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Reduction of Hydrodynamic Flow Measurement Error of Chordal Ultrasonic Flowmeter

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Abstract

In this work, ways of reducing the hydrodynamic flow measurement error of chordal ultrasonic flowmeter for the distributed location schemes of their acoustic paths are investigated. The method of calculating optimal location coordinates of the acoustic paths of ultrasonic flowmeters is considered in detail, using the analytical-empirical power law of the distribution of the velocity of the undistorted flow. As a result of the work, the authors calculated the optimal arrangement of acoustic paths for chordal schemes of two- and three-path ultrasonic flowmeters. It was established that optimization of the location scheme of the acoustic paths of chordal ultrasonic flowmeters allows reducing the hydrodynamic flow measurement error to the value of 0.05 % (for two-path flowmeters) and 0.1 % (for three-path). The developed approach is convenient when designing multipath ultrasonic flowmeters and their research in laboratory conditions.

Keywords: ultrasonic flowmeter; hydrodynamic error; power law; acoustic paths; chordal scheme.

1. The purpose of the work

Sensitivity of ultrasonic flowmeters (USMs) to the profile of flow velocity is described in many domestic [1-2] and foreign [3-6] scientific works. Thus, in the case of USM under the conditions of undistorted flows, a hydrodynamic flow measurement error (HDE) occurs [5], and under the conditions of perturbation of the structure of the velocity profile of various local pipe fittings, an additional flow measurement error (AE) arises due to the distortion of the flow structure [6].

The purpose of this work is to investigate one of the ways to reduce the HDE of the USM.

2. Presentation of the material

The occurrence of the HDE of the USM is due to the fact that the velocity of the flow, calculated from the value of passing of sound vibrations over and against the flow along its acoustic paths (APs) u_L, is always different from the actual value of the flow velocity of the averaged over the diameter of the measuring pipeline (MPL) [5]. The relationship between these velocities does not depend on the angle of inclination of the AP to the axis of flow, but is determined by the number of Re and the location scheme of the APs USM (the number of APs and the way of their spatial arrangement).

Currently, a significant number of location schemes of APs USM are proposed. We have carried out the classification of known location scheme of APs USM (see Fig. 1) and analysis of possible values the HDE of the USM for different location scheme.

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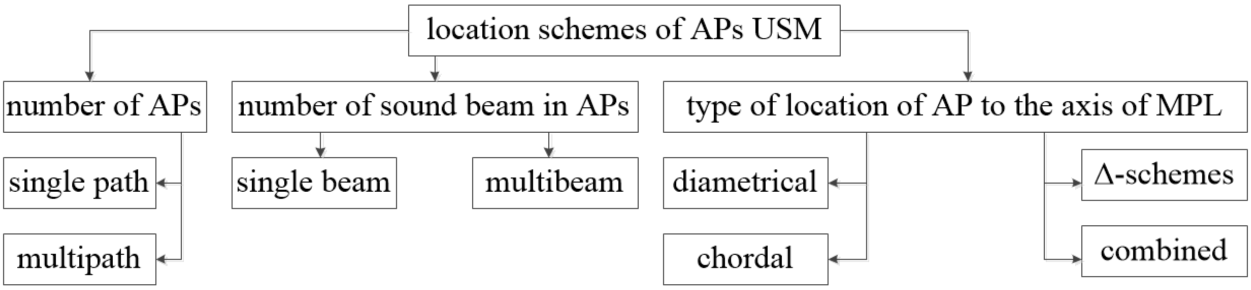

Fig.1. Classification of location schemes of APs USM.

In the case of the usage of an USM with a diametric location scheme of APs, when the sound vibrations are moving either along the MPL axis (inclination angle 0º) or at a certain angle to it (45... 60º), the velocity of the USM in an idealized profile of velocity is always greater than the average velocity in diameter MPL [5-7]. As a result, the HDE of the USM acquires the following values: for laminar regime, 33 % [5-7]; for a turbulent regime of 3... 8 % ($\mathrm{Re} = 10^3 \ldots 10^7$) [5-7]. In order to eliminate the HDE of USM with a diametric location scheme of APs, in their cost equation, a correction factor is introduced as a function of Re [5, 7].

In the case of using an USM with a chordal location scheme of APs, in order to eliminate the HDE, the developers of flowmeters of this type recommend:

1. To introduce into the flow equation of the USM calibration coefficient, obtained by the results of the calibration of the USM in the conditions close to the operation environment. In this case, not only the influence on the USM of the structure of the undistorted profile of the flow velocity, but also the influence of other parameters of the flow (pressure, temperature, composition of the measuring flow) [8] is eliminated.

2. Optimization of the location schemes of APs with the usage of numerical integration methods. This approach is most often used for USM with the number of APs $N > 4$ [7].

3. Optimization of the location schemes of APs with the usage of analytic-empirical laws for the velocity distribution of undistorted flow [6].

In this paper, the third approach is used to eliminate the HDE of two- and three-path chordal USM with the usage of the analytical-empirical power law of the distribution of the velocity of the undistorted flow.

3. Investigation of the HDE of USM

The formula for the analytic-empirical power law of the distribution of the velocity of the undistorted flow has the following form [3]:

$$u(i) = \left(1 - r(i)\right)^{\frac{1}{n}}, \tag{1}$$

where: $u(i)$ – normalized (at maximum, axial velocity) value of the flow velocity at the ith point of the cross section of the MPL; $r(i)$ – normalized (within the radius of MPL) the value of the radial coordinate of the ith point of the cross section of the MPL; n – number of Nikuradze, which is a function of Re.

The values of n for any Re are calculated by the equation [3, 5, 7]:

$$n = 11.269 - 3.019 * \lg(\mathrm{Re}) + 0.432 * (\lg(\mathrm{Re}))^2. \tag{2}$$

According to (2), the range of numbers $\mathrm{Re} = 1.1*10^5 \ldots 1.4*10^6$ corresponds to the values of n = 7, 8 and 9. For the same range in [9], one-peak analytic-empirical laws of distribution of distorted flow (functions Salami). Therefore, it is expedient in this work to perform the research for the indicated values of n, which will enable to further compare the results of research of USM in conditions of undistorted and distorted flows.

The volumetric flow rate expenditure flowing through the cross-section of MPL can be obtained by integrating the power law of distribution (1) [3]:

$$q = 2\pi \cdot \int_0^1 (r \cdot u)dr . \tag{3}$$

Applying the distribution law (1) and the geometric characteristics of the location scheme APs (see Fig. 2), we obtain the equation of the volume flow rate of multipath chordal USM [10]:

$$q_{USM} = \pi R^2 \cdot \frac{\sum_{i=1}^{N} u_L(i)}{N} = \pi R^2 \cdot \frac{\sum_{i=1}^{N} \left(\frac{1}{T(i)} \left[\begin{array}{l} \int_0^{\sqrt{R^2 - x(i)^2}} u\left(\sqrt{x(i)^2 + L^2}, \alpha + arctg\frac{L}{x(i)} \right) dL + \\ + \int_0^{\sqrt{R^2 - x(i)^2}} u\left(\sqrt{x(i)^2 + L^2}, \alpha - arctg\frac{L}{x(i)} \right) dL \end{array} \right] \right)}{N}, \tag{4}$$

where: α, $T(i)$ is the angle of rotation and the width of the plane in which the ith chordal AP USM passes relative to the horizontal plane; L – length of ith AP; $x(i) = 0... 1$ – coordinate of the location of the plane in which the ith chordal AP USM passes; N – number of chordal APs USM.

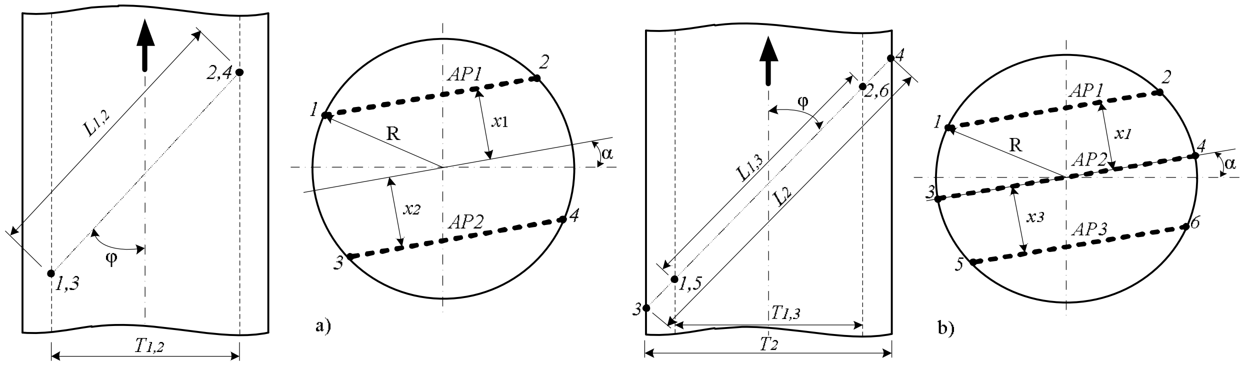

Fig.2. Picture of location schemes of two-path (a) and three-path (b) chordal USM.

Since in this work the case of standard horizontal installation of USM (angle α = 0°) is used, the formula (4) can be simplified as follows:

$$q_{USM} = \pi R^2 \cdot \frac{\sum_{i=1}^{N} \left(\frac{1}{T(i)} \left[\begin{array}{l} \int_0^{\sqrt{R^2 - x(i)^2}} u\left(\sqrt{x(i)^2 + L^2}, arctg\frac{L}{x(i)} \right) dL + \\ + \int_0^{\sqrt{R^2 - x(i)^2}} u\left(\sqrt{x(i)^2 + L^2}, -arctg\frac{L}{x(i)} \right) dL \end{array} \right] \right)}{N}. \tag{5}$$

In this work it is proposed to calculate the HDE of the USM taking for the exemplary value of expenditure, calculated by the formula (3):

$$\delta_{GD} = \frac{q_{USM} - q}{q} \cdot 100 . \tag{6}$$

The optimization of the location schemes of chordal APs using the power law of distribution is to determine the coordinate $x(i)$ of the AP location in which the HDE of the USM δ_{GD} will be equal to or close to zero. Fig.3 presents the results of the calculation of the HDE δ_{GD} for two-path chordal USM.

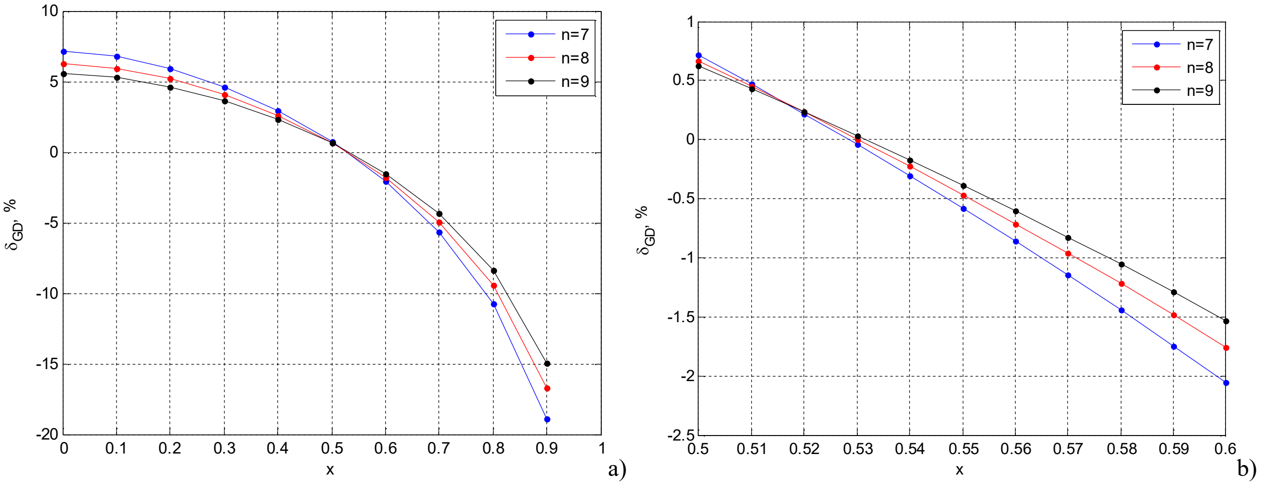

Fig.3. Dependence of HDE δ_{GD} of two-path chordal USM from the relative coordinate of the location of its APs: a) range x = 0... 0.9; b) range x = 0.5... 0.6.

Analyzing the results presented in Fig.3, it can be argued that the optimal coordinates of the location of the APs of the two-path chordal USM are $x_{1,2}$ = ±0.53R (δ_{GD} < 0.05 %). Fig.4 presents the results of the calculation of the HDE δ_{GD} for three-path chordal USM.

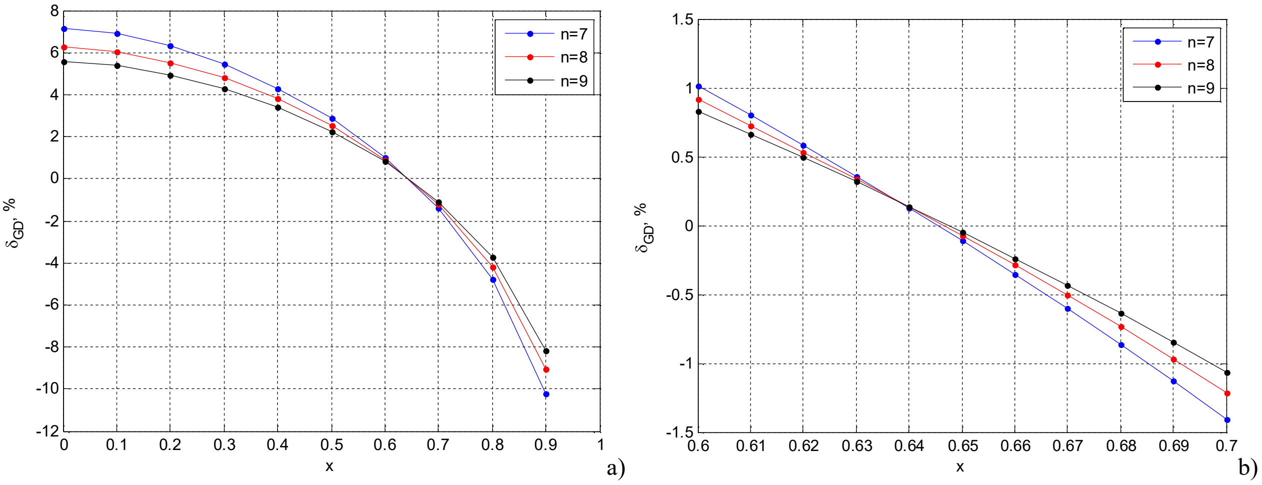

Fig.4. Dependence of HDE δ_{GD} of three-path chordal USM from the relative coordinate of the location of its APs: a) range x = 0... 0.9; b) range x = 0.6... 0.7.

It is shown in Fig.4 that the optimal coordinates of the location of the extreme APs (AP1 and AP3 in Fig. 2, b) of the three-path chordal USM are values $x_{1,3}$ in the range ± (0.64... 0.65)R (δ_{GD} <0.1 %).

4. Conclusion

According to the results of the research, it was established that:

1. Application of the analytical-empirical power law of the distribution of the velocity of undistorted flow is a convenient method for conducting research on the location scheme of APs chordal USM.

2. Application of optimized location scheme of the APs chordal USM allows reducing the HDE of the expenditure:

- to the value $\delta_{GD} < 0.05$ % for two-path chordal USM at $x_{1,2} = \pm 0.53R$;
- to the value $\delta_{GD} < 0.1$ % for three-path chordal USM at $x_{1,3} = \pm(0.64\ldots 0.65)R$, $x_2 = 0$.

The obtained results can be applied in the design of multipath USM and their research in laboratory conditions.

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Зменшення гідродинамічної похибки хордових ультразвукових витратомірів

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Анотація

В роботі досліджено шляхи зменшення гідродинамічної похибки вимірювання витрати ультразвуковими витратомірами для розповсюджених схем розташування їх акустичних каналів. Детально розглянуто спосіб розрахунку оптимальних координат розташування акустичних каналів ультразвукових витратомірів з використанням аналітико-емпіричного степеневого закону розподілу швидкості неспотвореного потоку. За результатами роботи авторами розраховано оптимальне розташування акустичних каналів для хордових схем дво- та триканальних ультразвукових витратомірів. Встановлено, що оптимізація схем розташування акустичних каналів хордових ультразвукових витратомірів дозволяє зменшити гідродинамічну похибку вимірювання витрати до значення 0,05 % (для двоканальних витратомірів) та 0,1 % (для триканальних). Розроблений підхід є зручним під час проектування багатоканальних ультразвукових витратомірів та їх дослідження в лабораторних умовах.

Ключові слова: ультразвуковий витратомір; гідродинамічна похибка; степеневий закон; акустичні канали; хордова схема.