INFLUENCE OF TEMPERATURE TRANSIENTS AND CENTRIFUGAL FORCE ON FAST RESPONSE PRESSURE TRANSDUCERS

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Abstract

This contribution focuses on the use of fast response semi-conductor pressure transducers to measure accurately the mean and fluctuating total pressure or static pressure in a wind tunnel environment.

The problem of angular sensitivity is briefly addressed when measuring total pressure. Then, the influence of temperature is described when testing under steady or transient temperature conditions. The influence of the rotational speed is analyzed when measuring with rotating transducers. The transfer function of a sensor-cavity system is addressed briefly.

Correction methods are proposed for both the effects of the temperature and the rotational speed. Several applications are presented covering turbulence measurement with a quasi-steady probe, static and total pressure measurements in the absolute frame and the relative frame.

Nomenclature

a: slope of linear calibration law
b: origin of linear calibration
O: origin of linear calibration
P: Pressure
S: slope of linear calibration law
T: temperature
Vs: Voltage that relates the temperature of the transducer

Introduction

The emergence of miniature semi-conductor pressure transducers allowed a considerable enhancement of the frequency bandwidth that can be covered by Pitot probe (total pressure), 3, 4 or 5 hole probes (static pressure and flow angles) and by pressure taps on end-walls. These tools are obviously very useful in a turbomachinery environment where the flow field is highly unsteady with blade passing events ranging between 1 and 10 kHz. There exists a large number of examples in the literature showing a routinely use of these types of transducers (Dring et al, 1982, Moss et al., 1997, Hilditch et al., 1998, Busby et al., 1999, Dénos et al., 1999...).

Unfortunately, the use of these transducers is not so straight forward. They are sensitive to temperature and need an appropriate correction (Batt et al., 1995, Gossweiler, 1996). The transfer function of the measurement system must be evaluated in order to determine the limitations in terms of frequency response and eventually correct the zones of resonance using compensation (Gossweiler, 1996).

In the case of probes, the geometry of the head is selected depending on the application (single, head, 3 holes, 4 holes), on the feasibility of the mechanical implementation of the sensors in a restricted volume; another concern linked to the head geometry is the minimization of unsteady spurious effects like the von Karman vortex street of the probe (Epstein, 1985, Ainsworth, 1995, Gossweiler, 1996, Brouckaert et al., 1998). An extensive literature survey on these fast response probes can be found in Sieverding et al. 2000.

This paper concentrates on the behavior of the transducers when submitted to temperature transients, like in blow-down wind tunnels, and centrifugal force. Correction methods are proposed in each case. The angular sensitivity of a fast response Pitot probe and considerations on the transfer function of transducers embedded in cavities are addressed briefly.

Finally, the applicability of these transducers for static pressure measurement on fixed end-walls or rotating blades and total pressure measurements with Pitot probe is demonstrated.

Working Principle

The Kulite pressure transducers are piezo-resistive semi-conductor sensors. 4 piezo-resistors are arranged in a Wheatstone bridge as shown in Figure 1. Two of them work in compression while the two others experience a tension in such a way that, when pressure is applied on the membrane, the overall resistance of the bridge does not change but the unbalance of the bridge is proportional to the pressure.

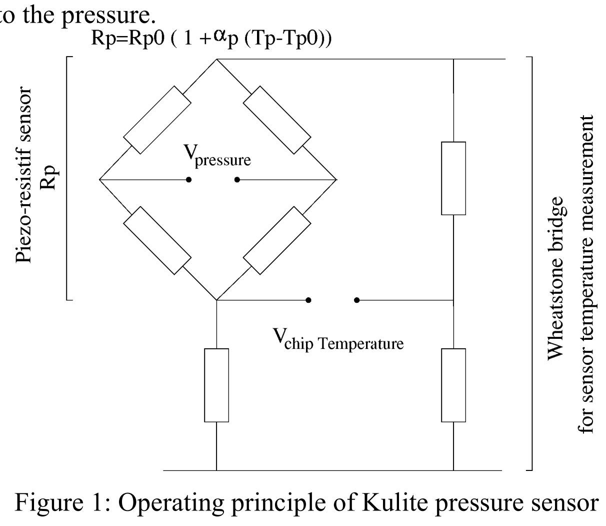

Figure 1: Operating principle of Kulite pressure sensor

It is well known that these sensors are sensitive to temperature: the overall resistance of the bridge changes linearly with temperature, which affects both the slope and the origin of the calibration law versus pressure.

Passive temperature correction can be achieved by adding an external resistor that minimizes the sensitivity to temperature but also reduces the overall sensor output. Due to the size of the compensation system and the implementation problems that results (especially for measurements in rotation), this technique is not used at VKI. A post processing correction, that allows a fine control of this error, is preferred.

In order to monitor both the pressure related by the transducer the temperature of the sensor membrane, a double Wheatstone bridge arrangement is used as shown in Figure 1. The voltage, which is proportional to temperature, is referred to as Vsense (Vs).

Angular sensitivity of a simple Pitot probe

Commercial packages are available from several companies where the chip is embedded in a cylinder, with or without protecting screen or protective coating. Such packages provide a simple solution to build a cheap fast response Pitot probe that, presumably, will measure the total pressure.

One of the first probes that was built at VKI was integrating a standard 15 PSI Kulite transducer (cylinder of 1.65 mm diameter and 9 mm length) on a stem. The transducer is protected by a screen consisting of a plate with small holes at the periphery as shown in Figure 2.

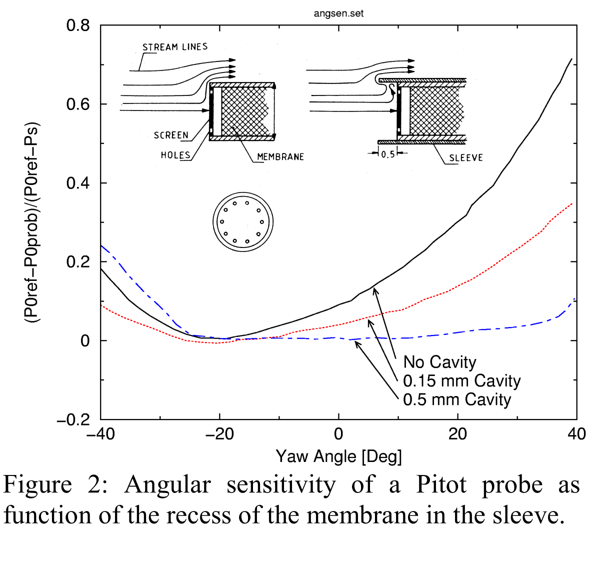

Figure 2: Angular sensitivity of a Pitot probe as a function of the recess of the membrane in the sleeve.

After calibrating the probe in a chamber, the Pitot probe was used to measure the total pressure in a jet. The total pressure was also measured with a pneumatic probe inside the settling chamber that precedes the nozzle. It was noticed that the discrepancy between the fast response probe and the pneumatic probe was increasing as the velocity of the jet was increased. Under 240 mbar of dynamic head, the fast response Pitot was indicating only 200 mbar.

A calibration of the Pitot as a function of the yaw angle revealed that the probe was very sensitive to the incidence and that the total pressure was recovered when the probe was at -20 deg with respect to the calibrating jet (see Figure 2). Although the dimensions of the transducer are small, the alignment of the cylinder with the stem was better than 20 deg. and the reason for the non-symmetrical shape of the curve is not well understood. It could be due to a bad positioning of the membrane.

In order to improve this situation, a sleeve was inserted around the transducer. Two recesses of the screen with respect to the extremity of the sleeve were tested: 0.15 mm and 0.50 mm. The sensitivity to incidence was improved successively as shown in the graph of Figure 2 and the measurement of total pressure in a jet were successful. Of course, the increase of the size of the cavity did reduce the resonance frequency: for the 0.5 mm recess, the resonance frequency went down to 20 kHz. Note that in this particular case, there are two cavities in front of the membrane: a first one constituted by the sleeve and a second due to the volume between the screen and the membrane. Part of the poor quality of the initial Pitot probe was attributed to the screen. The holes being located at the periphery, it is likely that the flow is not at rest in this region as shown by the streamline plot on the top of Figure 2. In the case of a cavity created by the sleeve, the stagnation of the flow is obviously improved and the sensitivity to incidence is reduced.

This experience demonstrates that, although this commercial package is supposed to be able to measure the total pressure, it is necessary to check that the probe works properly. Obviously, the design rules that apply for standard pneumatic probe are also valid for fast response probe. The next transducers that were purchased were not equipped with a screen but a thin RTV coating that does not create a cavity and preserves the frequency response of the membrane. This coating performs well in clean environment such as in wind-tunnels. Moreover, the membrane has a 0.3 mm recess with respect to the extremity of the cylindrical housing in order to improve the insensitivity to flow incidence.

Influence of temperature: calibration under thermal equilibrium.

This section deals with the calibration of a set of commercial Kulites transducers (25 PSI, absolute) that are dedicated to monitor the pressure in a turbine stage. Some of the transducers were embedded in the hub and tip end-walls to measure the static pressure downstream of the stator while others were inserted on a stem to measure the total pressure downstream of the rotor.

The transducers were calibrated according to the technique developed at Oxford (Ainsworth, 1995, Batt et al. 1995). Given that P=1/S(V-O) (S:slope, O:origin), they demonstrated that O and S both depend linearly on the temperature. The problem of this formulation is the appearance of a large number of terms when developing the expression with the sensitivities of the slope and the origin as a function of temperature. For simplicity, another formulation was chosen for the sensitivity of the slope and the origin to temperature.

With $P = a[bar/V]V + b[bar]$ and $T = a_{vs}V_s + b_{vs}$, the sensitivities of the slope and the origin as a function of temperature are written as:

$$a = \frac{da}{dT}(T - T_0) + a_0 \text{ and}$$

$$b = \frac{db}{dT}(T - T_0) + b_0$$

It can be demonstrated that, in the range of sensitivity to temperature of the slope and the origin of the present set of transducers, this second formulation is equivalent to the one of Oxford, provided the temperature variation with respect to the reference temperature T_0 does not exceed 50 K.

The transducers were calibrated in a sealed chamber that can be pressurized or depressurized. The chamber is placed in a controlled temperature oil bath. Once the temperature of the oil bath is stable, a calibration versus pressure is performed. The calibration is repeated for several temperatures. A sufficient duration is observed between the successive temperatures (at least 1/2 hour) in order to ensure that thermal equilibrium is reached. Finally, linear regressions are performed on Vs, the slope and the origin of the pressure law versus temperature. The mean values and standard deviations over the 10 Ps2 gauges in the range 20-50 ^{o}C are shown in Table 1. The gain of the amplifier that monitors the unbalance of the bridge for the pressure signal is 25.

	a_{vs} [C/V]	a (20^{o}C) [bar/V]	da/dT [bar/(VC)]	db/dT [bar/C]
Mean	-7.536	0.836	-0.00080	-0.0040
Std	0.057	0.067	0.00023	0.0030

Table 1: Average sensitivities to temperature for a set of 10 sensors

Note that an increase of temperature causes:
- a decrease of the slope a
- a decrease of the origin b

The pressure correction to be applied for a voltage of 1V (0.830 bar) for an "average" sensor are shown in Figure 3. The correction from the origin is by far the most important. The overall correction is not negligible.

Note that some of the points were performed while increasing the temperature between two successive points and others while decreasing the temperature. Surprisingly, if the calibration versus pressure is performed after a duration of 1/4 hour of thermal stabilization, a linear relationship is obtained for Vsense but not for the slope and the origin that suffer from an hysteresis effect. At least 1/2 hour of stabilization is necessary to obtain a linear dependence of the slope and the origin.

Among the sensors calibrated in this way, 10 were inserted in a cylindrical groove for static pressure measurements on he hub and tip end-walls (see Figure 7) and 2 were encapsulated in the stem of a probe for the stage downstream total pressure measurements (see Figure 14). The values of pressure given by the fast response transducers can be controlled thanks to pneumatic taps in the end-walls and thanks to a pneumatic Pitot probe placed downstream of the stage. The measurements of the fast response transducers obtained during a blow-down test were corrected for temperature and compared with their corresponding pneumatic devices. For time-averaged values of pressure ranging between 0.55 and 0.9 bar, the discrepancies between the fast response transducers and the pneumatic taps or probes were ranging between 20 to 80 mbar.

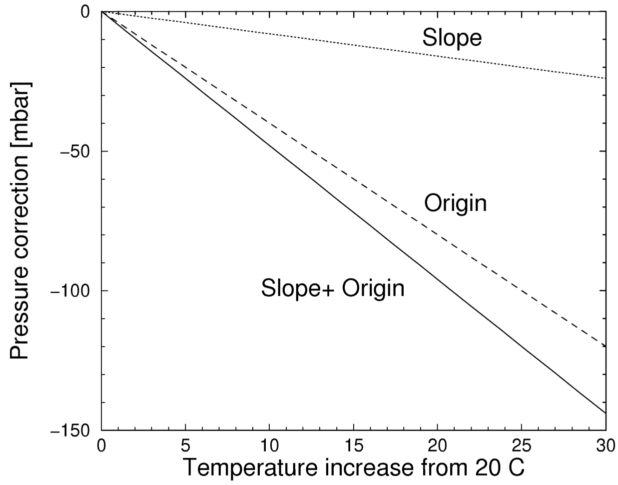

Figure 3: Pressure correction as a function of temperature for an "average" sensor and a voltage output of 1 V (0.830 bar)

These differences can be partially attributed to the fact that the calibration of the fast response transducers was performed with the bare cylinders (it is difficult to put the turbine casing in a controlled temperature oil bath). Some stress may result from the encapsulation of the transducers that modifies both the calibration law and the sensitivities to temperature.

Another reason is due to the fact that the temperature correction is not valid for a blow-down test. Indeed, the calibration versus temperature showed that a linear dependence as a function of temperature could be obtained on the slope and the origin only if the transducers were at thermal equilibrium. Obviously, the transducers are under thermal equilibrium prior to the blow-down (ambient temperature) but during the blow-down (about 0.5 s duration), hot gas flows over the end-walls and the probes, resulting in a temperature transient.

For these reasons, it was decided to perform calibrations in the test rig under transient conditions.

Influence of temperature: calibration under a temperature transient.

The calibration under transient conditions is performed as follows. The rotor is put into rotation under low pressure level (0.050 bar). While the rotor speeds-up (Figure 4.a, axis on the right), the ventilation losses increase, so does the temperature of the sensors (Figure 4.b). Then the air supply of the aero-brake (normally used after a blow-down test to decelerate the rotor) is opened (t=470 s) and air is released in the test section leading to a sudden increase of pressure (Figure 4.a, pneumatic) and temperature due to the compression in a closed volume.

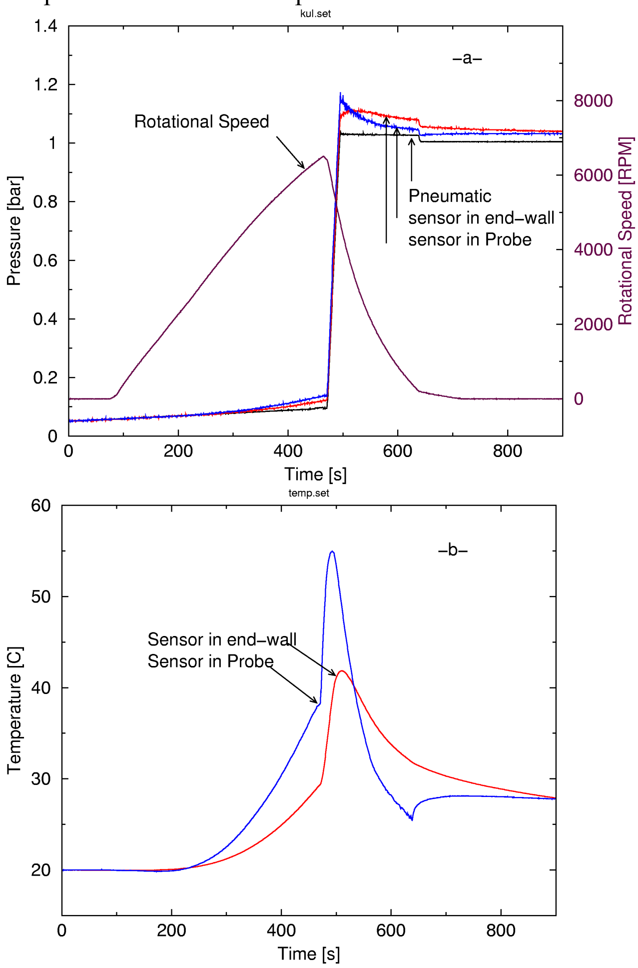

Figure 4: Evolution of: a) the rotational and the pressure (fast response sensor traces are not corrected for temperature) b) the transducer temperature during the transient calibration.

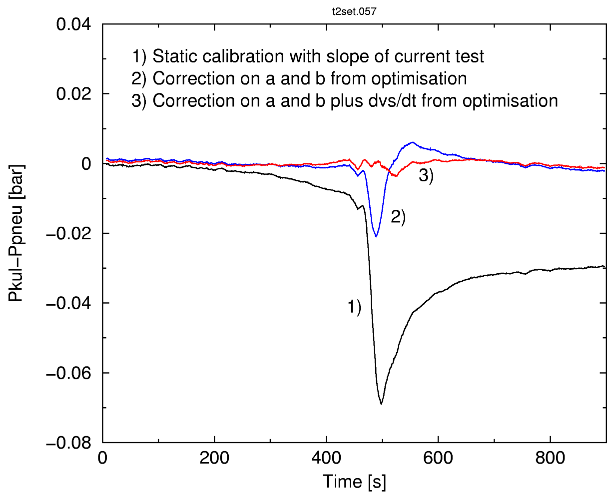

Figure 5: Errors on the sensor in end-wall for the different correction techniques

At t=500 s, the test section is opened to atmosphere thanks to an automatic valve. Due to the continuous admission of cold air from the brake, the test section stays slightly above atmospheric pressure and the sensor temperature starts to decrease. At t=630s, the brake is stopped and the pressure in the test section comes back to atmospheric pressure; the temperature continues to decrease.

Figure 4.a shows two sensor outputs (one in end-wall, one in probe) converted in pressure but not corrected for temperature together with the "true" pressure from a standard transducer connected to a pressure tap (pneumatic). The corresponding evolution of temperature for each sensor is shown in Figure 4.b. The temperature increase felt by the transducer in the probe is much higher than the one felt by the sensor buried in the end-wall which results in a larger distortion of the uncorrected pressure traces.

If the correction obtained from the calibrations under thermal equilibrium is applied, a large discrepancy is observed with the pneumatic tap as shown on Figure 5, curve 1), although the origin of the calibration law was recomputed so that the measurements of the fast response transducer and the pneumatic tap give the same value at t=0.

To improve this situation, it was decided to use a minimization routine from a Fortran mathematic library (Nag) which fits at best the corrected output of the fast response sensor to the pneumatic measurement using the model described above. This routine is a quasi-Newton algorithm that minimizes a function. Here, the function is the sum of the differences between the pneumatic trace and the sensor corrected trace to the square. From an initial guess, the routine tests the influence of each parameter on the first and second derivative of the function to find its minimum. This was performed using directly Vs instead of the temperature for simplification. The result is shown in Figure 5, curve 2). The error has decreased substantially with respect to the first correction technique but it seems that the model is unable to correct the part were the temperature transient is the largest. The error reaches 20 mbar in this zone. One could argue that the pneumatic tap has a slowest response than the fast response one and that the transient response cannot match. This argument is not valid here because the zone of disagreement exceeds 100 s and the frequency response of the pneumatic probe exceeds 50 Hz.

As it is suspected that the correction is not only function of the temperature but also of how fast the temperature changes, it was decided to add a correction term in the model linked to dVs/dt (t: time). The result is the third curve of Figure 5; the error is now below +/- 5 mbar. This transient term could be due to unsteady conduction between the sensitive membrane and its pillars. Due to the different size and heat storage capacity of the elements of the transducer, it is clear that when this one experiences a temperature transient, all the elements will not take simultaneously the same temperature. As a result, unsteady conduction takes place between the different elements and, similarly to short wires or thermocouples on large supports, the average temperature that is displayed hides a non uniform temperature distribution on the surface of the sensitive element.

Notice that the "speed" of the transient that was generated in this test is much slower than what is encountered in a blowdown test (duration: 0.5 s). For this reason, it was decided to exclude the correction of the transient in the blowdown test. The estimated accuracy of +/15 mbar is still satisfactory with respect to the values that are to be measured (between 0.6 and 0.9 bar).

Although the minimization routine is very powerful, one must keep in mind that it can find properly the coefficient of sensitivity to temperature only if the information is contained in the transient test namely if the temperature and pressure variations are broad enough. The use of the coefficients found by the routine in a range that exceeds the range of the calibration (extrapolation) is very dangerous.

Influence of the rotational speed

This section addresses the influence of the centrifugal force when measuring for example on a rotor blade. A typical blow-down test in the VKI turbine stage facility takes place as follows. In a first phase, the rotor is spun-up under almost vacuum (50 mbar) from 0 RPM close to the design speed (6300 RPM). During the 0.5 s blowdown , the speed rises further due to the power delivered by the turbine and the absence of energy absorption system (from 6300 RPM to 6700 RPM). During the run-up from 0 to 6300 RPM, large drifts were observed for some transducers. The sensitivity to temperature of the sensors that were implemented flush-mounted to the blade surface by the University of Oxford is very small. For this reason the effect of the centrifugal force was suspected. To illustrate this, the evolution of the pressure drift was plotted as a function of RPM^2 in Figure 6 for some selected gauges.

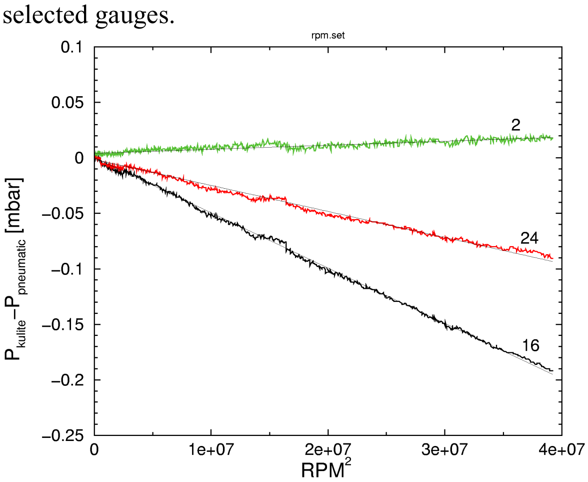

Figure 6: Drifts due to centrifugal force for some sensors

Drifts up to 0.2 bar are observed. The sensors no 24 and 16 are particularly sensitive to the centrifugal force because they are located on a section that is close to tip (85% span) on the pressure side. In this region, the surface of the blade is inclined with respect to the radial direction. As a result, the membrane of the transducer is also inclined and is very sensitive to the centrifugal force. On other sections (15 and 50%), the surface is not so much inclined and the drifts are moderated.

The linear laws shown in Figure 6 can be used to correct the drift on the origin, assuming the slope is not sensitive to the centrifugal force. An easier solution is to modify the origin of the calibration law of the fast response transducers so that they indicate the same pressure level than some pneumatic taps located in the test section prior to the blow-down. If this drift is moderated, the drift that will occur during the blow-down due to the increase of rotational speed from 6300 to 6700 RPM can be neglected (in the case of gauge 2 in Figure 6, this would amount to 2.6 mbar only). This is not the case for the most sensitive transducers (in the case of gauge 16, the drift would amount to -26 mbar) but this can be corrected with the linear law.

Resonance frequency when embedded below cavities

The testing of the transfer function of fast response transducers is a delicate task because it is difficult to generate excitations of well know shapes at high frequency.

Some feature like resonances can however be put into evidence when the probe is submitted to unsteady periodic flow with non-sinusoidal variations thanks to the harmonics of the spectrum. This is the case in a turbine stage with blade passing events. The FFT modulus of the signals recorder by three gauges that were embedded in the end-walls of the VKI turbine stage facility downstream of the vane according to the drawing in Figure 7 are shown in Figure 8.

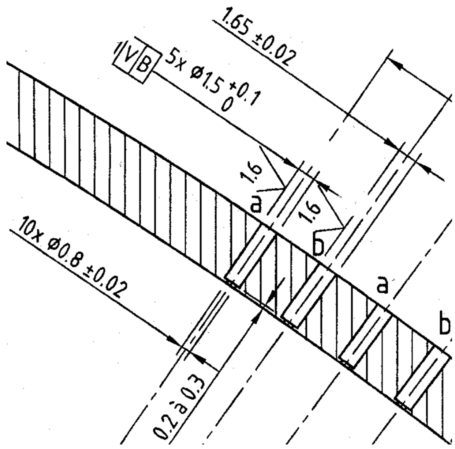

Figure 7: Geometry of the cavity and the orifice dedicated to host the fast response in the tip end-wall.

The signature of each transducer-orifice-cavity system is repetitive from test to test and each system has its own signature depending on small differences between the transducers, the cavities, the orifices and the positioning of the transducer in the cavity. Some resonance frequencies appear clearly on the spectrum and the frequency around which the resonance is seen changes depending on the transducers. Moreover, two resonances can be observed in each spectrum probably due to the two cavities: the short line of 0.8mm diameter 0.2 to 0.3 mm long and the cavity existing in front of the membrane of the transducer due to the 0.3 mm recess. These resonances give artificially emphasis to the noise or some harmonics that are located in these particular frequency bandwidths. In order to obtain a proper signal, one would need to know the exact transfer function and compensate the signal accordingly to remove the resonances.

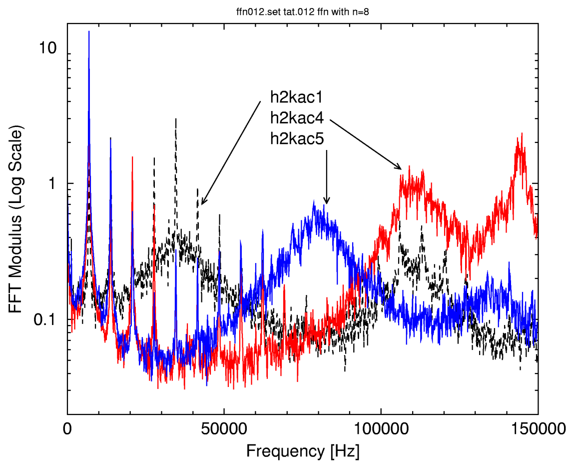

Figure 8: Modulus for FFT of 3 transducers signal when unsteady periodic pressure fluctuations at 4.6 kHz

Note that the graph is in logarithmic scale and that, for this particular application, there is at least one order of magnitude between the peak amplitude of the fundamental and the maximum amplitude of the resonance. In this case, only a low-pass filtering at 60 kHz was applied that removes most of the resonances.

Examples of applications

Measuring turbulence in a stator wake

In this first application, the use of a fast response Pitot probe to measure the turbulence in a stator wake is presented. Similar applications of this type of probe to measure turbulence are reported by Wallace and Davies 1996 and Gossweiler, 1996; they also performed a comparison with hot wire measurements. It is assumed that the velocity fluctuations are only generated by total pressure fluctuations and not by static pressure fluctuations.

The turbulence was first evaluated with the fixed probe at successive locations in the stator pitch as shown in Figure 9 (hollow squares). Each point corresponds to a blowdown test. In order to gain time, the probe was traversed across two successive vane pitches during the blow-down and the signals where sampled at high frequency (1 MHz). In the data reduction, it was assumed that, although the probe is moving continuously, all the data taken on a small portion of the displacement (in this case 1/34 of a pitch) could be considered as if it was measured by a fixed probe located in the center of the portion of the displacement. The results in terms of total pressure and turbulence are shown in Figure 9 with filled circles and filled diamonds respectively. The agreement between the two types of measurements (fixed and traversing) is excellent. A significant amount of tests can be saved with this technique.

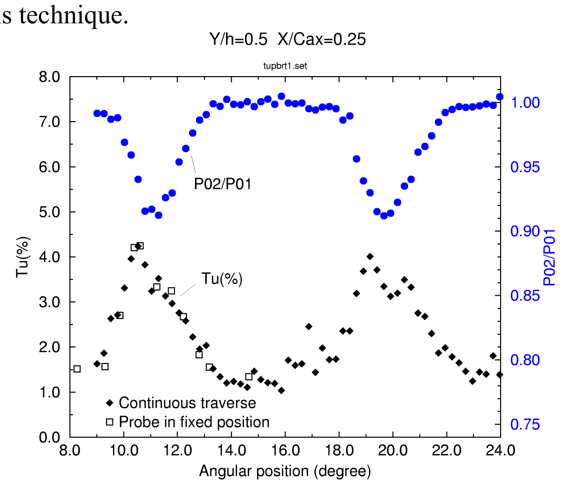

Figure 9: Measuring the turbulence downstream of a vane with a fast response pressure probe.

Traversing a jet in rotation

For this application, a Pitot probe with a 0.5 mm recess of the membrane was put into rotation downstream of several successive identical nozzles placed at the same radius. The relative total pressure measured by the probe for a jet passing frequency of 2.5 kHz is shown in Figure 10. One unexpected feature is the overshoot that occurs when the probe enters the jet (it does not happen when it exits the jet). This overshoot could be attributed to the resonance frequency of the probe, which was quite low in this case. With the knowledge of the transfer function of the probe, it would have been possible to remove it. Provided the effects of temperature and centrifugal force are taken into account, the level indicated by the probe after the overshoot is in good agreement with the relative total pressure computed from the absolute total pressure measured by a pneumatic probe in the chamber that feeds the nozzle and the peripheral speed of the probe.

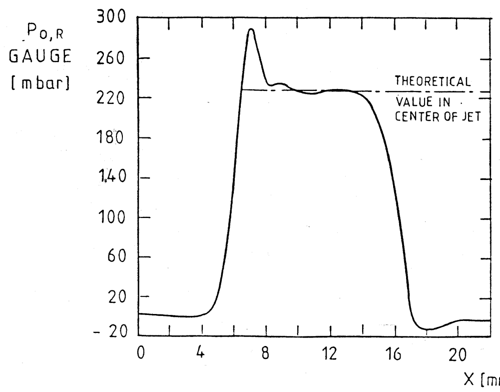

Figure 10: Relative total pressure measured by a Pitot rotating downstream of circular jets.

Measuring the rotor relative inlet total pressure in a transonic turbine stage

A small Pitot was inserted in the leading edge of the rotor. The axis of the probe is aligned with the computed time-averaged relative inlet angle. In a first attempt, the measured time-averaged relative inlet total pressure was lower than the static pressure measured by a transducer mounted flush with the surface in the region of the stagnation point. The transducer that was used was just equipped with the standard recess of the membrane of 0.3 mm. As a quasi 3D unsteady Navier&Stokes computation predicted that the relative inlet angle could change by 15 deg (+/- 7.5 deg) it was decided to install a sleeve with a conical entrance (see picture in Figure 11). The results compared much better with the static pressure measured at the stagnation point. The phase locked average of the fluctuations as well as the variation of the raw signal with respect to the phase locked (RMS curve) are reported in Figure 11. The abscissa represents the vane passing events. The steep pressure increase at phase 1.0 is due to the traverse of the vane trailing edge shock.

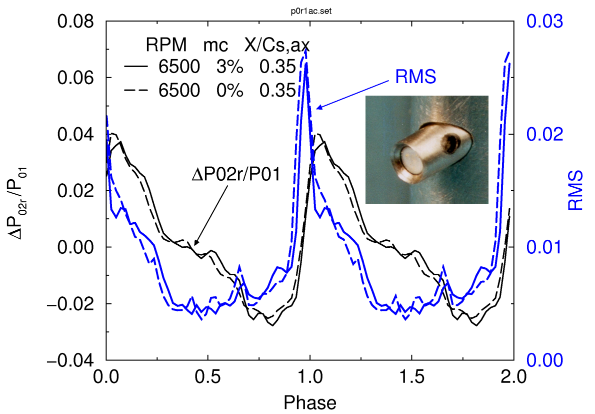

Figure 11: Relative inlet total pressure measured at the rotor leading edge in the turbine test rig.

Measuring static pressure on end-walls

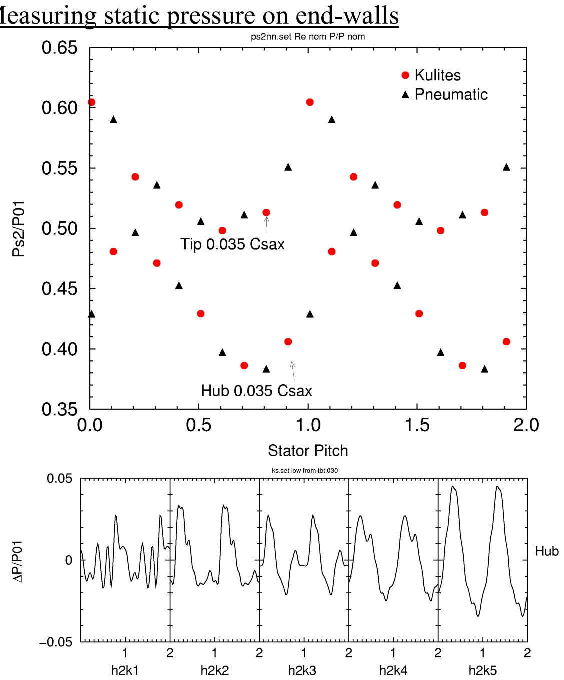

Figure 12: Steady and unsteady static pressure downstream of the vane in a transonic turbine stage.

These static pressure measurements were performed in the blow-down turbine test rig downstream of the vane in 5 points at hub and 5 points at tip. Pneumatic taps were also measuring the time-averaged static pressure in between the fast response transducers. The transducers were encapsulated in the end-walls as shown in Figure 7. The temperature correction was applied and the mean value of the pressure could be measured accurately as shown in the top graph of Figure 12 that reports together the steady measurements from the pneumatic taps and the fast response transducers. The unsteady component of the signal revealed large fluctuations at the rotor blade passing frequency (6.9kHz). Note that the vane flow is transonic.

Measuring static pressure on rotor blade end-walls

The static pressure around the rotor blade mid-span section was measured with transducers flush-mounted with the surface of the rotor blade implemented at the University of Oxford. The measurements are corrected for the centrifugal force only because the correction due to the sensitivity to temperature was negligible in this case. The measurements revealed the sweeping of the vane trailing edge shock in the leading edge region, on the suction side.

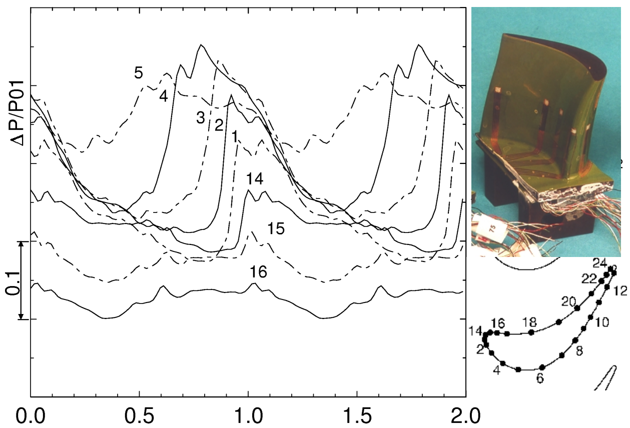

Figure 13: Unsteady static pressure in several points around the rotor blade in a transonic turbine stage.

Measuring the stage downstream total pressure with a fixed Pitot.

The measurements are performed with a twin head fast response probe (picture in Figure 14) in a fixed position downstream of the rotor. By changing the radius of the probe between two successive tests the unsteady flow field could be evaluated along a radius.

The measurements are corrected for temperature. The time-averaged quantities form the fast response probe compare very well with measurements performed with a pneumatic probe. The time-resolved total pressure measurements are plotted in Figure 14. In this case, the rotor exit flow field is in the transonic regime and the trailing edge shock causes a static pressure discontinuity. This discontinuity is felt in the absolute total pressure (steep gradients in the region 0.4 0.5. Note that the rotor exit flow field is transonic in the relative frame but the absolute exit Mach number is 0.6.

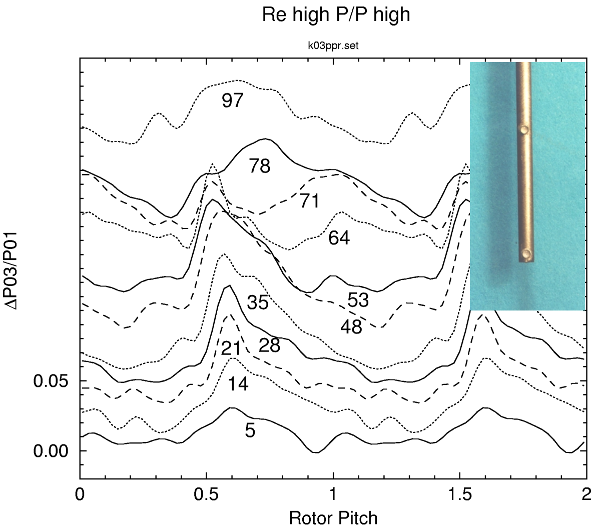

Figure 14: Stage downstream pressure when the rotor operates in the transonic range.

Conclusions

Fast response pressure transducers are very powerful tools for the investigation of steady and unsteady components of the static and total pressure in the stationary frame as well as in the rotating frame.

However, the same limitations that apply for pneumatic Pitot probes apply for fast response Pitot probes as far as the sensitivity to the flow incidence is concerned.

The sensitivity to temperature must be tested and controlled. Calibrations under thermal equilibrium are not well suited to correct the data obtained during transient tests. A powerful method using a minimization routine to find the coefficient of sensitivity to temperature during a calibration test under transient conditions was presented and successfully applied.

The effect of centrifugal force applying of the transducer membrane was demonstrated when measuring in rotation. Large drifts result when the membrane of the transducer is inclined with respect to the radial direction. The linear evolution of the drift as a function of RPM^2 can be used to correct the signals.

Finally, it is desirable to identify and control the bands of resonance in the transfer function of these measurement devices in order to avoid the amplification of the oscillations in these bands.

Provided that the user is able to take into account the above-mentioned phenomena and to judge whether or not a correction is required, these transducers can be used in a broad range of applications with a good accuracy. The presented examples showed their applicability to measure:

- turbulence in a flow with slow moving probes.
-steady and unsteady components of the static pressure in fixed or rotating end-walls, flush mounted with the surface or encapsulated underneath a short line.
- steady and unsteady total pressure with Pitot probe fixed or rotating; the correct measurement of the total pressure requires however that the range of insensitivity to flow incidence is broad enough.

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