The results of orifices acoustic impedance measurements at high sound pressure levels are presented. The amplitude of the oscillating velocity in the orifices at frequency 150 Hz varies in range from 0.1 m/s to 15 m/s. The thickness of the diaphragm is 2 mm, and the diameters of the orifices varies in the range of 3 – 20 mm. It is shown that the real and imaginary components of the impedance significantly depends on the diameter of the orifice in the nonlinear range. For the same oscillating velocity, the real part of the impedance increases and the imaginary part of the orifice impedance reduces while the increase of the orifice diameter. The possible reasons of such effect are discussed.

Keywords: impedance, orifice, velocity, diaphragm, measurement

1. Introduction

The impedance researches take a great part in measurements and calculations nowadays [1-5]. Reliable scientific data for architectural, medical and engineering designing are needed.

This paper is a generalization of the results of an investigation of the characteristics of the Helmholtz resonator on the channel end wall, published in [6], for high sound pressure levels in the channel, when the resonator characteristics become significantly nonlinear.

Studies of the nonlinear properties of the Helmholtz resonator take its place in a large number of papers, for example, in [7-18], which are mostly experimental.

In Ingard's works [9, 11], for small throat thickness, that is way smaller than its diameter, the value of the oscillating velocity in the throat that at some point determines the beginning of the nonlinear processes is proportional to its thickness, and with the increase of the throat thickness this dependence gradually decreases until it make no sense.

The influence of nonlinearities on the real part of the throat impedance (orifices in the septum) has been studied more accurately. This question was considered by Sivian [7], and in a large number of works by other researchers later on [8-14, 16-18]. It is shown that the real part of the impedance, which determines the dissipative losses, beginning from the specific value, intensively increases with the increase of the oscillating velocity amplitude in the orifice. The imaginary part of the impedance was investigated experimentally in [8,12-14, 16-18] - with the increases of oscillating velocity amplitude the imaginary part decreases, which corresponds with the decrease of the orifice attached length. However, the limits of the attached length decrease with the increase of oscillating velocity are still unclear. Theoretically, this question was not considered, although in [19] on the basis of energy analysis it was concluded that the linear attached orifice length in the presence of nonlinear processes is reduced by 5/8, i.e. more than half. In [18], descriptions of the real and imaginary parts of the acoustic impedance of the resonator neck by analytical formulas are also given, but it seems that the validity of formulas use is not sufficiently substantiated.
The purpose of this paper is to obtain reliable experimental data of the effect of oscillation velocity amplitude on the acoustic impedance of an orifice with different diameter values. All this will serve as the basis for the consistent nonlinear mathematical model of the Helmholtz resonator.

2. Measurements and experimental results

In experiments was used an impedance tube with an internal diameter \( d = 99 \text{ mm} \) with two microphones 1 and 2 at distances of 153 mm and 281 mm, respectively, from the end of tube, where a partition with an orifice was installed (Fig. 1). The thickness of the partition is 2 mm, and the diameter of the orifice in the partition \( d_0 \) varies from 4 mm to 15 mm. The sound source is a SVEN HT-500 speaker with a power of 120 W. To excite the speaker a sweep signal with a bandwidth of 10 Hz and a central frequency \( f_0 \) is used. The amplitude of the sweep signal varied, so that the sound pressure levels in the impedance tube could vary from 85 dB and 135 dB. The sound pressure was measured with a pair of 1/4" condenser microphones PSB 482C05. Then, the signals from the microphones were subjected to spectral analysis with the help of the B&K PHOTON + analyzer, which, by the transfer function method \([20]\), determined the reflection coefficient of the sound wave from the partition \( R \), and then the dimensionless acoustic impedance of the orifice in the partition

\[
Z = g^2 (1 + R)/(1 - R), \quad \text{where} \quad g = d_0/d.
\]

Figure 1. Scheme of the measuring device

In linear acoustics, the dimensionless acoustic impedance of an orifice

\[
\bar{Z} = \bar{R}_f + ik\bar{l}_e,
\]

where \( \bar{R}_f \) - dimensionless frictional resistance in the orifice, \( \bar{R}_f = 2k\delta\nu/\nu \); \( k = \omega/c \) is the wave number; \( \omega \) is the angular frequency; \( \delta\nu = (2\nu/\omega)^{1/2} \) - the depth of the boundary layer; \( \nu \) is the kinematic viscosity of air, \( \nu = 1.5 \cdot 10^{-5} \text{ m}^2/\text{s} \); \( l_e \) - effective orifice length, \( l_e = l + l_a \); \( l_a \) is the attached length of the orifice, which for not very large orifices (\( g < 0.25 \)) can be determined by the relation \([11, 21]\)

\[
l_a = 0.81(1-1.34g)d_0.
\]

3. Attached orifice length

The normalized attached length of the orifice is \( \bar{l}_a = l_a/l_{al} \), where \( l_{al} \) is the linear (maximum) attached length of the orifice of a given diameter, determined according to (2). The dependence of the parameter \( \bar{l}_a \) on the dimensionless oscillating velocity for two orifice diameters is shown in Fig. 2.

In this case, the dimensionless oscillating velocity was determined through a unit length \( l_0 = 10^{-3} \text{ m} \). In the linear mode, small values of the dimensionless oscillating velocity, the normalized attached length of the orifices independently from diameter is 1, but with an increase in the oscillating velocity and transition to nonlinear mode, this value decreases and reaches a new (minimum) constant level, the value of which is depends on the orifice diameter.
The dependence of the minimum level of the normalized attached length $\overline{r}_{\text{min}}$ from the parameter $g$ for the orifice diameters is studied and well approximated by a linear function:

$$\overline{r}_{\text{min}} = 0.15 + 3.5g.$$  \hspace{1cm} (3)

According to the presented data, in the nonlinear mode, the attached length of the orifice is significantly reduced, thus the nonlinear attached length can be less than half (or even 5/8) of the linear attached length, especially for small diameter orifices (small $g$). This means that the loss of kinetic energy of the sound wave occurs not only behind the aperture, where in the nonlinear mode it is transformed into jet energy, but that this process partially occurs in the vicinity of the orifice and inside the orifice. We can assume that this process is directly influenced by the edges of the orifice.
On the basis of the foregoing, the attached orifice length is represented in the form

\[ l_a = l_{a0}(1 - \Delta l_{an}), \]  

(4)

where \( \Delta l_{an} \) is the relative decrease of attached length of orifice due to nonlinear processes. In Fig. 3 points show the dependence of magnitude on the dimensionless oscillating velocity for two orifice diameters. The dependencies are obtained by recalculating the measurement data (Fig. 2), with use of the relation \( \Delta l_{an} = 1 - T_a \). Further, the approximation of these dependences was performed by a function of the form:

\[ \Delta l_{an} = (1 - T_{amin}) \frac{(A \bar{U})^B}{1 + (A \bar{U})^B} \]  

(5)

where \( A \) and \( B \) are some constants, their values are determined for each orifice diameter by the generalized regression method; \( \bar{U} = U/(\omega l_0) \). As a result, it was found that for all studied orifices constant \( A \approx 0.235 \). The value of constant \( B \) essentially depends on the diameter of the orifice. It can be found to be approximated by formula

\[ B = 3.4 + 800g^{2.5} \]  

(6)

As a result, with the help of (5), analytical dependences of the relative nonlinear decrease of the orifice attached length from the dimensionless oscillating velocity is found, shown in Fig. 3 by solid lines. It should be borne in mind that the value of the constant \( A \) has an inverse relationship to the length parameter used in determining the dimensionless oscillating velocity, while the constant \( B \) does not depend on this parameter.

The advantage of formula (5) in comparison with the previously proposed approximation formulas is that it describes a nonlinear decrease in the connected orifice length in the entire range of changes in the values of the dimensionless oscillating velocity.

4. Acoustic resistance of orifice

We will consider the dimensionless acoustic resistance of the orifice \( \bar{R} = R/(\rho c) \), representing it as a sum of linear \( \bar{R}_l \) and nonlinear \( \bar{R}_{al} \) components, \( \bar{R} = \bar{R}_l + \bar{R}_{al} \). The dimensionless linear resistance \( \bar{R}_l = 2k\delta_n(l/d_0 + \Delta_n) \), where \( k = \omega/c \) is the wave number; \( \delta_n = (2\nu/\omega)^{1/2} \) is the depth of the boundary layer in the orifice. The dimensionless attached length \( \Delta_n \) depends, as shown in [6], on the geometrical parameters of the orifice. Fig. 4 shows the graphical dependences of the dimensionless acoustic resistance \( \bar{R} \) of orifices of different diameters on the rms value of the oscillating velocity \( U \) in them for two values of the frequency \( f_0 \). As expected, starting from a certain value of the oscillating velocity \( U \), the resistance of the orifice, more precisely its nonlinear component \( \bar{R}_{al} \), begins to increase intensively with increasing \( U \). However, it was unexpected here that, regardless of the frequency \( f_0 \), the increase in resistance occurred more intensively for orifices of larger diameter.

Due to this, in the nonlinear mode with the selected value of the oscillating speed in the orifice, the larger diameter of the orifice corresponded to a greater acoustic resistance, whereas in the linear regime, the opposite picture occurs: the acoustic resistance is inversely proportional to its diameter.

Further, only the nonlinear resistance \( \bar{R}_{al} \) was investigated in more detail, which was determined by subtracting its linear part \( \bar{R}_l \) from the total resistance \( \bar{R} \), equal to the overall resistance for small values of the oscillating velocity \( U \). In this case, the reduced nonlinear resistance proportional to the dimensionless parameter \( l_0/d_0 \) was introduced \( \bar{R}_{al} = \bar{R}_{al} l_0/d_0 \), where \( l_0 \) is the unit length, \( l_0 = 10^{-3} \) m.
In order to obtain more universal characteristics, we introduce, as well as [15, 17, 18], a dimensionless velocity \( \bar{U} = U/\sqrt{\nu\omega} \). The graphical dependences of the reduced resistance on the dimensionless velocity are presented in Fig. 5 they show that these dependences practically ceased to depend on the frequency.

The measurements of the acoustic impedance of the orifice in the impedance tube show that in nonlinear modes, with the increase of sound pressure levels, the attached length of the orifice decreases till constant level, which is significantly lower than usually assumed. At high oscillating velocity values, the non-linear resistance of the orifice begins to increase significantly and it is proportional to the diameter of the orifice.
REFERENCES


5. Akhiyarov, V.V., Borzov, A.B., Suchkov, V.B., Shakhtar, B.I. and Sidorkina, Y.A. Calculation of the backscattered field by the method of the physical diffraction theory in the problem of diffraction from from impedance objects, *Journal of Communications technology and Electronics*, **60**(12), 1297–1304. (2017)


