Sound Attenuation in Media with Floating Particles

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Introduction

Problem of a small (less than the acoustic wavelength) foreign particle in medium, in which an acoustic wave propagates, is known since times of Rayleigh [1]. When considering interaction of an acoustic field with particles, suspended in a fluid, only monopole and dipole oscillations are usually taken into account [23].The dipole oscillations of particles, as known, occur along the direction of propagation of an acoustic wave. However, if the center of inertia of a particle does not coincide with the point of the buoyancy force application, a variable moment of force affects the particle in an acoustic field. This moment of force induces rotational oscillations of a particle. The angular oscillations of a particle in an acoustic field, obviously, will be accompanied by viscous friction in a fluid and relevant energy losses of an acoustic field. The rotationally oscillatory motion should be to some extent proper to all objects and particles, since the coincidence of center of mass and point of application of buoyancy force generally rarely takes place. Similar oscillations are possible, if the density distribution inside a particle is non-uniform. The angular oscillation amplitude is the stronger, the larger is the distance between the center of mass and the point of the buoyancy force application. Such situation can take place, when the particle is formed by several conglutinated particles of different density. It can be, in particular, materials subjected handling in ultrasonic devices of various functions or oceanic biological objects, such as phyto- or zooplankton. In this paper the proposed mechanism is theoretically considered, the solution of a problem of angular oscillations of a spherical particle with displaced center of mass in an acoustic field is given, the expression is obtained and the estimation of additional signal attenuation of a sound in a suspension of such particles are made.

Model

In Fig. 1 a schematic representation of the model is given. A spherical particle with an added point mass located on its surface is in a field of a plane acoustic wave.

In the given model, we do not take into account the compressibility of the particle, as well as of the added point mass, considering the particle surface as perfectly rigid. The added point mass can be both positive, and negative. In the latter case we can speak about a model of a spherical particle with a small perfectly rigid gas bulb adhered to it.

We shall suppose a random orientation of the particle in terms of the angle α between the vector directed from the particle center to the added point mass and the direction of acoustic wave propagation. We also assume, further, that the neutral buoyancy condition is valid, *i.e*. the average density of the particle is equal to density of the medium fluid, and the added point mass is much less than the total mass of the particle m: $|\Delta m| << m$.

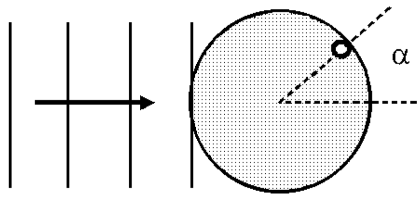

Fig. 1: A scheme of the problem.

Under these assumptions equations describing the rotational oscillation motion of such a particle in the acoustic field will be as follows:

$$J\ddot{\alpha} = M_{in} + M_{fr}$$
$$M_{fr} = -\frac{8}{3}\nu\rho R^3\dot{\alpha}\frac{3+6b+6b^2+2b^3-2ib^2(1+b)}{1+2b+2b^2}$$
$$M_{in} = -i\frac{k(-\Delta m)R\sin\alpha\, p(t)}{\rho} \qquad \text{eq. 1}$$
$$b = \frac{R}{\delta(\omega)}$$

Here: M_{in} - the moment of inertial forces effective on a spherical particle with mass m and moment of inertia $J=(2/5)mR^3$ due to the presence of the added point mass (Δm), $p(t)$ - amplitude of pressure in the sound wave, k - wave number, ρ - fluid density , $\delta(\omega)=\sqrt{2\nu/\omega}$ – thickness of the oscillating boundary layer, ν - kinematic viscosity of the fluid; M_{fr} – moment of forces of viscous friction in the rotational oscillations of a sphere [3].

Solving the eq. 2 for a periodic field of frequency ω, we obtain the following expression for viscous loss power at rotational oscillations of the particle in an acoustic field:

$$W = -\frac{\omega p^2\sin^2\alpha}{2\rho C^2}V\left(\frac{\Delta\rho}{\rho}\right)^2 b^2\frac{\gamma}{\gamma^2+\chi^2}$$
$$\gamma = \frac{3+6b+6b^2+2b^3}{1+2b+2b^2};\ \chi = 2b^2\frac{4+3b-2b^2}{1+2b+2b^2} \qquad \text{eq. 2}$$

where $V=(4/3)\pi R^3$ - is the particle volume, $\Delta\rho$ - the surplus density of particle substance above its average density, C – the sound velocity.

Consider now additional signal attenuation of a sound in a medium containing a suspension of such particles. If the concentration of particles in medium is n, the total loss power is connected to the field intensity of a plane wave I and the sound decrement ε of attenuation by the relation:

$$W n = -\varepsilon I = -\varepsilon p^2/2\rho C. \qquad \text{eq. 3}$$

Considering further, that the orientations of particles are uniformly distributed, we obtain for the decrement the following expression:

$$\varepsilon = \frac{\omega}{2C} nV \left(\frac{\Delta\rho}{\rho} \right)^2 G(R,\omega)$$
$$G(R,\omega) = b^2 \frac{\gamma}{\gamma^2 + \chi^2} \qquad \text{eq. 4}$$

Parameter *G(R,ω)* defines efficiency of development of such rotational motions of particles in an acoustic field at a given frequency. The dependence of parameter *G* from the dimensionless ratio *R/δ(ω)* is shown in Fig.2. This dependence is characterized by a maximum at *R/δ*=2.5.

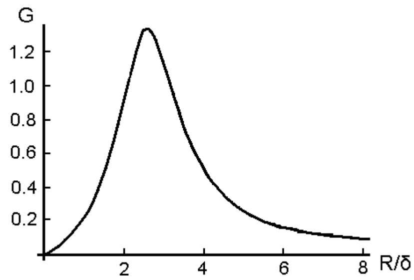

Fig. 1: Dependence of the parameter *G* on ratio *R/δ*.

Conclusion

Thus, in this paper a mechanism of rotational oscillatory motions of solid particles, suspended in fluid, with displaced center of masses in an acoustic field is suggested. A simple model of spherical particles with added point mass is discussed. In this model additional sound wave attenuation due to viscous losses at angular oscillations of particles is considered.

Let us make a quantitative assessment of the discussed effect. For a suspension of particles in water at the following values of parameters: R=25 μm, nV=0.01, $\Delta\rho/\rho$=0.15, $\nu=10^{-6}$ m^2/s the sound attenuation due to this mechanism, makes 6 dB/km at frequency 2.8 kHz and 10 dB/km at frequency 8 kHz. The further study of the examined effect can be useful for interpretation of experimental data on sound propagation in various suspensions.

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