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A Microflow Based Sound Pressure Microphone Suitable For Harsh Environments

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ABSTRACT

There are several cases where a sound field reconstruction or prediction is required under harsh conditions such as high temperature, humidity or chemical attack. A regular pressure microphone won't last long under these conditions. Electret based pressure microphones stop working well above 70 degrees centigrade and other types of pressure microphones often operate with a built in amplifier that does not function above 120 degrees centigrade. The functionality of a MEMS based microflow acoustic particle velocity sensor in air lies in the use of two heated platinum wires that are resistant to high temperatures and chemical attack. The wires are supported by silicon that has no other function than provide mechanical support. A pressure microphone is made based upon the particle velocity principle by putting a microflow inside the opening of an enclosure. In this paper a sound probe for harsh environments is created, combining particle velocity and pressure measurements in a harsh environment. Use of this sensor is possible up to 250 degrees centigrade, in humid and under most chemical environments. The probe realization as well as calibration measurements are presented.

INTRODUCTION

The Microflow [1], [2] is a particle velocity (a vector value) transducer and therefore it has a figure of eight directional response. In contrast, a pressure microphone measures sound pressure that is a scalar and thus has an omni-directional response. The use of both types of sensors at the same place provides all information of the present sound field. Especially the sound intensity, which is related to the product of sound pressure and particle velocity, is an important value for sound engineers. The intensity measurement provides information on the amount of sound that is radiated in to the far field.

In this paper a conversion method of pressure to particle velocity is described to make it possible to use a Microflow as transducer to measure sound pressure. This novel pressure sensor in combination with a regular used Microflow creates a sound intensity probe that is solely based on Microflow sensors.

A reason to make a transducer like this is the possibility of measuring acoustic pressure in a high temperature environment since the microflow is a sensor which is capable to withstand and work at very high temperatures. A second reason is that now a sound intensity probe is created that is based on two sensors that have the same operation principle. So, now the so made pressure sensor matches well with the particle velocity sensor in terms of stability and sensitivity of temperature, humidity etc. And in both cases the same type of amplifier and signal conditioning can be used.

In this paper a rigidly terminated tube is used to convert the pressure signal into a particle velocity signal that can be measured by a microflow sensor. This configuration is used to prove the concept; however other configurations are also possible. An early attempt was the use of a Helmholtz resonator but the system resonance is a disadvantage [3]. A well defined transfer function is crucial if the system is used for sound pressure measurements.

The Microflow can also be placed at a different location than the end of the tube; this has some advantages regarding the frequency response; this presented also in this paper. It is possible to create a fully damped tube or a horn type of tube and that will have another (probably flat) transfer function.

One can also think of placing a Microflow close to a membrane. In that case the sound pressure will deflect the membrane and the Microflow is able to detect the pressure induced deflection [4].

THEORY

As stated above, in this case the pressure to particle velocity converter is a small tube that is terminated rigidly at one end and with a Microflow at the open end or halfway the tube.

Figure 1: A standing wave tube rigidly terminated at $x=l$ and in which the gas is driven at $x=0$.

Inside the tube the sound pressure and particle velocity is given by [7]:

$$p(x) = -i\rho c U \frac{\cos(k(l-x))}{\sin(kl)} ; u(x) = U \frac{\sin(k(l-x))}{\sin(kl)}$$

Using U as the particle velocity at the entrance of the tube, $k = \omega/c = 2\pi f/c$ as the wave number, c as the speed of sound and ρ the density of air. If the Microflow is positioned at the end of the tube, the ratio of sound pressure and particle velocity is given by:

$$\frac{u(l)}{p(l)} = -i\rho_0 c \tan(kl)$$

The tangent varies from zero to infinity and so the frequency response of the system. The high values provide a high sensitivity but the zero value will result in no sensitivity at that specific frequency. If the Microflow is positioned half way the tube, the ratio between the sound pressure (at the end of the tube) and the particle velocity is given by:

$$\frac{u(x)}{p(l)} = \frac{1}{-i\rho c} \frac{\sin(k(l-x))}{\cos(kl)} = \frac{1}{-i\rho c} \frac{\sin(\frac{1}{2}kl)}{\cos(kl)}$$

This transfer function $u(x)/p(l)$ has one zero less in the relevant frequency bandwidth, see Figure. . Disadvantage of this arrangement is that the transfer function, and thus the sensitivity, is about 10dB lower at lower frequencies.

The configuration with the Microflow at the end of the tube is preferable for low frequency applications and the configuration with the Microflow half way the tube is more suited for higher frequencies.

Figure. 2: Transfer function $u(x)/p(l)$ for $L=38\text{mm}$ and $x=19\text{mm}$

Temperature sensitivity

The sensitivity level of the Microflown element is barely temperature dependant (less than 0.02dB/K [7]) and thus the temperature dependency of the new made pressure microphone is mainly due to the temperature dependency of the acoustic impedance.

The working temperature of a Microflown element can be up to 300 degrees centigrade, initial measurements performed show this.

The temperature dependence of the several constants in the equation is given by:

$$k = \frac{2\pi f}{c} \quad c = \sqrt{\kappa RT} \quad \rho = \frac{P}{RT}$$

With C the speed of sound, κ (kappa) the adiabatic index (1.402 for air), R the universal gas constant ($287 \text{ J/(kg}\cdot\text{K)}$ for air), T is the absolute temperature in Kelvin and P the ambient pressure (100kPa). For the configuration with the Microflown at the end at the tube the temperature dependent frequency response is given by:

$$\frac{u(l)}{p(l)} = \frac{\sqrt{T}}{-iP} \sqrt{\frac{R}{\kappa}} \tan\left(\frac{2\pi f}{\sqrt{\kappa RT}} L\right)$$

CONSTRUCTION

For the construction of the converter two tubes of steel with sizes 38mm and 58mm centimeter and a diameter of 3mm are used. One end is closed with a steel rod and at the other open end of the tube a microflown is placed. The Microflown is mounted on a printed circuit board (PCB) to make the connections to the measurement amplifier and the PCB is put in the tube.

Figure 3: Realization of the Microflow at the end of the tube.

MEASUREMENTS

To test if the device acts as a pressure microphone several measurements are conducted. The sensitivity of a microphone is not dependant on the orientation of the probe. The directivity of the device is measured in an anechoic room to check if the sensitivity is omni directional. To check if the sensor is sound pressure and not particle velocity sensitive, the response in a standing wave tube is measured. In such tube the difference between sound pressure and particle velocity is distinctive.

Polar pattern measurements

In theory a regular pressure microphone will not have a directional sensitivity. Sound pressure is a scalar value and a pressure microphone must therefore have an omni-directional characteristic.

Inside an anechoic room sound is coming from one direction only, so when the device is rotated in such an environment the sensitivity must not alter. Measurements of the frequency response are performed with the new sensor placed close to a reference microphone. The measurement is performed over two axes (a and b), see figure 4 below. For 96 steps of each 3.75 degrees this is done automatically to provide the most reproducible result.

Figure 4: The two axes of the directivity measurement.

As reference a reference microphone from G.R.A.S. is used with a sensitivity level of 14 mV/pa. It shows that the sensitivity is hardly dependent on the orientation of the tube; the sound probe under test shows to be omni directional, see figure 5.

Figure 5: polar plots, left figure is measured along the rotation 'a', right picture rotation 'b'

Frequency response

From one of the measurements of the polar pattern the transfer function is taken and compared with theory. With a length $L=38.0$ millimeter the result shown in figure 6 is obtained. The actual distance between the terminated end and the particle velocity sensor is 38.5 millimeter; the small deviation may be explained to finite precision in mounting of the sensor or termination. Another tube was mounted and herewith the actual and calculated length was 58mm, see figure 7.

Figure 6: The frequency response of a Microflown mounted at the open end of a 38mm tube.

Figure 7: The frequency response of a Microflow mounted at the open end of a 58mm tube.

Figure 8: The frequency response of a Microflow mounted at the middle of the 38mm tube (red line is modeled, black line is measurement).

Signal to noise ratio

Apart from the frequency response the equivalent acoustical noise of the sensor is measured to be able to compare the sensor to regular pressure microphones. In a silent environment the electrical output signal is measured. This is the noise level and is measured in 1Hz bandwidth. Compared with a frequency response (the sensitivity of the microphone as a function of the frequency) the signal to noise ratio (SNR) can be determined. The self noise of a sensor is given by the $94\text{dB} - \text{SNR}$.

A regular pressure microphone has an SNR larger than 100dB at 1 kHz and 94dB and the device has 90dB. It is therefore not practical for use in speech or music recording. For measurement purposes however the noise levels are of less importance because the probe will be most probably be used close to hot noisy objects like engines and exhausts. Furthermore for intensity measurements the cross spectrum of the pressure and the velocity signal is determined and with this technique the self noise of sensors is reduced significantly [8].

Figure 9: signal of regular Microflow, the 38mm device (Microflow at the open end of the tube) and the noise of both.

Standing wave tube measurements

Up to a certain frequency (for this tube: $f_{\max}=4.2$ kHz) in a standing wave the difference between sound pressure and particle velocity is distinctive [7]. At a point and frequency where the sound pressure is maximal, the particle velocity is minimal and vice versa. Measurements are performed by placing a reference pressure microphone at the closed end of the tube and the device, together with a regular pressure microphone, at place x in the tube. At the open end a loudspeaker produces white noise. The transfer function of a sound probe in the tube and a reference pressure microphone at the end of the tube is given by [7]:

$$\frac{p_{probe}}{p_{ref.}} = \cos(k(l-x)) \quad \frac{u_{probe}}{p_{ref.}} = \frac{i}{\rho c} \sin(k(l-x))$$

So from the frequencies of the maxima and the minima it can be derived if the sensor is pressure sensitive or particle velocity sensitive. At certain frequencies there will be a minimum in the transfer function between the pressure microphone and the reference microphone. These minima must overlap with the minima found in the transfer function between the device and the reference microphone.

A steel tube of 70 centimeters long is used with a reference microphone at one end, the 38mm long sound probe under test together with an additional reference pressure sensor and a reference particle velocity sensor at one third of the tube and a loudspeaker at the other end as sound source. Transfer functions between all sensors at one third of the tube and the reference microphone clearly show that the device is not sensitive to particle velocity but only to pressure variations.

Figure 10: The transfer functions between a reference microphone at one third of the tube and a reference microphone at the end of the tube and between the device under test and reference microphone at the end clearly show that the device is only sensitive to pressure variations.

Temperature measurements

The Microflown was tested up to 300°C and functioned properly. The self noise did not increase significantly (less than 3dB). This is because the noise of the Microflown sensor is caused mainly by thermal noise. The change in sensitivity of the Microflown element was measured to be 5dB over a 300K (0.017dB/K) temperature range.

CONCLUSION

The working principle of a new type of pressure microphone is demonstrated that operates not with a membrane but with a Microflown element in a small standing wave tube. Such microphone has a frequency response that is not flat; however a model of the response is presented and verified.

One advantage of this new pressure microphone is that it can be used at high temperatures. The device is successfully tested up to 300°C. The sensitivity of the device is temperature dependent and a model for this dependency is presented.

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