], there may be up to three loss cores in the downstream traverse plane. The numerical results of the present investigation show only two, two on either side of the cascade. Form, extent and magnitude of the losses are highly different due to the different $\varphi/\nu$ combinations and their effects on leading edge loading (Figure 5) and endwall flow (Figure 7). The left frame of Figure 14 shows a noticeable loss concentration of circular form close to the suction surface at $z/(h/2) = -0.90$. This is, in accordance with the relevant literature, the loss core of the so-called passage vortex, including the low momentum material of the inlet endwall boundary layer, cf. Sieverding [20]. The second loss core in the left frame of Figure 14 is in the suction surface / endwall corner. The highest losses of $\zeta_{v2} = 0.55$ are similar to these of the passage vortex.

Two loss cores may also be seen in the right frame of Figure 14. However, the passage vortex shows much smaller losses than those of the corresponding passage vortex in the left frame. The second loss core in the right frame of Figure 14 is, apart from a somewhat increased area, quite similar to the one shown in the left frame.

Figure 15 presents experimental total pressure losses in two
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Figure 14. Contour plots of the numerical total pressure losses at $\Delta x = 24$ mm (40% chord) downstream the trailing edge plane

Figure 15. Contour plots of the experimental total pressure losses at $\Delta x = 24$ mm (40% chord) downstream the trailing edge plane
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frames for the up- and downstream side of the cascade respectively. Both presentations are incomplete in so far as in both cases a 6 mm strip next to the endwall could not be traversed (due to a five-hole probe of corresponding shaft diameter). A comparison, as far as possible, between experimental and numerical results leads to the conclusion that the contour shapes are quite similar, but that the areas enclosed are somewhat smaller in the case of the experimental contour plots. A direct comparison between pitchwise averaged, experimental and numerical results will be presented in the next paragraph.

Mass Averaged Losses The data in Figures 14 and 15 were pitchwise mass averaged and spanwise plotted as shown in Figure 16. The agreement between the experimental and numerical losses is fairly good. However, the agreement is much better in their spanwise variations. Originally, it was assumed that, due to the lower leading edge loadings and the opposite directions of the primary and secondary flow, the front side of the cascade would produce lower secondary losses than the aft side one with the higher leading edge loadings and the unidirectional primary and secondary flow. Due to the different flow physics on either side of the cascade, it was guessed that the overall losses will also be different on both sides. However, the crossing of the loss curves does not allow a simple estimate of the overall losses without the missing losses close to the wall.

An analysis of the results revealed the possibility that the present cascade flow may be decomposed into an irrotational 3D primary flow and a rotational secondary flow. As a special feature of the flow, it turned out that the primary and secondary flow are of opposite direction on the upstream side of the cascade and unidirectional on the downstream side. This and different blade loading distributions led to highly different secondary flows and losses on the upstream and downstream side of the cascade.

NOMENCLATURE

Geometric and Flow Quantities

- $\beta$ = flow angle
- $b$ = axial chord length
- $c_p$ = pressure coefficient
- $\delta$ = boundary layer thickness
- $\delta^*$ = displacement thickness
- $\gamma$ = intermittency
- $h, H$ = test section width
- $H_{12}$ = shape factor
- $l$ = chord length
- $\lambda$ = stagger angle
- $Ma$ = Mach number
- $\nu$ = dihedral
- $p$ = static pressure
- $\varphi$ = true sweep
- $p_t$ = total pressure
- $Re$ = Reynolds number
- $Re_\Theta$ = Reynolds vorticity number
- $\sigma$ = axial sweep
- $t$ = pitch width
- $\Theta$ = momentum thickness
- $T_t$ = total temperature
- $Tu$ = turbulence intensity
- $\tau_W$ = skin-friction
- $W$ = absolute velocity
- $y^+$ = dimensionless wall distance
- $x, y, z$ = cascade coordinate system
- $\zeta$ = total loss coefficient
- $\zeta_{\text{CFD}}$ = total loss coefficient

Figure 16. Numerical and experimental total pressure losses for both sides of the cascade in comparison

4. SUMMARY AND CONCLUSIONS

Experimental and numerical investigations were performed into the effects of sweep and dihedral on the aerodynamic performance of a linear turbine cascade with $\varphi = \pm 26.5^\circ$ true sweep and $\nu = \pm 14.5^\circ$ dihedral (true lean) combining to $\sigma = \pm 30^\circ$ axial sweep with zero tangential lean. The corresponding results include, among other things:

i) experimental and numerical pressure distributions at a number of spanwise positions on both sides of the cascade,

ii) experimental and numerical inlet and exit data, local and pitchwise averaged data,

iii) numerical skin-friction lines and contour plots for the endwalls (upstream and downstream side) and blade surfaces (suction and pressure side),

iv) experimental and numerical transition lengths.
REFERENCES


