Investigation of Ultrasonic Flowmeter Error in Conditions of Distortion of Flow Structure

Vitalii Roman, Fedir Matiko

Department of Automation of Heat and Chemical Processes,
Lviv Polytechnic National University, UKRAINE,
Lviv, S. Bandery street 12,
E-mail: roman.vitaliycfd@gmail.com

Annotation – Ultrasonic flowmeter error caused by distortion of flow structure has been investigated in this paper. Minimum number of acoustic chordal paths of multi-channel ultrasonic flowmeter was determined that ensures the error caused by distortion of flow structure less than the specified limits ±0.3 %. The authors used Salami velocity function as a model of distortion of flow structure. Acoustic path configurations of ultrasonic flowmeter were determined using classical numerical methods of integration of Gauss-Jacobi. The authors improved the flow rate equation of ultrasonic flowmeter by introduction of calibration coefficient that was determined using symmetric component of Salami function.

Key words – ultrasonic flowmeter, flow structure, local fitting, Salami function, numerical method of integration, acoustic path, calibration coefficient.

I. Problems

Ultrasonic flowmeter (USM) is often installed at measuring pipeline (MP), which contain different types of local fittings (LF) – flap, bend, group of bends, etc. Each LF distorts the flow structure (velocity profile) that passes through it. The USM installed at a short distance after the LF (downstream the fitting) can measure flow with error δ_A, which is caused by distortion of flow structure. Value of the error δ_A varies with the type and location of LF, as well as the acoustic path configurations (their number) and may reach 10 % [1, 2]. One of the main way to reduce errors δ_A is increasing the number of acoustic paths (AP) of USM. In this paper a technique to reduce error USM which is caused by distortion of flow structure is investigated. This technique means determining of the minimum number of APs USM that provides δ_A error less than limits set by regulations.

II. Investigation USM error

Equation for the volumetric flow rate measured by multi-path USM can be written as this

$$q_{USM} = \pi R^2 \sum_{i=1}^{N} \left(\frac{w(i) 2\sqrt{R^2 - x(i)^2}}{\pi R} u_h(i) \right) \qquad (1)$$

where q_{USM} – volumetric flow rate at working conditions; R – internal radius of USM section (pipe in wich USM is installed) ; $x(i)$, $w(i)$ – position coordinate and weighting factor of i-th chordal AP USM; u_h – average flow velocity along the i-th chordal AP USM; N – number of the AP USM.

To select the $x(i)$ and $w(i)$ for a specified value of N use classic numerical methods of integration (NMI) [5]. In this paper two NMI is uses: Gauss-Jacobi (α, β = 0.5) and Gauss [3].

To apply the formula (1), it is necessary also to determine the flow velocity along the chordal AP u_h. In this work, the authors used to determine u_h analytical models of distortions of flow structure which professor L.A. Salami proposed. Functions Salami are dependencies of the relative flow velocity u/u_{max} of polar coordinates – angle θ and relative radius $r = R/R_{max}$. Functions Salami are based on experimental data and describe adequately kinematic structure of the flow at the exit of the fittings different types [4]. Each function Salami consists of two terms: one – describes the undistorted velocity profile (u_{sym}), and the second – describes the distorted velocity profile (u_{asym}).

We propose to use the following formula with polar functions Salami for calculation the average flow velocity along the AP

$$u_h = \frac{\left[\begin{array}{l} \int_0^{\sqrt{R^2-x^2}} u_{SAL}\left(\sqrt{x^2+l^2}, \theta + arctg\frac{l}{x} \right) dl + \\ + \int_0^{\sqrt{R^2-x^2}} u_{SAL}\left(\sqrt{x^2+l^2}, \theta - arctg\frac{l}{x} \right) dl \end{array} \right]}{2\sqrt{R^2-x^2}} \qquad (2)$$

where u_{SAL} – velocity profile (function Salami); θ – angle of measuring plane which passes chordal AP relative to the horizontal plane; l – length of chordal AP USM.

Position coordinates $x(i)$ and weights factors $w(i)$ APs defined for the flow velocity profile that is different to the velocity profile (u_{sym}) function Salami. Therefore, the results of calculating flow rate in equation (1) differ from the flow rate calculated by direct integration undistorted velocity profile (u_{sym}) function Salami. The calibration coefficient k_{cal} is proposed to introduce to the equation (1) in order to improve it:

$$k_{cal} = \frac{q}{q_{USM}} = \frac{2\pi \cdot \int_0^1 r(1-r)^{\frac{1}{n}} dr}{q_{USM}} \qquad (3)$$

where q – the volumetric flow rate calculated at an average flow velocity of the cross section of MP, obtained by direct integration of a power law distribution flow velocity (corresponding u_{sym}); q_{USM} – the value volumetric flow rate defined by the formula (1) in which the flow velocity along chordal AP u_h determined by the formula (2) provided u_{asym} = 0. Equation (1) with calibration coefficient k_{cal} is applied for investigation of USM error δ_A caused by distortion of flow structure:

$$\delta_A = \frac{(q_{USM} - q_{SAL})}{q_{SAL}} \cdot 100 \,. \qquad (6)$$

We propose to calculate the values of flowrate q_{SAL} using the values of the flow velocity at each point of the cross section of pipe defined with Salami function

$$q_{SAL} = \int_0^{2\pi} \left(\int_0^1 r \cdot u_{SAL}(r, \theta) dr \right) d\theta \,. \qquad (4)$$

Particularly integrating of function Salami P09 (5) with formula (4) is made in this work. Salami P09 function describes the distortion of the velocity profile downstream of a single bend:

$$u_{SAL} = u_{sym} + y_{asym} = \\ = (1-r)^{\frac{1}{9}} + \frac{2}{\pi^5} r (1-r)^{\frac{1}{4}} \theta^2 (2\pi - \theta)^2 \quad (5)$$

Fig.1 shows a three-dimensional flow velocity profile calculated with function Salami P09.

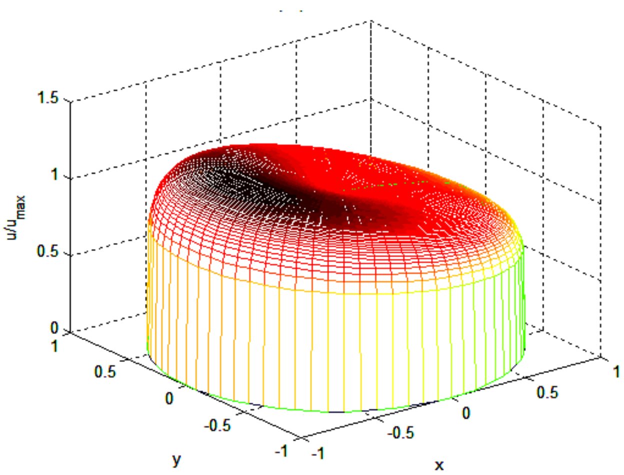

Fig. 1. 3D velocity profile described function Salami P09

For calculation USM error δ_A following limitations we use: the value of the angle θ = 90° (corresponding to a horizontal plane position chordal AP USM); $N = 1... 6$; calculation of x and w made for two mentioned above NMI.

Values of the calculated USM error δ_A using the velocity Salami function P09 is shown in Fig.2.

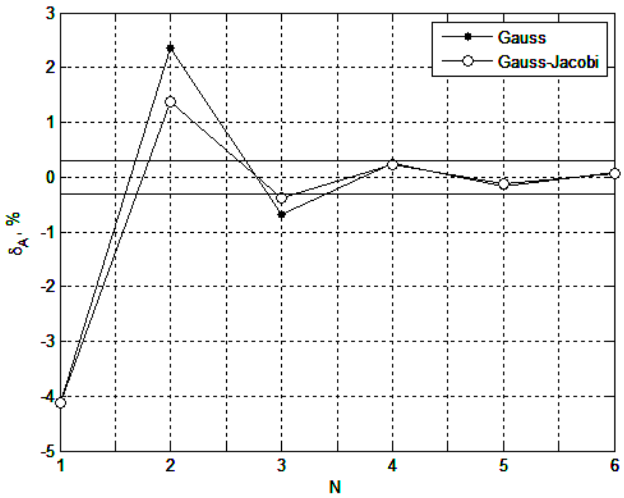

Fig. 2. Dependence of the USM error δ_A relatively N (θ = 90°) for flowmeters with the values of x and w found two NMI (flow structure – velocity function Salami P09)

As shown in Fig.2 of error δ_A decreases with increase in the number of AP USM.

For USM position coordinates placement and weighting factors APs which are calculated by the Gauss-Jacobi NMI at $N = 3$, the value δ_A = -0.385 %, and when $N = 4$, error δ_A = 0.220 %.

For USM position coordinates placement and weighting factors APs which are calculated by the Gauss NMI at $N = 3$, the value δ_A = -0.690 %, and when $N = 4$, error δ_A = 0.253 %.

According to [5] the influence of the distortion of flow structure on the result of the USM measurement is negligible at the following two requirements:

1) $|\delta_A| \leq 0.3$ %;

2) $(|\delta_{A(N)}| - |\delta_{A(N+1)}|) \leq 0.3$ %.

We confirm that these requirements are true for USM for which the characteristics x and w were received using Gauss-Jacobi NMI and Gauss NMI for the number of APs $N \geq 4$. Thus we recommend the number of APs $N = 4$. A further increasing of the APs number is not reasonable.

Conclusion

To measure the flow rate of distorted flow it's necessary to apply USMs with a multi-path chordal arrangement of APs. Applying the USM with four chordal APs allows measuring the flow rate of distorted flow with the error that does not exceed the limit values set by existing regulatory documents and are acceptable for commercial accounting of energy carriers.

It should also be noted that choice of NMI for construction of multi-path chordal USM is necessary only at $N < 4$.

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