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In situ, broad band method to determine the normal and oblique reflection coefficient of acoustic materials

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ABSTRACT

It has been shown that the combination of a particle velocity (u) sensor and a sound pressure (p) microphone can successfully be used to determine the reflection coefficient of acoustic materials [1-4].

In this paper, a practical measurement technique and a so called pu-probe impedance meter are described that require no Kundt's tube or anechoic room. The procedure allows fast (less than 60 seconds) sound absorption measurements under both normal and oblique angles of incidence on small test samples (less than 30*30cm). The total size of the pu-probe impedance meter is 60 centimeters and weights less than 1kg. The method can be used in combination with a sound card based software package.

At first, the pu-probe is calibrated in approximately 20 seconds. The frequency response of the impedance sensor is transformed to an impulse response. This response is time windowed to cancel out the room reflections.

After the calibration, the reflection coefficient (and the real and imaginary part of the impedance) of the acoustic materials are determined by putting the pu-probe in close proximity of the acoustic sample.

INTRODUCTION

The microflown is an acoustic particle velocity sensor that is invented at the University of Twente in 1994 [8]. In 1997 the sensor was commercialized. In this paper, the microflown will be referred to as particle velocity sensor.

Over the past ten years the particle velocity sensor is used to determine acoustic impedance. The first application was the measurement of the acoustic impedance of a horn loudspeaker with a pu-method. In the throat of a horn loudspeaker a pressure microphone (p) and a particle velocity sensor (u) was placed and the impedance was successfully measured [1]. Afterwards, two particle velocity sensors (in stead of microphones) where used in a standard Kundt's tube. This technique showed also that particle velocity sensors could be used to determine the acoustic properties of materials [2].

The acoustic impedance in the tube was determined by measuring the sound pressure and the particle velocity directly at one point in the tube [3]. Furthermore the ratio of intensity (I) over energy (E) was measured to calculate the reflection coefficient of the acoustic material. The basis of this method is that $I=0$ if the material is fully reflecting and $I=cE$ (c is the speed of sound) if the material is fully absorbent.

At the University of Leuven the pu-probe was used to determine the specific acoustic impedance at the surface of an absorbing material [4]. With this method the disadvantages of the Kundt's tube are avoided. Several disadvantages in the tube are the upper frequency limit, determined by the tube diameter, the fact that only the normal reflection coefficient can be obtained and that not all materials can be put in the tube. In [4] is proven that the acoustic reflection coefficient of materials can be measured broad band for both oblique and normal angles of incidence. The method is very fast, in 10 seconds the reflection coefficient for a certain angle of incidence can be obtained.

At the company DAF Trucks, an investigation is started into the practical use for the acoustic properties of car interior materials. Some preliminary measurements are shown in this paper.

A simple straightforward way of calibrating the pu-probe is a crucial step to create a practical setup. The calibration method is the main topic of this paper.

PU-IMPEDANCE SENSOR

The particle velocity sensor is an acoustic sensor measuring directly particle velocity instead of sound pressure, which is usually measured by conventional microphones. This transducer is a micromachined hot wire anemometer, based on *two* wires, instead of one as in the classical anemometer; see Fig. 1. The two short, thin, closely spaced wires of silicon nitride coated with platinum are heated by a DC current to about 300˚C. Their resistance depends on the temperature. A particle velocity signal in the perpendicular direction changes the temperature distribution instantaneously, because the upstream wire is cooled more by the airflow than the downstream wire. The resulting resistance difference is measured with a bridge circuit that provides a signal proportional to the particle velocity.

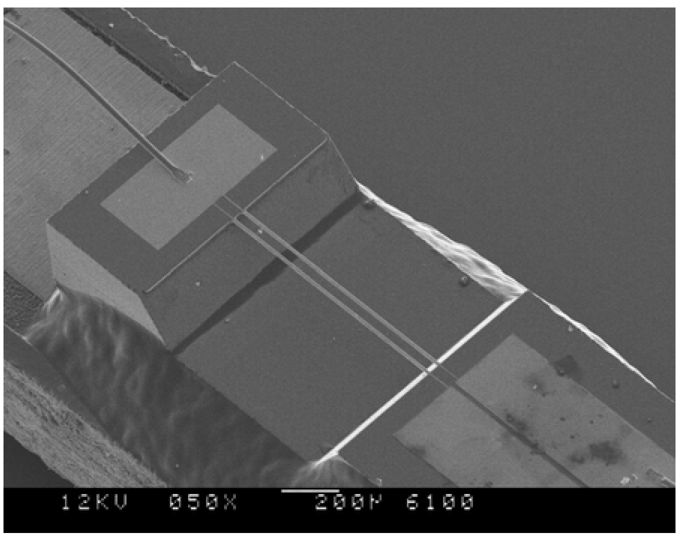

Fig. 1: The two wires of the particle velocity transducer.

At low frequencies the sensitivity of this particle velocity transducer increases 6 dB per octave. The behavior at very low frequencies is believed to be related to the thermal boundary layer on the wires. Between 100Hz and 1kHz the frequency response is relatively flat. Between 1kHz and 10kHz there is a rolloff of 6dB per octave, caused by a diffusion effect related with the distance between the two wires (about 40μm). The sensitivity decreases above 10kHz an additional 6 dB per octave because of the thermal heat capacity of the wires.

The frequency and phase response of a particle velocity sensor can be modeled by:

$$Sensitivity = \frac{LFS}{\sqrt{1+\left(\frac{f_1}{f}\right)^2}\sqrt{1+\left(\frac{f}{f_2}\right)^2}\sqrt{1+\left(\frac{f}{f_3}\right)^2}}$$

The particle velocity probe is combined with a small electret condenser microphone in the ½-inch sound probe shown in Fig. 2. The velocity transducer is mounted on a small, solid cylinder, and the condenser microphone is mounted inside another hollow cylinder. The geometry of this arrangement increases the sensitivity of the velocity transducer with about 10dB.

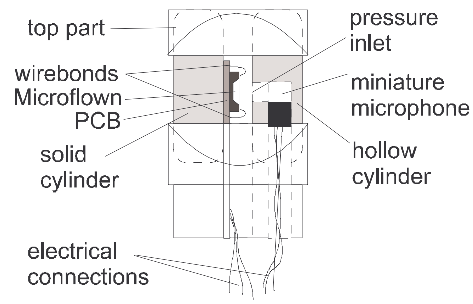

Fig. 2: Drawing of the outline of a pu-impedance sensor.

The pu-impedance sensor is mounted on a 40cm long rod with the electronic wiring through it. At the end of the rod, a 7-pin LEMO connector is mounted.

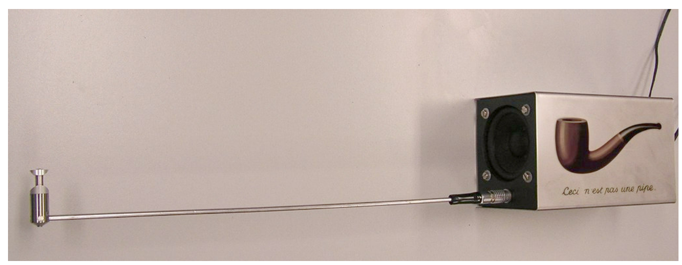

Fig. 3: Prototype of the pu-impedance sensor.

The pu-probe with the 40cm rod is connected to a loudspeaker box. Inside, a USB operated A/D and D/A converter and the preamps sound probes that are powered by an internal power supply are mounted, see Fig. 4.

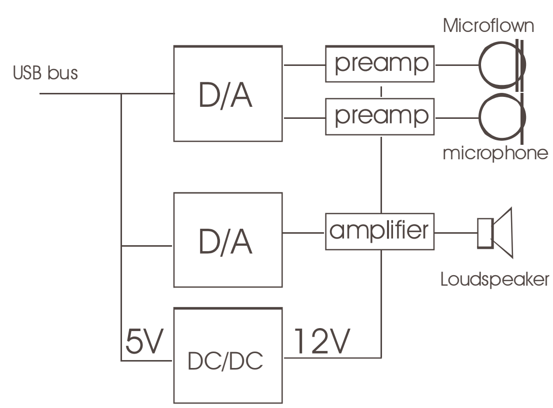

Fig. 4: Schematic signal processing of the pu-impedance sensor.

The A/D-D/A converter communicates with the computer through a USB bus that also powers the (pre)amplifiers.

CALIBRATION OF THE PU-IMPEDANCE SENSOR

The microphone and particle velocity probe do have completely different amplitude and phase responses. Without calibration, the pu-impedance probe would be useless. Because only the specific acoustic impedance has to be measured in this application, the absolute sensitivity of the individual transducers does not have to be known.

Even if both transducers (microphone and particle velocity probe) have an unknown frequency and phase response, an acoustic pu-impedance probe can be calibrated without a reference microphone; the known specific impedance (of air) is used as reference.

If the response of the acoustic pu-impedance probe is determined in an anechoic environment the output is given by:

$$Z'(f)=\frac{S'_{pu}}{S'_{uu}}=\left|\frac{S_{pu}}{S_{uu}}\right|' Exp^{i\varphi'_{pu}}$$

With Z' the output of the pu-impedance probe determined in an anechoic environment, S_{pu} the cross spectrum of *p* and *u* and φ_{pu} the phase shift between *p* and *u*. The inverse of this response is used as calibration value. The normalized (i.e. the impedance divided by ρc, with ρ the density of air and c the speed of sound) and calibrated response is now given by:

$$Z_n(f)=\frac{Z(f)}{Z'(f)}=\frac{\left|\frac{S_{pu}}{S_{uu}}\right|}{\left|\frac{S_{pu}}{S_{uu}}\right|'} Exp^{i(\varphi_{pu}-\varphi'_{pu})}$$

The calibration of the acoustic pu-impedance probe in an anechoic chamber is not very practical. Only some research labs have such facilities. Furthermore, to get complete free field conditions, one should measure far from the sound source and at lower frequencies such chambers are often not anechoic anymore. A more practical method is therefore developed.

The pu-impedance probe is positioned 20cm in front of a small loudspeaker. The specific acoustic impedance can be approximated by the impedance of a point source:

$$Z=\rho c\frac{ikr}{ikr+1}$$

With k=2πf/c and f the frequency. For lower frequencies (f<250Hz) the probe will be in the near field (r=0.2m). In the near field of the source, the particle velocity level is much higher than the sound pressure level. It shows in practice that room reflections do not influence the impedance when a measurement in the near field of the source is performed [7].

If the frequency is higher than 250Hz the probe is not in the near field of the sound source anymore and (room) reflections will influence the impedance. At higher frequencies (f>250Hz) the room reflections can be eliminated by the following method.

If the response of the pu-impedance probe is determined in a normal room the output is given by:

$$Z''(f)=\frac{S''_{pu}}{S''_{uu}}$$

From this complex transfer function Z”(f) an impulse response is determined by the inverse Fourier transformation,

$$z''(t)=\frac{1}{2\pi}\int_{-\infty}^{\infty} Z''(f)e^{i\omega t}d\omega$$

This impulse response is related to the impulse response of the pu-acoustic impedance probe and the room. However, in the impulse response, the room reflections occur later in time than the impulse response of the acoustic pu-impedance probe.

If the distance of the first reflection is for example larger than 1.5m, the path to reach the probe is at least of double length. So, the first possible impulse response of that reflection occurs 5ms after the start of the impulse response of the acoustic pu-impedance probe. Before the first reflection impulse response, the response is anechoic. The impulse response is windowed so that only the data of the first 5ms are used and the rest is set to zero. The windowed response is given by:

$$z'''(t)=\frac{1}{2\pi}\int_{-\infty}^{\infty} Z''(f)e^{i\omega t}d\omega \quad for\ \ t\le 5ms$$

$$z'''(t)=0 \qquad for\ t>5ms$$

The transfer function of this time windowed impulse response is determined by the Fourier transformation:

$$Z'''(f)=\int_{-\infty}^{\infty} z'''(t)e^{-i\omega t}dt$$

Because only a limited part of the measured impulse response is used, the lower frequencies are less accurate. If only the first 5ms are used (the distance between the first reflection position and the probe is larger than 1.5 meters), the method can be used for frequencies higher than 200Hz.

$$Z'''(f) = \int_{-\infty}^{\infty} z'''(t) e^{-i\omega t} dt \approx Z'(f) \quad \text{if } f > 200\text{Hz}$$

For frequencies higher than 200Hz the room reflections at a distance larger than 1.5m can be eliminated. The probe is located at a distance of 20cm of the sound source. Therefore for frequencies lower than 250Hz, the sound probe is in the near field of the sound source and room reflections do not influence the impedance and thus the calibration of the probe.

CALIBRATION MEASUREMENTS

In order to find the frequency response of the pu-impedance probe, the spectrum can be measured with a noise source and a FFT technique. In [5] it is shown that a sweep method gives better results. Therefore both the calibration and the measurement are performed with this sweep signal, see Fig. 5.

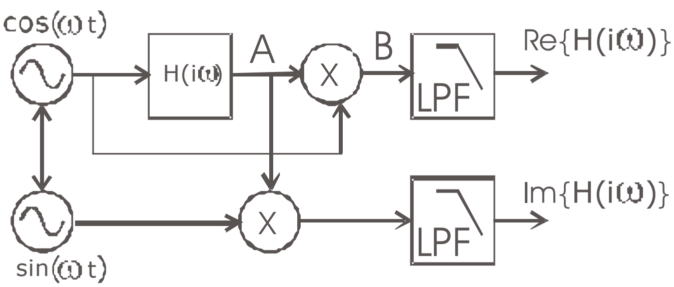

Fig. 5: Block diagram of a system that determines the imaginary and real part of a system by means of a sine signal.

If in Fig. 5 a cosine wave *cos(ωt)* is submitted to a system H(iω), the signal at position 'A' of the system will be:

$$A = \cos(\omega t) \times |H(i\omega)| \cos(\omega t + \arg\{H(i\omega)\})$$

After multiplying signal 'A' with the input signal *cos(ωt)* the signal at position 'B' of the system is:

$$\begin{aligned} B &= \cos(\omega t) \times |H(i\omega)| \cos(\omega t + \arg\{H(i\omega)\}) \\ &= |H(i\omega)| \cos(\arg\{H(i\omega)\}) \\ &\quad + |H(i\omega)| \cos(2\omega t + \arg\{H(i\omega)\}) \end{aligned}$$

After proper low pass filtering the real part of the transfer function remains:

$$|H(i\omega)| \cos(\arg\{H(i\omega)\}) = \text{Re}\{H(i\omega)\}$$

The imaginary part of the transfer function is determined in a similar manner.

If the input sine wave is swept through the frequency band of interest, the complex transfer function is known.

In Fig. 6 the frequency response of a pu-impedance probe is displayed. The red line is the response in a normal room, the reflections are clearly visible. The black line is the 5ms time-windowed response. The blue line is the model. A 'dip' in the frequency response of the probe around 5kHz is clearly noticeable. This dip can be explained by the electrical tuning of the pu-probe. Modern probes do not have this dip anymore.

The response is also measured with 90dB(A) background noise. This does not have any noticeable effect on the response.

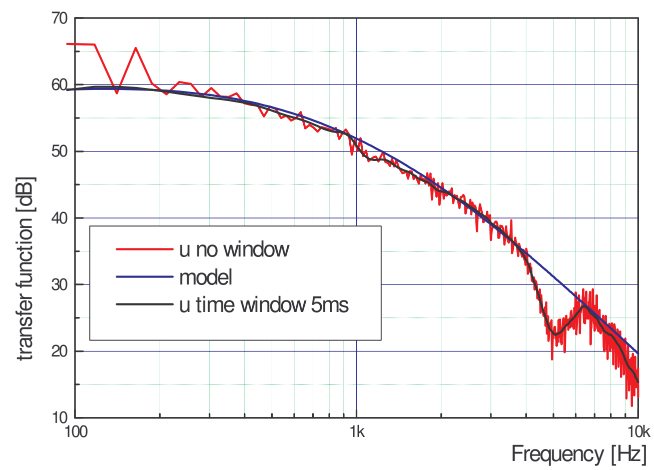

Fig. 6: The calibration measurement (Z'^{-1}) of the pu-impedance probe.

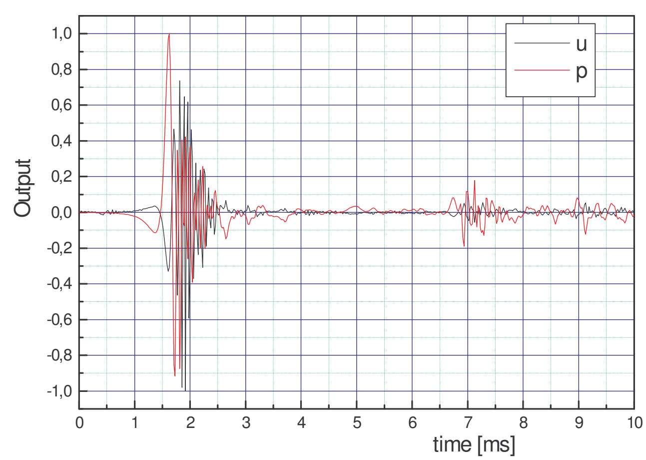

Fig. 7: The impulse response of the pu-impedance probe. The first reflections can be seen at 7ms.

FROM SURFACE IMPEDANCE TO REFLECTION COEFFICIENT

In [4] was shown that the reflection coefficient can be determined from the impedance measured close to the surface, see Fig. 8. In [4], a model is presented for the calculation of the reflection coefficient that involves also oblique angles of incidence. Here, a simplified model is given that is valid if the loudspeaker distance and frequency are sufficiently large (r>40cm, f>250Hz) and the measurement distance between the impedance probe and the acoustic material is sufficiently small (here 6mm).

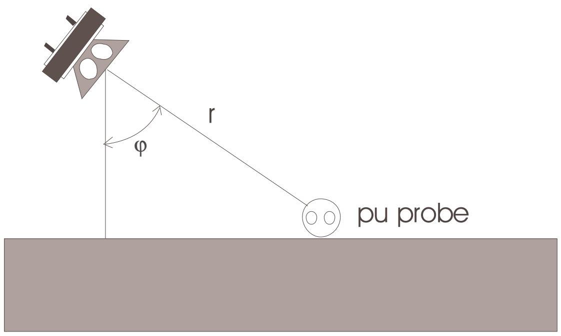

Fig. 8: Free field measurement set up.

If the sound source S is placed at a distance of r=40cm of the probe, and the distance probe-sample is very small (here 6 mm) the following model is valid for frequencies higher than 200Hz:

$$R(\varphi)=\frac{Z_n\cos(\varphi)-1}{Z_n\cos(\varphi)+1}$$

With Z_n the normalized and calibrated response of the pu-impedance probe and φ the measurement angle.

MEASUREMENTS

It is shown that the absorption coefficient obtained by the calibrated response of the pu-impedance probe resembles the response measured with the Tamura method [4]. In this method, sound pressure is measured in two planes and a two dimensional spatial Fourier transformation is used to calculate the angle dependent reflection coefficient. The results of these measurements, together with a simulation based on the model of Biot-Johnson-Allard are given in figure Fig. 9 for normal incidence and in Fig. 10 for oblique incidence [4].

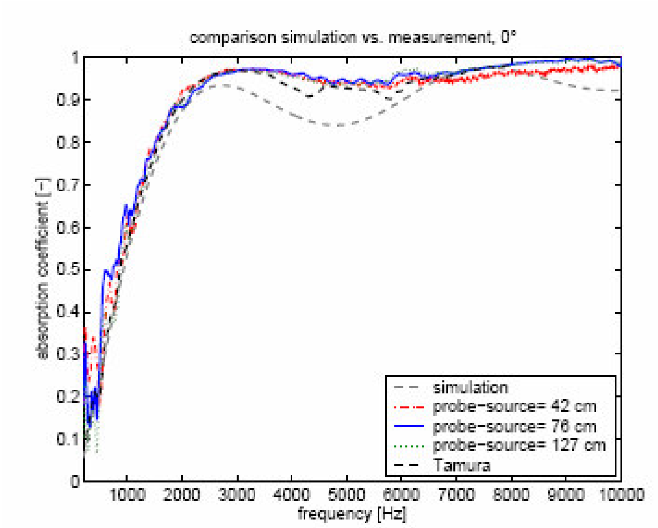

Fig. 9: Absorption measurements (normal incidence).

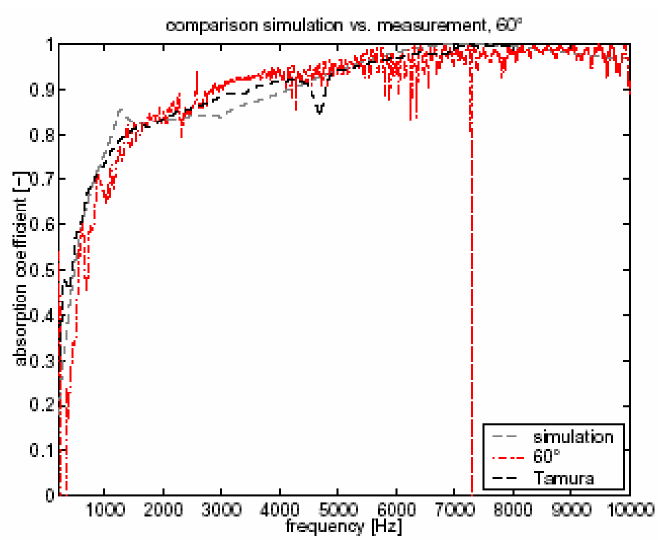

Fig. 10: Absorption measurements (60DEG oblique incidence).

At DAF Trucks preliminary tests were done to evaluate impedance measurements with a pu-sensor. The final goal is to be able to measure acoustic properties of materials applied in the interior of truck cabins. The pu-impedance sensor was calibrated as explained above and two types of foam were measured at several angles, see Fig. 11 and Fig. 12.

Fig. 11: Absorption measurements.

Fig. 12: The pu-impedance probe (left) and a reference pressure microphone (right) for verification purposes.

The behaviour of the foam is quite according to expectation: very high absorption above a critical frequency. This critical frequency depends on the thickness of the foam layer; 160 [mm] foam absorbs well above 300 [Hz] ($\approx 0.14\lambda$) and a layer of 80 [mm] foam performs well above 500-800 [Hz] ($\approx 0.1\lambda$ - 0.2λ).

In this experiment for 77° angle of incidence the resulting alpha value is not as expected; because the normal particle velocity is very small the measurements suffer from bad signal to noise ratio. It is expected that this is due to the fact that not enough sound power was used to drive the speaker and the distance between speaker and sensor was too large. New measurements will be carried out to investigate this matter.

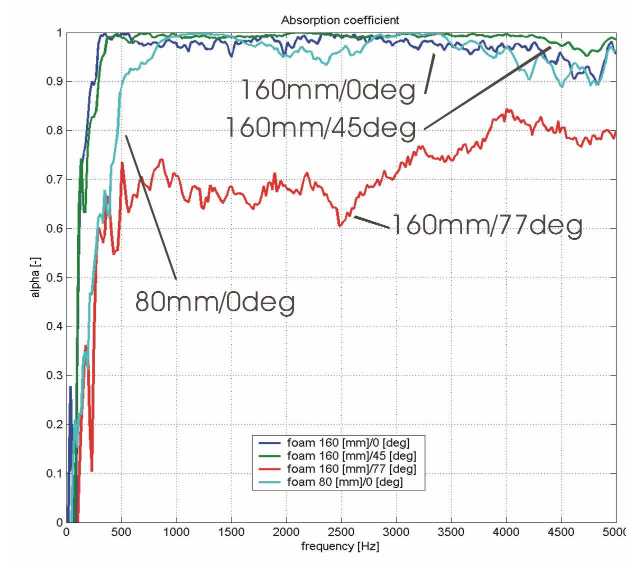

Fig. 13: Absorption measurements for different material thicknesses and angle of incidence.

CONCLUSION

In this paper, a method is given that allows fast, free field calibration of a pu-impedance probe.

Some measurements show that the pu-impedance probe is able to measure the normal and oblique reflection coefficient.

This probe is used in a set-up to measure the reflection coefficient of materials in situ and with only one frequency sweep measurement.

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