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DEVELOPMENT AND INVESTIGATION OF A FOUR-CHANNEL ULTRASONIC FLOWMETER WITH EQUAL SIGNAL PATHS

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Abstract

The paper proposes a new model of a four-channel ultrasonic flowmeter. The measuring device operates, unlike the classical one, with two groups of ultrasonic beams, and at the same time they have equal signal path lengths. Such a design makes it possible to reduce the measurement error, since it does not require taking into account the difference in the lengths of acoustic paths, as in traditional schemes, which arises as a result of pipe curvature. To confirm the operation of the flowmeter, its mathematical model is presented. The results were compared with the mathematical model of a classical four-channel flowmeter and showed higher accuracy indicators. In classical schemes, errors associated with geometry accumulate for each beam. In the proposed configuration, the errors have a common nature and are partially compensated, and therefore the overall measurement uncertainty is reduced. The total flow measurement error is estimated, which is 10–15% lower compared to classical flowmeters. The obtained results are also confirmed by modeling of flowmeters in the SOLIDWORKS Flow Simulation environment.

Keywords: ultrasonic flowmeter, measurement error, beam length, inclination angle, metrological evaluation, partial derivatives.

Introduction

Today, ultrasonic flowmeters are high-precision means for measuring the flow rate of liquids and gases in industrial and scientific applications. The main advantages are the absence of moving parts, operation in a wide range of working conditions, low losses, and high speed. Therefore, ultrasonic flowmeters are increasingly used in modern processes, for example in energy systems, in the oil and gas industry as metering devices [1]. At the same time, modern international and industry standards constantly increase the requirements for accuracy and reproducibility of measurement results. In commercial metering tasks, the norms of relative error are currently at the level of ±(0.5–1.0)% or lower [2, 3]. All this requires continuous improvement of instruments, detailed consideration of all error components, in particular geometric, temporal, and algorithmic. Classical designs of ultrasonic flowmeters operate with acoustic beams in which the path length differs due to pipe curvature, which leads to an additional geometric component of error and, as a result, unequal sensitivity of individual channels. As a result, accuracy and reproducibility decrease, especially under conditions of a variable flow velocity profile.

Thus, reducing the geometric component of error is an urgent scientific and technical task, which is especially evident in commercial metering of energy resources.

The aim of the work is to reduce the total flow measurement error by developing and substantiating the design of an ultrasonic flowmeter with equal signal paths, as well as in quantitative comparison of its accuracy with classical schemes.

Geometry and principle of operation of a flowmeter with equal signal paths

For multichannel ultrasonic flowmeters, the flow rate is determined by integrating the velocity profile over the cross-sectional area of the pipeline:

$$Q = \int_A v(x, y)\, dS.$$

In measurement practice, this integral is approximated by the quadrature method. For a four-channel flowmeter with Gauss–Legendre weights, the discrete sum is used [4]:

$$Q \approx S \sum_{i=1}^{4} w_i\ v_i$$

where:

S – cross-sectional area of the pipeline;

w_i – quadrature weighting coefficients (determined by the Gauss–Legendre method);

v_i – local (averaged along the beam) flow velocities measured along the i-th acoustic channel.

The velocities v_i correspond not to point values, but to integral estimates along the acoustic beams, that is: $v_i \sim \frac{1}{L_i} \int_{L_i} v(s)\, ds$. This means that the quadrature method is applied to the effective velocity profile formed by the geometry of the beams. The use of

Gauss–Legendre weights ensures minimal approximation error of the integral and optimal placement of channels y_i.

For a symmetric scheme, the flow rate is determined as:

$$Q = S \cdot v\_avg, \; Q = S \cdot v_{\text{avg}},$$

where v_{avg}– average flow velocity.

If the channels are arranged symmetrically and equal weights are used, then:

$$w_i = \frac{1}{4}, i = 1,2,3,4.$$

For a chordal scheme, the length of the acoustic beam L_i is determined as:

$$L_i = \frac{c_i}{\sin\theta},$$

where:

c_i – chord in the pipe cross-section (distance between entry and exit points of the beam on the wall);

θ – angle of inclination of the beam to the flow axis.

For a pipe of diameter D, the chords can be located, for example, at different distances y_i from the center of the section. Then the chord length is determined as:

$$c_i = 2\sqrt{\left(\frac{D}{2}\right)^2 - y_i^2} \,. \quad (1)$$

The velocity of the i-th channel is determined by the difference in transit time of ultrasound along and against the flow [5]:

$$v_i = \frac{L_i}{2}\left(\frac{1}{t_{i,\uparrow}} - \frac{1}{t_{i,\downarrow}}\right) \quad (2)$$

where:

L_i – length of the acoustic beam in the i-th channel;

t(i,↑) – signal transit time against the flow;

t(i,↓) – signal transit time along the flow.

For a four-channel flowmeter, the average flow velocity is determined as:

$$v_{\text{avg}} = \frac{1}{4}\sum_{i=1}^{4} wiv_i \quad (3)$$

or in expanded form: $v_{\text{avg}} = \frac{v_1+v_2+v_3+v_4}{4}$, where weighting coefficients take into account the position of the channel in the pipe cross-section.

Based on the above flow measurement model, it can be concluded that in classical multichannel ultrasonic flowmeters built according to the chordal scheme, acoustic beams pass along different chords of the pipe cross-section due to its curvature. As a result, the lengths of the measurement paths L_i differ, and along with them the signal transit times and their sensitivity to local changes in flow velocity.

This leads to the fact that each channel has individual sensitivity to flow velocity, as well as a different level of influence of measurement errors of time, coordinates, and installation angle of transducers. This, in turn, leads to non-uniformity of the weighting contributions of channels and complicates the correct approximation of the velocity integral. In addition, different beam lengths cause uneven accumulation of errors (temporal, geometric, temperature), which ultimately reduces the accuracy of flow determination, especially with a non-ideal flow profile. As a result, uneven accumulation of errors occurs and the procedure of calibration and compensation becomes more complicated.

The paper proposes a scheme with equal signal paths, which provides a geometric configuration in which all acoustic beams have the same length: $L_1 = L_2 = \ldots = L_n$. Fig. 1 shows the scheme of channel arrangement of a four-channel ultrasonic flowmeter [5].

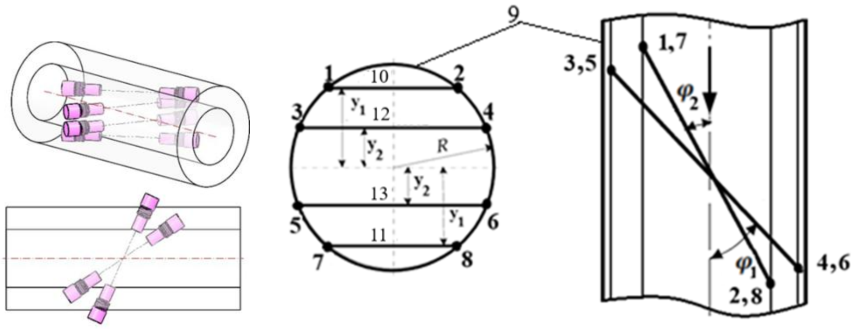

Fig. 1 – Layout of channels of a four-channel ultrasonic flowmeter with equal signal paths:
a) 3D model created in SOLIDWORKS Flow Simulation;
b) schematic representation of flowmeter channel designations.

The flowmeter contains extreme channels located at an angle φ_k relative to the pipe cross-section axis, having two pairs of ultrasonic transmitters-receivers 1,2 and 7,8 respectively. The second pair of middle ultrasonic transmitters-receivers is located at an angle φ_c and corresponds to numbers 3,4 and 5,6 respectively.

The angles φ_k and φ_c are selected in such a way as to obtain equal signal paths. Such a design of an ultrasonic flowmeter with equal signal paths allows the transition from a complex heterogeneous multichannel system to a more symmetric and metrologically consistent model, which ensures increased measurement accuracy and simplification of signal processing algorithms.

Let us consider the mathematical model of such a flowmeter based on its structural arrangement of ultrasonic signal paths. Let us assign indices for the middle pair of transmitters-receivers and their signal paths as 3,4, and for the side ones – 1,2.

The condition of equality of signal path lengths of a four-channel ultrasonic flowmeter for two neighboring asymmetric channels is represented as: $L_1 = L_2 = L_3 = L_4$. Then for asymmetric channels: $\frac{D}{\sin\varphi_c} = \frac{D}{\sin\varphi_к}$, **where $\varphi_к$ and φ_c are the beam angles relative to the flow for the edge and middle beams, respectively.** Using relation (1), we obtain:

$$\frac{2\sqrt{R^2 - y_1^2}}{\sin\varphi_c} = \frac{2\sqrt{R^2 - y_3^2}}{\sin\varphi_к} \quad (4)$$

where:

R – pipe radius;

y_1, y_3 – distances from the center to the corresponding beam.

Such geometry ensures the same length of beams within each group. This means that the average signal velocity for the middle beams with inclination angle $\varphi_с$ is determined as [6]:

$$v(y,\varphi_с) = \frac{\sqrt{R^2-y^2}}{\sin\,\varphi_с \cdot \cos\varphi_с} \cdot \left(\frac{1}{t_{с,\uparrow}} - \frac{1}{t_{с\downarrow}}\right). \quad (5)$$

And for the outer beams with inclination angle φ_k:

$$v(y,\varphi_к) = \frac{\sqrt{R^2-y^2}}{\sin\,\varphi_к \cdot \cos\varphi_к} \cdot \left(\frac{1}{t_{к,\uparrow}} - \frac{1}{t_{к,\downarrow}}\right). \quad (6)$$

Taking into account formulas (2–6), we obtain an expression for determining the average gas velocity taking into account the weights (coefficients) of each group of beams:

$$\boldsymbol{v_{esp}} = \frac{w_с \sum_{i=1}^{2} \frac{\sqrt{R^2-y_3^2}}{\sin\,\varphi_к \cos\,\varphi_к}\left(\frac{1}{t_{с,\uparrow}} - \frac{1}{t_{с,\downarrow}}\right) + w_к \sum_{i=1}^{2} \frac{\sqrt{R^2-y_1^2}}{\sin\,\varphi_к \cos\,\varphi_1}\left(\frac{1}{t_{к,\uparrow}} - \frac{1}{t_{к,\downarrow}}\right)}{2w_с + 2w_к}. \quad (7)$$

where t(c,↑), t(c,↓), t(k,↑), t(k,↓) are the transit times of ultrasonic beams upstream and downstream for the middle (3,4) and outer (1,2) beams, respectively, and w_c and w_k are weighting coefficients for each group of beams.

For the classical flowmeter, the average velocity is determined as:

$$v_{Cl} = \frac{1}{4} \sum_{i=1}^{4} w_i \frac{\sqrt{R^2-y_i^2}}{\sin\,\varphi \cos\,\varphi}\left(\frac{1}{t_{\uparrow,i}} - \frac{1}{t_{\downarrow,i}}\right) \quad (8)$$

where t(↑,i), t(↓,i) are the transit times of ultrasonic beams of the corresponding i-th channel upstream and downstream;

y_i – position of the i-th channel relative to the pipe center.

The classical Gauss–Legendre quadrature of a four-channel flowmeter typically uses the node coordinates of the outer channels $y_к = \pm 0.861136$ and the middle ones $y_с = \pm 0.339981$. The weighting coefficients of the corresponding channels are: $w_к = 0.347855$ and $w_с = 0.652145$ [7].

Let us calculate the measurement errors for the proposed and classical flowmeters and compare their values. The total relative error of flow measurement is determined as:

$$\frac{\Delta Q}{Q} = 2\frac{\Delta D}{D} + \frac{\Delta v_с}{v_с},$$

where $\Delta D/D$ is the relative error of determining the pipe diameter, and $\Delta v_c/v_с$ - is the relative error of the average velocity.

The error of the average velocity via partial derivatives for the model with equal paths will consist of the following components [8]:

$$\frac{\Delta v_{esp}}{v_{esp}} = \sqrt{t_{\uparrow,i}, t_{\downarrow,i}, \varphi_к, \varphi_c, y_к, y_c, L}.$$

For the classical flowmeter, the error of the average velocity (different paths) will include the following components:

$$\frac{\Delta v_{Cl}}{v_{Cl}} = \sqrt{t_{\uparrow,i}, t_{\downarrow,i}, t_{up,i}, \varphi, y_i, L_i}.$$

For a classical flowmeter with one angle but different beam lengths L_i, the error of the average velocity based on (7) takes the form:

$$\frac{\Delta v_{Cl}}{v_{Cl}} = \sqrt{\sum_{i=1}^{N}\left(\frac{\partial v_{кл}}{\partial t_{\uparrow,i}} \cdot \frac{\Delta t_{\uparrow,i}}{v_{кл}}\right)^2 + \sum_{i=1}^{N}\left(\frac{\partial v_{кл}}{\partial t_{\downarrow,i}} \cdot \frac{\Delta t_{,\downarrow i}}{v_{кл}}\right)^2 + \sum_{i=1}^{N}\left(\frac{\partial v_{кл}}{\partial y_i} \cdot \frac{\Delta y_i}{v_{кл}}\right)^2 + \sum_{i=1}^{N}\left(\frac{\partial v_{кл}}{\partial L_i} \cdot \frac{\Delta L_i}{v_{кл}}\right)^2 + \left(\frac{\partial v_{кл}}{\partial \varphi} \cdot \frac{\Delta \varphi}{v_{кл}}\right)^2}$$

where:

N – number of channels of the classical flowmeter;

L_i – path length of the i-th beam (each different, therefore geometric error is larger);

Δt(↑,i), Δt(↓,i), ΔL_i – corresponding measurement uncertainties.

For the model with equal signal paths based on (6), we obtain the expression:

$$\frac{\Delta v_{esp}}{v_{esp}} = \sqrt{\begin{array}{c}\sum_{i=1}^{2}\left(\frac{\partial v}{\partial t_{\uparrow,c}}\cdot\frac{\Delta t_{\uparrow,c}}{v}\right)^2+\sum_{i=1}^{2}\left(\frac{\partial v}{\partial t_{\downarrow,c}}\cdot\frac{\Delta t_{,\downarrow c}}{v}\right)^2\\ +\sum_{i=1}^{2}\left(\frac{\partial v}{\partial t_{\uparrow,к}}\cdot\frac{\Delta t_{\uparrow,к}}{v}\right)^2+\sum_{i=1}^{2}\left(\frac{\partial v}{\partial t_{\downarrow,к}}\cdot\frac{\Delta t_{,\downarrow к}}{v}\right)^2\\ +\left(\frac{\partial v}{\partial \varphi_c}\cdot\frac{\Delta \varphi_c}{v}\right)^2+\left(\frac{\partial v}{\partial \varphi_к}\cdot\frac{\Delta \varphi_к}{v}\right)^2\\ +\left(\frac{\partial v}{\partial y_к}\cdot\frac{\Delta y_к}{v}\right)^2+\left(\frac{\partial v}{\partial y_c}\cdot\frac{\Delta y_c}{v}\right)^2+\left(\frac{\partial v}{\partial L}\cdot\frac{\Delta L}{v}\right)^2\end{array}}$$

In these formulas, each contribution accounts for the influence of a separate parameter on the total error of the average velocity (ultrasonic transit times, inclination angles, beam coordinates, path lengths). This shows that the dominant sources of error are the installation angle and geometry (coordinate and path length), which is important to consider when optimizing the configuration of the flowmeter.

To estimate the total error, the following input data were used based on literature sources: $\Delta t = 0.1\%$, $\Delta\theta = 0.5°$, $\Delta y/R = 0.5\%$, $\Delta L/L = 0.5\%$, $\Delta D/D = 0.2\%$.

The simulation results showed that the error of the classical flowmeter was 1.65%, and with equal signal paths – 1.53%. Fig. 2 shows the graph of the dependence of the total error on the pipe diameter (50–500 mm).

These data show that the proposed geometry provides a reduction of the total error compared to the classical scheme. This approach clearly demonstrates that equal beam lengths reduce the geometric component of error. As can be seen from the graph, with increasing diameter, the error decreases, and the proposed model provides a consistently lower error level (~10–15% less). The difference between the total errors of the models is maintained over the entire range of diameters. At small diameters (50–100 mm), the error of both models is higher. With increasing diameter, the error gradually decreases, mainly due to a reduction in the relative error of diameter and signal transit time.

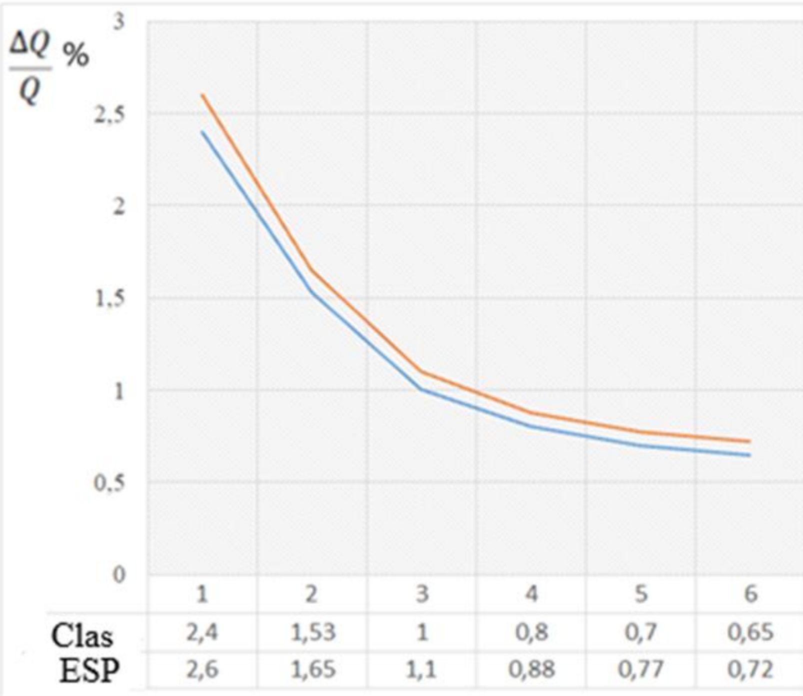

Fig. 2 – Dependence of the total flow measurement error on the pipe diameter for the classical model (red curve) and the model with equal signal paths (blue curve)

To confirm the obtained errors, modeling was carried out in the SOLIDWORKS Flow Simulation environment. Fig. 3 shows the modeled flowmeter with equal signal paths.

The results of the flowmeter operation were compared with a classical flowmeter modeled in the same way. During the simulation, local resistances were used over a wide range of flow rates. The simulation revealed that the proposed flowmeter has higher accuracy.

What causes the reduction of error in the flowmeter with equal signal paths? In our opinion, in the classical flowmeter the angular error makes a large contribution, because the angle between the direction of ultrasonic signal propagation and the flow direction enters the formula as a multiplier 1/(sin φ cos φ). This is an indirect relationship, but it makes the device very sensitive to deviations.

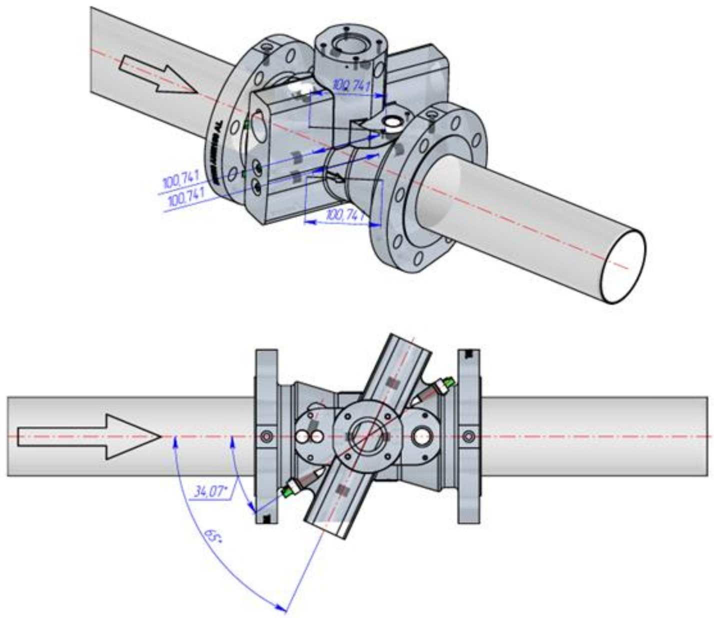

Fig. 3 – Model of a flowmeter with equal signal paths

In the model with two angles, the influence of the angle is partially compensated between the middle and outer channels. Therefore, the contribution of such an error is reduced. At the same time, the path length error remains the same for both models, since the geometry of beam propagation is different, but normalization by length gives a similar effect.

In addition, it should be noted that for large pipes (300–500 mm), the model with equal signal paths provides more favorable metrological characteristics, but the total error compared to the classical flowmeter becomes smaller by ~5–8%.

Conclusions

The proposed model of an ultrasonic flowmeter with equal signal paths reduces the geometric component of error and increases the accuracy of determining the average flow velocity. Equality of beam lengths ensures more accurate application of quadrature methods, since the weighting coefficients are not distorted by geometry. Numerical simulation showed that the total measurement error is reduced by 10–15% compared to the classical scheme.

The obtained results are confirmed by modeling of both the proposed and classical flowmeters in the SOLIDWORKS Flow Simulation environment.

It is established that with increasing pipe diameter, the total error becomes lower by ~5–8% compared to the classical scheme, but the model with equal signal paths still provides higher metrological characteristics.

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