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On Acoustic Amplification of Gas Pressure Pulsations in Metering Circuits

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Abstract: The procedure of selection of acoustic amplifier and correcting element parameters intended for pressure pulsation measuring circuits with small amplitudes in high gas temperature conditions is given. Outcomes of experimental researches of a metering circuit with the developed means of a signal amplification and correction of amplitude-frequency characteristics are presented.

Key words: Correcting element, acoustic amplifier, pulsations, experimental researches, frequency characteristics

INTRODUCTION

The important problem arising upon measurement of gas pressure pulsation with small amplitude in conditions of high temperature is transmission of a signal from a point of measuring to the pressure transducer with minimum dynamic distortions. When measuring pressure pulsation at a high gas temperature in a monitored object it is necessary to connect the primary transducer (sensor) to a pressure tap point by means of a tube. It is known that due to a resonance phenomena a distortion of a measured signal and a complementary error at low transducer sensitivity appear in the tube (Eggers, 1974; Karam, 1966; Nichols, 1962; Furletov *et al*., 2007; Eugen Ckudrzyk, 1971; Funk and Wood, 1974; Gimagiev and Bystro, 1981; Gimadiev *et al*., 1983; Bystrov *et al*., 1981). In this connection, there is still a necessity for acoustic amplification of pressure pulsation and development of the provisions eliminating resonance processes. An example of the monitored object showing necessity in application of developed elements is the jet acoustic gas temperature sensor in which it is necessary to eliminate influence of the intake channel on characteristics of the element and to amplify the weak signal transmitted from the temperature sensor to the pressure pulsation sensor.

DERIVATION OF DESIGN RELATIONSHIPS

When deriving the design relationships it was supposed that the test object is an ideal source of gas pressure pulsation; an energy loss of fluctuations along the length of a waveguide is considered according to the high-frequency theory (Shorin *et al*., 2000, 2007) losses of a fluctuation energy at a junction of channel sections and heat exchange with a surrounding medium are not considered.

In view of the accepted assumptions the complex amplitudes of pressure and flow fluctuations in ith cross-sections of the acoustic circuit (Fig. 1) are described by dependences:

$$p_{11} = p_{12}\mathrm{ch}(\Gamma_1 l_1) + Z_{w1} q_{12}\mathrm{sh}(\Gamma_1 l_1) \tag{1}$$

$$q_{11} = \frac{p_{12}\mathrm{ch}(\Gamma_1 l_1)}{Z_{w1} + q_{12}\mathrm{sh}(\Gamma_1 l_1)} \tag{2}$$

Where:

p_{11}, p_{12} = Complex amplitudes of pressure fluctuations
q_{11}, q_{12} = Complex amplitudes of flow fluctuations
$\Gamma_1 = \sqrt{Z_1 Y_1}$ = A wave propagation factor
$\Gamma_1 = \sqrt{Z_1 Y_1}$ = A wave resistance of the intake channel

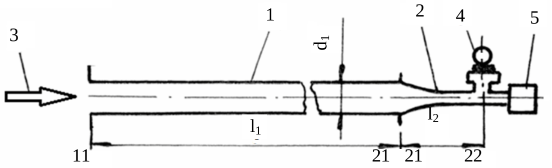

Fig. 1: The computational model of the gas metering circuit with the intake channel and the acoustic amplifier of pressure pulsations; 1: the intake waveguide channel; 2: the acoustic amplifier; 3: the pressure pulsation source (the test object); 4: the pressure pulsation transducer and 5: the acoustic correcting element

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Components of Eq. 1 and 2 Γ_1 and Z_{w1} are defined according to dependences:

$$Z_1 = R_1 + j\omega L_1,\ Y_1 = G_1 + j\omega C_1$$

Where:

$$R_1 = \frac{L_1\sqrt{\omega\omega_{v1}}}{2}$$

is an an acoustical resistance;

$$G_1 = \frac{(k-1)C_1\sqrt{\omega\omega_{v1}}}{2\sqrt{\Pr}}$$

is an acoustic conductance; $L_1 = 4\rho/\pi d_1^2$ is an acoustic inductance; $C_1 = \pi d_1^2/4kP_0$ is an acoustic capacity; $\omega_{v1} = 32v/d_1^2$ is a characteristic frequency; v is a kinematic viscosity of gas; k is adiabatic coefficient; Pr is a Prandtl number; P_0 is medium pressure; d_1 is an internal diameter of the intake channel.

The complex amplitude of pressure fluctuations at the output of the intake channel p_{11} is the parameter which is necessary to transmit to the output of the pressure pulsation transducer being amplified and with minimum dynamic distortions.

Therefore, in the further when defining frequency characteristics of the metering circuit p_{11} value is base concerning to which the remaining parameters will be compared down to cross-section 22 (Fig. 1).

Amplification of acoustic pressure fluctuations is carried out with the flared end (Fig. 2) in which the cross-sectional area varies according to exponential dependence:

$$A_x = A_{21}\exp(\alpha_A x) \tag{3}$$

where, $\alpha = (A_{21}/A_{22})l_2$. The acoustic amplifier is representable in the form of serial connection of the homogeneous sections (Fig. 2) which passage areas differ by an equal value $\Delta A = (A_{21}\text{-}A_{22})/n$ where $n \geq 2$, number of elements into which the section of the amplifier is divided, A_{21}, A_{22}: passage areas at the input of the amplifier and at its output.

Then lengths of ith sections and passage areas of the amplifier are defined under esquations:

$$l_{2i} = \frac{1}{\alpha_A} l_2 \left[\left(\frac{A_{21}\text{-}\Delta A}{2}\right)\Big/ A_{21}\right]$$

$$A_i = A_{i\text{-}1}\text{-}\Delta A$$

where, $A_1 = A_{21}$, $A_n = A_{22}$. In view of the accepted division of the acoustic amplifier the complex amplitudes of pressure and flow fluctuations in its ith cross-sections (Fig. 2) are described by dependences (Eq. 4 and 5):

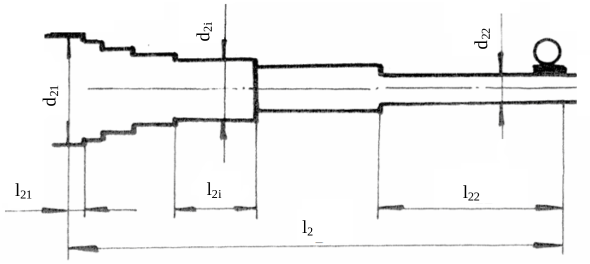

Fig. 2: The computational model of the acoustic amplifier of pressure fluctuations

$$p_1^{(i)} = p_2^{(i)}\mathrm{ch}(\Gamma_i l_i) + Z_{wi} q_2^{(i)}\mathrm{sh}(\Gamma_i l_i) \tag{4}$$

$$q_1^{(i)} = \frac{p_2^{(i)}\mathrm{sh}(\Gamma_i l_i)}{Z_{wi} + q_2^{(i)}\mathrm{ch}(\Gamma_i l_i)},\ i = 1...n \tag{5}$$

Parameters $\Gamma_i = \sqrt{Z_i Y_i}$, $Z_{wi} = \sqrt{Z_i/Y_i}$ in Eq. 4 and 5 are calculated using the expressions of the same form as for Z_1 and Y_1 (Eq. 1 and 2) with that difference that diameter d_1 is substituted with values:

$$d_i = \sqrt{\frac{4A_i}{\pi}}$$

The pressure pulsation transducer is installed as a by-pass unit to the correcting element at an exit from the amplifier and can have the tapped cavity volume V_p. The input acoustic conductance of this vacuity $Y_p = q_p/p_{22}$ is calculated by Eq. 6:

$$Y_p = j\frac{V_p\omega}{\rho c^2} \tag{6}$$

Where:

q_p = Complex amplitude of pressure fluctuations at the output in the pressure unit
c = Acoustic velocity in the actuating medium

In order to eliminate resonance phenomena in a metering circuit it is proposed to connect to an exit of the acoustic amplifier a non-reflecting load. Such load may be a long pipeline with a diameter equal to the diameter of the acoustic amplifier at its exit that is d_{22}. Then fluctuations at an exit from the amplifier transit into the load without reflecting and the pressure pulsation transducer registers only incident amplified pressure fluctuations. Considering awkwardness of the long pipeline, it is recommended to connect to the exit of the acoustic amplifier an acoustic load in the form of a set of capillary channels with the total passage areas close to the passage area at epy exit of the amplifier.

Complex amplitudes of pressure and flow fluctuations at the input in the capillary channel and at its output are linked by the dependences analogous to the intake channel:

$$p_{k1} = p_{k2}\mathrm{ch}(\Gamma_k l_k) + Z_{wk} q_{k2}\mathrm{sh}(\Gamma_k l_k) \tag{7}$$

$$q_{k1} = \frac{p_{k2}\mathrm{ch}(\Gamma_k l_k)}{Z_{wk} + q_{k2}\mathrm{sh}(\Gamma_k l_k)} \tag{8}$$

where, l_k is length of the capillary channel. Parameters $\Gamma_k = \sqrt{Z_k Y_k}$, $Z_{wk} = Z_k / Y_k$ are computed using the expressions the same by their form as for Z_1 and y_1 (Eq. 1 and 2) with the difference that diameter d_1 is substituted with diameter of the capillary channel d_k defined from the condition:

$$d_k = \frac{d_{22}}{\sqrt{N_k}}$$

where, N_k is number of capillaries. The number of capillaries N_k is as a result of computation in view of that the more capillaries and more their length than more uniform will be an amplitude-frequency characteristic of the metering circuit.

Boundary conditions at an output from the amplifier are equalities:

$$q_{22} = q_p + N_k q_{k1},\ p_p = p_{22},\ p_{k1} = p_{22} \tag{9}$$

Capillary channels at the output can be closed or a part from them can be connected to small capacity which promotes to some degree to decreasing of the required length of capillaries. Let's suppose that capillaries at the output are completely closed that is the requirement is satisfied for them:

$$q_{k2} = 0 \tag{10}$$

When computing frequency characteristics of the metering circuit the impedance method is applied which essence consists in that at first acoustic conductances of the circuit sections are defined with use of equalities Eq. 1-10 sequentially from the end of the circuit to its beginning down to cross-section 11 (Fig. 1):

$$Y_{k1} = \frac{q_{k1}}{p_{k1}} = \frac{\mathrm{th}(\Gamma_k l_k)}{Z_{wk}};\ Y_{22} = Y_{k1} + Y_p;\ Y_1^{(n)} = Y_{22};$$

$$Y_1^{(i)} = \frac{q_1^{(i)}}{p_1^{(i)}} = \frac{\dfrac{\mathrm{sh}(\Gamma_i l_i)}{Z_{wi} + Y_1^{(i+1)}\mathrm{ch}(\Gamma_i l_i)}}{\mathrm{ch}(\Gamma_i l_i) + Z_{wi} Y_1^{(i+1)}\mathrm{sh}(\Gamma_i l_i)},\ i = n...1 \tag{11}$$

$$Y_{12} = Y_1^{(1)};\ Y_{11}\frac{q_{11}}{p_{11}} = \frac{\dfrac{\mathrm{sh}(\Gamma_1 l_1)}{Z_{w1} + Y_{12}\mathrm{ch}(\Gamma_1 l_1)}}{\mathrm{ch}(\Gamma_1 l_1) + Z_{w1} + Y_{12}\mathrm{ch}(\Gamma_1 l_1)}$$

Then, under known complex amplitude at the input in the metering circuit or in the monitored object p_{11} and input conductance of the metering circuit Y_{11}, it is possible to define complex amplitude of flow fluctuations at the input in the circuit:

$$q_{11} = Y_{11} p_{11} \tag{12}$$

As p_{11} and q_{11} are known values then having transit from the beginning of the metering circuit to its end complex amplitudes of pressure and flow fluctuations in all chosen cross-sections down to the pressure unit are defined on the basis of equalities (Eq. 1-11). Upon that if the complex amplitude of pressure fluctuations in the cross-section 22 will be calculated that is p_{22}, it is possible to define the frequency function $W(\omega) = p_{22}/p_{11}$. And the amplitude-frequency characteristic of the metering circuit:

$$M(f) = \frac{|p_{22}|}{|p_{11}|}$$

where, f the cyclic frequency of pressure fluctuation.

EXPERIMENTAL RESEARCHES

Experimental researches were performed on the bench for the frequency tests of metering circuits (Gimadiev *et al*., 2006; Gimadiev, 2012; Shorin, 2012). Let's consider the computation and the experimental research of the metering circuit of the jet acoustic sensor of gas temperature in the capacity of an example (Fig. 3). When changing temperature of the gas flow the pressure fluctuation frequency at the outlet from the temperature transducer varies over the range of 7-9 kHz. Pressure fluctuations with small amplitude are transmitted to the output of the intake channel and further to the acoustic amplifier, the pressure sensor and the correcting element. Diameter and length of the intake channel were equal to $d_1 = 8$ mm, $l_1 = 1.4$ m. The acoustic amplifier has the form of the flared end in length of $l_2 = 48$ mm with diameters at the input and the output $d^{(1)} = 8$ mm and $d^{(n)} = 3$ mm, accordingly. A set of capillary channels (Shorin *et al*., 2007) is applied in the capacity of the correcting element. Computation of amplitude-frequency characteristics was performed with application of program RUDIP (Gimadiev, 2012) specially written by researchers with use of algorithmic language C++

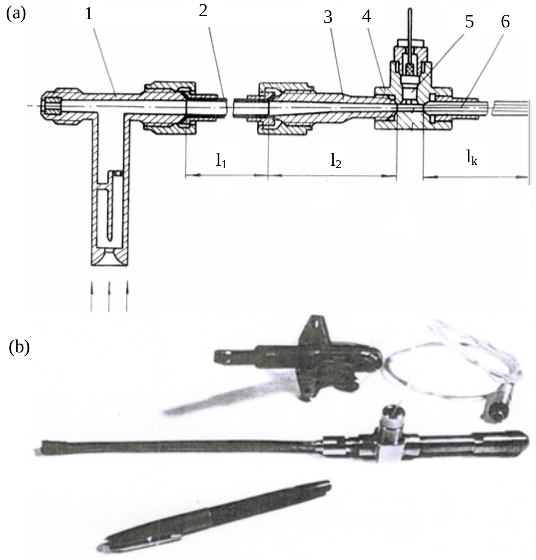

Fig. 3: a) The structural scheme and b) external view of the acoustic metering circuit; 1: the jet acoustic sensor of gas temperature; 2: the waveguide channel; 3: the acoustic amplifier; 4: the transition fitting; 5: the pressure pulsation transducer and 6: the capillary correcting element

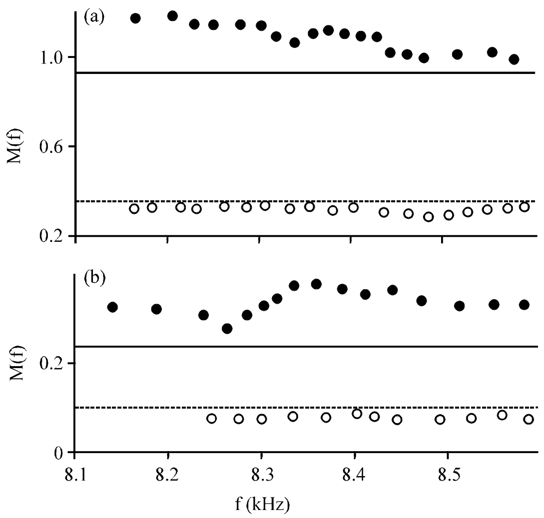

Fig. 4: The amplitude-frequency characteristic of the metering circuit at; a) $P_0 = 0.1$ Mpa and b) $P_0 = 0.2$ MPa. ----- shows computation; ○ shows experimental data without the acoustic amplifier and with the capillary correcting element ($d_k = 0.8$ mm; $l_k = 0.53$ m; $N_k = 100$); — shows computation; ● shows experimental data with the acoustic amplifier ($d_{21} = 8$ mm; $d_{22} = 3$ mm; $l_2 = 80$ mm) and the capillary correcting element ($d_k = 0.5$ mm; $l_k = 0.4$ m; $N_k = 34$)

(Fig. 4). The amplitude-frequency characteristic of the metering circuit at $P_0 = 0.1$ Mpa (Fig. 4a) and $P_0 = 0.2$ MPa (Fig. 4b).

Theoretical and experimental amplitude-frequency characteristics of the described metering circuit are presented in Fig. 4.

Under application of the designed acoustic amplifier, amplification of the signal in the circuit of the gas temperature sensor in 2.5-3 times is achieved at medium pressures 0.02 and 0.1 MPa (absolute). Different character of the discrepancy between theoretical and experimental results at various medium pressures can be caused by inaccuracy of mathematical model in high-frequency area of fluctuation processes and a deficient account of the flared end internal surface form of the acoustic amplifier.

CONCLUSION

Investigations confirm the real possibility to create metering circuits with acoustic amplification of the pressure signal in the form of a flared end and the element for correction of the amplitude-frequency characteristic in the form of the set of capillary channels.

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