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Imitation Modeling of the Flow Control Information System Elements

Kirill Gudkov
Department of Information Technologies and Systems
Penza State Technological University
Penza, Russia
gudkovk.pgta@gmail.com

Kirill Piskaev
Department of Information Technologies and Systems
Penza State Technological University
Penza, Russia
piskaevk@gmail.com

Tatyana Zhashkova
Department of Information Technologies and Systems
Penza State Technological University
Penza, Russia
chm-77@mail.ru

Marina Chirkina
Department of Information Computational and Systems
Penza State University of Architecture and Construction
Penza, Russia
chm-77@mail.ru

Abstract—**A number of issues related to the construction of an information processing system in a Coriolis flow meter using simulation models are considered. The paper presents simulation models of a straight-tube Coriolis flowmeter built in a Matlab/Simulink simulation environment. A simulation of the operation of the flow meter under various conditions of the flow of a liquid medium was carried out, and external vibration effects were simulated on both the flowmeter and its pipeline elements. On the basis of the obtained experimental data, the parameters of the data processing system were selected. The problems of the influence of external influences and ways to eliminate it are considered. In addition to external influences that adversely affect the accuracy of measurements, various physical limitations determining the maximum achievable accuracy of Coriolis flowmeters are analyzed. The processes of dynamic changes in the physical properties of bodies related to their molecular structure are considered, as well as technical and technological processes that can make changes to the accuracy parameters of a measuring device due to the variation of parameters of structural elements.**

Keywords—information system; data acquisition module; simulation; Coriolis flow meter; model-oriented design

I. INTRODUCTION

In modern technically complex systems, the debugging and verification process plays a special role. For this purpose, expensive prototypes are used. In addition, the design time is significantly increased, and the existing shortcomings and errors are detected only at the final stages. To solve this problem, it is advisable to use simulation at the design stage of individual components of the systems. Further, the developed models of individual parts of the system are combined with each other to debug their interaction. Such an application of simulation modeling is known as model-oriented design.

A separate class of technically complex systems is information-measuring systems of physical quantities of precision accuracy. In particular, control systems for the flow of liquids or gases based on Coriolis flow meters. The development of such a system using model-oriented design methods includes simulation modeling of the mechanical and electronic computational parts of the flowmeter [1-3].

These flowmeters have one or more flow tubes of a straight or curved configuration. Each configuration of the flow tube in a Coriolis mass flow meter has a set of its own vibration modes [4, 5], which can be of the type of simple bending, torsion, or mixed (connected) type. Each flow tube is driven to oscillate at resonance in one of these modes. Fluid flows into the flowmeter from the adjacent pipeline on the inlet side, is directed to the flow tube or pipes, and flows from the flowmeter to the pipeline connected to the outlet side of the flowmeter. The intrinsic vibration modes of a vibrating (oscillating) fluid-filled system are determined in part by the combined mass of the flow tubes and the material inside the flow tubes.

When there is no flow through the flow meter, all points along the flow tube oscillate in the same phase as a result of application of the excitation force. But as soon as the flow of material begins to flow, Coriolis accelerations lead to the appearance of different phases for each point along the flow tube [6, 7]. The phase on the inlet side of the flow tube has a delay relative to the excitation phase, while the phase on the outlet side is ahead of the excitation phase. On the case of the flow tube sensors are placed for generating sinusoidal signals carrying information regarding the movement of the flow tube. The phase difference between the two sensor signals is proportional to the mass flow rate of the material flowing through the flow tube.

Measurements in a Coriolis mass flow meter should be carried out with a high degree of accuracy, since it is often necessary that the obtained information on the mass flow has an accuracy of at least 0.15% of reference [8]. The signal processing unit, which receives the output signals from the sensors, measures the phase difference with high accuracy and produces the desired characteristics of the flowing processed material with the required accuracy, which is at least 0.15% of reference.

To achieve this accuracy, it is necessary for the signal processing unit to measure the phase shift of two signals with high accuracy, which come to it from the flow meter [9,10]. Since the phase shift between the two outputs of the measuring device is information that is used in the processing unit to obtain material characteristics, it is necessary that the processing unit does not add any phase shift that could mask the information phase shift created by the output signals of the sensor. In practice, it is necessary for this processing unit to have an extremely small intrinsic phase shift, so that the phase of each output signal shifts by less than 0.001% [11], and in some cases even less than a few millionth of a degree. The specified accuracy of the phase measurement is required if you need to achieve an accuracy higher than 0.15% for derived information regarding the material being processed..

II. MATERIALS AND METHODS

We chose MATLAB/*Simulink* as a simulation environment. It allows you to simulate both the mechanical components of the system and the system for collecting and processing information.

Let's consider the Simulink model of the mechanical part of the system. It allows you to explore the measurement of fluid flow parameters under various dynamically changing conditions. The flow rate of the fluid is directly proportional to the time delay between the left and right halves of the flow tube. The delay occurs due to the Coriolis force, which occurs during the oscillation of the flow tube with the fluid flowing in it. The direction of the Coriolis force in the left and right half of the tube is directed in opposite directions [3,12]. The coefficient of proportionality for each flowmeter depends on the mechanical properties of the pipe, the effect of the oscillatory mechanism and the transfer functions of the measuring transducers [3].

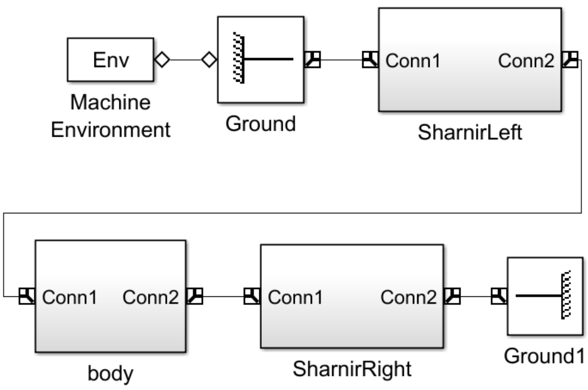


Fig. 1. Coriolis flow meter model

We describe in more detail the constituent parts of the model: *Sharnir Left* and *Sharnir Right* are the left and right hinges, respectively. They make the flow tube movable with respect to rigid *Ground* fittings, so that the pipe edges can only be moved in the *Ox* axis.

Let us consider in more detail the *Body* subsystem which includes the flow tube and pressure sensors (Fig. 2).

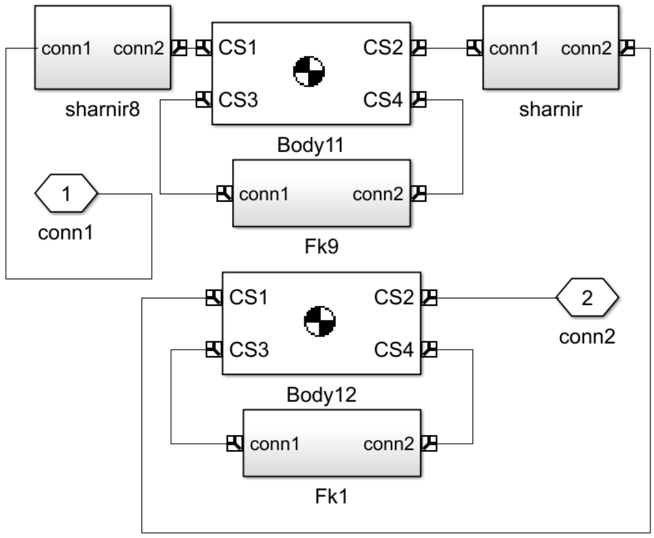


Fig. 2. Flow tube and sensor model

To describe the tube oscillations, we accept the restriction that does not allow oscillations to occur except for the vertical plane. In real flowmeters this is achieved by proper installation and calibration. The presence of lateral vibrations reduces the accuracy of measurement of flow parameters. Another limitation is the discreteness of the flow tube. This is due to the inability to accurately describe oscillatory processes by means of *Simulink*. Physical bodies are represented by absolutely solid elements with the possibility of an elastic connection between them. To circumvent this limitation, the pipe is represented by a finite set of small elements, the increase in the number of which allows bringing its mechanical properties closer to actual prototypes. For this, the parameters of the elastic compound are chosen empirically. In Fig. 2, two subsystems are demonstrated, including sets of blocks with imitations of a tube and a flowing fluid. The parameters of the tube include stiffness, damping properties, the weight of the tube, its deflection under its own weight and the presence of deposits that affect the diameter of the internal cross section and the mechanical characteristics of the object of modeling. The parameters of the fluid include density, velocity and temperature. The change in the parameters of the fluid causes a change in the parameters of the Coriolis force calculated in the same subsystems for each tube segment. The calculation of the Coriolis force is also influenced by the parameters specified by the forced vibration simulation unit. This block is shown in Fig. 3.

In the *Fcn* block, the initial parameters of the flow tube oscillation are set. During the simulation, they may change as the oscillation frequency corresponds to the resonant frequency of the tube filled with liquid. Depending on the oscillation frequency, the density of the fluid is calculated. In Data Store Write and Data Store Memory blocks, instantaneous flow rates are recorded and stored in memory to use it to calculate the Coriolis force. In the *Subsystem* block, the time delay values between the input and output signals are calculated. They are used as reference values when checking data obtained from simulation models of pressure sensors, in the simulation of which metrological and physical parameters were taken into account, namely, its dimensions, mass, elasticity of the sensitive element, maximum deflection and others. In the model, the stiffness and damping properties of the force measurement system were selected to implement the speed and sensitivity of the sensor. *Scope* reflects the simulated signal in timeline.

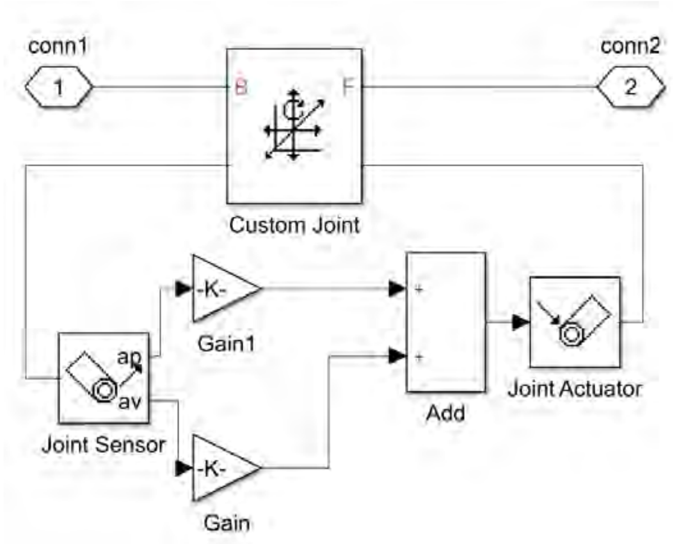


Fig. 3. Simulink model of the physical parameters of the tube

III. RESULTS

Let's perform a flow meter simulation using MATLAB/Simulink tools. To do this, we perform modeling based on an approximate mapping of a flexible body by a sequence of rigid bodies interconnected by spring and cushioning elements. Spring stiffness and damping coefficients are described by the functions of material properties and the geometry of flexible elements.

The modeling procedure should be divided into five stages:

1. The pipe is divided into discrete elements, and the degrees of freedom of each element are determined.

2. The degrees of freedom are given by means of connections in the middle of each element along the neutral axis.

3. According to the theory of a flexible body, the effective constants of the spring geometry, material properties and boundary conditions are determined.

4. Set the damping properties of each compound.

5. The resulting elementary segments are interconnected.

In this model, we simulate a thin-walled tube made of aluminum with a diameter of 60 mm. The operating frequency of the flow meter oscillations will be 350 Hz, the amplitude is 10 microns, which is a typical frequency for flow meters of similar sizes. The flow of fluid is simulated by measuring the mass of the elements of the tube and the effects on the blocks, calculating the influence of the Coriolis force; the remaining processes occurring in the pipeline as the fluid passes through it are not simulated. In the model, the parameters of the tube motion, the initial flow rate are set, the Coriolis force and its influence on the oscillation shape of the flow tube are calculated. In addition, the density and volume of water, the density and size of the tube, the damping coefficient and the stiffness of the hinges are specified.

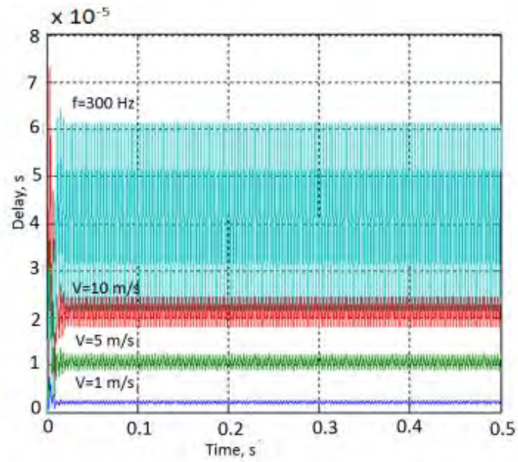
The angle of rotation, the relative angular velocity, the stiffness coefficient, the damping coefficient, and the force action between the elements are specified between the connecting elements.

The stiffness and damping coefficients are set in accordance with the calculated values of the tube deflection under the action of test forces.

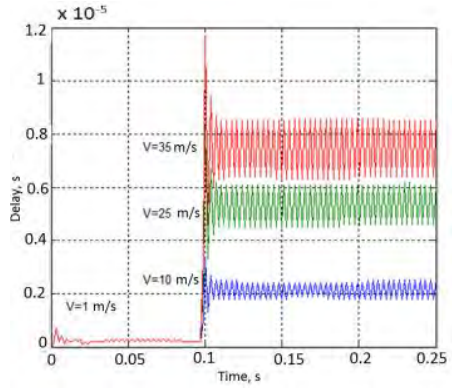
The model allows measuring the vector of projections of the absolute angular velocity of the point of the body to the port of which it is attached.

Let's perform a simulation of the liquid medium flow with different flow rates to establish the linearity of the model readings. Testing was conducted at speeds of 1 m/s, 5 m/s, 10 m/s. To analyze a fast-changing flow, we will model a fluid flow with a sinusoidal change in velocity (amplitude is 10 mm, frequency is 350 Hz). We also investigated the behavior of the system in the presence of a step change in the velocity of the liquid. The experiment results are presented in Fig. 4.

From the plots it can be seen that the noise component increases with increasing flow rate. This can only be due to the inaccuracy of the calculation of the time delay between parts of the pipe. In this case, the values lie within the same range and can be successfully averaged. Analysis of the sinusoidal input signal shows that the system manages to react to a periodic change in the fluid velocity. The amplitude of the output signal is constant and does not have significant deviations or heavily distorted results. When there is a step change in the flow velocity in the system, residual velocity oscillations are observed over a small time interval, but this results in output signal oscillations at a constant flow rate.



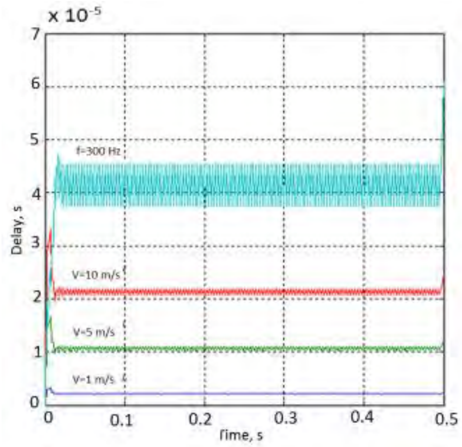
a



b

Fig. 4. Plots of the delay between two signals obtained from pressure sensors on the initial flow rate: a) constant flow rate, b) step change in the flow rate

Let's filter the obtained simulation results to improve the visibility of them. The results are presented in Fig. 5.



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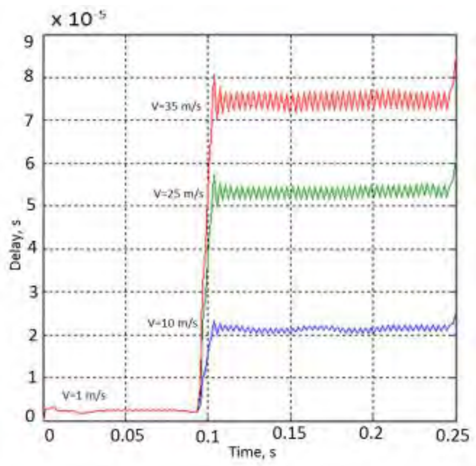

b

Fig. 5. Averaging the values of the delay between the two signals obtained from the pressure sensors depending on the initial flow rate: a) constant flow rate, b) step change in the flow rate

Due to the process of averaging the values, the roughly distorted measurement results were gotten rid of. The plots have become smoother. You may also notice that the higher the flow rate in the pipe, the greater the delay value. The time intervals difference between signals is measured in microseconds.

The measured flow is almost never perfect, most often it is influenced by external factors, for example, low speed, non-formation and pulsation of flow, roughness of the pipeline, multiphase environment (presence of air in water, presence of water in the steam), existence of mechanical impurities. Fig. 6 shows the plots where the fluid flowing through the pipeline is not ideal. These plots reflect the delay between two signals obtained from pressure sensors located at opposite ends of the pipe. Testing was conducted at speeds of 1 m/s, 5 m/s, 10 m/s and with noise, with amplitude of 8 mm and a frequency of 350 Hz.

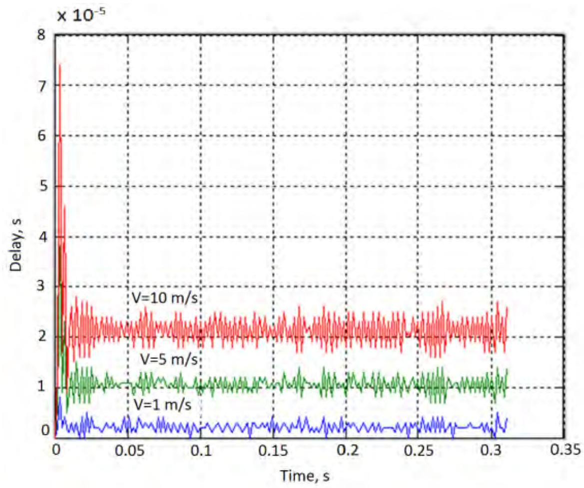

Fig. 6. Plots of the delay between two signals received from pressure sensors

Due to the distorted flow of fluid passing through the flow meter, the measurement result is incorrect. To prevent this, additional filtering is needed (Fig. 7) [13–16]. We apply a band-pass filter that provides suppression of signals outside the informative band, limited by the frequency of the flow meter.

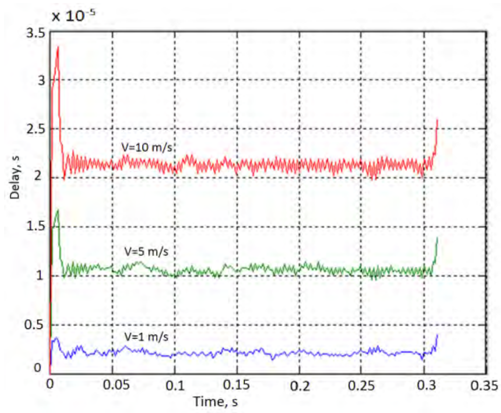

Fig. 7. Filtering delay values between two signals received from pressure sensors

Minor fluctuations are present in the signal. This is due to the coincidence of the operating frequency of the flow meter and the frequency band of industrial noise. In the works [17,18], the ways to eliminate such distortions in the informative signal are given.

From the obtained simulation results, you can calculate the signal-to-noise (SNR) ratio. The signal-to-noise ratio is a dimensionless quantity equal to the ratio of the power of the useful signal to the noise power. Table I shows the dependence of the SNR on the initial flow rate in the noisy and filtered delay values.

TABLE I. DEPENDENCE OF THE SNR RATIO ON THE INITIAL FLOW RATE IN THE NOISY AND FILTERED DELAY VALUES

The value of the initial flow rate, m/s	*SNR* in noisy delay values	*SNR* in filtered delay values
1	48.9955	39.8855
5	76.9414	0
10	89.6763	39.1864

The signal-to-noise ratio in the noisy delay values increases with the initial flow rate hanging, and the signal-to-noise ratio in the filtered delay values is approximately the same

IV. DISCUSSION

The use of a model-oriented approach allows to solve most of the design problems at the modeling stage. But there are a number of limitations. Namely, when creating a mass flow meter, it is necessary to calibrate it in order to reveal the maximum measurement accuracy. The simulation model will always show absolute (maximum for given modeling conditions) accuracy. To eliminate this effect, it is necessary to add a simulated interference into the model and artificially limit the accuracy of measurements. Let us consider in more detail the possible constraints that will adversely affect the accuracy of flow measurement.

Another limitation is sensor calibration. The calibration process includes the verification of sensor readings using working measurement tools. They have the measurement error $\delta_0 = \pm(0.1...0.2)\%$. If the developed sensor has a higher measurement error, then it is necessary to use more accurate working standards. Standards of the second class have the minimum error $\delta_0 = \pm0.15\%$, and the standards of the first class have $\delta_0 = \pm0.05\%$. The following calibration tools are working standards borrowed from other calibration systems. They provide measurement accuracy with an accuracy of $\delta_0 = \pm0.02\%$. The most accurate calibration tool is the primary standard with the error $\delta_0 = 2 \cdot 10^{-4}\%$ [19].

The achievement of the limiting accuracy of measurements is hampered by the presence of errors that cannot be completely eliminated or compensated for. During operation of a Coriolis flowmeter, the measuring tube continuously vibrates at its resonant frequency ω_p. Since the value of ω_p depends on the ratio $\sqrt{(k/m)}$, with constant tube geometries, it is possible to determine the dependence of ω_p on density ρ. In practice, for this purpose only water and air are used. But the density of water is not constant. The density of water varies within $\pm0.0000135 g/cm^3$. This value can significantly affect the sensor reading, causing an error of 0.00135% [19].

There are also significant technical problems in the formation of the flow with the required accuracy characteristics of mass flow and density. Therefore, the non-fulfillment of the condition $k = const$ requires the use of at least one more substance during the calibration process.

In the first approximation, the oscillations of the Coriolis sensor are considered harmonic. Increasing the amplitude of oscillation allows you to more accurately determine the magnitude of the Coriolis force. If the system's rigidity decreases with increasing amplitude, then the oscillating tube has a “soft” characteristic, but if it grows, then the oscillating tube has a “hard” characteristic of a non-linear restoring force. The presence of nonlinearity leads to the fact that terms appear in the differential equation of motion, in which the amplitude contains degrees greater than one. In this case, the replacement $\sin(\alpha) = \alpha$, as in simple harmonic oscillation, is not acceptable. It is necessary to decompose the *sin* φ function in the power 5 series $d^2 \cdot \varphi/dt^2 + \omega_0^2 \cdot \varphi = -e_1 \cdot \omega^3 - e_2 \cdot \varphi^5$. Taking into account the nonlinear terms of the fifth order, the measurement error does not exceed a thousandth of one percent [20], while using the harmonic model, we obtain restrictions on the maximum values of the angles of deflection. The dependence of the angles and the maximum achievable measurement errors are given in Table II.

TABLE II. QUANTITATIVE ESTIMATES OF THE RESTRICTIONS ON THE MAXIMUM VALUES OF THE ANGLES OF DEFLECTION

Maximum deflection angle φ in rad.	sin(φ)	Error (sin(φ) – φ)/sin(φ)
0.024492	0.024489	0.01%
0.077431	0.077353	0.1%

The wide temperature range of the environment and the substance to be measured along with the different influence of each structural element on the temperature error significantly complicates the corrective procedure. It is necessary to take into account not only the absolute temperature of each element, but also its weight, as well as its gradient between all elements. As a result, the measured values are adjusted for the temperature change of the elastic modulus, the mechanical stress of the measuring tube and the density of the flowing material.

It is also necessary to take into account the effect of body temperature on the force of gravity tested by it. Since the increment Δg of the acceleration of gravity in the first approximation is proportional to the acceleration *a* of external elastic forces acting on the body, the magnitude and sign of Δg depending on the direction of the vector *a*. When the elastic forces affect the force of gravity, a necessary consequence is the dependence of the force of gravity applied to the test body on body temperature. When the body temperature changes by 11 K/min, we get a mass change of 3.43 mg/min [21].

It should also be noted that there is a number of reasons, the effect of which on the technical characteristics of the flowmeter can only be taken into account through the average values or not at all. Since the flow meter is installed in the pipeline section, with each installation there will always be a different absolute average value of the mechanical stress of the measuring tube. In addition, the moments of effort, which are attached to the flanges of the flow meter, differ in both the value and the distribution of this moment around the circumference of the flange. Consequently, the suspension on both sides of the flow meter is not symmetrical.

Given that the mount is also not perfectly rigid, i.e. variable forces and moments are not completely extinguished (at the points of attachment no pure vibration nodes are formed), an asymmetric energy exchange with the pipeline occurs. In addition, all changes in the state of the external pipeline (from temperature to vibration) asymmetrically affect the accuracy of the changes.

As already mentioned, the resonant (excitation) frequency is about 300 Hz, i.e. is close to the industrial frequency. Consequently, the entire spectrum of external noise lying in the resonance band is amplified with the same coefficient as the useful signal.

V. CONCLUSIONS

This article is the result of research conducted as part of the state university assignment №2.6581.2017 / БЧ "Models and algorithms for identifying the technical state of complex microsystems using data on changes in the parameters of heterogeneous microstructures".

The models developed within the study showed that external influences make a significant negative contribution to the accuracy of determining the parameters of fluid flow. This drawback is almost impossible to eliminate with the existing methods of digital signal processing, since the frequency of the flowmeter coincides with the industrial noise zone and most of the developments are aimed at increasing the frequency of the flow meter to overcome the upper threshold of the industrial noise zone at 500 Hz [22]. But at this stage of development of engineering and technology, this frequency of the flow meter operation cannot be achieved for all types, sizes and designs of Coriolis flow meters [23,24].

In addition to external influences that reduce the accuracy of measurements, the work considers the physical limitations of the maximum permissible accuracy of Coriolis flowmeters. They are associated with the processes occurring in liquids used in the calibration of flowmeters in laboratory conditions. Technical limitations are also considered, which can significantly reduce the accuracy of the measuring device at its place of operation.

References

[1] R. Schweiger at al. “Methods for calibration of a mass flowmeter for supercritical helium, Advances,” Cryogenic Engineering, 1991, No. 37, pp. 147-154.

[2] W.Q. Yang and S. Liu, “Role of tomography in gas/solids flow measurement,” Flow Measurement & Instrumentation, 2000, No. 11 (3), pp. 237-244.

[3] K. Xu, W. Ni, and Z. Chen, “A signal processing method for Coriolis mass flowmeter based on time-varying signal model and lattice notch filter,” Chinese Journal of Scientific Instrument, 2006, No. 27 (2), pp. 596-601.

[4] W. Ni and K. Xu, “A signal processing method for Coriolis flowmeter based on time-varying signal model and normalized lattice notch filter,” Acta Metrologica Sinica, 2007, No. 28 (3), pp. 243-247.

[5] Y. Tu, F. Su, T. Shen, and H. Zhang, “Frequency tracking method and simulation for Coriolis Mass Flowmeter based on new adaptive notch filter,” Journal of Chongqing University, 2011, No. 34 (10), pp. 147-152.

[6] A. Svete, J. Kutin, G. Bobovnik, and I. Bajsić, “Theoretical and experimental investigations of flow pulsation effects in Coriolis mass flowmeters,” Journal of Sound and Vibration, 2015, No. 352, pp. 30-45.

[7] Q. Hou, K. Xu, M. Fang, C. Liu, and W. Xiong, “Development of Coriolis mass flowmeter with digital drive and signal processing technology,” ISA Transactions, 2013, No. 52 (5), pp. 692-700.

[8] H. Yang, Y. Tu, H. Zhang, and P. Yi, “Phase difference measuring method based on SVD and Hilbert transform for Coriolis mass flowmeter. Chinese,” Journal of Scientific Instrument, 2012, No. 33 (9), pp. 2101-2107.

[9] W. Liu, L. Zhao, K. Wang, Z. Feng, and O. Long, “Signal processing for Coriolis mass flowmeter based on Hilbert transform,” Acta Metrologica Sinica, 2013, No. 34 (5), pp. 446-451.

[10] H.C. So, “A comparative study of two discrete-time phase delay estimators,” IEEE Transactions on Instrumentation and Measurement, 2005, No. 54 (6), pp. 2501-2504.

[11] M. Shanmugavalli, M. Umapathy, and G. Uma, “Smart Coriolis mass flowmeter», Measurement, 2010, No. 43 (4), pp. 549-555.

[12] H. Yang, Y. Tu, and H. Zhang, “A frequency tracking method based on improved adaptive notch filter for coriolis mass flowmeter,” Applied Mechanics and Materials, 2012, No. 128-129, pp. 450-456.

[13] K.-J. Xu and W. Ni, “A lattice notch filter based signal processing method for coriolis mass flowmeter,” Acta Metrologica Sinica, 2005, No. 26 (1), pp.49-52.

[14] N.M. Vucijak and L.V. Saranovac, “A simple algorithm for the estimation of phase difference between two sinusoidal voltages,” IEEE Transactions on Instrumentation and Measurement, 2010, No. 59 (12), pp. 3152-3158.

[15] R. Hall, “Measuring mass flow and density with Coriolis meters,” InTech, 1990, No. 37 (4), pp. 45-46.

[16] S.C. Sharma, P.P. Patil, M.A. Vasudev, and S.C. Jain, “Performance evaluation of an indigenously designed copper (U) tube Coriolis mass flow sensors,” Measurement, 2010, No. 43 (9), pp. 1165-1172.

[17] M.Yu. Mikheev, T.V. Zhashkova, E.N. Meshcheryakova, K.V. Gudkov, and A.K. Grishko, “Imitation modelling for the subsystem of identification and structuring data of signal sensors,” Proceedings of 2016 IEEE East-West Design and Test Symposium, EWDTS 2016, 7807748.

[18] K.V. Gudkov, M.Y. Mikheev, V.A. Yurmanov, and N.K. Yurkov, “Mechanical measurements: a method of automatic verification of coriolis flowmeters,” in the field in Measurement Techniques, 2012, No. 2, pp.151-155.

[19] V.S. Aleksandrov, L.A. Badenko, and V.S. Snegov, “Macroscopic Fluctuations in the Density of Water,” Measurement Techniques, 2004, vol. 47, No. 3. pp. 295-299.

[20] G.D. Khomyakov, A.G. Safin, and N.V. Komissarov, “State Primary Standard of the Unit of Liquid Mass Flow Rate,” Measurement Techniques, 2003, vol. 46, No. 10, pp. 919-923.

[21] A.L. Dmitriev, E.M. Nikushchenko, and V.S. Snegov, “Influence of the temperature of a body on its weight,” Measurement Techniques, 2003, vol. 46, No. 2, pp. 115-120.

[22] M. Pereira, “Flow meters: Part 1,” IEEE Instrumentation and Measurement Magazine, 2009, No. 12 (1), pp.18-26.

[23] M. Yu. Mikheyev, K.V. Gudkov, V.A. Yurmanov, and N.K. Yurkov, “Systems for calibration testing of coriolis flowmeters,” Measurement Techniques, 2012, No. 8. pp. 927-931.

[24] M.J. Mikheev, V.A. Jurmanov, Al V. Kuts, K.I. Volodin, and K.V. Gudkov, “Method of increasing accuracy of testing flow metre,” RU. Patent 2 380 660, 27.01.2010.