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Ultrasonic methods for determining flows and velocity fields

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Abstract. This paper introduces research and development of a modern non-invasive device for determining flows and velocity fields. This device is based on the ultrasonic method. The measured fluid flow is surrounded by appropriate ultrasonic transmitters and receivers, which communicate with each other. A physical principle of this method consists in an interaction of sound waves with a flow, which generates a certain delay in sound waves transmission. The found quantity is thus time delay. The device is being designed as a flowmeter and with advanced and extended postprocessing as a tomograph, which reconstructs a 3D vector field for big volumes. This whole process requires the following: development of an appropriate design of the ultrasonic flowmeter and tomograph, testing the signal transfer and also various postprocessing methods on a measurement accuracy, building of a special verification experimental equipment and building of an electronic device as a control unit and data acquisition system.

1 Introduction

This paper deals with the development of two measuring methods for use in fluid mechanics. Both methods are based on the non-contact measuring principle in which ultrasonic transmitters and receivers are used as sensors, and the sound signal travelling through the flowing medium and the interaction of both of these moving entities is considered. In the case of the first measuring method, it is an ultrasonic flow measurement, in the case of the second method, it is a tomographic mapping of a 3D vector velocity field.

The gauge development involves the following tasks: selecting and testing active gauge elements, i.e. ultrasonic transmitters and receivers. This was the most crucial part of the construction, because several aspects had to be taken into account in the selection: design (especially small dimensions), physical (frequency characteristics, directional characteristics and wave range), microelectronics (control and power supply) and last, but not least, economics. The next step was the construction of meters (to choose the most suitable production technology, especially with regard to the exact placement of ultrasonic transmitters and receivers), prototype design of the control unit and, of course, related activities such as firmware development and control and the measurement software itself. Simultaneously with the construction of the meters themselves, it was necessary to build a verification measuring line and design a set of experiments that verify the sensitivity of measured quantities to different velocity fields (uniform, axially symmetric, deformed), humidity, temperature and temperature field, or turbulence intensity.

Currently, a number of methods are used for flow measurement - from point methods (pressure measurements using multi-hole probes, CTA, etc.) through integral methods (orifice measurements, rotameters, vortex flow meters, etc.) to area / volume methods (PIV). Ultrasonic methods also play an irreplaceable role in this enumeration, but all of them are sensitive to the velocity profile in the measured area and it is therefore necessary in almost all cases to use relatively large installation dimensions of the flow meter.

One of the main innovations of the developed flowmeter is the invariance of the velocity profile of the measured fluid, which significantly reduces its installation dimensions. This can be useful in many technical applications. At the same time, the whole system is designed so that it can be used on pipes of any cross-section (circular, rectangular, multi-walled, general shape).

There are also a number of methods for determining 3D vector fields. The main disadvantages of the methods used today lie either in the disproportionate complexity of the experiment itself (traversing with multi-hole probes), or in very expensive instrumentation in combination with a relatively limited size of the measured area (typically TOMO-PIV, Volumetric PIV). The vector ultrasonic tomograph should be able to eliminate both of these shortcomings. It should be noted that ultrasonic tomography for 3D vector field

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reconstruction is not an unknown imaging technique and its use, at least from a theoretical point of view, has been described in publications for over 40 years. But despite the undeniable advantages of this experimental method (rapid and non-invasive use) its extension is not significant.

The principle of the ultrasonic vector tomograph, for example, is well described in the theoretical work from Norton [1] or more recent work can be referred to the thesis of Jovanovic [2]. From the point of view of the currently available state of the art technology in the field of ultrasonic flow measurement, resp. velocity fields, it is necessary to mention the publication [3], in which the authors describe a device similar to the proposed ultrasonic tomograph. It is clear from the publication that the proposed measurement principle can be very useful for determining the velocity field.

The authors of this contribution assume the expansion of the HW part of the whole device so that it is possible to determine the impact angle of the ultrasonic beam.

In this area, it is also worth mentioning an older publication in which the authors also deal with the reconstruction of the velocity field using tomographic evaluation of the ultrasonic signal [4], [5] and [6]. The new publication [7] is also worth noting, in which the authors moved the field of application of the ultrasonic tomograph principle to the field of compressible fluid flow.

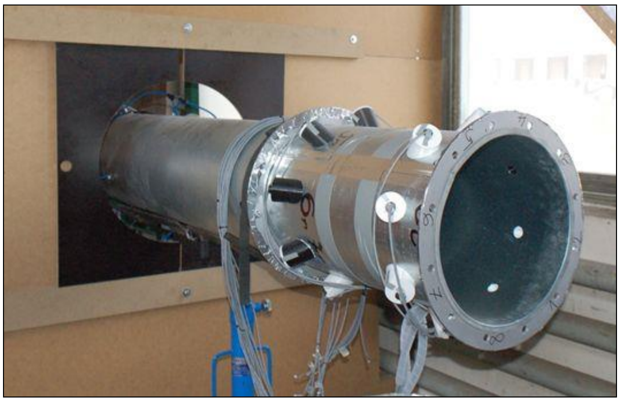

Fig. 1. Test prototype of ultrasonic flowmeter placed in 4Jtech laboratory, connected to an aerodynamic line.

2 Ultrasonic flowmeter

2.1 Principle

The basic principle of ultrasonic measurement of fluid flow is to determine the flight time of the signal from the transmitter to the receiver, because the sound signal interacts with the medium and this property is successfully used in the calculation of parameters, which are crucial for fluid mechanics. In order to be able to say that a flowmeter is invariant with respect to a velocity field, it is necessary to know the velocity field profile, or to measure and reconstruct it. Such advanced flowmeter, which will measure not only the average flow rate, needs to be designed in a tomo-configuration, such as the one in the figure below. The measurement procedure from the diagram in the figure below is, for example, the transmission of an ultrasonic wave sequentially from all transmitters to all receivers. One measurement contains a matrix of the number of transmitters x the number of receivers of the output signal values.

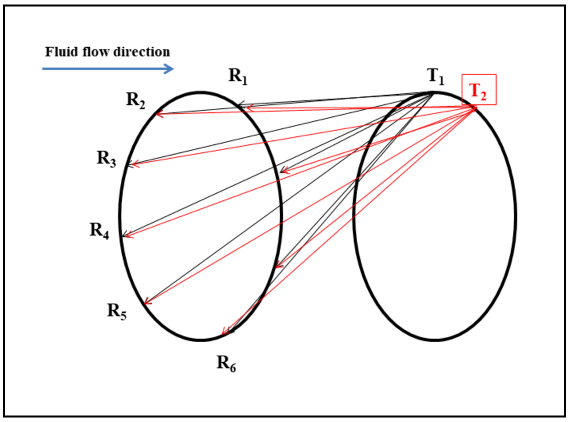

Fig. 2. Schema of the principle of transmission/ receiving of the signal.

2.2 Design

The design consisted of selecting and testing the most suitable active elements, i. e. transmitters and receivers, and selecting the appropriate technology for the production of the flowmeter body. In the case of the selection of transmitters and receivers, the directional characteristics is emphasized most. It is also necessary to take into account the range of the signal and dimensions of the elements. Along with this, it is necessary to think about an easily feasible power supply and control and signal reception. While the individual parameters of course sometimes contradict each other, the result is always a kind of compromise. However, the selection of sensors is the most important part of the entire design process, so special care was taken at the beginning to select and test the appropriate elements. Another part of the design was to choose the technology of the first test piece production. As the work progressed, the original technology was replaced with a new, more accurate technology for production, and with the possibility of a faster change in the basic dimensions of the gauges.

2.2.1 Sensors

The requirements for ultrasonic transmitters/ receivers for use in fluid mechanics are generally conflicting. In order for ultrasonic flowmeters to be suitable for measuring the velocity field, it is necessary to choose transmitters with the highest possible frequencies, ideally in the order of 100-1000 kHz. At such frequencies, the frequencies of the measuring technology no longer collide with the frequencies of possible non-stationarities of the flow field. However, transmitters/ receivers with such high frequencies generally have high power requirements. Another problem with such high frequencies is the weaker power of the transmitters/ receivers or the inappropriate dimensions.

A compromise was therefore chosen for Prototype 1 of the developed ultrasonic flow meter - often using transmitters/ receivers of small dimensions with a frequency of around 40 kHz. Their directional characteristics (specified by the manufacturer) are generally satisfactory and sufficient for the dimensions of Prototype 1 at this time.

Transmitters/ receivers were selected that met the required frequency, size, directional characteristics and price. During the first tests the directional characteristics of the supplied transmitters were verified, because the manufacturers often conceal their procedure for verifying this essential property and the reason is the fact that the directionality is measured in a rough resolution of ten degrees.

Finally, sensors designated MCUST and MCUSR were selected.

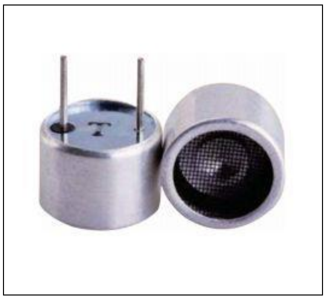

Fig. 3. Ultrasonic transmitters/ recievers chosen for testing.

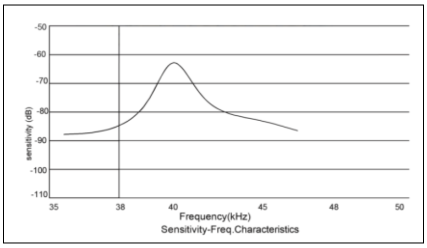

Fig. 4. Frequency characteristics for transmitters/ receivers MCUST/R.

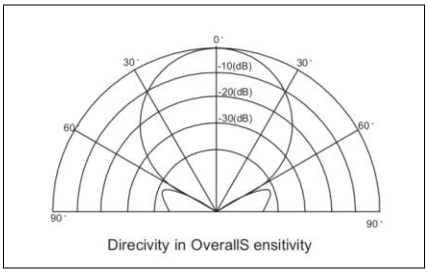

Fig. 5. Directivity for transmitters/ receivers MCUST/R.

2.2.2 Design

Prototype 1 is built for circular piping in a configuration that is least sensitive to the velocity distribution of the fluid flow. To assess the properties of the flowmeters three factors are compared: the hydrodynamic factor, the directional sensitivity factor and the range factor. In general, the more transmitters/ receivers used, the better accuracy is achieved. The highest accuracy is achieved in the arrangement, which the foreign literature refers to as D-Orth, ie double-orthogonal.

Test prototype (see Fig. 1) was made of air ducts and around its perimeter were placed transmitter and receiver holders printed on a 3D printer, while the storage was done in a D-orth configuration. In this arrangement, the first verification experiments were performed, in which the ultrasonic flowmeter was connected to a fan track in the 4Jtech laboratory. Soon after that prototype No. 1 was created, because it was clear that the design of the test gauge is lengthy, demanding to manufacture and also can not achieve the highest possible accuracy geometrically. The sensors holders have an oval surface and it is very laborious to achieve a precise oval, moreover in a precisely determined position, by cutting into sheet metal. The possible production of a custom made ultrasonic gauge would thus be unnecessarily demanding.

The main requirement in the design of prototype No. 1 was the geometric accuracy of the transmitters and receivers location so that for later calculations it is possible to precisely define the distance of the respective pairs (T-R), easy variability of the design (even with regard to later transition to the gauge of non-circular cross-section) and last, but not least, easy to manufacture. In the end, 3D printing seemed to be the most suitable for the prototype.

The considered diameter of the experimental line which the flowmeter of prototype No. 1 was designed for is 200 mm. The only minor obstacle was that the entire 3D flow meter, even with flanges, could not fit on the pad of the usual 3D printer, and it was necessary to divide it into 4 parts and glue them. Although the geometric accuracy in the distribution of ultrasonic flowmeter was slightly lower (the connecting surfaces also have a certain deviation at the height of the printing layer of 0.3 mm), it turned out that despite this small disadvantage, 3D printing is the best possible choice in all possible respects.

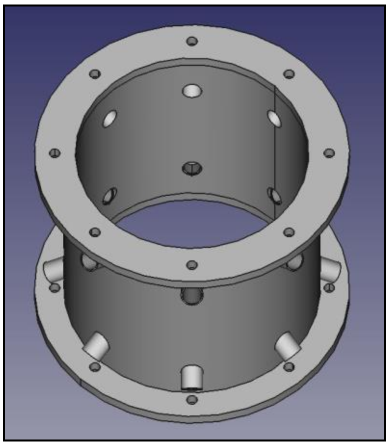

Fig. 6. The gauge design.

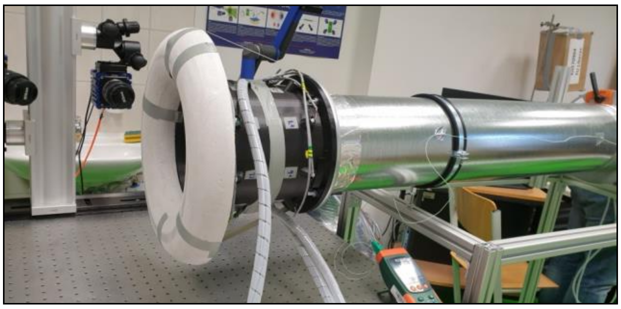

Fig. 7. The ultrasonic flowmeter prepared by 3D printing (together with an experimental line, see chapter 4 bellow).

2.3 Microelectronics

Overall, the control unit has the task of providing the operation of excitation and reception of ultrasonic signals, high-speed sampling of signals, their temporary buffering into the buffer and transmission for further processing.

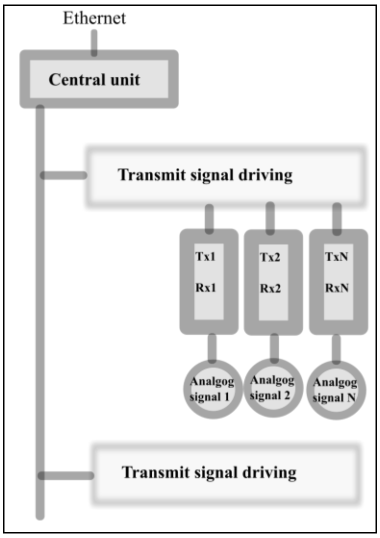

Fig. 8. Schema of the microelectronics.

The above requirements can be summarized, with respect to other parts of the flowmeter, in the following points:

- standard supply level 5 V, 12 V
- compact solution using commonly available components with long-term support
- sampling of analog signals at least 50 MHz
- AD converter resolution min. 8 bits
- at least 4 independent analog channels
- the size of the buffer covering at least the recording of all channels during the flight of the signal through the space of the flow meter
- sufficient computing power to process digital signal processing tasks

From the point of view of electronics, the most problematic part is the signal sampling and subsequent caching. Even with regard to other requirements, it is suitable to use FPGA type circuits, parallel AD converter, DDR type memory.

A standard Ethernet interface was chosen to connect the control unit to the computer. Due to previous experience with FPGA circuits, the Spartan 7 FPGA circuit family was chosen. Circuits of this type are able to process signals at the required sampling levels, they allow the connection of DDR3 type memories. Spartan FPGAs allow the MicroBlaze processor to be synthesized to combine a parallel and sequential structure.

The production of the original prototype was carried out using interconnected modules. The first part consists of a designed module containing the STM32F429 processor, Ethernet connection, IS42S16400J-7TLI memory with 4Mx16 organization, optional LCD display connection and SPI bus.

Power is provided by a standard 12 V adapter. The Ethernet interface operates at a standard speed of 100 Mbit. The board is connected via SPI bus to the FPGA module with a standard connector, data transfer speed is up to 1 Mbit / s. Each analog channel was implemented by one AD converter on a separate printed circuit board. The proposed printed circuit board is shown in the following figure.

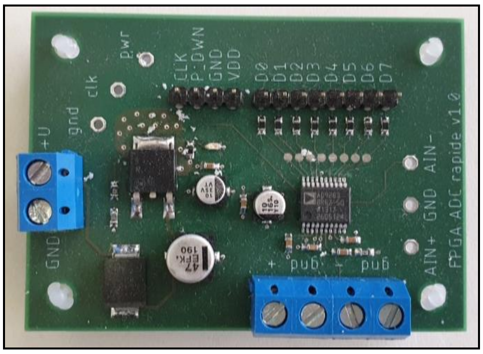

Fig. 9. AD converter.

2.4 First tests

The first verification measurement of a circular flowmeter was performed on a newly assembled experimental line in the laboratory of the Technical University in Liberec (see chapter 4 Experimental line). The evaluation of the obtained data is currently in process, because first it is necessary to obtain statistical data.This requires the evaluation of several hundred files in order to determine the optimal ratio of signal measurements between transmitter-receiver pairs and measurement accuracy.

It is also important to choose a more appropriate way of the signal time measurement approach itself. So far the evaluation is processed in two ways: a more laborious and statistically demanding way, which depends only on the received signal from all receivers and the accuracy of peak correlation, or a simpler simple time determination approach of finding time of flight between the leading edge of the transmitted signal and the beginning of the received signal. The second way can cause entering a significant error in determining the beginning of the received signal (see figure below; in this way, the received signal can be determined with an accuracy of 25 μs, which means that an uncertainty of

4% is introduced into the overall flow of the prototype ultrasonic flowmeter only by this input).

A processing method based on fast Fourier transform, inverse FT, threshold determination and phase shift should help this problem. However, due to the complexity of processing both evaluation methods, this problem has not yet been clearly solved.

Fig. 11 shows the course of signal processing by comparing two received signals (receivers differ in geometric determination, so the signals are correlated).

The essence is to find the maximum value of this correlation and clearly determine the position of the peak of this correlation on the axis of the number of samples (which corresponds to the time axis, at a sampling frequency of 50 Msps, the result is tens of microseconds).

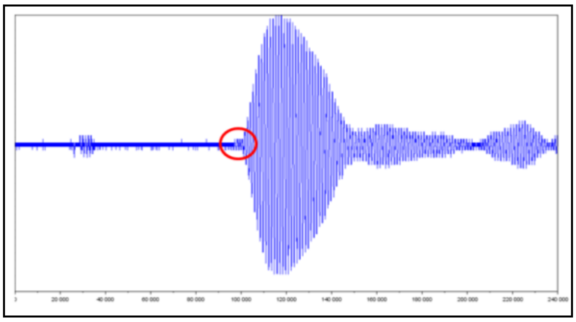

Fig. 10. Determining the beginning of the received signal for accurate flight time determination - a crucial parameter for low measurement uncertainty.

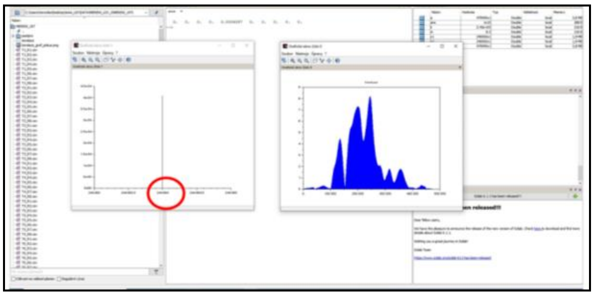

Fig. 11. Data processing procedure by the method of mutual correlation between signals.

3 Ultrasonic tomograph

3.1 Principle

Fig. 2 shows a flowmeter principle in a tomographic arrangement. Each of the transmitters generate a signal for all receivers, which is the principle that a 3D vector tomograph actually works on. However, for vector velocity field reconstruction, it is not sufficient to simply measure the travel time of a signal from one transmitter to one receiver; by evaluating measurements based on time of flight (time-of-flight, abbreviated TOF), one obtains the magnitude of the velocity vector, but not the direction.

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, which after linearization has the shape

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

where τ is time-of flight, τ_0 is reference time-of-flight, c is speed of sound and c_0 reference speed of sound, v is the flow velocity, s is vector tangent to the Γ trajectory, n is vector normal to the wave, Γ is sound ray trajectory.

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.

Put into practice, it is actually a measurement of the incident angle of the speed of sound vector. There are sophisticated precision optical methods that can be used to obtain this information, for example Braun and Hauck suggest the use of a Schlieren method [6], but this method can only be used with a tomograph with optical access, which would limit its use.

In her work, Jovanović [2] proposes a more easily applicable method. It is based on the TOF method, but this time between one transmitter and three receivers on the other side. The principle of the method can be seen in following figure.

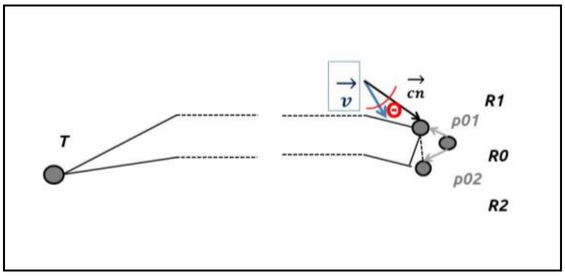

Fig. 12. Tripol showing the geometrical principle of ultrasonic tomograf measurement.

The travel times of the audio signal that interacted with the detected velocity field are obtained from the three receivers; from the difference of the detected times on the receivers R1-R0 and R2-R0, while in the case of the receiver R0 the magnitude of the velocity vector is evaluated, then distances are found and from them the angle of the velocity vector of the flow field by simple trigonometry.

3.2 Design and tests

The prototype, on which selected transmitters and receivers were tested, eventually consisted of one transmitter and five receivers in the configuration, see the photo below.

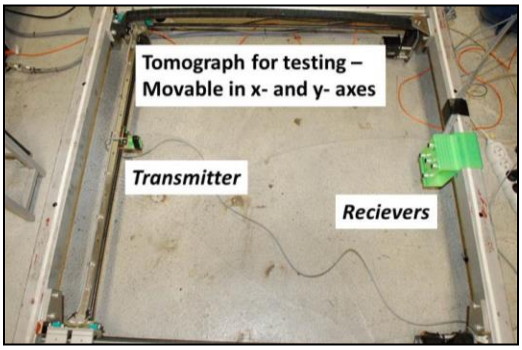

Fig. 13. The tomograph for principle testing (with no flow).

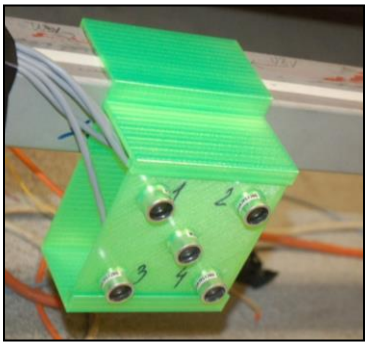

Fig. 14. The detail of the receivers organized in a rosette.

In addition to verifying the tomograph's operating principle, this test equipment was designed to quantify the effect of configuration on measurement uncertainty; the number of transmitters and receivers is one of the criteria, as well as, for example, determining their position relative to others as accurately as possible. Directionality was tested here (and thus the absolute distance and possible absolute size limit of the tomograph; for tomographic reconstruction of the velocity field and determination of the highest possible accuracy of determining the velocity vectors, it is important that one transmitter emits to as many receivers as possible).

The selection of sensors was similar to that one of the ultrasonic flowmeter. The main conditions for selection were high directionality and the expected range of min. 0.5m. However, the originally selected great transmitters and receivers from the Taiwanese manufacturer Pro-wave proved to be unsuitable due to the extremely high supply voltage requirements even for a relatively small tomograph; the power requirements for a tomograph which is intended to serve, for example, wind tunnel measurements for the automotive industry, are unimaginable. Thus, the already proven MCUST and MCUSR transmitters and receivers have been chosen for the smaller tomograph, which have already had several tests on the ultrasonic flowmeter. Although their directional characteristics are not as magnificent as the Pro-wave, tests on a test tomograph have shown solid results.

The tomograph for real operation on the aerodynamic line will have 24 transmitters and receivers. At the turn of the spring and summer of 2022, the first tests will take place, and the measurement of the wake behind the bluff body will follow immediately.

4 Experimental line

In addition to the flowmeter and the tomograph, it was necessary to design and build an experimental line, with the purpose to verify the functionality of the developed ultrasonic flowmeter. This will also be used to measure velocity fields using an ultrasonic 3D tomograph.

The line will serve as three different methods of measuring the flow and velocity fields of fluids: PIV, the ultrasonic flowmeter and tomograph, and was built as follows. The flowmeter and tomograph as developed meters will be measured for sensitivity to different velocity fields, humidity, and temperature fields. Comparative measurement of flow fields by the Particle Image Velocimetry method will be used to validate the set flow regime.

The line consists of the following components:

At the beginning of the measuring line (section A-B) elements will be placed that will ensure the setting of the required flow regime, i.e. even and uneven, or deformed velocity profile and elements to ensure turbulent flow of the required turbulence intensity. Turbulent screens for determining the effect of turbulence intensity on the measured flow will be made as gratings (with partitions 25 mm wide and 50 mm apart, 2 vertical, 2 horizontal) - the grating intensity designed in this way can achieve turbulence intensity Tu approx. 10-15% (at a distance of about 50 mm behind the screen - along the length of the ultrasonic flowmeter part, the intensity of turbulence will decrease exponentially with a coefficient of -5/7; it is desirable that this value be as high as possible at the location of ultrasonic transmitters and receivers).

In section B-C there is a glass pipe part for PIV measurement, a tested ultrasonic flowmeter (see photo below) or an ultrasonic tomograph will be installed here.

Section A-B is now omitted for verification measurements of the ultrasonic flowmeter and the line itself, and the glass part and the ultrasonic part are immediately fitted with a lead made of hardened polystyrene.

The IRIS 200 orifice, indicated in the figure below, was used to measure the flow. The flow is evaluated by measuring the pressure difference at the orifice using a TESTO 512 differential pressure gauge.

A KU200 valve for flow control, and a probe for measuring the temperature of the fluid (thermocouple type K) are installed in the section behind the measuring orifice. The line was powered by a radial fan CRMT / 4-225 / 90.

The glass part for measuring by the PIV method and the ultrasonic part do not have the same length. Thus, a control calculation and comparison of pressure losses for given lengths and material of these parts was performed.

The pressure losses of the glass part are 30% higher, but in absolute numbers it is only units of pascals, i.e. practically negligible. In this context, it was decided to produce a total number of three ultrasonic flowmeters of different lengths (the goal is to achieve the shortest possible part for the specified diameter of the measured pipe and determine the limit dimensions to achieve the required accuracy, or as a bonus to find a functional relationship between part lengths and accuracy).

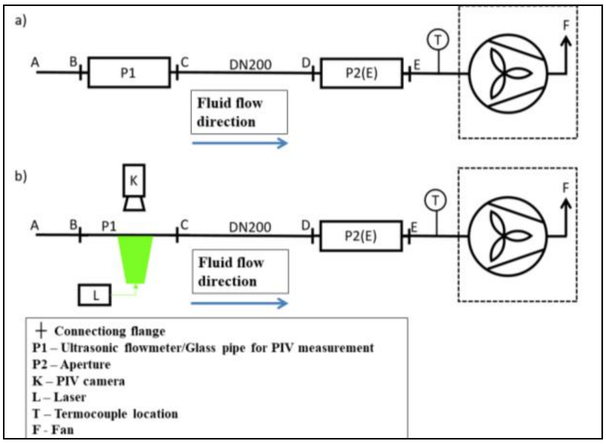

Fig. 15. Schema of the experimental line.

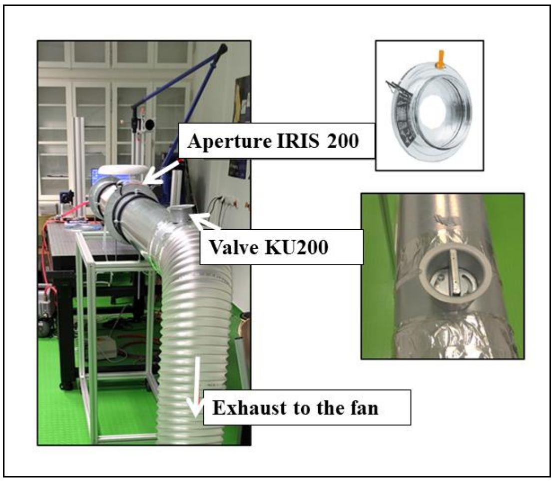

Fig. 16. Components of the experimental line.

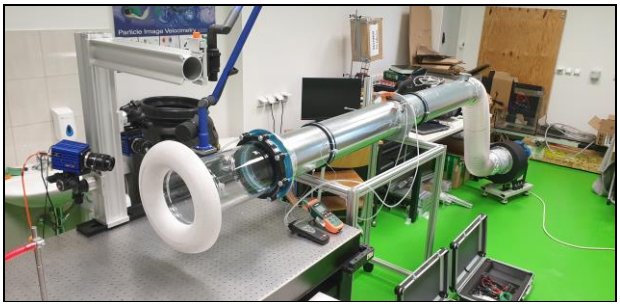

Fig. 17. The experimental line prepared for PIV measurement.

After the completation of the experimental line, the first verification measurements were performed. The flow was regulated by the KU200 aperture, which allows the aperture position to be set in the range of 0 ° (fully open) to 90 ° (closed). The flow results and the calculated velocity of the line are shown in the following graphs. The highest speed achieved on the experimental line when using the installed fan was 7.66 m / s at a flow rate of 0.24 m3 / s. Due to the fact that the full range of speeds required for testing ultrasonic devices (up to 20 m / s) has not been reached, an additional fan will be added to increase the transport pressure before the next measurement.

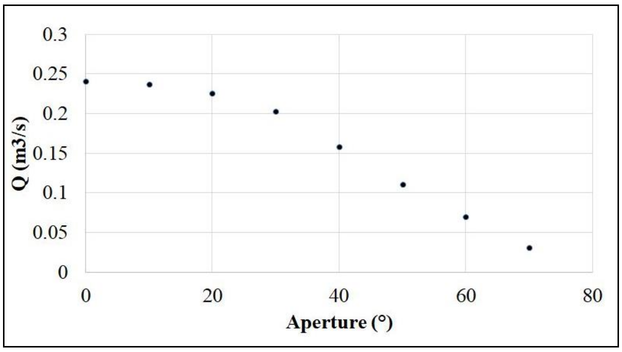

Fig. 18. The experimental line verification measurement result – the flow.

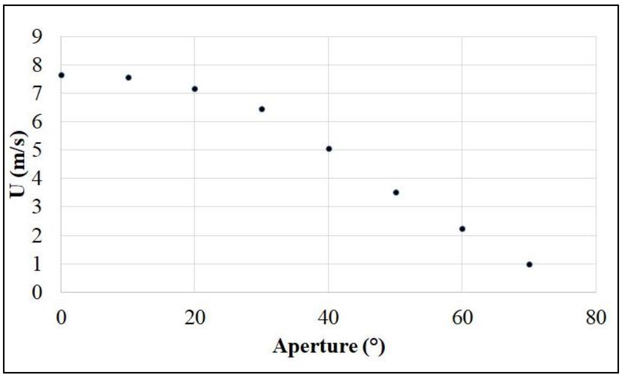

Fig. 19. The experimental line verification measurement result – the calculated velocity.

4.1 The error analysis

The default equation consists of speed of sound, time delay and geometry. It is necessary to determine partial uncertanties.

$$v_a = \frac{C - \dfrac{L}{\Delta t + \dfrac{L}{C}}}{\cos\alpha} \tag{2}$$

V_a is an axial velocity, L a sound travel distance, c speed of sound, α an angle between the gauge axis and the soudn wave direction and Δ tis the time difference.

Sound velocity uncertainty with respect to temperature measurement velocity is:

$$u_B(c) = \pm 0{,}18\, m.s^{-1} \tag{3}$$

The uncertainties of measuring the geometry of the flowmeter were estimated as (resulting from the meters and their capabilities):

$$\begin{gathered} u_B(L) = \pm 0{,}14\, mm \\ u_B(\alpha) = \pm 0{,}29\, ° \end{gathered} \tag{4}$$

The uncertainty of the determined measurement uncertainty Δt was determined as:

a) the uncertainty of type A_t of repeated measurements, where:

$$u_A(\Delta t) = \sqrt{\frac{\Sigma(xi - \bar{x})^2}{N.(N-1)}} = \pm 45\, ns \tag{5}$$

b) The type B uncertainty of Δt in the autocorrelator, we assume an error uniformly distributed over an interval of ± 10 samples, then:

$$u_B(\Delta t) = \frac{\Delta}{\sqrt{12}} = \frac{20}{100.10^6.\sqrt{12}} = \pm 57\, ns \qquad (6)$$

c) The combined uncertainty is as follows:

$$\boldsymbol{u_c(\Delta t) = \sqrt{u_A(\Delta t)^2 + u_B{}^2(\Delta t)} \;= \pm 72,6ns} \qquad (7)$$

Based on all partial uncertainties, the velocity uncertainty for highest experimental line velocity was determined to be:

$$\boldsymbol{v = (7,69 \pm 0,23)\, m.s^{-1}} \qquad (8)$$

5 Conclusion

The paper was devoted to the description of the development of flow and velocity field meters in fluid mechanics and all activities related to this development.

First of all, it was the preparation of an experimental line in the laboratory of the Technical University in Liberec, where the first verification tests of both the line itself and the ultrasonic flowmeter were performed. The line was designed as variable because the measurement will be performed by several different methods for many configurations. It was necessary to consider generators of various velocity field uniformity disorders, and to further consider the influence of different temperatures or humidity on the flow measurement, thus ensuring that it is possible to change these quantities for measurement purposes. The measurement plan also includes flowmeters of various cross-sections and extensive tomograph measurements, including 3D velocity field measurements behind the model - a bluff body body.

Another task was to prepare the ultrasonic flowmeter itself in terms of construction. The first test piece was made for use in measurements in the 4Jtech laboratory, but the production technology was gradually reworked into the first functional prototype for verification measurements at the Technical University. The production technology had to be modified with emphasis on higher geometric accuracy of transmitters and receivers location.

Simultaneously with the advancing construction, it was necessary to prepare the meters electronically. PCBs for signal excitation were made and the correct excitation signal was designed. A far greater challenge for the specialist was the design and construction of a control unit ensuring all the flow of data and energy between the transmitters, receivers and the evaluation unit (computer). Of course, it is possible to purchase a commercial DAQ system and save several months of research work, but a significant disadvantage of these data collections is their rapid obsolescence, when once acquired, a not cheap unit will eventually cease to be operated by the supplier, which will result in stopping firmware updates at the moment when the equipment ceases to be manufactured. The prototype of the control unit was therefore assembled on a programmable FPGA circuit and put into operation.

This part also intersects with the construction of the ultrasonic tomograph control unit, which is built on the same basis, but must serve a significantly higher number of channels (while the ultrasonic flowmeter currently has 8 transmitters and 8 receivers and accurate measurement requires 8x8 combinations, an ultrasonic tomograph to be tested on the experimental line, is designed for an array of 24 transmitters and 24 receivers which means a minimum of 24x30 triple signals that will need to be received and processed). The tomograph was tested in a miniature and electronically simplified version and without flow to determine the approximate size of the test tomograph for the experimental line, and the effect of geometry on the rough estimate of the uncertainty of the angle measurement, which is one of the two basic parameters for the ultrasonic tomograph principle.

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