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CONSTRUCTION VERIFICATION AND MODELING OF ACOUSTIC MEASURING PROBE

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Abstract. The paper presents a study of wave processes occurring in the experimental measuring acoustic probe. The probe is designed for contactless measurement of linear dimensions and micro-movements of physical objects using acoustic oscillations in the sound range. In the course of the study, an equivalent circuit of the probe in the form of a T-link band electric K-filter was drawn up. According to the design geometric parameters of the acoustic probe, the electrical parameters of the K-filter components are calculated. To verify the theoretical results, a set of experimental equipment was developed, and a method of experimental research was developed. Experimental studies have confirmed the possibility of designing acoustic probe using the proposed method of calculating the geometric parameters of its elements.

Keywords: measurement; contactless method; acoustics; interference; standing wave; micro-displacement; simulation; experiment.

Introduction and Problem Statement

In recent years, non-destructive methods of product control using acoustic methods have become widely used in research laboratories and enterprise industrial divisions. The main share of such methods and devices developed for their implementation relies on measuring systems that use ultrasonic acoustic waves, the operating range of which is in the range of 0.1–1.0 MHz [1], and are transmitted to the object of study by contact. In measuring instruments, ultrasonic vibrations can be transmitted through the air. Since the attenuation of ultrasound in air is quite significant [4] and increases in proportion to the square of the frequency, transmission through air is effective only for low-frequency oscillations [2, 3]. Both theoretical and experimental methods of control of linear dimensions and micro-movements of objects in precision engineering and instrument making are insufficiently developed [3], in the field of nanotechnology [12].

The paper presents development and research of a non-contact method for measuring the linear dimensions of parts and linear micro-displacements of objects using acoustic sound waves. The scientific research was carried out in the direction of using the effects of interference of sound oscillations and the formation of acoustic standing waves [5], [6].

Main Material Presentation

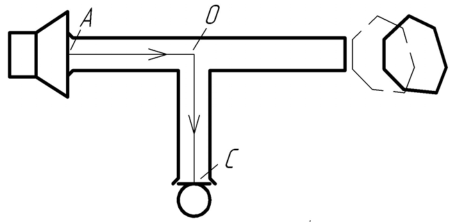
A transducer containing a speaker, a microphone and a sound guide was used to control the movement of the object of study using the phenomenon of sound wave interference [11]. Hereinafter, this converter is called a “probe”.

The probe operation diagram is shown in Fig. 1.

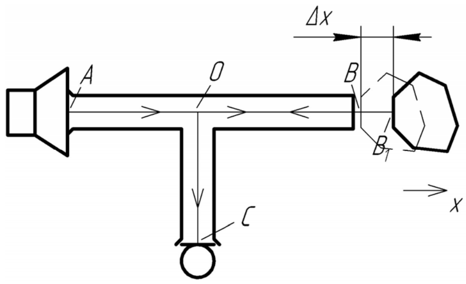
The length of the reference wave (Fig. 1, *a*) $l_1 = AO + OC$.

The length of the measuring wave (Fig. 1, *b*) $l_2 = AO + OB + BO + OC = AO + 2BO + OC$.

The length of the measuring wave when moving the object along the x-axis by a distance Δx is
$l_2' = AO + OB + \Delta x + \Delta x + BO + OC = AO + OC + 2BO + 2\Delta x$.
The difference in the course of the reflected wave Δl when moving the object is
$\Delta l = l_2' - l_2 = AO + OC + 2BO + 2\Delta x - AO - 2BO - OC = 2\Delta x$.



a



b

Fig. 1. Scheme of the difference in the length of the reflected wave in the probe when moving the object: a – the course of the reference wave; b – the course of the measuring wave when the object is moved

Let's assume that the sound wave from the speaker propagates in a homogeneous gaseous medium with a constant wavelength λ, taking into account the small dimensions of the probe and the small displacements of the object – with a constant amplitude *A*.

The phase state of the sound oscillatory process at the microphone input is defined as the sum of two oscillations – reference U_1 and measuring U_2 (measuring oscillation is created by the reflected wave at the initial position of the object in space, ie $\Delta x = 0$):

$$U_1 = A\cos\left(\omega t - \frac{2\pi}{\lambda} l_1\right); \quad U_2 = A\cos\left(\omega t - \frac{2\pi}{\lambda} l_2\right). \tag{1}$$

Combining both equations:

$$U = U_1 + U_2 = 2A\cos\left[\omega t + \pi\cdot\left(\frac{l_2}{\lambda} - \frac{l_1}{\lambda}\right)\right]\cdot\cos\left[\pi\cdot\left(\frac{l_2}{\lambda} - \frac{l_1}{\lambda}\right)\right]. \tag{2}$$

When moving an object in space by Δx, the total oscillation at the microphone input will consist of two oscillations:

$$U_1 = A\cos\left(\omega t - \frac{2\pi}{\lambda} l_1\right); \quad U_2' = A\cos\left(\omega t - \frac{2\pi}{\lambda} l_2'\right). \tag{3}$$

In this case, equation (2) will take the form

$$U = U_1 + U_2' = 2A\cos\left[\omega t + \pi\cdot\left(\frac{l_2'}{\lambda} - \frac{l_1}{\lambda}\right)\right]\cdot\cos\left[\pi\cdot\left(\frac{l_2'}{\lambda} - \frac{l_1}{\lambda}\right)\right], \tag{4}$$

or

$$U = U_1 + U_2' = 2A\cos\left[\omega t + \pi\cdot\left(\frac{l_2 + \Delta x}{\lambda} - \frac{l_1}{\lambda}\right)\right]\cdot\cos\left[\pi\cdot\left(\frac{l_2 + \Delta x}{\lambda} - \frac{l_1}{\lambda}\right)\right]. \tag{5}$$

The phase of the sound oscillation at the input of the probe microphone depends on the first factor

$$\cos\left[\omega t+\pi\cdot\left(\frac{l_2}{\lambda}-\frac{l_1}{\lambda}\right)\right], \tag{6}$$

and the amplitude of the second factor

$$\cos\left[\pi\cdot\left(\frac{l_2}{\lambda}-\frac{l_1}{\lambda}\right)\right]., \tag{7}$$

At any change in the value of the length of the measuring wave from the initial there is a change in phase, and most importantly – the amplitude of the total sound oscillation at the input of the microphone [7].

The main tasks posed in the calculation and design of the transducer-probe [2].

1. Achieving the maximum sensitivity, ie the maximum value of the modulus of the conversion factor K at a certain optimal operating frequency f_{opt}.

2. Achieving the maximum bandwidth, which is determined by the amplitude-frequency respons, ie. the dependence of the modulus of the conversion factor on the frequency. The main parameters of the frequency response are the operating frequency and bandwidth Δf / f_{opt}== $|f_{c1} - f_{c2}|$ / f_{opt}. Usually, in the theory of oscillations, the frequency values at which the signal amplitude decreases by $2^{0.5}$ times (–3 dB) from the maximum value are taken as the boundary values of the frequencies f_{c1} and f_{c2}.

Acoustic systems, and in particular the acoustic probe, are structurally different types of tubes, closed at one end or open at both ends, different types of volumes, resonators, combinations of tubes and volumes, open space, etc.

The method of electroacoustic analogies has been developed for the analysis of acoustic systems [1]. According to this method, the pressure p is considered analogous to the voltage, the oscillation velocity v is analogous to the current density, and the volumetric oscillation velocity is analogous to the current.

$$U_a = vS, \tag{8}$$

where S – is the cross section of the sound pipe.

For a pipe of length l acoustic mass:

$$m_a = m / S^2 = \rho l / S, \tag{9}$$

acoustic active resistance:

$$r_a = r_M / S^2. \tag{10}$$

For volume V the acoustic flexibility is

$$c_a = c_M S^2 = V / \gamma p_{a,c}. \tag{11}$$

The method of these analogies is convenient to use when considering devices consisting only of speakers, such as acoustic filters. Combinations of acoustic and mechanical systems can be considered with the help of electroacoustic analogies too. All mechanical resistance should be replaced by corresponding acoustic, and forces and speeds – on pressures and volume speeds according to formulas $z_a = z_M / S_M^2$, $p = F / S_M$, $U = \upsilon S_M$, where S_M – is the area of the diaphragm or membrane. Electromechanical analogies can also be used when considering purely acoustic systems, but in such an analog scheme, transformers with a transformation factor must be included in each junction of two sound conductors with different cross-sections. S_k / S_{k+1}, де S_k й S_{k+1} – cross-section of the sound pipe in adjacent parts of it, or all acoustic elements to be reduced to one cross section, such as the inlet S_o.

In all methods of drawing up analog circuits of acoustic systems, the acoustic system is first built, ie each element is replaced by components and circuits consisting of electrical elements: inductors, capacitors, resistors. For example, the diaphragm is replaced by a node consisting of mass, flexibility and resistance. Acoustic elements are replaced by electrical ones: a hole or a narrow tube – inductance, volume – capacity.

The acoustic probe considered in this paper (Fig. 2) is an open-type acoustic filter [9], the electrical circuit of which is shown in Fig. 3.

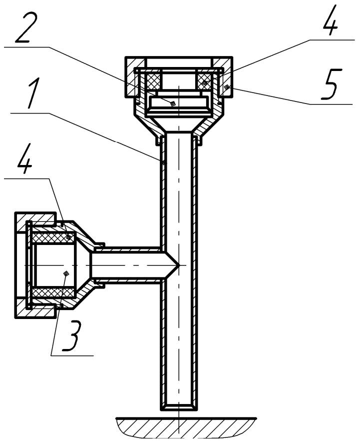


Fig. 2 Measuring probe:
1 – sound guide; 2 – dynamic capsule;
3 – microphone; 4 – sealant; 5 – cap nut

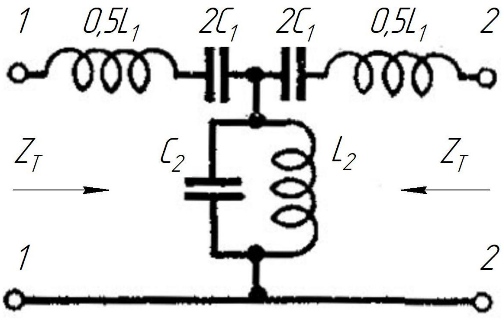


Fig. 3. The scheme of the bandpass filter type – K: T-shaped link

The characteristic resistance of the T-shaped link is determined by the formula [8]:

$$Z_T = \sqrt{Z_1 Z_2}\sqrt{1+\frac{Z_1}{4Z_2}} = R\sqrt{1-\eta^2}\ . \tag{12}$$

The cutoff frequencies of the bandpass filter are obtained from the expressions [10]:

$$\begin{gathered} f_{c1} = \frac{1}{2\pi}\left(\sqrt{\frac{1}{L_1 C_2}+\frac{1}{L_1 C_1}}-\sqrt{\frac{1}{L_2 C_2}}\right), \\ f_{c2} = \frac{1}{2\pi}\left(\sqrt{\frac{1}{L_1 C_2}+\frac{1}{L_1 C_1}}+\sqrt{\frac{1}{L_2 C_2}}\right). \end{gathered} \tag{13}$$

The calculation expression for the bandpass filter elements are determined by the expressions:

$$\begin{gathered} L_1 = \frac{R}{\pi\left(f_{c2}-f_{c1}\right)}; \quad C_1 = \frac{f_{c2}-f_{c1}}{4\pi R f_{c1} f_{c2}}, \\ L_2 = \frac{R\left(f_{c2}-f_{c1}\right)}{4\pi f_{c1} f_{c2}}; \quad C_2 = \frac{1}{\pi R\left(f_{c2}-f_{c1}\right)}. \end{gathered} \tag{14}$$

Calculation of the parameters of the equivalent electric filter according to the formulas given above gave the following results:

$L_1 = 45\ mH$; $L_2 = 28\ mH$; $L_3 = 79\ mH$;
$C_1 = 400\ nF$; $C_2 = 70\ nF$; $C_3 = 60\ nF$.

We make the electric scheme of replacement of the filter, using calculated values of parameters of elements of the scheme (Fig. 4).

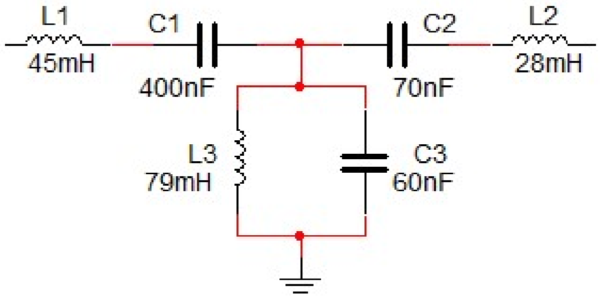


Fig. 4. The scheme of the electric filter with the calculated parameters of the elements

Slice frequencies:

$$f_{c1} = \frac{1}{2\pi}\left(\sqrt{\frac{1}{28\times10^{-3}\cdot0.4\times10^{-6}} + \frac{1}{28\times10^{-3}\cdot0.07\times10^{-6}}} - \frac{1}{\sqrt{28\times10^{-3}\cdot0.4\times10^{-6}}}\right) = 1{,}023\times10^{3}\,Hz;$$
$$f_{c2} = \frac{1}{2\pi}\left(\sqrt{\frac{1}{28\times10^{-3}\cdot0.4\times10^{-6}} + \frac{1}{28\times10^{-3}\cdot0.07\times10^{-6}}} + \frac{1}{\sqrt{28\times10^{-3}\cdot0.4\times10^{-6}}}\right) = 3{,}981\times10^{3}\,Hz. \quad (15)$$

Let's check this result with the help of a computer simulation using Electronics Workbench software (Fig. 5).

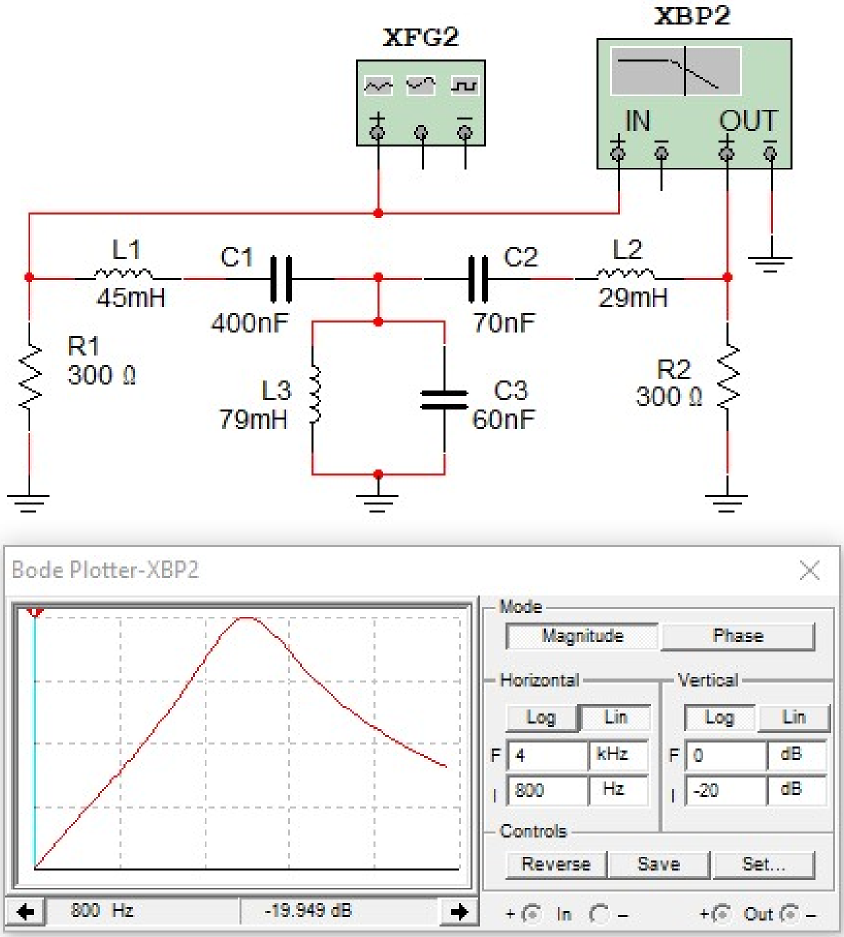


Fig. 5. Computer simulation of the amplitude-frequency characteristic of a bandpass filter

According to the simulation results, the filter bandwidth at the level of –3 dB was obtained:

$$f_{c1} = 2100\ Hz;\quad f = 2400\ Hz;\quad f_{c2} = 2700\ Hz.$$

Taking into account that we are looking at the product of sensitivities in radiation and reception, it is rational to take the frequencies f_{c1} and f_{c2}, at which K decreases to 0.5 of the maximum [2], ie at the level of –6.02 dB:

$$f_{c1} = 1900\ Hz;\quad f = 2400\ Hz;\quad f_{c2} = 3000\ Hz.$$

Experimental studies

Experimental studies were conducted to test the theoretical material. For this purpose, the experimental equipment schematically shown in Fig. 6.

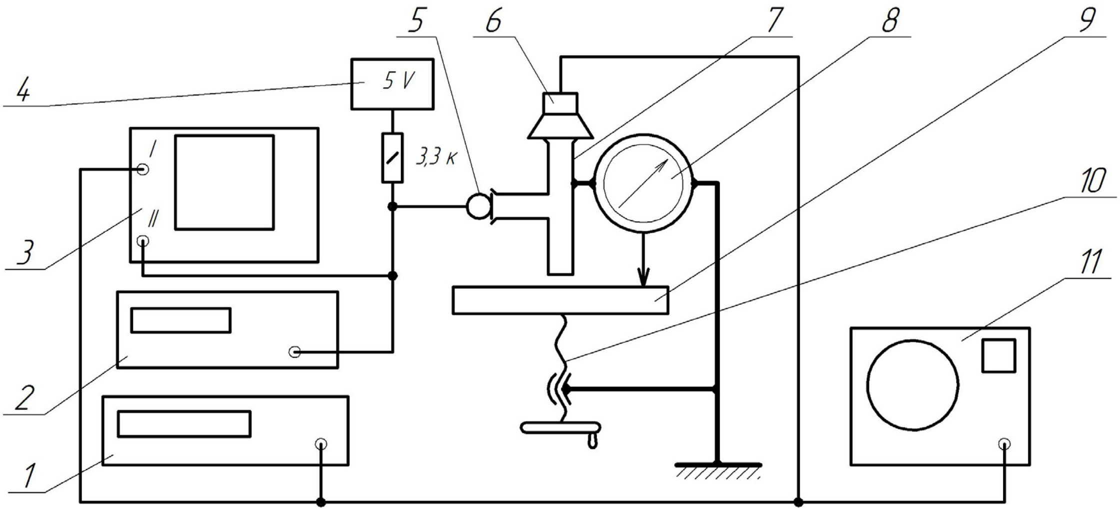


Fig. 6. Scheme of experimental equipment: 1 – frequency meter; 2 – electronic voltmeter; 3 – electronic oscilloscope; 4 – microphone power supply; 5 – microphone; 6 – dynamic capsule; 7 – measuring probe; 8 – clock type indicator; 9 – measuring table; 10 – micrometer screw; 11 – sound generator

The disassembled measuring probe is shown in Fig. 7.

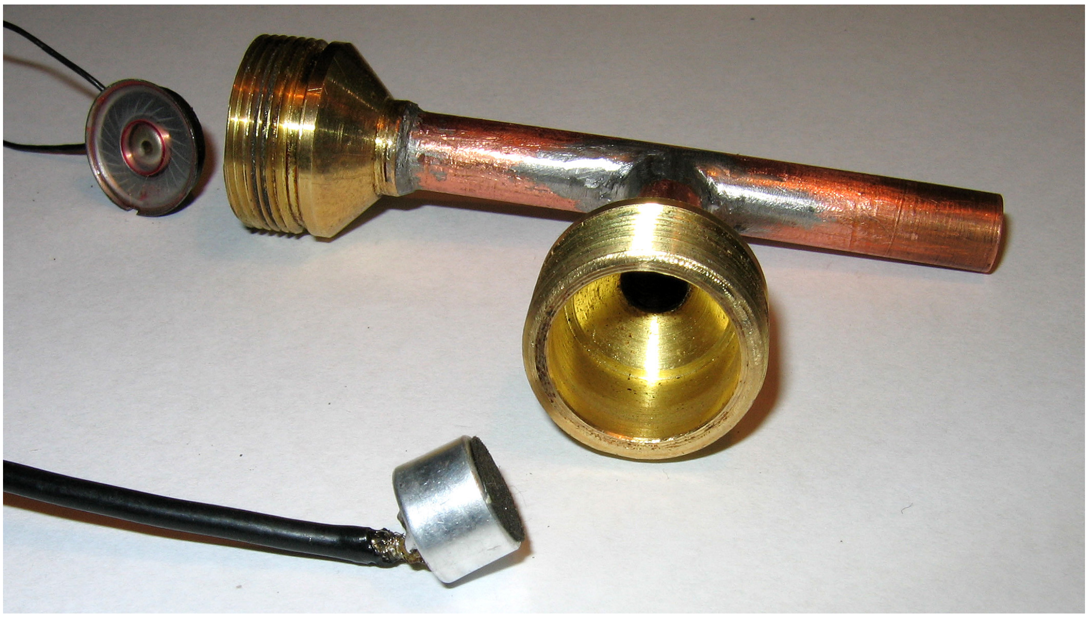


Fig. 7. Measuring probe in disassembled condition

Experimental studies were performed at several resonant frequencies of the measuring probe, namely at the frequency: 1045; 1907; 3074; 3957 Hz. The results of the experimental studies are presented in Fig. 9–11.

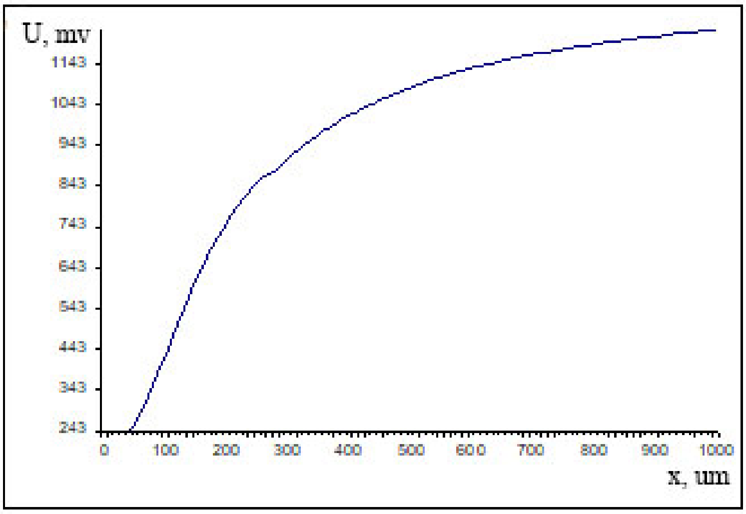


Fig. 8. Static characteristics of the measuring system at a signal frequency of 1045 Hz

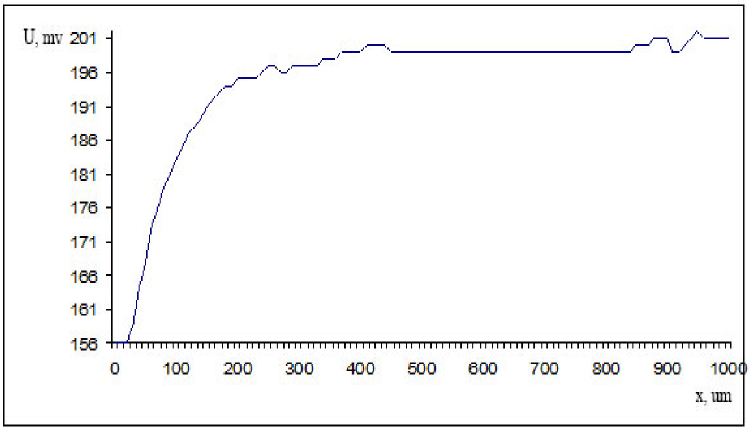


Fig. 9. Static characteristics of the measuring system at a signal frequency of 1907 Hz

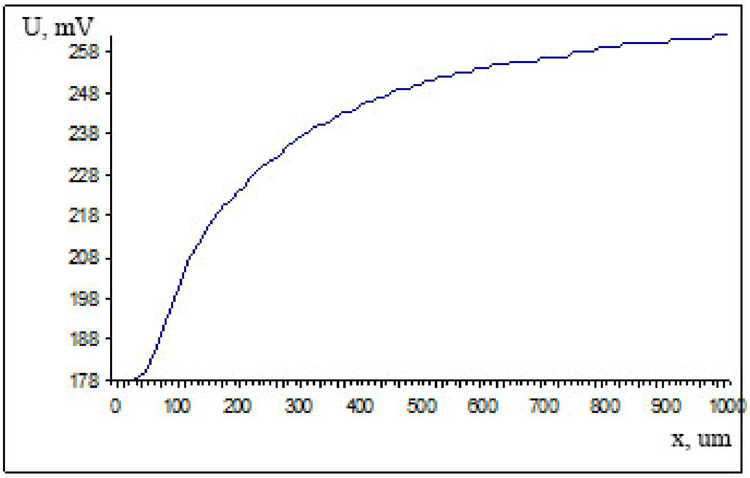


Fig. 10. Static characteristics of the measuring system at a signal frequency of 3074 Hz

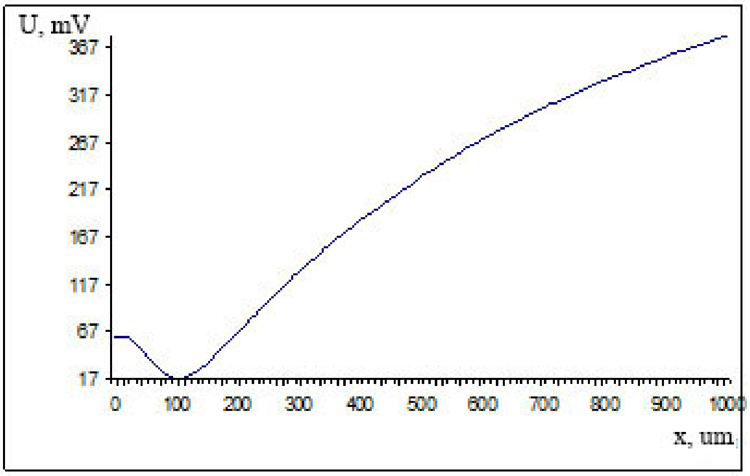


Fig. 11. Static characteristics of the measuring system at a signal frequency of 3957 Hz

As can be seen from the graphical dependences of the cutoff frequencies of the probe with sufficient accuracy correspond to the cutoff frequencies of the equivalent filter obtained by calculation. This means that the bandpass filter model of Fig. 4 can be used in the design of the acoustic probes structurally shown in Fig. 12.

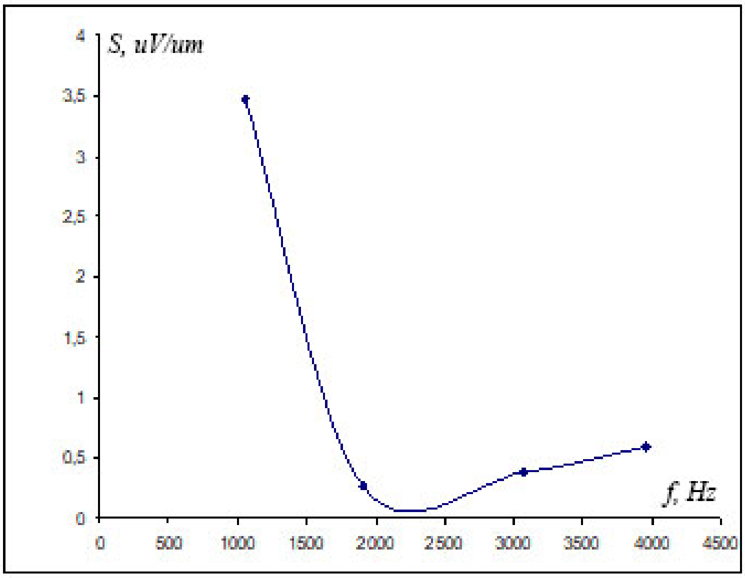


Fig. 12. Graph of probe sensitivity at different signal frequencies

Conclusions

The equivalent scheme of an acoustic probe developed in work and also the developed technique of calculation of geometrical parameters of elements of a probe gives the chance to carry out with sufficient accuracy synthesis and design of a design of an acoustic probe.

The advantage of acoustic measurements in the range of sound oscillations is the possibility of contactless control. The operation of the acoustic filter in the low-frequency range has a higher sensitivity of measurements than in the high-frequency, with the requirement of nonlinearity within ± 3 dB. The operation of the acoustic filter in the high frequency range has a wider limit of the measuring range.

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