THE μ -FLOWN

A NOVEL DEVICE MEASURING ACOUSTICAL FLOWS

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ABSTRACT

An acoustical wave consists of two elements, the acoustic pressure and the acoustic flow. Till now to determine the acoustic flow one has had, to measure the pressure and calculate the flow. So it would be convenient to have a sensor which is able to measure acoustical flows. At the University of Twente a novel device has been developed which fulfils this need. In this paper a short introduction to the governing principles of this dynamic flow sensor and some of its interesting applications will be presented. This micromachined device is called the *microflown*.

THE ACOUSTICAL FLOW SENSOR

The starting point of the investigation is the micro liquid flow sensor [1]. This sensor consists of three resistors located in the middle of a channel (Fig. 1). The two outermost resistors are used as sensors, while the resistor located in the middle is used as a heater. The dimensions of the sensor are in hundreds of micrometers. An applied flow causes a difference in temperature between the upstream and downstream sensors. The change of resistance in both resistors can be measured and leads to an electrical output proportional to the applied flow. While the displacement of the heated gas is measured, the sensitivity is reversely proportional to the frequency. For low frequencies the dynamic model will converge to the (quasi-) static flow sensor model. In contrast with the model of the static flow sensor [1], in which the gas flow transports the generated heat out of the system, there is no net heat transport in the model of the dynamic flow sensor.

Fig. 1: The flow sensor. The spacing between the Si_3N_4 bridges is $30\mu\text{m}$. Only two or three bridges are used. The value of a resistor on a bridge is about 30Ω

ACOUSTICAL THEORY

The acoustical domain can be described with two physical quantities, pressure and volume flow. However in the field of acoustics the particle velocity is used instead of the volume flow. The particle velocity is defined as the volume flow divided by the surface in which the wave propagates. The ratio of the pressure and the particle velocity is the specific acoustic impedance [2]. The specific acoustic impedance for a number of typical cases is discussed below:

The specific acoustic impedance of open air is given by [2]:

$$Z_s(r) = \rho \cdot c \frac{j r \frac{\omega}{c}}{1 + j r \frac{\omega}{c}} \quad (1)$$

using ρ is the density of the medium, c the velocity of sound in the medium and r representing the distance to the acoustical source. For a frequency of 100 Hz the ratio c/ω is 55 cm. For a larger radius eq. (1) is simplified to $Z_s = \rho c$.

Another case is a short tube with on one side an acoustical source and on the other a stiff, reflecting wall. The acoustic impedance in the tube in the longitudinal axis is dependent on both frequency and position [2].

The third environment is a tube of an infinite length. In practice the length will be finite but it can still be used if the measurement takes place before the first reflection reaches the measuring point. The specific acoustic impedance of an infinite tube is [4]:

$$Z_s = \rho \cdot c \quad (2)$$

In order to calibrate the μ -flown, it has to be remembered that this is a new device, so a reference μ -flown is not available. The solution of this problem has been found in using a reference pressure microphone and eq. (2). This impedance is independent of position and frequency which makes it well suited for transferfunction measurements.

The last definition we like to present here is the intensity. Intensity equals the product of the pressure and the particle velocity. Therefore it is a vector and related with the propagation of the power incorporated in an acoustic wave.

BOUNDARY CONDITIONS FOR PLANE WAVE PROPAGATION IN A CYLINDRICAL TUBE

For frequencies lower than f_c , called the cut-off frequency, only plane waves exist and non-plane waves vanish exponentially [7].

$$f_c = \frac{c}{d \cdot 1.71} \quad (3)$$

where d is the diameter of the tube.

Other types of waves are generated when the tube starts to resonate in the radial-circumferential flexural mode [6]. This effect is neglected here. In order to make a plane wave approximation, the viscous boundary layers should be thin [7]:

$$f_{\min} \gg \frac{2\nu}{\pi \cdot d^2} \quad (4)$$

where ν represents the kinematic viscosity of air.

Because of the finite length of a tube and the reflections at the end, the lowest frequency which can be measured is:

$$f_{\min} \approx \frac{c}{2 \cdot l} \quad (5)$$

where l is the length of the tube.

MEASURING ELECTRONICS "THE WHEATSTONE GADGET"

The *Gadget* is a new type of circuit especially designed to measure the small resistor variations of the μ -flown (Fig. 2).

Fig. 2: Measuring electronics: the Gadget.

The transfer function of the *Gadget* is [5]:

$$\Delta V_{\text{out}} = 2 \cdot I \cdot R_2 \cdot \frac{\Delta R_{\text{diff}}}{R} \quad (6)$$

in which ΔV_{out} is the AC variation in the output voltage as a result of the ΔR_{diff} , the differential resistance variation of R , the initial value of the μ -flown resistor.

The DC output voltage is:

$$V_{\text{out,DC}} = E - I \cdot R_2 \quad (7)$$

With I defined as:

$$I = \frac{E - U_{\text{BE}}}{R_1 + R_{\mu\text{flown}}} \quad (8)$$

The signal noise ratio of the *Gadget* is [5]:

$$\frac{S}{N} = \frac{2 \frac{\Delta R}{R} I}{\sqrt{1.25 \times 10^{-3} \frac{q \alpha_{\text{FE}}}{R^2} I^{-1} + \frac{4k}{R^2} (T_{\text{BJT}} R_{\text{bb}} + 2T_{\text{R}} R) + \frac{q}{10R} + 2qI}} \quad (9)$$

in which q is the charge of an electron, α_{FE} the forward current gain and T_{BJT} the temperature of the BJT. k is Boltzmann's constant, T_{R} the temperature of the sensing resistors. R_{bb} is the base series resistance of the BJT used.

MEASUREMENTS

Measurements of the described acoustical phenomena have been performed with the μ -flown in combination with a conventional pressure microphone. The experimental setup consists of a 20-meter-long tube in which the μ -flown and a reference microphone are mounted. By generating a burst and measuring within a specific timespan, the influence of reflections can be avoided.

Fig 3: Measurement setup I.

In an acoustical wave a pressure wave and a flow wave are inextricably related. In Fig. 4 and Fig. 5 is shown how the pressure and flow are altered after reflection. The first bursts are generated by forward propagating waves while the second bursts are generated by backward propagating waves.

Fig. 4: Acoustical response of a rigidly closed tube: phaseshift after reflection in particle flow and no phaseshift in pressure.

Fig. 5: Acoustical response of an open tube: phaseshift after reflection in pressure and no phaseshift in particle flow.

Another good example of what is possible with the combination of microphone and μ -flown is shown in Fig. 6: while the intensity of the forward propagating wave is positive the intensity of the backward propagating wave is negative.

Fig. 6: Acoustic intensity of a forward and backward propagating wave, in a rigidly closed tube.

The sensitivity, i.e. the ratio of the output voltage and the applied particle velocity, of the μ -flown is shown in Fig. 7. The acoustical impedance is $\rho c \approx 448 \text{ kg/m}^2\text{s}$ thus a pressure of 60 dB SPL, which equals 0.02 Pa, will result in a particle flow of $45 \text{ } \mu\text{m/s}$.

Fig. 7: Sensitivity of the μ -flown. The 'shs' configuration was used. The sensor and heater current were 10 mA each.

A different setup is used in the next measurement: a 40-meter-long tube with a loudspeaker in each end (Fig. 8).

Fig. 8: Measurement setup II.

One speaker generates a 150 Hz burst and the other a 200 Hz burst. The μ -flown and microphone are situated in the middle measuring both acoustic waves travelling in opposite directions (upper two curves, Fig. 9).

Fig. 9: Combining a pressure microphone with a μ -flown one can create a unipolar microphone.

Because in forward and backward travelling waves the particle flow is 180° phase shifted, the sumsignal of the upper two curves results in the forward travelling wave. The backward travelling wave is obtained by subtracting the output of the μ -flown from the output of the pressure microphone.

MULTIPLE CONFIGURATIONS

In the applied setup multiple configurations of the dynamic flow sensor are possible. The above-mentioned configuration is called a *sensor heater sensor* (shs) type of the μ -flown, describing the geometrical structure. Other possible configurations are *sensor sensor* (ss) and *sensor heater* (sh); see Fig. 10.

Fig. 10: Various microflown configurations.

It is possible to create a *microflown* with only two sensors, both heated by a current. This type of μ -flown has two fundamental advantages: the structure is simplified and measurements with a larger current gives a larger sensitivity to the applied acoustical flow. Furthermore only one sensor with a heater appears to perform. It is basically a hot-wire anemometer [3] but enhanced with a heater nearby. The interesting features of this type of μ -flown are

the fact that the output increases with the applied heater current and the possibility, in contrast with the hot-wire anemometer, to detect the direction of the flow (Fig. 11). The characteristic double frequency of a hot-wire anemometer vanishes with the increasing heater current.

Fig. 11: Response of the combination of the μ -flown and measuring electronics as function of the heater current in a heater sensor configuration. The sensor current was 10 mA

A remark about the configurations: it is possible to enlarge the sensor current. This causes the temperature of the sensor to rise and an increase of the sensitivity ($\Delta R/R$) of the various types of the μ -flown. A sensor is called a hot sensor when its heat-production is not negligible compared to that of the heater. In order to compare the various μ -flown types the sensitivity is a convenient value and is defined as the output of the μ -flown ($\Delta R/R$ in promille) at a frequency of 100 Hz, a sound pressure of 100 dB (2 Pa) and measured with a specific acoustic impedance of $\rho c \approx 448 \text{ kg/m}^2\text{s}$. Sensitivity measurements are presented in Table 1.

Table 1: sensitivity measurements.

Sensitivity of the various types of μ -flowns.			
sensor current	shs	ss	sh
2.5 mA	0.17‰	N.A.	0.05‰
10 mA	0.3‰	0.17‰	0.08‰

APPLICATIONS

The combination a dynamic flow sensor and a pressure sensor opens up a range of possible applications. With this setup it is possible to perform an analysis of the direction of energy in both gases and liquids (Fig. 6). By subtracting and adding the adjusted signals of a μ -flown and pressure microphone one can derive a stereo signal measured from one point. Another application is the measurement of the impedance in a system filled with liquid or gas, which gives information about the density and viscosity. Finally, a complete different application may be the use of a μ -flown as a feedback sensor in a loudspeaker system.

CONCLUSIONS

We have developed a small and easy-to-operate dynamic flow sensor, the μ -flown. When using, one has to take into account the $1/f$ behaviour. A significant improvement of the sensitivity of the complete device is to be expected from the combination of the μ -flown and the Wheatstone Gadget, when used in other configurations. The μ -flown makes it possible to measure the particleflow of an acoustic wave. In combination with a microphone it is possible to determine the propagation direction of an acoustical wave.

FURTHER RESEARCH

Our priority is to develop a more detailed analytical model, and to gain more insight into the temperature distribution. Finite element simulations will also be done.

With this insight it should be possible to design a more optimal μ -flown with regard to the transfer function (increasing $\Delta R/R$). So far we only have investigated the constant power principle; next we are going to investigate the constant temperature principle.

ACKNOWLEDGEMENTS

Pedro Roodenburg, who did the first promising experiments; Arnoud van der Wel for analysing the *Wheatstone Gadget* in detail and Edwin Potman and Jos Knippen for their technical assistance are greatly acknowledged.

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