ISSN 1068-3372, Journal of Contemporary Physics (Armenian Academy of Sciences), 2022, Vol. 57, No. 1, pp. 20–29. © Allerton Press, Inc., 2022.
Russian Text © The Author(s), 2022, published in Izvestiya Natsional'noi Akademii Nauk Armenii, Fizika, 2022, Vol. 57, No. 1, pp. 30–43.

Gas Flowmeter Based on Vibrating Wires

M. A. Aginian[a], S. G. Arutunian[a], G. S. Harutyunyan[a], E. E. Gukasyan[a], E. G. Lazareva[a, *], A. V. Margaryan[a], L. A. Poghosyan[a], M. Chung[b], D. Kwak[b], and R. Reetz[c]

[a] *Alikhanyan National Science Laboratory, Yerevan, Armenia*
[b] *Ulsan National Institute of Science and Technology, Ulsan, South Korea*
[c] *HTM-Reetz GmbH, Berlin, Germany*
**e-mail: ella.lazareva@yerphi.am*

Received September 9, 2021; revised October 25, 2021; accepted November 9, 2021

Abstract—The paper proposes a new type of gas flowmeters based on measurements of the deformations of the thermal field of the heater in the presence of a flow using vibrating wires. The advantage of such flowmeters as compared with the known ones using a similar thermal principle of operation is the improved accuracy of temperature measurements compared to resistance thermometers or thermocouples. The use of thin wires can also increase the speed of flowmeters. The use of wires 20–30 mm long allows the creation of wide-aperture inlet holes for gas streams. A natural property of the developed flowmeters is also in their bidirectionality. A sample of a flowmeter based on vibrating wires was made and the calibration experiments were carried out. An experiment was carried out in which a flowmeter was used to measure the acceleration.

Keywords: vibrating, wire, flow, air, flowmeter, thermal accelerometry, spirometry

DOI: 10.3103/S1068337222010029

1. INTRODUCTION

In many fields of science and technology, gas flowmeters are widely used. The measurement and separation of gas streams play an important role in the chemical, pharmaceutical, metallurgical, and aerospace industries, pharmaceuticals, ceramics, and many industrial processes. The measurement of gas flows and their dosing is also important in the manufacture of semiconductors, for example, for the organization of plasma deposition processes. To optimize fuel combustion in car engines, accurate air flowmeters are used.Gas flow measurement is important for high-temperature furnaces: the blowing of chambers of heating elements with protective gases, the measurement of exhaust gases generated in heating chambers during thermochemical processes (the exhaust gases can be aggressive, acidic, or alkaline, contain water vapor and dust).A special area of application of flowmeters is medicine, where these devices are used to diagnose certain diseases associated with measuring the patient's breathing. These measurements can be used to estimate the presence and severity of the disease (for example, in the case of asthma and COVID-19). Flowmeters are an integral part of ventilators using oxygen and other gases (for example, helium, nitric oxide).

Today there are many methods for measuring and dosing gas flows—Coriolis, ultrasonic, anemometric, electromagnetic, variable pressure drop, turbine, thermal [1]. For example, Coriolis flowmeters measure the Coriolis force that occurs when a gas flow moves along a curved line; ultrasonic flow meters are based on the change in the speed of sound in a moving medium; vortex flow meters are based on measurements of vortices behind a body in a streamlined flow; thermal, anemometric flow meters are based on measurements of thermal field distortions caused by gas flows; electromagnetic flowmeters are based on the principle of electromagnetic induction; in turbine flow meters, the flow rotates the turbine, the speed of rotation of which is measured and serves as an indicator of the amount of flow.

In science and technology, precision flowmeters are used, based on the measurement of the temperature gradient in the gas from a local heat source. The principle of operation is to measure these gradients depending on the flow rate. To measure the displacement of the thermal field, the following procedure is used: by a special device the gas flow is precisely divided in a known proportion (usually 1 : 100 and 1 : 1000), and this small part of the flow is conducted through a thin capillary. In the central part of the capillary, there is a heating wire wound around the capillary and two resistance thermometers in the form of additional windings on the capillary on both sides of the heating winding. Because of the peculiarities of the process of heat transfer from a gas to a thermometer, the real contribution is made by the mass flows of gases, therefore, flow meters of this type are usually called mass flowmeters. The class of such flowmeters is the most accurate among the existing ones, however, it imposes significant requirements on the manufacturing accuracy of all parts of the sensor. In addition, the gas must be under pressure (usually by several atmospheres) so that the measured amount of gas can pass through the capillary. Another disadvantage of capillary mass flow meters is their inertia due to the significant heat capacity of capillaries and thermometers.

Another class of flowmeters with a large inlet aperture and a thermal principle of operation are the so-called anemometric sensors, in which a similar idea of heat transfer, depending on the blowing of the thermometer, is implemented in a pipe with a sufficiently large cross-section. As a rule, thermistors are used here as thermometers. A distinction is made between hot and cold wire flow meters. In the case of a hot wire, the wire works both the heater and thermometer. In the case of cold wires, these wires are separated. Differential flowmeters have also been developed, in which conductive films are used as heaters and thermometers. In any case, the measurement is reduced to analog measurements of resistive thermometers. Anemometer flowmeters have lower accuracy and longer response times. These flowmeters are widely used in the automotive industry. For a detailed description of various technologies for measuring gas streams, including a comparison of their advantages and disadvantages, as well as information on their technical characteristics, see [2–5]. All these methods have their advantages and shortcomings; therefore, the task of developing new types of flowmeters aimed at expanding their area of application, increasing their accuracy and stability remains urgent.

In this paper, a new principle of operation of flowmeters is proposed, which is based on measuring the distortions of the thermal field around the heater during flow. The temperature of such distortions is measured using vibrating wires that act as fast-response precision thermometers.

2. OPERATING PRINCIPLE OF VIBRATING WIRE FLOWMETERS

For the diagnostics of beams in accelerators, the idea of using the vibrating wires as precision thermometers was proposed [6–9]. Such devices for measuring the profiles of beams of charged particle/radiation/neutrons, we call the monitors of vibrating wires (MVW). The principle of operation of such monitors is based on the high sensitivity to the vibration frequency of a wire fixed at the ends to the tension, which, in turn, is determined by the temperature of the string. The beams of charged particles or radiation incident on a wire leave part of the energy in the string material, which results in its heating and, as a consequence, the change in the frequency of its natural vibrations.

The excitation of natural oscillations is carried out using a magnetic field, which ensures the interaction of the current flowing through the string with the field. The wire is connected to the positive input of the operational amplifier. Such positive feedback increases random string fluctuations, from which the oscillations at the natural frequency survive because the Q-factor of just such oscillations is maximal (for more details on the scheme of self-generation of natural oscillations, see [9]).

The sensitivity of the string (a dimensionless coefficient that relates the relative change in frequency to the relative change in the length of the wire) is determined by the formula

$$\frac{\Delta F}{F} = \frac{\Delta\sigma}{2\sigma} = \frac{E}{2\sigma}\frac{\Delta L}{L} = \frac{E}{2\sigma}\alpha\Delta T, \tag{1}$$

where F is the initial frequency of the wire at the initial temperature, ΔF is a change in the frequency of the string caused by the overheating of the string by an amount ΔT, E is the elastic modulus of wire material, σ is the initial wire tension, α is the coefficient of thermal expansion of the string material (it is assumed that the measured object influence only the string - this assumption is close to reality for beams of charged particles/radiation). Typically, the initial string stress (the string tension during assembly) is 50–70% of the elastic limit of the material. The dimensionless ratio is several hundred. It should be noted that the sensitivity of resistance thermometers does not contain such a multiplication factor and, therefore, is significantly lower.

Typical monitor frequencies are in the 2–8 kHz range, and the frequency stability over several hours is ~0.005 Hz. The corresponding relative accuracy is a few units multiplied by 10–6. This value made it possible to measure the intensity of beams/radiation equivalent to an increase in the temperature of the string by fractions of a mK (for strings made of stainless steel—0.3 mK, bronze—0.6 mK, tungsten—1.0 mK). Vibrating strings are represented by precision thermometers with good accuracy and a wide dynamic

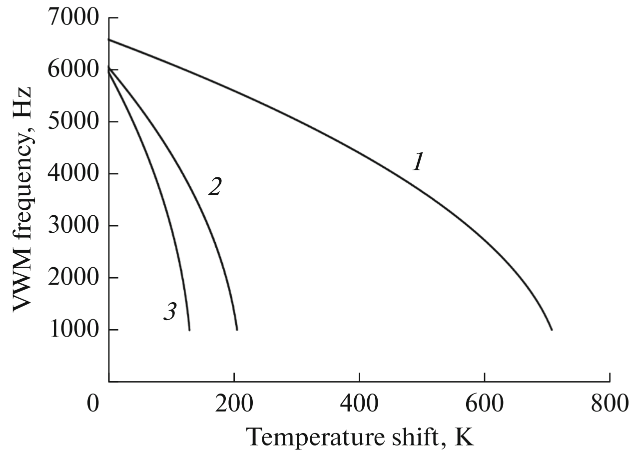

Fig. 1. Dependence of the frequency of a vibrating string on overheating in relation to the assembly temperature for strings made of *1*—tungsten, *2*—beryllium bronze (Beryllium Bronze—Cu97.5/Be2/Co-Ni0.5, UNS C17200), *3*—stainless steel (AISI 316).

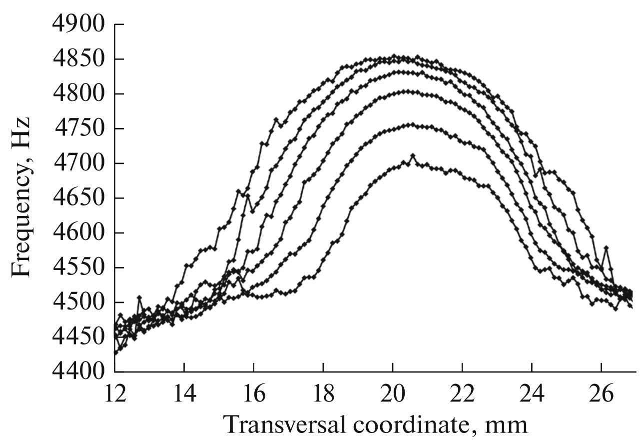

Fig. 2. Transverse profiles of strings in its various orthogonal sections, located at distances of 4 mm from each other (the lines of the profiles are located from bottom to top, in order of increasing distance from the nozzle that creates the jet).

range. Figure 1 shows graphs of the dependence of the frequencies of a string made of various materials on its overheating.

As one can see, the overheating range for a tungsten string extends up to ~700 K, for a bronze string > 200 K, and for stainless steel strings—up to temperatures of ~130 K. We emphasize that we are talking about overheating, assuming that the string resonator was assembled at room temperature, and during assembly, the string is stretched by 70% of the ultimate strength of the material. The case when the wire is stretched weakly and further cooled is also possible, however, this work does not consider this.

Note that attempts to measure gas flows using MVW were undertaken back in 2002 [10]. To increase the sensitivity of the frequency of the wire for its blow-off with gas, a special scheme was developed, when, in addition to the exciting oscillations at the natural frequency of the current, at the same time, the DC was also applied to the wire. Such a monitor made it possible to scan the cross-sections of wide gas jets. The string, depending on the local blowing flow, was cooled, which led to an increase in its frequency. Figure 2 shows profiles in different orthogonal sections of strings at a distance of 4 mm from each other.

The experiments were also carried out with gas (air) blowing through the aperture hole of the MVW, developed to measure the profile of the undulator radiation of the APS synchrotron radiation source (Argonne Lab, USA) [11]. In all cases, we used monitors designed for profiling beams of charged particles. The aperture of such monitors did not have a specialized gas-dynamic structure and did not provide effective interaction of gas flows with the string.

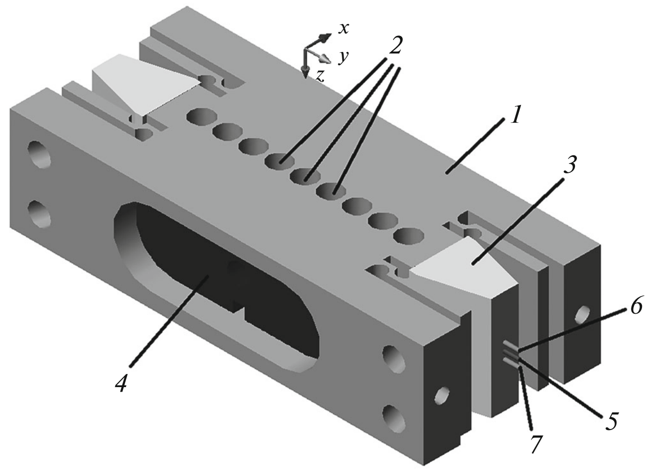

Fig. 3. Isometric view of the resonator of a vibrating wire flow meter. *1*—resonator housing (stainless steel/brass), *2*—intake holes, *3*—ceramic wedges, *4*—magnetic poles of the system for exciting natural vibrations of wire-thermometers, *5*—heating wire, *6*—windward thermometer string (string closest to the stream falling on the resonator), *7*—leeward thermometer wire (wire is located behind the heater).

3. DEVELOPMENT OF A FLOW METER MODEL

For flow meters based on vibrating strings, a special resonator has been developed that contains several wires (two strings-thermometers and a string-heater) and a channel that ensures effective interaction of the measured flow with the thermal field of the heater. The measured flux is directed into the magnetic field gap orthogonal to the wires, ensuring their streamlining along their entire length. Three strings are placed in one plane in the gap, the middle string is a heater and on the sides are vibrating strings-thermometer.

The general view of the resonator is shown in Fig. 3. The measured flow propagates along the Z-axis (in Fig. 3, from top to bottom). Following the terminology accepted in meteorology, the vibrating wire, on which the flux falls directly (in Fig. 3—the upper one), will be called windward, and on the lower string, where the heat flux from the heater is carried away, we will call the leeward wire [12]. For the strings and the heater, we used a 100 μm diameter stainless steel wire that had undergone a special heat treatment. All strings are sandwiched between wedge-shaped ceramic plates. The magnetic system consists of four permanent cylindrical magnets, short-circuited by magnetic poles. The measured flow through a system of special channels in the body of the flow meter (not shown) is fed to the receiving holes of the resonator.

The measured airflow spreads along the Z-axis and enters the intake holes at the end of the flowmeter body.

Figure 4 shows a section of the resonator with a plane passing through three-wire (a heater and two vibrating ones).

For a given geometry of the flow meter (length and diameter of strings, their relative position concerning the heater), the choice of the string material is an important parameter. For a heating wire, the high resistivity stainless steel is a good option. The same material can be used for the vibrating wires themselves. Selecting the same material for the heating and vibrating wires simplifies the assembly of the monitor because the ends of all three strings are clamped with one pair of ceramic wedges.

4. EXPERIMENTAL RESULTS, FLOW METER CALIBRATION

To calibrate the flowmeters, it is required to carry out several experiments in which, at given values of the flow, the change in the frequencies of the wires—thermometers for a fixed value of the current through the heating string—is measured.

The current through the heating wire was set using a stabilized current source circuit based on a microcircuit LM337.

Stable gas (air) flows were created by pumping air into a receiver with a large volume at a pressure of about 5–6 bar and passing the accumulated air through a thin valve opening. The airflow was measured using a GSB-400kl1 gas drum meter, which has the advantage of absolute measurements. In the experiment, a bidirectional valve was used, in one position, passing the flow through the flow meter of the vibrating string and in the other into the atmosphere. In the position of the valve releasing the flow into

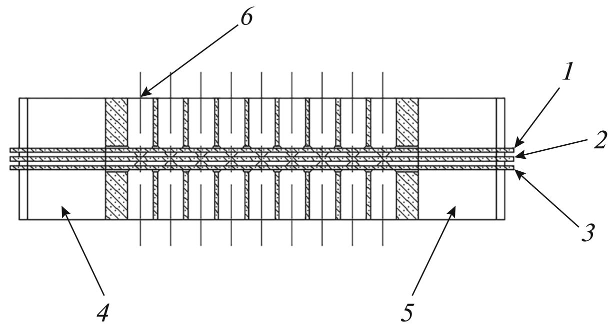

Fig. 4. Section of the resonator by the plane in which the wires are located. It is assumed that the measured flow spreads from top to bottom: *1*—windward wire, *2*—heater, *3*—leeward wire, *4* and *5*—planes of ceramic wedges, *6*—a row of the flow receiving holes at the end of the flow meter body.

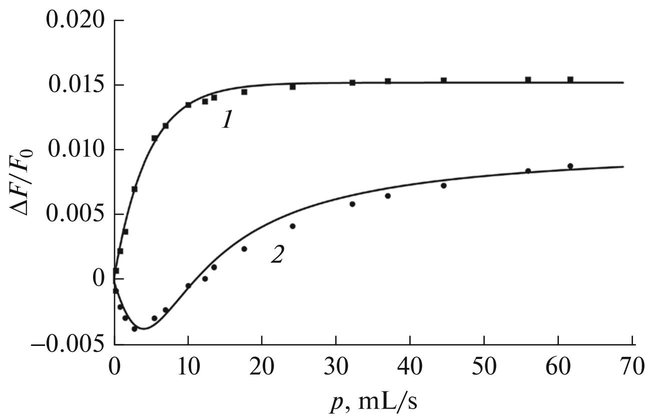

Fig. 5. Dependence of the relative changes in the frequencies of wires-thermometers on the value of the flux through the flow meter at a current through the heating wire of 50.4 mA. Circles - frequency signals from the windward string, *1*—fitting of these signals, squares—frequency signals from the leeward string, *2*—fitting of these signals.

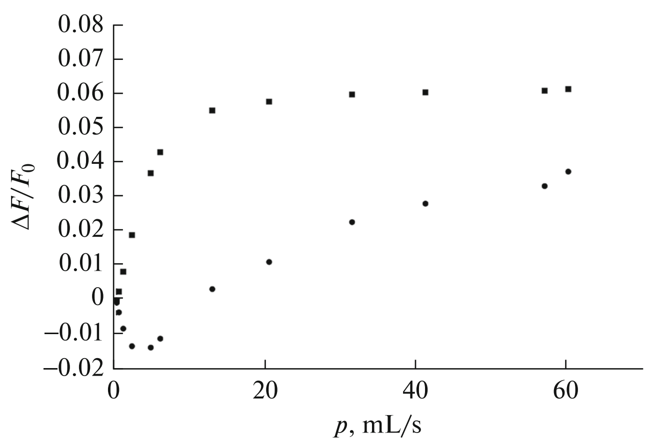

Fig. 6. Dependence of the relative changes in the frequencies of wires-thermometers on the value of the flux through the flowmeter at a current through the heating wire of 101 mA, circles—frequency signals from the windward wire, squares—frequency signals from the leeward wire.

the atmosphere, the flow rate was adjusted using a precision fine valve and by measuring the time required to pass a certain volume of air through the GSB counter. Figures 5 and 6 show the experimental results for two current values: 50.4 and 101 mA, respectively.

It can be seen from Fig. 5 that the behavior of the string frequencies depends significantly on the magnitude of the flow and the positioning of the strings relative to the heater (windward, leeward). The entire flow range was from 0 to 70 mL/ s. The windward string (marked as the first in Fig. 5) shows a rather steep, but monotonic increase in frequency with increasing flux, reaching the limiting value of ~0.015. The leeward string at low flows (up to 3–4 mL/ s) is additionally heated by the heat flux carried away from the heater, and the string frequency decreases. However, at flux values greater than this value, the cooling of the string by the measured flux exceeds the effect of heat transfer from the heater, and the string frequency begins to increase. In this case, the increase in frequency occurs much slower than for the windward string, and up to flux values up to 62 mL/s (the maximum value in this experiment), the frequency does not reach the limiting value. We also observed a similar picture in the experiment, when the current through the heating wire was 101 mA (see Fig. 6). With such a twofold increase in the current, the heat release on the string increases fourfold, which approximately corresponds to the new limiting value of the relative frequency shift of the windward string of 0.06. The ranges of the characteristic values of the fluxes are practically the same; therefore, we will choose the current values of 50.4 mA as the operating current through the string, and it is the data in Fig. 5 that we will choose for calibrating the flow meter.

Obviously, at low fluxes, when the changes in the frequencies of the windward and leeward wires have different signs, a differential method can be used, which also takes into account possible thermal drifts in the case of long-term measurements. For large values of flux, one should take into account the strong nonlinearity of frequency signals. It is proposed to divide the entire range of flux values into three areas:

—low flow range ($p < 3$ mL/s), in which the signals from both wires are proportional to the measured flow;

—windward string response range (3 ml/s $< p <$ 10 mL/s), in this region, the frequency of the leeward string undergoes an extremum and contains an ambiguity;

—range of non-linear response of the windward string ($p >$10 mL/s), in this region, the signal from the windward string reaches its limiting value, but the leeward string continues to maintain sensitivity to flux up to values 60–70 ml/s.

We will use the readings of the windward string as an indicator of the range selection. First, for each of the indicated ranges, we used a set of corresponding experimental data with linear regression for the readings of both strings for the first range, and quadratic regression for the second and third ranges, respectively, for the readings of the windward and leeward strings. However, a rather strong discrepancy of values (~ 10%) was found at the boundaries of the ranges with this approach. Therefore, we have developed a method for fitting experimental data with one function over the entire range of values. For indications of the windward string, a good result was given by using the function

$$\Delta F_1/F_{10} = A(1 - \exp(-p/B)), \tag{2}$$

where p is the flow value expressed in mL/s. For the values $A = 0.015$ and $B = 4.6$, the rms deviation of the analytical curve from the experimental values is 1×10^{-7}, which is quite acceptable. For the readings of the leeward string, we used a fractional function of the form

$$\Delta F_2/F_{20} = \frac{-ap + bp^2}{c + dp^2}. \tag{3}$$

Values $a = 0.011$, $b = 0.001$, $c = 6$, $d = 0.095$ give the root-mean-square deviation of curve (2) from the experimental points of the order 2.6×10^{-7}.

To use formulas (1) and (2), they should be reversed concerning the flow value p. For formula (2) we have:

$$p = B\ln\left(\frac{A}{A - \Delta_1}\right). \tag{4}$$

where $\Delta_1 = \Delta F_1/F_{10}$.

Inversion of formula (3) requires the solution of a quadratic equation, thus the whole construction is written in the form

$$p_\pm = \frac{a \pm \sqrt{a^2 + 4\Delta_2 c(b - d\Delta_2)}}{2(b - d\Delta_2)}, \tag{5}$$

where $\Delta_2 = \Delta F_2/F_{20}$.

Graphs of equations (4) and (5) are shown in Fig. 7.

Figure 8 shows the ranges of splitting signals from vibrating strings, which are stitched together by construction (functions with a carrier are applied over the entire range of frequencies/streams values).

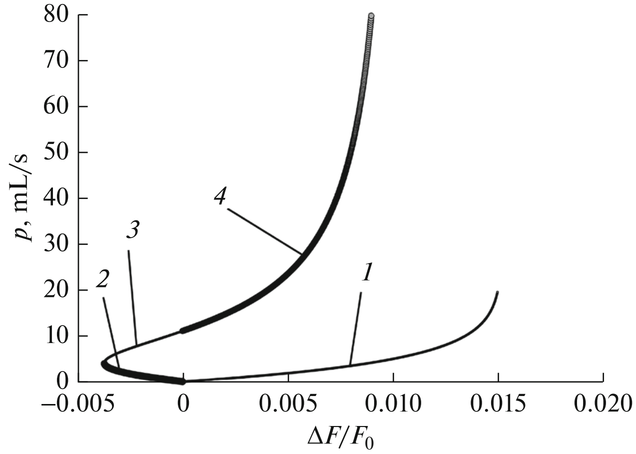

Fig. 7. Analytical calibration functions: *1*—the windward wire calibration function (formula (4)); *2*, *3*, *4*—the leeward wire calibration function (*2* and *3*— the roots of equation (5) with signs (–) and (+) for negative values Δ_2, *4*—the root of equation (5) with a plus sign for positive values Δ_2.

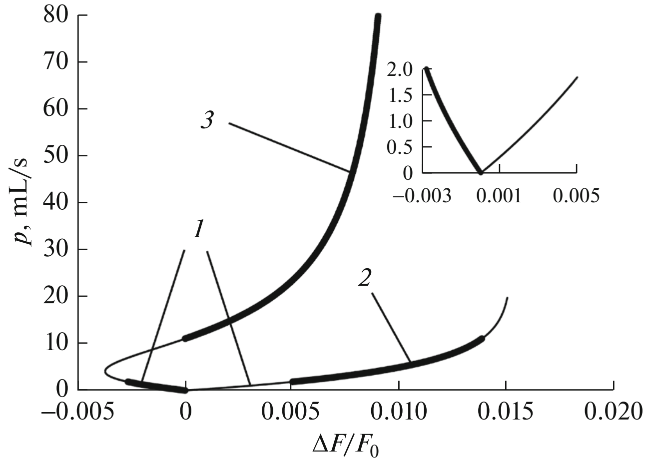

Fig. 8. Breakdown of calibration data into three characteristic ranges: *1*—the area of linear responses for both measuring wires, *2* and *3*—the areas of characteristic changes in the frequency of the windward and leeward wires, respectively. In the inset, the region *1* is enlarged.

So, combining the results obtained, we obtain the following formulas for three characteristic ranges of frequency responses:

The area of linear responses of both vibrating strings (range 1, $0 < \Delta_1 < 0.005$)

$$p = \frac{1}{2} B \ln\left(\frac{A}{A - \Delta_1}\right) - \frac{1}{2} \frac{a - \sqrt{a^2 + 4\Delta_2 c(b - d\Delta_2)}}{2(b - d\Delta_2)}, \tag{6}$$

(the above-mentioned differential method corresponds to the expansion of this formula in a series by small quantities Δ_1 and Δ_2);

The area of characteristic change in the frequency of the windward string (range 2, $0.005 < \Delta_1 < 0.0138$)

$$p = B \ln\left(\frac{A}{A - \Delta_1}\right); \tag{7}$$

The region of characteristic change in the frequency of the leeward wire (range 3, $0.0138 < \Delta_1$):

$$p = \frac{-a + \sqrt{a^2 + 4\Delta_2 c(b - d\Delta_2)}}{2(b - d\Delta_2)}. \tag{8}$$

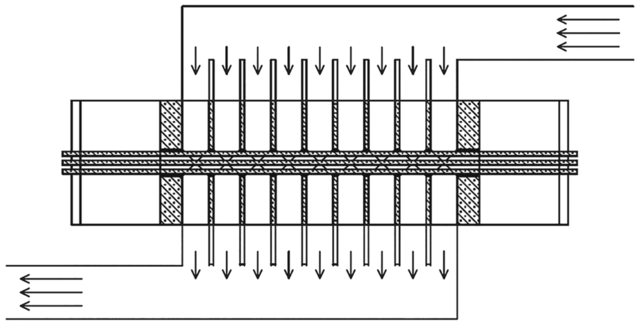

Fig. 9. Use of a flow meter as an accelerometer. As shown by arrows, the air flows in the flowmeter during the acceleration are directed upward.

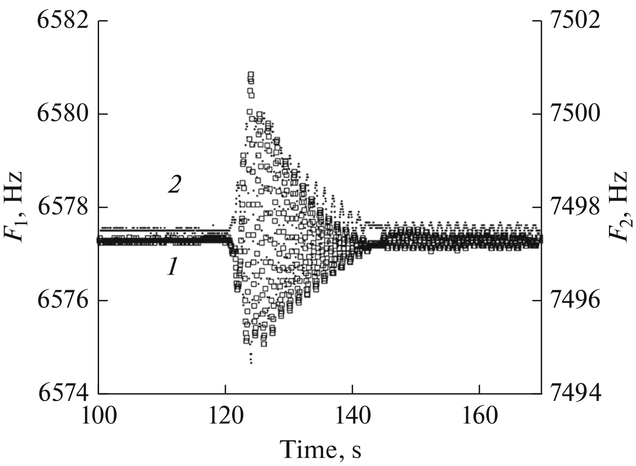

Fig. 10. Frequency data of vibrating wires of a flowmeter oscillating on a spring suspension: *1* and *2* are the signals from the windward (squares) and leeward (dots) wires.

5. FLOWMETER AS AN ACCELEROMETER

Interestingly, the distortion of the thermal field can also occur as a result of the jerk of the flowmeter. This effect was proposed for the development of accelerometers that do not contain a solid-state inert mass (see, for example, a review on the topic [13]). In the original work [14], which is cited as the first with a proposal to use the dependence of heat transfer on acceleration, it was proposed to use as a heater a cantilever-fixed plate with the possibility of movement (see also [15]). The complete rejection of any solids and the transition only on a gaseous medium was formulated in the patent [16] (see also [17]). The proposal included two thermosensitive elements installed in a hermetically sealed enclosure containing gas. The heat source in the gas creates convective currents, measured by thermometers. The linear acceleration applied to the body changes the convective currents, causing temperature differences between thermosensitive elements. A temperature difference is measured as the difference in the electrical resistance between two thermosensitive elements, which is proportional to the acceleration. An experimental demonstration of the method was shown in [18]. A typical uniaxial construction contains three wires in one plane (micromachined with dimensions of ~1 mm), one of which serves as a heater, and two wires on the sides are thermometers (see also [19]).

The design of the flowmeter developed by us was used practically without alterations as an accelerometer without inert mass. The flowmeter-accelerometer was located on a platform suspended by a spring. The axis of acceleration is directed in the plane of the strings perpendicular to their direction (see Fig. 9).

The results of measuring the frequencies of the flow meter are shown in Fig. 10. The inlet/outlet ports on the flowmeter were open to the air. The initial values of frequencies (6577.3 and 7497.5 Hz) made it possible to perform their rather fast measurements during 50.4 ms.

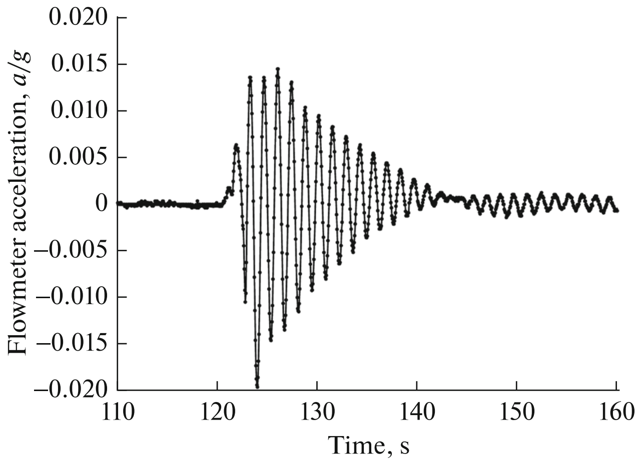

Fig. 11. The acceleration of the flowmeter body computed from the experiment results (in units of gravitational acceleration).

The acceleration is given in units of gravitational acceleration (the absolute values are estimated by the order of magnitude, based on the measurement of the maximum displacement of the flowmeter from an equilibrium position).

6. CONCLUSION

Flowmeters based on vibrating wires have been developed and manufactured, and the first experimental results have been obtained (Fig. 11). A detailed analysis of the calibration experiments was carried out and an algorithm for computing fluxes was developed based on the results of nonlinear frequency signals in the flux range approximately twenty times the range of linear responses of the windward and leeward wires. The flowmeter has also been used as an accelerometer, and the first encouraging results are also obtained here.

The developed device equipped with measurement visualization means and an interface with a computer can have a wide range of applications in various fields of science and technology, including spirometric measurements in medicine.

FUNDING

The study was carried out with the financial support of the Science Committee of the Republic of Armenia within the framework of the scientific project 20APP-2G001.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

1. https://portal.endress.com/wa001/dla/5000581/9936/000/01/FA00005D.pdf.
2. Bilinsky, I.I., Stasyuk, M.A., and Gladyshevsky, M.V., *Visnyk Natsional′noho tekhnichnoho universytetu "ХПІ"* (Bulletin of the National Technical University "KhPI"), no. 42, 2015.
3. Baker, R.C., *Flow Measurement Handbook*, UK: Cambridge University Press, CB2 2RU, 2000.
4. Thorn, R., *Basic Principles of Flow Measurement*, John Wiley & Sons, Ltd. ISBN: 0-470-02143-8, 2005.
5. Thorn, R., Melling, A., et al. *Flow Measurement, in: Measurement, Instrumentation, and Sensors Handbook, Electromagnetic, Optical, Radiation, Chemical, and Biomedical Measurement*, John G. Webster, Halit Eren, CRC Press., 2017.
6. Arutunian, S.G., Dobrovolski, N.M., Mailian, M.R., Sinenko, I.G., and Vasiniuk, I.E., *Phys. Rev. Spec. Top.? Accel. Beams*, 1999, vol. 2, p. 122801.
7. Arutunian, S.G., Mailian, M.R., and Wittenburg, K., *NIM A*, 2007, vol. 572, p. 1022.

8. Arutunian, S.G., Bergoz, J., Chung, M., Harutyunyan, G.S., and Lazareva, E.G., *NIM A*, 2015, vol. 797, p. 37.
9. Arutunian, S.G., Margaryan, A.V., Harutyunyan, G.S., Lazareva, E.G., Chung, M., Kwak, D., and Gyulamiryan, D.S., *JINST*, 2021, vol. 16, id. R01001.
10. Arutunian, S.G., Avetisyan, A.E., Dobrovolski, N.M., Mailian, M.R., Vasiniuk, I.E., Wittenburg, K., and Reetz, R. *EPAC-8* (June 2002, Paris, France), p. 1837, 2002.
11. Decker, G. et al., DIPAC, p. 36, 2007.
12. https://meteoinfo.ru/glossary/6915-2013-05-07-10-26-22.
13. Mukherjee, R., Basu, J., Mandal, P., and Guha, P.K., *Journal of Micromechanics and Microengineering*, 2017, vol. 27, p. 123002.
14. Hiratsuka, R., van Duyn, D.C., Otaredian, T., and de Vries, P., *TRANSDUCERS'91*, USA: San Francisco, p. 420, 1991.
15. Hiratsuka, R., D.C. van Duyn, T. Otaredian, P. de Vries, P. M. Sarro, *Sensors and Actuators A*, vol. 32, p. 380 (1992).
16. Dao, R.et al. *Convective Accelerometer and Inclinometer*, United States Patent 5581034, 1996.
17. Gaitan, M. et al. *Method of Manufacture of Convective Accelerometers*, United States Patent US 6171880 B1, 2001.
18. Leung, A.M., Jones, J., Czyzewska, E., Chen, J., and Pascal, M., *Micromachined accelerometer with no proof mass*, IEDM Technical Digest, p. 899, 1997.
19. Mailly, F., Giani, A., and Boyer, A., *Micromachined Thermal Accelerometer without Proof Mass.* Boston: Springer, 2006.

Translated by V. Musakhanyan