

SIMULATION OF THE OPERATION OF A FOUR-CHANNEL ULTRASONIC FLOWMETER WITH IDENTICAL SIGNAL TRAJECTORIES IN ACOUSTIC CHANNELS

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Abstract. In this work, a four-channel ultrasonic flowmeter with identical signal paths is proposed. Various designs of ultrasonic flowmeters have been analysed, and the rationale for developing such a measuring transducer is presented. The operation of the four-channel flowmeter was simulated both in the SOLIDWORKS Flow Simulation environment and using a classical analytical approach. The simulation results are presented in terms of the measurement error at specific flow rates, considering both the presence of a flow conditioning device and standard flow resistances. A comparative analysis of the obtained results demonstrates the advantages and potential of the proposed ultrasonic flowmeter with identical signal paths.

Keywords: four-channel ultrasonic flowmeter with identical signal paths, simulation, measurement error, flow preparation device, additional resistances

SYMULACJA PRACY CZTEROKANAŁOWEGO PRZEPŁYWOMIERZA ULTRADŹWIĘKOWEGO O IDENTYCZNYCH TRAJEKTORIACH SYGNAŁU W KANAŁACH AKUSTYCZNYCH

Streszczenie. W pracy zaproponowano czterokanałowy przepływomierz ultradźwiękowy o identycznych ścieżkach sygnału. Przeanalizowano konstrukcje przepływomierzy ultradźwiękowych. Przedstawiono uzasadnienie budowy takiego ultradźwiękowego przetwornika pomiarowego. Przepływomierz czterokanałowy symulowano w środowisku SOLIDWORKS Flow Simulation oraz w środowisku klasycznym. Wyniki symulacji przedstawiono w postaci błęd pomiaru dla określonego natężenia przepływu z wykorzystaniem urządzenia do przygotowania przepływu i rezystancji wzorcowych. Analiza porównawcza wyników pokazała perspektywę zastosowania proponowanego przepływomierza ultradźwiękowego o identycznych ścieżkach sygnału.

Słowa kluczowe: czterokanałowy przepływomierz ultradźwiękowy z identycznymi ścieżkami sygnału, symulacja, błąd pomiaru, urządzenie do przygotowania przepływu, dodatkowe rezystancje

Introduction

One of the most common means of measuring the flow of liquids and gases today is the ultrasonic flow meter (UFM), the foundations of which were laid back in the 1970s [3]. UFM's have proved effective in ensuring accurate, reliable, and cost-efficient gas metering in various applications – from industrial to domestic – as they offer a number of advantages: the absence of obstacles in the flow path and moving parts that can wear out; insignificant pressure losses; a wide measurement range; and the possibility of use in large-diameter pipelines. UFM's also allow flow measurements in both directions. In addition, they are characterized by the ability to determine additional flow parameters (density, speed of sound, calorific value). Despite these advantages, ultrasonic flow meters face significant difficulties when competing with mechanical flow meters, mainly due to their higher cost and the technical challenges associated with gas pipeline retrofitting [1].

Ultrasonic measurement represents a unified approach to using ultrasonic technology for liquid flow measurement, although each manufacturer employs somewhat different design solutions in the measuring transducer. Gas volume measurement under standard conditions is carried out by an indirect method, in which the result is obtained by calculation using various physical quantities that characterize the state of natural gas and are measured directly or indirectly, as well as constant or conditionally constant quantities, whose numerical values are entered into the system for a certain period of time at the periodicity specified in the contract and are used to calculate the gas volume [3, 8].

Despite the common measurement principle, ultrasonic flow measurements can be classified by either measurement method or informative parameter into amplitude-based, frequency-based (Doppler effect), phase-based, time-of-flight, and resonant types [2, 4, 12]. Recently, publications have appeared that describe measuring transducers utilizing not one, but several ultrasonic signal parameters simultaneously [14].

1. Research results

At present, the most widely used type of ultrasonic sensors are time-pulse ultrasonic sensors, which operate based on measuring the difference in the transit time of ultrasonic pulses

propagating upstream and downstream of the gas flow. By determining the difference in the travel times of the acoustic signals, the sensors calculate the average flow velocity, which is proportional to the volumetric flow rate of the gas [1, 3].

The average gas velocity v_i (m/s) along the acoustic path of the ultrasonic sensor is determined by the following equation:

$$v_{cep} = \frac{L}{2\cos\varphi} \cdot \left(\frac{1}{\tau_1} - \frac{1}{\tau_2} \right) = \frac{L^2 \Delta\tau}{2l\tau_1\tau_2} \quad (1)$$

where: φ – angle of inclination of the acoustic path of the ultrasonic signal relative to the axis of the measuring tube; τ_1 – transit time of ultrasonic pulses against the direction of gas flow; τ_2 – transit time of ultrasonic pulses along the direction of gas flow; L – length of the acoustic path; l – projection of the acoustic path length onto a line parallel to the pipeline axis; $\Delta\tau$ – difference between the time intervals of pulse propagation along and against the flow direction for the same acoustic path.

The volumetric gas flow rate under operating conditions V , without taking into account corrections, is calculated by

$$V = S v_{avg} \quad (2)$$

where S is the cross-sectional area of the internal cavity of the measuring section of the ultrasonic.

Unfortunately, determining the exact flow rate is not a trivial task, since the velocity required to determine the volumetric flow rate is, as noted above, the average velocity over the entire cross-section of the meter. In addition, flow profile distortion occurs – which is considered the main drawback of ultrasonic meters according to the international standard ISO 17089 [7].

To mitigate these drawbacks, ultrasonic meter developers use various approaches. One of the most common is increasing the number of acoustic channels. Multi-channel chordal ultrasonic flow meters (without additional flow conditioning devices), unlike single-channel diametral ones, are able to provide higher accuracy due to more effective coverage of the flow velocity profile [11, 13].

The operating principle of a multi-beam ultrasonic flow meter is to determine the flow rate based on the measured velocities along its acoustic channels (ACs), which are arranged along chords [4, 8]. The volumetric gas flow rate is then calculated using constant or variable weights based on known numerical integration methods (NIM) according to the appendix of IEC 60041 [5]. Integration of the measured velocities in a multi-channel ultrasonic flow meter allows, given



the theoretically averaged (or experimentally obtained) values of the flow velocities along all chordal ACs, the volumetric flow rate to be computed as follows [6, 10]:

$$q_{usm} = k_v A \sum_{i=1}^N [u_h(i)] k_h(i) \quad (3)$$

where k_v is the correction factor for the flow velocity profile; A is the cross-sectional area of the VT; $u_h(i)$ is the averaged flow velocity along the i -th chordal acoustic channel (AC); $k_h(i)$ is the weighting factor of the i -th chordal AC; N is the number of chordal ACs of the ultrasonic flow meter.

The Equal-Tab, Gauss-Jacobi, and OWICS methods are the three most common numerical integration methods used in the four-channel design of ultrasonic flow meters. Table 1 presents the positions of the acoustic channels y_i , which are normalized to the radius of the measuring tube, and the corresponding integration weights k_i for a four-channel ultrasonic flow meter according to these methods [10].

One limitation of this approach is that as the gas flows through the pipe, the integrated flow rate may deviate from the actual value, since individual calculations use weighting factors based on the assumption of laminar flow, i.e., a uniform velocity profile. Under turbulent flow conditions – which are a function of the Reynolds number and wall roughness – these deviations increase.

The arrangement of the acoustic paths, i.e., their cross-sectional configuration, is critical because it determines what information about the axial velocity distribution is available for calculating the average velocity. For example, velocity measurements obtained along a diametrical path are more sensitive to changes in the flow profile than those along eccentric paths, such as the mean-radius path. Double paths located in the same plane are significantly less sensitive to off-axis velocity components than single-path configurations. Other configurations, such as triple mid-radius paths, may be sensitive to off-axis components, but can be used in combination

to suppress or reduce the impact of turbulence and cross-flow. Straight paths can be implemented as single, double, or crossed.

The variability in the design of chordal acoustic channels in ultrasonic devices is regulated by standards [1, 3], according to which, depending on the configuration, multi-channel chordal ultrasonic devices are classified into three types:

- i -th the location of an arbitrary number of acoustic channels at distances from the pipe axis that differ from zero and half the radius (off-diameter);
- with the location of two acoustic channels at a distance from the pipe axis equal to half the pipe radius (equal radial);
- a combination of diametrical and chordal acoustic channels.

At the same time, the standard does not specify fixed angles of inclination of the acoustic channels relative to the gas flow direction. The values of the input angles for the acoustic channels are left to the discretion of the developer, which is the approach adopted in this work.

In this study, we propose a fourth type of multi-channel chordal ultrasonic device, which features equal-length signal paths but different signal input angles. The justification for the feasibility of such a flowmeter is described in the work [4].

Figure 1 shows the spatial arrangement of the acoustic channels. Specifically, Figure 1a presents a classical four-channel ultrasonic flowmeter, while Figure 1c illustrates a four-channel ultrasonic flowmeter with equal signal paths. In both configurations, the angles of inclination of the acoustic channels AC2 and AC3 relative to the flow remain the same ($\phi = \phi_1$), and the angle ϕ_2 of the proposed configuration was calculated to ensure that the signal paths of channels AC1 and AC4 are equal to those of channels AC2 and AC3.

As can be seen from the figure, the cross-sectional projections (Figure 1b) of the two flowmeters are identical. Let us justify the feasibility of creating such a flowmeter, simulate its operation, and compare the results with those of a classical flowmeter.

Table 1. Positions and integration weights for a four-channel ultrasonic flow meter

Methods AC number	Equal-Tab		GAUSS-JACOBI		OWICS	
Positions and weights	yi	ki	yi	ki	yi	ki
AC1, AC4	±0.25	0.304499	±0.309017	0.361803	±0.303783	0.356780
AC2, AC3	±0.75	0.195501	±0.809017	0.138197	±0.799639	0.142163

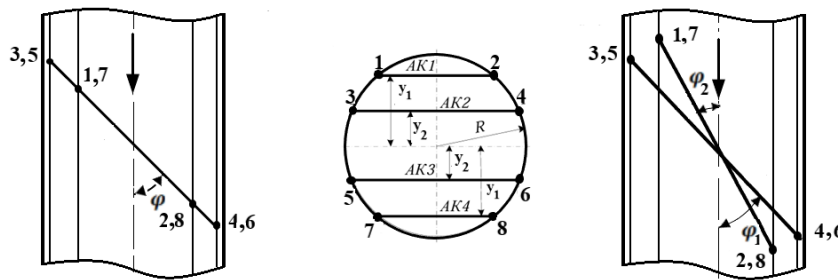


Fig. 1. Schematic of the spatial arrangement of acoustic channels in a four-channel ultrasonic flowmeter: a) classical ultrasonic flowmeter; b) cross-sectional view; c) ultrasonic flowmeter with equal signal paths

2. Mathematical justification

In a classical four-channel ultrasonic flowmeter, where all channels are located at the same angle relative to the flow, the curvature of the plane affects the path length and the signal propagation time. This means that the first and fourth channels will experience different time delays compared to the second and third channels. Consequently, there exists a systematic component of error in determining the average velocity, and thus the volumetric flow rate, since the average velocities of the first and fourth channels, as well as the second and third channels, are calculated along different paths.

We will perform a theoretical analysis of the influence of this error on the measurement of average velocity when

changing the geometry, and also simulate the behaviour of signals in such a flowmeter configuration.

The average velocity is defined as the ratio of the path length to the time taken to traverse this path. The longer the path, the more accurately the average velocity can be determined. Mathematically, the average velocity of the ultrasonic signal is expressed as:

$$V_m = \frac{S}{t}$$

where S is the path length and t is the time taken to cover this path.

If our measurements of time or distance contain an error, then the average speed with errors will be determined as

$$V_m^1 = \frac{S + \Delta S}{t + \Delta t}$$

where ΔS is the path error, Δt is the time error.

The relative error in calculating the average speed is defined as:

$$\delta = \left(\frac{\Delta S}{S} + \frac{\Delta t}{t} \right) \times 100\%$$

Thus, the larger the values of S and t , the smaller the fractional contributions, and consequently, the smaller the relative error. At a fixed path length, the relative error increases linearly with increasing velocity, because the transit time decreases, and the effect of the timing error on the result becomes more significant.

Figure 2 shows the dependence of the relative error on the path length and the average velocity. As can be seen from the graph, for example, at a velocity of 300 m/s, the relative error decreases from approximately 12% to around 3% when the path length increases from 40 mm to 200 mm.

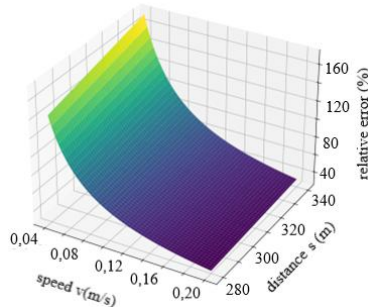


Fig. 2. Graph of the dependence of the relative error on the path length and average velocity

This explains why the average velocity is determined more accurately along longer paths or over longer travel times. The question of signal transit time measurement equipment remains important. It can be stated that if, in a four-channel transducer, the signal propagation paths in the first and fourth channels are increased to match the path lengths of the second and third channels, the error in measuring the average velocity will decrease.

In addition, all channels will have symmetrical time delays, simplifying measurement correction. Averaging values from channels with identical signal propagation conditions will reduce fluctuations caused by minor deviations in gas flow, such as those due to turbulence. In the ideal case of uniform gas flow, when the signals propagate along identical paths, all channels will be less sensitive to local inhomogeneities. If all channels have similar parameters, implementing correction and calibration models becomes easier. Collectively, these measures can improve the overall measurement accuracy.

3. Simulation results

Therefore, for a comprehensive consideration of the existing influences, it is necessary to first perform experimental modelling of the proposed ultrasonic flowmeter using computational fluid dynamics (CFD) methods [6, 9], since actual experimental studies require complex implementation (availability of flow measurement facilities and reference measurement instruments) and significant time resources. Figure 3 shows the appearance of an ultrasonic flowmeter with equal signal paths, modelled in the SOLIDWORKS Flow Simulation environment [12].

The inclination angles of the acoustic channels AC1 and AC4 were 34.07°, while the inclination angles of channels AC2 and AC3 were 65°. The internal diameter of the pipeline is 96 mm. The positions of the acoustic channels and the integration weighting coefficients were determined based on the Gauss–Jacobi method. A turbulent flow was simulated within the pipe. The static pressure at the inlet was 0.101325 MPa, the pressure at the midpoint of the meter was 0.100984 MPa, and the pressure at the outlet was 0.202241 MPa. The ambient temperature was 293.2 K, the medium was air, and the wall boundary condition was adiabatic.

At the inlet of the flowmeter, there was a straight section of pipe with a length of 10D and a flow conditioning device "K-Lab NOVA" [14], which includes a perforated disk with a central hole of diameter $(0.22664 \pm 0.00077)D$, eight holes of diameter $(0.16309 \pm 0.00077)D$, and sixteen holes of diameter $(0.12422 \pm 0.00077)D$, the centres of which are located on a circle with a diameter of 0.85 ± 0.5 mm [15].

In addition to the proposed ultrasonic configuration, the operation of a classical ultrasonic sensor with similar parameters was also simulated.

The further study of ultrasonic sensors with equal signal paths focused on determining the absolute error of flow measurement and comparing it with the error of a classical ultrasonic sensor for several given values within a specified measurement range. This included the sequential closure of the holes in the flow conditioning device and the use of an analogue scheme for comparing errors across several reference flow points over a wide measurement range. To evaluate the impact on the accuracy of gas flow measurement, the flow measurement results were compared with their reference values supplied to the flowmeter inputs. Five tests were conducted according to the requirements of the AGA-9 standard, and Table 2 presents the averaged results of the experimental modelling, showing the flow measurement errors for several reference points: 650 m³/h, 700 m³/h, and 750 m³/h standard set of resistances.

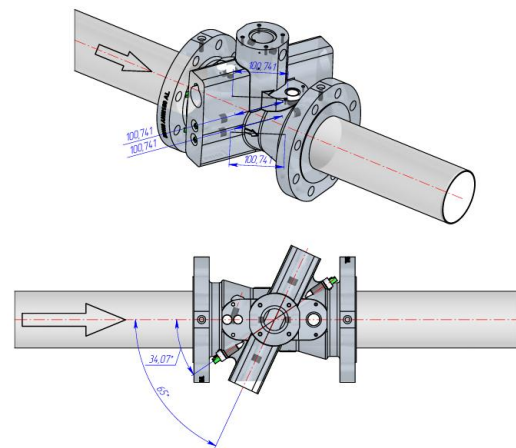


Fig. 3. The appearance of an ultrasonic flowmeter with equal signal paths, modelled in the SOLIDWORKS Flow Simulation environment

Table 2. Results of comparison of the average flow measurement error obtained by sequentially closing the holes in the flow conditioning device

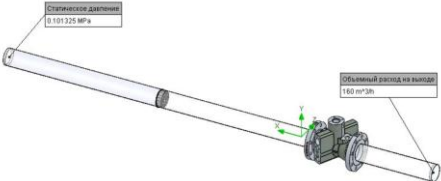
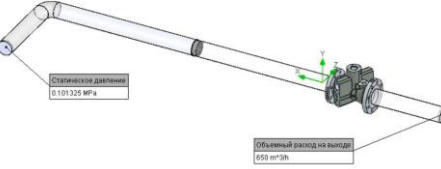
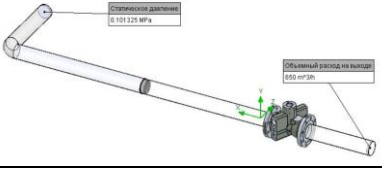
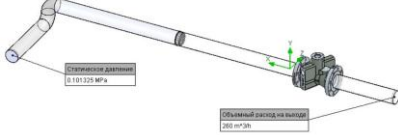
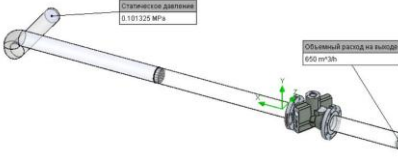
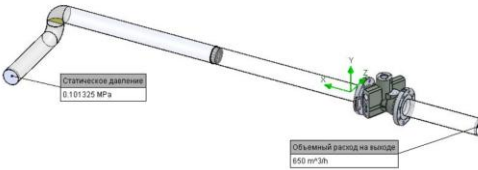
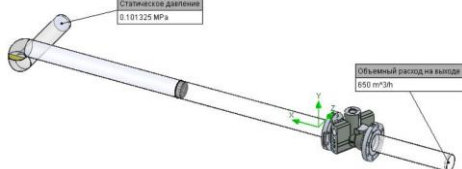
Schemes for closing holes in the flow preparation device	Flow rate m ³ /h	Measurement error		Note +/-
		Equal signalling pathways	Single angle of inclination	
	750	-0.835	-1.290	+
	700	-1.033	-1.285	+
	650	-0.838	-1.783	+
	750	-0.804	-1.249	+
	700	-1.158	-1.257	+
	650	-0.794	-1.750	+
	750	-0.866	-1.232	+
	700	-0.846	-1.250	+
	650	-0.814	-1.806	+
	750	-0.853	-1.285	+
	700	-1.106	-1.285	+
	650	-0.830	-1.789	+
	750	-0.836	-1.791	+
	700	-0.908	-1.314	+
	650	-1.202	-1.767	+

Ultrasonic studies over a wide measurement range at several reference flow points were conducted in accordance with the OIML R137 recommendation, which specifies testing procedures using different pipeline configurations upstream of the flowmeter to verify the stability of the measured values [8].

Table 3 shows the results of the obtained averaged values of absolute error (based on 5 tests) of measurements for the following reference points of flow rates 650 m³/h, 260 m³/h, 160 m³/h with additional supports: knee 0° and 180°, two knees 0° and 180°, two knees + echo 0° and 180°.

The proposed four-channel ultrasonic flowmeter with equal signaling pathways demonstrated a reduction in measurement error for most pipeline configurations. At the same time, CFD simulations revealed that in the presence of 0° and 180° bends, the effectiveness of the approach decreases. This is explained by the formation of an asymmetric velocity profile downstream of the bends, where the maximum velocity shifts away from the channel axis and turbulent structures are redistributed unevenly. Under such conditions, signal integration along the chordal paths does not provide full compensation of geometric errors, which leads to reduced accuracy compared to the classical design.

Table 3. Results of comparison of averaged flow measurement error by experimental simulation of flowmeter operation for several reference flow points using additional resistances

Converter circuit with additional resistances	Flow rate m ³ /h	Measurement error		Note +/-
		Equal signalling pathways	Single angle of inclination	
straight pipe 	650	-0.838	-1.783	+
	260	-0.914	-1.609	+
	160	-0.875	-1.400	+
knee 0° 	650	-0.782	-0.527	-
	260	-0.750	-0.416	-
	160	-0.650	-0.245	-
knee 180° 	650	-0.788	-0.538	-
	260	-0.722	-0.585	-
	160	-0.694	-0.347	-
two knees 0° 	650	-0.351	-1.397	+
	260	-0.202	-1.285	+
	160	-0.176	-1.115	+
two knees 180° 	650	-0.671	-1.485	+
	260	-0.646	-1.303	+
	160	-0.570	-1.275	+
two knees+echo 0 	650	-0.396	-1.320	+
	260	-0.228	-1.211	+
	160	-0.121	-1.210	+
two knees+echo 180° 	650	-0.891	-1.323	+
	260	-0.832	-1.026	+
	160	-0.751	-0.915	+

Thus, the limits of effective application of the proposed construction are determined by the hydrodynamic symmetry of the flow: for straight sections and combinations with two bends or flow straighteners, the scheme is efficient, whereas for specific cases with 0° and 180° bends, the use of additional flow conditioning devices is advisable, as confirmed by supplementary experiments.

4. Conclusions

Based on the analysis of scientific literature, a new design solution for a four-channel ultrasonic sensor with equal-length signal paths is proposed to improve the accuracy of multi-channel ultrasonic sensors. The proposed flowmeter was simulated in the SOLIDWORKS Flow Simulation environment.

As a result of experimental simulation under developed turbulent flow conditions, flow measurement errors were obtained for several points in a narrow range using a standard flow conditioning device with various hole closure combinations, as well as in a wide flow range using standard resistances. The measured errors were compared with the errors of corresponding reference flow rates obtained using a classical standard four-channel ultrasonic sensor.

Comparative analysis revealed the advantages of the proposed flowmeter, namely: higher accuracy, reduced influence of flow disturbances, and reduced sensitivity to measurement errors in developed turbulent gas flows.

Based on the results of this study, the proposed ultrasonic flowmeter (UFM) can be considered promising. Further research should focus on measuring the flow rate under different flow regimes, as well as on the development and experimental testing of a prototype.

References

- [1] Afandi, A., Khasani, Deendarlianto, Catrawedarma, I. G. N. B., & Wijayanta, S. (2024). The development of the ultrasonic flowmeter sensors for mass flow rate measurement: A comprehensive review. *Flow Measurement and Instrumentation*, 97, 102614. <https://doi.org/10.1016/j.flowmeasinst.2024.102614>
- [2] American Gas Association, & Transmission Measurement Committee. (2003). *Measurement of gas by multipath ultrasonic meters* (No. 9).
- [3] American Gas Association. (2007). *Measurement of gas by multipath ultrasonic meters* (No. 9).
- [4] Bilynskyi Y., & Stetsenko A. (2026). *Development and investigation of a four-channel ultrasonic flowmeter with equal signal paths*. <https://doi.org/10.5281/ZENODO.20276780>
- [5] CEI/IEC. (1991). 60041: Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump turbines. International Electrotechnical Commission.
- [6] Gryshanova, I., Pogrebniy, P., & Rak, A. (2013). *Investigation of optimal chord topology for multipath ultrasonic flow meters in distorted flows*. 16th International Flow Measurement Conference FLOMEKO.
- [7] International Organization for Standardization. (2019). ISO 17089-1: Measurement of fluid flow in closed conduits – Ultrasonic meters for gas. Part 1: Meters for custody transfer and allocation measurement.
- [8] International Organization of Legal Metrology. (2012). *OIML R 137-1 & 2. Gas meters*.
- [9] Krasilenko, V., Dubchak, V., & Diachynska, O. (2024). The theoretical basis overview for substantiating and choosing the ways and principles of building multi-valued logic computing systems. *Наука і Техніка Сьогодені*, (9(37)). [https://doi.org/10.52058/2786-6025-2024-9\(37\)-531-545](https://doi.org/10.52058/2786-6025-2024-9(37)-531-545)
- [10] Matiko, F., Roman, V., Matiko, H., & Yalinskyi, D. (2021). Investigation of ultrasonic flowmeter error in distorted flow using two-peak Salami functions. *Energy Engineering and Control Systems*, 7(2), 144–151. <https://doi.org/10.23939/jeecs2021.02.144>
- [11] Pannell, C. N., Evans, W. A. B., & Jackson, D. A. (1990). A new integration technique for flowmeters with chordal paths. *Flow Measurement and Instrumentation*, 1(4), 216–224. [https://doi.org/10.1016/0955-5986\(90\)90016-Z](https://doi.org/10.1016/0955-5986(90)90016-Z)
- [12] Roman, V., Masnyak, O., & Kostyk, I. (2024). SolidWorks flow simulation set up parameters for simulating ultrasonic flow meters. *Prospective Technologies and Devices*, 1(25), 123–130. <https://doi.org/10.36910/10.36910/6775-2313-5352-2024-25-19>
- [13] Tabin, J. (1987). Theoretical Analysis of the Ultrasonic Doppler Flowmeter for Measurements of High Flow Velocities. *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, 34(4), 467–471. <https://doi.org/10.1109/T-UFFC.1987.26968>
- [14] Yu, J., Lou, Q., & Ding, Y. (2024). Ultrasonic flowmeter error factors and technical aspects. *Journal of Measurement Science*. <https://doi.org/10.12338/j.issn.2096-9015.2023.0336>
- [15] Zanker, K. (1998). The effects of Reynolds number, wall roughness, and profile asymmetry on single- and multipath ultrasonic meters. XVII International North Sea Flow Measurement Workshop.

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