A NEW TEST FACILITY FOR INVESTIGATING FLUID-STRUCTURE INTERACTIONS USING A GENERIC MODEL

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ABSTRACT

A new type of test facility is presented which allows the investigation of fluid-structure interactions using a generic model. Rather than modeling the complex geometry of a turbomachine, this test facility, not yet up running, uses a 2D prismatic model located in a straight channel. It is made of engineered flexible material and can be made oscillating in a controlled way at variable amplitude mode shape and frequencies. Time-resolved measurements of both the unsteady surface pressure as well as the instantaneous model geometry will be performed and finally combined to results of interest. The new test facility modifies an existing wind tunnel featuring a straight rectangular cross section. The oscillating model used in the study is of 2D prismatic shape and has been investigated in previous studies where from base case data are available. In order to introduce capabilities for the planned fluid-structure tests, a flexible version of the model has been built. It is molded of polyurethane at defined elasticity and hardness, and actuated by a novel type of fully integrated mechanical oscillating mechanism. A frequency controlled AC servomotor will drive this oscillating mechanism. The whole drive train will be able to produce an oscillation of the model at variable amplitude and frequency up to 500Hz. At the same time, a 1D laser sensor will measure precisely the whole model displacement through a plexiglass window. The flow crossing the model can be set at different operating conditions. Time-resolved pressure measurements will be performed on the oscillating surface using Kulite fast response transducers. A new type of pressure paint developed at KTH / Physics Department will assist these measurements. While the instantaneous model shape will be scanned using laser triangulation technique through the top window, optical velocity measurement can be performed using the access through two sides windows. These include Schlieren as well as L2F and PIV. To date the facility has been redesigned and manufacturing is ongoing. Off-rig tests have been successfully performed on the oscillating model. First on-rig tests are intended at the end of the year 2002. The present contribution includes a review of the objectives and the measurement techniques that will be performed with the new test facility.

NOMENCLATURE

c_{ax}	[m]	Axial chord of the model
f	[Hz]	Frequency
E	[MPa]	Young modulus
k	[-]	Reduced frequency
M	[-]	Mach number
Q	[kg/s]	Mass flow
Re	[-]	Reynolds number
T_t	[K]	Total temperature
v_{ax}	[m/s]	Inlet axial flow velocity

1D	One dimensional
2D	Two Dimensional
3D	Three Dimensional
AC	Alternative Current
CNC	Computer Numerical Control
L2F	Laser-Two-Focus anemometry
MR	Measurement Range
OD	Offset Distance
PIV	Particle Image Velocimetry
PSD	Position Sensitive Detector
KTH	Royal Institute of Technology / Kungliga Tekniska Högskola
SO	Stand Off distance

BACKGROUND

Structure oscillating phenomena occur in many industrial applications in the field of energy technology. Under certain conditions a curved shape located in a uniform flow, such as a blade, an airfoil or the surface of a nozzle, can enter into a self-excited vibration known as flutter. In a flutter condition, aerodynamic loads can rapidly increase the amplitude of vibration of a structure until its failure. Performing unsteady pressure measurement to detect the fluctuations of aerodynamic loads is an efficient way to learn about flutter. Experiments on controlled vibrating models have been done to investigate such aerodynamic loads and evaluate the negative aerodynamic damping related to it. A driving system is creating an artificial oscillation of the structure, whose amplitude and frequency can be controlled. The compressor blade of Lehr and Bölcs [2000], for example, is made oscillating in a controlled plunging mode by a hydraulic excitation system. The high-speed pitching vibrator of Hirano et al. [2000], whose blade located in a linear cascade is able to reach a 500Hz frequency of oscillation, is another recent example of 2D mode shape controlled vibrations. In most of the cases, the vibrating structures are designed in metal to be close to real applications. Those stiff structures are difficultly run at flutter-operating points. Thus, large amplitudes of vibration at high oscillation frequencies prompt the failure of the structures. Moreover, recent research has already presented a 2D blade harmonically driven in a 3D mode shape controlled vibration such as in Queune et al. [2000]. To date, the flutter experimental investigations have been limited to stiff models made of metal, which cannot suffer high deformations. These models close to industrial applications are, in most of the cases, excited in a uniform flow and operating at oscillating conditions chosen between large amplitudes of vibration and high frequencies.

The new fluid-structure test facility presented here was built with the aim to investigate unsteady pressure measurements over a generic flexible structure. This structure has been designed, as a first version, prismatic to preserve a simple 2D geometry of the channel ground. Its shape creates a contraction in the test section in order to induce a shock wave in the airflow. This flexible model will be able to reach vibrating frequencies, characteristic of the flutter phenomenon, in a controlled way. Its oscillations are of a 2D bending mode shape nature but could be adapted to create 3D bending mode shape oscillations. Therefore, experiments are planned to further understand the unsteady interactions between this flexible model and subsonic/transonic flows. The choice of this generic prismatic structure has been motivated by its simple nature, which will allow a fundamental approach of the flutter phenomenon studied here. Moreover, base case data are available from previous studies where a static version of the same generic model has been investigated.

OBJECTIVES

Rather than modeling the complex geometry of a turbomachine and concrete industrial applications, this new test facility intends to avoid inertial effects, radial geometry or 3D aspect of the flow occurring in these applications in order to reach a deep theoretical understanding of the physics of aeroelasticty. Firstly, the test section including the generic model, the oscillation drive train, the geometry measurement system is described. Secondly, this paper intends to discuss the different measurement techniques planned to be used with the rest of the new test facility. Moreover, it exposes the motivation of such a design and discusses the development problems.

DESCRIPTION OF THE TEST FACILITY

The new test facility completes an existing modular transonic wind tunnel featuring a straight rectangular cross section presented by Bron et al. [2000]. The generic model, the oscillation drive train and the geometry measurement systems have been added to fulfill the requirements for new investigations. These components of the new test facility are described in detail below. Figure 1 shows the new test facility composition.

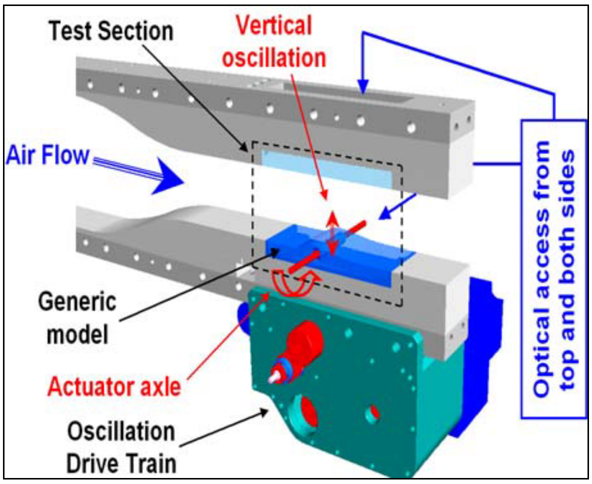

Figure 1: Test facility composition and optical access.

Test Section

A continuous working screw compressor driven by a 1MW electrical motor produces an airflow characterized by a mass flow of 4.7kg/s at 4 bar and 393K. The compressed air can be cooled down to a minimum temperature of 303K. The flow entering the test section can be set to different operating conditions characterized by different inlet Mach number, Reynolds number and reduced frequency. Mach and Reynolds numbers in the test section can be controlled. A large range of operating flow parameters can be reached, as it is presented in Table 1. The operating points can then be fixed according to the experimental set-up in order to reach the objectives of the planned investigations.

Mass flow (4 bar, 297 K)	Q = 4.7 kg/s
Total temperature	$303\ K \leq T_t \leq 353\ K$
Test section height	120 mm
Test section width	100 mm
Mach number inlet throat	$0.2 \leq M \leq 1$
Reynolds number for a characteristic length of 650mm	$43.10^3 \leq Re \leq 27.10^6$
Reduced frequency	$0 \leq k \leq 2.8$

Table 1: Operating flow parameters

As it is shown in Figure 2, the test section has been design to allow inserting different test models through the side windows on both upper and lower walls. By mounting geometrically minimised test models onto a model support part, it is possible to keep an easy access for instrumentation. Any test object that has a rectangular base will therefore fit in this support part. The dimensions were chosen to be 290mm long, 100mm wide and 25mm thick to be able to exchange the test objects easily through the side windows. The base part also features a large opening to the atmosphere to easily access and instrument the test object from the outside. Moreover, an excellent optical access from above can be obtained, for PIV or the geometry measurement system for instance, by inserting a optical glass window into the upper support part. Figure 1 shows the respective locations of these optical accesses. While the geometry measurement system will scan the instantaneous model shape through the top optical access, optical measurements can be performed using the two sides windows. These include Schlieren as well as L2F and PIV techniques.

All connections between surfaces were carefully sealed to prevent any leakage flow to the atmosphere. Moreover, all wind tunnel surfaces and connections between the different parts were manufactured with a very smooth finish to avoid boundary layer tripping. In order to allow cutting off the boundary layer to the atmosphere, the ground of the wind tunnel was designed with an opening located just upstream of the test section.

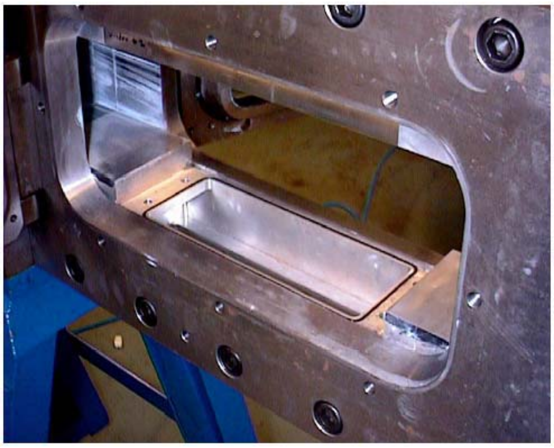

Figure 2: Base support part for test models. Taken from Bron et al [2000].

The design was made in such a way that the model support part on the lower wall is isolated from the other parts. The idea was to be able to lift the generic model up by simply inserting a flat plate under the whole support part. On one hand, a special cut out enables the support part to be equipped with a "nose" part, which will thereafter "cut" the incoming flow and redirect the boundary layer to the atmosphere. Two different noses are available at the moment: a sharp one and a round one equipped with pressure taps on the leading edge. Assuming that the nose is placed exactly at the edge of the boundary layer, the latter will be entirely blown out to the atmosphere. A new boundary layer will therefore grow from the leading edge of the nose, providing a clean precisely known flow in the test section. For more details see Bron et al. [2000].

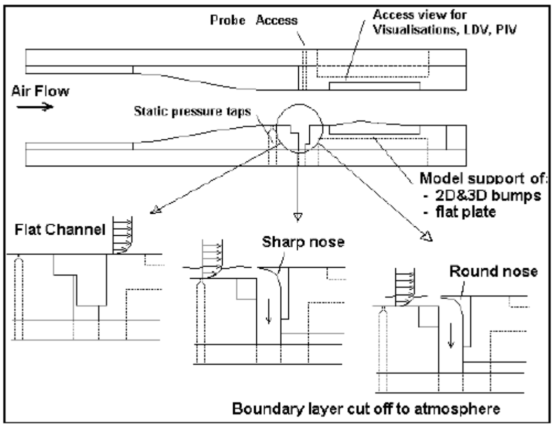

Figure 3: Three alternative configurations. Taken from Bron et al [2000].

On the other hand, a plug can also be inserted instead of a nose and thus provide a flat channel without boundary layer cut off. Three alternative configurations are therefore possible in the new test facility: a flat channel, a sharp or a round nose, as it is sketched in Figure 3. In order to assess the aeroelastic phenomena controlled flutter experiments are carried through. The model is for this purpose oscillated in a controlled mode and the aerodynamic response is measured on the model surface. By recombining the model motion and the response, and characterizing amplitude and relative phase lag the aeroelastic parameters of interest such as flutter stability are addressed. The model itself and the planned measurement technique are explained in to detail below.

The Generic Model

The generic model is molded of polyurethane at defined elasticity (E=36.10^6 MPa) and hardness (80 shore), by vulcanization over a steel metal bed. As it is shown in Figure 4, it includes a fully integrated actuator allowing smooth surface deformations as it is described later.

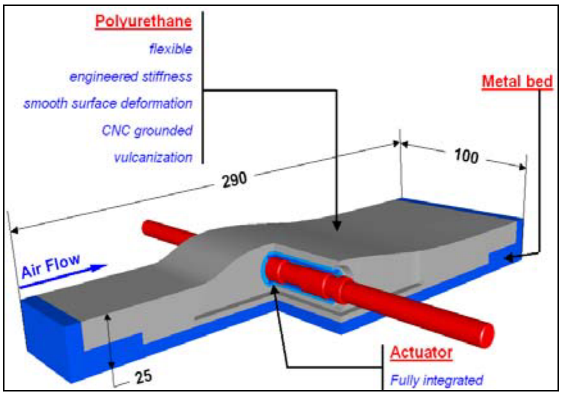

Figure 4: Cut of the Generic Model

The CNC grounded curved surface that is 290mm long and 100mm width will be mounted as part of the test section ground.

The oscillating model is of a generic kind in order to simplify the flutter phenomenon occurring during the planned experiments and to reach a better understanding of the physic of fluid-structure interactions. Its generic nature makes it also similar to many applications, such as a blade, an airfoil or the surface of a nozzle. It will also be used to validate numerical calculations. Its main individual quality is to be of a flexible material that allows it to reach high amplitude of deformation at high frequency corresponding to the vibrating range of the flutter phenomenon.

The requirements have been set up for the present study to oscillate the model at reduced frequencies from 0 to 2.8 at transonic flow conditions. From the expression of the reduced frequency based on the half chord given in Equation 1, a maximal oscillation frequency close to 500Hz has been determined. More information about the calculation of reduced frequency figures in Fransson [2002]. In the case of this new generic model, the chord is defined as the length of the model that is deforming (≈120mm). In this calculation, it has also been considered the Mach number at the inlet of the test section that can be set from 0.2 to 1.

$$k = \frac{2\pi\ f}{v_{ax}} . \frac{c_{ax}}{2} \qquad (1)$$

Table 2 gives the global requirements for the oscillation conditions that have to be completed by the oscillation drive train and the mechanical actuator of the generic model. Oscillation operating points will cover these ranges simultaneously.

Mode	1st bending mode
Amplitude	Variable from 0.1 to 0.5mm
Frequency	Variable from 10Hz to 500Hz
Shape	Sinusoidal

Table 2: Oscillations requirements.

A novel type of fully integrated mechanical oscillating mechanism actuates this flexible model in a controlled way. A rotating camshaft is composed of three identical prismatic cams on a cylindrical axle as it is shown in Figure 5. Several actuator axles will be manufactured with different camshaft shapes such that the flexible model can be run with vertical amplitudes in between +/- 0.1mm and +/- 0.5mm at oscillation frequencies from 0 to 500Hz. The whole system has been designed to reach an amplitude of 1mm at 500Hz. Moreover, a typical reduced frequency of k=0.35 is reach for a Mach number of 1 and an oscillating frequency of the model of 300Hz.

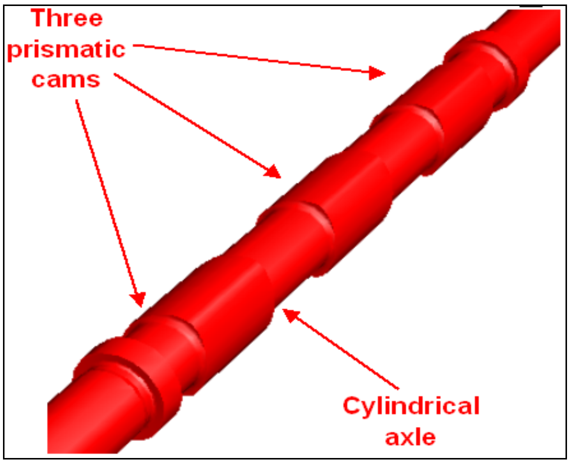

Figure 5: The camshaft

The camshaft is transmitting vertical oscillations to the actuator casing made of Ti by friction contact on two exchangeable bearing plates as it is shown in Figure 6.

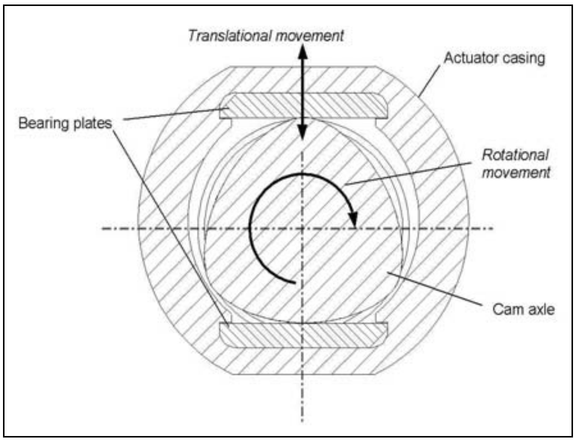

Figure 6: Section of the oscillating mechanism

The shape of the cams is such that one revolution leads to three identical sinusoidal translations of the actuator casing. By this way the titanium casing of the actuator is deforming vertically three times the flexible structure composing the model for one revolution of the camshaft. This corresponds to three vertical oscillations. Thus a rotational speed of the camshaft of 10,000 rpm leads to an oscillation frequency of 500 Hz of the flexible model. Previously, Figure 3 showed the way the model is intended to oscillate and the direction of the flow over it. The linear nature of the contact between the bearing plates and the camshaft allows the titanium actuator casing to rotate with the flexible structure. By this way, the flexible model is able to reach the second mode shape of oscillation. The first version of the generic model has been successfully tested with a low power electrical motor. It has reached 40Hz of oscillation frequency without problem.

After first static measurement, it has been noted that the maximal amplitude of the oscillation is slightly different from the one expected: oscillations were measured to –0.51mm/+0.47mm instead of ±0.5mm design amplitudes. Figure 7 shows the static amplitude measurement of the model made to check the value of the amplitude at the top of the generic shape. According to the Poisson coefficient of the polyurethane, a slight contraction corresponds to the elongation of the material during the bending of the model. This cannot be considered as a manufacturing defect. The higher, middle and lower position shapes of the oscillating model have been also measured with a CNC coordinate measuring machine. These measurements confirm maximal amplitudes included in [+0.461; +0.467] and minimal amplitudes included in [-0.514; -0.523]. The real surface of the model presents a battement defect fluctuating between -0.09mm and +0.12mm along a length of 70mm. This defect directly corresponds to 2D defect of the surface. As long as the amplitude of vibration is the only relevant parameter for these experiments, those defects will not affect the results of these experiments. As a result, the measure the deformed shape has validated the two-dimensionality of the deformation and the generic model can be considered 2D.

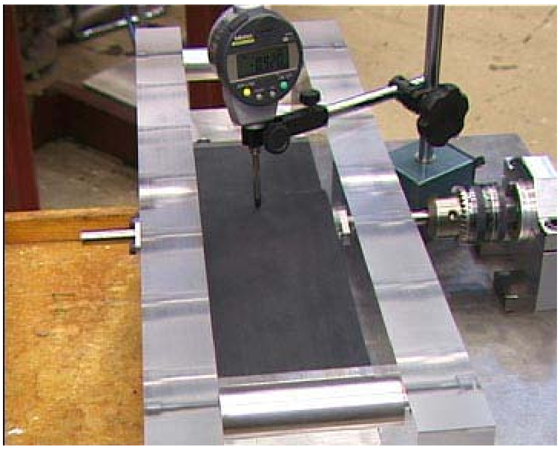

Figure 7: Static amplitude measurement.

This new test facility has the advantage to be adaptable to all the different camshafts that could be manufactured. A similar camshaft will be redesigned in the future to create different kinds of oscillation mode shapes. By introducing different phase angles between the three cams, it will be possible to create 3D structural oscillations. By mounting three actuators in the flexible model, it will be also possible to generate stripe oscillations.

The Oscillation Drive Train

The oscillation drive train is the mechanism transmitting the rotating power from the motor to the oscillating mechanism of the flexible model by double belts and pulleys transmission. Because of the moment fluctuation due to the high load oscillating on the actuator, the rotational velocity is not transmitted directly to the camshaft but by means of a secondary axle dimensioned to balance and mechanically control the inertia of the whole oscillation drive train. A frequency controlled AC servomotor will drive this oscillating mechanism. This servomotor is powerful enough to produce an oscillation of the flexible model at variable amplitude and frequency up to 500Hz.

The Geometry Measurement System

During oscillation, a geometry measurement system will measure precisely the model displacement through the top plexiglass window. This was considered necessary as the flexible structure interacts with the flow and thus will deform different then predicted. The geometry measurement system comprises a laser sensor determining precisely a displacement in one single point and in one direction with a bandwidth of 20kHz.

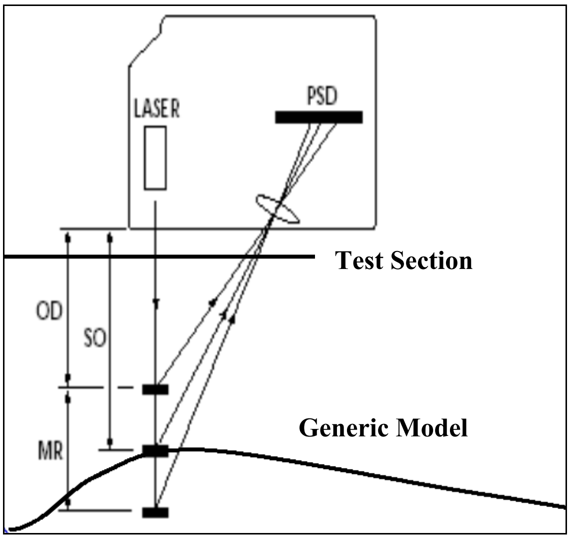

Figure 8: The laser triangulation measurement principle

The system measures displacements using triangulation. A laser source projects a beam of light onto the surface to be measured. At the surface the laser projects a spot of light at a first position. At some angle to the laser beam (up to ±30° from the perpendicular direction), a lens is used to form an image of this spot at an image plane located on a position sensitive detector (PSD). If the image is farther away from the sensor, the spot on the surface is formed at another position, and the image of this spot moves to another location on the PSD. By determining the position of the imaged spot and calculating the angles involved, the distance from the sensor to the surface can be determined. A linear moving system drives accurately this laser sensor over the test section to measure the whole model displacement through the top plexiglass optical access. Figure 8 shows the principle of the laser triangulation geometry measurement technique. The system will be used to determine the deformation of the model at the centerline. The number of measurement points along this centerline will be set in function of the oscillating frequency of the model to keep the measurement time under 2 to 3min for each stable oscillating frequency.

PLANNED MEASURING TECHNIQUES

Prior to unsteady measurements steady-state base case experiments will be carried out. These will be used to ensure stability and periodicity of the flow in the wind tunnel and to provide boundary conditions for numerical calculations. For the unsteady experiment different measurement techniques will be applied depending on the phenomena of interest. As all experiments will be carried out of distinct predefined operating conditions the results of the different techniques will contribute complementary to the physical understanding. Below a listing of the planned techniques is given.

- Schlieren
- 3D-L2F
- Steady state pressure measurement
- Unsteady pressure measurement

Each technique is shortly discussed below.

Schlieren Measurements

A conventional Schlieren system will be used to monitor the shock wave motion using a high-speed camera. The fluctuation of aerodynamic loads is linked to the shock wave motion. By post treating the results, it will be possible to connect this shock wave oscillation to the load force measured by the unsteady pressure measurements.

3D Laser-Two-Focus Anemometer

A state-of-the-art three dimensional Laser-Two-Focus Anemometer (3D-L2F) will be employed to measure the 3D mean velocity vector and the turbulence intensity at the inlet boundary as well as at different stations in the test section. This measurement technique will be also useful to define the whole flow field used as part of the boundary conditions. A complete description of the installation of this system could be found in Freudenreich [1998].

Steady state pressure measurement

A multichannel pressure measurement system (PSI 8400) is used for the steady state measurements as well as for monitoring the operating conditions during unsteady measurements. The system has an accuracy of 0.5% full scale, resulting in ±50Pa for the used 100kPa scanners. The combined error considering the barometer accuracy results to 0.5% in Mach number.

Unsteady Pressure Measurements

The data acquisition system used is a 32-channels high-speed data acquisition that will be used in conjunction with Kulite fast response transducers (XCQ-062). The system features a maximum sampling rate of 200kHz for all channels simultaneously and channel individual signal treatment. One version of the oscillating model will be equipped with Kulite transducers at discrete locations. Rather than integrating the transducers in the model, which is both flexible and deforming, the unsteady pressure will be tapped by means of PVC tubing that lead to transducers placed below the model. The tubes will end at a distance long enough to ensure full dissipation of the pressure wave. This technique, referred as long line probe, has been successfully employed previously as for example by Schäffer and Miatt [1985] or Sieverding et al [2000].

The working principle is that of a non-resonant system in which pressure fluctuations at the tube entrance are completely attenuated before reflecting back from the tube end, or attenuated to such a degree that reflections induce only insignificant measurements errors at the measurement station.

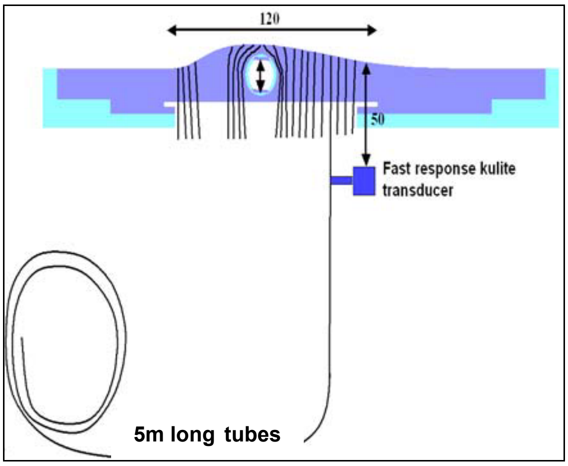

Figure 9: Long line pressure system.

Figure 9 shows the configuration of such a long line pressure system adapted to the present environment. A tube of 0.25 mm inner diameter and 2mm outer diameter will be used for the present application. The free ending part of the tube has been chosen to 5m for the present application. For practical reasons the tube will thereby be rolled up carefully in order to avoid premature pressure wave reflections. The system damps the pressure amplitudes strongly at frequencies above 1 kHz and causes equally a phase shift respect to the entrance pressure signal. The attenuation against frequency characteristics of the tube can easily be determined, see Olson [1957]. However, because of manufacturing defects or mishandling of the tube, a calibration is strongly recommended, see Chivers [1995], and will be done before commissioning of the test facility.

The chosen technique will allow using a large total amount of unsteady static pressure measurement locations. However only 32 taps will be sampled simultaneously. More than 200 pressure taps will allow integrating the time-dependent pressures obtained here into the aerodynamic damping coefficient. Such a pressure measurement will stay accurate even if high-pressure gradients (shock waves) are localized in the flow. The kind of transducers used here are very sensitive to changes in temperature as well as to acceleration effects of the model. Therefore, those will be located out of the oscillating structure and will be carefully calibrated under operational conditions. For this way to measure the unsteady static pressure over the model, it is very important to establish precisely the transfer functions associated to such a measurement system. Dynamic calibrations of the complete measuring chain, including amplifiers and filters, are thus necessary, both as regards the amplitude and phase angle response, especially in this application because the transducers are mounted at a non-negligible distance from the measuring points. Each tap will be calibrated dynamically using a calibration unit developed at KTH, see Vogt [2002]. The unit generates pressure pulses at variable frequencies that are ducted to a calibration head with integrated flush-mounted reference sensors. The transfer characteristic is thereafter determined applying PC-based signal analysis routines. The accuracy of the unsteady pressure measurement is also fundamental to the evaluation of the quality of this experimental campaign. A real experimental accuracy study will be led and linked to the base-line experiments like it has been done in Allegret-Bourdon [2002].

Synchronisation with the Geometry Measurement System

Both unsteady measurement and oscillating model geometry measurement have to be synchronized in time in order to reach a correlation of all the results. This will be done with an incremental shaft encoder located directly on one of the driving axle. This encoder is able to give precisely the angular position of the camshaft with 150 pulses per revolution.

Figure 10 explains the coupling between the geometry measurement system and the pressure measurement system. Figure 11 illustrates the synchronization of the measurements made with the encoder on the camshaft.

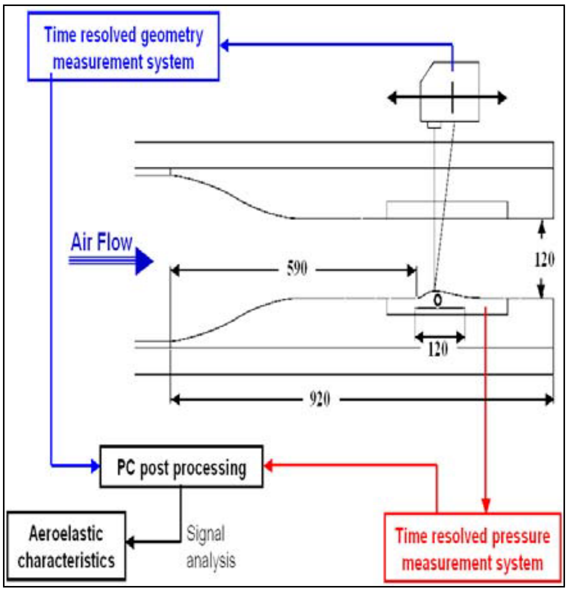

Figure 10: Coupling geometry measurement system and pressure measurement system

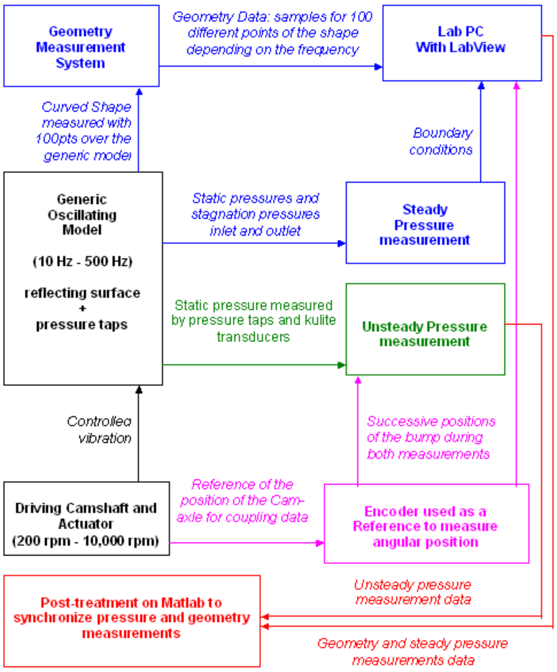

Figure 11: Synchronization of the measurements

From the couple including the driven camshaft and the oscillating generic model, several kinds of information are transmitted to four different acquisition systems:

- The geometry measurement system is measuring the curved shape displacement of the model. Data are then synchronized with Labview.
- The static pressures and stagnation pressures are measured by the steady state pressure measurement system. Data are synchronized with Labview and Mach numbers at the inlet and outlet are calculated with Matlab.
- Data of the precise position of the model from the encoder are recorded both by Labview and by one channel of the unsteady pressure measurement system.
- The unsteady static pressures are measured by the unsteady pressure measurement system as the same time as the reference position of the camshaft coming from the encoder.
- Data are finally post treated on Matlab, informations are synchronized with the help of the reference measurement of the camshaft position coming from the encoder.

CONCLUSIONS

The design of a new test facility for investigating fluid-structure interactions using a generic model has been presented. A generic flexible model will be used and a non-flexible version of the same shape has been studied earlier. The investigated prismatic 2D model will be mounted in a straight rectangular cross section of an existing transonic wind tunnel where this flexible generic model can be made oscillating in a controlled way. This displacement corresponds to a 1^{st} bending blade mode shape. The new mechanical oscillating mechanism driving the model is including a 3 cams axle, which is designed in such a way that bending amplitudes up to ±0.5mm could be reached at 500Hz maximal frequency. This removable camshaft will be redesigned to create 3D oscillations of the same 2D generic shape. To date the facility has been redesigned and manufacturing is ongoing. First tests have been successfully performed on the first version of the oscillating model off-rig. First unsteady tests on-rig with the presented new test facility are foreseen in the end of year 2002. Rather than modeling the aeroelastic behavior of a specific industrial application, the generic nature of this flexible model aims to provide a better fundamental understanding of the physics of aeroelastic problems. In the future, combined with an unsteady backpressure fluctuation system, the new test facility will be also able to combine unsteadiness from the transonic flows and from the oscillating model.

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