ANDRIUS TONKONOGOVAS

INVESTIGATION OF PULSATING FLOW EFFECT ON METERS WITH ROTATING PARTS

SUMMARY OF DOCTORAL DISSERTATION

TECHNOLOGICAL SCIENCES, ENERGETICS AND POWER ENGINEERING (06T)

Kaunas
2015

KAUNAS UNIVERSITY OF TECHNOLOGY
LITHUANIAN ENERGY INSTITUTE

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This scientific work was performed in 2009 – 2013 at the Laboratory of Heat Equipment Research and Testing of Lithuanian Energy Institute.

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KAUNO TECHNOLOGIJOS UNIVERSITETAS
LIETUVOS ENERGETIKOS INSTITUTAS

ANDRIUS TONKONOGOVAS

PULSUOJANČIO SRAUTO POVEIKIO MATUOKLIŲ SU BESISUKANČIOMIS DALIMIS DARBUI TYRIMAS

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1. INTRODUCTION

Relevance of the dissertation work and the problem of scientific research

Air flow rate and velocity measurements are very important in scientific investigations and in many manufacturing activities and environment protection when ensuring proper conditions of occupational safety and health and accounting of material and energetic resources. Conclusions of investigations in air flow can be adopted in other flows, for example, natural gas and water. Flow rate and velocity are the most popular characteristics in measurements.

Flow rate and velocity are usually measured using several types of meters. In practice mostly meters with rotating rotors are used, rotation frequency of which depends on the measured parameter (flow rate or velocity). Meters of such kind are assigned to the tachometric meter class. Based on the principle of operation, tachometric meters are classified into velocity (vane, turbine and mechanical anemometers) and positive displacement meters. Tachometric meter measures number of rotations of the sensor, which respectively is proportional to the volume of the flow and/or rotational frequency, which is proportional to flow rate velocity. Advantages of the tachometric meters are the following: wide dynamic range of measurement and high accuracy (unfortunately, it is achieved only under excellent flow conditions); disadvantages: low sensitivity and high inertia.

The objects of the work were tachometric meters of the following types:

- turbine flow meter and cup anemometers;
- positive displacement (rotary) flow meters.

It is worth noting that turbine gas meters are ones of the most important measuring devices for natural gas flow rate use. They measure up to 70 % of total natural gas use, which is currently 2.5 billion m^3 per year. Also these meters are widely used as basic measurement means in reference facilities for recreation of air (gas) volume and flow unit values and then transferring it to working standards or meters. In the measurement range from 200 to 9700 m^3/h of Lithuania's air (gas) volume and flow unit standard, five turbine meters are used. Usually turbine flow rate meters are operating under unstable conditions, i.e., when flow rate, velocity and, sometimes, direction of the flow change. Usually flow change is periodical, i.e., the meter operates when the flow is pulsing.

Air velocity meters usually work under high wind turbulence, which could reach several tens of percent. Their operation in a pulsating flow is affected by analogous factors as in the case of turbine flow rate meters. In the case of wind pulsations, the meters, due to their inertia, are not able to react to sudden changes of air flow velocity. Variation regularity of dynamic errors generated by these meters is especially important when measuring non-stationary wind speed and calculating wind energy from these measurements. The main difference between mechanical air velocity meters and turbine gas flow rate meters is the form and the size of an impeller that determine differences between aerodynamic forces and, respectively, response and dynamic errors.

The main parameters of flow pulsations are their frequency, amplitude and law of pulsation. These parameters have great influence on pulsation effect to readings of meters and measurement accuracy. However, until now all investigations concentrated on determination of a dynamic error when flow pulsates according to simple laws (usually cosine). However, usually the measured flows pulsate according to various complex laws, which differ from cosine. Also until now there was no any method for modeling of meter operation in a pulsating flow that varies according to any law of pulsation.

The aim of the dissertation

Investigate influence of air (gas) flow pulsations on operation and errors of tachometric meters (turbine meters, positive displacement flow meters and cup anemometers).

Tasks of the investigation

In order to achieve the objective the following tasks should be solved:

- Prepare an experimental method for determination of inertia time constant of tachometric meters and investigate their inertia characteristics;
- Prepare a numerical method for evaluation of the response and dynamic error of turbine flow meters and cup anemometers in a pulsating flow;
- Investigate influence of flow, which pulsates under simple (rectangular, triangle and cosine) and complex (met in practice) laws on response and dynamic error of turbine flow meters and generalize the obtained dependences;
- Investigate the influence of wind pulsations on response and dynamic error of cup anemometers and generalize the obtained dependences;
- Experimentally investigate influence of pulsations on dynamic error of rotary gas meters;
- Investigate influence of oscillating and reversal pulsing flow on performance of turbine flow meters;
- Prepare recommendations for application of the results of the work in practice.

Practical value of the work

Recommendations for elimination of dynamic errors of the meter working in a pulsating flows are prepared.

Scientific novelty of the work

- A new method for determination of the rotor's inertia time constant of tachometric meters according to its step response was created. This method assess the influence of current and excess frequency of rotor's rotation on time constant;
- A new numerical method was created for modelling of the response and dynamic error of turbine flow meters and cup velocity anemometers in a flow, which pulsates under any law. Patterns of the response and dynamic error dependencies on pulsation parameters applying newly created dimensionless variables were generalized.

Defensive statement

The following statements serve as defensive statements:

- Time constant of tachometric meters varies during the response and depends not only on the final but also on the excessive frequency of the rotor rotation. Initial frequency does not influence the character of the change of time constant;
- Dynamic error of turbine flow meters is influenced by amplitude, frequency and law of pulsation. Influence of frequency of pulsation occurs at 0.1 Hz, while at increase to 1 Hz due to inertia of meter readings in all cases their variation converges to sine pattern. At 2 Hz dynamic error reaches its limit value and remains constant. Limit value depends on law and amplitude of pulsation, which increase this value by quadratic law;
- Dynamic error of cup anemometers is determined by the minimal and maximal values of wind speed, pulsation frequency and coefficients which settle the decreasing rate of the velocity pulsation amplitude and frequency. Effect of frequency and amplitude of pulsation is similar to the turbine flow meters, however, the dynamic error of cup anemometers is negative when pulsation frequencies are lower than 0.01 Hz, and decreasing rate of the velocity pulsation amplitude is not equal;
- Dimensionless dynamic error of the turbine flow meters and mechanical cup anemometers with uncertainty ± 7 % summarises by exponential dependence under any law of pulsation;
- Influence of flow pulsations on the dynamic error of rotary flow meters is insignificant;
- Dynamic error of turbine gas meter in oscillating and reversal pulsing flow is generalized by parameter, which describes flow rate displacement in time.

2. EQUIPMENT AND METHODS OF EXPERIMENTAL INVESTIGATIONS

Experimental investigations of tachometric meters' (further – TM) response to sudden flow changes were carried out using a test facility, the principal scheme of which is shown in Fig. 2.1.

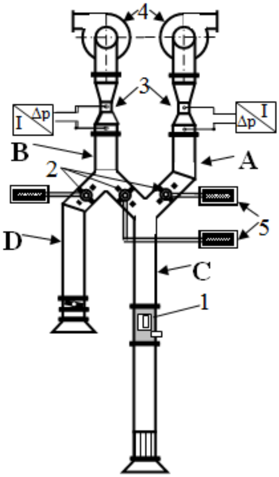


Fig. 2.1 Test facility for investigation of inertial forces of tachometric meters. *1* – meter under test; *2* – pneumatic valves; *3* – Venturi type flow meter; *4* – fans with adjustable speed; *5* – thermometers

The test facility consists of two aerodynamic tubes (*A* and *B*), each of which is separated by a pneumatic valve. In each tube air flow is created, controlled and measured separately, depending on the selected sudden air flow rate decrease or increase in the investigated TM. A sudden change of flow rate (velocity) in tube *C*, where the investigated TM is installed, is reached using pneumatic valves, which change the value of the initial flow rate (velocity) in tube *A* to the value of the final flow rate (velocity) in tube *B*. When the valves are switched, synchronic registration of the frequency of pulses of the investigated TM and the time, during which the impulse frequency settles, is started.

2.1. Experimental method for dynamic error determination

Investigations of the effect of a flow that pulsates under complex laws of pulsations were carried out in the test facility presented in Fig. 2.2.

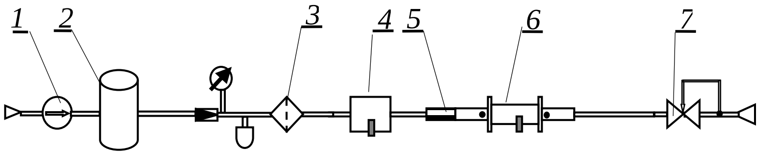


Fig. 2.2 Experimental test facility for investigation of dynamic error of flow meters. *1* – compressor; *2* – receiver; *3* – pressure regulator; *4* – turbine flow meter; *5* – acoustic filter; *6* – turbine flow meter; *7* – pressure regulator

The peculiarity of this facility is that a compressor is installed instead of a fan, and it ensures the necessary air flow; also a pressure regulator is installed that creates pulsations with varying patterns.

Reference flow was measured using a rotary gas meter (further RGM) that had been installed in front of the investigated turbine gas meter (further – TGM). A pressure regulator was installed at the end of the measuring section to create flow pulsations. In order to simulate pulsations of various forms, a branch with an electromagnetic valve, which was controlled manually as well as using software, was installed. The dynamic error of the investigated TGM was determined by comparing the readings of this meter to the readings of the reference RGM.

During the investigation, flow pulsation values were determined according to the measured differential pressure pulsations and the reference flow value. It was assumed that an instantaneous flow rate was proportional to square root of differential pressure $\sqrt{|\Delta p_i|}$ in reference meter. The data were processed in the following order:

– array of values of differential pressure Δp_i for one period of pulsation is determined;
– root values $\sqrt{|\Delta p_i|}$ of every member from the selected array are calculated. The absolute pressure value is selected since the flow often changes the direction under the regulator's operation;
– the mean value of the array $\left(\sqrt{|\Delta p_i|}\right)_{avg}$ is calculated;
– the array of dimensionless flow rate values $\overline{\sqrt{|\Delta p_i|}} = SIGN(\Delta p_i)\cdot\frac{\sqrt{|\Delta p_i|}}{\left(\sqrt{|\Delta p_i|}\right)_{avg}}$ is calculated.

This method was chosen since there were no technical tools to measure instantaneous flow rate values.

3. METHODS FOR DETERMINATION OF ROTATIONAL INERTIA TIME CONSTANT OF TACHOMETRIC METERS

The most important characteristic of any system that operates under variable external effect is time constant. This parameter – sometimes called inertia index – describes the system's response and nature of the effect. Time constant is a characteristic parameter of a non-stationary process system, to which linear differential equation of the first order can be applied:

$$\tau \frac{dy(t)}{dt} + y(t) = k \cdot u(t); \tag{3.1}$$

Here: τ – time constant s; $y(t)$ – response; $u(t)$ – input signal; k – conversion factor.

To determine the time constant, experimental results of the meters' step response to a sudden flow rate change were used by applying the following two methods:

- "37 %" method, which is known and used widely;
- A newly created method based on a detailed mathematical analysis of the response curve.

In the first method, an exponential change of the signal was assumed according to equation:

$$y(t) = y(0) \cdot e^{-\frac{t}{\tau}}. \tag{3.2}$$

It was assumed that the time constant remains the same during the entire time of the response. Regardless of the methodology of the task solution, the time constant was assumed to be the main parameter of the TM rotor, although for the TM this condition cannot be fulfilled or can be fulfilled partially.

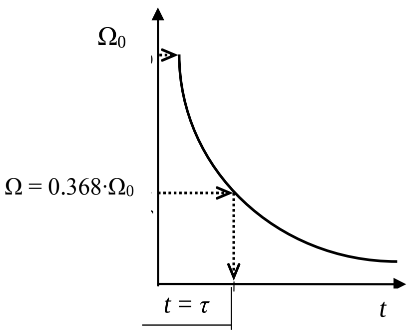


Fig. 3.1 Determination scheme of inertia time constant

Fig. 3.1 presents the scheme of determining inertia time constant applying the "37 %" method, according to which the time constant is defined as time during which dimensionless relative rotational frequency Ω changes from the initial value $\Omega_0 = 1$ to value $\Omega = 0.368 \cdot \Omega_0$.

Relative rotational dimensionless frequency Ω can be described using the following equation:

$$\Omega = \frac{\omega - \omega_{gal}}{\omega_{pr} - \omega_{gal}} = e^{-\frac{t}{\tau}}; \tag{3.3}$$

here ω – current TM rotor rotational frequency Hz; ω_{in} and ω_{fin} – initial and final TM rotor rotational frequency respectively Hz; t – time s.

The second method was applied assuming that the time constant is varying during the transition process.

In order to determine the dependency of time constant on current rotational parameters, the following method was applied:

– The response dependency in time of the investigated meter was approximated by a 6th degree polynomial

$$ln\Omega = a_1 t + a_2 t^2 + \ldots + a_6 t^6; \tag{3.4}$$

– and from dependencies of equation (3.3) and equation (3.4) the time constant expression was obtained:

$$\tau = -\frac{1}{a_1 + a_2 t + \ldots + a_6 t^5}. \tag{3.5}$$

This method can be applied to determine the time constant for all types of tachometric meters.

3.1. Method for determination of response and dynamic error of turbine meters

The scheme of dynamic error formation is shown in Fig. 3.2.

The finite difference method was applied to this modelling. Distribution of the meter rotor's rotations frequency ω in time equal to pulsation period was calculated

$$\Delta t_0 = 1/f; \tag{3.6}$$

here f – frequency of flow rate pulsation Hz.

Time Δt_0 was expanded into a large number of time intervals Δt_i ($\Delta t_i \ll \Delta t_0$). The initial frequency ω_{in_i} in every time interval Δt_0 was calculated according to the final frequency $\omega_{fin_{i-1}}$ known from calculation in the previous time interval Δt_{i-1} by evaluating the following condition

$$\omega_{in_i} = \omega_{fin_{i-1}} \tag{3.7}$$

and using experimentally determined response of the meter to a sudden change of flow rate applying Equation 3.7.

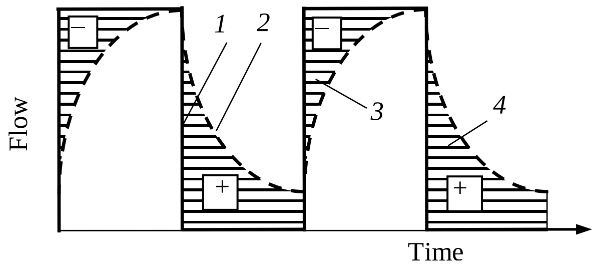


Fig. 3.2. The scheme of dynamic error formation: *1* – real flow rate; *2* – flow rate corresponding to the meter rotations; *3* – unregistered amount of gas; *4* – registered excess amount of gas

Flow rate Q_i was calculated according to its selected dependence $Q_i = f(t)$ and was assumed to be constant during the entire time interval Δt_i, i.e., the selected smooth curve of the flow rate change was modelled in a manner of stepwise dependence (Fig. 3.3).

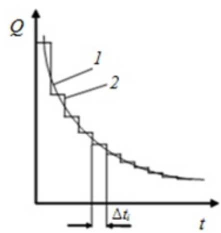


Fig. 3.3. Substitution of flow rate curve (*1*) to a stepwise pattern (*2*), with the length of a step Δt_i

Relative frequency $\Omega_{fin/in}$ was calculated according to dependence:

$$\Omega_{fin/in} = \omega_{fin_i} / \omega_{in_i} \, . \tag{3.8}$$

For modelling a specific meter, the time constant value was determined by the experimental investigation results of this meter.

Values and equations used for calculations are presented below:

– The passing flow rate according to the meter readings:

$$Q_{m_i} = \omega / k_{imp} \, ; \tag{3.9}$$

– Average real flow rate Q_{avg} during time Δt_0:

$$Q_{avg} = \left(\sum Q_i\right)/\, n \;; \tag{3.10}$$

– Average flow rate according to the meter readings:

$$Q_{avg_{sk}} = \left(\sum Q_{avg_i}\right)/\, n \,; \tag{3.11}$$

– Dynamic error:

$$\delta = \left(Q_{avg_{sk}} - Q_{avg}\right)/Q_{avg} \tag{3.12}$$

The provided equations make the mathematical model of the process under consideration.

Contrary to TGM, mechanical air velocity meters (further – MAM) operate in open atmospheric flows usually under strong turbulence that could reach several tens of percent. In order to model such complex form fluctuations of wind velocity, the following parameters of pulsations were determined:

- Minimal v_{min} and maximal v_{max} velocity values;
- Wind velocity pulsation frequency f;
- Coefficient k_v ($k_v \geq 0$), which defines the decrease rate of the velocity pulsations amplitude (the amplitude decreases according to an arithmetic progression) within one cycle of pulsation. At $k_v = 0$ the value of the velocity amplitude remains constant. When the value of this parameter increases ($k_v > 0$), the decrease rate of pulsation amplitude values becomes faster;
- Coefficient k_t ($k_t \geq 0$), which defines the decrease rate of the velocity pulsations frequency (frequency also decreases according to arithmetic progression) within one cycle of pulsation. At $k_t = 0$ the value of the velocity frequency remains constant. As the value of this parameter increases ($k_v > 0$), the decrease rate of pulsation frequency values becomes faster;
- Number of peaks in one impulse of pulsation.

While modelling air velocity pulsations, it was assumed that there would be eight peaks in one pulsation. After choosing the maximum and minimum air velocity values, wind pulsations corresponding to laws, met in practice, were modelled.

3.2. Methods for summary of the results

The obtained results were summarised applying dimensionless parameters provided in Table 3.1.

Table 3.1. Dimensionless parameters

Parameter name	Expression
Dimensionless amplitude of gas flow rate pulsation	$\Delta\overline{Q} = \dfrac{\Delta Q}{Q_{avg}} = \dfrac{Q_{\max} - Q_{\min}}{2Q_{avg}}$
Dimensionless amplitude of air velocity pulsation	$\Delta\bar{v} = \dfrac{v_{max} - v_{min}}{v_{avg}}$
Dimensionless flow rate	$\overline{Q} = Q / Q_{avg}$ $\overline{Q}_{max} = Q_{max} / Q_{avg}$ $\overline{Q}_{min} = Q_{min} / Q_{avg}$
Dimensionless amplitude of pulsation of meter readings	$\Delta\bar{q} = \dfrac{q_{max} - q_{min}}{2q_{avg}}$
Dimensionless relative amplitude of pulsation of meter readings	$\Delta\bar{q}_{rel} \equiv \Delta\bar{q} / \Delta\overline{Q}$
Dimensionless frequency of flow rate pulsation	$\bar{f} = f \cdot \tau$
Dimensionless time	$\bar{t} = f \cdot t$
Dimensionless dynamic error	$\bar{\delta} = \delta / \delta_{lim}$

The limit dynamic error value δ_{lim} depends only on the law of pulsation and dimensionless pulsation amplitude $\Delta\overline{Q}$ and can be described using the following equation:

$$\delta_{lim} \sim C_a \cdot \Delta\overline{Q}^{\,2} . \qquad (3.13)$$

Analysing an oscillating and reversal pulsing flow using the method under consideration when the flow changes its direction periodically, instead of dimensionless amplitude, it is convenient to introduce a new dimensionless parameter *C*, which describes displacement of the pulsating flow rate in respect of time axis – in fact, dimensionless flow rate displacement in respect of 1 and is related to dimensionless amplitude $\Delta\overline{Q}$:

$$C = \frac{1}{\Delta\overline{Q}}\,;\ C = \left(\overline{Q}_{max} + \overline{Q}_{min}\right)/\,2 = \overline{Q}_{avg}\,;\ C = 1 + \overline{Q}_{min}\,;\ C = \overline{Q}_{max} - 1 \qquad (3.14)$$

It can be applied simulations in the case of reversal pulsing flow. Values $C \geq 1$ correspond to single direction pulsations, $0 \leq C < 1$ correspond to double direction pulsations (reversal pulsing flow), case $C = 0$ corresponds to a oscillating flow which average flow rate value is zero.

4. RESEARCH OF RESULTS OF INERTIA OF TACHOMETRIC FLOWMETERS

During analysis of measurement results of the tachometric meter response, it was determined that under the same boundary conditions, the response time of different type of meters depends directly on physical characteristics of the meter (mass, size) and on the material of which the meter's impeller or rotor is made and its size. Moreover, the response time due to torque depends directly on the final flow rate value Q_{fin}.

The manner of the rotary meter response differs basically from the turbine flow rate and cup air velocity meters response. Measuring of the rotary meter principle is based on periodic displacement of the measured air flow from the chambers. So, in the case of a sudden change of flow rate, frequency of rotary meter rotor determines the initial flow rate value.

Applying method "37 %", the averaged inertia time constant was determined according to the measured responses of the turbine flow rate meters to a sudden flow rate change. As in the case of the response, the final flow rate value also greatly affected the time constant. Three different types of meters have been investigated. The time constant dependencies of the analysed meters on the final flow rate Q are shown in Fig. 4.1.

Time constant of a turbine flow meter in gas with fixed physical properties (first of all density and viscosity) is described by the following dependence:

$$\tau = B \cdot \left(\frac{Q_{fin}}{100} \right)^n ; \qquad (4.1)$$

here Q_{fin} – final flow rate m^3/h.

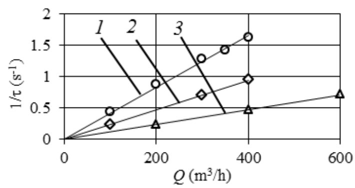


Fig. 4.1. Inertia time constant τ dependence of three types of turbine meters on the final flow Q; *a* – meter 1; *b* – meter 2; *3* – meter 3

Coefficient C and indicator n in this equation can be determined pretty accurately and easily applying a semi-experimental method. In all cases, degree indicator n is more or less close to 1. Density ratio of metal and plastic impellers ρ_{met}/ρ_{pl} is very close to the ratio of inertia time constant τ_{met}/τ_{pl} of these impellers. This means that time constant τ is inversely proportional to the final flow rate and directly proportional to the moment of inertia I of the turbine impeller.

During the investigation, analysis of the measured response of the meter was performed. Fig. 4.2 demonstrates a typical change of dimensionless frequency Ω of a tachometric meter in time. The following presentation of the results allows better understanding the nature of the meter's response. The straight line means that the meter's response varies in time exponentially with a constant exponent, while the time constant remains the same during the response process. The appearance of curves means that the exponent and the time constant changes during the transitional process. Thus, if the curve is bent downwards, the exponent value in this field decreases, and the time constant increases.

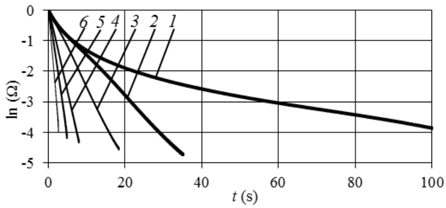


Fig. 4.2 Dependence of the dimensionless relative frequency of the turbine meter on time when the flow rate starts decreasing from Q_{in} = 700 m^3/h to (*1–6*) – Q_{fin} = 0; 50; 100; 200; 300; 500 m^3/h

A detailed analysis of tachometric meters performance was carried out analysing their response to a sudden change of the flow rate. A typical dependence of the time constant on excessive frequency (the difference between the current and the final rotational frequencies) is shown in Fig. 4.3 (*a*) for low excessive frequency, and in Fig. 4.3 (*b*) for high excessive frequency. In the first case, results for increasing as well as for decreasing flow rate change are provided.

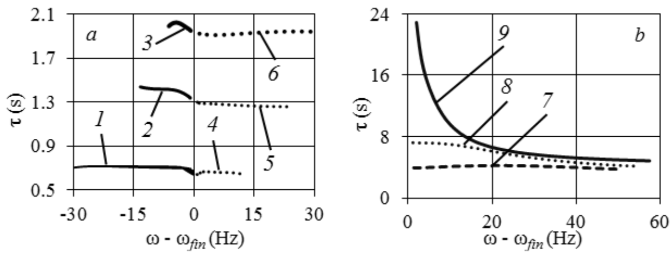


Fig. 4.3. Time constant dependence of the turbine meter on the difference between the current and final frequencies. *a:1–3* Q_{in} = 50 m^3/h, Q_{fin} = 500; 300; 200 m^3/h; *4 – 6* Q_{in} = 700 m^3/h, Q_{fin} = 500; 300; 200 m^3/h; *b* – Q_{in} = 700 m^3/h; *7–9* Q_{fin} = 100; 50; 0 m^3/h

Analysis of Figure 4.3 shows that time constant changes significantly during the response process, and the change is basically non-linear. The average value of the time constant is higher when the flow rate change is increasing (Fig.

4.3 *1–3*) compared to the case when the flow rate change is decreasing (Fig. 4.3 *4–6*). The value of the time constant starts increasing when the final value of the flow rate approaches the lower measuring boundary of the meter (Fig. 4.3 *7–9*). When the final value of the flow rate approaches 0, the value of the time constant is increasing exponentially.

For different values of initial flow rate and the same values of final flow rate (Fig. 4.3, *1* and *4*; *2* and *5*; *3* and *6*), the point of intersection of the time constant coincides within the accuracy boundaries. This means that the initial flow rate value does not influence the time constant.

While analysing changing of the time constant of the cup air velocity meters, it was observed that non-monotonous dependence manner is related to different effect of influencing factors. Aerodynamic forces of the flow accelerate transition process; however, the effect of stopping factors is determined by parameters of the transition process that are difficult to name because of great uncertainty. At low excessive frequencies, dispersion of results grows significantly. This is determined by decrease in the difference of the measured frequencies and by increase of the uncertainty of the results. For the final velocity, inertia time constant depends on the values of the final velocity and is inversely proportional to it.

The change manner of time constant corresponds to the change manner of rotational frequency. When the rotational frequency decreases and approaches the final value, the time constant increases. When the final rotational frequency increases, increase of the time constant slows down. When the values of the rotational frequency are high, the increase of the time constant stops and indicators of its decrease appear.

Response characteristics of the chamber flow rate meters to a sudden flow rate change are similar to analogous characteristics of the turbine flow rate and cup air velocity meters, and the same methods for summary of the results as in the case of turbine meters can be applied using experimentally determined dependences of change of the inertia time constant of the meters that have several peculiarities.

5. MODELLING RESULTS OF TURBINE METER RESPONSE AND DYNAMIC ERROR

Investigations of turbine meter response and dynamic error were carried out when the flow pulsated according to simple (cosine, rectangular, triangle) and complex (that occur in practice) laws. Each complex law was obtained as a sum of elementary cosine pulsations at various amplitudes and frequencies. Equations and forms of such pulsations are shown in Table 5.1.

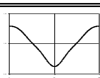
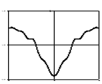
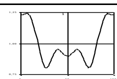
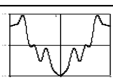
At low frequency (0.01–0.05 Hz), there was practically no inertia, the meter was able to follow even sudden flow changes, and its readings differed only slightly from the real flow value. When the frequency increased to 0.5 Hz, inertia was quite strong; however, the meter reacted to the flow change even at low amplitude. At frequency that reached 10 Hz for calculation conditions, the meter was not able to follow flow changes and its readings were practically constant and higher than the average flow rate value.

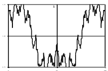
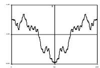
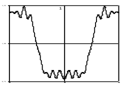
In all cases, the meter readings vary at the same frequency as the flow rate; however, phase displacement and amplitude decrease is apparent. For triangular, cosine and complex laws of pulsation, the meter readings change according to cosine law when pulsation frequency increases. Maximum and minimum of the meter readings are displaced in time in respect of the flow rate maximum and minimum and are reached when the meter reading equals to the instantaneous real flow rate. For rectangular law of pulsation, the meter readings vary according to complex exponential law. Maximum and minimum of the readings are reached during a sudden change of the flow rate. In all cases the bigger the amplitude of the meter readings, the bigger the amplitude of flow pulsation.

Dynamic errors and dimensionless amplitudes of the meter reading pulsations considering the flow rate pulsation frequency were calculated for all analysed laws of pulsations. Dependencies of dynamic error on frequency and amplitudes flow pulsation are shown in Fig. 5.2 (rectangular law of pulsation) and Fig. 5.3 a (complex law No. 1 of pulsation see Table 5.1). The following common dependences can be seen. At low frequencies f < (0.01–0.001) Hz, dynamic error is practically zero. When the frequency values exceed the indicated values, the error increases till a certain limit value that depends on flow pulsation law and amplitude.

The obtained results coincide with the results provided in [1]. However, document [1] does not indicate characteristics of the meter inertia, and the obtained results are only for a rectangular law of flow pulsation.

Table 5.1. Modelling of flow pulsations according to complex law

No.	Pulsation law	Form of pulsation	Coeff. C_a in Eq (2.14)	Coeff. k in Eq. (5.4)
1	$\overline{Q}$ =1+ $\Delta\overline{Q}_{nom}$ ·cos(2·π·t·f) – 0.09 $\Delta\overline{Q}_{nom}$ ·cos(4·π·t·f) + 0.07 $\Delta\overline{Q}_{nom}$ ·cos(6π·t·f)) - 0,04 $\Delta\overline{Q}_{nom}$ ·cos(8π·t·f)		44.24	5.8
2	$\overline{Q}$ =1+ $\Delta\overline{Q}_{nom}$ ·cos(2·π·t·f)- 0,25 $\Delta\overline{Q}_{nom}$ ·cos(4π·t·f) + 0.09 $\Delta\overline{Q}_{nom}$ ·cos(6·π·t·f) - 0,05 $\Delta\overline{Q}_{nom}$ ·cos12π·t·f) + 0.07 $\Delta\overline{Q}_{nom}$ ·cos(14π·t·f)) - 0,04 $\Delta\overline{Q}_{nom}$ ·cos(18π·t·f)		42.71	5.2
3	$\overline{Q}$ =1+2/3 Δ $\Delta\overline{Q}_{nom}$ ·cos(2·π·t·f)+1/2 $\Delta\overline{Q}_{nom}$ ·cos(4π·t·f) -1/4 $\Delta\overline{Q}_{nom}$ cos(8π·t·f)		48.93	5.7
4	$\overline{Q}$ =1+4/5 $\Delta\overline{Q}_{nom}$ ·cos(2·π·t·f)-1/4 $\Delta\overline{Q}_{nom}$ cos(8π·t·f) + 1/7 $\Delta\overline{Q}_{nom}$ ·cos(16π·t·f) – 1/12 $\Delta\overline{Q}_{nom}$ ·cos(20·π·t·f)		38.26	5.1

5	$\overline{Q}=1+\Delta\overline{Q}_{nom}\cdot\cos(2\cdot\pi\cdot t\cdot f)-0.35\,\Delta\overline{Q}_{nom}\cdot\cos(6\pi\cdot t\cdot f)+0.25\,\Delta\overline{Q}_{nom}\cdot\cos(28\pi\cdot t\cdot f)-0.09\,\Delta\overline{Q}_{nom}\cdot\cos(46\cdot\pi\cdot t\cdot f)-0.05\,\Delta\overline{Q}_{nom}\cdot\cos(96\pi\cdot t\cdot f)+0.07\,\Delta\overline{Q}_{nom}\cdot\cos(120\pi\cdot t\cdot f))-0.04\,\Delta\overline{Q}_{nom}\cdot\cos(150\pi\cdot t\cdot f)$		35.60	5.4
6	$\overline{Q}=1+\Delta\overline{Q}_{nom}\cos(2\cdot\pi\cdot t\cdot f)-0.35\,\Delta\overline{Q}_{nom}\cos(4\pi\cdot t\cdot f)+0.25\,\Delta\overline{Q}_{nom}\cdot\cos(14\pi\cdot t\cdot f)-0.09\,\Delta\overline{Q}_{nom}\cdot\cos(22\cdot\pi\cdot t\cdot f)-0.05\,\Delta\overline{Q}_{nom}\cos(48\pi\cdot t\cdot f)+0.07\,\Delta\overline{Q}_{nom}\cos(60\pi\cdot t\cdot f))-0.04\,\Delta\overline{Q}_{nom}\cos(76\pi\cdot t\cdot f)$		34.49	5.2
7	$\overline{Q}=1+\Delta\overline{Q}_{nom}\cos(2\cdot\pi\cdot t\cdot f)-0.25\,\Delta\overline{Q}_{nom}\cos(6\pi\cdot t\cdot f)+0.09\cdot\Delta\overline{Q}_{nom}\cos(10\cdot\pi\cdot t\cdot f)-0.05\,\Delta\overline{Q}_{nom}\cos(24\pi\cdot t\cdot f)+0.07\,\Delta\overline{Q}_{nom}\cos(30\pi\cdot t\cdot f))-0.04\,\Delta\overline{Q}_{nom}\cos(38\pi\cdot t\cdot f)$		59.86	4.7

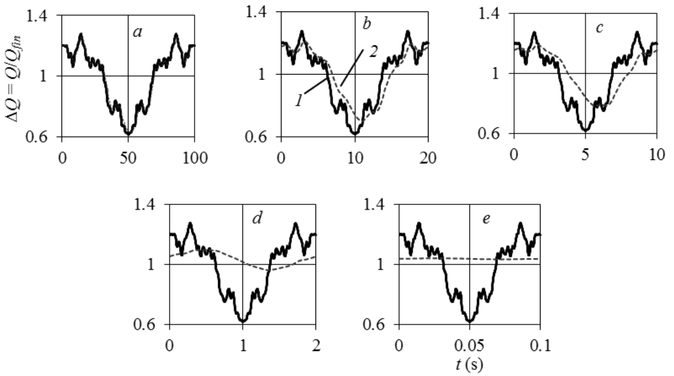


Fig. 5.1. Response of the turbine meter on flow pulsation at different frequencies pulsations, flow when flow rate pulsates according to complex law No. 6 (see Table 4.1). *a* – *f* = 0.01 Hz; *b* – *f* = 0.05 Hz; c – *f* = 0.1 Hz; *d* – *f* = 0.5 Hz, *e* – *f* = 10 Hz

Calculation results of the pulsation amplitude of rotational frequency of the meter rotor, concerning the flow rate pulsation frequency, are provided in Fig. 5.3 *b* at complex flow rate pulsation frequency No. 1 (Table 5.1) respectively to various pulsation amplitudes of flow rate frequency. The pulsation amplitudes of dynamic error and meter readings correlate with each other depending on flow rate pulsation parameters. When the flow rate pulsation amplitude increases, pulsation amplitude of the meter reading also increases. When flow rate pulsation frequency *f* increases, the response amplitude decreases, and retardation according to phase increases.

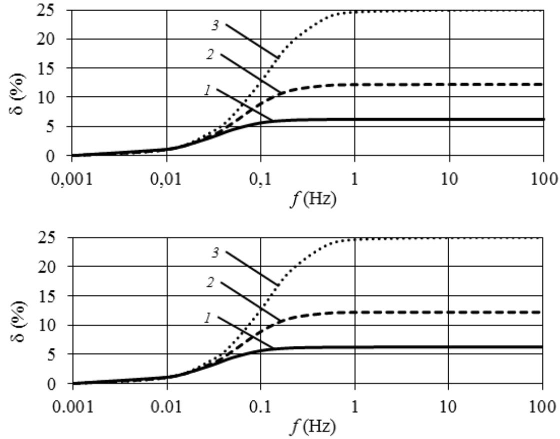


Fig. 5.2. Dynamic error dependence on flow pulsation frequency at different pulsation amplitudes and rectangular law. *1, 2, 3* – $\Delta\overline{Q}$ = 0.25; 0.35 and 0.5 respectively

Summarising the obtained results, it is evident that at pulsation frequency approx. (1–2) Hz, dynamic error reaches the limit value and stops increasing. Within the field or error limit value, the meter readings practically do not change, and inertia characteristics of the meter have no influence on dynamic error. This frequency increases coherently when the law of flow rate pulsation changes from triangle to rectangular. When the amplitude increases, the frequency limit value also increases. For more inert meters (higher values of time constant), the increase areas of the error curve move towards the lower frequencies, i.e., the limit value is reached earlier; for less inert meters, the process is the opposite. The meter's inertia decreases with decreased friction in bearings, better aerodynamics of the meter, decreased mass of the meter's impeller and increased gas pressure.

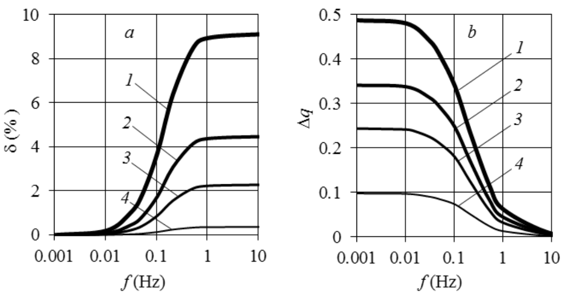


Fig. 5.3. Dynamic error of a turbine meter (*a*) and pulsation amplitude of the meter's rotational frequency (*b*) when the flow rate pulsates according to complex law No. 1. *1–4* $\Delta\overline{Q}$ = 0.5; 0.35; 0.25 and 0.1 respectively

Fig. 5.4 shows dependence of the limit dynamic error of the meter on dimensionless amplitude values.

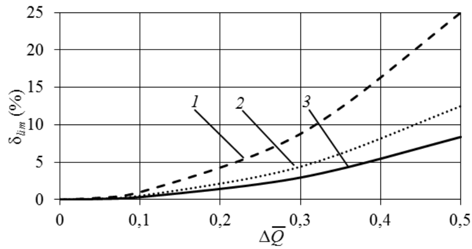


Fig. 5.4. Dynamic error limit value dependence on the law of the flow pulsation: 1, 2 and 3 – rectangle, cosine and triangle law's respectively

It can be seen that in all cases at any law of pulsation, this dependence on amplitude is quadratic and determined by Equation (2.14). The biggest error is obtained for rectangular law of flow pulsation. For cosine law the error is two times lower. The minimal error value is obtained for triangle law of pulsation; however, it is close to values obtained for the cosine law. Quadratic dependency of the dynamic error on change amplitude remains at high amplitudes (> 10 %) and other (≠ 1 Hz) frequencies.

Analysis shows that results of the dynamic error can be summarised using dependencies of dimensionless dynamic error on dimensionless parameter $\overline{f}$.

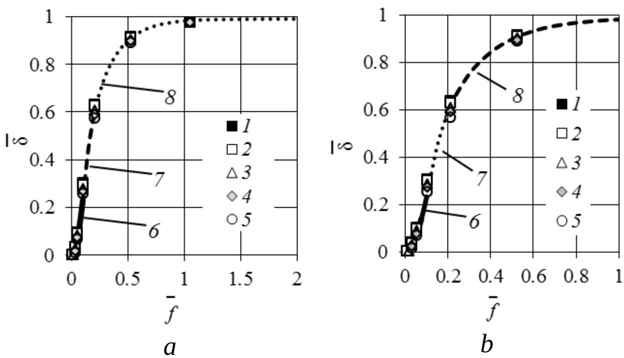


Fig. 5.5 Summarised dynamic error dependence on dimensionless flow pulsation frequency at different pulsation amplitudes. Q_{avg}= 400 m^3/h; *1*–5 – ΔQ = 0.05; 0.1; 0.25; 0.35; 0.5; *6* – approximation curve. *a* – cosine, *b* – triangle law of flow pulsation

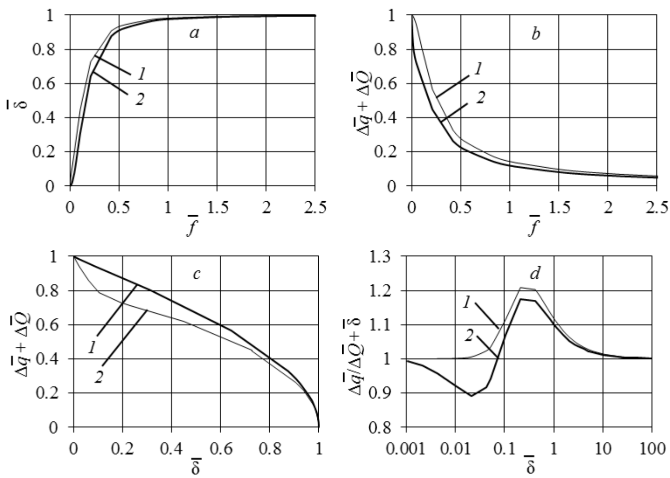


Fig. 5.6 Amplitude dependencies of summarized dynamic error of the turbine meter and the meter reading pulsation. *a* and *b* – amplitude dependencies of dynamic error and of readings pulsation on flow rate pulsation frequency; *c* and *d* – relation between amplitudes of dynamic error and readings pulsations. *1* – flow rate pulsations according to law No. 1; *2* – flow rate pulsations according to law No. 5 (see Table 5.1)

Fig. 5.6 shows summarised (dimensionless) turbine flow rate meter dynamic errors $\bar{\delta}$ and amplitude dependencies of rotational frequency pulsation of the rotor on flow rate pulsation frequency when they change according to laws No. 1 and 5 (Table 4.1) and dependencies that demonstrate relation between parameters $\bar{\delta}$ and $\Delta\bar{q}$.

Calculations were performed for the turbine meter with a metal impeller at values 0.05; 0.1; 0.25; 0.35 and 0.5 of relative flow rate pulsation amplitude $\overline{\Delta Q}$. Dimensionless dynamic error of the meter depends only on dimensionless pulsation frequency $\bar{f}$.

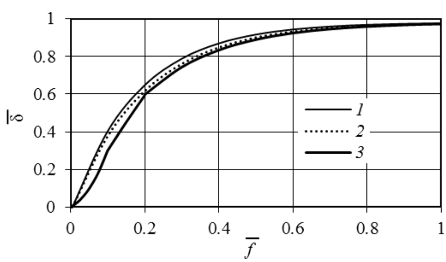


Fig. 5.7 Dimensionless dynamic error of the turbine meter at the analysed complex pulsation laws and limit values of coefficient *k*: *1* – k_{min} = 4.7; *2* – k_{max} = 5.8; *3* – k_{avg} = 5.2

It changes exponentially and can be summarised by the following equation (see Fig. 5.7):

$$\bar{\delta} = 1 - e^{-k\bar{f}} \, . \qquad (5.1)$$

This equation can be applied to any other turbine flow meter given that the inertia constant of the meter is known.

Coefficient *k* values at various laws of pulsations are provided in Table 5.1. Constant *k* values considering the law of flow rate pulsation vary in range of (4.7–5.8). As can be seen in Fig. 5.7, difference between results at limit *k* values is not significant. Thus, with uncertainty that does not exceed ±7 % average *k* value k_{vid} = 5.2 can be used for all analysed complex laws of pulsation.

6. MODELLING RESULTS OF CUP ANEMOMETER RESPONSE AND DYNAMIC ERROR

The method used for the turbine meters was applied for calculation of response and dynamic error of the cup air velocity meter. The only difference was that in case of the turbine meters, the inertia time constant was assumed to depend only on the final flow rate or the final rotational frequency. In case of the determining time constant of velocity meter influence of not only the final frequency but also of excess (difference between the current and the final) frequency value were evaluated. These dependencies were described by linear expressions.

The calculation results of the investigated anemometer's response to the modelled wind velocity fluctuations are shown in Fig. 6.1 at the following conditions: v_{max}=20 m/s; v_{min} = 5 m/s; k_V =0.5; k_t = 0.25; general pulsation frequency (0.01 ÷ 10) Hz.

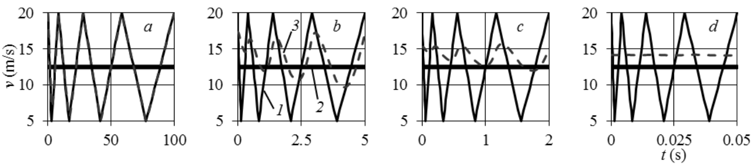
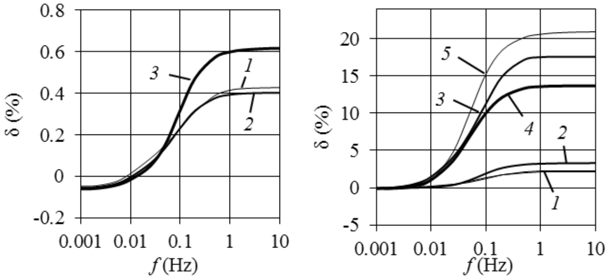


Fig. 6.1. Response of the cup velocity meter to wind fluctuations. 1 – instantaneous wind velocity; 2 – average wind velocity; 3 – response of the air velocity meter. *a, b, c, d* *f* = 0.01; 0.2; 0,5; 20 Hz respectively

At small pulsation frequency values ≤ 0.01 Hz, the cup velocity meter does not show rotational inertia (the same as in the case of the turbine flow rate meters); thus, it accurately repeats the air velocity pulsations. Also at increased pulsation frequency, the meter is not able to follow the real velocity value, and the response of the meter becomes a straight line that is higher than the average flow rate value.



a *b*

Fig. 6.2. Modelling results of dynamic error of the cup anemometer at k_t = 0.5 and v_{max} = 10 m/s. *a* v_{min} = 1 m/s; *1–3* – k_v = 0.1; 0.5 and 1 respectively; *b 1–2* – v_{min} = 7.5 m/s, k_v = 0.5 and 1 respectively; *3–5* – v_{min} = 1 m/s k_v = 0.1; 0.5 and 1 respectively

Numerical modelling results of the dynamic error and the meter's response for flow pulsation at parameters k_v = (0.1; 0.5; 1); k_t = 0.5 are shown in Fig. 6.2. Manner of the shown dependencies is the same as for case of turbine gas meter. At small pulsation frequencies, the influence of inertia is practically non-existent, and the dynamic error is close to 0. When the frequency increases, the dynamic error also starts increasing until its limit value. As the frequency further increases, the rotational frequency of the meter's rotor becomes constant, and the dynamic error ceases to change. The character change of the relative swing of the meter readings corresponds to the character change of the dynamic error; however, they are of opposite directions.

Contrary to the turbine flow rate meters, dynamic errors and curves of the dimensionless amplitude layer out at different values of coefficient k_v. Moreover, separate curves intersect again. This can be explained by influence of an average velocity on inertia time constant.

During the investigation, it was determined that at small pulsation frequencies (0.001–0.01) Hz and when coefficient k_v and k_t values are >0, dynamic error of the air velocity meter is negative (see Fig. 6.2 *a*). This happens because increase and decrease of rotational frequency are not symmetrical in respect of velocity axis. The modelling results are confirmed by other researchers as well [2, 3].

Besides frequency, the value of dynamic error is also influenced by the form of pulsation impulses that is described by coefficients k_v and k_t.

Figure 6.3 shows the influence of coefficient k_t on the dynamic error of the air velocity meter. The figure demonstrates that the influence of coefficient k_t on the value of dynamic error is insignificant.

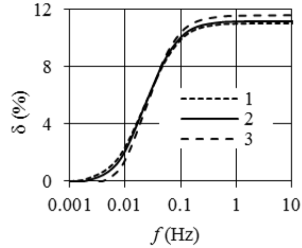


Fig. 6.3. Parameter k_t influence on dynamic error. v_{max} = 20 m/s, v_{min} = 2 m/s, k_v = 0.5. *1–3* k_t = 0; 0.25; 0.5 respectively

Figure 6.4 shows dependency of the limit dynamic error value on air velocity pulsations amplitudes at different values of coefficient k_V and velocity.

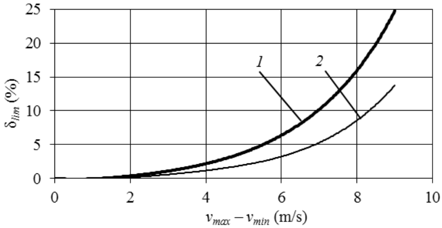


Fig. 6.4 Limit dynamic error dependence on difference between maximal and minimal value of velocity. k_t = 0.25. *1* – k_v = 0; *2* – k_v = 0.6

The same as for the turbine flow rate meters, the dynamic error value increases according to the square law when difference between maximal and minimal value increases. The absolute maximal velocity value does not influence the dynamic error value.

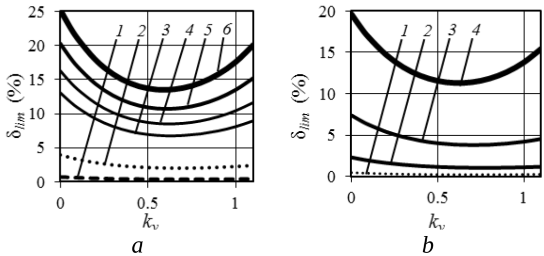


Fig. 6.5. Dynamic error limit value dependence on impulse amplitude k_v. k_t = 0.5. *a* v_{max} = 10 m/s; *1–6* – v_{min} = 7.5; 5; 2.5; 2; 1.5; 1 m/s respectively; *b* v_{max} = 5 m/s; *1–4* – v_{min} = 4; 3; 2; 1 m/s respectively

Dynamic error limit value dependence on parameter k_v is shown in Fig. 6.5. At constant operational conditions, the dynamic error limit value decreases by half by the increase of coefficient k_v value from 0 to 0.6. Further, as k_v increases, the dynamic error limit value also starts increasing.

The obtained investigation results were summarised using variables $\bar{f}$ and $\bar{\delta}$ that are described in Subsection 3.2. The results are shown in Fig. 6.6. The dependence summarises dynamic error values at the following parameters: v_{maks}= (5–20) m/s, v_{min} = (1–15) m/s, k_t = (0–0.5), k_v = (0.1–1), f = (0.001–100) Hz.

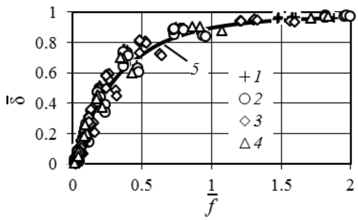


Fig. 6.6. The dependence summarised by dynamic error of the air velocity meter. v_{min} = 1 m/s. *1–4* – v_{max} = 20; 15; 10; 5 m/s respectively; *5* – approximation curve according to Equation (6.1)

All calculation results were approximated using the following equation:

$$\bar{\delta} = \overline{0{,}985} \cdot \left(1 - e^{-2{,}9 \cdot \left(1 - \bar{f}/6 \right) \bar{f}} \right); \qquad (6.1)$$

This dependence with uncertainty ±7 % applies at dimensionless frequency value within boundaries $\bar{f}$ = (0 – 2).

7. EVALUATION OF DYNAMIC ERROR OF THE ROTARY FLOW RATE METERS

The scheme of the test facility that was used in the investigation is shown in Fig. 2.2 according to the method described in Subsection 2.1. Errors of rotary gas meters are defined by leakages of gas through the gaps between vanes and body of the meter. Due to this, flows pulsations do not significantly influence accuracy of the rotary flow meter [4, 5].

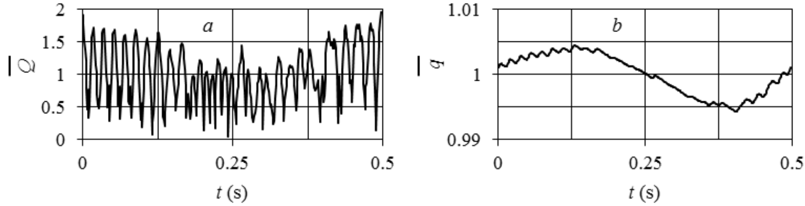


Fig. 7.1. Regime 1: *a* – experimentally determined flow rate pulsation in time; *b* – theoretically calculated response of the turbine flow rate meter

Experimentally obtained and theoretically calculated values of dynamic error are provided in Table 7.1.

The meter's response to pressure pulsations and dynamic error were calculated using calculated instantaneous values array $\overline{\sqrt{|\Delta p_i|}}$ and data about the time constant τ dependence of the investigated meter on flow rate. Examples of measurement and data processing at three different forms of flow rate pulsations are shown in Fig. 7.1.

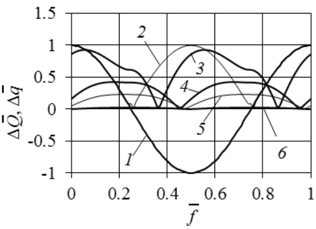
Table 7.1. Dynamic error values

Regime No.	Q_{avg} m^3/h	Frequency of pulsation f Hz	Dimensionless amplitude of pulsation $\overline{\Delta Q}$	Dynamic error δ %	
				Experiment	Calculation
1	26.77	1	0.1	10.6 ± 3 %	11.05
2	27.76	0.8	0.45	15.2 ± 3 %	17.1
3	21.77	0.4	0.6	33.5 ± 3 %	36.2

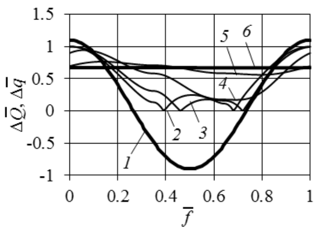
While evaluating uncertainties of the measured values, it is assumed that experimental and numerical results show a good correspondence. Thus it again proves advantages of the created model and its universal application.

8. DYNAMIC ERROR OF THE TURBINE FLOW METER IN THE REVERSAL FLOW

The meter's response to flow rate pulsations was analysed according to triangle and cosine laws in dimensionless form at different pulsation frequencies and several values C < 1, i.e., for oscillating and reversal flows. Figure 8.1 demonstrates a dimensionless response of the meter to the flow rate pulsation according to cosine patter at the flow when 0 ≤ C <1.



a



b

Fig. 8.1. Dimensionless response of the meter to the flow rate pulsation according to cosine law at periodical change of the flow direction. *a:* C = 0.1, *1* – relative change of the flow rate; *2–6* – relative readings of the meter at: $f{\cdot}T$ = = 0.0053; 0.106; 0.526 and 52.8; *b:*

C = 0.6, *1* – relative change of the flow rate; *2–6* – relative readings of the meter at: *f·T* = 0.005, 0.026, 0.106, 0.53 and 52.8 respectively

When dimensionless pulsation frequency is increasing, inertia becomes stronger and rotational frequency of the meter increasingly falls behind the flow rate pulsation frequency. The response amplitude decreases. At high values of $\bar{f}$, the meter stops reacting to the flow rate pulsations, and its rotational frequency remains constant. When the flow rate value passes though zero and the direction of the flow changes, the response changes as well. Regardless of whether the flow rate increases or decreases, rotational frequency of the meter starts increasing when zero value is reached. Hence, rotational frequency registered by the meter is never negative.

Figure 8.2 shows calculation results of dynamic errors. The meter errors are influenced by the same factors as the response. Besides inertia of the rotor, another factor becomes apparent – the modern turbine meters do not react to the change of the flow rate direction and send all pulses to the register. Influence of these two factors is different at different *C* and $\bar{f}$ values. Due to this $\bar{f}$ influence of dimensionless frequency on dimensionless error is non-monotonous, and this feature most clearly manifests in *C* = (0.25–0.5).

A small change in value *C* from *C* = 0.35 till 0.36 calls for a sudden change in error δ/δ_{lim} character from *C* as well as from $\bar{f}$. At approximate value *C* = 0.355, dimensionless error reaches its highest value +25 and suddenly changes to value -25. The dimensionless error sign changes, because at *C* = 0.355 the limit value of error passes through zero and changes its sign.

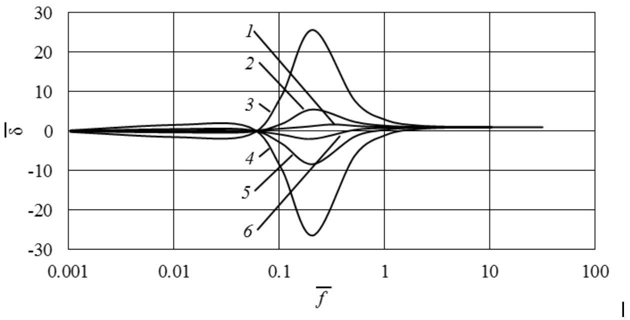


Fig. 8.2. Dynamic error dependence on dimensionless flow rate frequency at cosine pulsation dependence and periodic change of the flow direction: *1–6* – respectively *C* = 0.3; 0.34; 0.35; 0.355; 0.36; 0.38

In all cases at high frequency values, $\delta/\delta_{lim} = 1$, and this corresponds to δ_{lim} definition. Analogous results were obtained at different laws of pulsation as well as at complex laws. Figure 8.3 shows limit error δ_{lim} dependency on *C* at two laws of flow pulsation: triangle and cosine. The error changes greatly by its absolute value as well as by its sign in the region of changing sign pulsations when $0 \leq C < 1$. When $C = 0$, i.e., the total flow rate is zero, the limit error reaches negative value δ_{rib} = -100 %.

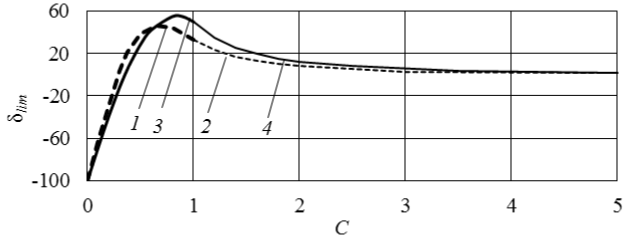


Fig. 8.3. Limit error dependence on *C*: *1* and *2* – triangle law of pulsation, flow with and without sign change respectively; *3* and *4* – cosine law of pulsation, flow with and without sign change respectively

CONCLUSIONS

In this thesis, performed experiments of step response of turbine flow meters in the range (0–1000) m^3/h, rotary flow meter in the range (0–100) m^3/h and cup anemometers in the range of (0–20) m/s and also performed numerical simulations of behavior of flow meters in flow, which pulsates with frequency (0.001–100) Hz and amplitude 0.05–0.65 allow to state the following conclusions:

1. The method for determining the inertia time constant of rotor of tachometric flow meters according to step response was created, which allow the assessment of dependence of inertia time constant on the initial, final and excessive frequency of rotation of the rotor. It was determined, that initial frequency of rotation of the rotor does not affect the value of time constant, however time constant depends on the excessive frequency of rotation non-linearly. Time constant is inversely proportional to the final value of frequency of rotation.
2. Numerical simulation method for determination of response and dynamic error of turbine flow meters was created, when the flow rate pulses according to simple (cosine, rectangular and triangular) and complex laws. Influence of frequency of pulsation starts to manifest at 0.1 Hz, while increasing by 1 Hz variation of meter reading in all cases converges to cosine pattern. At frequency more than 2 Hz limit value of dynamic error is reached, which depends on law and amplitude (by quadratic law) of pulsation.
3. Change of response and dynamic error of mechanical cup anemometer is determined by the minimal and maximal value of velocity pulsation, frequency of wind speed pulsation and change rate of pulsation frequency and amplitude. Influence of change of frequency is similar to turbine flow meters, except low frequencies (less than 0.01 Hz) along with irregular pulsations at which dynamic error is negative.
4. By applying the complex of dimensionless variables generalized regularities of response and dynamic error of turbine gas meters and cup anemometers with uncertainty ±7 % allows to define response and dynamic error of the meters when flow pulses under any law of pulsation.
5. Response regularities of rotary flow meters to flow pulsations was determined, which are similar to the response of turbine flow meters. Change of flow rate in these meters follows rotational frequency changes of their rotor, hence the measurement errors is defined by leakages through the gaps between the rotors and body thus influence of flow pulsations is small.
6. Using dimensionless parameter, which describes flow rate displacement in time, summarised dependences of dynamic error and limit value of dynamic error allows to define response and dynamic error of turbine gas meter in oscillating and pulsing reversal flow.

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REZIUMĖ

Darbe ištirta oro srauto pulsacijų įtaką tachometrinių ir kaušelinių greičio (debito) matuoklių veikimo principai ir paklaidos esant pulsuojančiam srautui. Sudarytas skaitinis modelis, leidžiantis nustatyti tachometrinių matuoklių atsaką ir dinamines paklaidas esant įvairiems pulsacijų dėsningumams. Naudojant nedimensinių parametrų modelį apibendrintos tachometrinių matuoklių atsako ir dinaminės paklaidos priklausomybės. Analizuojant gautus eksperimentinius tyrimo ir teorinio modeliavimo rezultatus parengtos rekomendacijos dėl dinaminės paklaidos prognozavimo ir mažinimo. Būtina pabrėžti, kad turbininiai dujų matuokliai yra vieni svarbiausių gamtinių dujų vartojimo debito matavimo priemonė Jais matuojama iki 70% bendrojo gamtinių dujų vartojimo, o turbininiai dujų matuokliai plačiai naudojami kaip pamatinės matavimo priemonės etaloniniuose įrenginiuose oro (dujų) tūrio ir srauto vieneto vertėms atkurti. Taigi darbe sprendžiami uždaviniai turintys praktinį taikomą pobūdį, o taip pat nemažiau svarbūs moksliniu požiūriu.

Vykdant darbą sukurtas ir realizuotas aerodinaminis įrenginys matuoklio inercijos jėgoms tirti, o taip pat eksperimentinis įrenginys debito pulsacijų įtakai turbininiams matuokliams tyrinėti. Sukurti laiko pastoviųjų nustatymo pusiau eksperimentinį ir skaitinio modeliavimo metodai. Tyrimais nustatyta, kad

turbininių debito matuoklių dinaminę paklaidą lemia pulsacijų amplitudė, dažnis ir kitimo dėsningumas, o ribinės dinaminės paklaidos kinta pagal kvadratinę priklausomybę. Kaušelinių oro greičio matuoklių dinaminę paklaidą lemia srauto greičio mažiausia ir didžiausia vertės, pulsacijos dažnis bei koeficientai, apibūdinantys greičio pulsacijos amplitudės ir dažnio mažėjimo tempą. Nustatyta, kad pulsacijų dažnio ir amplitudės įtaka yra analogiška turbininiams debito matuokliams. Tai naujai gauta informacija apie matuoklių su besisukančiomis dalimis veikimo principus leidžianti gerinti tachometrinių ir kaušelinių oro greičio matuoklių darbo aspektus ir įvertinti šių prietaisų dinamines paklaidas.

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