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FAST RESPONSE PRESSURE TRANSDUCERS FOR THE INVESTIGATION OF WAKE-INDUCED TRANSITION ON A HIGHLY LOADED LP TURBINE

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ABSTRACT

The effects of periodic wake passing on the LP turbine profile T106D-EIZ were studied in the High-Speed Cascade Wind Tunnel using a moving bar wake generator, surface-mounted miniature pressure transducers and a wake rake equipped with fast-response differential pressure sensors. Blade pitch was increased compared to design point conditions to achieve a higher blade loading. As a result, a large separation bubble formed on the suction side of the surface and allowed to study unsteady boundary layer development in detail.

Eight LQ-125 *Kulite* miniature pressure sensors with absolute reference were flush-mounted onto the suction side of the center blade covering a region between 0 and 0.7 times chord length to measure the time-resolved profile pressure distribution. Mean pressure values were recorded simultaneously with adjacent conventional static pressure tappings. The advantage compared to the hot film measurements is that the calibrated sensors yield surface pressures easily comparable to the output of numerical calculations. To determine unsteady profile losses, a wake rake was constructed. Seven XCS-063 *Kulite* differential pressure transducers are spaced 4 mm apart with conventional pitot probes in between to serve as a reference for the values recorded with the fast-response sensors. Preliminary investigations showed that the blockage effect of the wake rake does not significantly affect the measurements.

First results showed that for steady flow conditions the time-averaged mean values of the surface-mounted sensors correspond to the data measured with conventional pressure tappings. Wake traverses with a five hole probe downstream of the center blade demonstrated no measurable influence of the instrumentation on the flow characteristics of the blade. Data acquired using the wake rake was compared to those of the five hole probe and showed that the results in the wake path match adequately, but that the rake performs poorly in the blade passage flow where pressure differences reach values around zero.

For unsteady flow conditions, the surface-mounted sensors were able to resolve the pressure fluctuations caused by the bar wakes, but did not provide the necessary spatial resolution to identify some of the expected wake-boundary layer interaction phenomena. Time-resolved total pressure losses show the wake moving across the blade passage and the beneficial effect of the becalmed region. Further improvements in the evaluation process are outlined to enhance the quality of the data set.

NOMENCLATURE

Latin

c_{ax}	[m/s]	axial velocity
c_p	[-]	pressure coefficient
d	[m]	diameter
e	[m]	distance of the measurement plane
E	[V]	voltage
f	[Hz]	frequency
l	[m]	chord length
p	[hPa]	pressure
T	[s]	bar passing period

t	[m], [s]	pitch, time
u	[m]	coordinate in circumferential direction
U	[m/s]	bar velocity
x	[m]	blade surface position
w	[m/s]	relative velocity

Greek

ω	[-]	total pressure loss
β	[°]	flow angle
Δ	[-]	difference between two values

Abbreviations

EIZ	Generator of unsteady inlet flow condititions
FS	Full scale
L2F	Laser-Two-Focus
LDA	Laser Doppler Anemometry
M	Midspan
Ma	Mach number
PS	pressure side
Sr	Strouhal number $Sr = f*l/c_{ax}$
SS	suction side
Re	Reynolds number
TE	trailing edge

Subscripts

1	cascade inlet plane
2	cascade exit plane
2th	downstream conditions for isentropic flow
b	bar
k	tank conditions
t	total
x	local

INTRODUCTION

The flow in turbomachines is known to be highly unsteady. In turbines, upstream stages shed wakes that impinge on the following blade row and influence boundary layer development and loss generation. A reduction in total pressure loss for turbines documented by some authors stimulated the interest in further investigations. Considerable work in the past years using flat plates, cascades and rig tests revealed the basic effects of wake passing like early onset of transition, the suppression of a laminar separation bubble and the existence of the becalmed region. Curtis et al. (1996) showed that by considering unsteady flow conditions in the design process, blade loading can be increased without sacrificing performance. An excellent overview of the research done on wake-induced transition in the past years is provided by Hodson (1998). However, the underlying physics is still not yet completely understood.

As all experimental work is extremely expensive and time-consuming, the next goal is an adequate numerical treatment of the problem by developing a model that is able to predict the aerodynamic performance of the blade by considering the effects of wake-induced transition. This calls for a profound understanding of the dynamic process and displays a need not only for time-averaged, but also for fluctuating flow quantities. Unsteady codes are already used for modeling boundary layer development. To be able to validate the results produced by these codes, comprehensive unsteady data is required.

Pneumatic fast-response multi-hole probes have been widely used to determine unsteady flow field characteristics. Compared to non-intrusive techniques like LDA or L2F, they are easier to use and provide a higher signal-to-noise ratio. Additionally, they are more robust than hot wire probes, but have the great disadvantage that they must be intruded into the flow. For maximum accuracy, designers have to meet two detrimental requirements: small size to minimize interaction effects between probe and flow while at the same time conserving a high frequency response to resolve unsteady fluctuations. The development of fast response aerodynamic probes began as soon as 1973 when Senoo et al. built a multihole probe with the pressure sensors being located inside the shaft to measure the flow conditions at the exit of a pump impeller. Due to their large size, the frequency response of 1.5 kHz was rather poor compared to today's designs. Shreeve et al. (1978) used miniature pitot probes with diameters of 2.4 and 1.6 mm to investigate high speed compressor flow. It soon became clear that the crucial point in using miniature pressure transducers is their dependency on temperature changes. Multihole probe design continued with a spherical five hole probe by Kerrebrock et al. (1985) and a four-sensor cylindrical probe by Epstein et al. (1985), who avoided the influence of changes in temperature with a calibration procedure before and after each measurement period. Due to the heat capacity of the probe head, temperature effects were negligible. Since then, several other authors reported the development of wedge-type probes (e.g. Bubeck and Wachter (1987), Ainsworth et al. (1994)). The probably most comprehensive study on fast response probe behavior was conducted at the ETH Zürich Turbomachinery Lab with the development of the FRAP® System (Kupferschmied et al. (1999)). Measurements with a fast-response total pressure probe to evaluate aerodynamic performance of a turbine cascade subjected to wake passing are reported by Funazaki et al. (1999).

One of the first applications of miniature pressure sensors to study boundary layer characteristics known to the author is the work of Grollius (1980). He integrated transducers in the suction and pressure side of a model turbine rig to measure pressure fluctuations on the blade surface. A similar application is described by Chivers (1981), who instrumented fan blades with commercially available *Kulite* transducers to investigate fan flutter phenomena. A step towards miniaturization was taken by Ainsworth et al. (1990) and Sieverding et al. (1998) by mounting the semi-conductor chip directly onto the blade surface to be able to increase the surface density, instrument thinner parts of the blade and improve the frequency response of the transducers. A squirrel cage wake generator with moving bars – a setup very similar to the one reported in this paper – was used by Liu and Rodi (1994) to measure unsteady surface pressures on a turbine cascade blade. They detected periodic pressure fluctuations in response to wake passing, but could not identify a significant influence on the blade pressure distribution.

By using commercially available fast-response *Kulite* miniature pressure transducers on the suction side blade surface and in the blade wake, the measurement system presented in this paper will help to complete the already available data set on the T106D-EIZ cascade with time-dependent flow quantities. Compared with commonly used hot film measurements which avoid a tedious (and quite impossible) calibration procedure and provide only qualitative data, the fast response sensors are calibrated and generate quantitative results. The experimental work will be compiled as a test case available for future download and is intended for the validation of numerical methods, which is already in progress using the TRACE_U code developed by DLR Cologne.

EXPERIMENTAL APPARATUS

Turbine Cascade

The reported measurements were performed on a large scale LPT cascade (Fig. 1) consisting of 5 aft-loaded blades which represent the mid-span section of the PW2037 LPT rotor. As the objective was to increase the lift coefficient by about 30 %, blade pitch was raised to t/l=1.05 as compared with design point conditions (t/l=0.799) to achieve a higher blade loading. The blade geometry was not adapted accordingly and a large separation bubble formed on the suction side starting at approximately 60% axial chord.

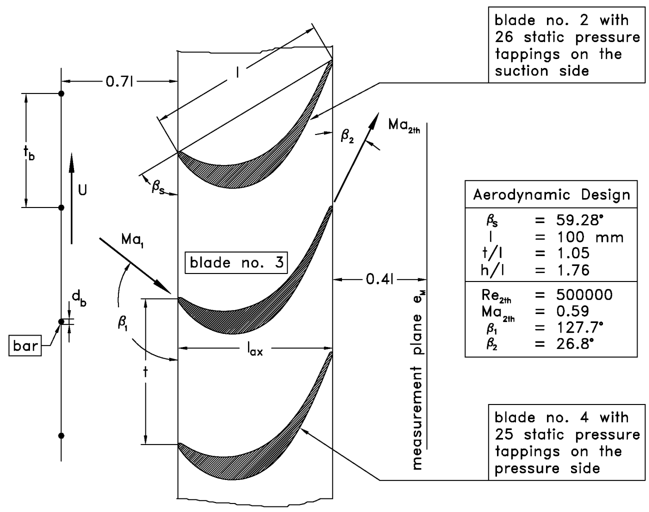

Fig. 1: T106D-EIZ cascade design

Test Facilities

All experimental data presented in this paper was obtained using the High-Speed Cascade Wind Tunnel of the Universität der Bundeswehr München. This continuously operating open loop facility is situated inside a large pressurized tank and can reach Mach numbers of up to Ma = 1.05 in the test section. It allows Mach and Reynolds number to be varied independently in order to achieve flow conditions typical for modern gas turbines. The turbulence intensity in the test section can be adjusted using different turbulence grids upstream of the nozzle. The temperature is kept at a constant level by an extensive cooling unit. A detailed description of the facility can be found e.g. in Sturm and Fottner (1985).

The periodically unsteady flow caused by the relative motion of rotor and stator rows and its influence on the turbine cascade is simulated by a moving bar type wake generator with a bar diameter ratio of d_b/l=0.02. The cylindrical steel bars create a far wake very similar to the one produced by an actual airfoil (Pfeil and Eifler, (1976)). Standard 1D hot wire measurements in the cascade inlet plane presented in Stadtmüller et al. (2000) were used to match the velocity deficit and the turbulence intensity of the bars and the actual blade. Oil-and-Dye pictures were taken at selected operating conditions to ensure that the flow field at midspan was two-dimensional and unaffected by secondary flow effects.

The distance ratio between the bars and the cascade inlet plane is about x/l=0.7 (see Fig. 1). The belt mechanism drives the bars with speeds of up to 40 m/s, thus generating Strouhal numbers between 0.42-1.68 for the investigated test cases. This so-called EIZ (Erzeuger Instationärer Zuströmung) and its constructional principles are explained by Acton and Fottner (1997) in greater detail. However, it should be noted that the maximum bar speed of 40 m/s is still too slow to produce a Strouhal number and inlet velocity triangle representative for modern gas turbines. The data acquired with this setup is therefore not suited for the in-depth analysis of boundary layer development in real turbines.

Measurement Techniques

The measurement system consists of two basic parts: the probe or blade with the integrated pressure transducers and the data acquisition unit with an A/D-converter and a low pass filter. A conventional pitot probe located approx. 500 mm upstream of the cascade was used to determine the time-averaged inlet stagnation pressure p_{t1}.

Sensors mounted on the blade surface

The time-averaged and time-resolved profile loading was determined from the profile pressure distribution. A total of eight *Kulite* LQ-125 fast-response pressure sensors were embedded into the suction side of the center blade. The transducers with a range of 0 to 350 hPa were used with absolute reference as supplied by *Kulite*. A passive temperature compensation module was integrated into the lead. To be able to mount the probes, small pockets were milled into the blade surface before the sensors were fixed using a special silicone glue (Hylosil) to dampen the influence of blade vibrations and to avoid strain forces on the device. A B-screen manufactured by *Kulite* was used to protect the sensor chip from external damage, which reduced the frequency response of the transducer by forming a small cavity. Problems typically encountered in rig tests like sensitivity to radial acceleration, large temperature drifts or extremely thin section were less relevant for this application. To minimize any interference between the instrumentation and the flow field, the blade was finally carefully polished, which destroyed two of the eight sensors.

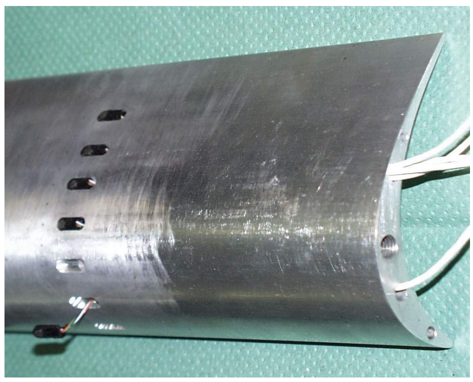

Fig. 2: Blade with LQ-125 *Kulite* sensors

Preliminary numerical investigations showed that the pressure fluctuations on the suction side reach its maximum value at the leading edge and decay rapidly over the blade surface. Therefore, the sensors were placed equidistantly starting from the leading edge up to the end of the separation bubble.

An aerodynamic calibration of the mounted transducers for steady flow conditions was performed by placing the blade inside the pressurized tank of the wind tunnel. A thermocouple located close to the instrumented blade was used to monitor the temperature to be at a constant level of 40°C during the calibration procedure. Results yield an almost linear dependency between sensor output voltage and pressure level inside the tank. No dynamic calibration has been carried out.

Additional static pressure tappings were placed at the same chord position as the *Kulite* sensors. Following a method proposed by other authors (e.g. Bubeck and Wachter (1987)), the influence of the temperature-dependent offset voltage can then be handled by superimposing data from these pressure tappings to the results of the fast-response pressure sensors. During the tests, it was realized that for the almost constant temperature conditions as experienced in the wind tunnel, the temperature offset was negligible. Static pressure tappings at midspan on both the suction and the pressure sides of the adjacent blades were connected to a Scanivalve system and allowed the surface pressure distribution and therefore the blade loading to be measured. These tappings were used for previous investigations and are therefore – although providing redundant information – very reliable.

Five-hole probe traverses behind the original (plain) blade and the one with integrated sensors showed no measurable influence of the instrumentation regarding total pressure losses or outlet flow angle. A picture of the partially instrumented blade is shown in Fig. 2.

Probes in the wake rake

The aerodynamic performance at different operating points was evaluated by computing stagnation pressure losses with a pitch-wise traversing five-hole probe and the new fast-response wake rake in a plane $e_M/l=0.4$ (see Fig. 1) downstream of the cascade exit plane.

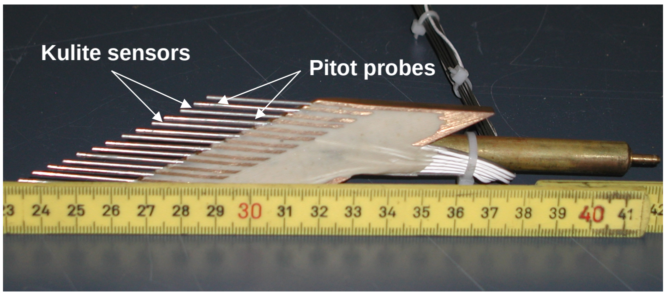

Fig. 3: Wake rake with *Kulite* sensors and conventional pitot probes

The design of the new wake rake (Fig. 3) is similar to that of a pitot rake and has been validated in previous measurements with a traversing five-hole probe. The fast response sensors are paired with conventional pitot probes which provide the mean pressure values (with the limitations as described in Weyer (1975)) while the semi-conductor chips are used to measure the fluctuating component. The outer diameter of the *Kulite* sensors is 1.62 mm and of the pitot probes 1 mm. The sensors are used in differential pressure mode with the reference pressure p_{t1} being supplied through the probe shaft; this is similar to the probe design e.g. of Kupferschmied (1998). A B-screen was used to protect the sensor chip. The transducers cover a range from 0 to 350 hPa, which is the smallest available from *Kulite*. As all transducers are oriented in the same plane, it is impossible to measure any flow angles. For the results presented in this paper, the DC signal of the fast-response sensors was evaluated and compared to the data produced with the pitot probes. As the pressure differences measured in the blade passage are very small, this causes large relative errors on the unsteady data (electrical resistor noise is limiting the resolution, see Gossweiler et al. (1994)). For future investigations, it seems to be more promising to superimpose the AC pressure signals with the time mean pressures measured with the pitot probes.

A static calibration of the *Kulite* sensors has been performed inside an environmental chamber for various pressure and temperature levels within the limits expected for the measurements to be able to directly evaluate the transducer signals. The dependency between voltage and calibration pressure is linear with a change in temperature only affecting the offset voltage. An example of the calibration is given in Fig. 4. The signal offset can be readjusted before every run. Due to the small size of the sensors, errors resulting from blockage or dynamic flow effects around the probe head do not significantly affect the signals if compared to the data of the time-averaged measurements.

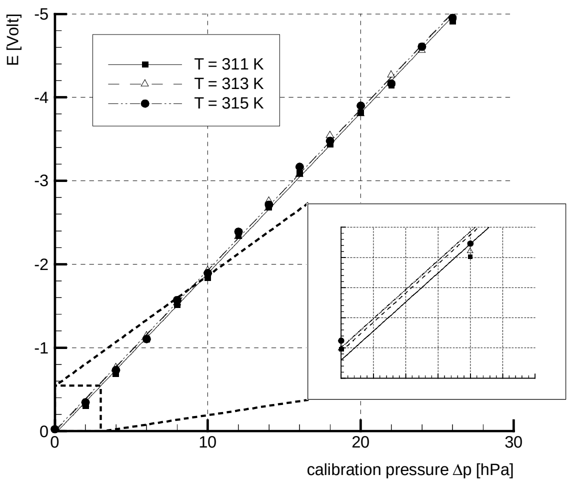

Fig. 4: Calibration data for the *Kulite* sensors in the wake rake

Data Acquisition and Evaluation

The *Kulite* sensors were connected to a 14 channel signal amplifier with integrated low-pass filter (eight-pole Butterworth; 48 dB/octave) before being digitized with a 12-bit A/D-converter at a sampling rate of 62.5 kHz/channel. A once-per-revolution trigger mechanism ensured that the wake passing effects were studied for wakes produced by identical bars. Data acquisition and probe control are integrated into a computerized system as shown in Fig. 5.

For steady flow conditions, the aerodynamic loading of the blades was determined by computing the isentropic Mach number and c_P distributions according to Eq. 1 and 2

$$Ma_{is,x} = \sqrt{\frac{2}{\kappa - 1}\left[\left(\frac{p_{t1}}{p_x}\right)^{\frac{\kappa-1}{\kappa}} - 1\right]} \qquad (1)$$

$$c_{P,x} = \frac{p_x - p_K}{p_{t1} - p_K} \qquad (2)$$

with p_{t1} being the total pressure measured with the pitot probe upstream of the cascade inlet plane. p_K is the pressure level inside the tank. The total pressure losses were calculated using Eq. 3

$$\omega = \frac{p_{t1} - p_{t2}}{p_{t1} - p_K} \qquad (3)$$

with p_{t2} being measured with the sensors in the wake rake.

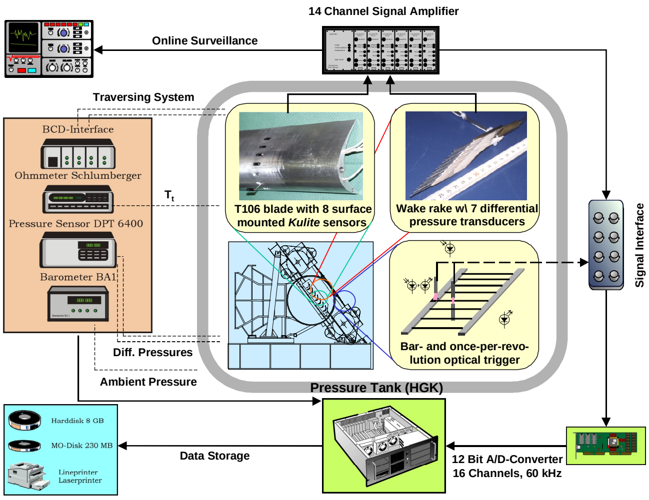

Fig. 5: Schematic drawing of the measurement system

For unsteady inflow conditions, data processing was done using the well-established PLEAT technique (Phase Locked Ensemble Averaging Technique, Lakshminarayana et al. (1974)) in order to separate random and periodic signals. A total of 500 ensembles was logged with each run. After the ensemble-averaging process, the data was evaluated using the same equations as above with the blade passing period being an additional variable.

Errors

The accuracy of the fast-response probes on the blade surface and in the wake rake is estimated to be ±1 hPa (0.15% FS non-linearity and hysteresis according to the sensor specification plus additional errors from the amplification and digitalization process as well as electrical noise). The pressure tappings on the blade surface were measured with a Scanivalve system with an overall accuracy of ±0.2 hPa. The total pressure losses determined with the five hole probe traverses are accurate within ±0.06 hPa; the reference pressures p_{t1} and p_K were read using a DPT6400 pressure scanner with an error of ±0.2 hPa.

FIRST EXPERIMENTAL RESULTS

Measurements for steady conditions

In a first step, measurements were taken for steady inflow conditions. The data recorded with the *Kulite* transducers was time-averaged and compared to the output of conventional measurement techniques to assess the performance of the fast response system and to be able to eliminate systematical errors.

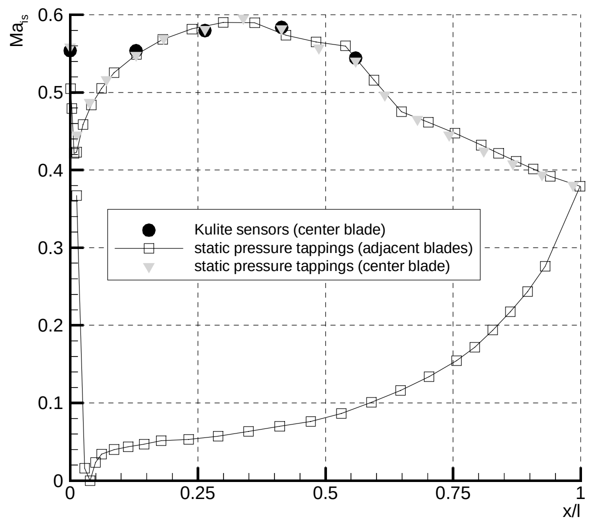

Fig. 6: Isentropic Mach number distribution for Ma_{2th} = 0.4, Re_{2th} = 200.000, no turbulence grid

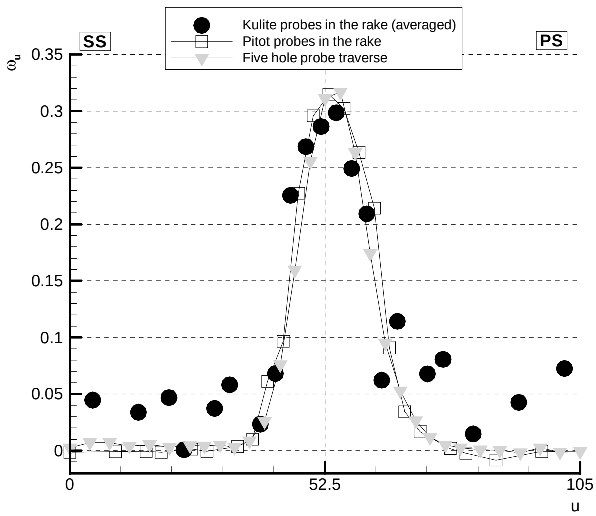

Fig. 7: Total pressure loss coefficient for Ma_{2th} = 0.4, Re_{2th} = 200.000, no turbulence grid

Figure 6 shows the isentropic Mach number distribution calculated with the time-averaged data of the surface-mounted pressure sensors together with results obtained from static pressure tappings in the center and adjacent blades. The pressure tappings on the adjacent blades return both pressure and suction side values and were used for all previous measurements performed in the last years. The additional static pressure tappings in the center blade are used to verify the output of the *Kulite* sensors. It can be seen that the static pressures on the suction side are almost identical for both the center and adjacent blades, which indicates nearly constant inflow conditions over the cascade height. The time-averaged data for the fast-response probes agrees very well with the conventional results. With decreasing Reynolds number and consequently lower surface pressure values, the fast-response sensors perform less accurate and tend to overestimate the local pressure (not shown in this paper).

The calculated values of the total pressure loss coefficient ω_u are plotted in Fig. 7. It is evident that the agreement between the five hole probe traverse and the pitot probe data of the wake rake is quite well. The Kulite sensors are able to match the position and amplitude of the blade wake, but perform poorly in the freestream region were total pressure losses reach values close to zero. This is due to the large range of the *Kulite* sensors, which causes considerable relative errors for small measurement values.

Data for unsteady inflow

Measurements for unsteady inflow conditions were taken for a variety of Reynolds, Mach and Strouhal numbers including a variation of cascade to bar pitch ratio and bar speed. However, the results presented in this paper will focus on one specific operating point to demonstrate the basic effects of wake passing identifiable in the high frequency pressure data.

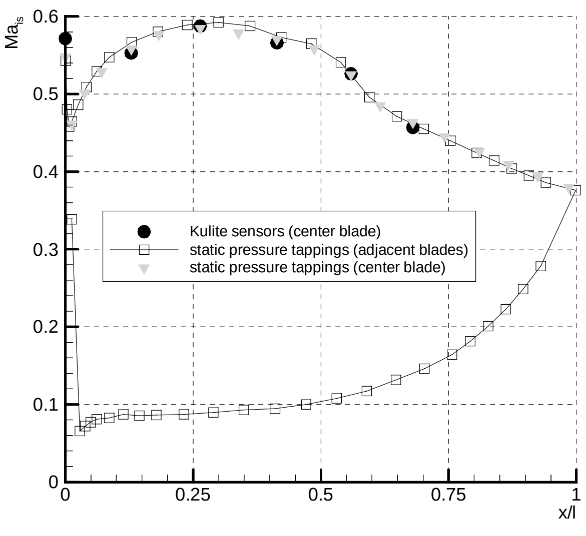

Fig. 8: Isentropic Mach number distribution for Ma_{2th} = 0.4, Re_{2th} = 200.000, t_b = 80 mm, U_b = 10.7 m/s, no grid

With an exit Reynolds number of Re_{2th} = 200.000 and Mach number of Ma_{2th} = 0.4, the flow conditions are similar to the ones discussed for the steady results. No additional turbulence grid was used as the effects of turbulence generated by the bar wakes would superimpose to the turbulence produced by the grid, therefore increasing complexity of the boundary layer development. The bar speed was set to U_b = 10.7 m/s with a bar to cascade pitch ratio of approx. 0.8 (t_b = 80 mm).

The time-averaged isentropic Mach number distribution for unsteady inflow conditions is shown in Fig. 8, again in combination with results obtained from static pressure tappings. The agreement between conventional and fast response data is again remarkably good. Due to slots at the upper and lower end of the cascade that are necessary to move the bars, a loss of mass flow occurs if the wake generator is installed. This results in a change of the inlet flow angle which in turn alters the isentropic Mach number distribution (and consequently the blade loading), especially in the leading edge area. By comparing Figures 6 and 8, this is obvious.

Fig. 9 displays the ensemble-averaged isentropic Mach number distribution using the form of space-time diagrams. Non-dimensionalized wake passing time along the ordinate is plotted over non-dimensionalized chord length along the abscissa, which allows the propagation velocity of phenomena caused by the wakes to be extracted directly from the experimental data. The wake center impinges on the leading edge of the suction side e.g. at t/T = 1.5 (**1**), where due to a decrease of the local incidence angle maximum static pressures and consequently minimum velocities occur (see Fig. 10).

In between the wakes (**2**), the suction peak resulting from the change in inlet flow angle yields maximum isentropic Mach numbers. This is similar to the behavior shown by Fan and Lakshminarayana (1994) for their calculations on a compressor blade with the described effects being inversed for turbine blades.

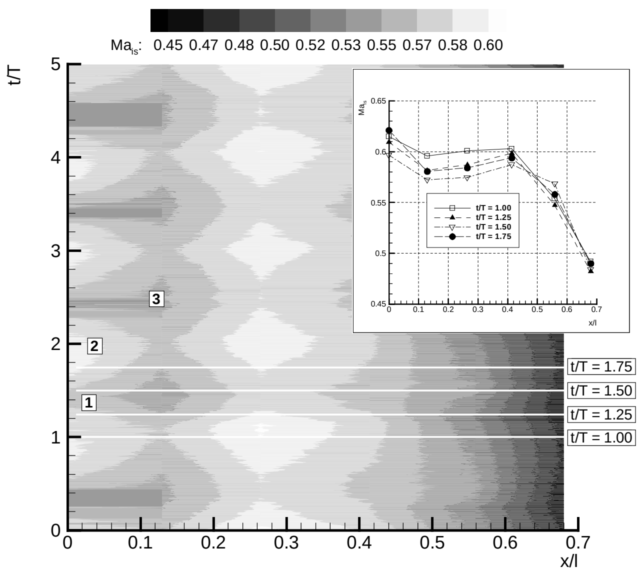

Fig. 9: Space-time diagram of the isentropic Mach number distribution for Ma_{2th} = 0.4, Re_{2th} = 200.000, t_b = 80 mm, U_b = 10.7 m/s, no grid

The wake moves then along the blade surface and is again identifiable when lowering the maximum Mach number around 0.3 times x/l with the position corresponding to the one measured with the static pressure tappings. From previously conducted hot film experiments, it was expected that the wake helps to suppress the laminar separation bubble. The four time traces included in Fig. 9 show the opposite behavior with a bubble being present at the time the wake passes. It should be noted that the wake path in reality is neither linear nor horizontal. For a bar speed of only 10.7 m/s, the velocity triangle is very flat. This might justify the idealization of the wake path as done in Fig. 9, but even when considering a certain slope, the detection of a bubble for t/T = 1.5 as well as the enlargement of the low velocity region (**3**) between the leading edge and the maximum remains unexpected. This is likely a problem of the limited spatial resolution (only six sensors on the blade surface) and calls for more sensors to be mounted on the surface, especially in the region before and where laminar separation occurs.

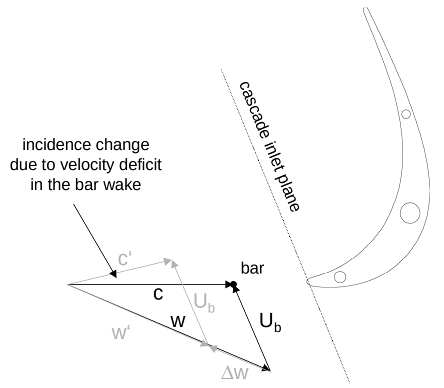

Fig. 10: Schematic velocity triangle in the cascade inlet plane with and without wakes

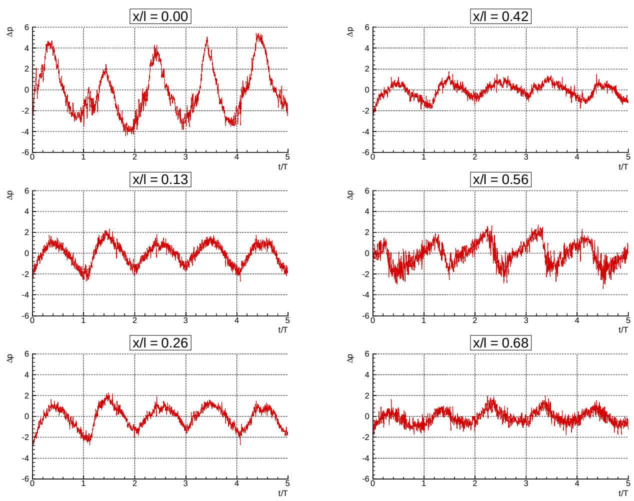

Fig. 11: Ensemble-averaged time traces of fluctuating pressure on the suction side for Ma_{2th} = 0.4, Re_{2th} = 200.000, t_b = 80 mm, U_b = 10.7 m/s, no grid

The ensemble-averaged time traces of the unsteady pressure fluctuations for the different sensor positions on the suction side are plotted in Fig. 11. The rapid decay of the pressure fluctuations starting from the leading edge is clearly visible. The phase shift starting at the leading edge and the different behavior of the transducer located at x/l = 0.56 (in the transitional region) need further investigation, but might depend on the angle the wake enters the cascade inlet plane and the location the wake hits the blade surface.

The ensemble-averaged total pressure loss coefficient is plotted in Fig. 12, again in the form of a space-time diagram. The blade wake around u ≈ 52 mm is clearly marked by maximum values of total pressure loss. The bar wake enters the blade passage coming from the suction side e.g. at t/T ≈ 2.0. As total pressure losses resulting from the bars are not compensated in the plot, the wake path is identifiable from elevated values in the passage flow where pressure losses are around zero. When the wake approaches the blade surface, it interacts with the boundary layer. At point **4**, the losses resulting from the bars are superimposed to those produced on the suction side boundary layer. Following the wake, the so-called becalmed regions with its laminar-like character should reduce separation and therefore pressure losses. This effect is visible in the experimental data in the area marked with **5**. The blade losses on the pressure side seem to be almost uninfluenced from wake passing.

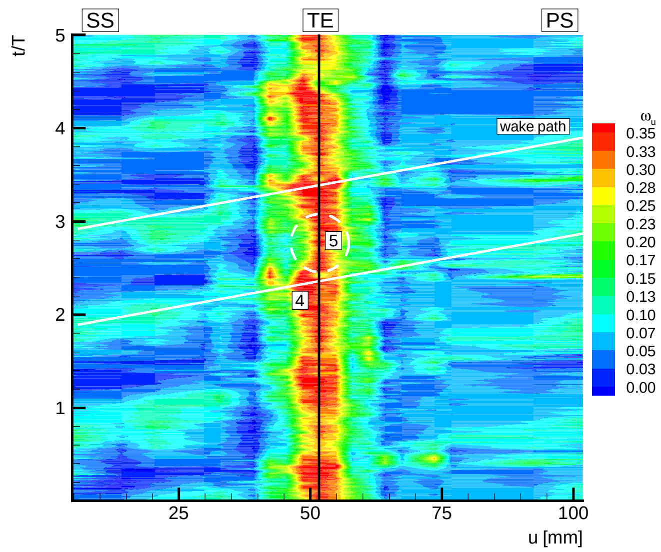

Fig. 12: Space-time diagram of the total pressure loss coefficient for Ma_{2th} = 0.4, Re_{2th} = 200.000, t_b = 80 mm, U_b = 10.7 m/s, no grid

CONCLUSIONS

A system to measure time-resolved pressure fluctuations has been developed to investigate the effects of wake passing on a highly loaded LP turbine cascade. Commercially available *Kulite* sensors were glued onto to suction side surface of the center blade. A wake rake with differential pressure transducers was designed and successfully tested. As the sensors are calibrated, they provide quantitative data easily comparable to the output of numerical simulations.

The capability of the surface-mounted sensors to follow pressure fluctuations caused by wakes shed from moving bars has been demonstrated for various operating points. The ensemble-average technique as previously employed for the evaluation of hot film signals was adapted for the use with fast-response pressure probes. Space-time plots of the isentropic Mach number distribution showed the impingement of the bar wake on the leading edge and the wake path along the surface. The limited spatial resolution with only six sensors on the blade surface generated unexpected results and demonstrated the need for a more dense instrumentation. Future comparisons with previously acquired hot film data will allow for an assessment of the performance of the fast-response transducers by verifying the results.

Time-resolved data of the total pressure loss coefficient identified the beneficial effect of the becalmed region. Further improvements in the data evaluation process like using the time-mean pressures recorded with the pitot probes as reference for the ensemble- and time-averaged voltages of the *Kulite* sensors are planned. Larger reference pressures for the differential pressure probes seem to be more suitable to use the range of the fast-response sensors, but will not improve overall accuracy. A different low pass filter setting might be valuable for future investigations by removing some of the high-frequency fluctuations not necessarily needed for the understanding of the wake passing process.

Numerical calculations using the TRACE_U code developed by DLR Cologne are presently conducted and will provide an insight into the wake-boundary layer interaction process. The location where the wake hits the suction side and the angle under which it enters the cascade inlet plane are especially interesting for the future analysis of the fast-response data.

ACKNOWLEDGMENTS

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