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Interaction a Sound Signal with a Multilayer Object Containing Bubbly Liquid

R N Gafiyatov

1 Institute of Mechanics and Engineering - Subdivision of the Federal State Budgetary Institution of Science «Kazan Scientific Center of the Russian Academy of Sciences», 2/31 Lobachevsky str., Kazan, 420111, Russia

E-mail: gafiyatov@mail.ru

Abstract. The mathematical model that determines the interaction of sound signal with multilayer object containing multifractional bubbly liquid is presented. For the model of media with three layer the wave transmission and reflection coefficients are calculated. The influence of characteristics of the dispersed phase on the investigated coefficients is shown.

1. Introduction

The investigations of wave dynamics and acoustics of disperse media are of significant interest. Currently, the basics of mechanics and thermophysics of bubbly liquids, as well as the most significant results in the study of wave processes in these environments are presented in monographs [1-9].

The propagation of acoustic waves in a two-fractional mixture of liquid with bubbles is investigated in [10-12]. A mathematical model of the propagation of sound waves in the two-fractional mixture of liquid with polydisperse vapor-gas and gas bubbles with phase transitions is shown in [13-15]. The propagation of acoustic waves in multifractional mixtures of liquid with gas and vapor-gas bubbles of different sizes and different compositions is studied in [16-20].

The interaction a sound signal with an object containing two-fractional bubbly liquid is studied in [21]. In this study the sound wave transmission and reflection through a multilayer object containing a multifractional bubbly fluid layer is investigated.

2. Mathematical model

Linearized equations for one-dimensional disturbances in a multifractional mixture of liquid with bubbles are obtained from the general equations of motion for bubbly mixtures [1]. The dispersed phase consists of N+M fractions having various gases in bubbles and different in the bubbles radii. Phase transitions accounted for N fractions. The total bubble volume concentration is small. Solving this system this dispersion relation is obtained:

$$
\left( \frac{K_s}{\omega} \right)^2 = \frac{1}{C_f^2} + \frac{\rho_{10}}{P_0} \left( \frac{(S_{10} + S_{1j})(S_{2i} + S_{3j})}{S_{2i} + S_{2j} - i\omega} + S_{gi} + S_{gj} \right)
$$

(1)

where $C_f$ is the frozen speed of sound ($C_f = C_1/\alpha_{10}$) and also the following notations are adopted:
\[ S_{ij} = \sum_{i=1}^{M} H_{ui} , \quad S_{ij} = \sum_{j=1}^{N} H_{ij} , \quad S_{3i} = \sum_{i=1}^{M} H_{3i} , \quad S_{3j} = \sum_{j=1}^{N} H_{3j} , \quad S_{2i} = \sum_{i=1}^{M} \left( \frac{m_{i}}{\tau_{T_{ij}}} + H_{2i} \right) , \]

\[ S_{2j} = \sum_{j=1}^{N} \left( \frac{m_{j}}{\tau_{T_{ij}}} + H_{2j} \right) , \quad S_{R_{i}} = \sum_{i=1}^{M} \left( \frac{a_{2i0}}{N_{R_{i}}} \left( 1 - \frac{M_{A_{ij}}}{M_{3i}} \right) \right) , \quad S_{R_{j}} = \sum_{j=1}^{N} \left( \frac{a_{2j0}}{N_{R_{j}}} \left( 1 - \frac{M_{A_{ij}}}{M_{3j}} \right) \right) , \]

\[ H_{1i} = \frac{m_{i}}{\tau_{T_{ij}}} \left( \frac{M_{1}M_{A_{ij}}}{M_{3i}} + M_{2i} \right) , \quad H_{1j} = \frac{m_{j}}{\tau_{T_{ij}}} \left( \frac{M_{1}M_{A_{ij}}}{M_{3j}} + M_{2j} \right) , \quad H_{2i} = \frac{m_{i}}{\tau_{T_{ij}}} \frac{M_{1}b_{i}}{M_{3j}} , \quad H_{2j} = \frac{m_{j}}{\tau_{T_{ij}}} \frac{M_{1}b_{j}}{M_{3j}} , \]

\[ H_{3i} = \frac{N_{3i}L_{4i}}{N_{R_{i}}(L_{4i} - \delta N_{2j})} , \quad H_{3j} = \frac{N_{3j}L_{4j}}{N_{R_{j}}(L_{4j} - \delta N_{2j})} \]

\[ M_{1i} = \left( N_{3i} + M_{2i} \right) , \quad M_{2i} = \frac{N_{2i}}{N_{R_{i}}} , \quad M_{3i} = 1 + N_{3i}(1+b_{i}) + M_{4i} , \quad M_{4i} = \frac{1}{N_{R_{i}}} \left( 1 + N_{2i} (1+b_{i}) \right) , \]

\[ N_{ij} = \frac{i \omega \tau_{T_{ij}}}{m_{j}} - 1 , \quad N_{ij} = 1 , \quad N_{2j} = i \omega \tau_{T_{ij}} - 1 , \quad N_{2i} = i \omega \tau_{T_{ij}} - 1 , \quad N_{3j} = k_{2j} \left( c_{j} - R_{j} \right) - 1 + G_{j} , \]

\[ N_{3i} = k_{2i} \left( c_{i} - R_{i} \right) - 1 , \quad L_{3j} = E_{j} \left( 1 - i \omega \tau_{j} \right) , \quad L_{3j} = - \frac{i \omega k_{2j}}{(1 - k_{3j}^{0})^{T}} + \Delta R_{j} - L_{ij} \left( 1 + b_{j} \right) , \]

\[ L_{3j} = 1 - G_{j} \left( 1 + b_{j} \right) , \quad L_{4j} = L_{ij} + \Delta R_{j} N_{2j} , \quad k_{2j} = \frac{i \omega \tau_{T_{ij}}}{c_{j}} , \quad k_{2i} = \frac{i \omega \tau_{T_{ij}}}{c_{i}} , \quad b_{j} = \frac{c_{i} \tau_{T_{ij}}}{c_{j} \tau_{T_{ij}}} , \quad b_{i} = \frac{c_{i} \tau_{T_{ij}}}{c_{j} \tau_{T_{ij}}} , \]

\[ N_{R_{j}} = \frac{-(i \omega)(a_{j0})^{2}}{3(t_{j}G_{R_{j}} + 1)p_{0}} , \quad N_{R_{i}} = \frac{-(i \omega)(a_{i0})^{2}}{3(t_{j}G_{R_{i}} + 1)p_{0}} \]

\[ \omega = \frac{a_{j0}^{2}}{4v_{1}} , \quad \omega = \frac{(a_{j0})^{2}}{4v_{1}} , \quad \omega = \frac{a_{j0}}{C_{1}(a_{j0})^{1/6}} , \quad \omega = \frac{a_{i0}}{C_{1}(a_{i0})^{1/6}} , \quad \mu_{j0} = \frac{\rho_{j0}}{\rho_{10}} , \quad m_{i0} = \frac{\rho_{i0}}{\rho_{10}} , \quad m_{j} = \frac{\rho_{j0}}{\rho_{10}} , \quad m_{i} = \frac{\rho_{i0}}{\rho_{10}} , \quad i = 1,2,\ldots M , \quad j = 1,2,\ldots N . \]

Here, \( \alpha \) – the volume concentration, \( \rho \) – the radius of the bubbles, \( p \) – the pressure, \( \rho^{*} \), \( \rho \) – the true and average densities, \( c \) – the specific heat capacity, \( R \) – the gas constant, \( k \) – the weight concentration, \( \nu \) – the kinematic viscosity, \( \lambda \) – the thermal conductivity, \( \tau \) – the relaxation time. Subscript 1 refers to the parameters of the liquid phase, 2 – disperse phase, \( C_{1} \) – the velocity of sound in pure liquid.

Dispersion relation (1) (i.e. the function of the complex wave number \( K \), on the frequency \( \omega \)) determines a propagation of acoustic waves in the multifractional mixtures of liquid with vapor-gas and gas bubbles of different gases (different initial volume contents, different initial radii and different thermal properties of fractions) with the interphase diffusion mass transfer.

In analysing the interaction between an acoustic signal and a multilayer object (Fig. 1), the following method of calculations is used. According to [22], the result of the transmission and reflection of a plane monochromatic wave \( \exp(iK_{x}x - \omega t) \) from a multilayer object is the plane waves \( T \exp(iK_{x}x - \omega t) \) and \( R \exp(iK_{x}x + \omega t) \), where \( T \) and \( R \) are the wave transmission and reflection coefficients, respectively, determined in terms of the layer impedances \( Z_{i} \) and the entry impedances of the layer boundaries \( Z_{i}^{in} \). For a three-layer medium the coefficients \( T \) and \( R \) are as follows:
Here, $d_2$ is the thickness of the layer with bubbles, $K$ is the wave number, $\omega$ is the perturbation frequency, and $\rho$ is the layer density. For a homogeneous layer, the wave number is determined as $K_j = \omega/C_j$, where $C_j$ is the speed of sound in the $j$-th layer.

\begin{align}
T &= \prod_{j=1}^{2} \left( \frac{Z_j^{in} + Z_j}{Z_j^{in} + Z_{j+1}} \exp[iK_jd_j] \right) \\
R &= \frac{Z_2(Z_2 - Z_3) - i(Z_2^2 - Z_2Z_3)\tan(K_2d_2)}{Z_3(Z_1 + Z_3) - i(Z_1^2 + Z_1Z_3)\tan(K_2d_2)} \\
Z_j &= \rho_j K_j, \quad Z_2^{in} = \frac{Z_1 - iZ_2\tan(K_2d_1)}{Z_2 - iZ_2\tan(K_2d_2)}, \quad j = 1, 2, 3.
\end{align}

\section{Results}

We will consider the sound signal transmission through the three-layer medium, namely, water-water with bubbles-water. The mixture pressure $p_0=0.1$ MPa and the temperature $T_0=288$ K. Disperse phase of bubbly liquid contain vapor-air bubbles, bubbles of carbon dioxide with water vapor and bubbles of helium. Let the bubble layer thickness be $d_2=5$ mm, the bubble radii $2$ mm (vapor-air bubbles), $1$ mm (bubbles of carbon dioxide with water vapor), $1.5$ mm (bubbles of helium), $f_0=1630$ Hz (resonance frequency of $2$ mm bubbles) and the volume content $\alpha_0=0.01$. The calculations were performed according equations (1), (2).

On the figures 2, 3 the influence of the volume content of bubbles in layer with bubbles on the sound wave transmission and reflection is shown. For curves $1 - \alpha_0=0.01$, curves $2 - \alpha_0=0.015$, curves $3 - \alpha_0=0.02$. Three fractions of the disperse phase with different initial radii leads to the appearance of three local minima and maxima on this coefficients. This is due to the difference in the values of the resonance frequencies of the intrinsic vibrations of bubbles of each fraction. Also noticeable that a maximum of the reflection coefficient and a minimum of the transmission coefficient are observable in the region of the resonance frequency of the bubbles. An increasing the volume content of bubbles leads to an increase the reflection coefficient and to a decrease the transmission coefficient, correspondingly, on the entire frequency range. The increasing the volume content of bubbles, the range near the resonance frequency, where the wave transmission coefficient takes near-zero values (opposite effect on the reflection coefficient), also expands.
Figure 2. Coefficient of sound transmission through a bubbly screen at different volume content.

Figure 3. Coefficients of sound reflection through a bubbly screen at different volume content.

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