A TECHNIQUE FOR USING RECESSED-MOUNTED PRESSURE TRANSDUCERS TO MEASURE UNSTEADY PRESSURE

Vogt, D. M.
The Royal Institute of Technology
Chair of Heat and Power Technology
Stockholm, Sweden

Fransson, T. H.
The Royal Institute of Technology
Chair of Heat and Power Technology
Stockholm, Sweden

ABSTRACT

The present paper describes a technique for using recessed-mounted miniature pressure transducers to measure unsteady pressures in turbomachine related test facilities. Rather than embedding transducers at the desired measurement location as it is done traditionally the presented technique proposes to mount the transducers in a recessed manner. The advantage of such setup is that the transducer can be mounted away from deterioration sources such as excessive acceleration and high temperature. Furthermore by choosing an exchangeable type of mounting one single transducer can be used to serve several measurement locations subsequently such as to increase spatial resolution at moderate costs. The setup needs however to be calibrated dynamically, as recessing the transducers leads to damping and lagging of the pressure perturbation, which can be assessed by transfer functions. A new experimental apparatus has therefore been developed that allows dynamic calibration of the setup at relevant parameters for determination of the transfer function in the frequency domain.

INTRODUCTION

The experimental investigation of unsteady flow phenomena is of continuous interest in turbomachine related research topics. Several studies have addressed problems related to fluid-structure interaction that can lead to high cycle fatigue (HCF) and the disintegration of engine parts. In case of forced response the forcing is due to a systematic temporal unsteadiness in the observer frame of reference (let it be a turbomachine rotor), which might be caused due to spatial discontinuities in the stationary frame of reference or by flow instabilities. The phenomenon of flutter on the other hand denotes a self-excited and self-sustained resonant oscillation of the aeroelastic system that can lead to structural failure in a short period of time. When studying such problems experimentally one of the central questions is the forcing exerted by the fluid on the structure. To determine the forcing one can either aim at measuring the cause, i.e. the pressure perturbation, or the effect such as the deflection of a structure. Although both types of measurements can lead to concluding on system stability, the former method yields spatially resolved data and therefore allows a more intimate treatment of the phenomenon.

Traditional techniques for measuring unsteady pressures comprise the use of miniature fast response pressure transducers (e.g. piezo-resistive transducers) that are embedded in the test object at the measurement location, see for example Manwaring et al. (1996) or Sanders et al. (2002). By mounting the transducers flush with the test object surface the dynamic transfer characteristics are ideally those of the transducer only and might yield distortion-free data up to few 100 kHz. Care must however be taken in case the transducers are placed on vibrating objects as the pressure signal might be spoilt by vibration-induced signals. By calibrating the setup at no-flow conditions this effect can successively be filtered out from the measured signal. Furthermore dynamic calibration of the mounted pressure transducers should be performed such as to account for signal distortions that might arise from the mounting of the transducers. Although the technique of using direct mounted pressure transducers represents the most straightforward way of measuring unsteady pressure it has its limitations in the operating range of the transducers in terms of maximum allowed acceleration and temperature range.

Capacitive, variable reluctance or optical sensors are although less commonly being employed as alternative sensor technique. Lately the application of pressure sensitive paint has appeared as novel pressure measurement technique, see for example McLachlan (1995) or Klein (2000). The technique is based on the oxygen-quenching effect that modifies the luminescence intensity of organic molecules whilst excited by light. Proper calibration allows relating the intensity to pressure. This technique has successfully been used in steady-state wind tunnel testing however has to date found little application in unsteady testing. Although the dynamics of the quenching process allowed measurements at relevant frequencies of the order of kHz the diffusion of oxygen into the binder material containing the organic molecules currently limits dynamic application to the order of few Hz.

NOMENCLATURE

Variables

a	speed of sound, m/s
d	capillarity tube inner diameter, m
f	frequency, Hz
j	complex variable, $j = \sqrt{-1}$
k	wave number, [1,2, 3,…]
p	pressure, kPa
s	signal, V
G	complex transfer function
L	tube length, m
V_c	sensor cavity volume, m^3
λ	wave length, m
ω	frequency, rad/s

Subscripts

0	total length
line	associated to tap-tube-cavity
sens	associated to sensor
tap	associated to tap

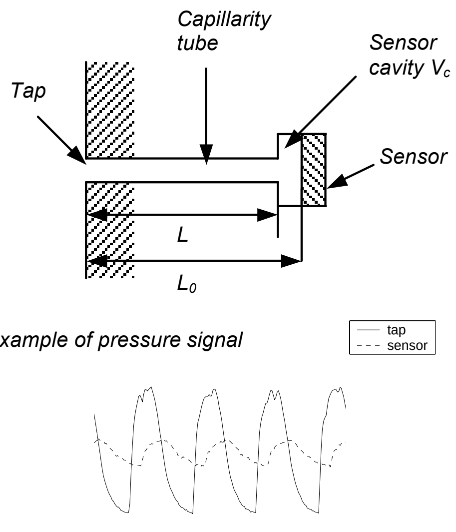


Figure 1. Principle of recessed-mounted pressure transducer and signal sample

DESCRIPTION OF THE METHOD

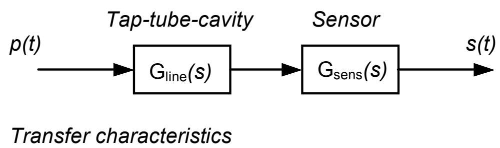
The technique presented herein suggests using fast-response pressure transducers that are mounted in a recessed way and connected by a miniature capillarity tube to the measurement location, see figure 1. The advantage of such setup is that the transducer can be mounted at a location of favorable operating conditions (low acceleration, low temperature) and that a single transducers can be used to measure several locations although consecutively. Due to the arrangement comprising capillarity tube, sensor cavity and the sensor itself the setup features resonance frequencies that limit the measurable frequency range. The setup can either be modeled as organ pipe assuming that a λ/4 wave will establish in the capillarity tube yielding the following resonance frequencies

$$f = k \cdot \frac{a}{4L_0}, \; k = 1,2,3.. \qquad \text{Eq. 1}$$

On the other hand the setup can be modeled as Helmholtz resonator with the resonance frequency to be evaluated from

$$f = \frac{\pi}{2} a \sqrt{\frac{d^2 \pi}{4 L V_c}} \qquad \text{Eq. 2}$$

Although the resonance frequencies often are seen as the only limitation when using a recessed arrangement in terms of upper frequency limit the dynamic transfer characteristic up to this limit are far from ideal. The process of propagation of pressure perturbations in capillarity tubes as well as the exchange of gas at the measurement location (i.e. tap) are complex and are leading to attenuation and phase shift of the pressure signal that needs to be described by a dynamic transfer function (Dibelius and Minten, 1983).



$$G(j\omega) = G_{line}(j\omega) \cdot G_{sens}(j\omega)$$

Figure 2. System representation of recessed-mounted measurement setup

Schematically the system can be represented as depicted in figure 2 consisting of a transfer part from the chain “tap-tube-cavity” and the transfer of the sensor itself. Berg and Tijdeman (1965) have theoretically described the dynamic transfer properties of arrangements of thin tubes and volumes by recursion formulae. Comparisons of the theoretical results to experimental data have shown that for small amplitudes the system behaves linearly and that the dynamic transfer properties could be predicted to a high degree of accuracy. The magnitudes of unsteady pressure perturbations in the targeted applications of the technique presented herein are however assumed being of considerable magnitude exceeding the assumption of linearity of pressure propagation in capillarity tubes.

In the presented technique dynamic calibration has been used as alternative way of determining dynamic transfer characteristics. A harmonic pressure perturbation signal has been applied at the tap whilst signal recordings have been acquired over a range of frequencies from the recessed-mounted sensor. A sensor that has been placed right at the tap in a miniature cavity has thereby referenced the pressure signal at the tap. A siren type pressure pulse generator has been used to generate a harmonic pressure perturbation. The dynamic transfer characteristics have been determined at each measured frequency from the harmonic components of the sensor and reference signal respectively as

$$G(j\omega) = \frac{\hat{p}_{sens}(j\omega)}{\hat{p}_{ref}(j\omega)} \qquad \text{Eq. 3}$$

Once the dynamic transfer characteristics over the frequency range of interest has been determined the setup was employed for unsteady pressure measurements. The signal at the tap was then obtained from signal reconstruction in the frequency domain by applying the inverse dynamic transfer function to the sensor signal as follows

$$\hat{p}_{tap}(j\omega) = G^{-1}(j\omega) \cdot \hat{p}_{sens}(j\omega) \qquad \text{Eq. 4}$$

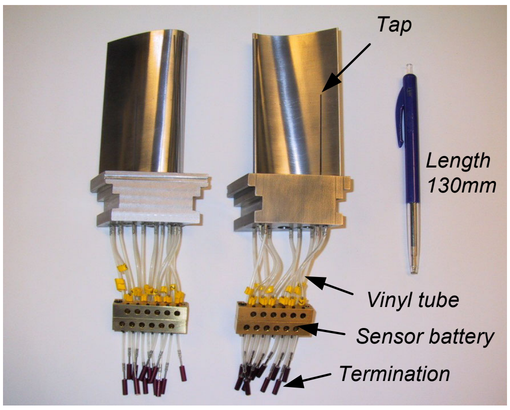


Figure 3. Test objects

DESCRIPTION OF TEST OBJECTS

A series of low-pressure turbine rotor blade profiles were equipped with recessed-mounted dynamic pressure instrumentation for determining unsteady blade loading during flutter. Pressure taps of 0.4mm diameter (0.8% of blade chord) were distributed on different blades and connected by miniature capillarity tubes (inner diameter 0.5mm) to the lower end of the blade root where they ended by a bulged tube for connection of flexible pressure tubes. A flexible vinyl tube (inner diameter 0.8mm) was used to connect the capillarity tubes to a battery for exchangeable mounted fast response transducers. The length of the vinyl tube was for the present investigation kept constant to 53mm. The setup is shown in figure 3.

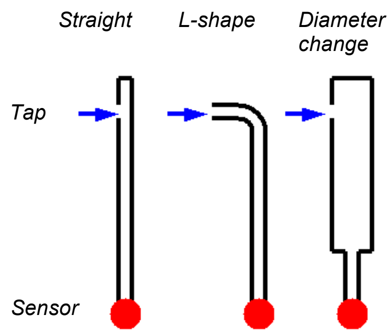


Figure 4. Shapes of connection tubes

Depending on the location of the tap on the blade the capillarity tubes were either straight or L-shaped. All capillarity tubes were embedded in pre-milled grooves into the blade surface and covered with filler that has been ground to restore the original blade surface.

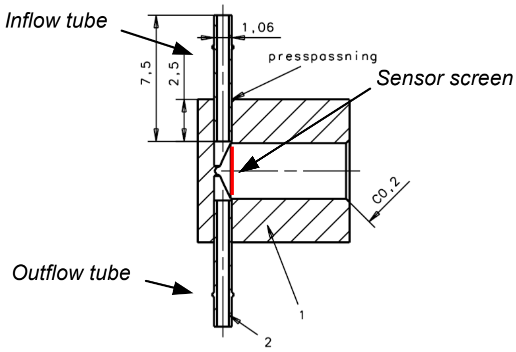
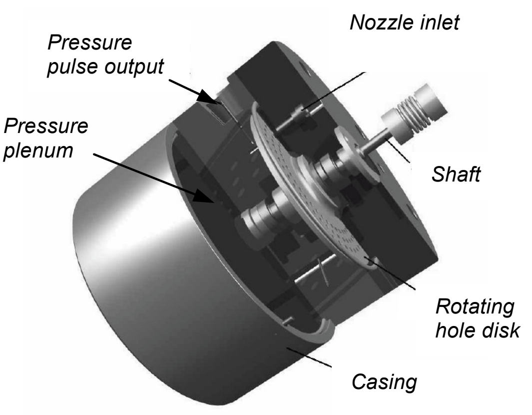


Figure 5. Section through sensor battery

Straight tubes were sealed on one end had the pressure tap drilled through the tube wall. L-shaped tubes faced the tap in direction of tube axis and were included where it was possible to include the tube on the opposite side of the blade. The latter type was preferred, as the blade surface at the measurement location remained unaffected. In addition one type of connection featured considerable change in tube inner diameter (larger part inner diameter 1.2mm, smaller part inner diameter 0.7mm). The different types of connection tubes tested are sketched in figure 4.

The sensors were placed in a sensor battery in exchangeable manner and normally to the axis of the pressure line such as to allow the pressure perturbation wave to travel across the sensor surface. In this sense the sensor receptable hole featured one in- and one outflow tube. A section through the sensor battery is shown in figure 5. The outflow tube was connected to a vinyl tube that was terminated at two different lengths. One long length (length app. 5m) was tested to allow dissipation of the pressure wave until tube termination. The effect of a short termination tube was tested by having a tube length of app. 20mm.



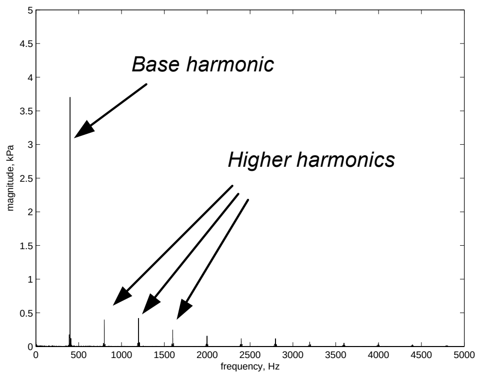


Figure 6. Pressure pulse generator and sample of frequency spectrum

DESCRIPTION OF THE CALIBRATION SETUP

The calibration setup consisted of a pressure pulse generator, a miniature reference cavity that was placed over the tap to calibrate and a high-speed data acquisition system.

The pressure pulse generator was of siren type and produced a harmonic pressure perturbation signal at variable frequency, amplitude and mean level. Pressurized air was directed via a miniature nozzle onto a rotating hole disk that was driven by a speed controlled DC motor. The intermittent pressure jets behind the hole disk discharged into a cylindrical cavity that was tapped on the side to extract pressure pulses. The pressure pulses were finally transmitted by a flexible capillarity tube to a reference cavity that was placed over the tap to calibrate. Symmetry of the flow channel was ensured in the cavity by providing on in- and one outflow tube that has been connected by a long termination such as to avoid pressure reflections from the end by allowing dissipation of the pressure wave. The amplitude of the pressure perturbation was controlled by regulating pressure at the inlet of the miniature nozzle. The hole disk was placed in a pressure chamber the pressure level of which could be controlled from external thus allowing for variations in mean pressure level of the resulting perturbation. The hole disk featured three rows of holes on different diameters but with the same amount of holes yielding three different temporal jet patterns and thus three different shapes of the pressure signal. The resulting pressure perturbation featured a dominant base harmonic component and various higher harmonics of considerable smaller magnitude. A picture of the pressure pulse generator and a sample spectrum is included in figure 6. Only the base harmonic was used to determine the dynamic transfer characteristic.

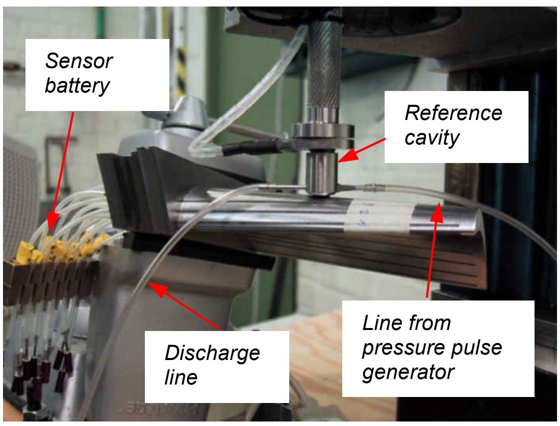


Figure 7. Calibration setup

The reference cavity was of 1.8mm in diameter and 3mm in height and was sealed by an O-ring at the interface between the cavity and the test object at the tap location. A flush-mounted piezo-resistive fast-response transducer (Kulite XCQ-062, 1.6bar abs) was included in the reference cavity and served as reference pressure signal. This reference sensor was embedded on the opposite side of the tap to calibrate such as to ensure symmetric deployment of the pressure wave in the cavity with respect to tap. The placement of the reference cavity over a tap on a test turbine blade during calibration is shown in figure 7.

At the end of the capillarity tube the pressure was measured by a fast-response piezo-resistive pressure transducer (Kulite XCQ-062, 1.6bar abs) that was contained in a sealed receptable, which could be inserted in exchangeable manner into the sensor battery. Both reference sensor and the sensor to calibrate have been calibrated statically using a static calibration unit (Druck DPI-603, 100Pa accuracy) to minimize uncertainties due to non-linearity, hysteresis and drift over time. The signals of the reference sensor and the sensor to calibrate have been acquired by a digital high-speed data acquisition system (Kayser-Threde KT8000) that also provided stabilized 10VDC sensor excitation. The system featured 32 channels with programmable amplifiers, 14bit A/D conversion for each channel and a maximum sampling rate for all 32 channels simultaneously of 200kHz. Each channel could be programmed individually such as to set gain and a low-pass filter with variable cut-off frequency. The present tests were performed with a gain of 25, no low-pass filtering and at a sampling rate of 20kHz.

The accuracy of the sensors after static calibration was estimated to ±30Pa for the unsteady part of the signal. The resolution of the A/D-converter added with ±30µV (gain 25), which corresponded to ±50Pa taking into account the transfer characteristic of the sensor. This yielded a total measurement accuracy of ±80Pa for the sensors.

The calibration procedure included the following steps:

- Placement of reference cavity over tap to calibrate and check for pressure tightness
- Acquisition of reference and recessed sensor signals at a number of frequencies within the range of interest
- Signal processing of both signals to yield complex spectra at perturbation frequency and determination of transfer function

RESULTS

The dynamic transfer characteristics are below presented in terms of magnitude ratio and phase. A magnitude ratio equal to unity indicates that the measured magnitude is equal to the magnitude at the tap. Magnitude ratios of smaller than unity indicate that the measured magnitude is smaller than the magnitude at the tap and that the system features attenuation. Positive values of phase indicate that the sensor signal is lagging the perturbation at the tap. The transfer characteristics are shown in the range of 0 to 600Hz.

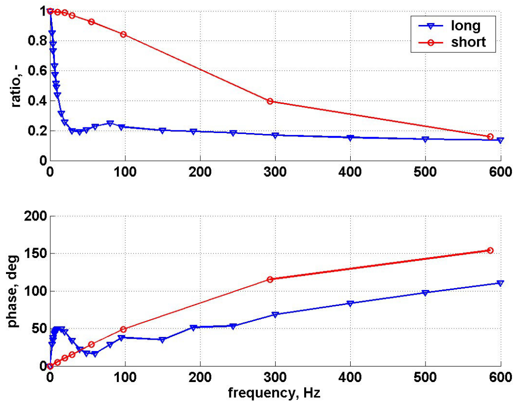


Figure 8. Effect of tube termination

The effect of tube termination is addressed in figure 8. Whereas the long termination leads to a steep fall of the magnitude ratio at low frequencies down to 0.2 the short termination gradually decreases with increase in frequency. At 600Hz the magnitude ratios for both types of tube termination are almost identical. The phase shows strong non-monotonic behavior for the long termination length in the range between 0 and 150Hz. This behavior is assumed as resonance that is due to the increased tube length. The short termination tube shows highly monotonic behavior and therefore suggests that deteriorating influences from pressure reflections due to the short termination length are of insignificant importance. Note that the frequency resolution has been chosen on the background of pre-test measurements indicating regions of high second derivatives. Due to low second derivatives in the region between 70Hz and 600Hz for the short termination the frequency resolution could be kept rather low thus allowing time-efficient dynamic calibration.

Although both types of termination could be used for unsteady pressure measurements the long termination incorporates potential errors due high attenuation and its non-monotonic behavior, which requires high frequency resolution of the transfer characteristics.

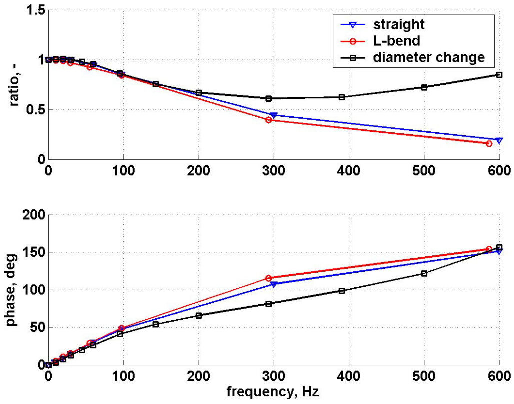


Figure 9. Effect of tube shape

The effect of tube shape is shown in figure 9 by comparison of transfer characteristics from a straight and a L-bended tube and a tube with change in inner diameter. Whereas the straight and the L-bended tube show similar characteristics (falling tendency in magnitude ratio, increasing tendency in phase) the tube with change in inner diameter features a falling tendency in magnitude ratio between 0 and 300Hz, thereafter an increasing tendency. This suggests that at lower frequencies the propagation of the pressure wave is comparable to the one in constant diameter tubes whereas at higher frequencies pressure recovery is gradually occurring obviously due to the change in tube inner diameter.

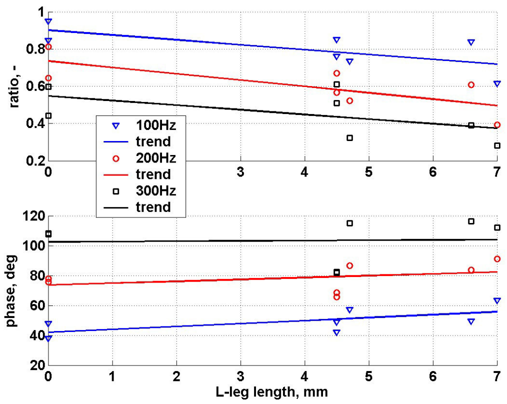


Figure 10. Effect of length of L-leg

Comparing straight and L-bended tubes it can be recognized that the L-bended type features tendential lower magnitude ratio, i.e. higher attenuation and increased phase shift. Both effects are assumed being due to the increase in total tube length rather than the presence of tube bend. The latter might though also induce a minimal change in tube inner diameter, however the effect of such is not obvious from the measured characteristics. To give evidence to this interpretation the influence of variations in L-leg length has been addressed. The straight tube has thereby been taken as extreme case with L-leg length equal to zero. A number of transfer characteristics were acquired with L-leg lengths varying between 0 and 7mm. The comparisons are included in figure 10 plotting the magnitude ratio and phase versus L-leg length at three different frequencies (100Hz, 200Hz and 300Hz). In addition first-degree polynomials have been fitted using the least-square method for recognizing trends.

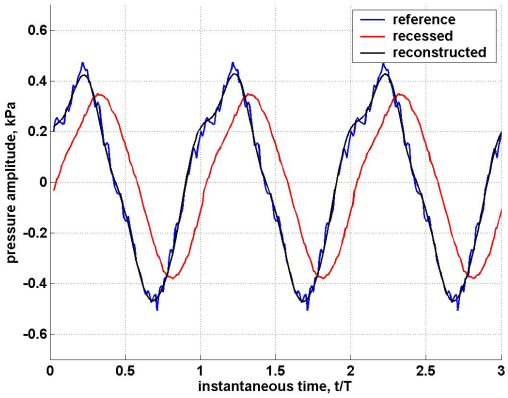


Figure 11. Sample of signal reconstruction

A trend of falling magnitude ratio and increasing phase with increasing L-leg length can be observed. The trends are thereby similar for the three plotted frequencies. Although considerable scatter is present it indicates that the increase in L-leg length solely is responsible for the change in dynamic transfer properties and that the presence of the bend does not have any major influence. The scatter in the data is assumed being due to the fact that no ultimate control of the exact dimension of tube inner diameter and tube shape can be assured. Even if an exact theoretical description of the physical system existed a rather large uncertainty had therefore to be taken into account due to uncertainties in the exact geometry of the capillarity tube setup.

Finally the attention shall be drawn on the reconstruction of the pressure signal at the tap to proof the method and to assess the quality of the proposed measurement setup. The signal at the tap has thereby been reconstructed from the sensor signal by applying the inverse transfer function in the frequency domain as outlined further above. Figure 11 shows a sample of sensor signal, reference signal (i.e. signal at the tap) and reconstructed signal. Firstly it can be stated that the reconstructed signal agrees to high degree with the reference signal. Secondly it can be recognized that the higher harmonics of the reference signal are not contained in the reconstructed signal. This is due to the fact that the dynamic transfer characteristics have only been described up to a maximum frequency. Frequencies above that frequency are suppressed in the signal reconstruction. In other words it can be expressed that the reconstruction process acts like a low-pass filter with the filter frequency equaling the maximum frequency of the transfer function. Estimated total accuracy of the proposed setup is ±130Pa for pressure perturbation magnitude and ±3deg for perturbation phase taking into account tube system and sensor transfer characteristics. The accuracy of phase determination is though dependent on the magnitude of the pressure signal and attains ±6deg for amplitudes that are of the order of the perturbation magnitude accuracy.

CONCLUSIONS

A technique for using recessed-mounted pressure transducers for measuring unsteady pressure has been presented. The technique has been compared to existing unsteady pressure measurement techniques and its physical characteristics have been discussed. As the transducer no longer is placed at the measurement location frequency-dependent attenuation and phase lag is present and must be accounted for by a dynamic transfer characteristic. This characteristic can finally be applied to reconstruct the unsteady pressure signal at the measurement location.

Rather than applying a theoretical description of the dynamic transfer characteristic the setup of recessed-mounted pressure transducer has been calibrated dynamically. A pressure pulse generator has been used for supplying harmonic pressure perturbations that have been referenced in-situ at the calibrated tap. Dynamic transfer characteristics yielded from signal analysis of reference and sensor signal. Other than theoretical descriptions of transfer characteristics the present method is also valid for large perturbation amplitudes.

To conclude on applicability of the proposed technique for unsteady pressure measurements the frequency content of the phenomenon to be measured has to be estimated in advance. In the present case the base harmonic has been estimated to 500Hz and the aim has been set up to acquire spectral contents up to the fourth harmonic. The setup of recessed-mounted pressure transducers has in the present application proven as successful technique up to 2kHz. At higher frequencies the attenuation of the signal gets larger and by this harming the measurement accuracy.

It has been recognized that constant tube inner diameters are to be preferred as the transfer characteristics are of monotonic nature. The presence of one bend did not show any harmful effect. What concerns the choice of capillarity tube inner diameter no ultimate recommendations can be given. The choice should however be performed with respect to tap diameter, sensor cavity volume and size of sensor.

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