Transmission and reflection of sound wave from a layer of liquid with gas bubbles

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Abstract. The problem of reflection and transmission of sound wave through the two-layer medium containing a layer of bubble liquid is considered. A comparison of the reflection and transmission of wave coefficients with known experimental data is presented.

1. Introduction

Waves propagation in complex layered media is an active subject of research. A layered medium containing bubble liquid is of particular interest [1] - [10]. This is due both to natural processes, such as bottom layers containing gas bubbles in the seas, lakes or near the surface [1, 2], and technological processes [3, 4]. For example, in [4] the description of construction and characteristics of the combined panel consisting of two glass or polycarbonate, the space between them is filled with bubble liquid, to protect information both on acoustic, optical, electromagnetic, and technical channels is shown.

There are several experimental studies. In [7] the two-layer medium water - water with bubbles - air is considered and reflection coefficient when the acoustic wave falls normally on the water side is experimentally determined, and in [8] the two-layer medium water - water with bubbles - water is considered and transmittance through bubble screen is found experimentally.

Problems of acoustics of bubble liquids in a particular setting are considered in [11] - [22].

In this paper on the basis of the methodics described in the book [25] and dependence of the wave number on the frequency of the disturbances for the bubble liquid, obtained in [13] reflection and transmission of sound wave through the bubble liquid are investigated.

2. Mathematical model.

To determine the transmission and reflection from two-layer medium coefficients, a diagram of which is shown in fig. 1, the following method of calculations is used. According to [21], the result of the reflection and transmission of a plane monochromatic wave $\exp i(\omega t - Kx)$ from multi-layer media will be plane waves $R \exp i(\omega t + Kx)$ and $T \exp i(\omega t - Kx)$, where R and T – reflection and transmission of the waves coefficients, which are defined through layers impedances Z_j and input impedances of layers borders Z_j^{in}. For a two-layer medium reflection and transmission coefficients are of the form

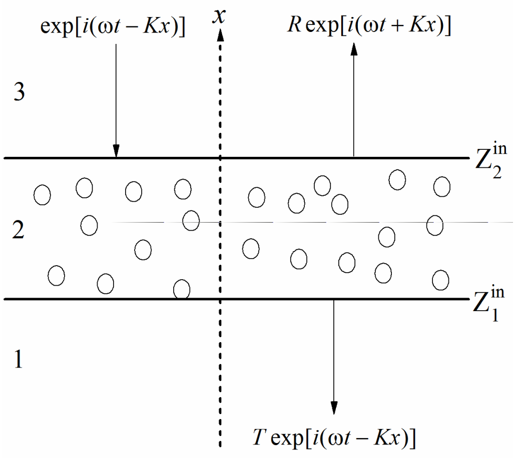

Figure 1. Scheme of the media.

$$R = \frac{Z_2^{in} - Z_3}{Z_2^{in} + Z_3}, T = \prod_{j=1}^{2} \left(\frac{Z_j^{in} + Z_j}{Z_j^{in} + Z_{j+1}} \exp iK_j d_j \right) \quad (1)$$

$$Z_j = \rho_j \frac{\omega}{K_j}, Z_2^{in} = \frac{Z_1 - iZ_2 \tan(K_2 d_2)}{Z_2 - iZ_1 \tan(K_2 d_2)} Z_2, i^2 = -1, j = 1, 2, 3$$

Here d_2 – the thickness of the bubble layer, K – wave number, ω – frequency of disturbances, ρ – density of the layer. For a homogeneous layer the wave number is defined as $K_j = \omega/C_j$, where C_j – the speed of sound in the j -th layer. Since in the second layer bubble liquid will be considered, i.e., non- homogeneous and absorbing medium, to determine, in general, a complex wave number $K_2 = K_*$ the relation obtained in [13] will be used. This dependence of a complex wave number on the disturbances frequency is given by

$$\left(\frac{K_*}{\omega} \right)^2 = \frac{1}{C_f^2} + \frac{3\alpha_{20}\alpha_{10}\rho_{10} \langle Q \rangle}{3\gamma_{20} p_{10} - \langle QS \rangle} \quad (2)$$

$$Q = 1 + \phi, \phi = 3(\gamma_{20} - 1) \frac{y \coth y - 1}{y^2}, y = \left(-\frac{i\omega a^2}{\kappa_{20}} \right)^{1/2}$$

$$S = \frac{i\omega a^2 h \rho_{10}}{1 + ht}, h = \frac{4\nu_{10}}{a^2} - i\omega, t = \frac{a}{C_1 \alpha_{20}^{1/6}}$$

$$\langle h \rangle = \frac{1}{\rho_2} \int_{\Delta a} N_0(a) g_0(a) h da, \rho_2 = \int_{\Delta a} N_0(a) g_0(a) da, g_0(a) = \frac{4}{3}\pi a^3 \rho_{20}, \Delta a = [a_{\min}, a_{\max}]$$

Here, the subscript 1 refers to the parameters of the liquid phase, index 2 – to the parameters of the bubbles, 0 – the initial undisturbed state. The parameters α determine the volume content, ρ_{10} – liquid density, ρ_{20} – density of gas in bubbles, p_{10} – pressure, C_f – frozen velocity, is almost equal to the speed of sound C_1 in pure liquid, γ – the adiabatic index, κ – coefficient of the gas thermal conductivity, ν_{10} – the kinematic viscosity of the fluid, $N_0(a)$ – function of bubble size distribution.

3. The results of calculations.

Let us consider the acoustic signal passing through the two-layer medium: water - water with bubbles of air - water. Let the thickness of the bubble layer is 4 mm, the radius of air bubbles

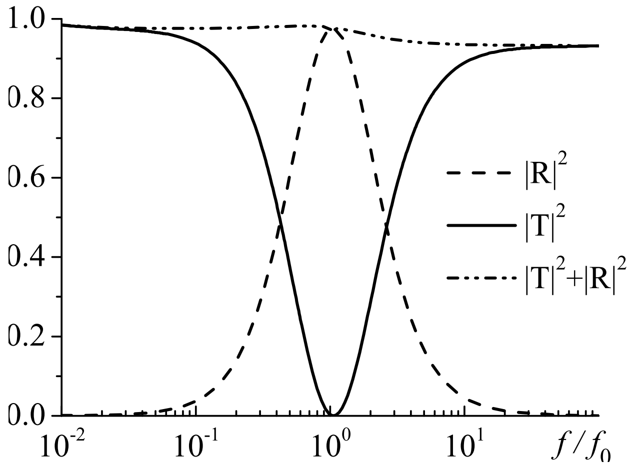

Figure 2. The coefficients of reflection and transmission of sound through the bubble screen: $\alpha_{20} = 0.01$, $a_0 = 2$ mm, $d_2 = 4$ mm, $f_0 = 1630$ Hz.

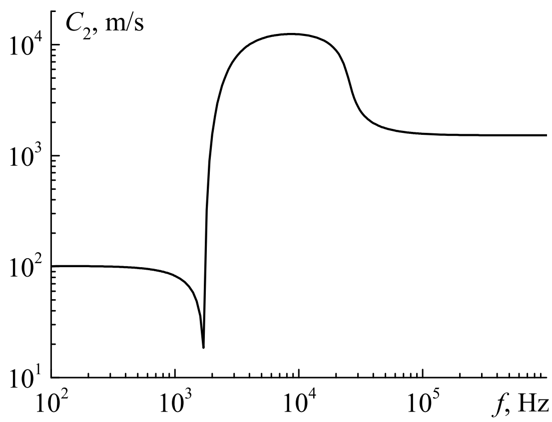

Figure 3. Dependence of phase velocity on frequency of disturbances in bubble layer: $\alpha_{20} = 0.01$, $a_0 = 2$ mm.

is 2 mm, the volume content of 1%. The pressure of a mixture is 0.1 MPa, temperature is 288 K. The calculations we will make using the formulas (1) and the equations (2). Fig. 2 shows the dependences of reflection and transmission of the waves coefficients on the dimensionless disturbances frequency through the bubble layer. As can be seen from this figure, in the resonant frequency area of bubbles the minimum of transmission coefficient and the maximum of reflection coefficient are observed, i.e., at a given frequency bubble layer almost completely reflects incident acoustic wave. If you add up the values of these coefficients, the result is always less than one, because the wave energy is partially absorbed by the bubbles at oscillation due to viscosity and process of thermal conductivity.

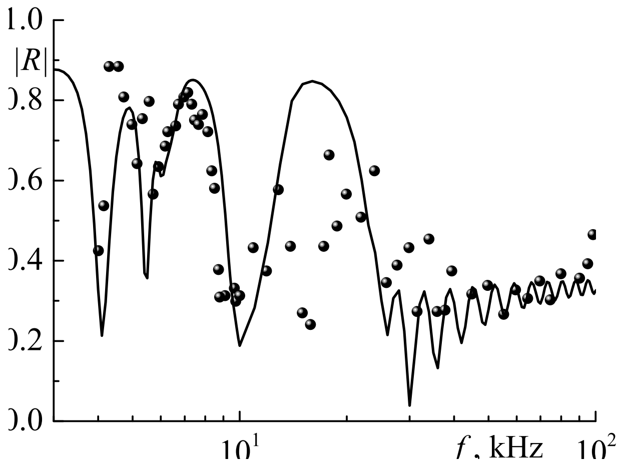

Figure 4. Comparison of reflection coefficient with experimental data [7] for medium: water – bubbly liquid – air; $\alpha_{20} = 0.032\%$, $d_2 =$ 10 cm.

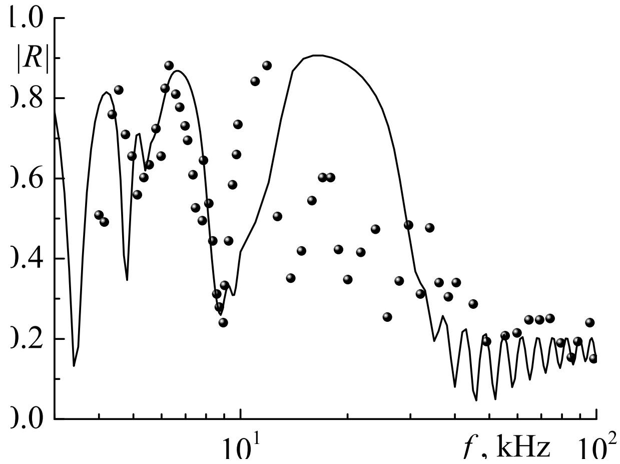

Figure 5. Comparison of reflection coefficient with experimental data [7] for medium: water – bubbly liquid – air; $\alpha_{20} = 0.052\%$, $d_2 =$ 10 cm.

Figures 4 – 6 show a satisfactory agreement between the theoretical curves of reflection and transmission coefficients with known experimental data.

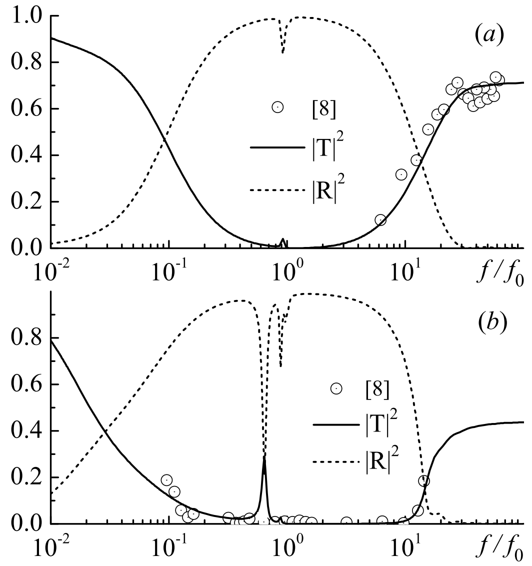

Figure 6. Comparison of reflection and transmission coefficients through the bubble screen with experimental data [8]; a – $\alpha_{20} = 0.015$, $a_0 = 2$ mm, $d_2 = 1.5$ cm, $f_0 = 1630$ Hz, $b - \alpha_{20} = 0.01$, $a_0 = 0.5$ mm, $d_2 = 1.2$ cm, $f_0 = 6523$ Hz.

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References

[1] Shagapov V Sh and Sarapulova V V 2015 *Acoustical Physics* **61** 37
[2] Gusev V A and Rudenko O V 2015 *Acoustical Physics* **61** 152
[3] Leroy V, Strybulevich A, Page J H and Scanlon M G 2008 *J. Acoust. Soc. Am.* **123** 1931
[4] Zelmanskiy O B, Petrov S N and Kazeka A A 2013 *Doklady BGUIR* **78** 30
[5] Nigmatulin R I, Gubaidullin D A and Nikiforov A A 2014 *Doklady Physics* **59** 286
[6] Baranowska A 2012 *Archives of Acoustics* **37** 287
[7] Lee K, Choi B K and Yoon S W 2002 *Journal of the Korean Physical Society* **40** 256
[8] Tien T M 2001 *Sound propagation through a bubble screen at finite gas-volume fraction* (Taiwan: National Cheng Kung University)
[9] Gubaidullin D A and Fedorov Yu V 2016 *Doklady Physics* **61** 499
[10] Marr K W 1981 *On the design of an acoustically isolating bubble screen for the Carr inlet acoustic range* (California: Naval Postgraduate School)
[11] Commander K W and Prosperetti A 1989 *J. Acoust. Soc. Am.* **85** 732
[12] Gubaidullin D A, Nikiforov A A and Gafiyatov R N 2012 *High Temperature* **50** 250
[13] Gubaidullin D A and Fedorov Yu V 2013 *Journal of Applied Mathematics and Mechanics* **77** 532
[14] Gubaidullin D A, Gubaidullina D D and Fedorov Yu V 2013 *Fluid Dynamics* **48** 781
[15] Nigmatulin R I, Gubaidullin D A and Fedorov Yu V 2013 *Doklady Physics* **58** 261
[16] Fuster D and Montel F 2015 *J. Fluid Mech.* **779** 598
[17] Gubaidullin D A and Gafiyatov R N 2014 *J. Phys.: Conf. Ser.* **567** 012020
[18] Gafiyatov R N, Gubaidullin D A and Nikiforov A A 2013 *Fluid Dynamics* **48** 366
[19] Gubaidullin D A and Fedorov Yu V 2015 *Fluid Dynamics* **50** 61
[20] Gubaidullin D A, Gubaidullina D D and Fedorov Yu V 2014 *J. Phys.: Conf. Ser.* **567** 012011
[21] Gubaidullin D A, Nikiforov A A and Gafiyatov R N 2016 *J. Phys.: Conf. Ser.* **669** 012019
[22] Gubaidullin D A, Gubaidullina D D and Fedorov Yu V 2016 *J. Phys.: Conf. Ser.* **669** 012011
[23] Gubaidullin D A, Nikiforov A A and Gafiyatov R N 2015 *High Temperature* **53** 240
[24] Gubaidullin D A and Fedorov Yu V 2016 *Acoustical Physics* **62** 179
[25] Brekhovskikh L M and Godin O A 1989 *Acoustics of Layered Media* (Moscow: Nauka)