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CONTENT

METHOD OF FORMING ADAPTIVE WEIGHTING COEFFICIENTS OF A TOF FLOWMETER BASED ON RESONANCE CHANNEL DATA OF SOUND VELOCITY

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Abstract

This paper proposes a method for adaptive formation of weighting coefficients in a multichannel ultrasonic time-of-flight (TOF) flowmeter using independent information on the speed of sound in the working medium obtained from a resonant RES channel. Unlike the conventional approach, in which the contribution of individual acoustic paths is determined by constant spatial weights, the proposed method additionally modifies the basic weighting coefficients according to the current metrological consistency of each TOF channel. For each TOF channel, the mean flow-velocity component along the acoustic path (v_i) and the effective speed of sound (c_i) are determined from the measured ultrasonic signal transit times in the downstream and upstream directions. An independent estimate of the speed of sound (c_{RES}) is provided by a resonant channel oriented perpendicular to the main flow direction. An algorithm has been developed that implements sequential determination of the TOF- and RES-channel parameters, evaluation of their metrological consistency within a moving time window, formation of reliability coefficients, normalization of adaptive weights, and monitoring of an integral reliability indicator of the measurement structure. Based on the discrepancy between c_i and c_{RES}, a dimensionless reliability coefficient is formed and used to modify the basic spatial weight. The resulting adaptive weight is defined as the normalized product of these quantities. To reduce the influence of individual outliers, robust estimation of the inconsistency within a moving time window is proposed. In addition, an integral indicator (Sq) is introduced to characterize the preservation of reliable spatial information.

Keywords: ultrasonic flowmeter, TOF, resonant channel, speed of sound, adaptive weighting coefficients, multichannel measurements, quadrature integration, channel diagnostics, fault tolerance.

Introduction

Ultrasonic flowmeters are widely used for measuring gas flow rates in industrial and commercial systems. For gas flowmeters operating on the principle of acoustic signal transit-time measurement, requirements for design, metrological characteristics, calibration, and diagnostics are specified, in particular, by ISO 17089-1 [1].

The operating principle of a TOF flowmeter is based on the difference between the ultrasonic signal propagation times in the downstream and upstream directions. The result obtained from an individual acoustic path represents the velocity averaged along that path, whereas determination of the mean velocity over the entire cross-section requires combining the results from several acoustic channels. The effects of the velocity profile and turbulence on transit-time measurements were investigated, in particular, in [2].

In multichannel ultrasonic flowmeters, the method used for spatial integration of the results from individual acoustic paths plays a significant role. For this purpose, Gauss-Jacobi methods, OWICS, modified Gaussian quadrature schemes, as well as algorithms in which the acoustic path positions and their weighting coefficients are optimized according to the velocity profile are employed [3-5]. In particular, Zheng, Zhao, and Mei [3] demonstrated that, for non-ideal flow profiles, optimization of the acoustic path positions and corresponding weights can reduce the overall integration error. Tang et al. [4] proposed an approach for integrating data from a multichannel ultrasonic flowmeter with weight optimization based on the Levenberg-Marquardt algorithm. Various approaches to optimizing the weighting coefficients of multichannel ultrasonic flowmeters are known [3-5]; the distinguishing feature of the method proposed in this study is the use of an independent RES-based estimate of the speed of sound as a criterion for the current reliability of individual TOF channels. Hybrid ultrasonic systems combining different physical measurement principles are also known. For example, the Duosonics system combined transit-time and pulse-Doppler methods [6]. In the present study, a different hybrid structure is proposed, in which a multichannel TOF flowmeter is supplemented with an independent acoustic resonant RES channel.

Determination of the speed of sound from the resonance frequencies of gas-filled acoustic cavities is a well-established method in acoustic metrology. NIST studies have demonstrated the use of cylindrical and spherical acoustic resonators for high-accuracy determination of the speed of sound in gases [7, 8]. Resonance methods have also been applied directly to methane and gas mixtures similar in composition to natural gas [9, 10].

In the proposed system, the RES channel is not used for direct multiplication or correction of the flow velocity determined by the TOF method, as presented in [11]. Instead, its function is to provide an independent acoustic reference quantity, c_RES, against which the speed-of-sound estimates c_i obtained from the individual TOF channels are compared. This comparison enables a transition from a fixed set of spatial weights to an adaptive algorithm:

$$c_{RES} \rightarrow (c_i - c_{RES}) \rightarrow q_i \rightarrow g_i q_i \rightarrow w_i \rightarrow v_{ad}.$$

The objective of this study is to develop a method for adaptive formation of weighting coefficients in a multichannel TOF flowmeter by using the speed of sound independently determined by the RES channel as a criterion for the metrological consistency of individual TOF channels.

Measurement Principle and Adaptive Weighting Method

The proposed measurement system comprises N inclined TOF channels and an additional resonant RES channel. The TOF channels provide measurements of the ultrasonic signal propagation time in the downstream and upstream directions. The RES channel is oriented predominantly transverse to the main flow direction and is intended for independent determination of the speed of sound. Figure 1 shows the general configuration of the hybrid TOF-RES flowmeter. The measurement section is designed as a flanged pipeline module, with acoustic transducers of the multichannel TOF system and the additional RES channel installed in its body.

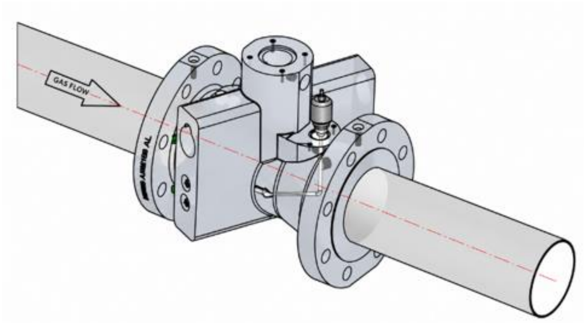

Fig. 1. General view of the design of the hybrid ultrasonic TOF-RES flowmeter

The transverse arrangement of the RES channel is a key design solution that reduces the influence of the main axial component of the flow velocity on the measurement of the speed of sound. In this case, we have

$$\boldsymbol{v} \cdot \boldsymbol{n}_{RES} \approx 0$$

where $\boldsymbol{v}$ is the axial flow-velocity vector, and $\boldsymbol{n}_{RES}$ is the unit vector in the direction of acoustic-wave propagation in the RES channel.

At the same time, the RES channel is not completely insensitive to the hydrodynamic state of the medium, since the measurement result may be affected by secondary flows, temperature and concentration gradients, and other spatial nonuniformities. For the i-th acoustic path, in the idealized model, the signal transit time in the direction of the flow is determined as [1, 2]:

$$t_{i,\downarrow} = \frac{L_i}{c_i + v_i \cos\theta_i} \quad (1)$$

Against the flow:

$$t_{i,\uparrow} = \frac{L_i}{c_i - v_i \cos\theta_i} \quad (2)$$

where L_i is the acoustic path length, θ_i is the angle between the acoustic path and the flow direction, v_i is the mean flow velocity projected onto the acoustic path, and c_i is the effective speed of sound along the path.

From Eqs. (1) and (2) for the signal transit times in the downstream and upstream directions, respectively, the following expression for the mean flow velocity along the i-th acoustic path is obtained:

$$v_i = \frac{L_i}{2\cos\theta_i}\left(\frac{1}{t_{i,\downarrow}} - \frac{1}{t_{i,\uparrow}}\right). \quad (3)$$

At the same time, the same transit-time measurements make it possible to determine the effective speed of sound along the i-th acoustic path:

$$c_i = \frac{L_i}{2}\left(\frac{1}{t_{i,\downarrow}} + \frac{1}{t_{i,\uparrow}}\right). \quad (4)$$

Equation (3) is important for the proposed method because, in the idealized model, the speed of sound is directly eliminated from the differential expression for v_i. Therefore, the independently measured value c_RES does not need to be introduced into Eq. (3) as a multiplicative correction factor. Instead, Eq. (4) provides an additional estimate c_i for each TOF channel, which can be compared with the independent RES-based estimate.

Thus, each TOF channel provides two estimates: v_i, the mean flow-velocity component along the acoustic path, and c_i, the effective speed of sound along that path. The mean flow velocity for a multichannel system can be represented using spatial weighting coefficients, as in [3, 4]:

$$v_{base} = \sum_{i=1}^{N} g_i\, v_i\,. \quad (5)$$

whereg_i is the basic spatial weighting coefficient of the i-th acoustic path.

The weighting coefficients are normalized such that their sum is equal to unity:

$$\sum_{i=1}^{N} g_i = 1. \quad (6)$$

The values of the weighting coefficients g_i should be determined by the geometry of the acoustic paths and the selected spatial integration method. For circular pipes, the Gauss-Jacobi, OWICS, and modified quadrature integration methods are among the approaches reported in the literature [3, 5].

For a specific circular flowmeter design, the values of g_i should be determined separately according to the actual positions of the acoustic paths and the selected integration model.

Unlike a TOF channel, the informative parameter of the RES channel is not the single-pass transit time of an acoustic pulse, but the natural resonance frequency of the acoustic system [7-9]. For an idealized one-dimensional resonator, the standing-wave condition can be written as

$$L_{RES} = \frac{n\lambda_n}{2}, \quad (7)$$

where L_{RES} is the effective length of the resonant acoustic path, and λn is the wavelength corresponding to the n-th mode.

The speed of sound is determined from the resonance frequency as

$$c_{RES} = f_n\lambda_n = \frac{2L_{RES}f_n}{n} \quad . \quad (8)$$

This expression provides the practical formula for calculating the speed of sound. Measurement of the speed of sound from the natural frequencies of acoustic resonators has a well-established metrological basis. At NIST, cylindrical and spherical resonators have been used for high-accuracy measurements of the speed of sound in gases [7, 8]. For methane, the speed of sound has also been determined from the frequencies of radial acoustic modes of a spherical resonator [9]. Thus, the transverse orientation of the RES channel reduces the influence of the main axial component of the flow velocity on the estimate of c_{RES}.

In the proposed method, the independent RES-based estimate is used as a reference quantity for determining the metrological consistency of each TOF channel. For this purpose, the following difference, i.e., the absolute deviation between the speed-of-sound estimates, is introduced:

$$\Delta c_i = c_i - c_{RES} \ . \quad (9)$$

Assuming that the estimates are uncorrelated, the standard uncertainty of their difference, in accordance with the rules of uncertainty propagation [12], is determined as

$$u_{\Delta c_i} = \sqrt{u^2(c_i) + u^2(c_{RES})} \ , \quad (10)$$

where the uncertainty of the speed of sound for the i-th TOF channel, according to Eq. (4)

$$u(c_i) = \sqrt{\left[\frac{1}{2}\left(\frac{1}{t_{i,\downarrow}} + \frac{1}{t_{i,\uparrow}}\right)u(L_i)\right]^2 + \left(\frac{L_i}{2t_{i,\downarrow}^2}u(t_{i,\downarrow})\right)^2 + \left(\frac{L_i}{2t_{i,\uparrow}^2}u(t_{i,\uparrow})\right)^2},$$

is described by the corresponding uncertainty-propagation expression. Similarly, the uncertainty of the resonant-channel estimate is determined from the uncertainty-propagation relation for the RES-channel model (8)

$$u(c_{RES}) = \sqrt{\left(\frac{2f_n}{n}\cdot u(L_{RES})\right)^2 + \left(\frac{2L_{RES}}{n}\cdot u(f_n)\right)^2}.$$

In the proposed method, the normalized metrological inconsistency of the i-th TOF channel is characterized by the parameter

$$z_i = \frac{c_i - c_{RES}}{u_{\Delta c_i}}. \quad (11)$$

The parameter z_i indicates how significant the discrepancy between the TOF- and RES-based estimates is relative to their combined standard uncertainty. This approach takes into account not only the difference between c_i and c_{RES}, but also the uncertainty associated with their determination.

To transform the normalized metrological inconsistency into a dimensionless reliability coefficient, a Gaussian function is proposed:

$$q_{i,c} = \exp\left(-\frac{z_i^2}{2}\right). \quad (12)$$

The dimensionless reliability coefficient indicates that, as the normalized inconsistency z_i increases, the value of q_i smoothly decreases from 1 to 0 according to a Gaussian law. This provides a gradual transition from a fully reliable channel to an unreliable one, without abrupt changes.

If necessary, the proposed coefficient (12) can be supplemented with additional component parameters and, in the general case, can be expressed as

$$q_i = q_{i,c} \cdot q_{i,SNR} \cdot q_{i,t} \cdot q_{i,corr}.$$

where $q_{c,i}$ is the consistency criterion based on the speed of sound (metrological criterion), $q_{i,SNR}$ is the acoustic-signal quality criterion (signal-to-noise ratio), $q_{i,t}$, is the temporal stability criterion (long-term consistency of the measurements), and $q_{i,corr}$ is the reliability criterion for determining the transit time or the correlation-peak position.

If the condition $c_i \approx c_{RES}$ is satisfied for all channels, then $\sum g_j = 1$. In this case, the weights remain unchanged because $q_i \approx g_i$. Accordingly, $w_i \approx g_i$, and the adaptive estimate of the mean flow velocity coincides with the baseline estimate, $v_{ad} \approx v_{base}$. This means that the RES criterion does not modify the weighting coefficients but merely confirms their validity, and the system operates as a conventional multi-channel TOF flowmeter.

The spatial information is represented by the basic weighting coefficients g_i, which reflect the geometry and arrangement of the acoustic paths within the flow cross-section. They ensure correct integration of the velocity profile under normal operating conditions. The adaptive component is the reliability coefficient q_i, which characterizes the current quality and reliability of the measurement in each TOF channel. It accounts for consistency with the RES channel, the signal-to-noise ratio, temporal stability, and correlation-based criteria. Therefore, it is proposed to form the adaptive weight w_i of the i-th TOF channel as the normalized product of its basic spatial weight g_i and its current reliability coefficient q_i:

$$w_i = \frac{g_i \cdot q_i}{\sum_{j=1}^{N} g_j q_j}. \quad (13)$$

If all channels operate correctly ($q_i \approx 1$), then $w_i \approx g_i$. If one of the channels degrades ($q_i < 1$), its contribution is automatically reduced, while the remaining channels are assigned larger weights.

Normalization by the denominator ensures that the system always preserves the weighting balance:

$$\sum_{i=1}^{N} w_i = 1. \quad (14)$$

For the RES-based criterion, using Eq. (13), the normalized adaptive weight can be written in expanded form as

$$w_i = \frac{g_i \exp\left[-\frac{(c_i - c_{RES})^2}{2\sigma_c^2}\right]}{\sum_{j=1}^{N} g_j \exp\left[-\frac{(c_j - c_{RES})^2}{2\sigma_c^2}\right]}. \qquad (15)$$

Equation (15) is the principal relationship of the proposed method for adaptive formation of weighting coefficients. Figure 2 illustrates the scheme for forming the adaptive weighting coefficients of a four-channel TOF flowmeter. The quantities w_i are the adaptive weights of the four TOF channels, which jointly form a single estimate of the mean flow velocity at a given instant of time.

The adaptive estimate of the mean flow velocity is determined as

$$v_{ad} = \sum_{i=1}^{N} w_i v_i \,. \qquad (16)$$

For additional diagnostic assessment of the state of the multichannel measurement system, an integral information completeness indicator is proposed:

$$S_q = \sum_{i=1}^{N} g_i q_i. \qquad (17)$$

If all channels are consistent with the RES-based estimate, then Sq ≈ 1. A decrease in Sq indicates that the fraction of the basic spatial information satisfying the reliability criterion is reduced. When a threshold Spor, which acts as a comparator, is introduced, the condition Sq ≥ Spor should be satisfied.

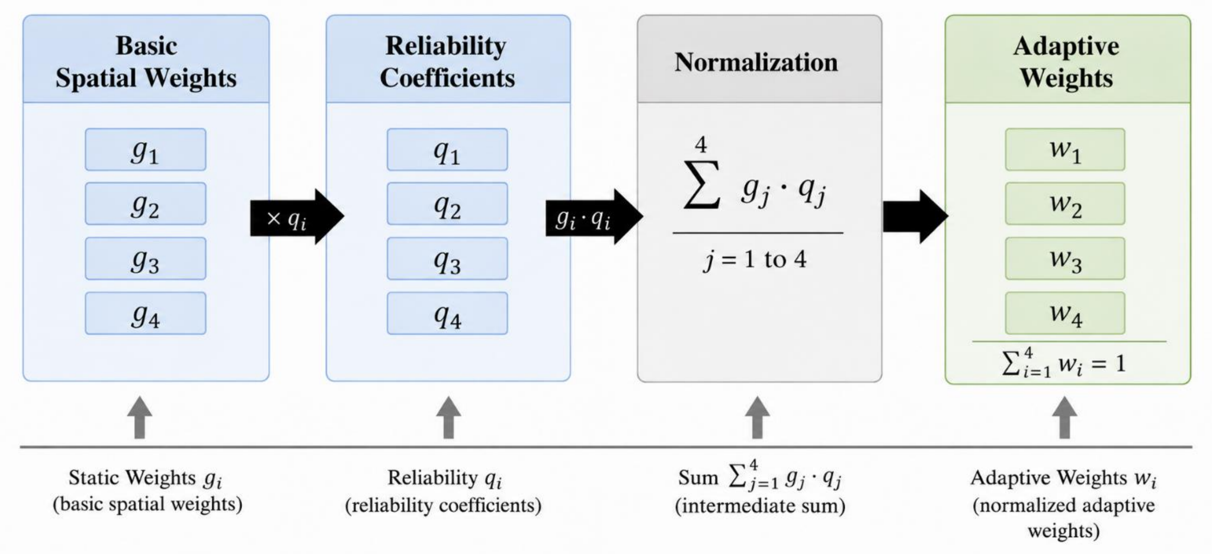

Fig. 2. Scheme for forming adaptive weighting coefficients of a four-channel TOF flowmeter

The value of Spor can be determined from the results of modeling, calibration, and experimental studies. When Spor ≤ Sq < 1, there is a partial loss of reliable information, and individual channels are assigned reduced weights.

The instantaneous difference c_i - c_{RES} may contain random fluctuations. Therefore, at time instant k, it is proposed to use the median difference over a window containing Nw measurements, i.e., to perform temporal averaging of the channel reliability using a median estimate of the deviation:

$$\widetilde{\Delta c_i}(k) = \text{median}\{c_i(r) - c_{RES}(r)\}$$
$$r = k - N_w + 1, \dots, k \quad (18)$$

Thus, for each channel, the median deviation over the most recent data window of length Nw is used. The duration of the averaging window is determined as

$$T_w = \frac{N_w}{f_s}, \qquad (19)$$

where fs is the rate at which the TOF-RES data sets are generated.

At a high fs, the window covers a shorter time interval and the system responds more rapidly to changes, whereas at a low fs, the window covers a longer time interval and the estimate becomes more stable but less sensitive to rapid fluctuations. The updated channel reliability is determined as

$$q_{i,c}(k) = \exp\left[-\frac{\widetilde{\Delta c_i}^2(k)}{2\sigma_c^2}\right]. \qquad (20)$$

Using the median instead of the mean makes the algorithm less sensitive to isolated anomalies or outliers. The updated reliability coefficient q_i reflects the long-term consistency of the channel with the RES-based estimate. This approach makes it possible to distinguish persistent systematic deviations from random noise. This increases the reliability of the algorithm: channels are not rejected because of short-term fluctuations, but if discrepancies persist over time, their weight is reduced. As a result, the system achieves a balance between sensitivity and stability.

Conclusions

A method for the adaptive formation of weighting coefficients for a multichannel TOF flowmeter and an associated algorithm have been proposed, in which an independent measurement of the speed of sound by a resonant RES channel is used as a criterion of metrological consistency for individual TOF channels.

It is shown that the independent value c_{RES} does not need to be introduced into the basic TOF measurement equation as a direct multiplicative correction factor. In the proposed structure, the RES channel performs a diagnostic and metrological function and is used to form the reliability coefficient q_i.

The relationship between the resonance frequency and the speed of sound is demonstrated; determination of the resonance frequency from the frequency response, the use of several acoustic modes, and the transition from the idealized relationship to the calibration function Fcal are considered.

It is proposed to form the resulting weight as the normalized product of the basic spatial weight g_j and the current reliability coefficient q_i. This approach keeps the geometric function of the quadrature weights separate from information about the current state of the measurement channel.

For practical implementation of the method, experimental verification of the RES-channel parameters, the statistical limits of the natural difference (c_i - c_{RES}), the diagnostic threshold Spor, and the behavior of the algorithm under spatial nonuniformity of temperature and gas composition are required. Confirmation of improved metrological accuracy in a real hybrid TOF-RES flowmeter should be the subject of further numerical and experimental investigation.

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