UNSTEADY FLOW MEASUREMENTS BY MEANS OF SCHLIEREN-OPTICAL TECHNIQUES IN A TRANSONIC TEST FACILITY WITH OSCILLATING BLADES

by

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Summary:

The present contribution describes the design and performance of a test facility, which has been built in order to investigate transonic flow phenomena like unsteady shock boundary layer interaction and oscillation of shock waves at single blades and in linear cascades. The central blade can either be mounted elastically or mechanically driven to pitching vibration.

Furthermore, various schlieren visualization techniques for the analysis of generally unsteady flows and unsteady periodic flows are described in principle and illustrated by typical results. The flow visualization is supplemented by the laser-density gradient-technique, which simultaneously measures the density gradient fluctuations in two perpendicular directions.

1. Introduction

At transonic speeds in axial-flow turbomachines, oscillations of shock waves and unsteady viscous flow effects are likely to occur. These flow oscillations might cause flutter and failures of the blades due to aeroelastic effects. Theoretical models to predict this type of transonic blade flutter are sparse and ought to be improved in the future /1/. In order to support this development, various driven cascade experiments /2,3,4/ have been initiated, which mainly deal with measurement of the airfoil dynamic surface pressures and subsequent calculation of the cascade stability parameter, supplemented to some extend by flow visualization to examine the shock wave dynamics. However, little information is available so far on the associated unsteady boundary layer flow. Therefore, the purpose of our experimental study is to investigate the interaction of shock waves and boundary layers at freely or forced vibrating blades.

In this paper, a complete description of the test facility and the measurement techniques is given. The design and performance of the windtunnel with test sections for single blade and linear cascade experiments and of the mechanical blade drive mechanism is presented. Finally, the application of various schlieren-optical measurement techniques to the analysis of shock and boundary layer fluctuations is discussed and illustrated by typical results.

2. Description of the test facility

2.1 Windtunnel

The experimental investigations of shock and boundary layer oscillations are carried out in a transonic windtunnel, which is continuously supplied with air by a compressor and works in an open or partly closed loop. The maximum mass flow is 5,5 kg/s with a total inlet pressure of 3,5 bar and a total inlet temperature of around 305 - 315 K. Two interchangeable test sections are available for single blade and linear cascade measurements (Fig. 1).

The single blade test section (Fig. 1a) is 80 mm wide and 100 mm high. Mach- and Reynolds number can be varied independently of each other. The test Mach number is regulated by choking the flow downstream of the test section in a variable sonic throat. A variation of Reynolds number in the range of $0{,}6 \times 10^6 < Re_c < 2{,}1 \times 10^6$ based on blade chord c = 50 mm is achieved by changing the pressure level in the tunnel. The upper and lower endwalls of the tunnel are perforated with 60^o inclined holes of diameter 1 mm. The open area ratio amounts to 6%. The walls are hinged at their leading edges to allow for wall divergence up to 1^o. Additionally, the boundary layers at the upper and lower wall can be controlled by bleeding using movable diffuser flaps located at the trailing edges of the perforated walls. Thus wall interference and blockage effects are reduced. The performance of the windtunnel was checked by measuring the axial Mach number distribution without model installed. The results shown in Fig. 2 for a wall divergence of 0 min revealed a nearly constant Mach number distribution at Mach numbers up to M = 0,95. Higher Mach numbers up to M = 1,10 can be obtained by a divergent setting of the walls.

For measurements in cascades with small deflection angles another test section (80 x 100 mm) was built. Fig. 1b shows the cascade tunnel with a steam turbine rotor tip section cascade /5/ installed. The inlet flow periodicity can be adjusted by means of a boundary layer bleed system using slotted walls with 20% open area. The outlet flow is controlled by tailboards which are hinged at the trailing edges of the upper and lower end blade. Tailboards were chosen in order to avoid the periodic disturbance of the cascade flow caused by an instability of the free shear layers as reported from linear cascade experiments /6,7/. The tailboards were designed according to /13/ as slotted walls with an attached chamber (Fig. 1b), which largely reduces shock wave reflections. The cascade consists of three blades forming four blade passages. This fairly low number was chosen in favour of the blade chord length, which should be large to make boundary layer studies easier. However, the flow periodicity obtained in the first measurements was quite satisfactory, see for example Fig. 3.

2.2 Blade oscillation system

Pitching oscillations of the blades are realized by two different ways. In one case the blade is mounted elastically and thus can be forced to oscillate by aerodynamic excitation. Alternatively, the blade can be oscillated in pitching motion by a drive mechanism in order to study the unsteady flow around oscillating blades.

The elastical blade mounting is sketched in Fig. 4. On both sides of the blade rods are fixed. They are fitting through holes in the perspex side walls and are clamped outside the tunnel. The sealing is simply done by a couple of rubber O-rings. The clamping is arranged such that the upper side of the blade is fully accessible to optical flow measurement. The blade vibration is measured by strain gauges which are glued on the torsion rods between the side wall and the clamping. Typical values of the blade eigenfrequency are in the range from f = 400 Hz to f = 800 Hz depending on mass inertia of the blade and elasticity of the torsion rods. This means, that the blade eigenfrequency is of the same order of magnitude as the frequency of self excited shock wave boundary layer oscillations observed with 12% thick double circular arc blades. The amplitudes of pitching oscillation of the blade were fairly small, the maximum value of + 0,08 deg was measured when severe shock wave boundary layer oscillations occured.

Larger pitching oscillations up to ± 1,0^{o} can be obtained using the mechanical blade drive mechanism (Fig. 5). In principle this mechanism is a mass-spring system working in resonance mode. It consists of two identical parts mounted on either side of the tunnel and driving the blade simultaneously. Both trunnions of the blade are supported in special bearings close to the perspex side walls which pick up the lift and drag force of the blade. The driving force of the electromagnetic shakers (Ling Dynamic Systems Vibrator Model 200) acts on arms which are attached to the torsions springs. By altering the diameter and the length of the torsion springs, the resonance frequency of this system can be varied. Again, strain gauges are applied to measure the blade vibration.

One important design criteria of the drive mechanism was not to disturb the single pass schlieren-optical measurement of the flow. In the actual design, the upper side of the oscillating blade is fully accessible to optical techniques.

3. Unsteady schlieren visualization techniques

3.1 Common features

In compressible flows, effects like unsteady boundary layer separation, oscillation of shock waves and vortex shedding are accompanied by time dependent density gradients which can be visualized and measured by schlieren techniques. In the following, three methods are described which differ mainly in the way of recording the time variant schlieren images. A conventional single pass Toepler schlieren technique is applied with a double z-arrangement of the optical components. The light source is a flash lamp (Nanolite KL-L, Fa. Impulsphysik) with a flash duration of 20 nsec. This short exposure time assures that the schlieren images are free of motion blur effects. Especially, turbulent spots in the boundary layer and wake flow become visible and thus the laminar to turbulent transition region or the shedding of vortices in the wake flow /8/ can be detected. This is demonstrated for instance in Fig. 6 showing the transonic flow around a 8% DCA-blade at 2^{o} incidence. While the boundary layer is turbulent well ahead of the shock wave on the upper side (suction side) of the blade, the lower side (pressure side) boundary layer is laminar in front of the shock wave and undergoes transition close to the trailing edge. The picture shown was obtained with a single frame camera synchronized to the lamp control unit via the x-contact of the camera.

3.2 Multi-shot spark exposure

While the single frame (and single spark) exposure gives an instantaneous picture of the flow, the analysis of an unsteady flow field naturally requires a series of frames. This can be accomplished by means of a high speed camera or in the specific case of periodic flows by the delay-time technique as described below. However, sometimes it is desired to obtain more easily an impression of the magnitude of unsteady flow effects. This led to the idea to expose a single frame by a series of sparks from a stroboscopic light source meaning that successive, instantaneous pictures of the flow field are overlayed on one frame. Such multi-shot spark exposures were taken for instance to measure approximately the amplitude of shock wave motion (see Fig. 7). The frequency of the self excited shock wave oscillation was measured in advance by the laser-density gradient-technique /9/, see chapter 3.5. Then the control unit of the lamp was adjusted to provide a series of eight sparks resolving one time period of the oscillating shock, as illustrated in Fig. 7. In the frame shown in Fig. 7 one can clearly distinguish the respective positions of the shock waves. The number of eight sparks was considered in this specific case to be the best compromise between time resolution and image contrast.

3.3 High speed camera

The use of a high speed camera is quite common in unsteady flow visualization. However, in the majority of schlieren-optical applications the high speed camera is used, for the sake of simplicity, in conjunction with a continuous light source /10/ instead of a flash lamp. Unfortunately, for high speed flow visualization the effective exposure time might be too high. For instance, the rotating prism camera (Hitachi Model 16 HM, 16 mm) that we used, provides a maximum framing rate of 10,000 pictures/sec. The corresponding exposure time is 20 µsec, taking a camera shutter constant of 5 into account. At a velocity of 300 m/sec a flow particle moves over the considerable distance of 6 mm during exposure. Therefore, the resolution of turbulence structures in high speed flows requires the use of a flash light source.

In contrast to the continuous light source, the spark lamp has to be synchronized to the high speed camera. With our equipment, this is achieved by means of an optical pick-up installed inside the camera. The trigger pulses of the pick-up are fed successively into an event switch, an amplifier and finally into the control unit of the lamp (Fig. 8). The event switch interrupts the trigger pulses, until the camera is accelerated to the appropriate speed. This is necessary in order to avoid a premature safety shut off of the spark lamp by the control unit. Due to restrictions of the lamp, a few hundred frames of the high speed film can thus be exposed at a framing rate of 10 kHz. A typical high speed film sequence is presented in Fig. 9 showing one period of shock wave boundary layer oscillation at a 12% DCA-blade at zero incidence.

Despite the smaller negative format (= 10% of single frame camera) of the high speed film all desired information on the boundary layer flow (transition, separation) can be deduced. A detailed discussion of results from the film is given in /11/ and therefore is omitted here.

3.4 Analysis of periodic flows

Another schlieren recording technique was developed for the analysis of periodic flows at high frequencies, where the maximum framing rate of the high speed camera would be insufficient.

The method termed "time delay technique" requires a trigger signal, which defines a specific phase of the unsteady flow (see Fig. 10). The trigger signal is fed into a time delay module, which provides an amplified signal shifted in phase against the original trigger. This delayed signal triggers the control unit of the lamp. A second input to the control unit is connected to the shutter-contact (x-contact) of the single frame camera. The control unit is operated such that a single flash triggered by the delayed signal is released immediately after the shutter contact has closed. Thus, every single photograph represents a specific phase of the unsteady flow. The temporal resolution of this method is almost unrestricted, unless deviations from flow periodicity occur. Furthermore, a simple 35 mm camera and standard film material can be used providing high quality frames.

Besides this newly developed technique, a similar method should be mentioned which has been published earlier in this symposium series /8/. Thereby the unsteady, periodic flow is recorded by a TV-camera making use of the "slow motion" effect which is a special feature of the control unit of the stroboscopic light source.

Both schlieren visualization techniques have been successfully applied to the analysis of the rotor-stator interaction in a supersonic compressor stage, where the high speed camera could not be applied efficiently due to the limited framing rate (rotor blade frequency f = 4,2 kHz).

3.5 Laser density gradient technique

The laser-density gradient technique (LDG) has been developed in order to measure simultaneously two components of the density gradient in unsteady compressible flows. As shown in Fig. 11, it consists of a laser light source (low power He-Ne-laser) and a position diode. The output signal of this diode is sensitive to the position of the laser beam and thus the deflections Δx, Δy of the beam by density gradients can be measured. A more detailed description of the LDG-technique has been given in the previous symposium /9/.

In the meantime, the LDG-method has been successfully applied to the measurement of frequency and amplitude of shock wave oscillations /11/ and the determination of vortex shedding frequencies. As a typical result of the latter case, Fig. 12 shows the frequency analysis of the LDG-signal in the wake of a flat plate with a rounded trailing edge. A distinct frequency at about 6 kHz attributable to vortex shedding can be recognized. The corresponding inlet Mach-number is M = 0,125 , a value where usually incompressible flow is assumed. This result clearly demonstrates the high sensitivity of the LDG-technique to density gradient fluctuations.

4. Conclusions

In the first part of the present paper, the design and performance of a transonic test facility is described, which offers the opportunity to investigate the unsteady interaction of shock waves and boundary layers at freely or forced vibrating blades.

The test section for single blade measurements is equipped with perforated walls which largely reduce blockage effects and shock reflections.

The linear cascade test section features boundary layer bleed in front of the cascade and movable tailboards with slotted walls downstream. Although the number of blades installed is low, the flow periodicity is satisfactory. The mechanical blade drive mechanism works in resonance mode and provides a pitching motion of the blade at maximum amplitudes of ± 1,0 deg.

In the second part, schlieren-optical measurement techniques are discussed and illustrated, capable of resolving details of the boundary layer flow at high oscillation frequencies. Framing rates up to 10.000 pictures/sec are provided by a high-speed camera, synchronized with a nanosecond flash lamp. Even higher time resolution can be achieved by the time delay technique for the analysis of periodic flows. The laser-density gradient-technique is well suited for the measurement of very small density gradient fluctuations at high frequencies.

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a)

b)

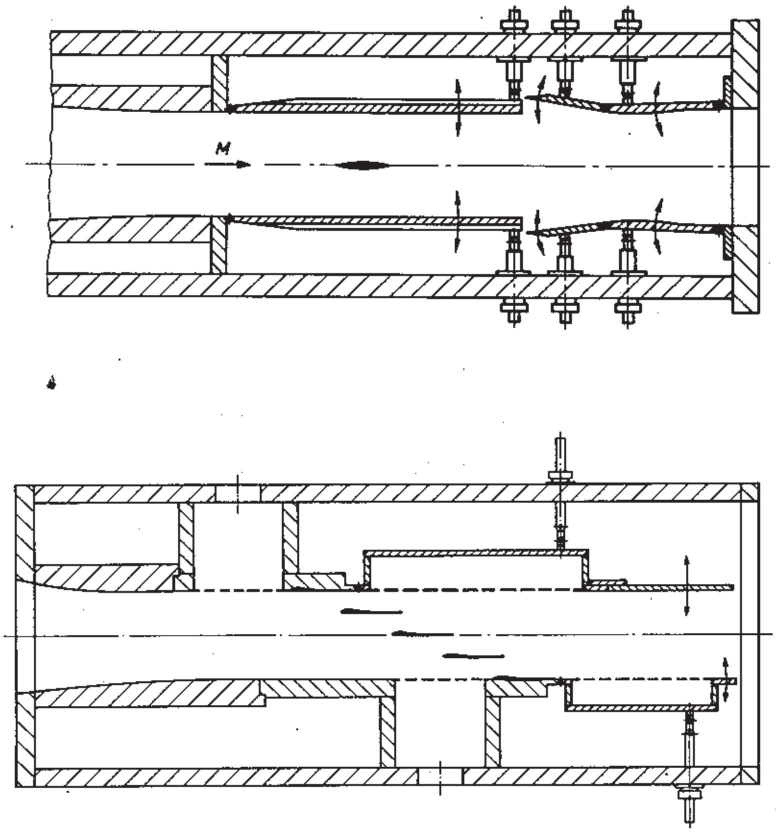

Fig. 1: Test section for single blade (a) and linear cascade (b) measurements

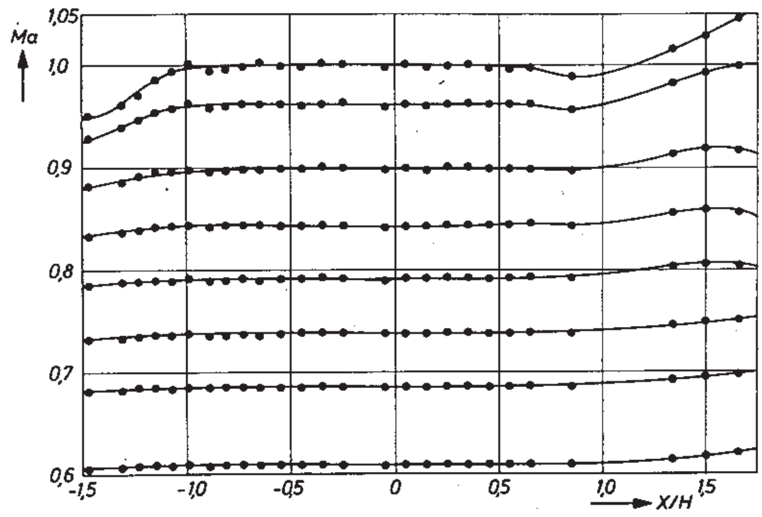

Fig. 2: Axial Mach number distribution in the transonic wind-tunnel without model installed; wall divergence 0 min; tunnel height H = 100 mm

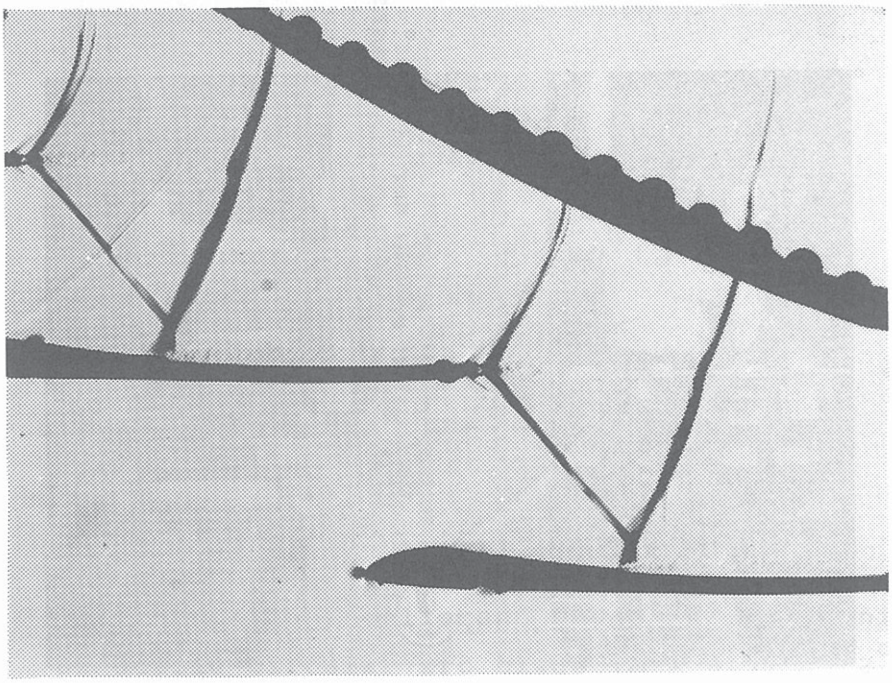

Fig. 3: Steam turbine rotor tip section cascade: stagger angle 24^{o}; pitch to chord ratio 0,9 ; $M_{2\ is}$ = 1,03
Re_c = $1,4 \times 10^6$

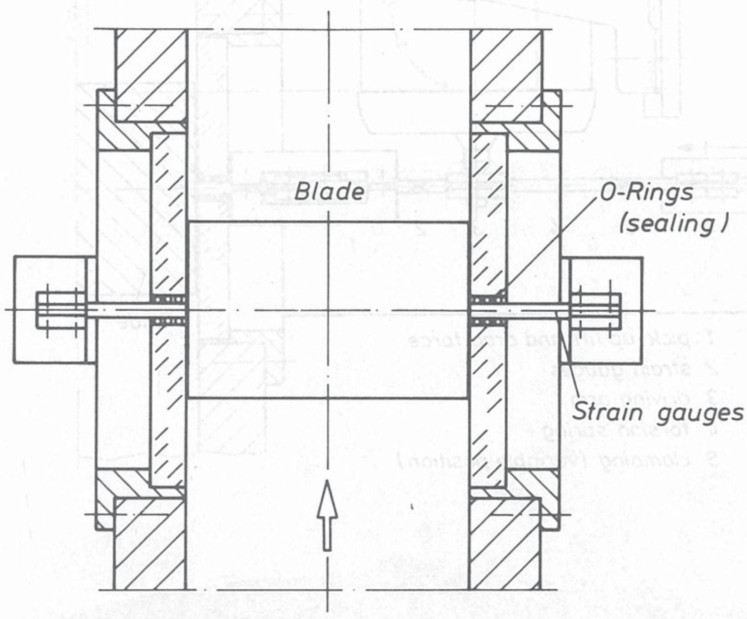

Fig. 4: Elastical blade mounting

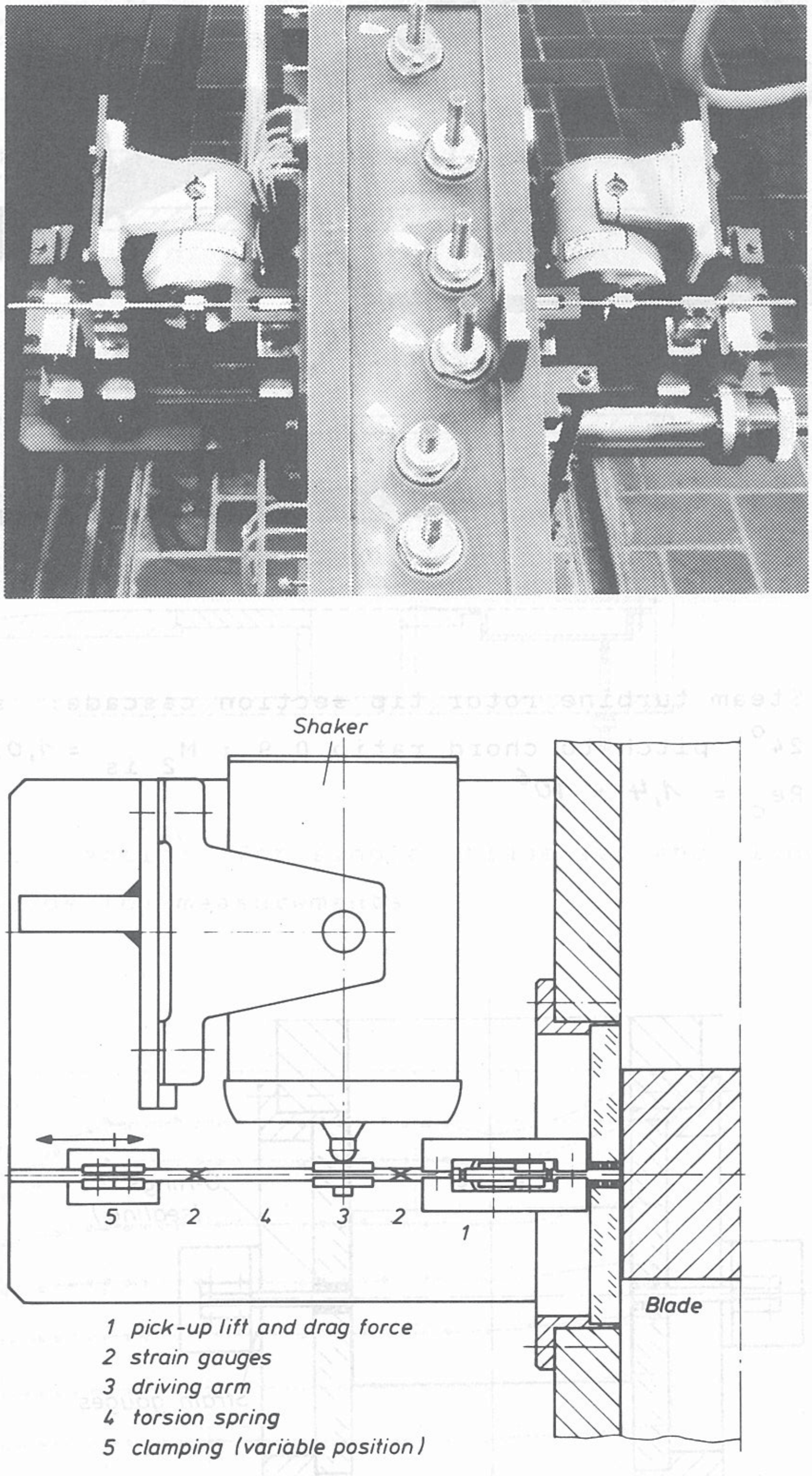

Fig. 5: Mechanical blade drive mechanism

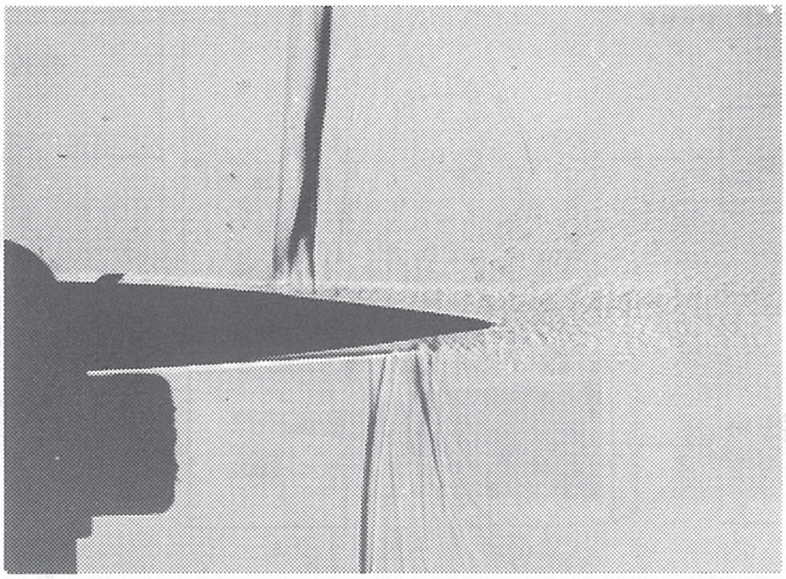

Fig. 6: Instantaneous schlieren image of transonic flow on a 8% double-circular arc blade ($M = 0{,}91$, 2^{o} incidence)

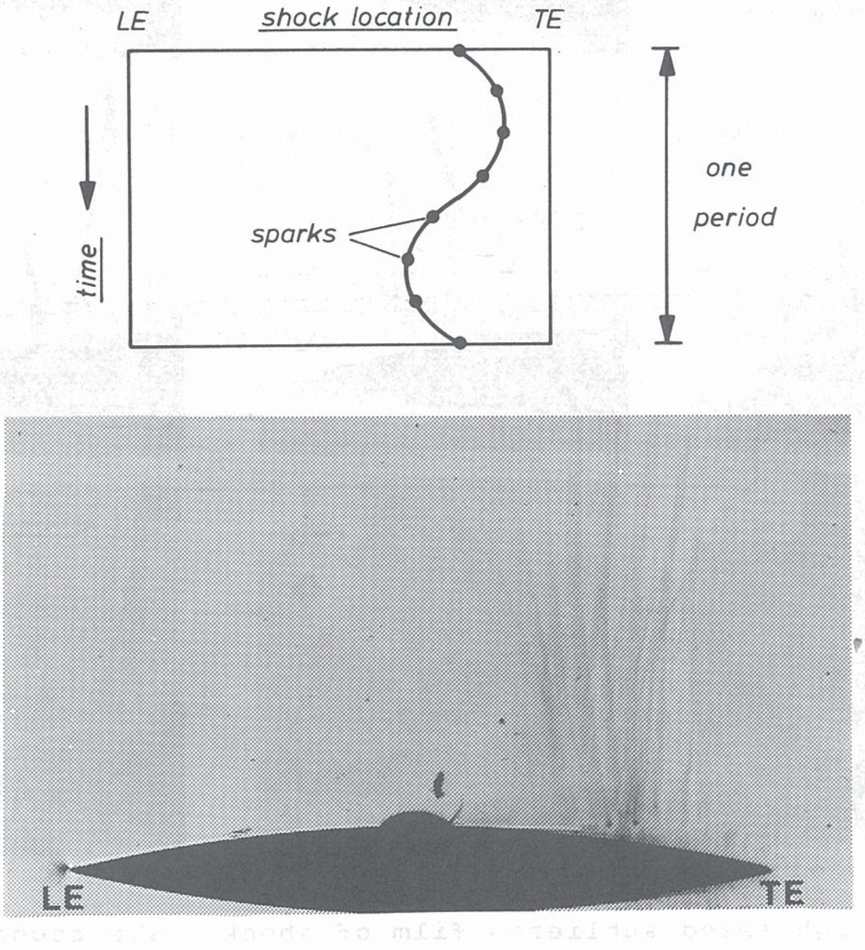

Fig. 7: Visualization of shock wave oscillations by a multishot spark exposure (12% DCA-blade, $M = 0{,}84$, f_{shock} = 940 Hz)

Fig. 8 see next page

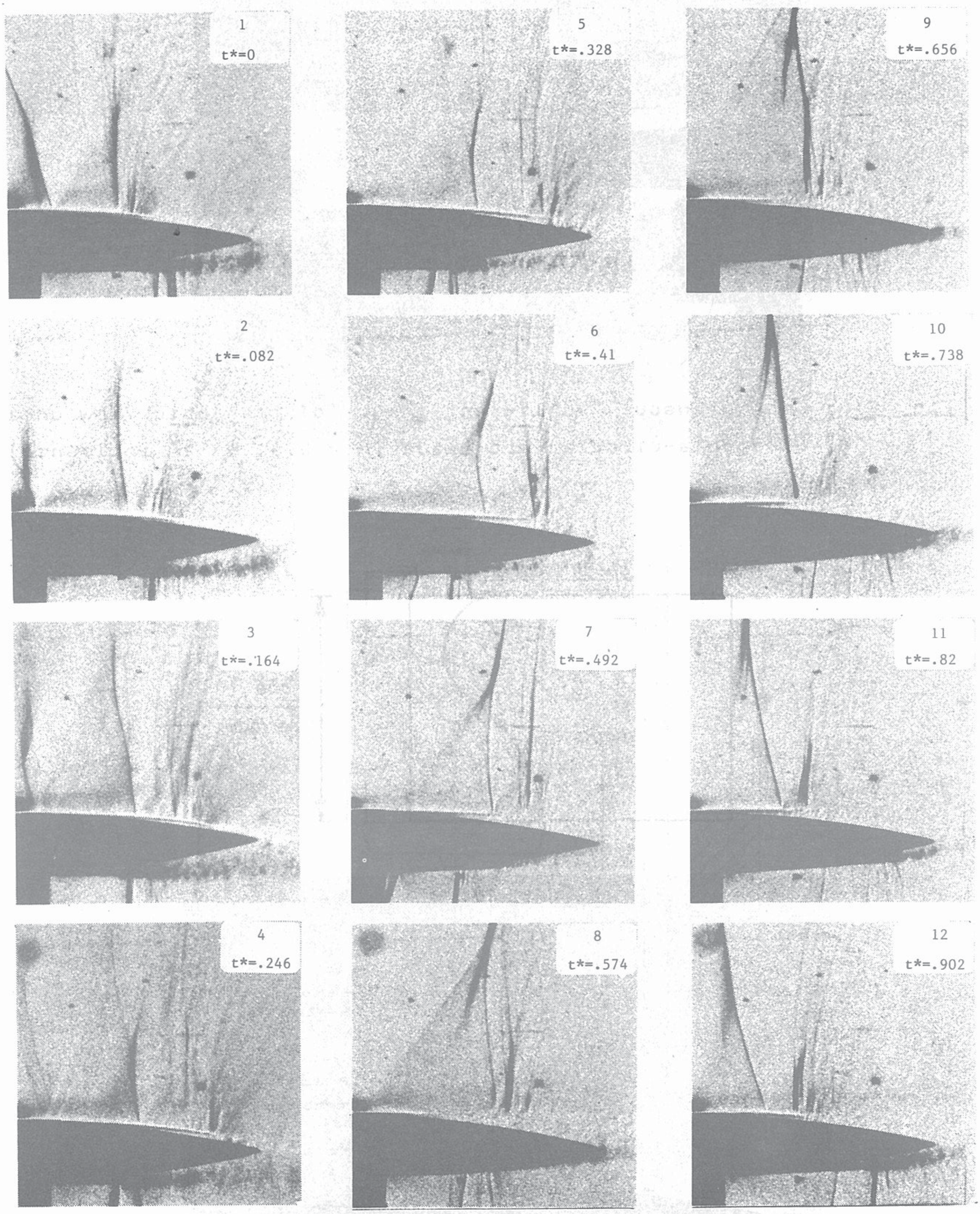

Fig. 9: High speed schlieren film of shock wave boundary layer oscillation (12% DCA-blade, M = 0,82 , Re = 6,4 x 10^5 , f = 780 Hz)

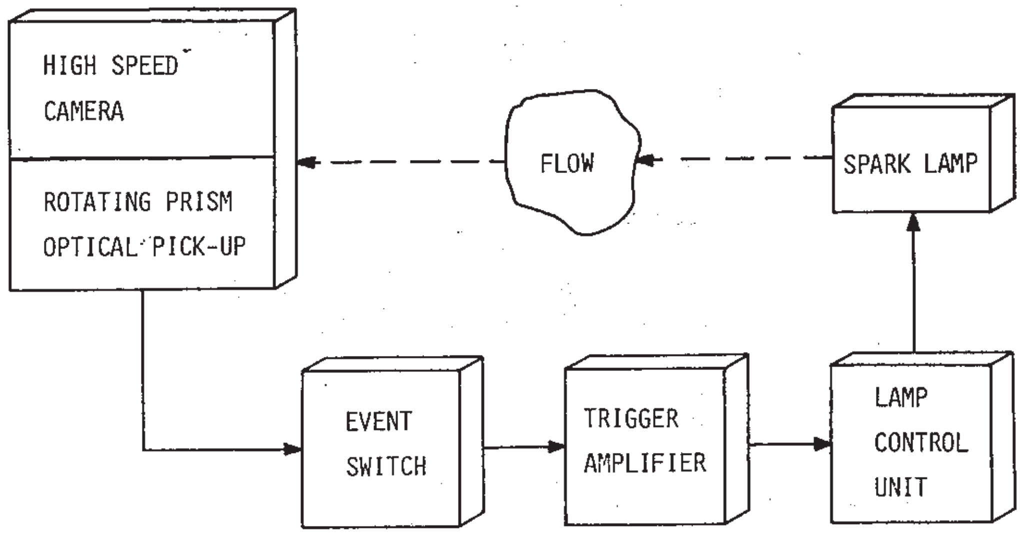

Fig. 8: Synchronization of high speed camera and spark lamp (Nanolite)

Fig. 9 see previous page

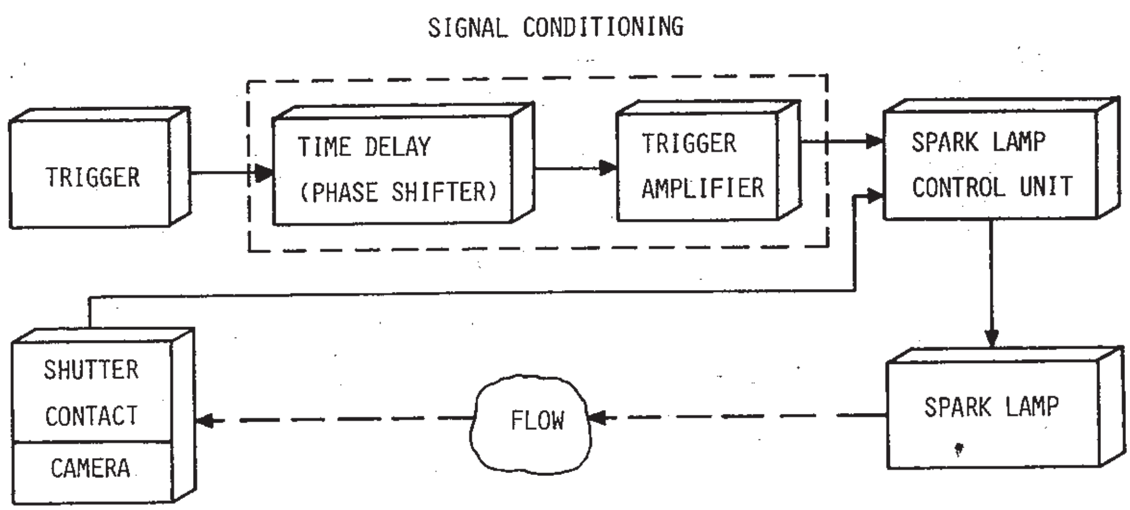

Fig. 10: Analysis of periodic flows: time delay technique

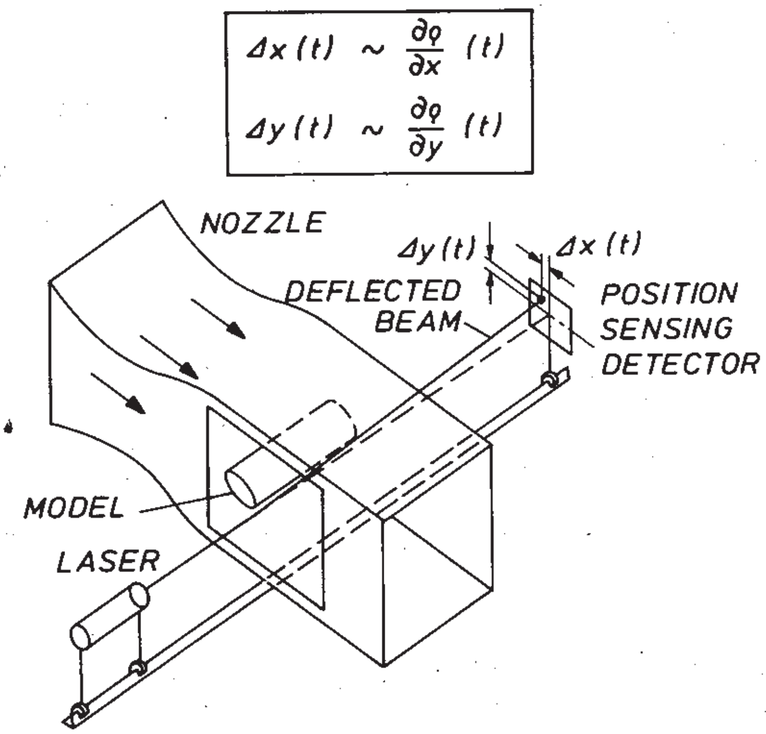

Fig. 11: Schematic view of the laser-density gradient measurement technique (LDG) for two-dimensional flow measurements

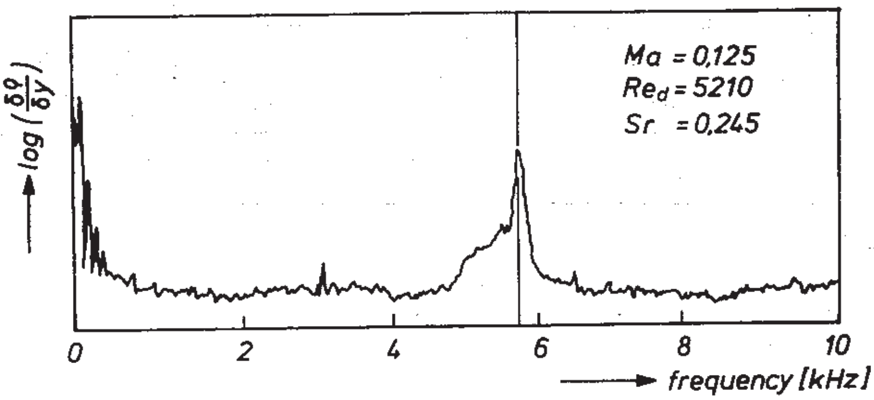

Fig. 12: Low Mach number LDG-measurement result of vortex shedding frequency at a flat plate (d=3 mm) with round trailing edge