ROTATION MOTION OF SMALL PARTICLES IN SOUND FIELD AND POSSIBLE MECHANISM OF SOUND PERCEPTION

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It is known several mechanisms of perception of sound by hydrobionts. However for simple organisms like small crayfish it is not clear how they can detect sound. One of possibilities is to detect oscillation water motion by microhairs. In this paper it is analyzed a physical mechanism of rotation oscillations of small particles in acoustic field and it application to a problem of sound perception by some hydrobionts.

INTRODUCTION

Small organisms in the ocean can get information on ambient condition by perception of specific sound signals. From the other hand, they can influence on sound propagation, generating, for example, echo-signals for sonar systems of whales, dolphins, etc. Among small ocean organisms are phyto- and zoo-plankton, crayfishes, and small fishes.

Plankton can change acoustic properties of sea water. But having density and compressibility of the matter very closed to water small plankton cells can not influence strongly on sound. The only possibility to make essential influence on acoustic properties of medium is gas bubbles associated with cells. In such a case at low frequencies sound velocity in plankton suspensions depends on the plankton concentration. At high frequencies an acoustic reverberation from plankton can be observed. The sound scattering cross section of plankton can increase due to gas cavities associated with plankton cells. Such gas cavities has been found in many kinds of phyto- and zoo- plankton [1-5].

Dispersion of sound velocity may be expected in phytoplankton suspensions since alga cells contain gas cavities [1-5]. In experiments sound velocity was measured with the phase and the resonance methods [1-5] with the relative accuracy of 10^{-5}.

Investigations conducted with different methods obviously shows that phytoplankton cells contain gas cavities. It was found that the larger cells have larger cavities. But relative volumes of cavities compared to the volume of cells are larger for smaller cells [5]. This suggests that the main function of gas vacuoles is to maintain neutral buoyancy.

Results of investigation of zooplankton show that long-range vertically migrating species of some euphauziids can use gas bubbles (swimbladder) to control their buoyancy that is similar to fishes. No migrating species do not contain any swimbladders [4]. The scattering cross sections of all of these species are derived mainly by mechanical properties of their bodies and are not essentially influenced by their swimbladders.

It follows from the existence of bubbles in phyto- and zoo-plankton that in aggregations of such organisms one can observe sound velocity decrease. However measurements showed complicated dependence of sound velocity in alga solutions on frequency. It was observed both increased and decreased sound velocities relatively to the sound speed in pure water at the same temperature (Fig. 1) [4].

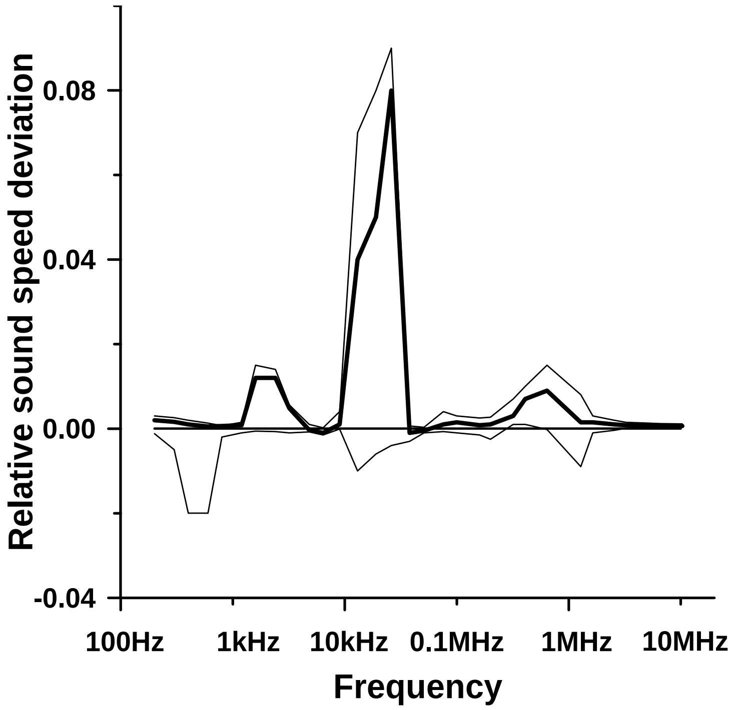

Fig.1 The averaged over 26 species sound velocity dispersion in phytoplankton solutions of volume concentration of cells of 10^{-4}. Hard solid line is the averaged curve. Thin lines show maximum and minimum values

Such an unpredicted properties open a question on physical mechanism the phenomenon. It is still unresolved.

When considering interaction of an ultrasonic field with the particles suspended in a fluid only dipole oscillations developing in the line of the ultrasonic wave propagation are usually taken into account. However if the center of inertia of a particle does not coincide with the point of Archimedean force application, an alternate moment of forces affects it, periodically rotating the particle. This moment of force induces rotational oscillations of a particle [6,7]. 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.

Such a rotational/vibrational motion should be to some extent inherent to all bodies and particles, since the conjunction of the center of inertia and the point of Archimedean force application is rather unlikely.

It can be, in particular, oceanic biological objects, such as phyto- or zooplankton. Such oscillations are visible, if the density inside a particle is essentially non-uniform, while their angular amplitude is the higher; the more is the distance from the centre of inertia to the point of buoyancy force application.

In many cases such sound induced oscillations of particles can noticeably affect its propagation [6,7]. For example the sound absorption in the phytoplankton suspension may increase as a result. Unfortunately, we can not yet explain sound velocity increase in phytoplankton solution with this mechanism. But this effect can be also used by water organisms perceiving relative motions of fluid with the help of hair cells, used as a mechanism of sound wave reception [8].

A number of mechanisms of perception of oscillatory motions of fluid by water organisms [9] are known. The simplest one can be associated with the reception by hair cells. It is believed, that this mechanism is appropriate to Crustacea. In the frequency range of 10-300 Hz their sensitivity to oscillatory velocity amounts 20-100 micron/s, that corresponds to the sound pressures of 30-150 Pa [10]. (For comparison: by fishes with a swimming-bladder the sensitivity in the range of 100-3000 Hz reaches up to 0.1 Pa). The experimental researches have shown, that the performance of the mechanoreceptive system (including information processing) is well matched with the frequency properties of magnetohydrodynamic perturbations [11]. Apparently, the nervous system of even such "primary" organisms is capable to isolate the perturbations caused by exterior action from the ones related to their natural motion [12], and also to identify such an action by its space-time characteristics. Besides a mechanoreceptive system has a strongly marked dynamic sensitivity: actions which spatial scale well compared with the body size of an organism [11] are received most effectively.

Apparently, the last mentioned property makes impossible the sound wave detection by means of sensing filaments (sensillas). Yet, in the range of 10-300 Hz, where the mechanoreceptive system sensitivity of Crustacea reaches its maximum, the sound wavelengths are much longer than the animals' bodies. If an organism has almost neutral buoyancy, it advances together with the ambient fluid, the motions of particles of water of rather symmetrically located body areas are identical and insignificant, and so the sound reception by sensillas is excluded. The account of rotational oscillations can cardinally change the situation. The circular fluid motion will result in opposite deflection of sensillas in different body areas, so the ultrasonic oscillations can be perceived.

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.

1. PHYSICAL MODEL OF PARTICLE ROTATION IN SOUND FIELD

In Fig. 2 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*: $|\Delta m| << m$.

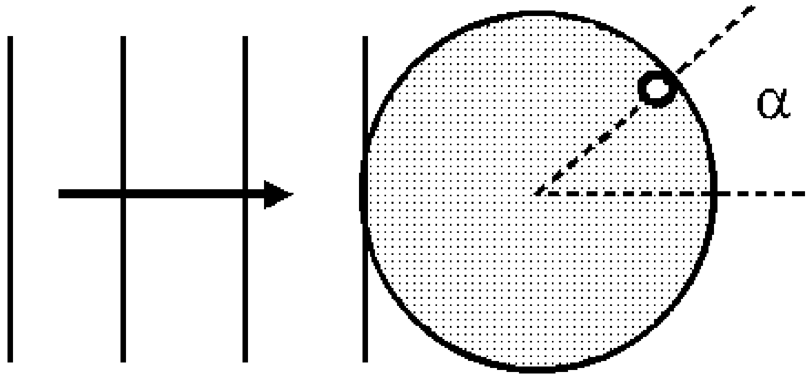

Fig.2 A scheme of the problem

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

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

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 (OBL), ν - kinematic viscosity of the fluid; M_{fr} – moment of forces of viscous friction in the rotational oscillations of a sphere [13].

Solving the equation (1) for a periodic field with frequency ω, we obtain the following expression for viscous loss power at rotational oscillations of the particle in an acoustic field:

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

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:

$$W\,n=-\varepsilon I=-\varepsilon p^2/2\rho C.$$

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

$$\varepsilon=\frac{\omega}{2C}nV\left(\frac{\Delta\rho}{\rho}\right)^2 G(R,\omega)$$
$$G(R,\omega)=b^2\frac{\gamma}{\gamma^2+\chi^2} \qquad (3)$$

Parameter $G(R,\omega)$ 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 $R/\delta(\omega)$ is shown in Fig. 3. This dependence is characterized by a maximum at R/δ=2.5.

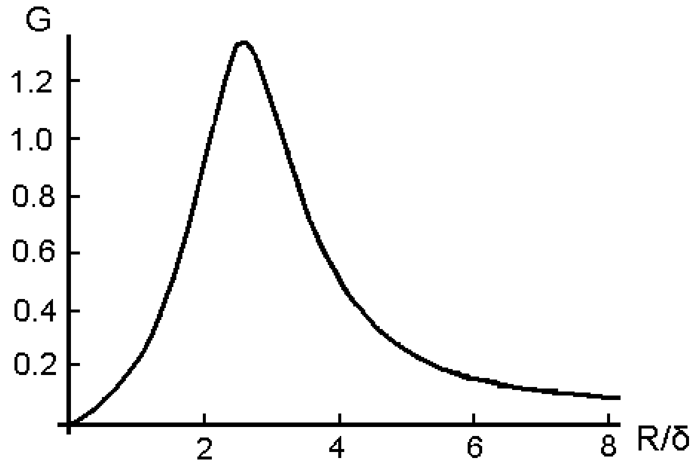

Fig.3 Dependence of the parameter G on ratio R/δ

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.

2. SOUND PERCEPTION MECHANISM

For qualitative examination of the suggested mechanism we shall consider a simplified model of a body of an organism. We will assume a spherical form of the body with the density some lower than the density of water, loaded with an added point mass Δm on its surface (Fig. 2). The average density we shall take equal to the density of water (the neutral buoyancy requirement) together with the condition $\Delta m/m$ <<1 (m is the total body mass). To explore resonant effects, we shall take into account gravity. The viscous losses by the sphere rotation we shall take into account for the case, when the depth of oscillating boundary layer (OBL) $\delta(\omega)=\sqrt{2\nu/\omega}$ is much less than the sphere radius R [13]. In order the ultrasonic wave could influence sensillas, OBL should be also less than their length l. In particular, for water (ν =10^{-6} m^2/s) with l=1 mm and l =0.3 mm this requirement will be held for the frequencies over 0.3 and 3.5 Hz respectively. Omitting intermediate calculations, we shall give expression for the gain-transfer characteristic. For our purposes it is natural to define it as the relation of the difference of tangential velocities of the sphere surface in the diametrally opposite areas and the oscillatory velocity of particles in the sound wave:

$$H(\omega)=\frac{2R^2(\Delta m/m)\omega^2}{\frac{2}{5}R^2\omega^2-(\Delta m/m)Rg-iR\omega\sqrt{2\nu\omega}} \qquad (1)$$

where g is the acceleration of gravity.

The general form of the frequency response function corresponds to the response of a high-pass filter (HPF). This expression has some remarkable features. At the resonant frequency (or HPF cutoff frequency)

$$\omega_{res}=\sqrt{\frac{5}{2}\frac{\Delta m}{m}\frac{g}{R}}$$

it is

$$H(\omega_{res})=\frac{2R}{\delta(\omega_{res})}\frac{\Delta m}{m} .$$

As well as in case of zooplankton cells, the relation of the added mass to the total body mass can be written as $\Delta\rho/\rho$ where $\Delta\rho$ is the body density deficit (without taking into account the added mass) related to the average density ρ. This relation can to some extent characterize the density non-uniformity inside a body. At the frequencies essentially exceeding the resonance, the gain tends to $H(\omega)=5\Delta m/m$. Within the framework of the accepted approximation at $\Delta\rho/\rho$ = 0.1, for example, it will give the quantity of 0.5. Thus, at high frequencies the signal from a sound field is transmitted in the mechanoreceptive system almost without distortions (if, certainly, the nervous system of the considered order of hydrobionts is capable to isolate such a differential effect).

Having divided $H(\omega_{res})$ by $H(\omega>>\omega_{res})$, we obtain the characteristic of the system resonant properties:

$$\frac{H(\omega_{res})}{H(\omega>>\omega_{res})}=\frac{2R^{\frac{3}{4}}}{5}\frac{\left(\frac{5}{2}\frac{\Delta m}{m}g\right)^{\frac{1}{4}}}{(2\nu)^{\frac{1}{2}}} \qquad (2)$$

The value of the sphere radius at which this quantity turns to unity, at $\Delta m/m$=0.1 is R_0=0.4 mm and separates the domains of relaxation and resonant behavior. If $R>R_0$, the frequency response function has a marked maximum which can exceed its value at high frequencies more than by an order of magnitude (cross labeled line in Fig. 4). Hence, even some resonant amplification of a signal from a sound field is possible. However, the body shape of a Crustacea animal is rather far from spherical and abounds prominences (limbs, antennas, etc.). Therefore viscous resistance at its oscillations will be much more, than for a sphere, and the resonance will not be so distinctive.

Let us analyze the applicability of the assumed approaches. The figure shows together with the dependence of the resonant frequency on sphere radius for $\Delta m/m$=0.1 (the solid line) also the lower boundaries relevant to the constant value of depth OBL, equal 0.5 mm *(f*=1.3 Hz, dashed line) and to the constant relation $\delta(f)/R$=0.1 (chain line) . The vertical dashed line shows the left-hand boundary of the resonant domain. From the Fig. 4 it is clear, that there is an area of the characteristic sizes from cm fractions to the first ten in cm and frequencies from unities up to hundreds in Hz (shaded), relevant to the actual sizes of sea Crustacea and to the range of their peak sensitivity where our approximations hold. Thus, from the physical point of view such a mechanism of perception of sound is quite practicable.

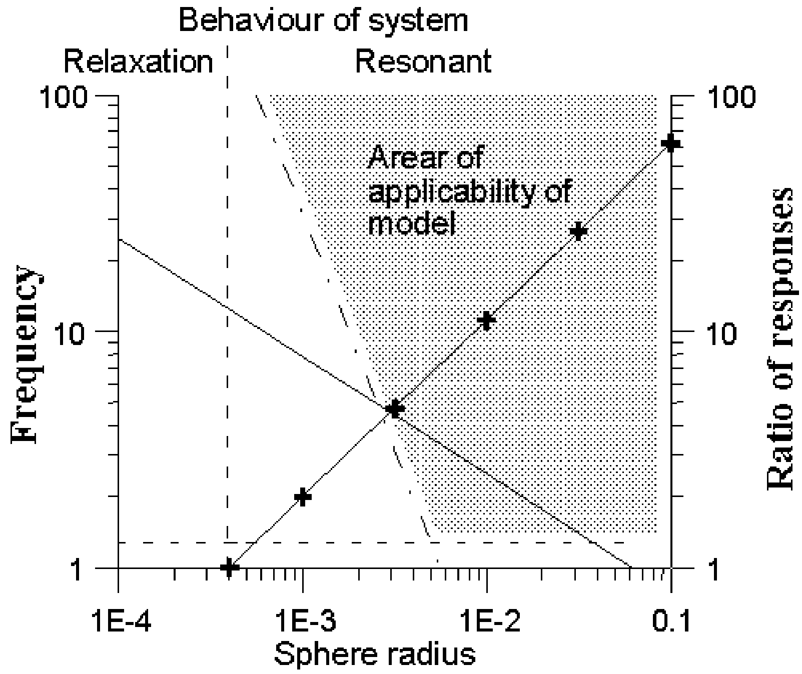

Fig.4 Dependence of the resonance frequency and ratio of responses $H(\omega_{res})/H(\omega>>\omega_{res}$ on sphere radius

3. CONCLUSION

In this work we theoretically considered a physical mechanism of rotation oscillatory motion of small particles in acoustic field. The mechanisms is related to the unbalanced distribution of density inside particles producing noncoincidence of center of inertia of a particle with the point of buoyancy (Archimedean) force application. Rotation oscillations can be responsible for the additional sound attenuation in suspensions of particles of neutral buoyancy and can serve as a possible mechanism of sound perception by small hydrobionts having sensillas. Theoretical estimations confirm the physical practicability of these phenomena. However the critical word here belongs to the experiment.

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