Multipoint ultrasound flowmeter

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Abstract

A concept of a new kind of flowmeter is presented. The flowmeter is based on a multipoint time-of-flight (TOF) measurement of ultrasound signal through a moving fluid. The concept of the flowmeter corresponds with 3D tomographic methods, the output (besides flow rate) will be the distribution of all three velocity components in the monitored volume. The advantage of the new concept is its invariance of indicated airflow to the velocity field. This paper presents the concept of the device and briefly discusses the planned work: background research, simulation of the evaluation algorithm, development of HW and SW solution and prototype construction. The prototype will then be tested in a water tunnel.

Key words

flowmeter, 3D tomography, ultrasound measurement, velocity measurement

1. Concept

Consider a large number (*n*) of ultrasound transceivers spaced around a control volume with fluid flow (Figure 1). In each step one transceiver sends an ultrasonic pulse to the control volume and all remaining transceivers act as receivers that measure the time-of-flight (TOF) of the ultrasonic signal through the control volume. This step is repeated until all *n* transceivers have been in the transmitting role and *n*!/2 TOF signals are obtained. The signals will be distorted by the fluid flow and the calculation of flow rate from these signals lead to reconstruction of the 3D velocity field in the control volume.

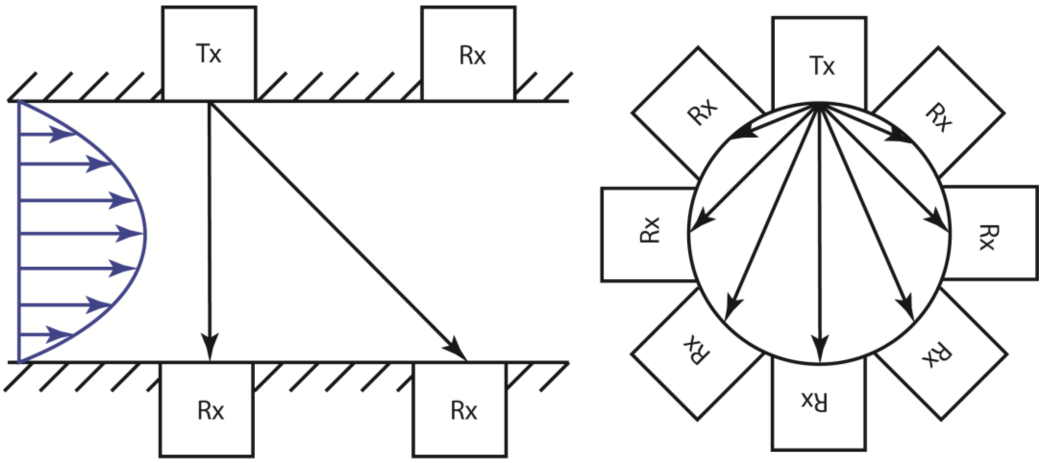

Figure 1.*Principle of the new flowmeter.*

2. Similar principles

2.1 Tomography

The principle of the proposed flowmeter is very close to the principle of tomoghraphy – a set if integral values along beam paths is used to reconstruct an image. Tomoghraphy is widely used in medical applications either in the form of classical X-ray CT (Computed Tomography) or in the form of ultrasound tomography.

The X-ray CT reconstructs an image in a two-dimensional section of the investigated object. The solution to the inverse problem of the 2D reconstruction is well known, some of the algorithms are well covered by [3]. The CT simply traverses along the direction perpendicular to the scanning plane to get a 3D image. This procedure is obviously not applicable to the new flowmeter.

The ultrasound tomography measures the TOF of many signals in a plane to reconstruct a 2D image. There has been an experimental 3D tomograph [1] that is by principle very close to the proposed flowmeter and will be of inspiration for transforming the reconstruction techniques from 2D to 3D.

2.2 Ultrasonic Doppler Method

In the case of liquid flow measurement it would be convenient to use the Doppler frequency shift information besides TOF to map the fluid flow such as proposed by Takeda [2]. The new flowmeter might be able to use this additional information for more accurate measurement however, it is not planned to be considered in order to keep the concept simple for general fluid measurement.

3. Evaluation technique

3.1 Fluid velocity TOF measurement

The TOF of an ultrasonic signal going through a control volume is being influenced by a fluid flow. The flow does not only influence the TOF and the frequency of the signal but also the shortest path of the signal from the transmitter to the receiver which should be taken in account by the evaluation algorithm. This deflection will be neglected as small fluid velocities will be considered compared to the speed of sound in the fluid (see Figure 2)

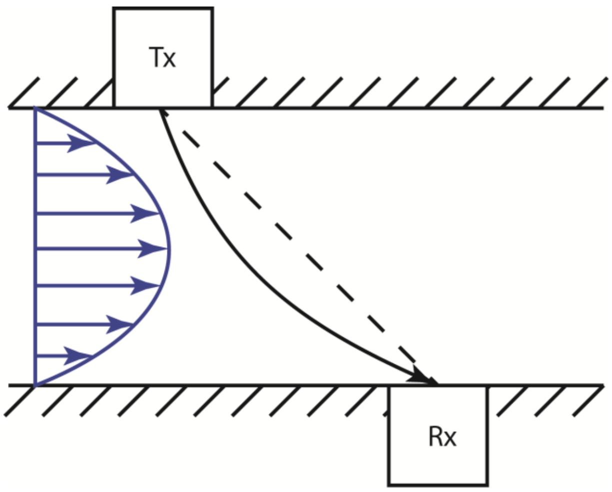

Figure 2.*Deflection of an ultrasonic signal.*

3.2 Image reconstruction

There are numerous 2D tomography image reconstruction algorithms available spanning from simple algebraic solutions to complicated iterative algorithms [3]. The algebraic reconstruction technique (ART) is easiest to grasp as it operates over a discretized space where it considers linear shift of the rays' properties (TOF in our case). The image is then found as a solution of a system of linear equations. This technique will be modified to match the need of the new flowmeter – to create a system of equations describing all three velocity components in the control volume. The flow rate through the control volume will then be obtained by a simple integration of the velocity field.

3.3 Simulations

A set of simulations will be run to ensure that the reconstruction technique is working as desired. Synthetic velocity fields will be generated and corresponding TOFs will be calculated as inputs to the reconstruction technique. Airflow rate error and local velocity error will be monitored to check the reconstruction procedure.

4. Limitations and potential difficulties

There are several difficulties expected along the development and testing process. Reflections of the ultrasound waves might bring difficulties to the pulse detection and cause scatter of the measurement data. Generally noise is an issue and will be treated at the HW level by a careful design of the amplification and sensing circuits. Additional filtering might be necessary in the image reconstruction process but is not planned to be implemented in the testing version. The transceivers must have a wide directivity angle to ensure that most transducers have a direct line-of-sight signal propagation however, it is expectable that this will not be the case for some of them. This might cause troubles if reflections are picked up for the TOF measurement and will need to be treated in the postprocessing. Deflection of the ultrasonic signal will be neglected as small fluid velocities are supposed. This will probably be true for most cases of liquid flow but may not necessarily be true when gas flow is measured. If the need arises it will be necessary to implement a ray tracing algorithm such as one covered by [4].

5. Testing

5.1 Prototype construction

A working prototype will be constructed for water airflow measurement. The HW of the electronics will be developed in-house as low cost solution based on available ultrasonic transceivers. The solution will be based on ATmega microcontrollers on the HW side and Matlab on the postprocessing side.

5.1 Testing water tunnel

A water tunnel will be built for the purpose of testing the prototype (Fig. 3). The tunnel will be equipped with a reference flowmeter to monitor the accuracy of the new sensor under various conditions. The maximum flow rate is designed to be 0.1 m^3/s in a circular test section of 0.25 m in diameter giving a maximum velocity of 2 m/s.

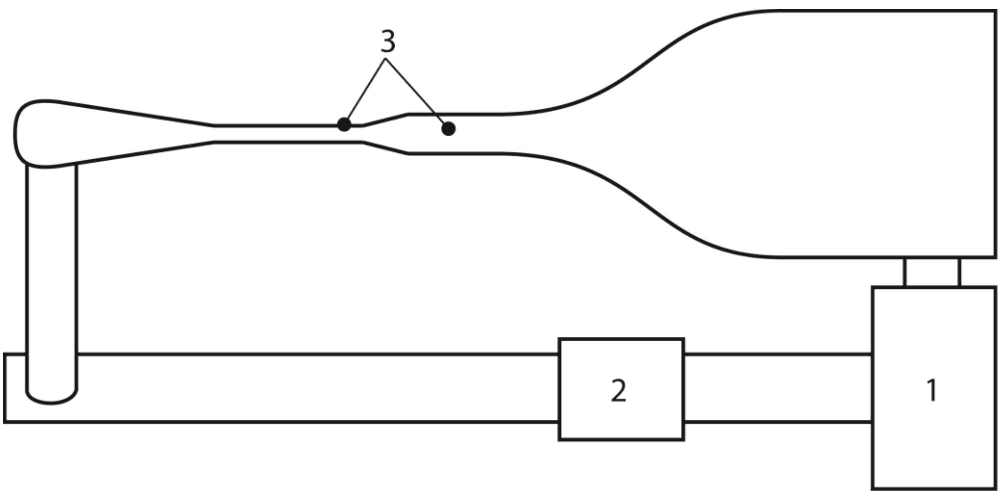

Figure 3.*Water tunnel for experimental testing of the flowmeter. 1-pump. 2-circular test section. 3-rectangular test section*

5.3 Planned tests

Tests will be performed to verify the accuracy of the flowmeter under ideal conditions of a fully developed velocity profile for varying flow rate – repeatability and noise will be estimated. Most of the testing will be aimed at the verification of the major advantage of the flowmeter over currently available principles – the velocity field invariance. Obstacles will be placed in front of the test section to generate non-homogenous velocity fields and airflow rate error will be monitored.

6. Application

We need to look at the application of the new flowmeter from two perspectives. On one side it is the measurement of flow rate of fluids in pipes (gases or liquids) where a major advantage of the new concept compared to currently used flowmeters is that it puts almost no restrictions on the velocity field. From a practical point of view this means that there would be no requirement of straight pipe in front of the flowmeter and so the installation requirements would be very beneficial.

Another vast application area is the measurement of all three velocity components in a volume past bodies in fluid dynamics problems. It would present a new method besides traversing a single point velocity probe or the volumetric PIV. Although the new method will suffer from poor local value prediction (as any tomographic method) it will be much easier and faster to setup and also to perform the experiment.

7. Conclusion

A new concept of flowmeter was presented. The feasibility of the concept was backed up by comparison with tomographic methods that are widely used in medical applications. The new flowmeter would be beneficial for both industrial and research applications where it would bring an easy way of investigating flow rate and velocity distribution in a control volume. The scheduled work covers the development of the HW, SW and postprocessing solution with experimental verification of the concept.

References

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