DOI 10.5162/iCCC2024/P22

Flow Measurement by Means of Wideband Ultrasonic Signals in Acoustic Waveguides

Jorge M. Monsalve[1], *Marcel Jongmanns*[1], *Sandro G. Koch*[1], *Harald Schenk*[2]
[1] *Fraunhofer IPMS, Maria-Reiche-Straße 1, Dresden, Germany,*
[2] *Brandenburg University of Technology Cottbus-Senftenberg, Platz der Deutschen Einheit 1, Cottbus, Germany*
jorge.mario.monsalve.guaracao@ipms.fraunhofer.de

Summary:

An alternative method to measure flow (and speed of sound) in a duct with ultrasound is presented, not based on the high-frequency emission of a pulse across the duct's diameter but on the low-frequency emission of a wave packet across the duct's length. MEMS electrostatic transducers were implemented to transmit wideband signals that lead to a robust time delay estimation via cross-correlation. Measurement of the speed of sound was consistent with an alternative sensing method, and that of flow velocity was consistent with the waveguide's dimensions.

Keywords: Acoustic waveguide, ultrasound, flowmeter, speed of sound, MUT

Introduction

Ultrasonic signals have been widely used to measure flow in pipes [1], not requiring interaction of the fluid with mechanical parts nor bringing about an additional pressure loss. In the classical configuration, two ultrasonic transducers are placed at diametrically opposite points of the pipe's wall pertaining to two closely spaced sections, such that ultrasound is transmitted at a certain angle (usually 45°) from one transducer to the other in both flow directions (upstream and downstream). However effective, this method has some physical limitations that are inherent to its geometrical configuration. Firstly, the sound path is relatively short, set to be nearly 1.4 times the pipe diameter, which reduces the resolution capabilities for applications with small pipes. In addition, the emitted sound beam is bent with the flow, such that after a certain flow velocity the emitted waves do not reach the receiver. This configuration also compels the designer to seek for a transducer with a high operation frequency in order to achieve a high resolution and a focused beam emission; nevertheless, emission at high frequencies results in an unavoidable spreading loss (~1/r amplitude reduction) [2], higher absorption losses [3], and likely also multi-path reflections.

Here we propose an alternative method to measure flow with ultrasonic waves, based on acoustic propagation in waveguides. Instead of emitting high-frequency waves that spread within the pipe in all directions, we turn the pipe itself into a waveguide by operating at a lower frequency. Below a certain critical frequency, acoustic excitations within a duct are only allowed to propagate as plane waves, because the relatively large wavelength does not permit standing waves to be formed in the cross section [2]. This implies that ultrasonic signals can be propagated along the duct across large distances, excluding altogether the spreading loss and multi-path reflections whilst operating at frequencies where absorption is negligible. Therefore, the sound path can be extended arbitrarily to make the estimation of the time of flight more sensitive to small changes in the flow velocity or the speed of sound. The waveguide condition also allows the duct to be bent without provoking reflections. These factors make a waveguide flowmeter advantageous for the measurement of flow and the speed of sound in gas conduits of small diameter (mm-range). In this report we show an implementation of a waveguide flowmeter with a MEMS ultrasonic transducer.

Method

We constructed a waveguide flowmeter according to the scheme in Fig. 1. It consists of two identical branches that are joined together at the gas inlet and outlet. The purpose of these two branches is to split the flow in equal proportions, so as to perform one measurement where sound travels with the flow and one where it travels against it. Each branch is therefore coupled to an electroacoustic transmitter at one end and to a receiver at the opposite end. Given that sound is not only directed towards the waveguide but also diverted towards the gas inlet and outlet, sound absorbers are provided to supress acoustic interferences between the two waveguides. The critical frequency under which only the zeroth mode propagates along the waveguide can be obtained by an analysis of the Helmholtz equation applied to the cross section. In the case of a cylinder, this condition holds for a ratio between diameter and wavelength less than ~ 0.586 (see [2]), which yields 40 kHz for the design diameter of 5 mm (assuming a speed of sound of 343 m/s). We further implemented a density sensor (TrueDyne® DGF-I1, not shown in Fig. 1) to calibrate the speed of sound. We used an oscilloscope (Rohde & Schwarz® RTB2004) to generate and capture the signals of the transmitters and receivers.

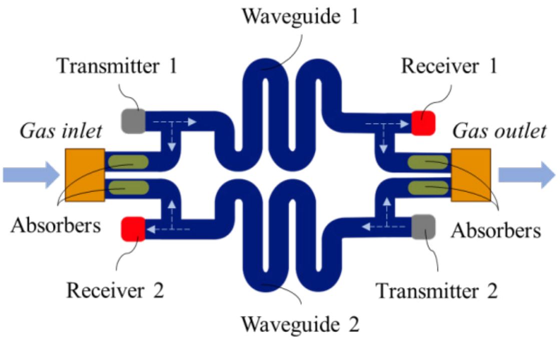

Fig. 1. Scheme of a flowmeter consisting of two acoustic waveguides, each coupled to an ultrasonic transmitter and a receiver.

Two different kinds of electrostatic MEMS transducers were implemented for the transmission and reception of ultrasound. The transmitter is a special kind of capacitive micromachined ultrasonic transducer (CMUT), which operates with *laterally* oscillating microbeams instead of vertically vibrating membranes (for which we denote it as ‘L-CMUT’ [4]). This L-CMUT has a relatively low *Q* factor that, despite dampening the response near its natural frequency, grants it a relatively large bandwidth. The receiver, on the other hand, was a commercial MEMS microphone (Knowles® SPH18C3LM4H-1) based on the classic membrane principle. Coupling these two elements enables the transmission of wideband signals, which are profitable for a more accurate time delay estimation based on a calculation of the cross-correlation integral [5]. We selected a ‘chirp’ signal sweeping from 14 to 20 kHz and Hann window for the measurements.

The classical method to calculate the flow velocity and speed of sound is based on the direct measurement of the travelling time of the acoustic waves; nevertheless; here we depart from this paradigm towards a relative time delay estimation with respect to a reference signal, as this was proven to yield more accurate measurements. The direct estimation of the time that it takes the acoustic waves to travel from the transmitter to the receiver requires comparing the sent signal against the received signal, but these two are not identical because both the transmitter and the receiver act as filters themselves, altering the final shape of the received signal. Instead of comparing these two signals, we compute the relative time shift between two received signals: one used for calibration (e.g. without flow) and one obtained at the desired measurement conditions. These two received signals are nearly identical in shape, so the cross-correlation between them offers a very accurate estimation of the relative time shift. The estimation of the time of flight of the calibration signal is still necessary to compute the sound paths of both waveguides (which are not perfectly identical), but it is performed only once. With this alternative strategy, the flow velocity and speed of sound are calculated according to Eq. (1) and (2), respectively. Here, c_x and c_r are the speed of sound at the measurement and reference conditions, respectively; v_x and v_r refer likewise to the flow velocity. L_1 and L_2 are the sound paths of waveguides ‘1’ and ‘2’, and $\Delta t_{1,2}$ are the relative time shifts between the reference and measurement signal at the corresponding waveguides.

$$2c_x = \frac{L_1}{\Delta t_1 + \frac{L_1}{c_r + v_r}} + \frac{L_2}{\Delta t_2 + \frac{L_2}{c_r - v_r}} \tag{1}$$

$$2v_x = \frac{L_1}{\Delta t_1 + \frac{L_1}{c_r + v_r}} - \frac{L_2}{\Delta t_2 + \frac{L_2}{c_r - v_r}} \tag{2}$$

A mass flow controller (Bronkhorst ® EL-FLOW Select) was used to introduce a controlled flow of air into the waveguide flowmeter. Flow was varied from 0 to 10 L/min in steps of 0.5 L/min, performing ten time-of-flight measurements per variation. The measurement at 0 L/min was used to calibrate the sound paths based on the measured values of pressure (P) and density (ρ), from which the corresponding speed of sound can be calculated according to Eq. (3), assuming an adiabatic constant (γ) of 1.4.

$$c = \sqrt{\gamma P/\rho} \tag{3}$$

Results

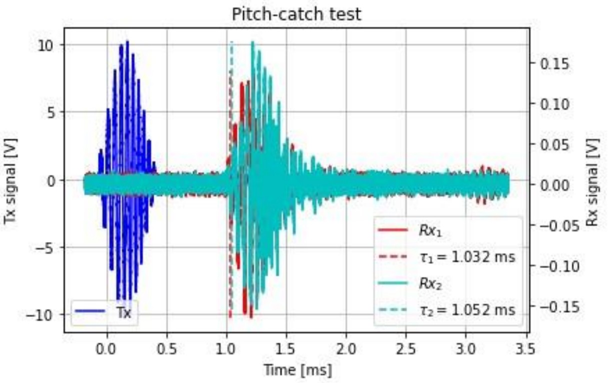

Fig. 2. Sample of the measured signals (both sent to the transmitters and detected from the receivers) for the measurement at 0 L/min.

A sample of the measured signals can be observed in Fig. 2. The transmitted signal (left axis) corresponds to the mentioned chirp between 14 and 20 kHz with the respective window. The received signals (right axis) mostly follow the shape of the transmitted signal, except for a small trailing edge, beginning at $t \approx 1.5$ ms, that corresponds to a residual wave packet from a higher mode. Note that the transmitter is not perfectly linear, so the second harmonic might excite the next higher mode of the waveguide at 40 kHz. The graph also presents the estimation of the time delay between the sent and received signals, according to the peak of the cross-correlation integral. Based on the measured values of pressure and density, the speed of sound was estimated as 329.5 m/s for this reference measurement, which yields a calibration of the two sound paths as 340 and 347 mm—despite our attempt to make both waveguides identical by design, a slight difference in the sound paths can be detected and taken into account.

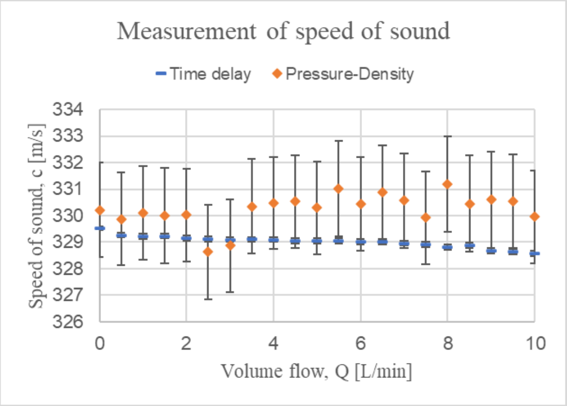

Fig. 3. Calculated speed of sound for the whole range of flow measurements, both as obtained by time delay estimation and as estimated from the density sensor.

Figure 3 shows the calculation of the speed of sound for all the values of volumetric flow that were configured with the mass flow controller. As expected, the speed of sound, calculated with Eq. (1), remains approximately constant for the different values of volume flow. These results were compared against the estimation following from the measured pressure and density, according to Eq. (3). The calculation from the ultrasonic signals is all but one case within the uncertainty margin of the calculation from the density sensor, which possesses a very fine temperature and pressure resolution (0.06 K and 500 Pa, respectively). It is also noticeable how the uncertainty from the acoustic method is significantly lower.

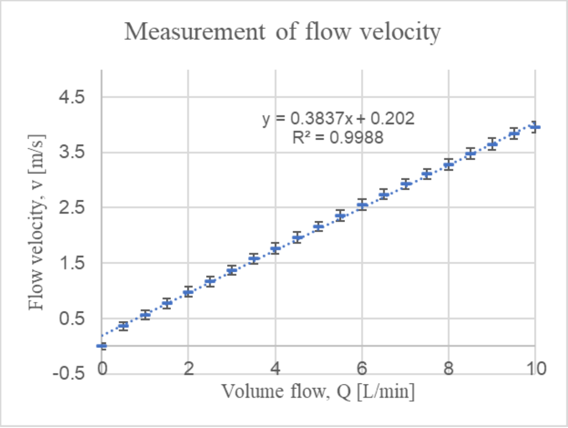

Fig. 4. Calculated flow velocity as a function of the regulated volume flow.

Figure 4 shows the obtained values of flow velocity as a function of the volume flow. The changes of 0.5 L/min between measurements (corresponding to steps of ~ 0.2 m/s) not only led to different nominal values of the flow velocity but were also distinguishable considering the uncertainty bars. A highly linear behaviour between these two variables is observed, whose proportionality constant leads to an estimation of the waveguide's diameter as 5.3 mm (close to the design value of 5 mm). The performed linear regression also reports an unexpected intercept. Apparently, the step from 0 to 0.5 L/min departs from the linear trend for unknown reasons.

Conclusion

A conduit of small diameter can be utilised as an acoustic waveguide to transmit ultrasound with negligible losses across a path much larger than the conduit's diameter and so perform measurements of flow velocity and speed of sound with high accuracy. This requires an acoustic excitation below a critical frequency, such that only the zeroth propagation mode of the waveguide is activated. Usage of MEMS electrostatic transducers with a wideband frequency response enabled the transmission of wideband signals for a high-resolution time delay estimation through cross-correlation. The acoustic measurement of the speed of sound of air was consistent with the calculation following from a commercial MEMS density sensor, and the measurement of flow velocity reached a resolution of 0.2 m/s with a nearly linear behaviour with respect to the introduced flow, the slope of which was consistent with the waveguide's diameter.

Acknowledgement

This work was supported by the Fraunhofer Internal Programmes under Grant No. SME 685 400

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