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Development of clump-on sonar flow meter using symmetry channel model

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Abstract. In connection to methods developed for determining of “liquid–gas” volume-mass parameters, research has been carried out by a group of scientists from South Ural State University and University of Dundee, where the current manuscript presents a new method for measuring a liquid and gas flow rate. Method able to measure a turbulent flow convective velocity through the pipeline wall and volumetric flow rate of a liquid and gas. A brief description of G. Taylor’s “frozen turbulence” hypothesis is given on the basis of which the method works. Main scientific problems associated with its proof in relation to the problem of determining the convection velocity of turbulence are identified. Mathematical modeling was performed in the CFD computational fluid dynamics package using the hybrid eddy-resolving turbulence model SBES to determine an optimal configuration of the experimental setup. This model contains 2-D symmetry domain to decries simulation time. In this article describe correlation between 2-D symmetry model and full-scale tests. Result of experimental tests are presented. Therefore, novelty of this investigation is noninvasive method for flow measurement and experimental confirmation that it works.

Keywords: Non-invasive sonar flowmeter / symmetry flow channel: turbulence convection / frequency-wavenumber spectrum / eddy-resolving turbulence model / volume flow rate

1 Introduction

The most important issue in fluid and gas dynamic is to determine the turbulent flow characteristics by acoustic signal parameters. Turbulence is a complex physical process and currently has many unresolved issues. One of them is the mathematical description of the dissipation process of turbulent vortices in a boundary layer.

From a practical side, the study importance is due to modern trends in instrument engineering aimed at energy efficiency and cost reduction. Currently, non-invasive methods for measuring the flow rate of liquid and gaseous in pipelines have become widespread. This is the next stage in the measuring instrumentations.

One such promising device is a clamp-on sonar flow meter, which determines the flow rate based on the characteristics of turbulent vortices in a boundary layer. The proposed technology makes it possible to decide on the parameters of a turbulent flow in a boundary layer through a solid wall, including measuring the volumetric flow rate of liquid, gaseous and multicomponent media without inserting into a pipeline and without interfering with the flow. The developed apparatus increases safety because there is no damage to the pipeline from inserting a flow meter and reduces losses during product transportation since there is no obstruction to the flow. Additionally, it is possible to reinstall flow meters on different sections of the pipeline without stopping the flow and does not require stopping the process during verification.

The main problem in creating a clump-on sonar flow meter is a mathematical method for processing the output signal. This method makes it possible to isolate a useful signal from a set of noise coming from the sensors and determine the phase velocity of moving vortex fields that correspond to the flow velocity of the medium in the pipeline. After that, the volumetric flow rate is calculated from the flow velocity.

To date, this technology is being studied by a scientist from the US, Dr. Daniel L. Gysling. He has several scientific publications [1,2] and patents for inventions [3] which describe the possibility of measuring convective flow velocity through a solid wall using piezo-film sensors. At

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the same time, there is no clear description of the physical process based on which this measurement method is implemented, as well as a detailed description of the signal processing method. It is only known that the flow measuring method is based on J. Taylor's hypothesis about "Frozen turbulence" while the signal processing methods and parameters of this physical phenomenon are not disclosed. However, based on his patents, two companies Cidra and Expro offer flow meters on the market that operate on the above principle.

Sonar-based clamp-on flow meters have emerged as a robust technology for measuring volumetric flow rates in various industrial applications, including pulp and paper, oil and gas, and chemical processing [4]. These meters utilize an array of sensors to detect and interpret pressure fields within pipes, employing two main techniques: tracking turbulent eddies and comparing acoustic wave propagation speeds. The technology can measure both single and multiphase flows, providing accurate volumetric flow rates and compositional information such as entrained gas content in liquid-continuous mixtures [5]. Recent developments in ultrasonic clamp-on flowmeters have focused on addressing uncertainties caused by flow profile distortions and pipe wall conditions, using numerical simulations and experimental validations to improve accuracy [6]. These non-intrusive, clamp-on devices offer ease of installation and lower operating costs, making them increasingly attractive for industrial and residential applications [5,6]. Where on one hand, a transit time ultrasonic flowmeter has been reported that uses a symmetry channel model to estimate the velocity profile and compensate for swirl, improving flowmeter accuracy [7], on the other hand, most recently, a computational fluid dynamics analysis has been used to compensate for flow disturbances in ultrasonic clamp-on flowmeters [8]. The average rate of fluid flow without requiring flow-disturbing devices has been measured sing an ultrasonic flow meter using cross-correlation technique [9]. In the book of TsAGI professor Dr. A. Yu. Golubev's [10] presents existing methods for near-wall pressure pulsations representation in the frequency-wave spectra but there is no description of methods for measuring pressure pulsations through the wall and filtering the received signal.

In connection with the above, the creation of a method for determining the turbulent flow parameters from the acoustic signal values and a device for determining the volumetric flow rate based on it is an urgent task.

2 Method of non-invasive flow measurement

In the proposed method, the physical carrier of the useful signal is turbulent vortices located in the boundary layer [11]. They are transported at an average flow velocity as they move downstream. The vortices pulsate as they move along the flow and break up into smaller components.

The method is based on Taylor's "frozen turbulence" hypothesis [12], which states that the convection speed of turbulent eddies Uc does not depend on the pulsation component $u'(t)$ and is equal to the average flow velocity. Therefore, knowing the vortex pulsation frequency $-$ f и and wave number $-$ k it is possible to determine the velocity of turbulent convection (1) or phase velocity.

$$U_c = \frac{f}{k}, \tag{1}$$

The signal source uses vortices moving in or near the boundary layer in a turbulent flow, which can be defined as the instantaneous pressure value (2):

$$P(x,t) = P(x) + p(x,t), \tag{2}$$

where $P(x)$ $-$ static pressure, $p(x,t)$ $-$ a centered function describing pressure pulsations random in space and time, which in turn can be represented as a sum (3) hydrodynamic $p(x,t)$hd, acustic $p(x,t)$ac and other components of pulsation pressure $p(x,t)$ other.

$$p(x,t) = p(x,t)_{hd} + p(x,t)_{ac} + p(x,t)_{other}. \tag{3}$$

To measure volumetric flow rate a useful signal source is the hydrodynamic component $p(x,t)_{hd}$ of the pulsating pressure since vortex convection occurs precisely in this part of the signal. The useful signal $-$ hydrodynamic pressure pulsation $-$ is separated from other signals using wavelength and frequency band filters. However, reading the signal at a point is not enough, because to calculate a convection velocity it is necessary to determine parameters of converting vortex, such as the vortex pulsation frequency $-$ f and its wave number $-$ k. For this purpose, spatial spectral processing is used. Useful signal is located in frequency band from 10 to 500 Hz and wavenumber band from 0.001 to 30 (1/meter).

In accordance with the above, method [13] is presented in the form of a functional diagram in Figure 1. The source of the useful signal is the turbulent vortices pos. 1 convecting in the flow of the measured medium. Signals received from sensors pos. 2 are subjected to spatial (wave) filtering then frequency (bandpass). After that to the input of K-Omega signal processing module pos. 3 a filtered signal is received from all sensors simultaneously. It is containing the values of pressure pulsations of turbulent vortices $p(x,t)_{\underline{hd}}$ in the convective part of the spectrum, where it is subjected to frequency-wave processing according to dependence (4).

$$S(k,f) = \frac{1}{MN}\sum_{m=0}^{M-1}\sum_{n=0}^{N-1} p(x_m, t_n) e^{-i2\pi\left(\frac{f_n t}{N} + \frac{k_m x}{M}\right)}, \tag{4}$$

where S $-$ frequency-wavenumber spectrum, k $-$ wave number, f $-$ frequency, N $-$ samples number, M $-$ sensors number, p $-$ set of signals (two-dimensional matrix) from sensors after filtering, n $-$ rows, m $-$ columns, x $-$ distance between sensors, t $-$ time.

Based on the signal processing results, two-dimensional frequency-wave spectra are constructed pos. 4. Each point lying at the top of the front determines the convection velocity for certain vortex or turbulent scale. Thus, it is possible to determine the convection velocity of a vortex field in flow and not of an alone wave. To do this, a linear approximation of convective ridge is performed values and

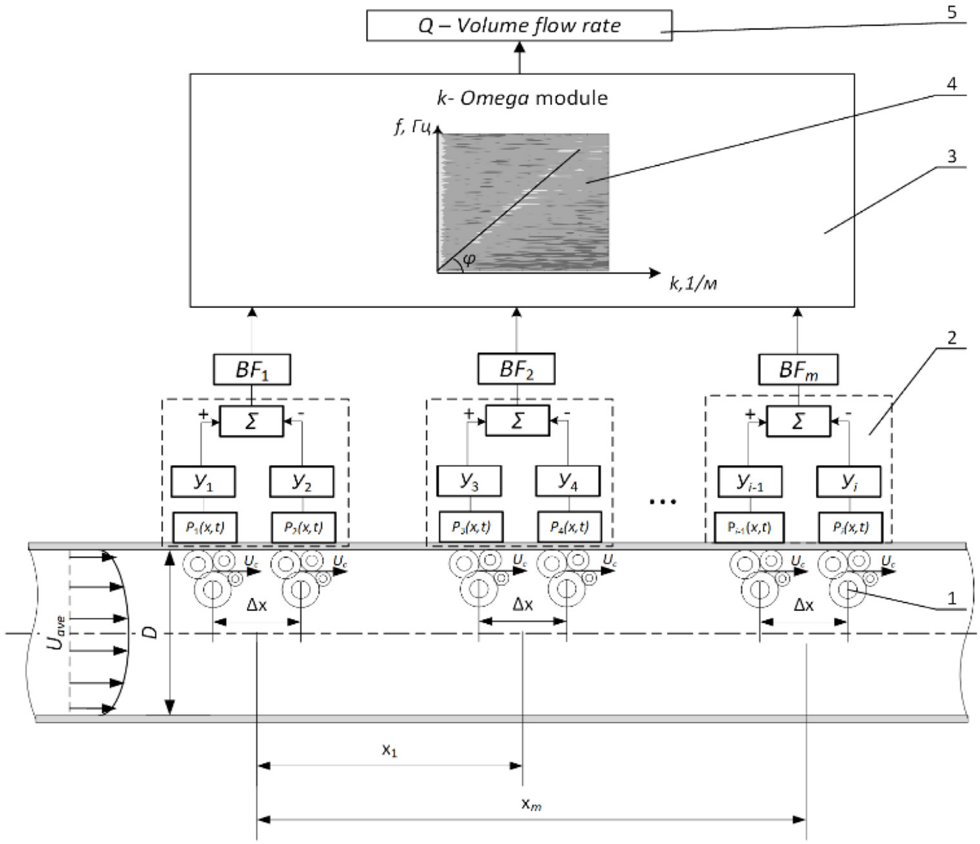

Fig. 1. Functional structure of the non-invasive flow measurement method.

the line inclination angle φ Angle values are transferred to the module pos. 5, where the convection velocity of vortexes U_c. can be calculated. Knowing the convection velocity, it is possible to calculate the average flow velocity Uave through the transfer coefficient γ and from the average flow velocity calculate the volume flow rate Q (5). The transfer coefficient γ is determined from the experiment or CFD calculation. When the average flow velocity is specified and the convective velocity is measured.

$$Q = \frac{U_{ave}\pi D^2}{4} = \frac{\gamma U_c D^2}{4} = \frac{\gamma \pi D^2 \tan(\varphi)}{4}. \quad (5)$$

This is how the non-invasive method of volumetric flow rate determination of liquid and gas in a pipeline works based on spatial-temporal filtering and frequency-wave-number signal processing.

3 Numerical simulation using symmetry flow channel model

In order to check the method performance and reduce the number of parasitic parameters affecting the result, a simulation model of a clamp-on sonar flow meter was built.

Numerical simulation was performed in a two-dimensional symmetry state in the ANSYS CFX software. The computational domain is a flat channel 1 meter long, 14 millimeters high with specified symmetry conditions [14]. This simulates a flat channel of infinite width [15]. This makes it possible to obtain fluid flow along a flat surface. Turbulence model SBES (scale-based eddy simulation) [16] model allows simulating turbulent pulsations of pressure and velocity in a flow without averaging them completely. The result is a pulsating flow and does not require a high-density mesh in coordinates parallel to the channel wall as for the LES turbulence model. Additionally, it should be noted that the model does not have a pipeline wall unlike the full-scale prototype. There are no vibrations, wave reflections and other physical phenomena that affect the quality of the result. The model contains 36 points for recording the amplitude of pressure pulsations over time, located along the channel axis with a step of 3 millimeters. This achieves maximum resolution of pressure pulsation fields along the wavelength (wave number – k).

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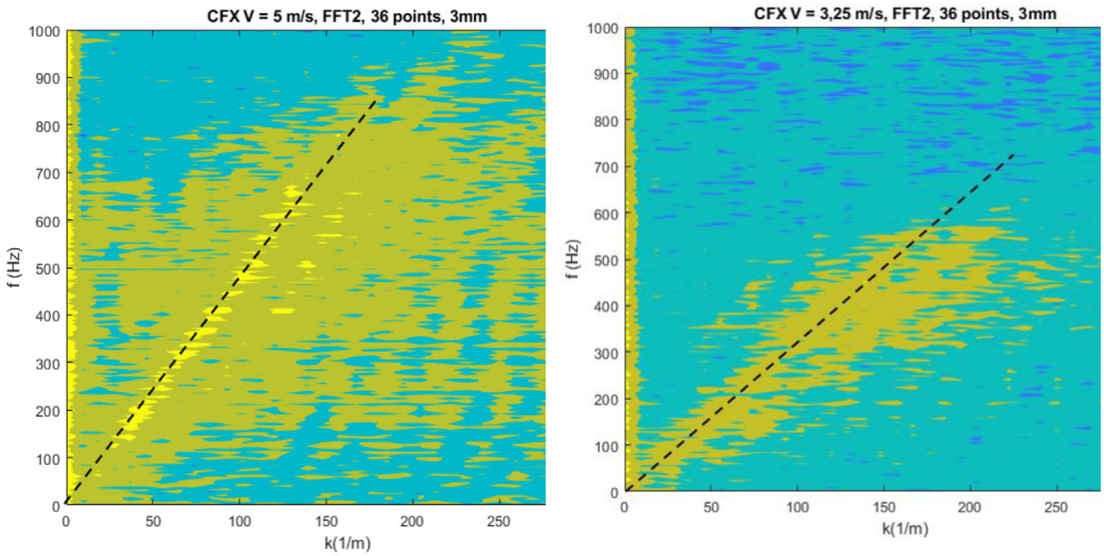

(a) **(b)**

Fig. 2. Frequency-wavenumber spectrum determining the phase velocity of movement of turbulent vortexes.

This simulates a flat channel of infinite width [15]. This makes it possible to obtain fluid flow along a flat surface. We used 2D planar channel rather than an axisymmetric model because axisymmetric model is two-dimensional, and we used a flat channel model with a thickness of one cell and symmetry conditions. This is due to the fact that the pulsations of turbulent vortices are three-dimensional and eddy-resolving turbulence models work only in a three-dimensional formulation. Turbulence model SBES (scale-based eddy simulation) [16] model allows simulating turbulent pulsations of pressure and velocity in a flow without averaging them completely. The result is a pulsating flow and does not require a high-density mesh in coordinates parallel to the channel wall as for the LES turbulence model. Additionally, it should be noted that the model does not have a pipeline wall unlike the full-scale prototype. There are no vibrations, wave reflections and other physical phenomena that affect the quality of the result. The model contains 36 points for recording the amplitude of pressure pulsations over time, located along the channel axis with a step of 3 millimeters. This achieves maximum resolution of pressure pulsation fields along the wavelength (wave number – k).

Calculations were performed for two fluid flow velocities 5 and 3.25 m/s. During the simulation process, for each calculated case 5000 readings (samples) were recorded with a time step of 0.0005 s. For example, for a speed of 5 m/s the pressure pulsation is 40 Pa.

Based on the processing results using the above algorithm, two-dimensional frequency-wavenumber spectra were constructed (Fig. 2). On which the convective rige is clearly visible and angle of its inclination corresponds to the average flow velocity in the channel. If we divide the frequency value by the wave number for a point lying within boundaries of the convective rige, we obtain the free-stream velocity. For example, $200\,\text{Hz}/40(m-1) = 5\,\text{m/s}$, which corresponds to the inlet velocity specified in the simulation 5 m/s. The convective rige behaves similarly for the velocity 3.25 m/s but its inclination angle is less.

Thus, based on the simulation results using symmetry 2D model, it was established that the proposed method for determining the volumetric flow rate works.

However, in real conditions it is not possible to install sensors at a distance of 3 mm. Therefore, the small wavenumber bandwidth is compensated by the number of sensors and an increase in the number of time steps (samples).

5 Development of experimental prototype

5.1 Sensor device for clamp-on flow meter

The mechanical part of the clamp-on flow meter (Fig. 3) consists of a casing pos. 1 and clamp pos. 2. The clamp consists of ten sections pos. 2 one strip pos. 3 and four spacers pos. 4.

The section is made in two halves. One of the halves is made with rectangular holes intended for the output of wires installation and positioning of sensitive element with sensitivity 1 volt per micro strain. A strip is installed on this half with rectangular holes intended for mounting and connecting a sensitive element – piezo film. The structure is held together with screws.

The design was created to solve the following issues:
- ensuring fixation and tight pressing of a sensitive element – piezo film to outer wall of a pipeline.
- analog-to-digital converter board placement.
- EMI protection.

The assigned issues are solved by the fact that the sensitive element – piezo film pos. 5 is installed through the holes in a clamp pos. 2 and clamp provides fixation and

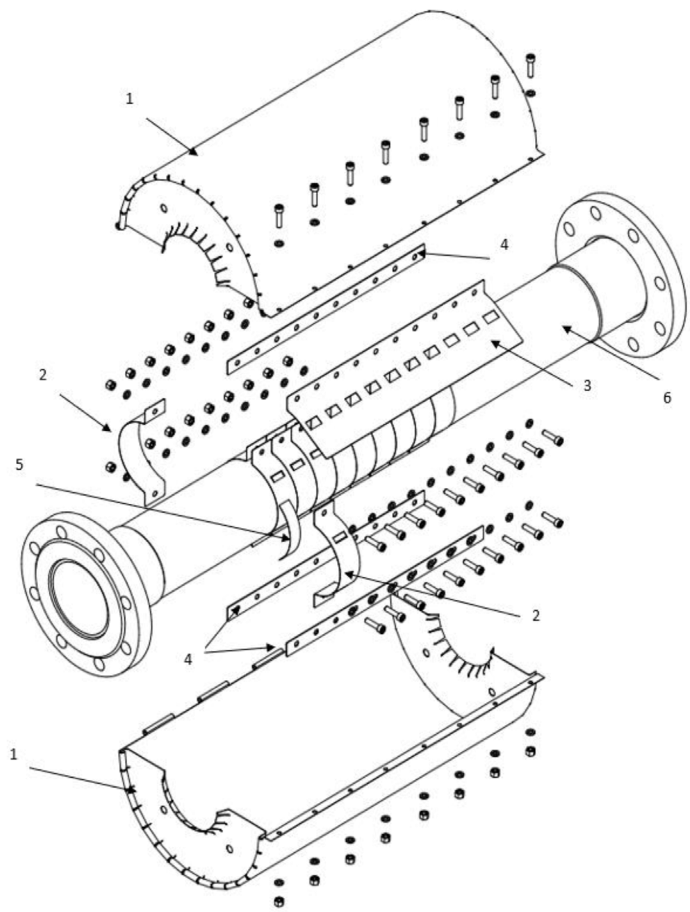

Fig. 3. Mechanical part of clamp-on flow meter.

tight pressing. The control electronics are mounted on the bar pos. 3 and connects to the sensitive element pos. 5. On the pipeline (flow part) pos.6, at the installation site of the device, a casing pos.1 is installed on top of the clamp to protect against the influence of electromagnetic interference.

The developed design [17] protects the useful signal from interference, allows the electronics to be placed in close proximity to the sensitive element and tightly fixes. The pipe wall thickness and the roughness of the inner wall affect the signal quality. For example, as the thickness of the pipe wall increases, the amplitude of the useful signal will decrease.

5.2 Pre-processing block

Purpose of the pre-processing block (PB) (Fig. 4) is to improve the quality of processing analog signals from the sensors of a clamp-on sonar flow meter.

The problem is solved by taking analog signals from the sensors, amplifying and filtering them. Firstly, removing long-wave acoustic components of pressure pulsations, then filtering out the high-frequency component of the signal. After filtering, the remaining part of a signal is subjected to further processing. The design of the pre-processing block includes analog signal sensors, each of

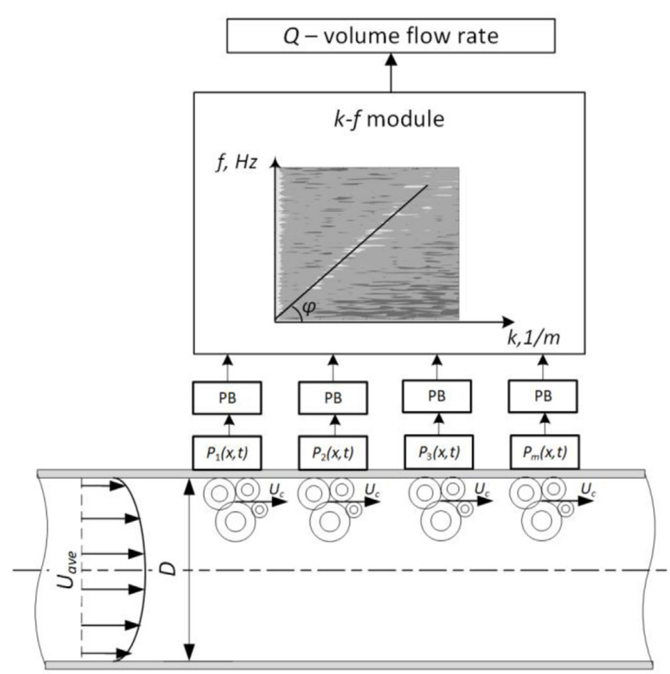

Fig. 4. Pre-processing block on the functional scheme of a clamp-on sonar flow meter.

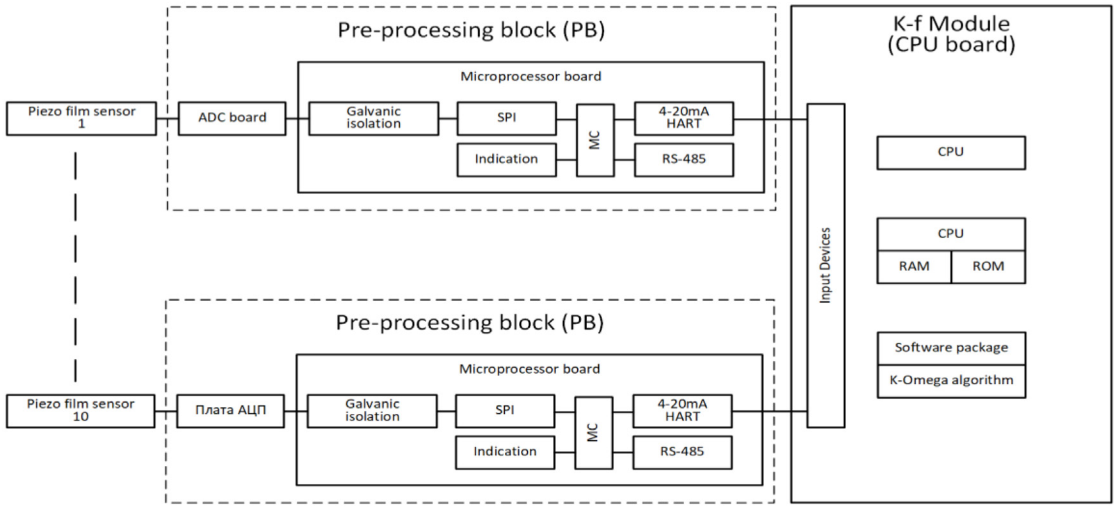

Fig. 5. Functional structure of the clump-on sonar flow meter "K-Omega P1".

which is connected to an amplifier associated with a filtering element connected to a filtered signal processing module.

The operating principle of the pre-processing block (Fig. 5), according to the functional diagram, is as follows. The piezo-acoustic sensor is connected to an analog-to-digital conversion (ADC) board, in which the signal is amplified, filtered by frequency, and analog-to-digital conversion is performed. The microprocessor board receives the digital signal value via the SPI interface with a specified sampling frequency of 5 kHz. Next, measured values are accumulated and transmitted in packets via the RS-485 interface for subsequent digital processing in the k-omega module using above algorithm.

The design contains 10 sensors, respectively 10 amplifiers with ADC. As a temporary solution, a microprocessor board and an indication board are used for each sensor. The minimum number of time points is 4096 and space points is 8.

5.3 K-Omega module

The K-Omega module is designed to calculate volumetric flow, namely:

- recording signals from a set of sensors into a two-dimensional matrix.
- signals normalization from sensors.
- filtering by wavelength.
- filtering by frequency band.
- performing frequency-wavenumber processing and constructing a two-dimensional turbulent spectrum.
- calculation of volumetric flow.

The functional structure of the K-Omega module is shown in Figure 5. The module contains: a central processor, RAM and ROM, input devices for connecting a pre-processing unit. Control software and higher-level software for calculating volumetric flow rate are also available.

The input parameter is a two-dimensional numerical array containing a signal filtered by wavelength and frequency, accumulated over a certain period of time. Each array column corresponds to one sensor. Next, each column of array is normalization and transferred to a frequency processing, where spectral processing is performed by the Fourier transform for each column of array. Then the array enters the wave processing cycle, where wave spectral processing is performed using the Fourier method.

To represent correct frequency-wave spectra, the dimensions of frequency and wave number are determined using the Nyquist criterion.

After that, a two-dimensional frequency-wave graph is constructed. It is show convective maximum is clearly visible. Slope of which determines the convection velocity of turbulent vortices and the volumetric flow rate, respectively.

6 Testing of the experimental prototype

The tests were carried out on the METRAN-UPA-2000 flow stand. The installation was put into operation in 2016 and found to comply with the requirements for the secondary standard. To determine sensitivity provided by device at various flow rates, tests was performed at five flow velocity from a maximum of 10 m/s to a minimum of 1 m/s.

The prototype contains 10 piezo-film sensors, so after wave filtering, 9 points enter spectral processing.

The signals were recorded on a laptop for subsequent processing using a wave-frequency processing algorithm.

For processing, 10 thousand samples were taken with a recording interval of 0.0002 s. Signal recording time is 1s and the maximum frequency is 5 kHz.

Based on the test results, five two-dimensional contour graphs were constructed corresponding to the specified flow velocities. Flow velocities and volumetric flow rates are respectively calculated from the slope of a trend line

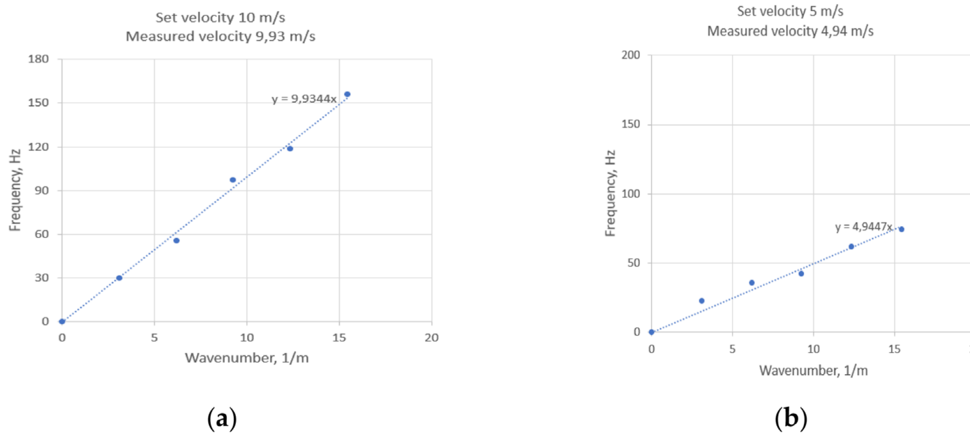

Fig. 6. Test results.

Table 1. Tests results.

Flow rate. м^3/ч	Measured velocity. m/s	Measured flow rate. m^3/h	Reference accuracy. %
283	9.93	281	–0.8
226	7.85	222	–1.5
141	4.94	140	–0.5
84.8	9.48	268	65
28.3	9.10	257	81

constructed from the maximum points of the frequency-wavenumber spectrum. During signal processing, bandpass filtering was applied to remove noise in order to more accurately determine the slope of the convective ridge.

As can be seen from the test results at flow velocities of 10, 8 and 5 m/s, a convective ridge is clearly observed (Fig. 6), which corresponds to the flow velocity (shown by the dotted line). At lower flow velocities of 3 and 1 m/s, the picture is not as clear as for 10, 8 and 5 m/s.

This is due to several factors. The main reason is the presence of noise in the low-frequency region of the spectrum, where the convective ridge is located at low flow rates. The noise is caused by 50 Hz network noise. The second reason for unclearly representation of the convective ridge is the decrease in the vortex flow energy as the flow velocity decreases.

Table 1 presents the measurement results. From the results it is clear that the flow rates are close to the specified ones at velocities of 10, 8 and 5 m/s, but at 3 and 1 m/s do not correspond to the reference ones. Tested clamp-on sonar flowmeter measures volumetric flow rate.

The given error at high and medium flow rates is ± 1.5%, at low flow rates the value was 81%.

7 Conclusions

Symmetry channel numerical model is two hundred times faster than on a 3D one without loss accuracy and quality results. It is confirmed experimental test results.

As part of research, a clamp-on sonar flow meter prototype was created. It is containing 10 piezo-film sensors, pre-processing block and a module for calculating volumetric flow rate.

Based on the tests results of an experimental prototype, it was established that the developed mathematical method makes it possible to determine the volumetric flow rate of liquid and gas in a pipeline using space-time filtering and frequency-wavenumber signal processing. The source of useful signal is turbulent vortices that convect in a measured medium flow.

Thus, validity of J. Taylor's hypothesis of "frozen turbulence" for determining the convective ridge in a pipeline through a solid wall was confirmed. At the same time, further research is required to determine the limits on minimum flow rate at which the hypothesis will be valid.

However, prototype cannot provide error of ±1.5% over a dynamic range of 1:10. This is due to the presence of electrical noise, non-synchronous recording of signals from piezo-film sensors and a decrease in the energy of pulsating vortices as the flow speed decreases.

The developed solution increases safety, since there is no damage to the pipeline from inserting a flow meter, and reduces losses during product transportation, since there is no obstruction to the flow.

The developed method and device will find wide application in the oil and gas industry, mining, chemical and metallurgical industries. This device can measure the speed of sound by using an acoustic ridge to calculate the speed of sound, similar to how a convective ridge is used to calculate convective velocity. Therefore it is possible to measure the flowrate of components within a multiphase flow using the device being described in this manuscript. Flow rate can be measured through a non-metallic pipeline, such as plastic.

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Conflicts of interest

The authors report there are no competing interests to declare.

Data availability statement

Data will be made available on reasonable request.

Author contribution statement

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Aleksei Krivonogov. The first draft of the manuscript was written by Pavel Taranenko and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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