Periodicity and repetitivity of unsteady measurements of an annular turbine cascade at off design flow conditions

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ABSTRACT

A two-dimensional section of a gas turbine cascade has been investigated experimentally in an annular non-rotating cascade facility as regards to its steady-state and time-dependent aerodynamic characteristics at off-design flow conditions. The blades vibrated in the first traveling wave bending mode.

Steady-state and unsteady data were obtained for an off-design incidence angle of about 22° and for an isentropic outlet Mach number of M_{2s}=1.19. At this flow condition, a separation bubble was present on the suction surface close to the leading edge. A shock appeared at trans- and supersonic outlet flow conditions on the suction surface. The data showed high unsteady loads close to the leading edge and in the shock region. It was found that the steady and the unsteady pressures in the shock region on the blade surface seemed to be very sensitive to small changes in the flow conditions.

The periodicity and repetitivity of the steady and the unsteady pressures (σ=180°) was checked at several circumferential channel positions. This was done to figure out to which extend test data obtained in an annular ring channel can serve as a basis for the comparison with numerically obtained data.

The aim of this paper is to show where problems may arise when comparing calculated results with test data.

NOMENCLATURE

Symbol	Explanation	Dimension
c	Blade chord length	m
$\tilde{c}_p(x,t)$	Unsteady perturbation pressure coefficient: $\tilde{c}_p(x,t) = \frac{1}{h} \cdot \frac{\tilde{p}(x,t)}{\bar{p}_{w1} - \bar{p}_1}$	
$\tilde{c}$	Quasi-steady perturbation pressure coefficient	-
f	Blade vibration frequency	Hz
h	Dimensionless (with chord) bending vibration amplitude	-
k	Reduced frequency: $k = \frac{\omega \cdot c}{2 \cdot u_2}$	-
M	Mach Number	-
p	Pressure	mbar
$\tilde{p}$	Unsteady perturbation pressure	mbar
Re	Reynolds number: $Re = \frac{c \cdot u_1}{\nu_1}$	-
t	Time	sec
t	Blade pitch	m
u	Velocity	m/s
x	Coordinate along chord	m
z	Circumferential position	m

β	Flow angle	deg
β_g	Stagger angle	deg
δ	Blade vibration direction	deg
ν	Kinematic viscosity	m^2/s
ω	Circular frequency of the blades	rad/s
σ	Interblade phase angle σ is positive when blade "n+1" leads blade "n"	deg
ϕ	Phase angle. Positive when disturbance leads blade "n"	deg
Ξ	Aerodynamic damping coefficient	-

Subscripts:

ic	Influence coefficient
p	Pressure
s	Isentropic
w	Stagnation values
1	Upstream flow conditions
2	Downstream flow conditions
1B	First bending mode

Superscripts:

n	Influence of blade "m" on blade "n"

INTRODUCTION

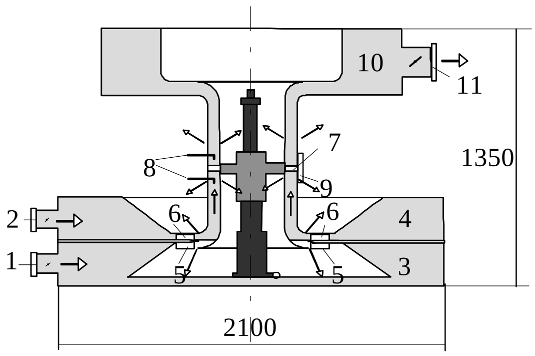
Vibration-related fatigue failures have been, and remain, a major concern for turbomachine manufacturers and operators world-wide. If such a failure appears, it has major consequences and can become extremely expensive.

The agreement between theoretical and experimental results in the domain of turbomachine blade aeroelasticity ranges from extremely good to extremely bad, depending on such factors as geometry and flow condition, but also on experimental procedure and numerical method. Generally, it can be concluded that the low subsonic attached flow can be predicted reasonably well today, whereas the transonic flow conditions on realistic profile types show discrepancies between theory and experiments. Almost no data or prediction models are available for stalled flow. Thus, a large need exists for both well-documented experimental test cases and for appropriate prediction models. Also, previous experimental data showed that the unsteady effects from separations or from a shock wave can be of considerable importance.

Experiments were done to obtain steady state and time dependent informations about pressure responses at high incidence flow angles with separated flow regions and near oscillating shock waves. The problem of periodicity and repetitivity of steady-state and unsteady measurements at high incidence angles was already mentioned by Bölcs, Fransson and Körbächer (1991). Tests that were performed to check the periodicity and repetitivity of the measurement are presented in this paper in more detail. It is believed that those problems are also found in other test rigs and thus a discussion of them will be of general interest.

TEST FACILITY AND INSTRUMENTATION

The tests on the presented cascade were performed in the non-rotating annular cascade tunnel (Fig.1) at the Swiss Federal Institute of Technology, Lausanne (Bölcs, 1983; Bölcs et al., 1991). The flow angle in the test section can be regulated from 0° to ±75° (measured from axial), and the inlet Mach number can be varied from 0.3 to 1.6. The flow conditions are measured with aerodynamic probes and pressure taps. Schlieren optics and laser holography can be used for flow visualization.



1,2 inlet valves
3,4 outer and inner settling chambers
5,6 outer and inner preswirl vanes
suction
7 test cascade
8 aerodynamic probes
9 cylindrical optic
10 outlet chamber
11 outlet valve

Fig.1: Annular ring channel

For time-dependent measurements the blades in the test cascade are mounted on elastic springs and are driven into a vibration mode by a vibration control system (Kirschner et al., 1980). Each blade is suspended on a spring-mass system. The spring is designed to reproduce the first three eigenfrequencies and the vibration direction of the first bending mode, as determined from the blades in the full-scale turbine. The blades are forced into vibration by individual electromagnetic exciters, each with its own feed-back loop (Fig.2).

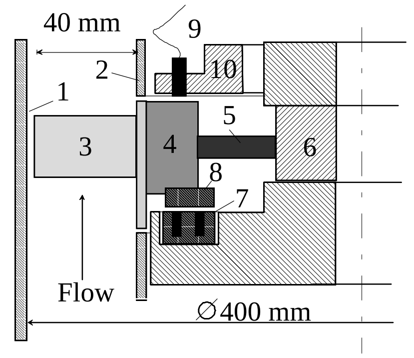


Fig.2: Blade vibration system

Details about the model-cascade and the nominal flow condition of the section under investigation are given in Fig.3 and Table 1. The model blade section is overlapped for about 45% of the chord length.

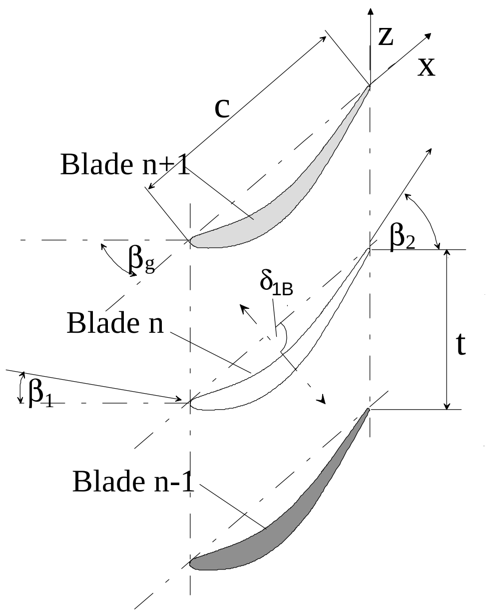


Fig. 3: Model cascade geometry

Eight blades are furnished with pressure taps and five blades are equipped for unsteady pressure measurements with piezoresistive pressure transducers (ENDEVCO Model 8515-50A and KULITE Model LQ-5-080). The ENDEVCO transducers are embedded in the blades and connected to the surface through taps, whereas the KULITE transducers are flush mounted on the surface. The way how the transducers are mounted does not influence their response. The transducers were calibrated for fluctuating pressures and for acceleration forces (Körbächer, H.; 1990&1991).

Number of blades:	20
Blade span:	40 mm
Chord (c):	77.8 mm
Maximum blade thickness:	7.7 mm
Camber :	40.8°
Hub diameter:	320 mm
Tip diameter:	400 mm
Pitch (mid-span)(t):	56.5 mm
t / c (mid-span):	0.72
Minimal section (mid-span):	28.5mm
Stagger angle (β_g):	49°
Bending mode eigenfrequency (f_{1B}):	205±2Hz
Bending mode direction (δ_{1B}):	90°
Reynolds no. (Re):	$0.7 \cdot 10^6 \div 1.3 \cdot 10^6$
Pressure taps, Suction surface:	31
Pressure taps, Pressure surface:	8
Pressure taps, Trailing edge:	14
Pressure transducers, Suction surface:	19
Pressure transducers, Pressure surface:	9
Reduced frequency k_{1B}:	0.1366

Table 1: Model cascade geometry and nominal flow conditions.

STEADY STATE RESULTS

To examine the flow around the model cascade at off-design flow conditions, tests were done at an inlet flow angle of β_1=33°. The nominal inlet flow angle for the cascade is β_1=10.5°.
From the blade surface Mach number distributions and from surface paint flow visualizations, it was concluded that a separation bubble exists from the leading edge to approximately 30% chord length on the suction surface. From this point onwards, the suction surface flow accelerates as it was also seen for the nominal inlet flow angle (A. Bölcs, T.H. Fransson, H. Körbächer; 1991).
The separation bubble and the region were the shock impinges on the blade surface are of special interest because it is very difficult to do calculations for these cases. It is thus necessary to have a good experimental data base to compare the calculations with measured test cases. It is important to know how reliable such measurements are, especially in areas such as a separation bubble or a shock region on the blades.

STEADY STATE PERIODICITY AND REPETITIVITY

The cascade was rotated in circumferential direction in steps of 18° (which is the spacing of the blades) over an arc of 180°. Steady and unsteady measurements were taken to examine the circumferential periodicity of the surface Mach number distribution on the blade surfaces in the channel. To figure out if the Mach number distribution differs in different blade channels on the suction surface, pressure tabs were located at the same chord wise position on two blades (Blade 9 and Blade 14 - Fig.4 indicates the blade numbers and the circumferential positions). The outlet Mach number was chosen to be M2s~1.19. At this Mach number a shock impinged onto the suction surface.

The inlet and outlet flow conditions could not be measured at all circumferential cascade positions since the stream probes are fixed at one position and can not be rotated with the cascade. Thus, the flow conditions were always measured at the same circumferential positions (probe 1 and probe 2 in Fig.4). Small differences in the Mach number distribution close to the leading edge at different circumferential positions of the cascade may result from slightly changing inlet flow conditions in circumferential direction.

The cascade positions of the blades with the pressure taps do not coincide with the cascade positions of the blades with the unsteady pressure transducers, so no direct comparison of steady and unsteady measurements can be made for a certain angle of grid rotation. The Mach numbers did not change much during the rotation of the cascade on the pressure side. The periodicity is good there.

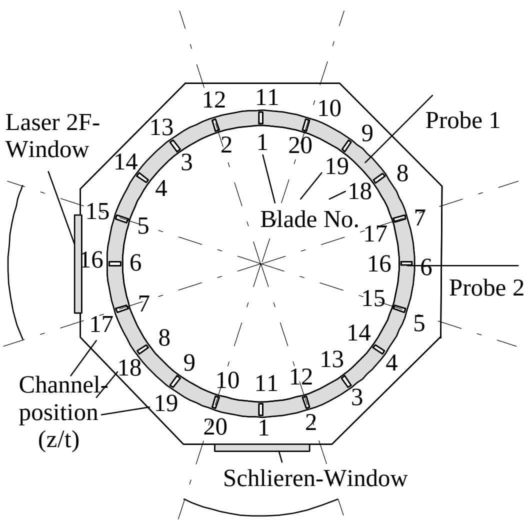


Fig.4: Channel and blade positions

On the suction surface, the differences between the highest and the lowest measured Mach numbers at different chord-wise positions during the rotation of the cascade are not very large for the pressure tap positions until about 65% chord length (Fig. 6). The difference is larger for the tap at x/c=0.15 inside the separation bubble. This shows that the Mach number distribution on the blade surface does not depend very much on the blade and its position in the channel until about 70% chord length. Further downstream, it can be seen that at one circumferential channel position there seems to be a strong shock at 75% chord length and at an other position a weaker shock at 80% chord length with a following decrease in Mach number. At around x/c=0.8, the differences between minima and maxima become very large. They reach up to a difference of 0.25 in Mach number. Thus, the periodicity is not very good in the area were the shock impinges onto the blade surface.

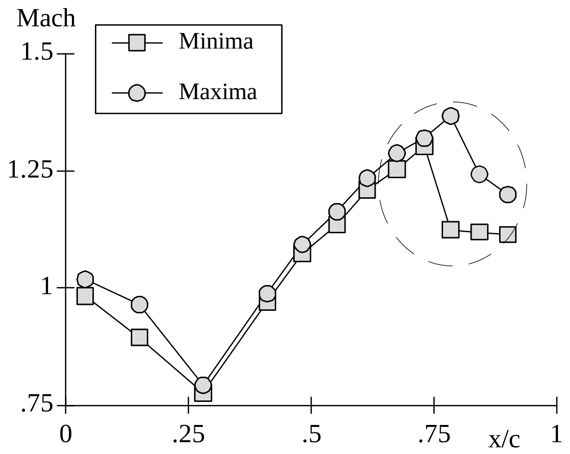


Fig.5: Steady state minima and maxima for blade 9 (M_{2S}=1.19; β_1=33°)

Figure 6 shows how Mach numbers vary on the two blades with the pressure taps at the same chord-wise coordinates. The blades (no. 9 and no. 14) are five spacings apart.

At x/c=0.04, close to the leading edge of the blades, the Mach numbers are approximately the same when both blades are in the same circumferential channel position. For x/c=0.73, the measured Mach numbers on the two blades are still very close but for x/c=0.842 and x/c=0.9 larger variations can be seen over the circumference of the channel. Different Mach numbers can be seen at these chord-wise coordinates on the two blades even at the same circumferential channel position.

The question arising is, if it is possible to perform repetitive measurements on a blade near a shock, taking into account the behavior shown above. For verification, repeated steady measurements were done at the same circumferential position of the blades in the channel. The results show that the repetitivity is excellent except in the immediate neighborhood of the shock (Fig.7, x/c=0.842). It was found that the repetitivity at this position is even better than it is shown in Fig.7 because the measurements started when the channel had not yet reached its working temperature. This caused a slight difference in total pressure between the measurements. The difference between the measurements is due to this effect.

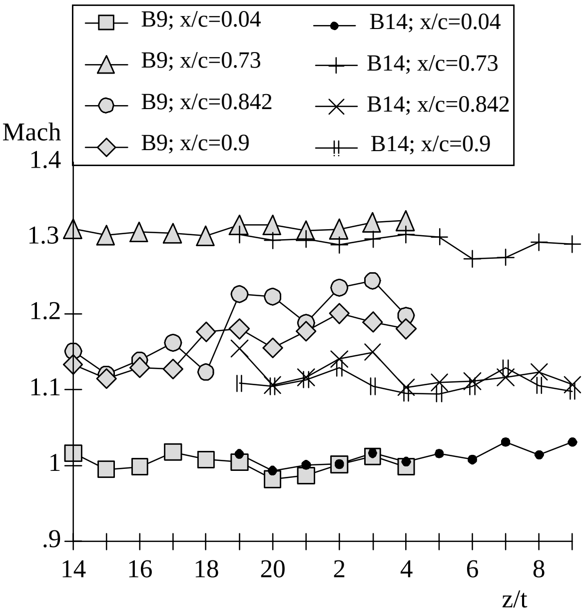


Fig.6: Comparison of steady state periodicity of two blades (M_{2S}=1.19; β_1=33°)

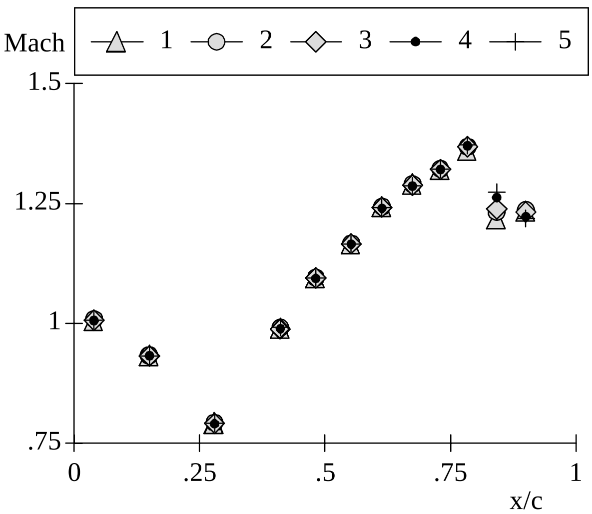


Fig.7: Repetitivity on blade 9 (M_{2S}=1.19; β_1=33°)

A reason for the sensitivity of the chord wise position where the shock impinges onto the blade surfaces can be seen regarding the situation of the shock in the blade channels of the turbine cascade (Fig.8). Such a configuration was seen in Schlieren pictures of the same profile in the linear test facility of LTT at similar flow conditions (A.Bölcs & O. Sari; 1987). In real flow cases, the shock is not attached to the trailing edge of the blades but emerges from the wake behind the blade. It impinges not directly onto the blade surface but onto the boundary layer of the blade. Hence, small changes in the outlet flow conditions may change the form of the wake and thus the point where a shock impinges onto the blade.

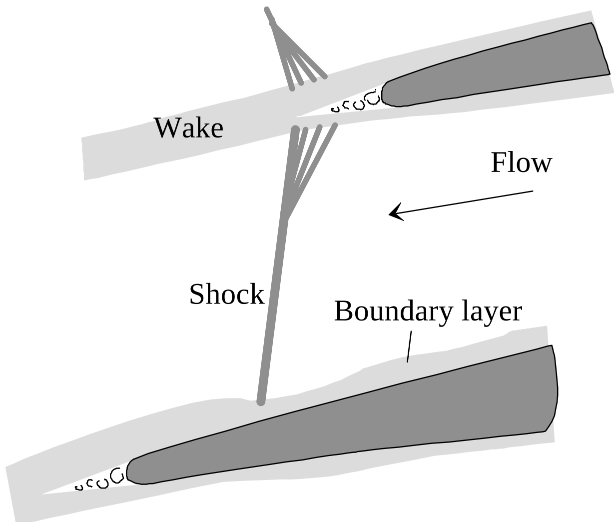


Fig.8: Shock situation behind the trailing edge

The shock strength and position depend strongly on the wake form and on the thickness of the boundary layer. The stability of the wake and thus of the shock is influenced to a great extend by the form of the trailing edges of the blades (O. Sari; 1989, A.Bölcs & O. Sari; 1991). It was also found that the dead water region behind the trailing edge fluctuates periodically near sonic conditions (M_{2S}~1.0 to M_{2S}~1.2) and introduces an unsteadiness to the wake flow. This causes the shock to vibrate. The vibration frequency is not necessarily correlated to the blade vibrations as the phenomenon occurs also when the blades are not vibrating. This should be kept in mind when analyzing the unsteady data near the shock region. Minor changes in the trailing edge form lead to a displacement of the shock too. The shape of the model cascade blades was checked, but no differences beyond the tolerances (0,02 mm) were found. However, there may be slight deviations in the trailing edge profile shapes that deform the wake and thus influence the shock position. This would be a possible explanation for differences of the shock positions on different blades.

Strong three-dimensional effects can be expected as the span-to-chord ratio of the blades is only 0.5 for the examined model cascade. In the tests, the inlet and outlet flow conditions were regulated to have a constant Mach number distribution over the channel height. For the given test case, the inlet Mach number varied between M1s=0.38 and M1s=0.41 in span-wise direction from z/h=0.2 to z/h=0.8 channel height. Boundary layers are present at the channel walls that have an estimated thickness of up to 20% of the channel height at each side wall. No wall boundary layer suction could be applied for the presented cascade. A slight non-periodicity in the thickness of the side wall boundary layers over the circumference of the annular channel could affect the downstream flow conditions of the cascade to such an extend as to influence the shock position. A change in the boundary layer thickness was not checked as the stream probes could not be rotated in circumferential direction.

Features other than the in- and outlet flow conditions that are believed to cause the shock positions to vary are the tip clearance, the blade spacing, the cap between the vibrating blades and other small deviations from an ideal geometry. Small deviations of these features can neither be prevented with real nor with model blades and are very difficult to determine for a cascade under operating conditions. It is believed that not only one single effect is responsible for the deviations in the Mach number and pressure distribution from blade to blade and in circumferential direction. Probably a combination of several effects causes ambiguities in the test data. Further tests should be conducted to determine exactly the main influences.

The facts mentioned above should be kept in mind when comparing calculated results with test data.

The conclusion is that it is important to obtain a shock with the proper strength in numerical codes. For the given example, good agreement between the shock position in calculations and the ones found in the tests is of secondary importance as the shock position is very sensitive and depends on many factors that can not be reproduced in calculations. It is believed that this is a statement which is more or less true for other experimental test cases too. The separation bubble on the other hand is a relatively stable phenomenon for the given test case. Once algorithms are available to calculate the separation bubble, the calculated data and the test data can be compared for flow cases similar to the one shown above.

TIME DEPENDENT PERIODICITY AND REPETITIVITY

It is obvious that the steady state periodicity and repetitivity of the pressures on the blade surfaces will also affect the time dependent periodicity and repetitivity of the unsteady pressures on the blade surfaces. The vibration amplitude and the phase relation between the blades are regulated by a control system in controlled vibrating cascade experiments. The actual blade vibration amplitudes and phases fluctuate around pre-set values because of flow perturbations. This is especially true at off-design flow conditions. These fluctuations affect the exactness of the evaluation of the unsteady pressure measurements. Uncertainties are expected from the fact that the unsteady pressures are fairly small and the signals have a high noise level. This results in unsteady pressure data that are only "most probable values" within certain confidence intervals. In general, smaller unsteady Cp-values have higher relative confidence intervals because of the lower signal-to-noise ratio. The method how these confidence intervals are obtained is described in detail by D. Schläfli (1989). It is necessary to show the extent of the possible errors of the measurements especially when comparing test data with numerical data. In the following graphs the average confidence intervals for a 95% probability are given for each chord-wise transducer position.

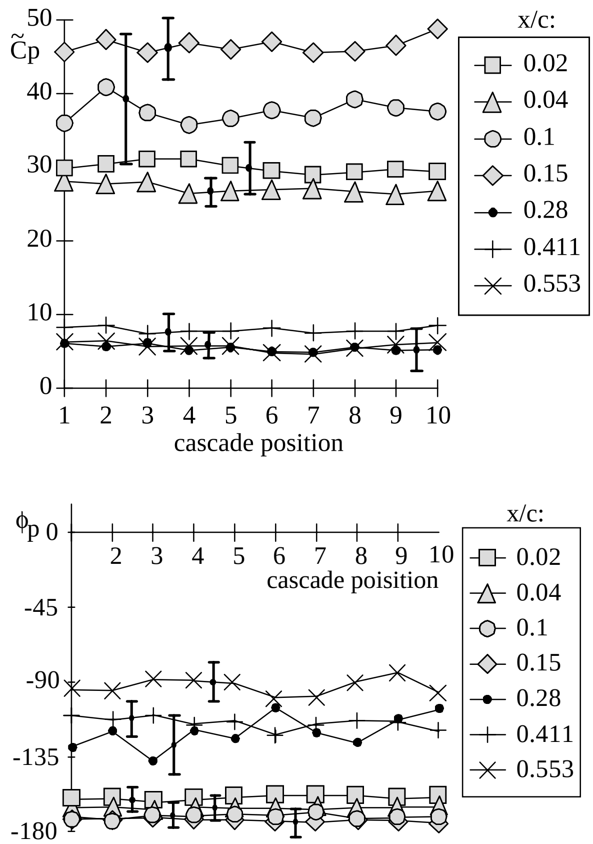


Fig.9: Periodicity on the suction surface near leading edge on different blades (M_{2S}=1.19; β_1=33°, σ=180°)

Figure 9 shows that transducers from the leading edge until up to 60-70% chord length on the suction-side surface show a very good periodicity. The spread of the unsteady pressure amplitudes and the unsteady phase angles in circumferential direction are within the confidence intervals. The consistency of the unsteady pressures along the chord length is good when measurements of different blades are mixed. There are no abrupt changes in amplitude or phase angle when data for neighboring-chord wise positions of transducers on different blades are compared.

The periodicity on the pressure side can be considered as good as the spread of the unsteady pressure data in circumferential direction is within the confidence intervals (Fig.10).

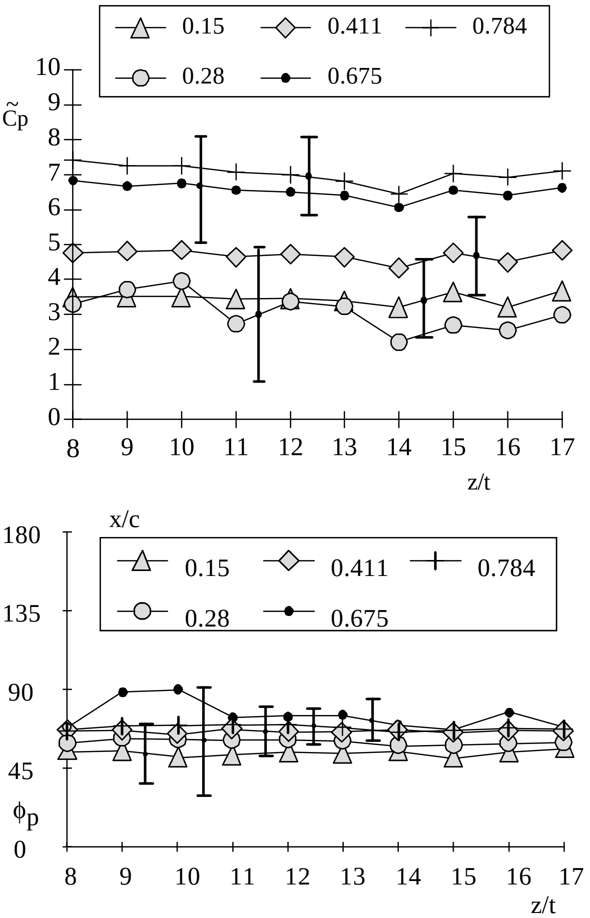


Fig.10: Periodicity on the pressure surface on blade 3 (M_{2S}=1.19; β_1=33°, σ=180°)

The situation is totally different for the blade region downstream of about 60% chord length on the suction side where a shock impinges onto the blade. Here, it can be seen that for a transducer on the blade number 4 at x/c=0.675 the periodicity of the unsteady pressure amplitude is worse than that for one at x/c=0.553, which is quite good (Fig.11). For the position x/c=0.784 on this blade a periodicity is hard to see. Here, unsteady pressure amplitudes vary from as low as Cp~5 to as high as Cp~35. The variation of the amplitudes in circumferential direction at x/c=0.675 and x/c=0.784 is much higher than the confidence intervals. Thus, it must be assumed that the differences are due to the different circumferential positions of the cascade. The periodicity of the unsteady pressure phases on the other hand is good.

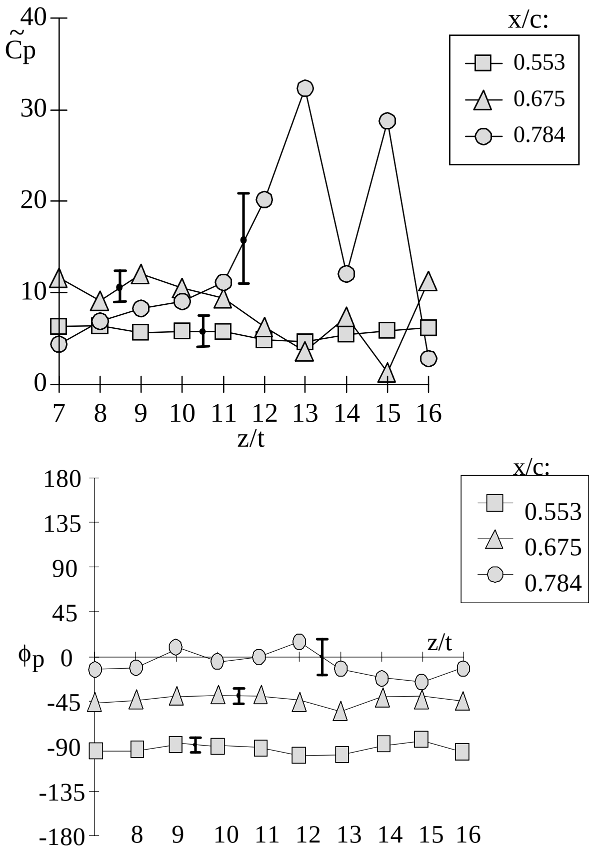


Fig.11: Periodicity on the suction surface near a shock on blade 4 (M_{2S}=1.19; β_1=33°, σ=180°)

On another blade (number 2) the transducers are situated further downstream. It can be clearly seen that the highest non-periodicity is found for the transducer position at x/c=0.821 which shows the highest unsteady pressure level (Fig.12). On this blade, the shock is believed to be situated near this transducer position. Further downstream, the unsteady pressures decrease and the periodicity improves (x/c=0.918). This shows that the non-periodicities are caused by the shock who changes its position as the cascade is rotated. With this change of position the unsteady pressures in this region also change. Yet, measurements in the same circumferential position on the same blades show good repetitivity. This was shown by A.Bölcs, T.H. Fransson and H. Körbächer (1991).

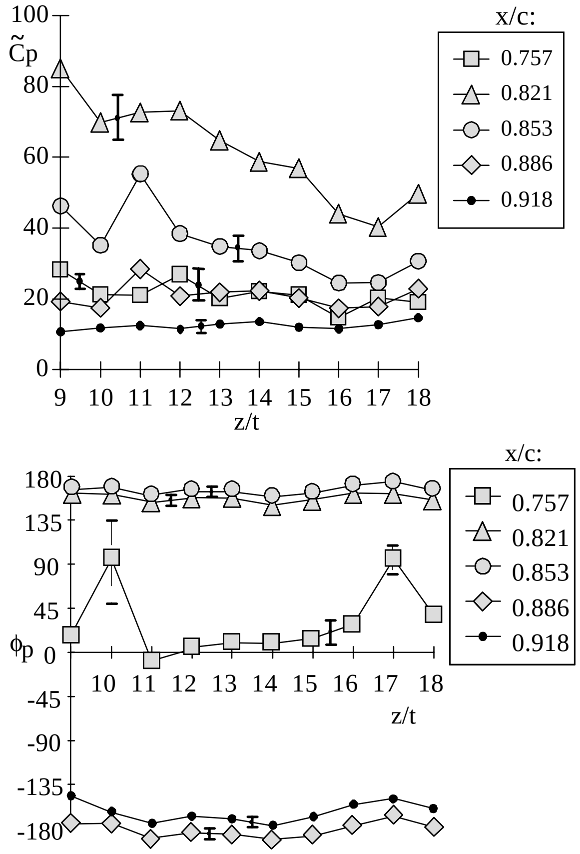


Fig.12: Periodicity on the suction surface near a shock on blade 2 (M_{2S}=1.19; β_1=33°, σ=180°)

An interesting fact is that the periodicity of the unsteady pressure amplitudes and the unsteady phase angles do not behave necessarily in the same way. At x/c=0.821, the unsteady pressure amplitude has a poor periodicity but the phase angle periodicity is excellent. At x/c=0.757, the phase angle periodicity is poor but the pressure amplitude periodicity is good. This could mean that the highest gradient in chord-wise direction of the unsteady pressure amplitude and the highest phase angle gradient are not exactly at the same chord-wise position near the shock.

From the evaluation of measurements it can be concluded that in the region of an expected shock time-dependent data from different blades should not be mixed when comparing the unsteady behavior of blades. Only measurements that were taken in the same circumferential channel position on the same blade can be compared.

The conclusion for the comparison of calculated unsteady data with measured unsteady data is that it is more important to obtain a shock with the proper strength in the numerical codes than to get the exact shock position. The chord wise position of the shock may vary from blade to blade in experimental cases. A more detailed experimental examination of the shock region is necessary to understand the effects of the shock on the unsteady pressures. On the other hand, the separation bubble shows a periodic and repetitive behavior for the steady and for the unsteady test data.

APPLICATION OF THE INFLUENCE CO-EFFICIENT TECHNIQUE

A problem concerning the application of the influence coefficient technique was encountered during the evaluation of the experimental data of the presented cascade and shall also be shown in this paper. The authors believe that it is of general interests since it addresses possible problems that may appear when comparing experimentally and numerically obtained influence coefficient data.

Once the results in the traveling wave mode have been obtained, a data reduction into influence coefficients is done (Fransson, 1990; Széchènyi and Girault, 1983; Hanamura et al., 1980). The influence coefficients are calculated for a range of interblade phase angles (i.e. 20 measurement in steps of 18°). If unsteady data are measured at more interblade phase angles than blades are considered for an influence coefficient decomposition, then the influence coefficients are calculated for the best possible fit (with the method of the least squared errors). Thus, the reconstruction of the unsteady data with the influence coefficients is an interpolation of the measured data over the interblade phase angle range. Another advantage of using the reconstructed data is that unsteady data can be compared at interblade phase angles (i.e. with calculated values) that were not measured.

Explanations of the influence coefficient technique can be found in literature (i.e. D. Schläfli; A. Bölcs & T. H. Fransson; E. Szecheny etc.).

When tests at interblade phase angles around 0° (0°,-18°,+18°) were included for calculating the influence coefficients for the presented cascade, the reconstruction of the unsteady pressures using the influence coefficients of only 7 blades did not fit very well with the original unsteady data (Fig.13). It was believed that 7 blades (the reference blade and three neighboring blades in each direction) are enough for the decomposition into influence coefficients. The common assumption was made that the influences of blades further away can be neglected. Here, obviously this cannot be done. Higher order elements, that means blades further away, have to be included to get a good fit.

When the tests with interblade phase angles around 0° were not considered when calculating the influence coefficients, the fit even with only 7 blades considered was very good except around 0° (Fig.13). The example in Fig.13 is representative for all chord wise transducer positions in the sense that always a better agreement could be found when leaving out tests around 0°. This was also found for the phase angles of the unsteady pressures.

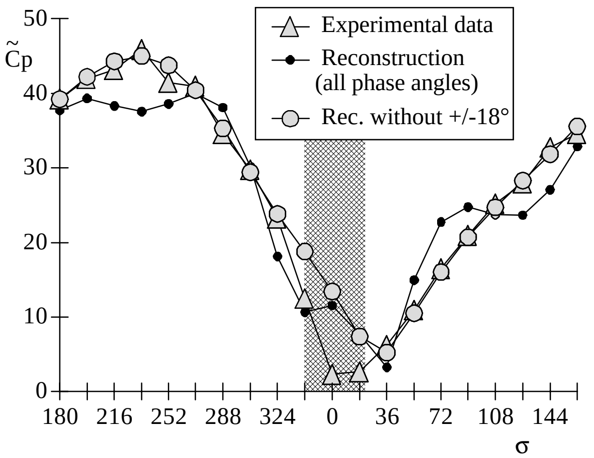


Fig.13: Example of the reconstruction of unsteady pressure amplitudes at different interblade phase angles
(M_{2S}=0.93; β_1=33°; x/c=0.15)

The reasons why the reconstruction of the data from the influence coefficients are erroneous when including interblade phase angles around 0° for the given cascade can not be discussed in this paper. Sufficient data is not available at the present time. The unsteady data around 0° interblade phase angle are difficult to obtain as the excitation of the blades seems to be very strong at that interblade phase angle. It could not be found if the excitation was caused by the flow or by mechanical vibrations. The excitation control system had difficulties to keep a pre-set amplitude and phase relation of the blades. Yet, the minimum aerodynamical damping for the cascade is at 306° interblade phase angle (Bölcs, A.; Fransson, T. H.; Körbächer, H.; 1991). At this interblade phase angle the vibration mode was kept without difficulties. Acoustical resonances could be another explanation. They should appear at -1.1° and 0.6° interblade phase angle in the upstream region and at -8.7° and 0.5° interblade phase angle in the downstream region. Further tests have to be performed to give an answer to this problem.
With this example it shall be shown that it is important to verify that the experimental influence coefficients really reconstruct the measured unsteady data. For a comparison of calculated and measured influence coefficients the number of blades and the interblade phase angles upon which the decomposition is based should be preferably the same.

SUMMARY

Tests have been made to examine the steady as well as the unsteady repetitivity and periodicity of measurements at off design flow conditions with a turbine cascade in an annular channel.
The shock position seems to be very sensitive to changes in flow conditions. This influences the circumferential periodicity but does not affect the repetitivity under the same outlet flow conditions. Comparisons off calculated results with test data in the shock region may be ambiguous.
The behavior of the separation bubble is stable. Good repetitivity as well as circumferential periodicity was found. Thus, the variation of the shock position is probably not caused by variations of the inlet flow. For the separation bubble region it should be possible to calibrate numerical codes with test data.
The influence coefficient technique can be applied except for phase angles around 0° interblade phase angle for the presented cascade.
The obtained results are specific to the presented cascade. However, the authors believe that the statements about the sensitivity of the shock region and the stability of the separation bubble region are generally valid for similar cascades and flow conditions.

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