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FEASIBILITY JUSTIFICATION FOR A HYBRID ULTRASONIC FLOWMETER FOR NATURAL GAS

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Research field: ultrasonic natural gas flowmeters

Abstract

The possibility of creating a hybrid ultrasonic flowmeter of natural gas is presented, which combines a four-channel ultrasonic transit-time method (TOF) and a resonance method. A mathematical description of such a flowmeter is given, the errors of the classical and the proposed flowmeter are estimated, the gain in accuracy and resistance to external factors are shown.

Keywords: ultrasonic flowmeter; natural gas; transit-time method; resonance method; hybrid measurement; speed of sound; measurement error; gas metering.

Introduction

At present, ultrasonic flowmeters are high-precision means for measuring the flow rate of liquids and gases in industrial and scientific applications [1]. Their main advantages are the absence of moving parts, operation in a wide range of operating conditions, low losses and high speed. In commercial metering tasks, the norms of relative error are currently at the level of $\pm(0.5-1.0)$ % or lower [2-4].

Classical ultrasonic natural gas flowmeters are based on the transit-time method (TOF). Their error significantly depends on the speed of sound c , temperature T , pressure P , as well as the velocity profile. For an inclined beam (angle θ), the flow velocity along the i -th beam is determined as

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

where:

L_i - pipe diameter ;

$t_{i,\uparrow}$ - signal transit time against the flow;

$t_{i,\downarrow}$ - signal transit time along the flow.

Transit times depend on the speed of sound c , which is calculated by a known formula taking into account the real properties of the gas:

$$c = \sqrt{\frac{\gamma RTZ(p)}{M}},$$

where:

γ — adiabatic index (ratio of heat capacities C_{p}/C_{v});

R — universal gas constant ($R=8.314$ J/(mol·K));

T — thermodynamic temperature of the gas (in Kelvin);

$Z(P)$ — gas compressibility factor, which takes into account deviation from the ideal gas; depends on pressure P ;

M — molar mass of the gas (kg/mol).

In a multi-channel system, for example a four-channel one, if the channels are arranged

symmetrically, equal weights are used, i.e.

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

then the average velocity is calculated as

$$v_{\text{avg}} = \frac{1}{4} \sum_{i=1}^4 v_i.$$

Thus, in standard formulas, as we can see, c and v are calculated using the same time parameters $t_{i,\uparrow}$ and $t_{i,\downarrow}$. Any systematic error in time measurement (for example, synchronization error, signal delays) simultaneously distorts both results - both the flow velocity and the calculated speed of sound. In a pipeline at high pressure or deviation from ideal gas, the speed of sound changes. This is especially manifested during the transition from laminar to turbulent flow regime. The gas composition is not ideal, temperature gradients take place. In addition, gas effects associated with pressure are observed. Theoretical formulas, as noted, often use averaged values, which, although reduce the total error, in some cases it may also increase. Thus, errors arise because the nominal value of c is used, which does not correspond to real conditions. Therefore, recently in scientific articles new measuring converters appear, which simultaneously use several methods and, accordingly, several informative parameters of the ultrasonic signal. This makes it possible to perform so-called cross measurements. The most well-known example of a hybrid TOF+Doppler flowmeter is the Duosonics system from Fuji Electric, which combines (TOF) and Pulse Doppler methods. Also, in scientific literature, studies of Kobe University are described, where the TOF method is calibrated using an ultrasonic Doppler velocity profile (UDV). The TOF method measures the average linear flow velocity. The ultrasonic pulse Doppler method (UDM) provides data on the flow velocity profile and allows estimating local flow velocities [5].

The combination of methods increases the accuracy and reliability of measurements in complex flows – turbulent, aerated, with impurities.

In this work, the possibility of creating a hybrid ultrasonic flowmeter, which would combine the TOF and resonance method, is considered. The development of such a flowmeter is the purpose of the work.

Research results

The scheme of the proposed hybrid ultrasonic flowmeter combines TOF and resonance method (RES) [6]. Fig. 1 shows the scheme of spatial arrangement of the flowmeter channels, four pulse channels of which operate according to the TOF method and are located at

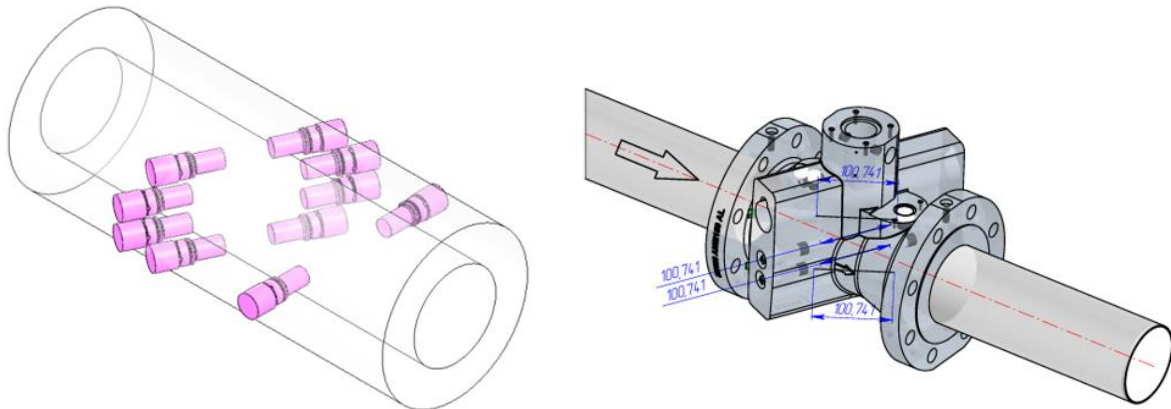


Fig. 1. Scheme of arrangement of channels of the hybrid ultrasonic flowmeter designed in the SOLIDWORKS Flow Simulation environment

For what purpose was the resonance channel applied? The resonance method operates on another physical principle or uses another measurement configuration, providing an independent source of data about c . This allows the system to cross-check the results. At the same time, resonance methods have higher sensitivity to small changes in acoustic impedance or medium density than pulse methods, especially in media with high attenuation (gas, vapor), and can also control temperature. In addition, with this approach, the reliability of the entire measurement system is significantly increased. If the value of c obtained from pulse channels suddenly differs from the value of c obtained from the resonance channel, this is an indicator of a problem: either one of the sensors is clogged/faulty, or bubbles or impurities have appeared in the flow. In real conditions, the gas mixture may contain impurities, moisture, CO₂, CH₄, etc.

Thus, the proposed scheme is more reliable, makes it possible to obtain additional redundant information, which makes the final result — flow measurement — more resistant to errors arising under the influence of external factors. This means that in this case the flow velocity will be determined using an additional correction function, which is introduced into formula (1) and we obtain the expression

$$v_i = \frac{L_i}{2\cos\theta} \left(\frac{1}{t_{i,\uparrow}} - \frac{1}{t_{i,\downarrow}} \right) \cdot K_{nl}(c), \quad (2)$$

where: $K_{nl}(c)$ — correction coefficient.

The correction coefficient is introduced to match the real speed of sound c_{real} with the nominal c_{nom} used in the basic flow formula. Then:

$$K_{nl}(c) = \frac{c_{real}}{c_{nom}} \quad (3)$$

The real speed of sound can be determined by the formula:

$$c_{real} = \frac{2Lf_{res}}{n} \quad (4)$$

where:

n — harmonic number;

an angle to the flow. The fifth channel is located perpendicular to the flow and operates according to the resonance method. The scheme of the hybrid flowmeter is designed in the SOLIDWORKS Flow Simulation environment.

f_{res} — resonance frequency of the resonator.

Then the flow velocity will be determined taking into account formulas (2)–(4) as

$$v_m = \frac{L}{2\cos\theta} \left(\frac{1}{t_{i,\uparrow}} - \frac{1}{t_{i,\downarrow}} \right) \cdot \frac{2Lf_{res}}{nc_{nom}}. \quad (5)$$

Thus, a resonator at ultrasonic frequency can be integrated into a hybrid flowmeter as a correction module of the speed of sound, which operates by analogy as TOF plus UDM. This provides a more accurate and stable measurement system [7].

We perform an analysis of errors for the classical and the proposed flowmeter. Let us denote the relative error as $\delta v = \frac{\Delta v}{v}$.

For the classical model: $v_{TOF} \sim c^2 \cdot \Delta t$. Then the error of the classical scheme will be determined as

$$\delta v_{TOF} \approx 2 \frac{\Delta c}{c} + \frac{\Delta L}{L} + \tan\theta \Delta\theta + \delta_t.$$

$$\text{In this case } \delta_t = \frac{\Delta t_{i,\uparrow}}{t_{i,\uparrow}} + \frac{t_{i,\downarrow}}{t_{i,\downarrow} - t_{i,\uparrow}} + \frac{\Delta t_{i,\downarrow}}{t_{i,\downarrow}} - \frac{t_{i,\uparrow}}{t_{i,\downarrow} - t_{i,\uparrow}}.$$

$$\text{After rounding we obtain that } \delta_t \approx \frac{\Delta t}{\Delta t_{diff}}.$$

Let us consider the errors of the proposed scheme. For this, we represent formula (5) as

$$\delta v_m = A \cdot B, \text{ where } A = \frac{L}{2\cos\theta} \left(\frac{1}{t_{i,\uparrow}} - \frac{1}{t_{i,\downarrow}} \right), B = \frac{2Lf_{res}}{nc_{nom}}.$$

Then the total relative error for the product will be determined by the sum

$$v = \delta A + \delta B,$$

$$\delta A \approx \frac{\Delta L}{L} + \tan\theta \Delta\theta + \delta_t.$$

$$\delta B = \frac{\Delta L}{L} + \frac{\Delta f}{f} + \tan\theta \Delta\theta - \frac{\Delta c_{nom}}{c_{nom}}.$$

The total error of the scheme will take the form:

$$\delta v_m \approx 2 \frac{\Delta t}{t} + \frac{2\Delta f_{res}}{f_{res}} + \frac{\Delta L}{L} + \tan\theta \Delta\theta$$

If we assume that $c_{nom} = \text{const}$ (calibration) and the geometry does not change, we obtain a simplified expression of measurement error:

$$\delta v_m \approx \delta t + \frac{\Delta f_{res}}{f_{res}}$$

Based on the obtained dependencies, the following conclusions can be made: the classical TOF has a high dependence on the speed of sound ($\sim c^2$), the error is mainly determined by $2\delta c + \delta t$. At the same time, the influence of temperature and gas composition is quite high, which requires the use of temperature and pressure sensors. In the hybrid TOF+RES the dependence on the speed of sound and gas composition is compensated, the influence of temperature is much smaller, the error is mainly determined by time and frequency parameters $\delta t + \delta f$. Thus, in the classical TOF the speed of sound is the source of the main error, and the hybrid model eliminates the error from the speed of sound.

We perform a numerical calculation of errors for two schemes using generally accepted values of relative errors of components of the total error.

For the classical flowmeter: $\delta c/c = 1\%$; $\delta(\Delta T)/\Delta T = 0.5\%$, but averaging due to 4 channels - $5\%/ \sqrt{4} = 0.25\%$; $\delta L/L = 0.2\%$; $\delta(\cos \theta)/\cos \theta = 0.1\%$; $\delta t = 0.1\%$.

Then the total relative error is:

$$\begin{aligned} \frac{\delta v}{v} &\approx 2 \cdot 1\% + 0.25\% + 0.2\% + 0.1\% + 0.1\% \\ &\approx 2.65\%. \end{aligned}$$

For the hybrid flowmeter, the error $\delta c/c$ is much smaller, since c is measured by f_0 . For example, $\delta c/c \approx 0.01\%$ (frequency meter provides very high resolution). Other errors are the same.

Then:

$$\begin{aligned} \frac{\delta v}{v} &\approx 0.2\% + 2 \cdot 0.1\% + 0.25\% + 0.2\% + \\ &0.1\% \approx 0.85\%. \end{aligned}$$

Thus, the hybrid TOF+RES method reduces the total relative error approximately from **2.65%** to **0.85%** mainly due to replacing the dominant uncertainty of the speed of sound and a much smaller error of the resonance frequency.

How does the measurement error change with a change in the speed of sound? For a classical flowmeter, the change in velocity is proportional to the change in flow velocity, i.e. $\frac{\delta v}{v} \approx \frac{\delta c}{c}$. For a hybrid flowmeter, such dependence is absent. This means that with a relative change in the speed of sound, the error remains practically unchanged. Fig. 2 shows the graph of dependence of the relative error on the relative change in the speed of sound in the range $(-0.1; 0.1)$.

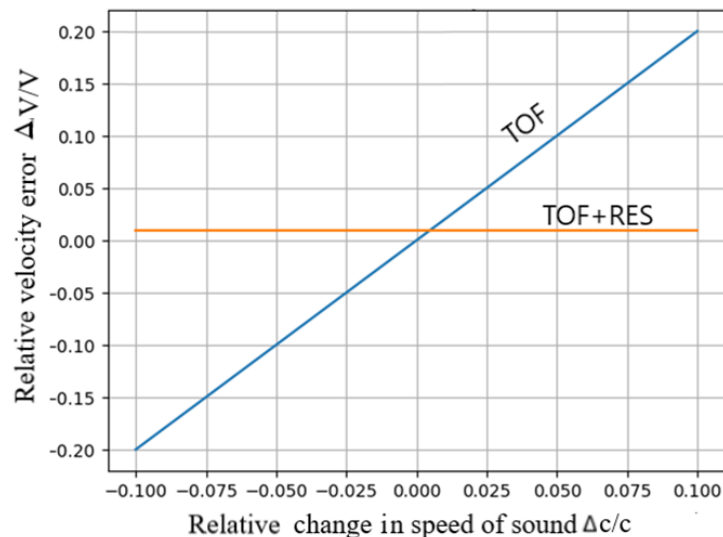


Fig. 2. Graph of dependence of relative error on relative change of speed of sound for classical and hybrid flowmeter

An increase in the relative change of the speed of sound is observed in transitional and turbulent regimes. This means that in such regimes the relative error of the classical flowmeter increases as shown in Fig. 3, which

is not observed in the hybrid one. This is the advantage of the proposed flowmeter. The remaining errors are mainly determined by the accuracy of time and frequency measurements.

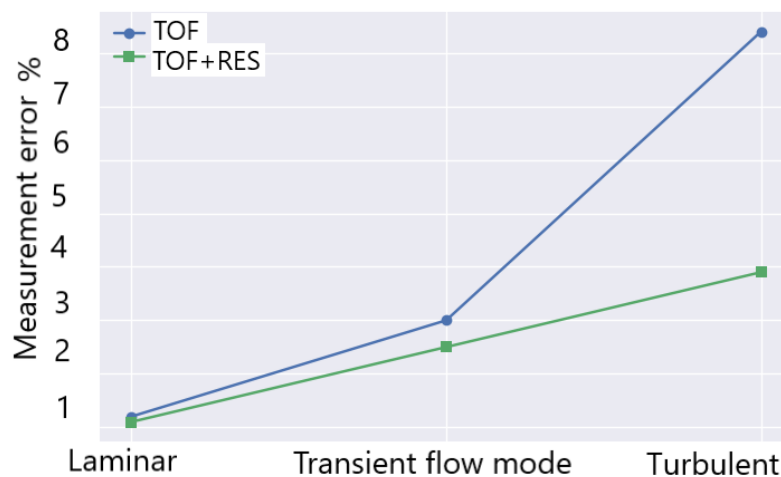


Fig. 3. Dependence of measurement error when changing gas flow regimes

Thus, the resonator at ultrasonic frequency can be integrated into a hybrid flowmeter as a correction module of the speed of sound, operating by analogy as TOF + Doppler method. This provides a more accurate and stable measurement system.

Conclusions

The proposed mathematical model of a hybrid ultrasonic flowmeter combining the TOF method with the resonance method, which measures the speed of sound. This makes it possible to perform cross measurements, but at the same time redundancy in the system is obtained. The errors of flowmeters are estimated, their numerical values are obtained, which answer what the advantages of the hybrid device are. Unlike classical TOF flowmeters, the proposed approach allows eliminating the influence of changes in the speed of sound on the measurement result, which significantly increases accuracy under varying thermodynamic conditions. This provides a reliable and more accurate and stable self-calibrating measurement system.

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