Cascade Testing
Paper 2

EVOLUTION OF SIDE-WALL UNSTEADY PRESSURES PRODUCED BY FORCED BLADE VIBRATIONS

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ABSTRACT

The propagation of unsteady pressure, created by a vibrating turbine blade, has been investigated in a linear test facility. An electromagnetic excitation system forces the centre blade to oscillate in the bending mode. The interaction between the blade oscillations and the flow is investigated with high response piezoelectric pressure transducers.
The time-dependent pressure was measured in a field within the two centre blade passages at the facility side wall with 13 x 8 grid points. The unsteady pressure signals are related to the motion of the vibrating blade. The evolution of the unsteady pressure distribution has been measured for sub-, trans- and supersonic flow conditions. In addition the adjacent time-dependent blade surface pressure distributions were measured at mid-span. The experimental data is assembled in contour maps for different blade positions. Time-stepped animations of the propagation of the unsteady pressure perturbations are presented.

INTRODUCTION

Under certain circumstances the amplitude of a vibrating blade can increase until destruction of the blade. These so-called flutter phenomena are the consequence of the interaction between the vibrating blade and the created unsteady pressure, in the flow field.

Time-dependent measurements on rotating turbomachinery parts are difficult to perform. Controlled vibration of turbomachinery blades is an excellent way to study this interaction between a vibrating blade and the unsteady pressure.

In the present paper a measuring technique using a small number of piezoelectric transducers to measure the unsteady flow field is described. The unsteady flow field is measured in the two centre blade passages, where a satisfyingly good flow periodicity is achieved.

TEST FACILITY

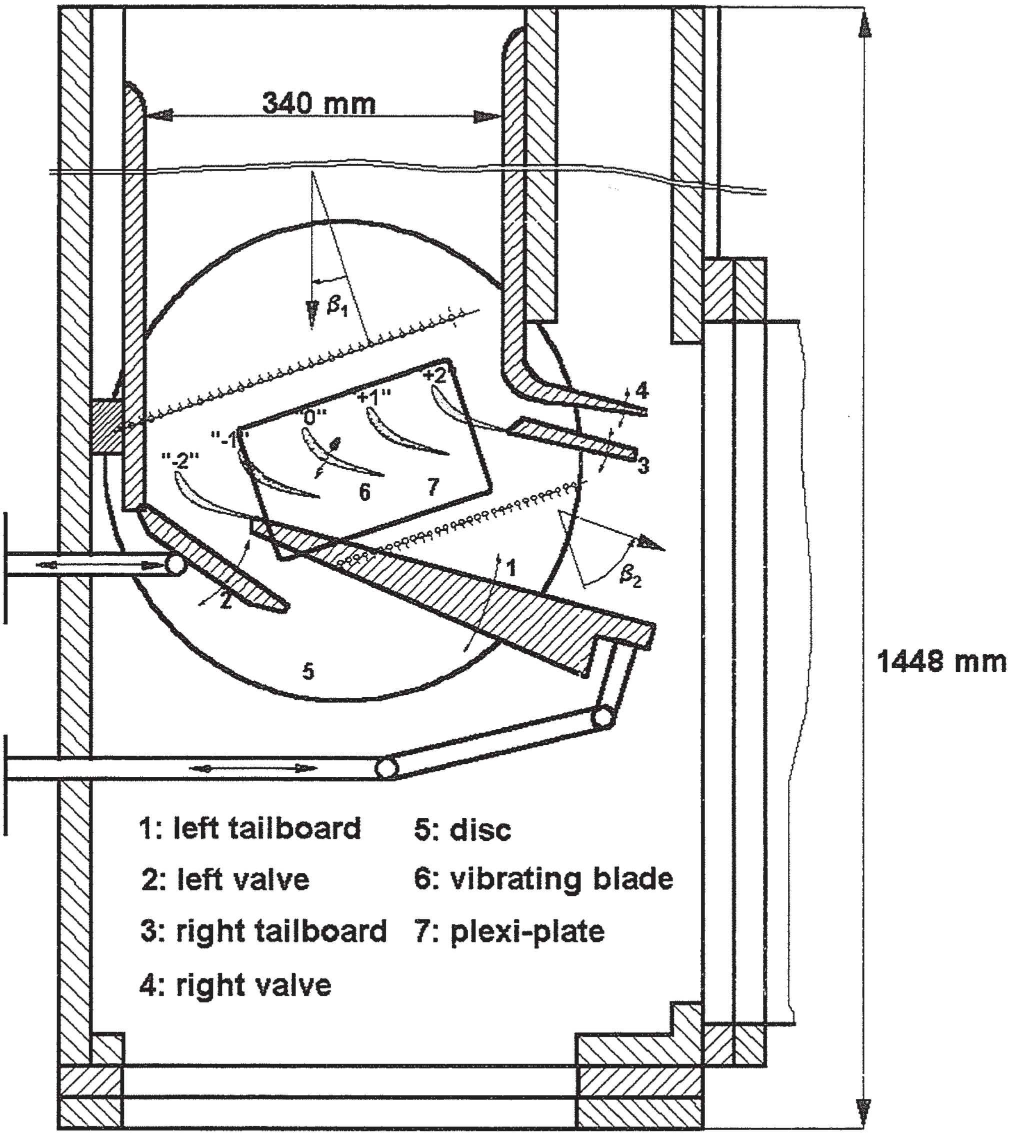


Figure 1. *The linear facility.*

The linear test facility has a flow surface of 100 x 340 [mm] and is equipped with a linear turbine cascade, Fig. 1. The turbine cascade is composed of five blades. The facility is equipped with two tailboards and two valves with which is it possible to achieve a periodic up- and downstream flow in the cascade. The tailboards and the valves are controlled with hydraulic cylinders. The angle of attack is changed by turning the disc on which the cascade is mounted. The total pressure and the total temperature are measured with an aerodynamic pressure probe and thermocouple elements, respectively in the stagnation chamber upstream of the test section. Forced blade vibration tests have been conducted in the linear test facility. The centre blade produced the unsteady pressure as it was forced to vibrate in the bending mode. The measurements were taken at the facility side-wall as well as at the blade surfaces at mid-span. The unsteady pressure flow field measured at the

side-wall is taken at the tip of the vibrating blade, consequently tip clearance effects are captured in the measurements as well.
The compressed air for the test facility is provided by a continuously running four stage radial compressor which has a maximum mass flow rate of 10 kg/s and a maximum pressure ratio of 3.5.

MEASURING TECHNIQUE

Different methods to measure the unsteady flow flied in a turbine cascade have been investigated. A time-dependent L2F-method, a holographic method and measurements with piezoelectric pressure transducers have been conducted.

A time-dependent L2F-method has been conducted. It was concluded that the variation of the flow velocity was too small in relation to the errors achieved with the unsteady L2F-system.

Experiments with a holographic measuring system have been tested. As the circular disc with the vibrating blade fixation system prevents transversal visualisation systems, the circular disc was mirror polished. This was sufficiently good to producing Schlieren images. For the holographic system different vibrating modes from the moving circular disc (the facility side-wall) were superimposed on to the holographic images. This resulted in enormous image processing efforts to remove the superimposed image for each measured flow condition. Furthermore, reliable processing programs would have been to a great advantage.

Normally to measure the time-dependent flow field in two blade passages a relatively high number of pressure transducers are needed. As the pressure transducers are expensive it is desirable to minimise the number of transducers required. As the measured unsteady pressure is related to the blade motion, it is possible to divide the desired unsteady flow field measurements into several equal measurements, using fewer pressure transducers. This is the main principle associated with this measuring technique.
The transducer positions at the side-wall can be seen in Figs. 2 and 3. The unsteady flow field is assembled of measurements taken at 104 different points. To carry out the side-wall time-dependent measurements eight tap constructions, with embedded pressure transducers, were used. Additional steady-state pressure measurements were accomplished with threaded tubes, which were similarly screwed into the side-wall measuring grid. The time-dependent flow field was measured as the eight taps constructions were moved from row to row until all thirteen rows had been investigated for each flow condition. In Fig. 4 the dimensions of a tap construction are shown.

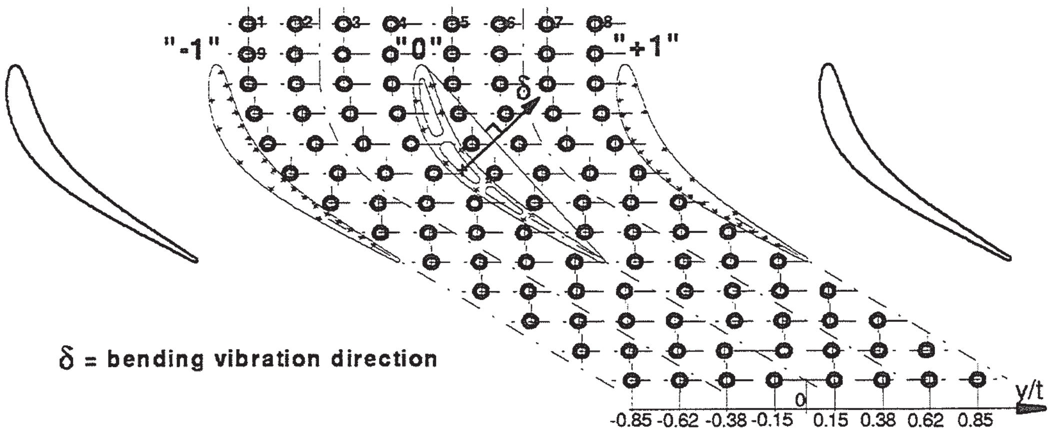


Figure 2. *Position of the thread holes in the side wall in which the different taps constructions are screwed in.*

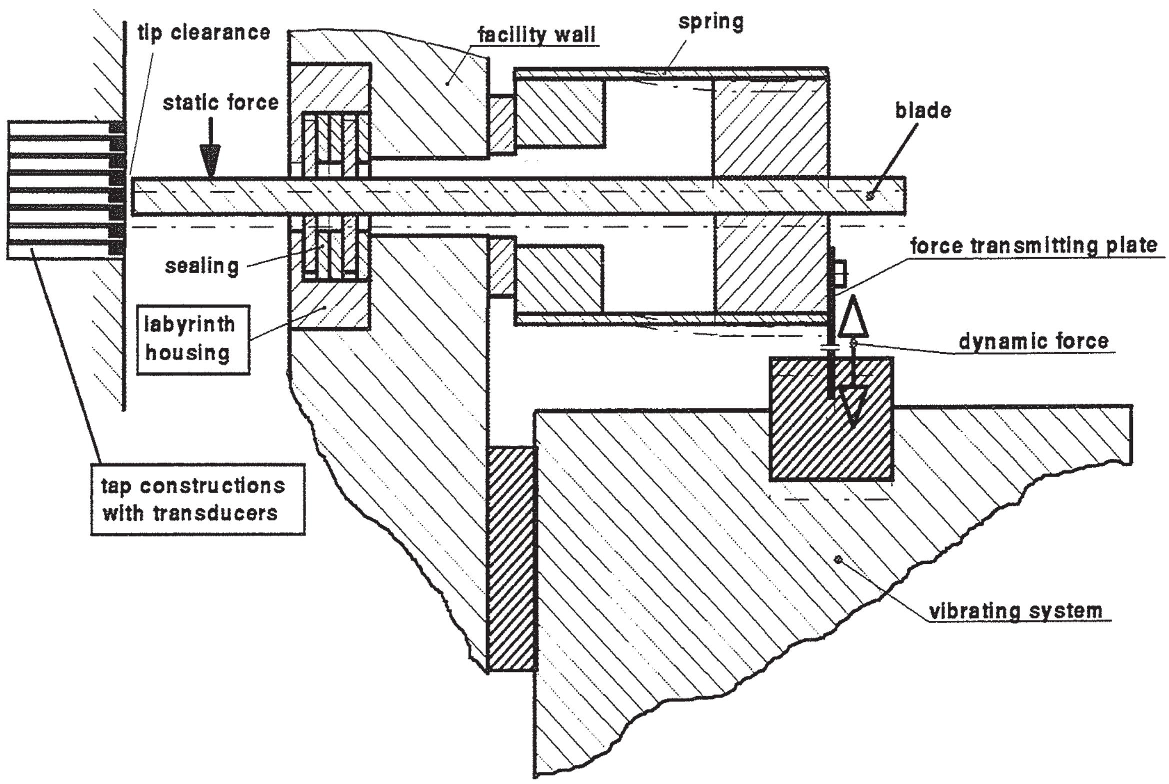


Figure 3. *Test section with surroundings.*

DATA ACQUISITION

The pressure transducers work after the principle of a Whetstone-bridge and the detuning of the bridge results in an output voltage, which is in general very small and has to be amplified. Thus, a whole measuring chain is built up for each transducer. Each chain consists of a transducer, amplifiers, electronic filters, data acquisition cards and a computer. The acquisition card transforms the analogue time-dependent pressures and blade oscillation signals into digital values. It consists of a high speed analogue-digital (A/D) converter and a multiplexer module and an acquisition of maximum 32 channels consecutively is possible. The data acquisition card is a KEITHLEY DAS-1800 HS-2.

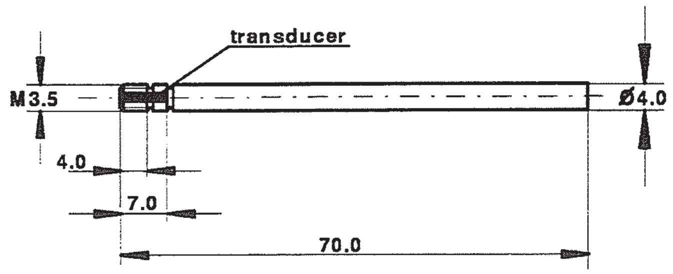


Figure 4. *A pressure transducer mounted into a moveable tap construction, dimensions in [mm].*

DATA EVALUATION

The transducers together with the whole measuring chain were calibrated with another high response piezoelectric transducer which served as a reference. The reference transducer was calibrated statically. It has been controlled against other chosen reference transducers and produces an almost constant static sensibility over several years. This static calibration (sensitivity) of the reference transducer is equal to the slope of the line representing the relation between a given static pressure and the output voltage from the transducer. The dynamic calibration of the transducers was conducted without high- or low-pass filters in the reference measuring chain, as a clean pressure signal is desired and necessary, with neglecting time lag effects.
The blade motion is measured with an accelerometer, which is imbedded in the oscillating blade. The possible measurement error of the accelerometer is given to 2% from the producer Bruel&Kjær.

The method applied to evaluate the time-dependent quantities in this work is an ensemble averaging technique. The goal of the technique is to reduce the huge amount of time-dependent data into comprehensible, useful and well-defined coefficients and at the same time the data spread is statistically analysed to estimate the random error of the signals. The ensemble averaging method is based on the averaging of sampled data with a subsequent Fourier-transformation of the averaged signals. The method needs a well-defined trigger, which in the case of controlled blade excitations is the blade vibration signal. The real time for each sampled value is corrected for filters and amplification influences, and then placed in the corresponding place in the first period of each measured signal. The concept of superimposing all the sampled values in the first time period is the principle of this averaging method, as in this time period a great quantity of the noise and random signals for a local average will cancel out.

DEFINITIONS

The unsteady pressure coefficient is defined as,

$$\tilde{c}_p(x,t) = \frac{\tilde{p}(x,t)}{p_{w1} - p_1} \frac{\text{chord}}{\text{amplitude}} \qquad (1)$$

where $\tilde{p}(x,t)$ is the fluctuation amplitude of the 1st harmonic of the time-dependent pressure at the reference frequency, p_1 is the upstream static pressure and p_{w1} is the upstream stagnation pressure, chord = 87.9 [mm], blade amplitude = 0.3 [mm]. The unsteady pressure $\tilde{p}(x,t)$ together with the phase angle Φ_p are derived from an FFT transform. The phase angle is defined as the angle between the blade motion and the produced unsteady pressure and is positive when the unsteady pressure disturbance leads the blade motion.

In each measured point at the side-wall the unsteady pressure coefficient and the phase angle are known. The imaginary part of the unsteady pressure is then defined as,

$$\text{Im}[\,\tilde{p}\,] = \tilde{p}\sin(\,\Phi_p\,) \qquad (2)$$

and then adding the influence of the different time steps (which corresponds to different blade positions of the centre blade),

$$\tilde{p}\sin(\Phi_p + \omega t) \qquad (3)$$

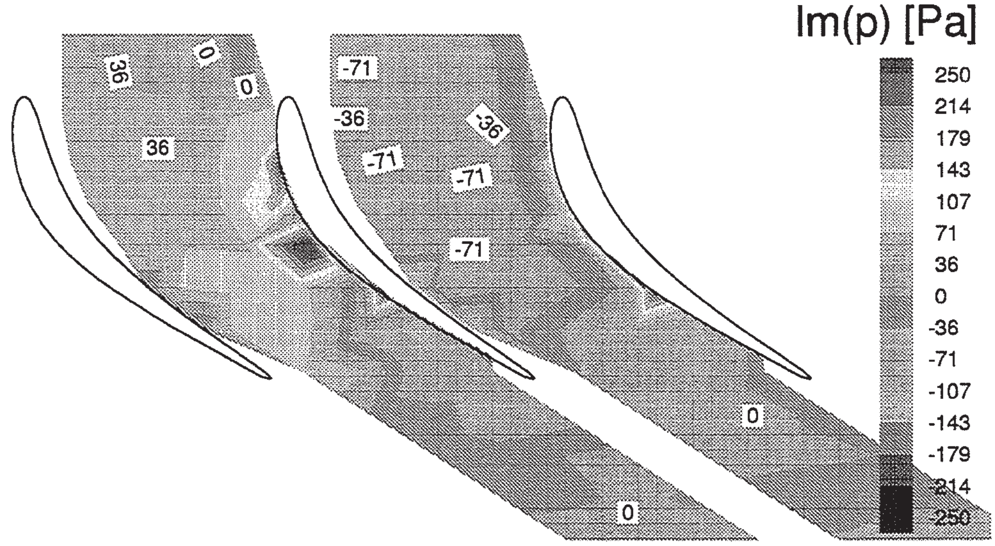
where, $\omega t = 0, 45, \ldots, 315°$.

The different blade positions correspond to the times according to a sinusoidal function, as the blade motion is given by $h(t) = h \sin(\omega t)$, where h = blade amplitude.

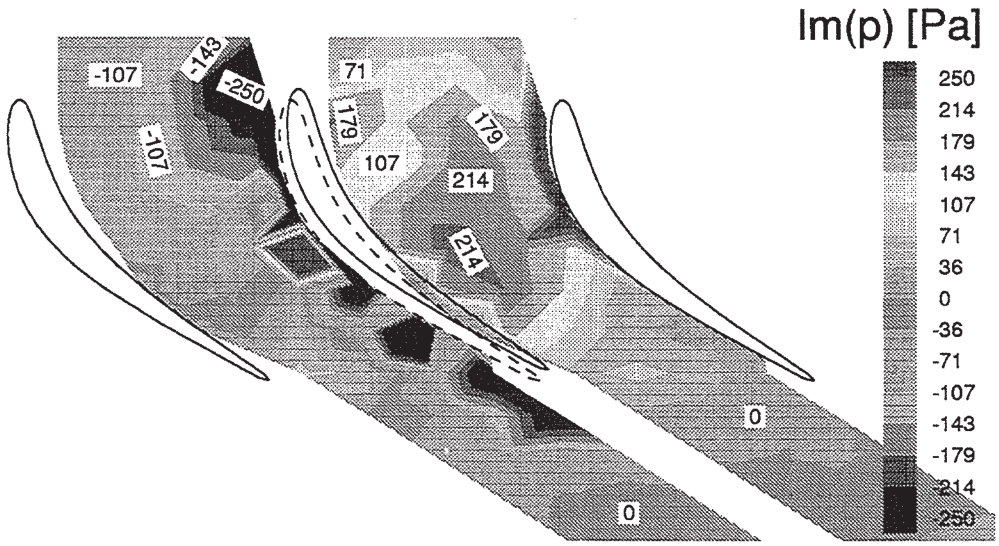
RESULTS AND DISCUSSION

The measurement of a single unsteady pressure row (eight transducers) takes about 30 [sec] including start-up, regulating and shut-down times of the blade vibrating system. The tap constructions average changing time, from row to row, is about four minutes, which was the most time consuming part during the time-dependent side-wall measurements. A proposed improvement here is as follows: Instead of using thread tap constructions, fast connections are available on the market which would tremendously decrease the tap constructions moving time. The easiest way to carry through the time-dependent measurements would, if possible, be to move the "side-wall" it self. Finally, the technique to use a reduced number of pressure transducers is relatively inexpensive in relation to other non intrusive time-dependent measurement techniques.

The propagation of the unsteady pressure around the vibrating centre blade can be studied using the ensembled flow field maps of the imaginary part of the unsteady pressure according to Eq. 3, Figures 5a and 5b below. The Figures below represent the imaginary part of the unsteady pressure (coefficient) for different blade positions, that is the time-averaged unsteady pressure with respect to the blade motion. The first image corresponds to the blade in the centre position, upward blade motion, the second corresponds to the upper blade position (maximum against the pressure side of the vibrating blade).



5a. In the centre blade position, upward blade motion.



5b. In the upper blade position.

Figure 5. *Imaginary part of the measured time-dependent pressure. The side-wall measurements are interpolated with mid-span blade surface measurements.*

From the measurements it was concluded that,

- the influence of the perturbations produced by the vibrating blade extends upstream at a distance approximately 20 - 30% of the blade chord length. No propagation of the produced unsteady pressures have been observed downstream of the cascade,
- in the centre region of the blade passage the steady-state measurements are in good agreement with calculated steady-state pressures, and
- the variable tip clearance vortex oscillates with the frequency of the vibrating centre blade. The tip clearance flow at the tip of the vibrating blade shows a strong periodic behaviour.

The evaluation process of the flow field conditions is on-going. The physics concerning the propagation of the time-dependent pressure are investigated with different physical models.

SUMMARY

The propagation of unsteady pressure, created by a vibrating turbine blade, has been investigated in a linear test facility. The interaction between the blade oscillations and the flow is investigated with high response piezoelectric pressure transducers at the facility side wall with 13 x 8 grid points.

The time-dependent pressure measurements at the facility side-wall using a reduced number of piezo-electric pressure transducer works very well. Instead of using over 100 pressure transducer eight transducers have been applied.

The measurements result in insightful time-dependent pressure contour maps, representing different blade positions in the blade cycle. To date, no conclusions regarding the unsteady side-wall pressure perturbations. The aim of the results is to allow for a better understanding of the interaction between a vibrating blade and the created unsteady pressure in the flow.