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ULTRASONIC METHODS FOR DETERMINING FLOW RATE AND VELOCITY FIELD

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Abstract: *Non-invasive flow measurement in fluid mechanics using an ultrasonic signal is successfully used in industry. The use of this method for measuring air pollution is not so widespread, which is detrimental in the field of regulation of air-conditioning equipment and the verification of their parameters. In these fields, its application would be widespread. This paper is dedicated to the theory and description of the development of an ultrasonic flow meter for measuring air flow. The physical principle of such a device consists in the interaction of the transmitted sound wave with the flow field, which causes the sound wave to deviate from its path and thus delay or accelerate the traveling signal. This time deviation is a quantity intended to be gained and the flow rate is then determined from it. Another area where the ultrasonic principle can be used is the complete reconstruction of the vector field. The principle of an ultrasonic tomograph for use in fluid mechanics is also known and described, but its implementation is a huge challenge; demands are placed mainly on the software part of the development.*

Keywords: Ultrasonic flowmeter, Ultrasonic tomograph, Fluid flow measurement.

1. Introduction

Dozens of methods are currently used to measure the flow rate. The choice of a suitable flow meter always depends on a large number of factors, from the type of flowing medium to its physical and chemical properties, temperature, possible installation dimensions, accessibility, expected measured values, measurement uncertainty, accessibility and controllability of the flow meter and others. A general overview of flow meters and in particular a comprehensive summary of their possible uses can be found in (Furness, 1991).

Ultrasonic flowmeters belong to the group of non-invasive methods, which is one of their main advantages. Others include, for example, easy installation dimensions and easy application. The history of their development is described in (Lynnworth, 2006).

Despite the large number of possibilities offered by the ultrasonic flowmeter market, it is still possible to find areas that can be researched and innovated. The next logical step in the development of the ultrasonic flowmeter is to upgrade the developed device to be able to map the 3D velocity field, called a tomograph.

The ultrasonic flowmeter thus works with the time difference that the interaction of the sound wave with the flow causes, compared to the transit time of the sound wave between the transmitter and receiver without the flow. An ultrasonic tomograph basically uses this quantity as well, but in order to obtain a velocity vector it is also necessary to know the angle of the sound wave by which it deviates. A detailed elaboration of the mathematical approach is discussed, for example, in (Johnson et al., 1977). Another crucial paper on ultrasonic tomography was published by Braun and Hauck (1991).

Among the more recent works it is necessary to mention the dissertation thesis by Jovanović (2008) which, in addition to a detailed mathematical analysis of the problem, argues with the works of Johnson et al (1977) and Braun and Hauck (1991) (according to whom it is not entirely appropriate to use the time-of-flight of a sound wave to determine the angle of its deflection). Jovanović presents mathematical and practical reasons for measuring the angle of incidence of a sound wave after interaction with a flow field only by measuring the time-of-flight.

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Due to the complexity of data processing, there are not many practical tomographic examples of measurements in fluid mechanics in world literature. Liu et al. (2014) tomographically reconstructed the velocity field in a circular pipe and performed measurements for relatively low velocities and the Reynolds number (1 m/s, 25000 respectively).

2. Ultrasonic principle in fluid mechanics

The time-of-flight of the signal between the transmitter and the receiver is expressed by a curve integral containing elements with the speed of sound and the flow rate.

$$\tau = \int_{\Gamma} \frac{1}{u_g} ds = \int_{\Gamma} \frac{1}{(cn + v).s} ds, \tag{1}$$

where . denotes the scalar product. Linearized with Taylor expand series, it leads to

$$\tau \simeq \int_{\Gamma} \frac{1}{c_0 n.s} ds - \int_{\Gamma} \frac{(\Delta\, cn + v).s}{(c_0 n.s)^2} ds \simeq \tau_0 - \frac{1}{c_0^2} \int_{\Gamma} (\Delta\, cn + v).ds$$
$$\rightarrow (\tau_0 - \tau)c_0^2 = \int_{\Gamma} (\Delta\, cn + v).ds\,, \tag{2}$$

where τ is time-of flight, Γ is sound ray trajectory, u_g is the group velocity, s is vector tangent to the Γ trajectory, c is speed of sound, n is vector normal to the wave front, v is the flow velocity, c_0 reference speed of sound, τ_0 is reference time-of-flight. However, the right side does not lead to a clear solution.

If a substitution is done with the Helmholtz´ decomposition of the velocity field into a solenoidal and a curl-free part, and this equation is solved on a vector field, information about the solenoidal component of the flow cannot be obtained. The right part of the equation only provides information about the longitudinal interaction of the sound wave with the velocity field. For a complete reconstruction of the velocity field, it is also necessary to obtain information about the transverse interaction.

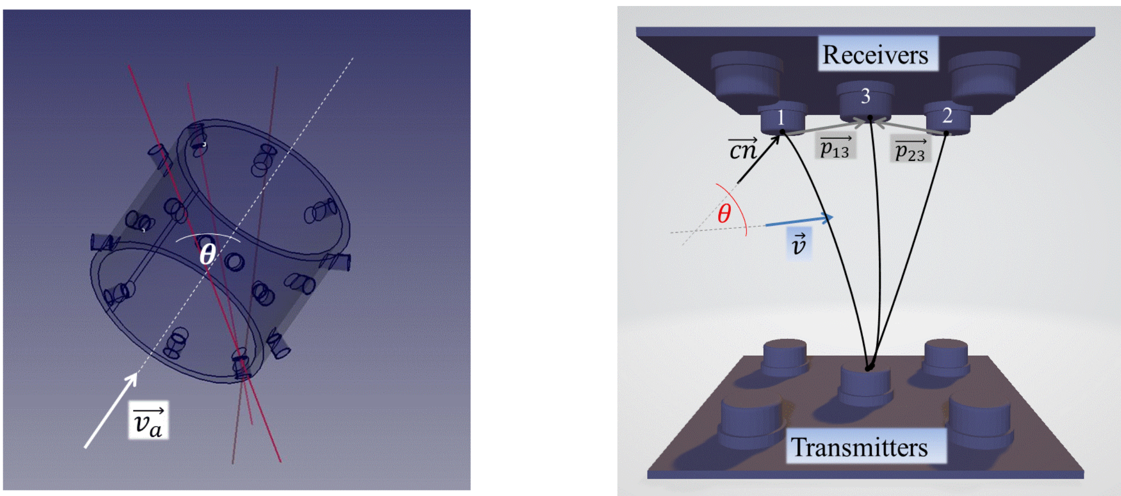

Fig. 1: The ultrasonic flowmeter with the designed transmitters/receivers location with indicated tomographic principle (left picture), the tomographic gauge setting and angle measurement principle (right picture).

Put into practice, it is actually a measurement of the incident angle of sound velocity vector. Jovanović (2011) suggests to come from the equations of dipoles (the geometric principle of this solution is depicted in Fig. 1):

$$n_R = \frac{u_g - v}{||u_g - v||} \tag{3}$$

$$u_g.p_{13} = \left||u_g|\right|^2 (\tau_3 - \tau_1), \quad u_g.p_{23} = \left||u_g|\right|^2 (\tau_3 - \tau_2)\,, \tag{4}$$

where v indicates the local speed, p denotes position vector.

The simplified equation (1) applied to the flowmeter depicted in Fig. 1 leads to a very easy use in the case of ultrasonic flowmeter. The mean axial velocity is then calculated from signal travelling downstream and upstream using a simple equation

$$v_a = \frac{L}{2 \cdot \cos\theta}\left(\frac{1}{\tau_1} - \frac{1}{\tau_2}\right), \tag{5}$$

where v_a is the axial velocity, L is the distance between transmitter and receiver, θ is the tilt angle of transmitters/receivers and τ_1 and τ_2 downstream and upstream soundwave time-of-flight with fluid flow.

However, this simple principle contains a great pitfall in the exact determination of the received signal inception, leading to cross-correlation or more advanced methods utilization for signal post-processing.

3. Ultrasonic flowmeter building and measurement and tomograph first tests

As the flowmeter is to be developed as an invariant to the velocity profile, an experimental line for validation tests had to be prepared and built. This line was designed as variable, mainly because there will be another verifying method used for the velocity profile measurement (this method will be Particle Image Velocimetry). At the beginning of this line, generators of various velocity field uniformity disorders will be located. The ultrasonic flowmeter also will be tested for different temperature, humidity and turbulence intensity influence on the measurement uncertainty. Different shapes of a cross-section also will be tested; the line is also prepared for extensive testing of the ultrasonic tomograph, designed as a linear array of transmitters/receivers.

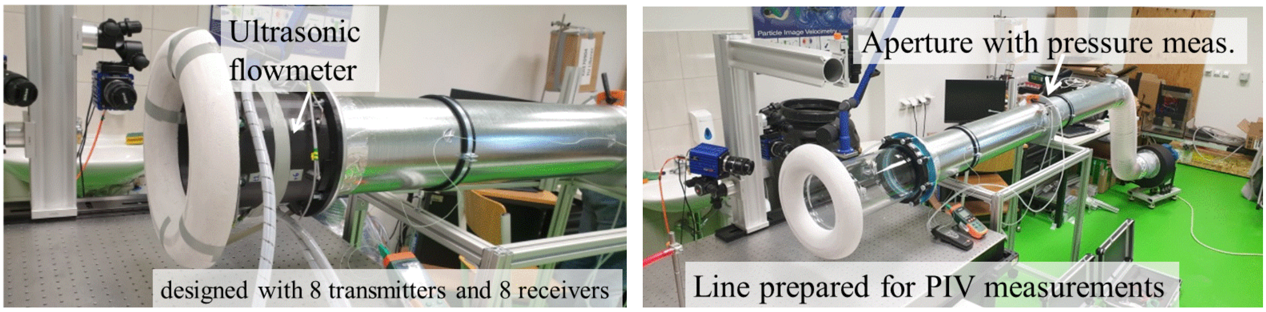

Fig. 2: The variable experimental line for the testing of ultrasonic measurement: the ultrasonic gauge (left picture), a glass part for PIV measurements (right picture).

There were two big challenges in construction preparation of the ultrasonic flowmeter: the geometry and the transmitters/receivers choice. The main design requirement was the geometric accuracy of the transmitters and receivers location. For later calculations, it is necessary to precisely define the distance of the respective pairs (T-R), so 3D printing with precisely defined geometry seemed to be the most suitable option. The electronic part of the gauge was another great task. So, several different transmitters/receivers were selected for the first tests and their directional characteristics were verified. Eventually the T/R operating at 40kHz were chosen for both gauges, ultrasonic flowmeters and ultrasonic tomograph, and the whole electronics for excitation, reception and processing the signal was built.

The first tests of this ultrasonic flowmeter were made with the intent to find out the limits of the present hardware, software and post-processing setup when measuring low flow rates. The results are depicted in the graphs below. The flowmeter results were compared to the pressure measurement provided by measuring the pressure difference at the orifice using a TESTO 512 differential pressure gauge (and later calculation of the flow rate).

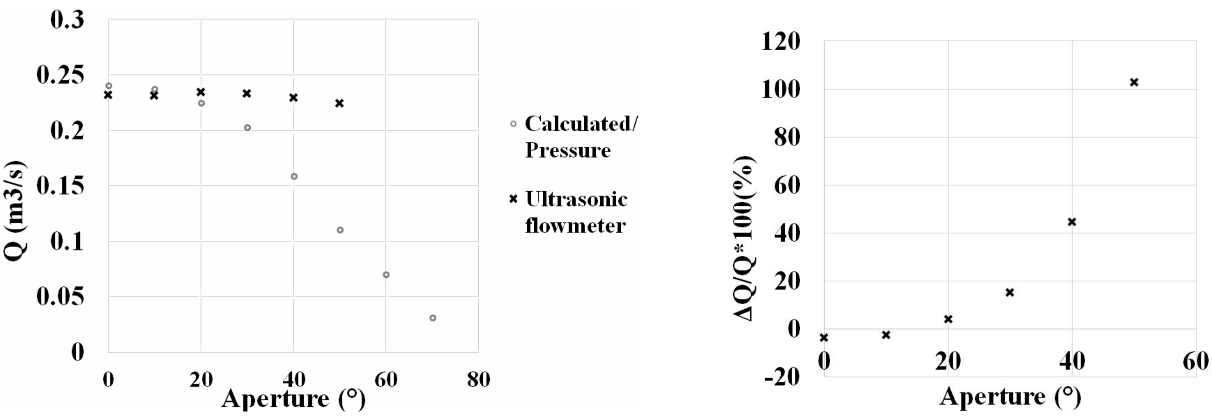

Fig. 3: The ultrasonic flowmeter test results in comparison with pressure results (left picture), an uncertainty of the measurement (right picture).

For ultrasonic tomograph principal tests, there were two possibilities. One was to use existing ultrasonic flowmeter and first gained data and evaluate them, thereby obtaining information about the velocity field in a section perpendicular to the flow field. As this is a useful feature, this procedure is currently being developed; the inverse part of the problem is software-challenging. The second possibility was to prepare a small linear tomograph (as depicted in Fig. 1). The first tests, unfortunately, were contradictory and unrepresentative.

4. Conclusions

In the paper, the first phase of the development of ultrasonic flowmeter and ultrasonic tomograph has been presented. The main challenge of this development is disposing of the velocity-profile dependency influencing the flow rate results. From a hardware point of view, the construction was needed to be prepared to maximize geometric accuracy. The second challenge was to process the received ultrasonic signal involving cross-correlation method instead of using simple time-of-flight determination method. This attitude should enable the results to be more accurate, especially in the case of low flowrate. The results from the first verification tests shifted the measurement of the flow rate towards the lower values in comparison with the first generation of ultrasonic flowmeter (which was not described in the paper), but only for a narrow range of flow rates and velocities of the experimental line (around 0.25 m3/s, more than 7 m/s, then uncertainty was max. 4%). The first tests from the linear tomograph were contradictory, possibly due to incorrectly selected postprocessing of the data.

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