Unsteady Pressure Response to an Oscillating Normal Shock Wave in a Nozzle

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1. Abstract

The present paper describes the investigations made on an oscillating normal shock in a two dimensional nozzle. The test setup simulates a vibrating turbine cascade and the movement of a normal shock on the suction side of the blades. The shock in the simulation is moved by a periodic pressure perturbation downstream.

The measuring techniques employed are reported in detail. The non-harmonic side wall pressure distributions are compared to the harmonic shock oscillation. The shock influence on the wall is noticed upstream of the visualized shock position and the shock amplitude decreases with increasing frequency of the downstream reference pressure. For the reduced frequencies studied (k=0->0.18, based on a reference length of 71 mm and the inlet velocity of M=0.7) no significant phase lag between the shock movement and the responses of the pressure transducers could be noted.

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2. Nomenclature

Symbol	Explication	Dimension
f	frequency	[Hz]
H	nozzle height	[-, mm]
H^*	throat height	[mm]
k	reduced frequency $f = \frac{2\cdot\pi\cdot f\cdot H^*/2}{q_{inlet}}$	[-]
M	Mach number	[-]
p	static pressure (steady state)	[mbar]
$\tilde{p}$	Perturbation part of unsteady static pressure	[mbar]
p_{tot}	total pressure	[mbar]
q_{inlet}	inlet flow speed	[m/s]
Re	Reynolds number (based on inlet flow) $Re = \frac{\rho\cdot H^*\cdot q}{\mu}$	[-]
t	time	[s]
x	coordinate in streamwise direction	[-, mm]
μ	dynamic viscosity	[kg/(ms)]
ρ	density	[kg/m^3)]
ω	rotational frequency $\omega = 2\cdot\pi\cdot f$	[1/s]

3. Problem

Time-dependent pressure measurements on turbomachinery blades are often performed with pressure transducers mounted on the blades. These high-response transducers are either "flush-mounted" on the blade surface or mounted inside the blades, in which case a certain amplitude and phase lag between the true oscillating pressure and the response of the pressure transducer may have to be considered. The pressure measured with transducers mounted this way in transonic flow corresponds obviously, after calibration, with the pressure on the wall, but the relationship between the wall pressure response and an oscillating shock wave in the transonic free stream flow is not straightforward. Studies [Edwards, 1987] indicate that for frequencies up to around 160 Hz the response of the unsteady wall pressure fluctuations and a shock movement in the free stream

may be considered to be instantaneous. However, it is not clear which influence the unsteady shock-boundary layer interaction has on the local unsteady lift on an oscillating airfoil, how large the pressure fluctuations are for a given shock movement or how the pressure amplitudes and phase angles correlate with the flow changes in the free-stream in the presence of a large boundary layer.
Several newly developed time-dependent numerical models, based on the fully non-linear, or linearized, Euler or Navier-Stokes equations indicate certain physical aspects of the flow, such as a change in the pressure amplitude over the shock wave with increasing frequency and a non-constant time averaged shock position. Some of these models assume that the pressure response on, for example, a harmonically vibrating blade, is harmonic. This is certainly not the case for oscillating strong shock waves.
The objectives of the present study are to determine the relationship between an oscillating shock wave and the wall pressure response, and to establish reference data for validation of numerical models treating shock waves oscillating in nozzles. For this simultaneous measurements of shock position and the unsteady pressure evolution on the side wall in a nozzle under the influence of an oscillating normal shock had to be performed. Different measuring problems concerning the behavior of unsteady pressure transducers under the influence of an oscillating shock in the presence of a thick boundary layer should be investigated.

4. Solution chosen

An experimental study of the relationship between a shock oscillating in a Laval nozzle and the corresponding time-dependent wall pressures was undertaken.

4.1 Test facility

A Laval nozzle with a width of 40 mm was prepared for the purpose. The facility is equipped with nozzle liners giving a converging-diverging section with a continuous first derivative of the area (Figs. 4.1). The inlet and outlet height of the test section is 80 mm and the throat height is 71 mm. A window is situated in the aft part of the convergent-divergent section and gives access for non-intrusive measurement techniques.
A four-stage radial, continuously running turbocompressor (pressure ratio 4, 10 kg/s mass flow) is used as air source.

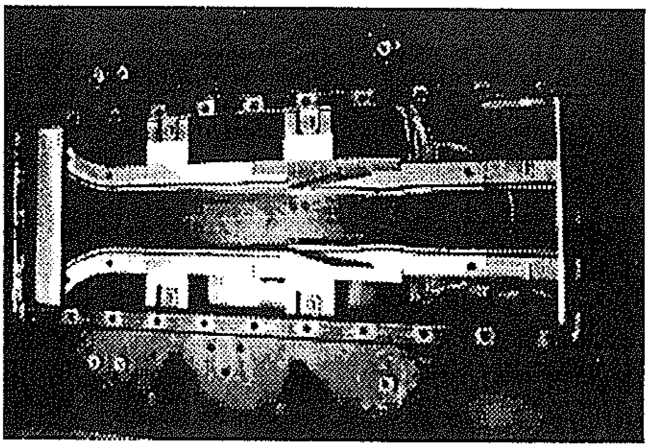
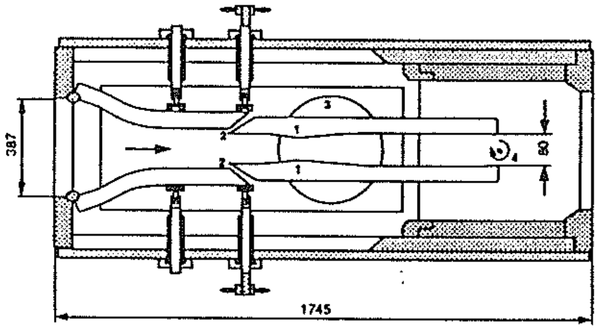


Figure 4.1a: Photo of the nozzle



1 nozzle liner
2 boundary layer bleed
3 Schlieren window
4 rotating exciter

Figure 4.1b: Schematic view of the nozzle used

On the nozzle liners the boundary layer is cut off before the throat (Fig. 4.2). The air is blown by the flow behind the nozzle liners and again mixed with the main stream at the exit of the nozzle. The incoming boundary layers at the side walls are not modified and thus fairly thick boundary layers are present on the side walls.

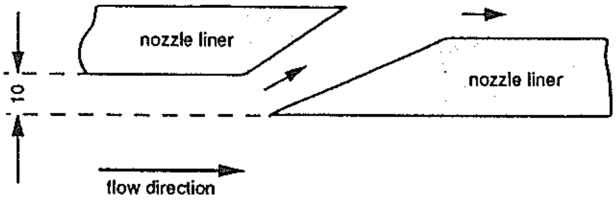


Figure 4.2: Schematic view of the boundary layer cut-off knife on nozzle liners

4.2 Oscillating shock

A normal shock is created in the test section of the nozzle by regulating the exit pressure of the nozzle. The oscillation of the shock is realized by a cylindrical rod with elliptical cross-section situated at the outlet of the nozzle formed by the liners (480 mm downstream of the throat, Fig. 4.1b). This rod is rotated by a hydraulic motor. The losses created by the wake of the rod are varying in time and in this way the outlet pressure of the nozzle is changed periodically. By this variation the normal shock is excited to oscillation. Excitation frequencies between 0 and 180 Hz are possible with the present test set-up as for each revolution of the rod two excitation cycles are executed for the shock movement.

For the present tests the shock is always oscillating in the divergent section of the nozzle. Upstream of the shock, depending on its position, Mach numbers between 1.2 and 1.4 are reached.

4.3 Instrumentation

The static pressure distribution along the nozzle liners is controlled by pressure taps.

The side wall of the nozzle is equipped with 80 pressure taps where either small tubes for static pressure measurement or tubes containing an unsteady pressure transducer[1] can be screwed in. These taps are situated on a plate which represents equally the mirror plate of the double-pass Schlieren system ("3" in Fig. 4.1b). Eight tubes containing unsteady pressure transducers were used for the present test series. The manufacturing was performed in a way that the pressure transducers were sitting just behind the surface of the mirror plate with a negligible dead volume that is. The transducers were calibrated for steady state and dynamic pressure, including the whole measuring chain (volumes, amplifiers, filters, etc.) while they were mounted in their corresponding measuring positions.

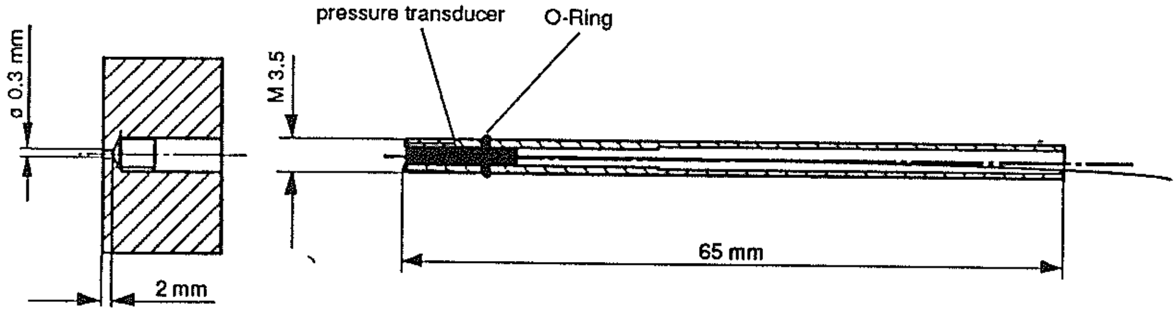


Figure 4.3: Tube containing an unsteady pressure transducer

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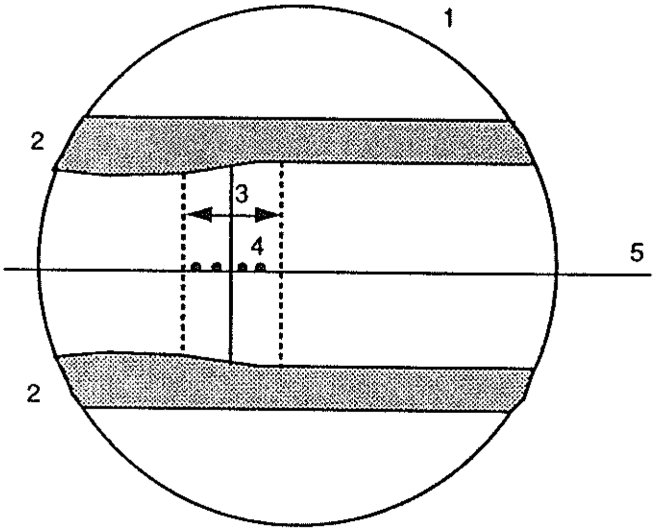
[1] Pressure transducer ENDEVCO, model PS 8514-50, range: 0 - 3.4 bar, accuracy: 0.5 % Full Scale

The shape of the shock wave and position is observed by a reflecting Schlieren system using a video camera and a stroboscopic flash synchronized with the camera. Furthermore, the shock position, its shape, the boundary layers and the flow velocities up- and downstream of the shock, are also determined with a Laser-2-Focus system, both for "steady-state" and time-dependent operating conditions at different frequencies. Finally, holographic interferometry was used to get some supplementary information about the boundary layers on the nozzle liners close to the shock for the steady state flow.

For the unsteady measurements the flow field is observed with the reflecting Schlieren system. The flash is then replaced by a continuous light source. The shock position is found by a line scan camera[2] which observes one line of the Schlieren picture normal to the shock (Fig. 4.4).



1 Schlieren window
2 nozzle liner
3 moving shock
4 unsteady pressure transducer (mounted in mirror plate)
5 line observed with line scan camera

Figure 4.4: Position of observed line and pressure transducers

A mask with well-known position is fixed on the window to allow the geometrical definition of the shock position in the channel. Fig 4.5 shows a schematic Schlieren picture and a corresponding schematic signal of the line scan camera, and Fig. 4.6 shows a real camera signal. From the position of the dark parts (= low voltage on the diodes), the masks and the shock wave can easily be identified against the light parts of the image (= high voltage on the diodes). The distance left free by the

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[2] Line scan camera Reticon, model LC-1901

mask was for these tests 40 mm. The Schlieren picture is projected on the sensitive line of the camera composed by 1024 photodiods (pixels). Under consideration of about 800 pixels within the range of the distance left free by the mask, a resolution of 0.055 mm is reached. The so found shock position is obviously, as with any Schlieren pictures, integrated over the nozzle height.

Simultaneously the unsteady pressure distribution on the nozzle side walls is measured by the time-dependent pressure transducers fixed in the mirror plate.

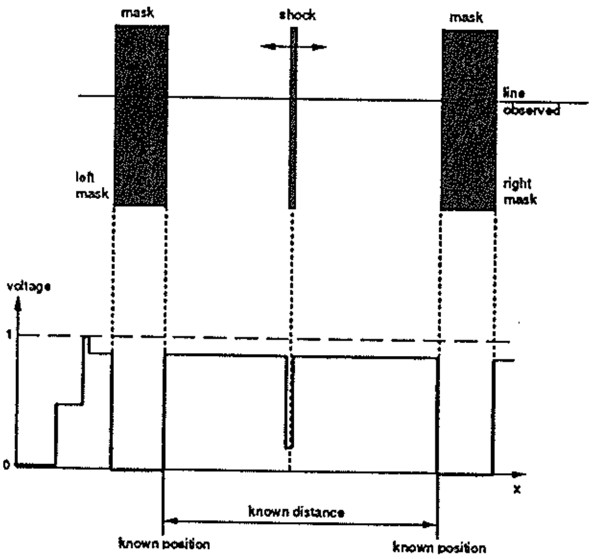


Figure 4.5: Schematic illustration of Schlieren visualization and a line scan camera signal

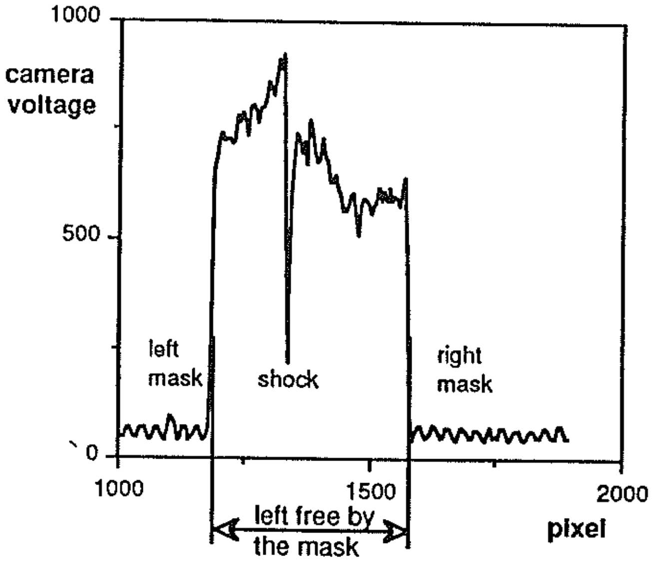
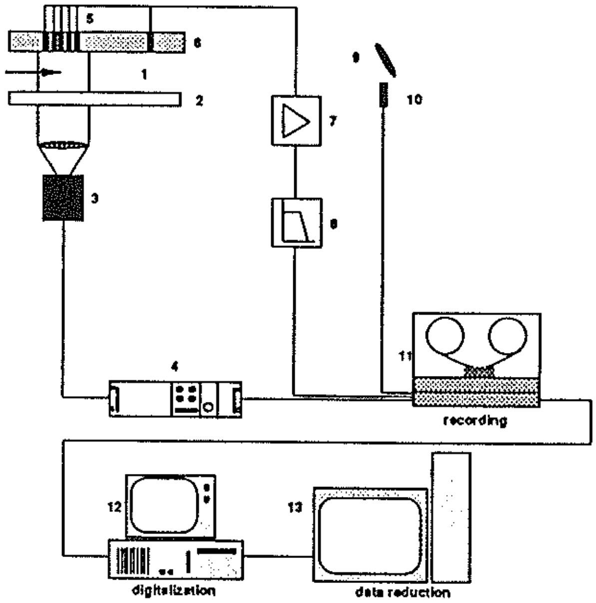


Figure 4.6: Untreated signal of line scan camera with shock

The signals of the camera and the pressure transducers are recorded (see Fig. 4.7

that gives a view of the complete measuring system) together with a triggering signal of the exciter on a analog data recorder[3] and digitized off-line. The digitized signals of the line scan camera can give the position of the shock in the moment when the line scan camera "froze" the momentaneous picture before writing out the voltage of all the diodes.

The trigger signal allows to locate the moment when the picture was taken inside one excitation period. As the phenomenon studied is periodic a signal averaging for the pressure transducer signals and for the shock positions can be made. All results are then presented within one excitation period.



1	flow channel
2	window (Plexiglas)
3	line scan camera
4	control electronic
5	unsteady pressure transducer
6	mirror plate
7	amplifier
8	low pass filter
9	rotating exciter
10	rpm counter
11	recorder
12	personal computer
13	workstation

Figure 4.7: Schematic view of the measuring system

Fig. 4.8 shows the positions of the unsteady pressure transducers, with respect to the nozzle, for the measurements here presented. The pressure transducers were positioned such that some are located slightly outside of the shock oscillation range, and others were the shock always would be present. One transducer was mounted as far downstream from the shock as possible to measure the pressure oscillation at the outlet (pressure transducer p8).

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[3] Tape recorder KYOWA, model RTP-802A

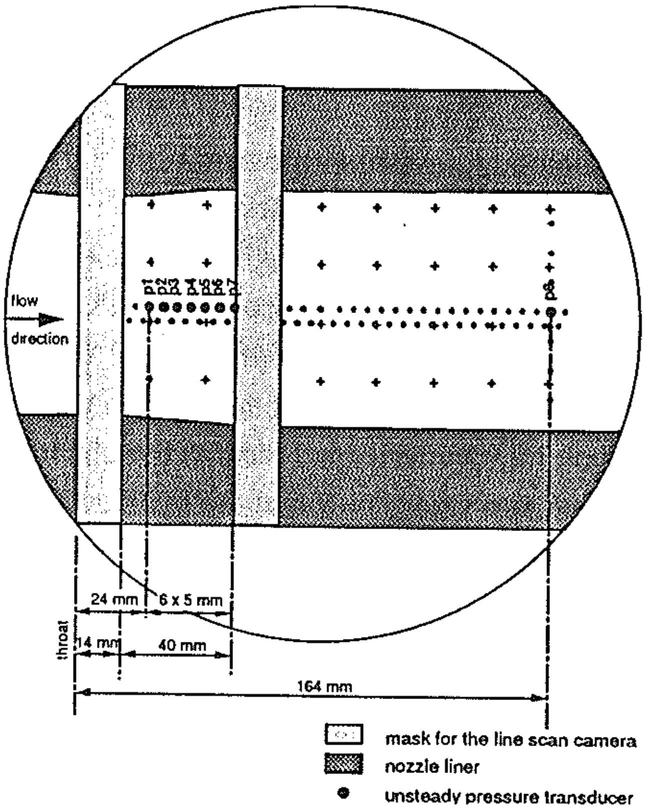

Figure 4.8: Positions of the unsteady pressure transducers during the tests

5. Discussion of results

The flow conditions at the inlet of the nozzle during the here presented tests were:

Mach number $M_1 = 0.70$

static pressure $p_1 = 1215$ mbar

total pressure $p_{tot\,1} = 1680$ mbar

The Reynolds number realized was, based on the throat height and the inlet flow conditions, $1 \cdot 10^6$.

The maximum Mach number in front of the shock was, depending on the shock location, between 1.15 and 1.30.

The Mach number at the outlet was situated, equally depending on the shock position, between 0.78 and 0.83.

By different means, including Laser-2-Focus velocimeter and Pitot probes, large boundary layers, up to 12 mm after the shock, on the side walls were observed. These large boundary layers lead to a flow information transport from the subsonic region downstream up to the supersonic region upstream. The pressure transducers feel the presence of the shock in a larger region than it is expected in a flow with smaller boundary layers. Further information about the steady state results can be found in Ott [1992].

The evolution of the unsteady pressures measured by the different transducers together with the shock positions as determined by the line scan camera are shown in Fig. 5.3 for the excitation frequency of 20 Hz. All results are presented within one excitation period. The positions of the pressure transducers are marked in the diagram with the shock position, i.e. in the lower diagram. The presentation chosen allows one to correlate the signal of a pressure transducer with the motion of the shock wave with the aid of the vertical lines relating the upper and lower diagrams in each figure. This correlation shows clearly that the pressure transducer "feels" a change in the pressure before the shock reaches the corresponding geometrical locations. For small excitation frequencies the upstream influence distance corresponds to expected values for steady state [Inger, 1982]. For higher frequencies the upstream influence distance increases for the shock moving downstream while it remains in the same order of magnitude as for small frequencies for the shock moving upstream. For the highest excitation frequencies here performed there exists no longer a domain of constant pressure while the shock is far away from the location of the pressure transducer.

It is clearly noted that the average shock movement is harmonic, whereas the pressure transducer response obviously is non-harmonic. Nevertheless, it is also to observe that the pressures have their extreme values at the same instant as the shock is in one of its extreme positions. The boundary layer increases the zone of influence of the shock, but there is no phase lag between the shock movement, as measured with the line scan camera and the Schlieren system, and the unsteady pressure evolution. This conclusion is valid for all frequencies up to 180 Hz.

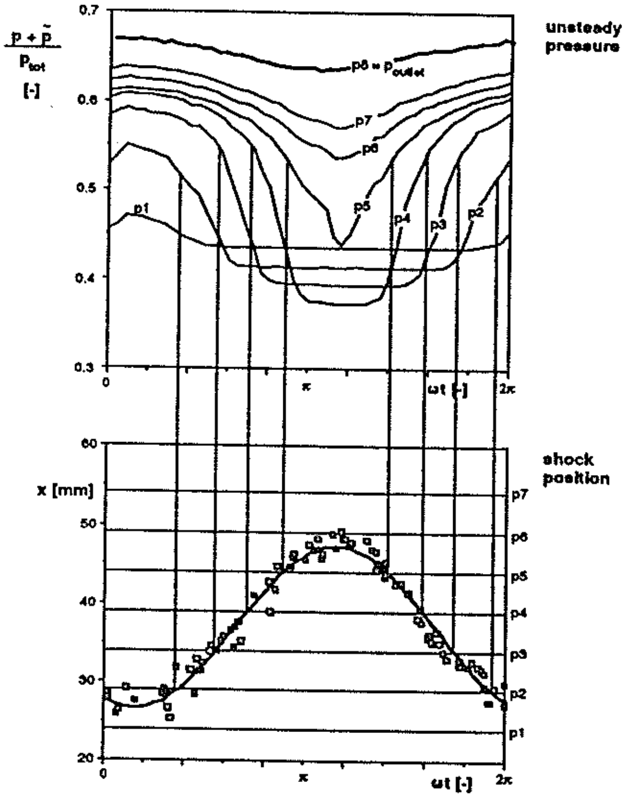

Figure 5.1: Unsteady pressure evolution together with shock position (excitation frequency 20 Hz)

Further information about the unsteady results can be found in Ott [1992] and Bölcs et al [1993].

6. Conclusions

From the experimental investigation of a strong shock wave oscillating in a nozzle, and the measurement of the corresponding pressure fluctuations, the following conclusions can be drawn as regards to measuring techniques:

- For the reduced frequencies studied here (k=0->0.18) it is permissible to consider the time-dependent pressure response on a wall as quasi-steady. No phase shift could be found between the oscillating shock wave and the side wall pressure response.
- The pressure amplitude in the region where the shock moves decreases with increasing excitation frequency. The decrease depends on the boundary layer

thickness.

- The influence of the shock wave is noticed in the pressure response upstream of the shock position. This influence distance behaves for low excitation frequencies as expected. For higher frequencies the upstream influence distance is larger for a shock moving forwards in streamwise direction than for a shock moving backwards.
- The evolution of the unsteady pressure under the normal shock passing by has a big non-harmonic behavior.

7. References

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