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EXPERIMENTAL INVESTIGATION OF UNSTEADY PRESSURE BEHAVIOURS IN A LINEAR TURBINE CASCADE

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Abstract

Unsteady flow effects have been investigated for sub-, trans- and supersonic exit flow conditions in a turbine cascade. Specifically, experimental forced bending blade vibrations—with one oscillating blade—were performed in a linear cascade. The blade frequency was 160 Hz. The resulting unsteady pressures were measured with piezo-electric pressure transducers along blade surfaces at mid-span and on the facility side-wall. The cascade is composed of five blades. The aims were: 1) to achieve a better physical understanding of unsteady pressure propagations within cascades; 2) to achieve a better understanding of disturbing influences on measurements in linear cascades; 3) to evaluate possible influences of tip clearance on unsteady measurements at blade mid-span; 4) comparison with existing prediction models for design and analysis and creation of a database of experimental data. Systematic investigations have been conducted in a linear facility for sub-, trans- and supersonic exit flow conditions to achieve the aims above. It was found that side-wall unsteady pressure measurements can provide a good indication of the unsteady behaviour throughout the cascade. For transonic exit flow conditions a tailboard influence can occur in the outlet cascade region. Single blade vibrations in turbine cascades produce a different pressure propagation behaviour in each of the two blade passages around the oscillating blade. The local damping at mid-span is not significantly influenced by a change in tip clearance or a slightly non-periodic flow.

Nomenclature

c	blade chord length [m]
$\tilde{c}_p$	unsteady pressure coefficient
f	blade vibration frequency [Hz]
h	bending vibration amplitude dimensionless (with chord)
H	blade span; $H / c = 1.14$

Greek letters:

β	flow angle, against the axis [deg]
γ	stagger angle [deg]
δ	blade vibration direction [deg]
Φ_p	phase angle; positive when disturbance leads blade "m" [deg]

i	incidence angle, positive against pressure side [deg]
k	reduced frequency, $k = \omega c/U_2$
M	Mach number
p	pressure [N/m^2]
$\tilde{p}(x,t)$	perturbation pressure [N/m^2]
t	cascade pitch; $t / c = 0.73$
	superscript:
$-$	mean value
$\sim$	perturbation value
	abbreviations:
TB	a calculation with two simulated tailboards downstream of the cascade
TEO	distance between the blade trailing edge and the grid boundary outlet in the Euler calculations, non dimensionalised with the axial chord length
σ	interblade phase angle; σ is positive when blade "+1" leads blade "0" [deg]
τ	tip clearance, % of total width H = 100 mm [% or mm]
Ξ	aerodynamic damping coefficient
	subscript:
1	upstream conditions
2	downstream conditions
ic	influence coefficient
p	pressure related
s	isentropic
loc	local

Introduction

In structure/fluid interactions, relatively small structural oscillations can develop into resonance, a phenomenon capable of generating powerful and destructive forces, which is able to damage almost any structure. Interaction between such structural oscillations and the resulting induced unsteady pressure forces constitutes the phenomenon called aeroelasticity which can potentially lead to flutter. Flutter can completely destroy constructions such as large bridges, aircraft-wings and turbomachinery blades. These aeroelastic phenomena should of course be avoided, and hence it is extremely important that one is capable of predicting such unsteady aerodynamic interactions. To achieve a better physical understanding of unsteady pressure perturbations, measurements of unsteady pressure flow fields were conducted using piezo-electric pressure transducers on the test facility side-wall.

In an annular facility the flow periodicity is automatically fulfilled, however in a linear facility a limited number of blades are used and the periodicity is influenced. Linear turbine cascade testing require tailboards downstream of the cascade to obtain periodic flow though, up- and downstream of the cascade. Satisfyingly good periodicity is generally attained in the centre blade passages. Measured results are repeatedly used to validate flow solvers. Therefore, it is extremely important that test results are as accurate as possible. Numerical calculations with and without simulated downstream tailboards were conducted to study the influence of downstream tailboards acting on unsteady measurements within the cascade.

To conduct forced bending blade oscillation testing a tip clearance generally exists between the vibrating blade and the facility side-wall, which produces a tip clearance vortex in the cascade. Such vortices induce 3D flow effects and the unsteady forces acting on the blades are also influenced. To obtain an unsteady pressure distribution along the blades equivalent to the real distribution, the unsteady pressures are generally measured at mid-span. However, the tip clearance can drastically vary (about $\tau = 0$ - 2.5%) depending on facilities and setups. The influence of such tip clearance on the unsteady behaviour along the blade surfaces at mid-span can be important with regards to the unsteady pressure behaviour and stability conditions. The tip clearance influence on the unsteady behaviour along the blade surfaces at mid-span was investigated for varying tip clearance using piezo-electric pressure transducers embedded into a blade.

Still today a large requirement for extensive unsteady data for design and analysis exists. Steady and unsteady flow fields and blade surfaces data for sub-, trans- and supersonic exit flow conditions cover some of these domains where extensive data is needed for comparison with flow solvers. The experimental results along the blade surfaces at mid-span and on the side-wall were compared with three existing 2D flow solvers. A database of the steady and unsteady data was assembled.

The present paper represents a concise summary of a dissertation work (Norryd, 1997) conducted at LTT in Lausanne.

Test facility and cascade geometry

Essentially unsteady flow effects have been investigated in the linear facility shown in Figure 1a. The dimensions of the inlet flow section are 100 x 340 mm. The cascade (53% overlapping) is composed of five turbine blades numbered "-2", "-1", "0", "+1" and "+2". There are two adjustable tailboards and valves used to ensure a satisfyingly uniform flow through, up- and downstream of the two centre blade passages. The inlet incidence angle is varied by turning the round plate (No. 5) on which the cascade is mounted. The static pressure distributions in pitch-wise direction up- and downstream of the cascade together with the upstream stagnation pressure is used to determine the in- and outlet isentropic Mach number. The isentropic exit Mach number in the case of supersonic outlet flow is determined by the mass flow and the known flow quantities (M_r, β_r) in a reference position on a blade surface (Bölcs et al., 1986 and Norryd, 1997). Figure 1b shows a developed double-sided labyrinth (Norryd et al., 1994) around the oscillating blade. This design reduces the leakage secondary flow through the gap between the side-wall and the vibrating blade. For the unsteady investigations the centre blade "0" was forced to vibrate in a pure bending mode. The "unsteady" measuring blade, Figure 1b, contains 12 piezoelectric transducers—10 at the suction side and two at the pressure side—in addition to four static pressure taps. The piezo-electric transducers are embedded at mid-span. The measured signals were assumed to be unaffected by the transducer mounting methods. The blade surface is smoothed with a two-component epoxy after the mounting. A perfectly smooth blade surface finishing was obtained.

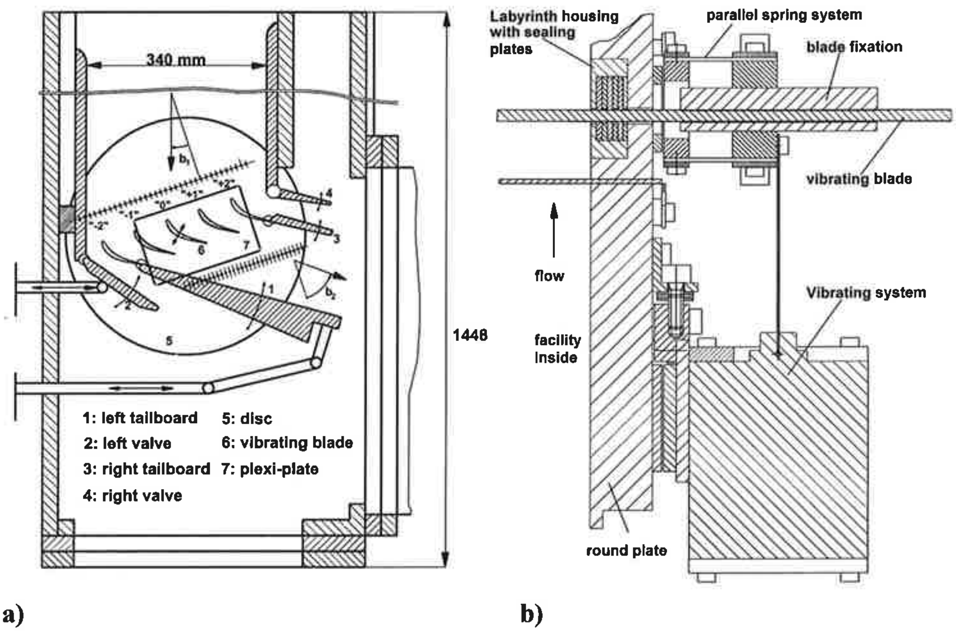


Figure 1. Linear Test Facility.

Figure 2 shows the side-wall measuring grid and the dimensions of a moveable tap construction. Eight pressure transducers—embedded in moveable tap constructions with screw-mounts—were utilised to conduct the side-wall time-dependent measurements.

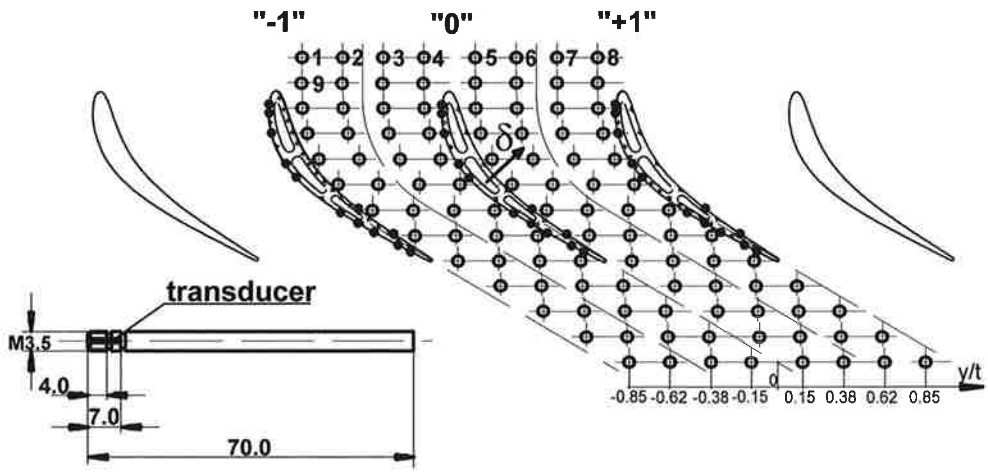


Figure 2. Side-wall measuring grid and a moveable tap construction.

Evaluation and analysis of the time-dependent data

The procedure to evaluate the measured signals is the ensemble averaging technique. This method requires a well-defined trigger signal which in this case is the blade oscillation. With a known blade frequency each sampled data point is corrected for the time-shift effects due to the components in the measuring chains, according to the calibrations, and placed in the corresponding place in the first period of each signal. The first period is subsequently divided into 128 intervals and the local averages are calculated in each interval. For these local averages much of the data spread is cancelled out, which is the great advantage with this evaluating technique. Approximately 25000 data points are taken per channel, which results in about 200 sampled data points in each interval. This was found to be a sufficient number to conduct statistical analysis on the measured data. An FFT-function is used to determine the exact amplitudes and phase shift of the averaged signals. The first harmonic of each signal is considered. It can be shown that the damping behaviour of a vibrating blade depends only on the unsteady pressure components with the same frequency as the blade oscillation (Schläfli, 1989 and Széchényi et al. 1983), as the total energy input into the vibrating blade from the fluctuating pressure components with frequencies separated from the blade frequency result in zero over time.

Definitions and data presentations

The oscillating blade is considered as a rigid body undergoing a sinusoidal motion. This defines the blade oscillation non dimensionlised by the blade chord as,

$$h(t) = \mathrm{Re}[\, h\, e^{i(\omega t)}] = h \cos(\omega t) \quad (1)$$

where the motion is defined as positive in δ-direction against the neighbouring blade "+1", Figure 2. In Eq. 1, h is the blade vibration amplitude of the 1st harmonic of the reference frequency. The reduced frequency represents a comparison between down-stream flow velocity (in a turbine), blade chord and blade oscillation frequency as:

$$k = \frac{\omega c}{U_2} \quad (2)$$

The reduced frequency in the present work was between $0.22 < k < 0.61$. The unsteady pressure coefficient is defined as,

$$\tilde{c}_p(x,t) = \frac{\tilde{p}(x,t)}{(p_{w1} - p_1)} \frac{1}{h} \quad (3)$$

where $\tilde{p}(x,t)$ is the fluctuation amplitude of the time-dependent pressure at the reference frequency, p_{w1} is the upstream stagnation pressure, p_1 is the upstream static pressure and h is the dimensionless blade amplitude. The unsteady pressure amplitude $\tilde{p}$ together with a phase angle, Φ_p, are derived from an FFT transform for each time-dependent signal. The phase angle indicates the angle between the blade motion and the induced unsteady pressure and is defined positive when the unsteady pressure leads blade motion. This phase angle relation is essential for the evaluation of unsteady data. The instantaneous unsteady pressure coefficient can be expressed by:

$$\tilde{c}_p \sin(\Phi_p + \omega t) \tag{4}$$

where, $\omega t = 0, 45, \ldots, 315°$. The blade motion is represented by $h(t) = h \sin(\omega t)$ and the oscillating blade moves against the pressure side for a positive blade motion.

Error estimation of the measured signals

The transducers signals: The piezoelectric transducers were calibrated and re-calibrated (before and after measurement tests) regarding the sensitivity and phase shift. Systematic errors of less than 1% in the sensitivity and 0.2° in the phase angle were determined. The error bars of 95% confidence interval (random error) of the unsteady pressure coefficients measured along the blade surfaces and on the side-wall depend on the measuring position. They are evaluated as follows; (1) in the inlet region: ±3% along the blade surfaces, ±8% on the side-wall; (2) in the outlet region: ±20% along the blade surfaces, ±30 - 40% on the side-wall. The larger errors in the outlet region are a result of the relatively small unsteady pressure amplitudes measured there.

Results from tests regarding unsteady pressure propagation behaviour

Side-wall measurements have been interpreted for a subsonic flow condition at nominal incidence angle and minimum tip clearance. The aim was to investigate the unsteady pressure propagation behaviour within the cascade.

The oscillating blade produces propagating pressure waves. A wave, produced from the pressure side of the blade "0" propagates in the inlet of the pressure side passage against the flow and in the outlet with the flow. For this reason the wave is accumulated near the leading edge of blade "+1" and high unsteady pressure magnitudes are formed. However, the pressure wave near the trailing edge is taken with the flow and small unsteady pressure magnitudes are developed. Furthermore, however, Figure 3 and Figure 4 show that the unsteady pressure propagates in an almost quasi-steady manner in this pressure side passage, as the phase angles in the flow field are relatively constant. This indicates an almost instantaneous propagation behaviour, related to the blade frequency.

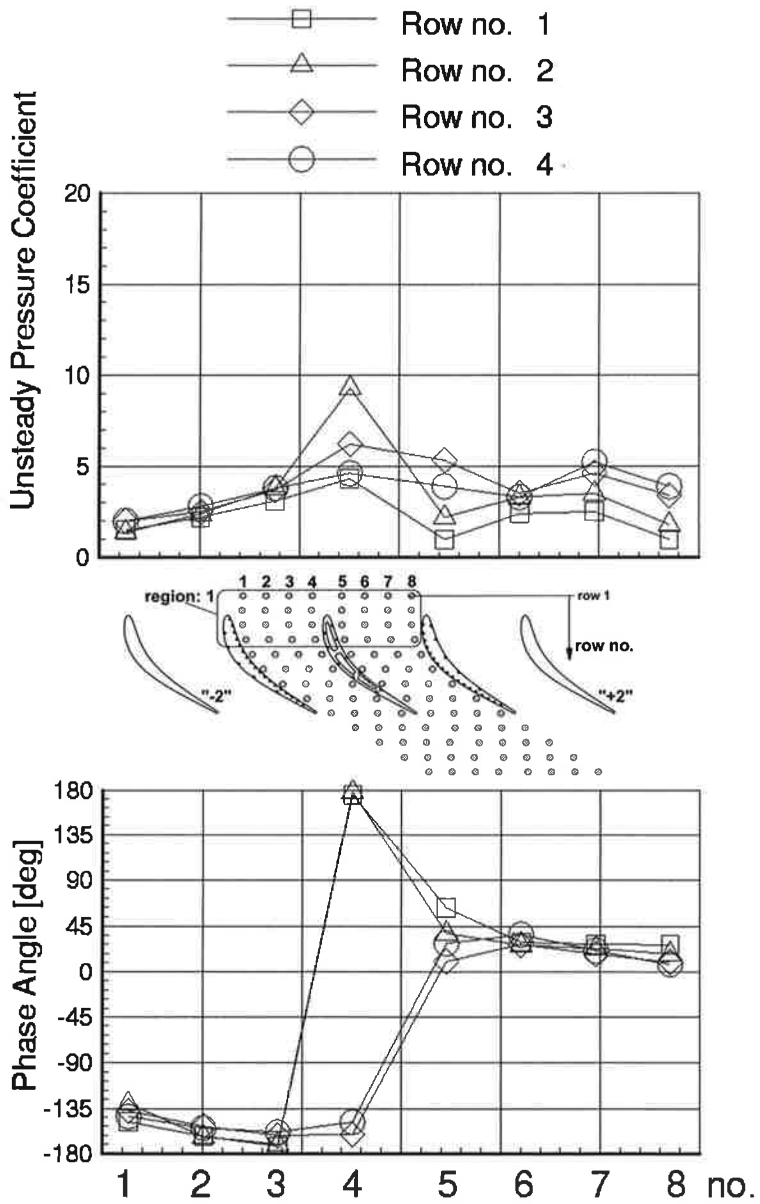


Figure 3. Unsteady pressure coefficient and phase angle distributions measured at the facility side-wall in the leading edge region: $M_{2S} = 0.75$ and $i_1 = 12.0°$.

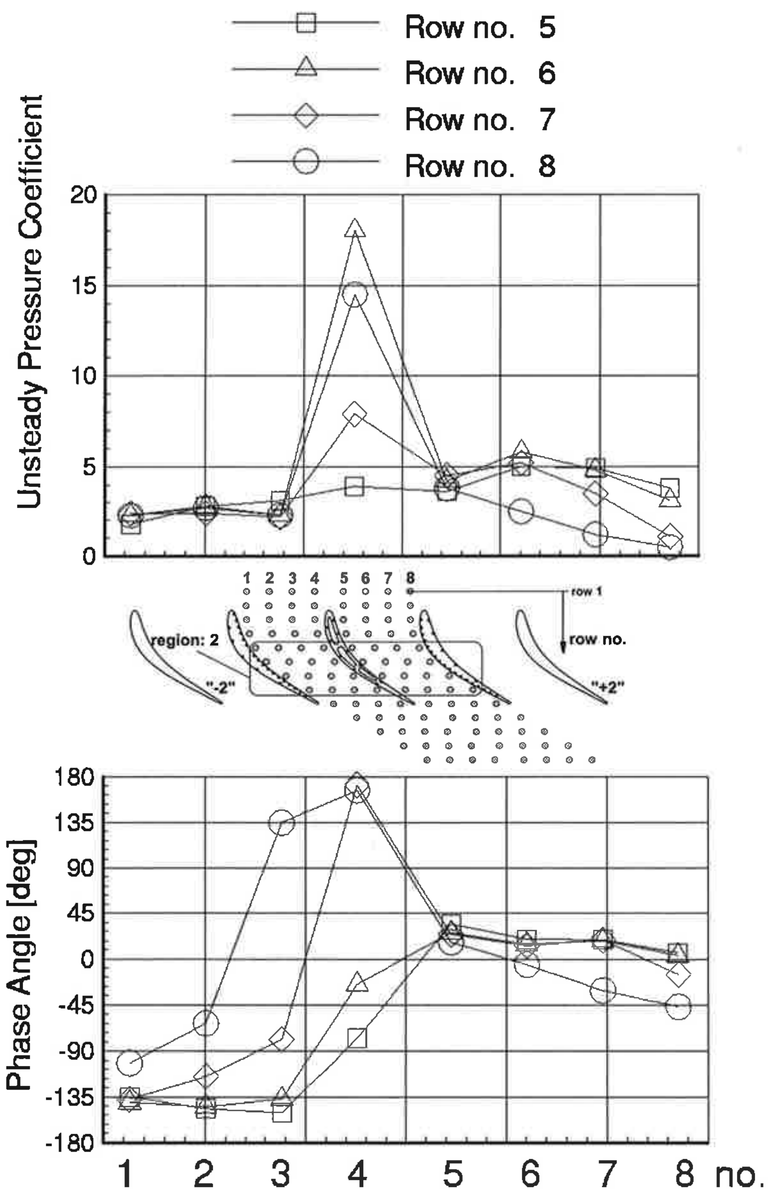


Figure 4. Unsteady pressure coefficient and phase angle distributions measured at the facility side-wall in the overlapped cascade part region: $M_{2S} = 0.75$ and $i_1 = 12.0°$.

A pressure wave produced along the suction side of the oscillating blade is always propagating downstream with the flow. Hence, there are only small unsteady pressure magnitudes produced along the pressure side of blade "-1". Figure 4 indicates that the time-dependent effects are important in this blade passage, especially in the outlet region

of the cascade (see Figure 4). The high unsteady pressure coefficients near the oscillating blade in the suction side passage arise due to the tip clearance leakage flow, although the tip clearance is the minimum one (0.5%).
From these observations it was concluded that the unsteady pressure propagation behaviour in the cascade is not symmetric in the two passages around the centre blade and the total propagation behaviour cannot be described using quasi-steady models.

Results from numerical tests regarding tailboard influences on cascade measurements

The blade surface steady and unsteady mid-span measurements have been compared using three existing 2d flow solvers; FINSUP (a potential code), EULERLTT (an Euler based code), UNSFLO (a coupled Navier-Stokes/Euler code). The aims were: 1) to predict the measurements with the existing flow solvers; 2) to investigate the influence of downstream tailboards on the steady and unsteady pressure distributions along the blade surfaces; 3) to analyse stability (local damping) tendencies between the measurements and calculations. The UNSFLO and EULERLTT calculations were compared with and without simulated tailboards downstream of the cascade for two flow conditions (Norryd, 1997). The FINSUP calculations were conducted only with periodic boundaries. The study treated sub-, trans- and supersonic exit flow conditions with two inlet flow angles.
Figure 5 and Figure 8 show the isentropic Mach number distributions comparisons between the measurements and the calculations. It is observed that the agreement is generally good, except near shocks.
Figure 6, Figure 7 and Figure 10 show unsteady features along blade "0". The overall unsteady pressure magnitude is well predicted for a nominal inlet flow angle from the leading edge to about 60% of the chord along the blade suction side. The corresponding phase angle distributions differ by about 30 - 40° between the measurements and the calculations. This can be important for the local damping, especially for Φ_p around 180°, since the sign of the local damping is determined by the phase angle, and therefore determines if a flow condition is aerodynamically damped or excited. For subsonic flow (see Figure 6) downstream of 60% chord along the blade suction side the unsteady pressure magnitudes are low, which results in a small influence on blade stability.
In Figure 5 and Figure 8 comparisons between simulated tailboards and periodic boundaries downstream of the cascade can be studied. Concerning the isentropic Mach number distributions no significant influence occurs for the subsonic flow, as well as for transonic exit flow in the inlet and overlapped cascade regions. The normal shock position on the centre blade seems to be slightly influenced by the tailboard for both the calculation as well as the measurement (see Figure 8). On blade "+1" no significant influence of shock position is observed. For the periodic downstream boundaries (without tailboards), the normal shocks appear at about 80% of the chord. Also, for transonic exit flow a tailboard influence on the measurements can occur in the outlet cascade region.
Figure 6 and Figure 10 exhibit the blade surface unsteady features along blade "0". It is observed that no significant influence occur between the calculations with and without

simulated tailboards downstream of the cascade for the overall subsonic flow and for the transonic exit flow condition in the inlet and overlapped cascade regions. In the outlet region for the transonic exit flow conditions differences are observed when, comparing the unsteady UNSFLO blade surface calculations with and without the downstream tailboards (Figure 10). A tailboard influence is also observed from the EULERLTT comparisons in this outlet region. The UNSFLO calculation without tailboards predict relatively strong peaks in the unsteady pressure coefficient distributions on both blade 0 and +1 at about 80% of the chord (steady-state shock positions). The calculation with tailboard shows a small visible peak in unsteady pressure amplitude at about 95% of the chord, corresponding to the shock position. This suggests that the downstream tailboards stabilise the motion of the normal shock. It was found that a tailboard influence on the measurements can occur in the outlet cascade region.

Figure 7 shows the local damping of the measurement and calculations along the oscillating blade for the transonic as well as the subsonic flow condition for nominal inlet flow angle ($i_1 = 12.0°$). The calculations result in damped flow conditions in the inlet along both the suction and pressure side, but the measurements indicate an excited flow condition near the leading edge along the blade suction side. The measured transonic case is unstable for almost the whole blade suction side. Differences between measurements and calculations can occur when the calculation method cannot predict separations in a proper way.

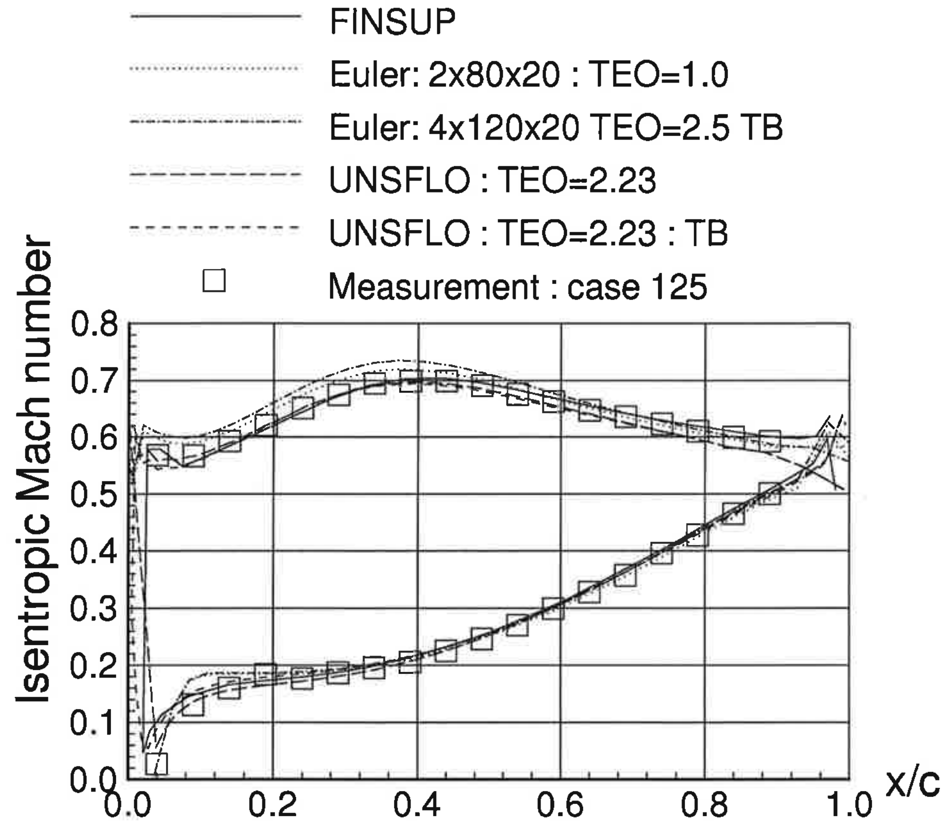


Figure 5. Comparison of FINSUP, EULERLTT and UNSFLO calculations together with measured data showing isentropic blade surface Mach number distributions along blade "+1", i_1 = 12.0°, M_{2s} =0.58.

It is found that the steady and unsteady blade surface measurements are generally well predicted by the existing flow solvers, apart from within the regions around shocks and flow separation. Hence, the accuracy of the measurements is supported by good comparison with the calculations. A tailboard influence on the measurements can occur in the outlet flow region for transonic exit flow condition. Even though the unsteady pressure coefficient and phase angle distributions are relatively well predicted, differences in the local aerodynamic damping between the measurements and the calculations occur.

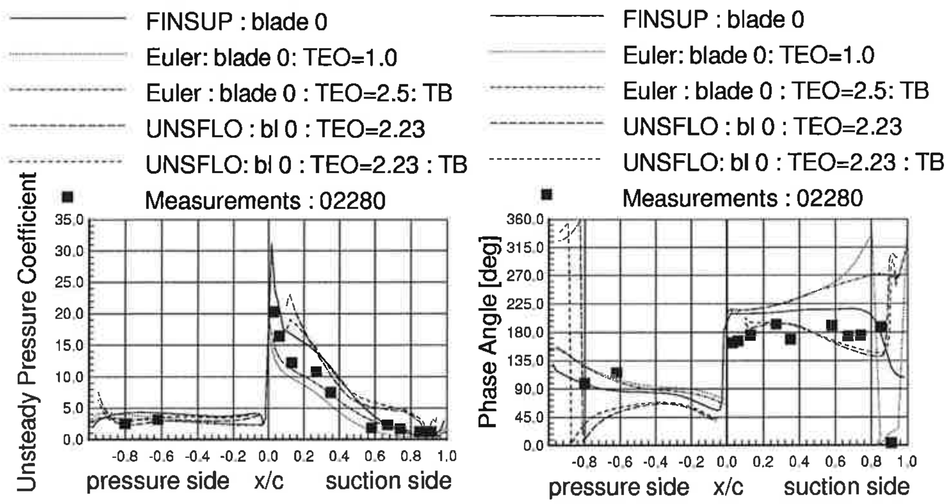


Figure 6. Comparisons of blade surface unsteady pressure magnitude and phase angle distributions between FINSUP, EULERLTT and UNSFLO calculations and measured data along the blade "0", $i_1 = 12.0°$, $M_{2S} = 0.58$.

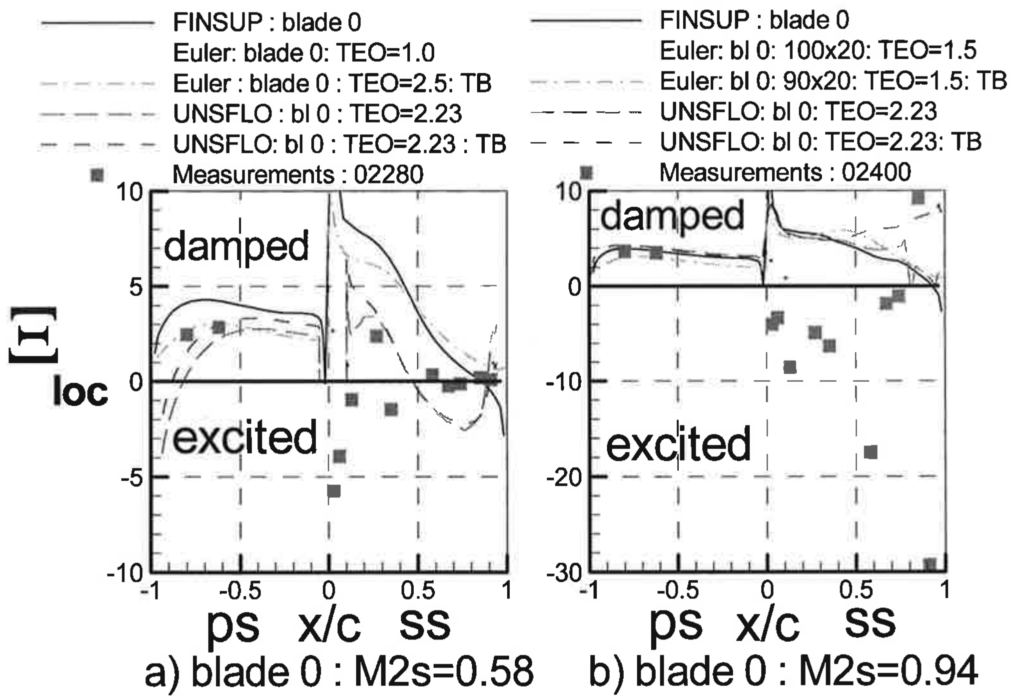


Figure 7. Comparison of the local damping along blade "0" between measurements and calculations for a) a subsonic, $M_{2S} = 0.58$, and a transonic case, $M_{2S} = 0.94$.

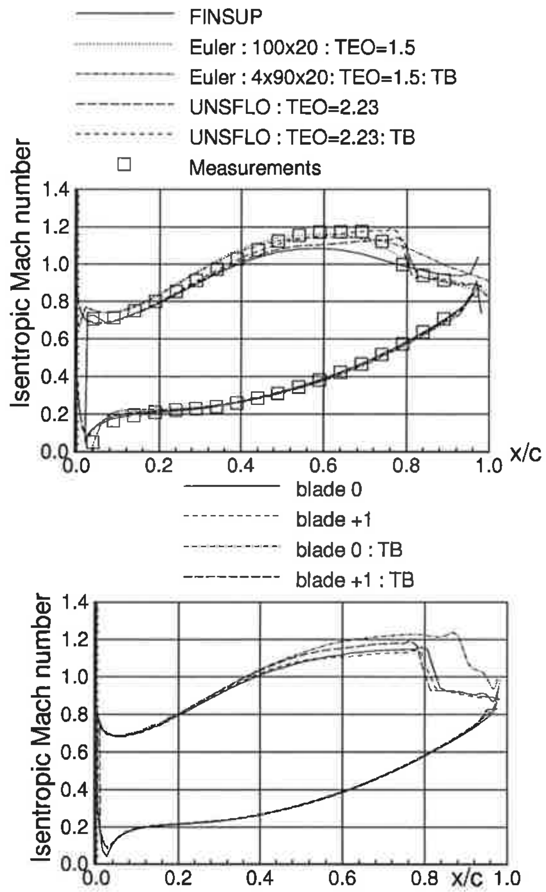


Figure 8. Calculations and measured data comparisons of isentropic blade surface Mach number distributions, $i_1 = 12.0°$, $M_{2s} = 0.94$.

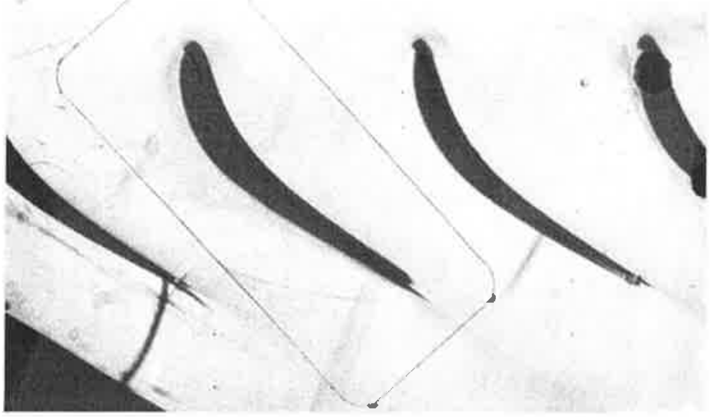


Figure 9. Schlieren image of the flow condition, $i_1 = 12.0°$, $M_{2s} = 0.94$.

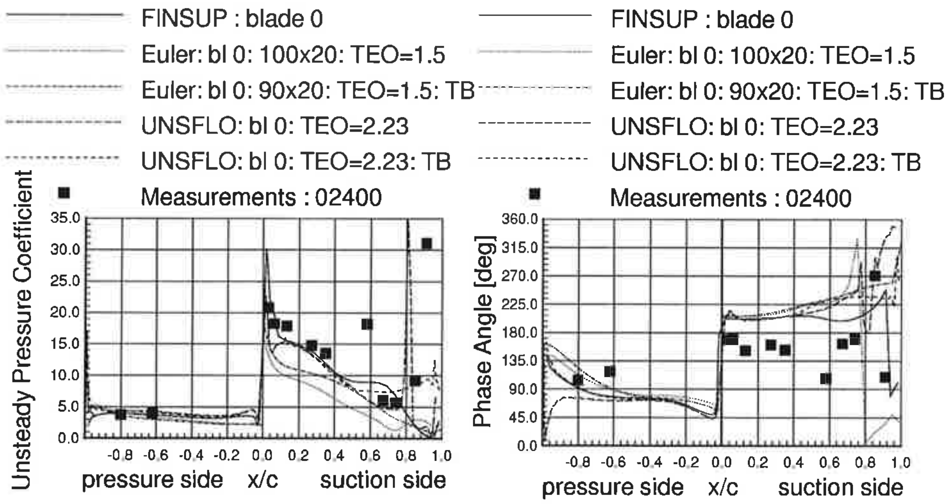
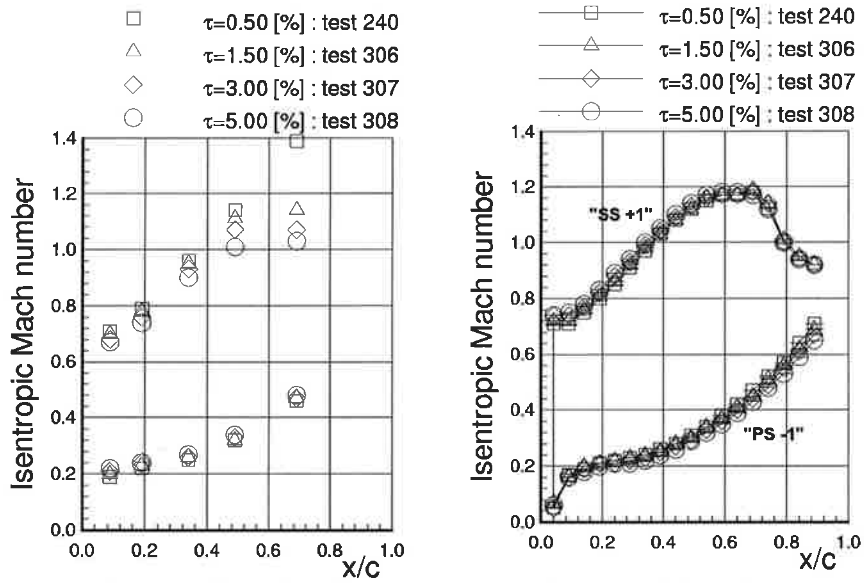


Figure 10. Comparisons of blade surface unsteady distributions between the calculations and the measured data along blade "0", $i_1 = 12.0°$, $M_{2s} = 0.94$.

Results from tests regarding the influence of tip clearance on blade surface mid-span measurements

For the measurements with varying tip clearance the tip clearance is only changed at blade "0". The neighbouring blades "1/-1" have no tip clearance between the wall and the blade profile. The aim was to investigate the influence of tip clearance on the isentropic Mach number and the unsteady features along the blade surfaces at mid-span within the cascade passages on both sides of blade "0".

Figure 11 exhibits the isentropic Mach number distributions along blade "0" at mid-span for a transonic exit flow condition at normal incidence angle. It is observed that the distribution along blade "0" is influenced by a change in tip clearance, while the neighbouring blade suction side distributions are almost unaffected. Along the suction side of blade "0" the isentropic Mach number distribution is decreased for an increased tip clearance. The change in Mach number distribution is strongest for transonic exit flow condition. The reason for that is the reduced flow surface because of the arising tip clearance vortex. The decrease in isentropic Mach number because of the reduced flow surface is strongest for transonic flow velocities, as a small change in flow surface changes the flow velocity drastically. The tip clearance flow changes the cascade exit pressure, which also influences the position of the shock at transonic exit flow conditions.



a.) Blade "ss 0" and "ps 0" b.) Blade "ss +1" and "ps -1"

Figure 11. Blade surface isentropic Mach number distributions along the three centre blades for four tip clearances for transonic exit flow, $M_{2S} = 0.94 : i_1 = 12.0°$.

Figure 12 shows the unsteady mid-span blade surface distributions for the corresponding transonic exit flow case. The unsteady measurements generally show a reduced unsteady pressure magnitude at mid-span for an increased tip clearance, as the pressure waves from the oscillating blade are dispersed over the tip clearance at the blade tip. The dispersion of the unsteady pressure magnitude is observed to be most pronounced near the leading edge in the suction side region of the oscillating blade. The mid-span phase angle distribution along the vibrating blade suction side is not significantly influenced by a change in tip clearance. Since the phase angle is very dominating for the calculation of the local damping, the local damping is as well not significantly influenced by a change in tip clearance. The unsteady pressure features along the neighbouring blades at mid-span are not importantly influenced by a change in tip clearance on blade "0", as

they have no tip clearance. For transonic flow condition, the shock position and the shock influenced unsteady pressure magnitudes are modified by a change in tip clearance, since it changes the steady exit flow conditions.
It was found that a change in tip clearance can effect both steady- and unsteady blade surface pressure distributions at mid-span, however, the local damping is not significantly affected, as the phase angle remains relatively constant.

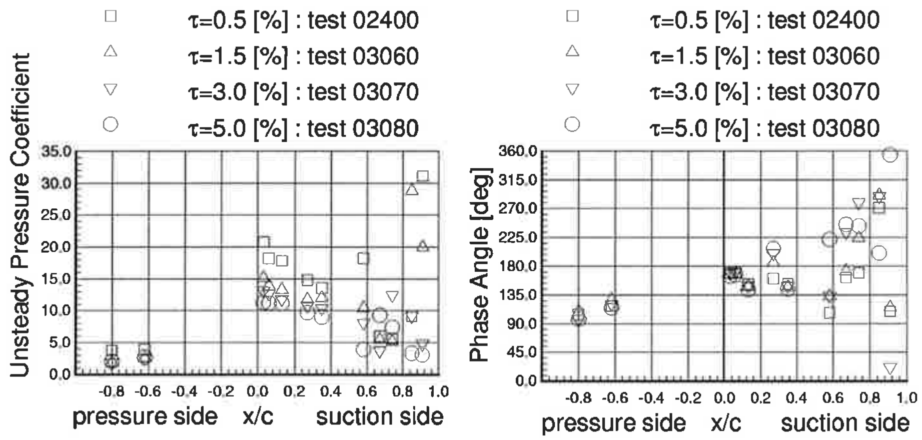


Figure 12. Unsteady pressure coefficient and phase angle distributions along blade "0" for transonic downstream flow conditions ($M_{2S} = 0.94$) for four different tip clearances.

Final conclusions

- Unsteady flow field investigations can be conducted applying piezo-electric transducers at the facility side-wall to measure unsteady pressure. Specifically, it was found that side-wall measurements can provide a good indication for the unsteady behaviour throughout the cascade.

- Calculations show a negligible tailboard influence on the unsteady features for subsonic flow. However, for transonic exit flow condition an tailboard influence can occur in the outlet cascade region, without disturbing the inlet and overlapped cascade regions.

- Single blade vibrations in turbine cascades produce a different pressure propagation behaviour in each of the two blade passages around the oscillating blade. The total propagation behaviour cannot be described using quasi-steady models.

- A change in tip clearance influences both steady- and unsteady blade surface pressure distributions at mid-span. The local damping at mid-span is not significantly influenced by a change in tip clearance and a slightly non-periodic flow.

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References

Bölcs A., Suter P. (1986) Transsonische Turbomaschinen, Wissenschaft und Technik : Taschenausgabe, Karlsruhe, G. Braun.

Norryd M., Bölcs A. (1994) Development of a Sealing construction to Prevent Leakage Flow During Flutter Tests in a Linear Cascade, 12th Symposium on Measuring Techniques for Transonic and Supersonic Flow in Cascades and Turbomachines, Prague, Czech Republic, 12-13 September.

Norryd M. (1997) Experimental Investigation of Unsteady Flow Effects including Tip Clearance in a Turbine Cascade, PH. D. These No. 1661, Presentée au Département de génie Mécanique, EPF-Lausanne.

Schläfli D. (1989) Experimentelle Untersuchung der instationären Strömung in oszillierenden Ringgittern, PH. D. These No. 800, Presentée au Département de Mécanique, EPF-Lausanne.

Széchényi E., Girault J. P. (1983) An Aeroelastic Testing Technique in a Straight Cascade Wind Tunnel, Aeroelasticity In Turbomachines, Proceedings of the Symposium "Measuring Techniques in Transonic and Supersonic Cascades and Turbomachines", Aachen, Germany.