6. CONCLUSIONS

Nowadays, it is possible to make cascade tests at transonic Mach number range using optical methods. Till now, the accuracy of transonic inlet flow angle measurements was about $\pm 2^{o}$ or much worse. With the L2F system, we used, one can resolve 0.2^{o}, that means an accuracy of about $\pm 0.1^{o}$ (low turbulence level in the inflow).

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Unsteady flow measurements in straight cascades

by

C. H. Sieverding

1. INTRODUCTION

The cascade tunnel as experimental check for theoretical blade calculation schemes on one side and blade performance data producing instrument on the other side plays still an important role in the turbomachinery world. Contrary to the flow in rotating machinery, the cascade flow is looked at as being basically 2-dimensional and steady. However, contrary to the "two-dimensionality" which has often been the subject of long discussions, the "steadiness" of the flow has hardly been put into question until recently. Nowadays, however, it is recognised that two basically different kinds of instable flow phenomena occur in cascade tunnels: the first one is linked to the cascade tunnel itself, the second one to the blade wake flow.

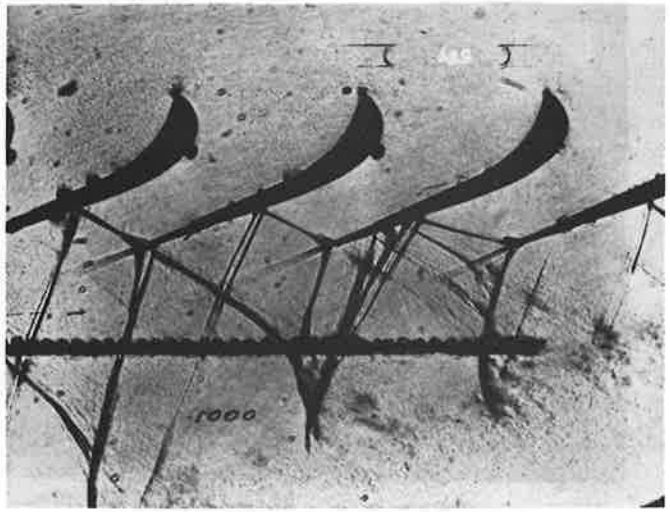
2. UNSTEADY FLOW PHENOMENA IN CASCADE TUNNELS

Everybody who has had the occasion to watch the transonic or supersonic outlet flow behind a turbine cascade with a continuous schlieren optical system, has probably noticed that the shocks appear rarely as sharp defined density gradients but look in general rather blurred indicating a light oscillating motion of the shock system. High speed movies taken at VKI and the AVA-Göttingen have shown that these instabilities can be much more dramatic as one might expect from simple schlieren observation. The shock oscillations are in fact associated with drastic changes of the wake flow direction. The flow variations reach their maximum in the transonic range.

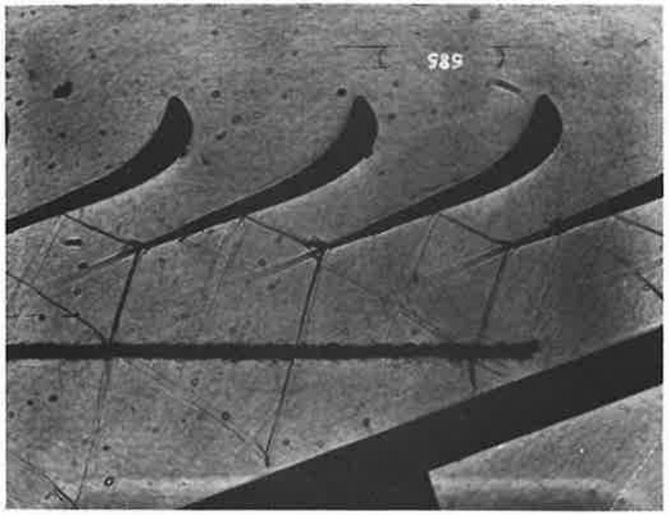
The reason for the above described instabilities can be found by comparing the two schlieren pictures in Fig. 1 which shows the supersonic flow field of a transonic turbine cascade. Both photographs are taken at approximately the same outlet flow Mach number (averaged over the central pitches). The difference lies in the test section geometry at the cascade extremities downstream of the trailing edge plane. In the upper photograph the cascade extremity is characterized by a sudden area enlargment in pitchwise direction while in the lower photograph a tailboard is attached to the end blades. Obviously the highly turbulent free shear layer behind the sudden area expansion is a considerable source of instability. The use of tailboards eliminates the free shear layer and consequently the outlet flow is much more stable. Unfortunately, the experience has shown that the use of tailboards is only advisable in cases where the outlet angle is a strong function of the outlet Mach number i.e. for the most transonic turbine cascades at medium and high supersonic outlet Mach numbers.

Fig. 2 shows two examples for the second type of unsteady flow in cascade: (a) convergent turbine blade cascade and (b) a model simulating the overhang section of a convergent cascade. The photographs indicate in both cases the existence of a vortex street behind the blade trailing edge which is due to the alternative rolling up of the suction side and pressure side blade boundary layer into vortices. The trailing edge shock system oscillates at the same frequency at which these vortices are shed off the trailing edge. Contrary to the first described flow instability the present one is a blade characteristic and is independent of the environment in which the blade is tested i.e. in straight or annular cascade tunnels or in rotating machinery.

Lawaczeck and Heinemann (Ref. 1 and 2) used several optical methods for the determination of the vortex shedding frequency. The unsteady flow measurements at VKI were made using fast response pressure transducers.

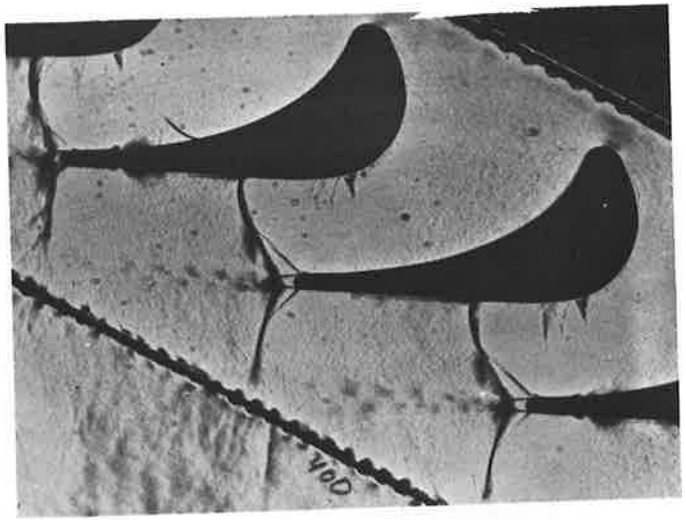


SUDDEN AREA ENLARGMENT

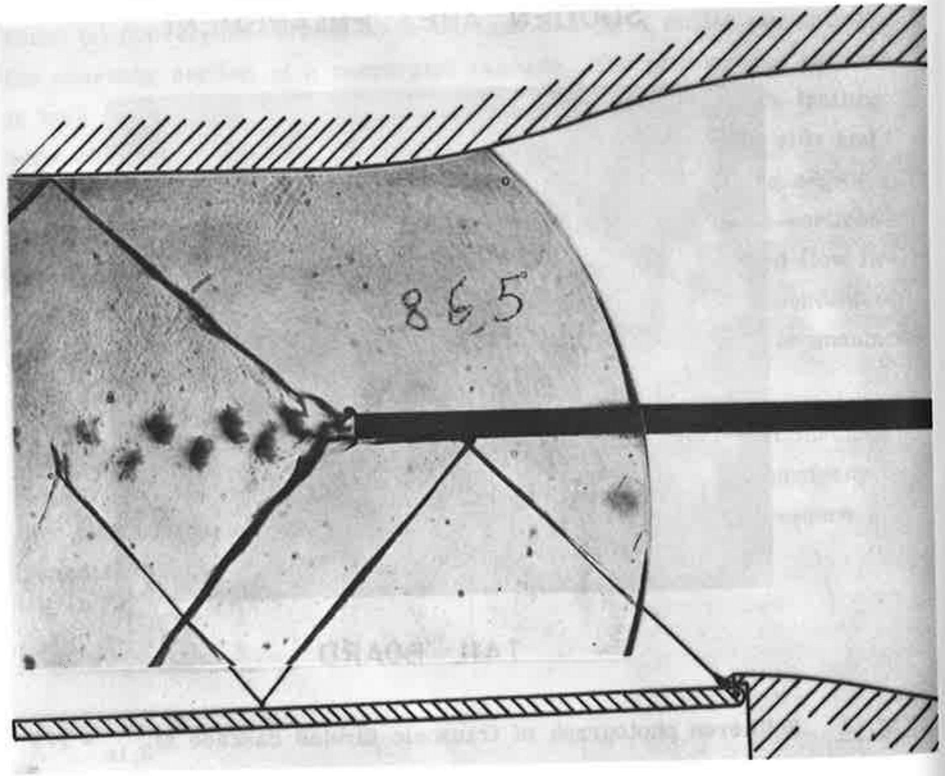


TAIL BOARD

Fig. 1 Schlieren photograph of transonic turbine cascade $M_{2,is} \simeq 1.3$



a) CONVERGENT TURBINE CASCADE



b) MODEL SIMULATING OVERHANG SECTION OF CONVERGENT TURBINE CASCADE

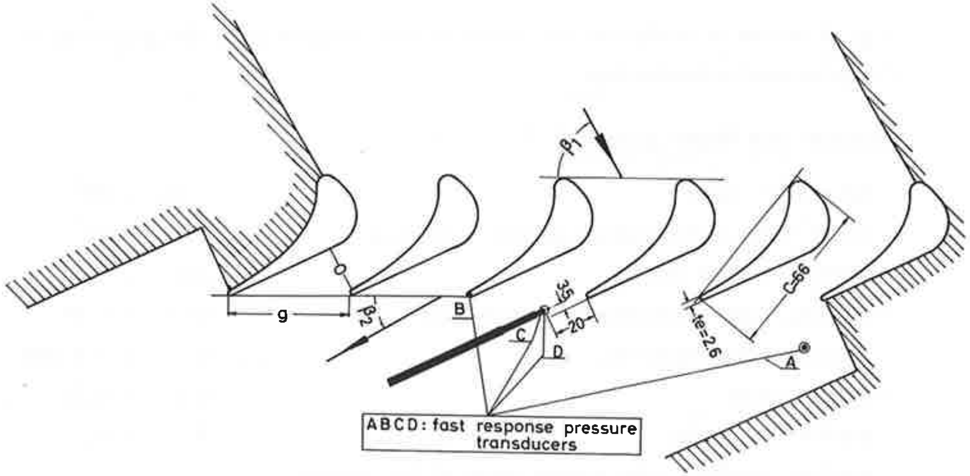


Fig. 3 Sketch of cascade with pressure transducers

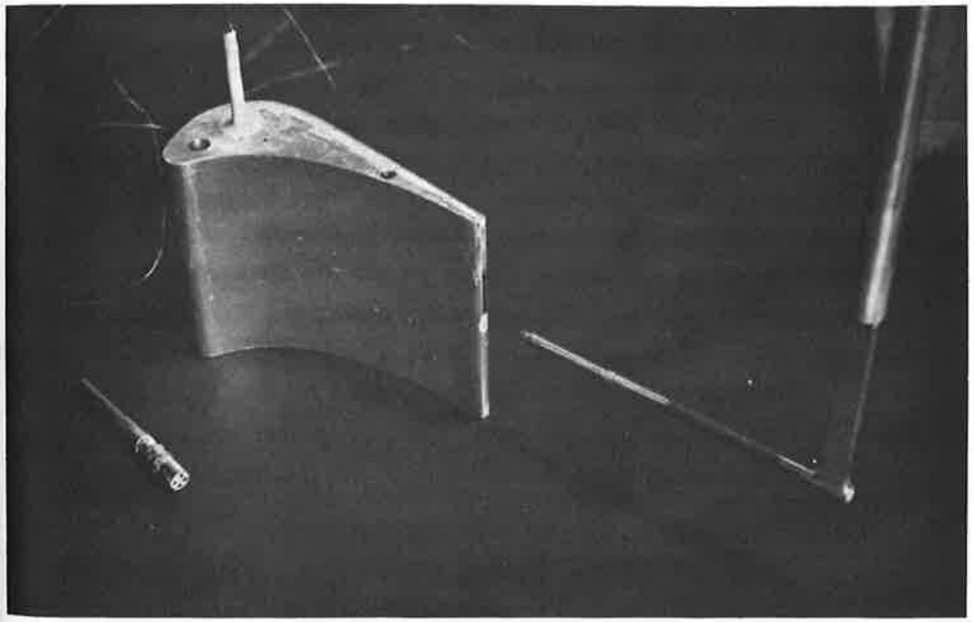


Fig. 4 Photograph of blade and probe with pressure transducers

3. CASCADE AND INSTRUMENTATION

Fig. 3 shows a sketch of the cascade test section with the positions of the pressure transducers.

Cascade and blade geometry

- inlet flow angle	$\beta_1 = 60^o$
- outlet flow angle (based on arc s in o/g)	$\beta_2 = 25^o$
- pitch to chord ratio	$g/c = 0.75$
- trailing edge thickness to chord ratio	$te/c = 0.04$
- trailing edge thickness	$te = 2.6$ mm
- aspect ratio	$h/c = 0.75$
- number of blades	$N = 6$
- straight suction side downstream of the throat	

Pressure transducers

Four Kulite fast response pressure transducers were used for these tests. Their position is indicated in Fig. 3.

Transducer A: on the side wall behind the area enlargment
B: in the trailing edge of a blade
C: in the head of a pitot probe at blade mid-span
D: on the side wall opposite to the probe.

All transducers are flash mounted. Their tip diameter is 2 mm. Fig. 4 shows a photograph with the Kulite probe and the blade instrumented at the trailing edge with a Kulite pressure transducer. The transducers are connected either to an oscilloscope or to a frequency analyser. The range of the available frequency analyser was limited to 20 KHz. The outlet Mach number was derived from wall static pressures measured by a multimanometer at an axial distance behind the trailing edge plane equal to 1/2 chord length.

Flow conditions

- outlet Mach number range	$0.3 \leq M_2 \leq 0.95$
- Reynolds number, based on outlet velocity and chord length (nearly linear increase with M_2)	$0.5 \times 10^6 \leq RE \leq 1.5 \times 10^6$
- turbulence level	$Tu < 1\%$

4. TEST RESULTS

Cascade tunnel unsteadiness

The flow unsteadiness was measured simultaneously with the transducers A and B (Fig. 3) i.e. in the free shear layer and the blade trailing edge. A typical oscilloscope trace is shown in Fig. 5 which is taken at a mean outlet Mach number $M_{2,is} = 0.92$. The similarity between the traces of both transducers allows the conclusion that a direct coupling effect exists between the flow unsteadiness in the free shear layer and the cascade flow. It is a low frequency phenomenon which in the present case is of the order of 400 Hz.

Blade wake unsteadiness

A frequency analyser was used for the measurement of the shedding frequency of the trailing edge vortices. The transducers B, C and D were used for this part of the tests. Fig. 6 shows a typical trace obtained with the pitot probe at an isentropic outlet Mach number $M_{2,is} = 0.5$. The curve indicates a clear peak at about 14 KHz (selected band width 3%).

The variation of the vortex shedding frequency in function of the outlet velocity is presented in Fig. 7. Due to the limited range of the frequency analyser tests could be carried out only in the Mach number range $M_2 \approx 1.0$. The frequency increases almost linear with M_2, from 12 KHz at $M_{2,is} = 0.3$ to 20.5 KHz at $M_{2,is} = 0.92$.

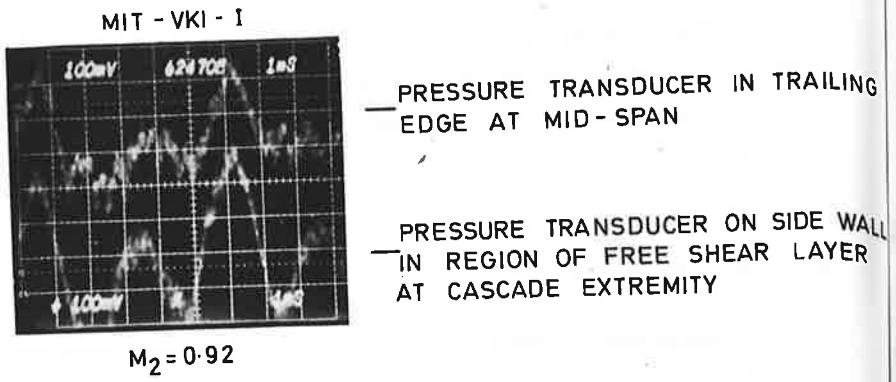


Fig. 5 Oscilloscope traces of flow unsteadiness in the free shear layer and at the blade trailing edge

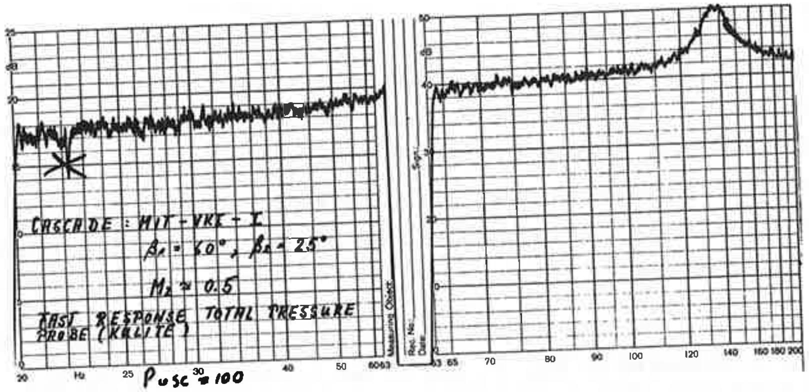


Fig. 6 Typical frequency analyser trace of trailing edge vortex measured with total pressure probe

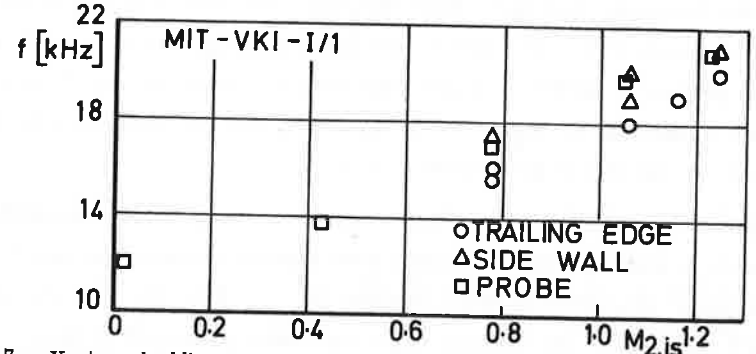


Fig. 7 Vortex shedding frequency versus isentropic downstream Mach number

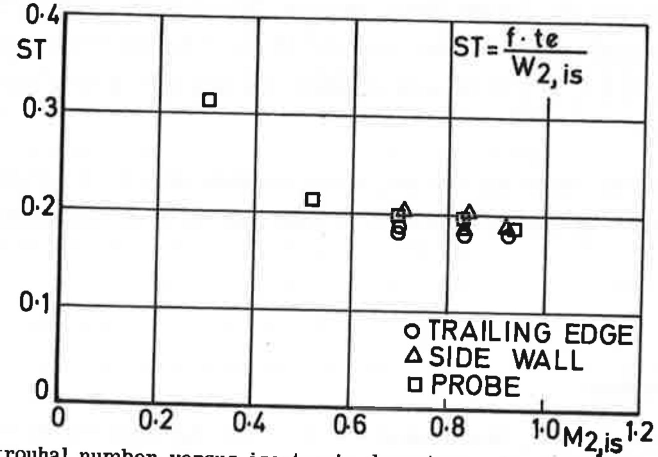


Fig. 8a Strouhal number versus isentropic downstream Mach number

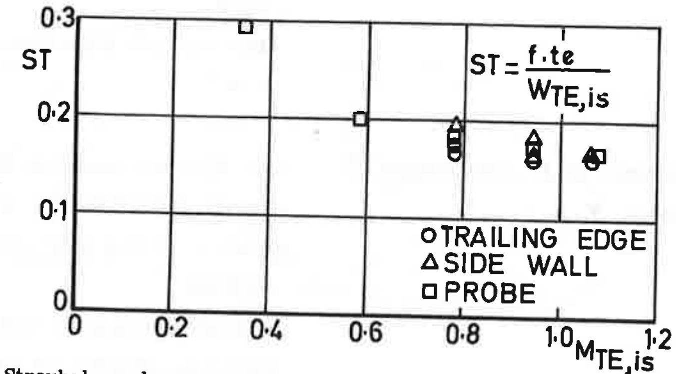


Fig. 8b Strouhal number versus isentropic Mach number before separation at trailing edge

In the transonic and high subsonic range the vortex shedding affects almost equally the static pressures (trailing edge and side wall) and the total pressure (probe at mid-blade height). However, in the low subsonic range, up to $M_{2,is} \approx 0.5$, the tests did not indicate any measurable effect on the static pressures.

Figures 8a and 8b present the Strouhal numbers (vortex shedding frequency x trailing edge thickness/free stream velocity) in function of the isentropic downstream Mach number $M_{2,is}$, Fig. 8a, and the isentropic Mach number at the trailing edge just before separation $M_{TE,is}$ (mean value between suction side and pressure side Mach numbers), Fig. 8b. Except for the lowest Mach number ($M \approx 0.3$) for which the total pressure probe indicates a Stouhal number of $S \approx 0.3$, all other values lie in the range $0.2 \leq S \leq 0.15$ with a slight decrease in S with increasing Mach number.

So far the tests did not yet allow to draw definite conclusions as to the pressure variations involved in this type of flow unsteadiness.

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A new technique for controlling the exit flow periodicity of supersonic cascades

by
H. Starken

Upstream and downstream flow periodicity are two of the important conditions to be observed in all cascade test. This periodicity condition is directly connected to the boundaries of the cascade in the circumferential direction. Considerable efforts have been directed in the last years to this problem especially in the transonic and supersonic flow region, because only the solution of this problem justifies the application of the simple two dimensional cascade model. If such a solution is not found, only the annular and rotating cascades could be used.

The inlet flow problems have been solved in the past, but we had still difficulties in the exit flow region. As has been shown by LICHTFUSS [1], neither solid walls (Fig. 1) nor free jet boundaries (Fig. 2) do give periodic exit flow at supersonic velocities having an axial subsonic component.

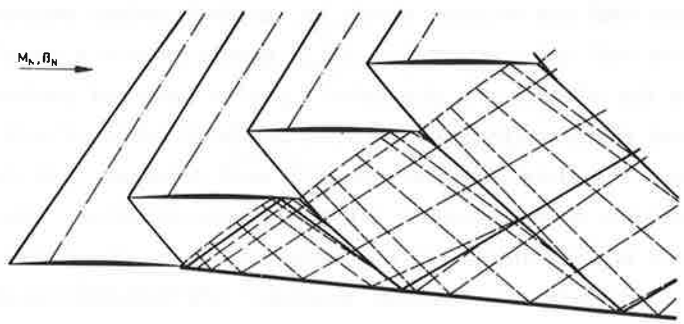

Fig. 1 Solid wall boundary (Ref. [1])