Proceedings of the Institute of Acoustics

SOUND RESONANCE SCATTERING BY SHELLS IN A FLUID

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1. INTRODUCTION

The low-frequency resonance scattering of sound by finite elastic shells has emerged as a timely problem in recent years. Various methods have been developed for the solution of such problems, including the finite-element method, the T-matrix method, matching of asimptotical expansions, etc. We note that the practical application of any method is limited either by insufficient speed and storage capacity of present-day computers or by the difficulty of using it for physical analysis of the structure of the scattered field. In addition to these methods, therefore, it is always useful to have model analytical methods for solving the problem of sound scattering by shells in a fluid, because they can be used to determine the contribution of both the geometrical and the elastic properties of the shell to the scattered field. The method used to solve the diffraction problem is based on the Kirchhoff integral [1]. Real solutions of the dispersion relation for a thin cylindrical elastic shell are obtained [2]. It is shown that the reaction of medium has a significant influence only on flexural waves. The experimentally observed increase in the low-frequency scattering amplitude in the region of angles of incidence of a plane sound wave on the shell close to the axis of the cylinder is also explained. Radiation impedance of limited cylindrical area is calculated in [3].

2. INFLUENCE OF THE REACTION OF THE MEDIUM

It is generally known that the amplitude of a plane sound wave scattered by a cylindrical elastic shell increases abruptly when the condition

$$\mathrm{Im}\,(Z_{\gamma}^{m} + Z_{s}^{m}) = 0 \qquad (1)$$

holds [1], where Z_{γ}^{m} and Z_{s}^{m} are the Fourier components of the mechanical impedance of the shell and the radiation impedance respectively:

$$Z_y^m = \frac{i}{\omega} \frac{c_{l_0}^2 h \rho_M}{R^2} \left(\frac{D_0^m}{D_{33}^m}\right) ; \quad Z_s^m = i\rho_{av} \omega R \frac{H_m^{(1)}(\varkappa R)}{(\varkappa R) H_m^{(1)\prime}(\varkappa R)} . \quad (2)$$

Here c_{l_0} is the longitudinal wave velocity in a plate of the same material as the shell; $c_{l_0}^2 = E/\rho_M (1-\nu^2)$; E , ρ_M , ν are the Young's modulus, density, and Poisson ratio of the shell material; h and R are the thickness and radius of the centroidal surface of shell; D_0^m and D_{33}^m are the principal determinant and corresponding minor of the system of equations of motion describing the free vibrations of "dry" infinite thin cylindrical shell [1]; $\varkappa = \sqrt{k_{c_2}^2 - k^2}$; $H_m^{(1)}(\varkappa R)$ and $H_m^{(1)\prime}(\varkappa R)$ are the Hankel function of the first kind of order m and its derivative with respect to the argument, $H_m^{(1)}(\xi) = J_m(\xi) + iY_m(\xi)$, and the branches of the Bessel function $J_m(\xi)$ and the Neumann function $Y_m(\xi)$ are chosen so that $J_m(\xi)$ and $Y_m(\xi)$ are real functions for positive real values of the argument ξ .

The objective of the present study is to analyze the conditions under which Eq. (1) is valid and the scattering amplitude thus acquires resonance maxima. Inasmuch as we investigating the scattering of a plane sound wave $\Phi_{\rightarrow} = A_0 \exp(ik_x x + ik_y y + ik_z z)$, which is determined by the wave vector $\vec{k}_{av} = \{k_x, k_y, k_z\}$ and which has a fixed frequency ω , we are interested only in the real solution of Eq. (1). Moreover, the function $k(\omega)$ obtained in the present study will be used to analyze the resonant vibrations of a bounded simply supported shell with eigenfunction $\Psi_p(z) = \sin[k_p(z + L/2)]$, $k_p = \pi p / L$. We require $k(\omega)$ in the interval [0 , ∞], because resonant vibrations of the indicated type $\Psi_p(z)$ are excited by an incident wave with any $k = k_{av} \cos\theta_0$ (θ_0 is the angle between the direction of sound incidence and the longitudinal axis of the shell). Here a discrete series of values of k_p corresponds to points situated on very curves $k(\omega)$ calculated below over the entire range of variation of k .

We consider the function $F(y, \Omega_{l_0}, m) = Z_y^m + Z_s^m$. On the basis of Eq. (2) it has the form :

$$F(y, \Omega_{l_0}, m) = Z_y^m + Z_s^m =$$

$$= i\rho_n c_{l_0} \frac{\sqrt{12\delta}}{\Omega_{l_0}} \left[\frac{D_0^m}{D_{33}^m} + \beta \frac{\Omega_{l_0}^2}{\sqrt{12\delta}} \cdot \frac{H_m^{(1)}\left(\sqrt{\Omega_{av}^2 - y^2}\right)}{\sqrt{\Omega_{av}^2 - y^2} \cdot H_m^{(1)\prime}\left(\sqrt{\Omega_{av}^2 - y^2}\right)}\right], \quad (3)$$

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where

$$\delta = h^2/12R^2 \; ; \; \Omega_{\ell_0} = k_{\ell_0} R = \omega R / c_{\ell_0} \; ; \; \Omega_{av} = k_{av} R = \omega R / c_{av} \; ;$$

$$y = kR \; ; \; \beta = \rho_{av} / \rho_M \; ; \; D_0^m = \det \| L_{ij}^m \| \; ;$$

$$D_{33}^m = L_{11}^m L_{22}^m - L_{12}^m L_{21}^m$$

in the latter expression

$$L_{11}^m = \left[\Omega_{\ell_0}^2 - y^2 - a m^2 \right] ; \; L_{12}^m = L_{21}^m = - b m y \; ; \; L_{13}^m = L_{31}^m = i \nu y \; ;$$

$$L_{22}^m = \left[\Omega_{\ell_0}^2 - a y^2 - m^2 \right] ; \; L_{23}^m = L_{32}^m = i m \; ; \; a = (1 - \nu)/2 \; ;$$

$$L_{33}^m = \left[1 - \Omega_{\ell_0}^2 + \delta (y^2 + m^2)^2 - \delta (2m^2 - 1) \right] ; \; b = (1 + \nu)/2 \, .$$

Separating the function (3) into real and imaginary parts, we obtain the equations

$$\operatorname{Im} Z_y^m = \rho_M c_{\ell_0} \frac{\sqrt{12\delta}}{\Omega_{\ell_0}} F_y^{(i)} (y, \Omega_{\ell_0}, m) , \tag{4}$$

$$\operatorname{Im} Z_\beta^m = \rho_M c_{\ell_0} \frac{\sqrt{12\delta}}{\Omega_{\ell_0}} F_s^{(i)} (y, \Omega_{\ell_0}, m) , \tag{5}$$

$$\operatorname{Re} Z_s^m = \rho_M c_{\ell_0} \frac{\sqrt{12\delta}}{\Omega_{\ell_0}} F_s^{(r)} (y, \Omega_{\ell_0}, m) , \tag{6}$$

where

$$F_y^{(i)}(y, \Omega_{l_0}, m) = \frac{\Phi_0^m}{\Phi_{33}^m} = \Big\{ \left[1 - \Omega_{l_0}^2 + \delta (y^2 + m^2)^2 - \delta (2m^2 - 1) \right] +$$

$$+ \left[\frac{m^2(\Omega_{l_0}^2 - y^2 - am^2) + 2b\nu m^2 y^2 + \nu^2 y^2 (\Omega_{l_0}^2 - ay^2 - m^2)}{(\Omega_{l_0}^2 - y^2 - am^2)(\Omega_{l_0}^2 - ay^2 - m^2) - b^2 m^2 y^2} \right] \Big\}, \quad (7)$$

$$F_s^{(i)}(y, \Omega_{l_0}, m) =$$

$$= \begin{cases} \beta \dfrac{\Omega_{l_0}^2}{\sqrt{12\delta}} \dfrac{1}{t} \dfrac{[J_m(t) J_m'(t) + Y_m(t) Y_m'(t)]}{[J_m'(t)]^2 + [Y_m'(t)]^2}, & y \le \Omega_{av}, \quad t = \sqrt{\Omega_{av}^2 - y^2}, \\ \beta \dfrac{\Omega_{l_0}^2}{\sqrt{12\delta}} \dfrac{1}{t^*} \dfrac{K_m(t^*)}{K_m'(t^*)}, & y > \Omega_{av}, \quad t^* = \sqrt{y^2 - \Omega_{av}^2}, \end{cases} \quad (8)$$

$$F_s^{(r)}(y, \Omega_{l_0}, m) = \quad (9)$$

$$= \begin{cases} \beta \dfrac{\Omega_{l_0}^2}{\sqrt{12\delta}} \dfrac{2}{\pi t^2} \dfrac{1}{[J_m'(t)]^2 + [Y_m'(t)]^2}, & y \le \Omega_{av}, \\ 0, & y > \Omega_{av}. \end{cases}$$

Here $J_m(t)$, $Y_m(t)$, and $K_m(t)$ are Bessel and Neumann functions and modified Bessel functions of the third kind (Macdonald functions). The following identity for the Wronskian of the Bessel and Neumann functions is taken into account in the derivation of Eq. (9) :

$$W\{J_m(z), Y_m(z)\} =$$

$$= J_m(z) Y_m'(z) - J_m'(z) Y_m(z) = \frac{2}{\pi z}$$

We thus seek the real solution $y(\Omega_{\ell_0})$ of the equation :

$$F_y^{(i)}(y, \Omega_{\ell_0}, m) + F_s^{(i)}(y, \Omega_{\ell_0}, m) = 0. \qquad (10)$$

The solution of Eq. (10) has been investigated previously for $\beta = 0$, i.e., when the reaction of the medium surrounding the shell is disregarded [$F_s^{(i)}(y, \Omega_{\ell_0}, m) = 0$] [1]. In the present report we find the solutions of Eq. (10) for $\beta \neq 0$. We first consider the case $m = 0$.
The asimptotic behavior of the function $F_s^{(i)}(y, \Omega_{\ell_0}, 0)$ defined by Eq. (8) in the neighborhood of the line $y = \Omega_{av}$ follows from the properties of the functions $H_0^{(1)}(z)$, $K_0(z)$ and their derivatives occurring in the function :

$$F_s^{(i)}(y, \Omega_{\ell_0}, 0) \sim \beta \frac{\Omega_{\ell_0}^2}{\sqrt{12\delta}} \ln \sqrt{|\Omega_{av}^2 - y^2|} \; ; \; y \to \Omega_{av} . \qquad (11)$$

Substituting Eqs. (11) and (7) with $m = 0$ in Eq (10), we obtain (in the limit $y \to \Omega_{av}$)

$$F_y^{(i)}(y, \Omega_{\ell_0}, 0) + \beta \frac{\Omega_{\ell_0}^2}{\sqrt{12\delta}} \ln \sqrt{|\Omega_{av}^2 - y^2|} =$$

$$= \left\{ \left[1 - \Omega_{\ell_0}^2 + \delta y^4 + \delta \right] + \frac{\nu^2 y^2}{(\Omega_{\ell_0}^2 - y^2)} \right\} + \beta \frac{\Omega_{\ell_0}^2}{\sqrt{12\delta}} \ln \sqrt{|\Omega_{\ell_0}^2 - y^2|} = 0 . \qquad (12)$$

Inverting Eq. (12) and invoking the expansion $\sqrt{1-x} \approx 1 - x/2$ for $x \ll 1$, we find that the solution $y(\Omega_{\ell_0}) = \Omega_{av}$ is a two-valued solution of Eq. (10) for the case $\beta = 0$, $m = 0$ in the limit $\beta \to 0$:

$$y_{1+,1-}(\Omega_{\ell_0}) = \lim_{\beta \to 0} \left\{ \Omega_{av} \pm \frac{1}{2\Omega_{av}} \exp\left[-\frac{2\sqrt{12\delta}}{\beta\, \Omega_{\ell_0}^2} F_y^{(i)}(\Omega_{av}, \Omega_{\ell_0}, 0) \right] \right\}, \qquad (13)$$

where the plus sign corresponds to one solution, and the minus sign corresponds to the other. It shoud be noted that β tends to zero from the left or right in the case, depending on the sign of the function $F_y^{(1)}(\Omega_{av},\Omega_{\ell_0},0)$. For example, β tends to zero from the right ($\beta \to 0+0$) for values of the frequency Ω_{ℓ_0} such that $F_y^{(1)}(\Omega_{av},\Omega_{\ell_0},0)$ is positive. In the case of negative values of $F_y^{(1)}(y,\Omega_{\ell_0},0)$, on the other hand, β tends to zero from the left ($\beta \to 0-0$). We note that $\beta > 0$ in the real physical problem ($\beta = \rho_{av}/\rho_M$ is the ratio of the density of the medium surrounding the shell to the material density of the latter). Consequently, the indicated two-valued solution $y_{I+,I-}(\Omega_{\ell_0})=\Omega_{av}$ will exist wherever the function $F_y^{(1)}(\Omega_{av},\Omega_{\ell_0},0)>0$ in the limit $\beta \to 0$ for $m = 0$ with the exception of solutions of the equation $F_y^{(1)}(y,\Omega_{\ell_0},0)=0$, which correspond to quasiflexural and quasilongitudinal waves.

We now consider the solutions of Eq. (10) for $\beta > 0$. The two-valued solution $y(\Omega_{\ell_0})=\Omega_{av}$ branches into two solutions $y_{I,II}(\Omega_{\ell_0})$ in accordance with the asymptotic relation (13) for values of the frequency Ω_{ℓ_0} such that the function $F_y^{(1)}(\Omega_{av},\Omega_{\ell_0},0) > 0$ (this is the segment OA in Fig. 1), i.e., when the mechanical impedance of the shell Z_y^m exhibits elastic behavior. The two-valued solution $y(\Omega_{\ell_0})=\Omega_{av}$ branches into two complex-conjugate solutions for values of the frequency Ω_{ℓ_0} such that the function $F_y^{(1)}(\Omega_{av},\Omega_{\ell_0},0) < 0$ (this is the segment AB in Fig. 1), i.e., when the mechanical impedance of the shell Z_y^m is a mass reactance. Figure 1 shows the real solutions of Eq.(10) calculated on a computer in the case $m = 0$ and $m = 1$ for steel shells in water ($\nu = 0.3$; $E = 2\cdot10^{11} N/m^2$; $\rho_M = 7.8\cdot10^3 kg/m^3$; $h/R = 0.1$ and $h/R = 0.2$; $c_{av} = 1500\ m/s$; $\rho_{av} = 1\cdot10^3 kg/m^3$). The solution I and II have the line $y = \Omega_{av}$ as an asymptote in the limit $\Omega_{\ell_0} \to 0$. As in the case $\beta = 0$, the solution III has a low- frequency asymptotic behavior corresponding to longitudinal waves in an unbounded rod in the limit $\Omega_{\ell_0} \to 0$: $y = \sqrt{1-\nu^2}\,\Omega_{\ell_0}$. As the frequency Ω_{ℓ_0} is increased from zero, the solutions II and III move away from the origin, diverge, and then begin to converge with a further increase in Ω_{ℓ_0} untill, at a certain value of Ω_{ℓ_0}, they form a branch point at some point C with coordinates (y_B , Ω_B), when $y_{II}(\Omega_B) = y_{III}(\Omega_B) = y_B$. In the neighborhood of the branch point C the asimptotic behavior of the solutions II and III has the form:

$$(y_{II,III} - y_B) \sim \pm c_B\sqrt{\Omega_B - \Omega_{\ell_0}}\ ;\ \Omega_{\ell_0} \to \Omega_B \qquad (14)$$

where $c_B > 0$ is a constant.

As mentioned, the solutions II and III become complex conjugates with a further increase in the frequency Ω_{ℓ_0} ($\Omega_{\ell_0} > \Omega_B$). It must be added here that,a qualitative restructuring of the solutions of Eq. (10) does not take place for $\beta \neq 0$ in the cases $m = 1,2,\ldots$ This result is attributable to the fact, which follows from Eq. (8), that the function $F_y^{(1)}(y,\Omega_{\ell_0},m)$, $m \geq 1$ does not any singularities for real values of Ω_{ℓ_0} and y .

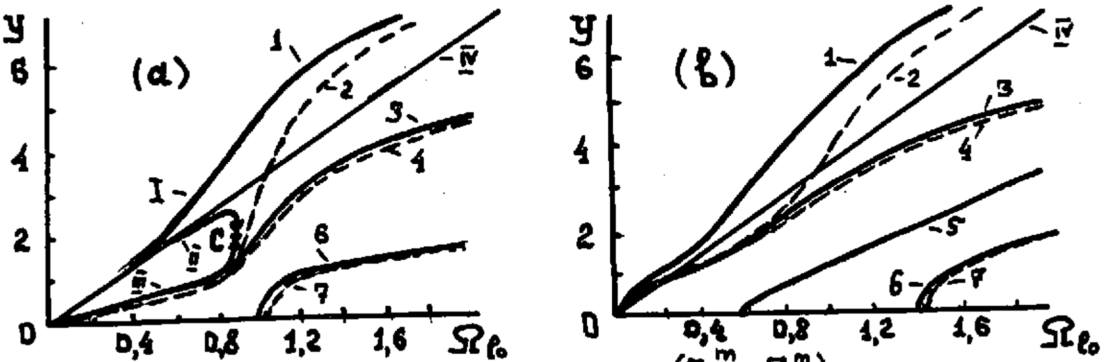

Fig. 1. Real roots of the equation $Im(Z_y^m + Z_s^m) = 0$ vs frequency. 1, 3) Quasiflexural branch for $h/R = 0.1$ and $h/R = 0.2$, respectively; 5) quasishear branch; 6) quasilongitudinal branch and $Im\, Z_y^m = 0$; 2, 4) quasiflexural branch for $h/R = 0.1$ and $h/R = 0.2$, respectively; 7) quasi-longitudinal branch; (IV). $y = \Omega_{av}$ in the case : a) $m = 0$; b) $m = 1$.

Thus, several results can be drawn from the foregoing analysis : The reaction of the medium has a significant influence only on flexural modes. It is evident from the graphs in Fig. 1 that this influence causes a major change in the angular and frequency ranges where the condition for spatial coincidence holds for these waves :

$$k = k_{av} \cos\Theta \qquad \text{or} \qquad y = \Omega_{av} \cos\Theta. \tag{15}$$

Here Θ is the angle between the wave vector of the incident wave and the positive z direction, which coincides with the longitudinal axis of the shell. For example, the spatial coincidence condition (15) does not hold for any angles of plane-wave incidence for sufficiently thin shells ($h/R \lesssim 0.1$) in the case $m = 1$ (see Fig. 1). This means that resonance maxima corresponding to the first mode will be absent in the experimental directivity patterns for the backscattering (echo return) of sound by thin cylindrical steel shells in water. Consequently, the positions of the resonance maxima (in the angular scattering patterns) corresponding to flexural modes must be determined by solving the dispersion relation (1), i.e., with allowance for the reaction of the medium.

The analysis shows that the scattering-amplitude maxima corresponding to shear and longitudinal modes (see Fig.1) are determined very accurately by the positions of the dispersion curves for the "dry" shell.

The emergence of a new branch (see Fig. 1, branch II) of the dispersion equation (1) in the case $m = 0$ for sufficiently thin shells ($h / R \lesssim 0.1$) in the low-frequency range ($\Omega_{\ell_0} < 1$) will cause the scattering amplitude to increase in the vicinity of angles of sound incidence close to the cylinder axis ($\theta \sim 0^\circ$). This conclusion is also confirmed by experiments on the backscattering (echo return) of sound by cylindrical steel shells in water. Fig. 2 shows experimental directivity patterns for the backscattering of sound by cylindrical steel shells. It is evident from the patterns that the scattering amplitude increases in the vicinity of angles of sound incidence close to the cylinder axis ($\theta \sim 0^\circ$).

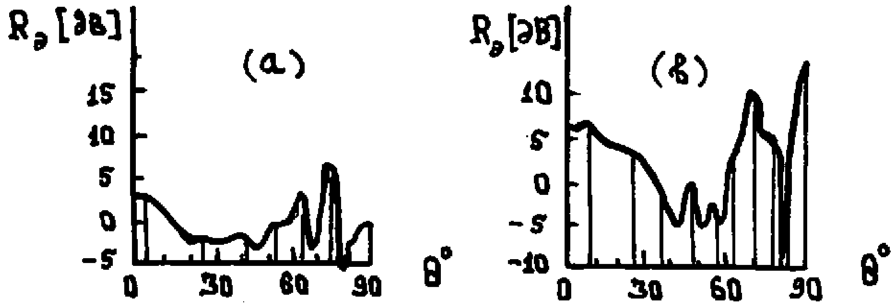

Fig.2. Directivity patterns for backscattering of sound by cylindrical shells in water. a) $L/R \approx 9.9$, $h/R \approx 0.06$, $\Omega_{\ell_0} \approx 0.6$; b) $L/R \approx 9.1$, $h/R \approx 0.01$, $\Omega_{\ell_0} \approx 0.73$.

3. CONCLUSION

This method can be used to relate the characteristic features of the scattered field to the geometrical and elastic parameters of a finite cylindrical shell, and it can be used, e.g., in the design of scatterers with prescribed characteristics of the directivity patterns. It provides a natural means for taking the shell inhomogeneitly into account and for analyzing other end-support conditions, and it can be extended to other slender or elongated shell configurations.

4. REFERENCES

[1] V V MUZUCHENKO & S A RYBAK, 'Low-frequency resonance scattering of sound by finite cylindrical shells (review)', Sov. Phys. Acoust., 34(4), p325 (1988)

[2] V V MUZYCHENKO & S L SKOROKHODOV, 'Influence of the reaction of the medium on low-frequency resonance sound scattering by cylindrical shells', Sov. Phys. Acoust., 34(2), p161 (1988)

[3] V V MUZYCHENKO & S A RYBAK, 'Sound scattering by limited elastic shells', in: Proc.Int Congr.on Recent Developments in Air & Structure Born Sound & Vibration, Auburn Univ., AL, USA, Vol.2, p751 (1990)

Proceedings of the Institute of Acoustics

INFLUENCE OF PHYTOPLANKTON ON SOUND PROPAGATION IN THE OCEAN

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In the ocean acoustics the alive bio-specimen are well known to influence on the sound propagation. For instance, R. J.Urik [1] concerning the topics of reverberation noted that "...the scattering centers giving the volume reverberation are undoubtedly of a biological nature, i.e. they are specimen living in the sea". Also he supposes the influence of other objects: sinking dust, detrit, microturbulence and so on to be a small factor. So the ocean population can play a significant role in forming the effects of sound channels originating from known hydrophysical reasons. For instance, D E Weston [2] asserted that the data on forward-scattering could give information about 1) sea surface, 2) sea bottom, 3) bubbles and fishes, 4) inner waves and other large scale motions of sea, i.e. he arranged the influence of fishes higher than the influence of inner waves.

At 50-th years when acoustics of the ocean began only to take its roots,the fields of phytoplankton were considered as as possible factor for considerable scattering of the sound. As result of in situ experiments D Cushing [3] noted that the most clear echo-signals corresponded to the layers with high concentrations of diatoms and detrit. (Barents Sea, frequences 10 kc and 30 kc, concentration of cells $N > 10^6$ 1/l). Also D E Weston [4] noted the reason for existence of nonmigratihg acoustically detected layers in thermocline (H~35 m) "...organisms containing though even very small gas cavities" may occur (Nord Sea, August, diatom bloom $N > 10^6$ 1/l). That is enough the gas content of

0,25 ml/m^3 (2,5*10 $^{-7}$) in the layer with thickness about 1 inch that the scattering coefficient on the frequence 10 kc was about R > - 50 db. With time however the phytoplankton came out from consideration as spontaneous factor for acoustical effects. The reason was that the physical characteristics of particles similar to phytoplankton cells (density ~1.01 - 1.10 g/cm^3, dimensions <0,3 mm) give too low scattering coefficients of natural thickenings. The phytoplankton as we know was mentioned only as indirect factor: in phytoplankton thickenings may be increased the concentration of zooplankton and mictophids and the latters are considered the main factors of volume sound scattering in acoustically detected layers. As other factors sharp gradients with depth of temperature and salinity are considered.

Miester and coworkers [5] investigated the influence of plankton on acoustical properties of water (attenuation and dispersion of sound velocity). The last properties are most interesting for us. In the paper [5] the authors observed that a suspension of green algae *Scenedesmus* with water did not alter the sound velocity even for very high concentration, which were 10^2-10^5 times of natural concentration. (Dimensions of the algae were about 10 μ and concentration 8 g/l). But in the paper [5] the authors recieved that the sound velocity in suspension of *Artemia* eggs gave a dispertional curve with f ~7 Mc and $\Delta c/c$ ~ 1 * 10^{-3}. (Dimensions of the particles were 230 μ, concentration 20 g/l (or 11 * 10^3 particles per cc) This dispersional curve could be intepretated in terms of presence of gas bubbles in the medium.But the dispersion and absorption data were explained with nonrigid sphere theory.

The influence of gas bubble accumulation on sound velocity is [6]:

$$c_o = c \times \left[1 - \frac{3\,\beta}{2a^2 (\omega_R/c_o)^2} * \frac{y^2\,(y^2-1)}{(y^2-1)^2+\delta^2} \right]$$

here c, c_0 - sound velocity with and without gas bubbles, β - volume gas content (cc/cc), a - radius of bubble, $\omega_R=2\pi f_R$, f_R, f - resonance and current frequencies, $y = f_R/f$.

The value of $\Delta c/c$ has order of $1*10^{-3}$ for conditions which we will be used later (a = 0.5 μ, $N \sim 1*10^5$ cell/cm^3, f =7.5 Mc).

Some years ago somebody of us began to examine the connection of gas bubble with the phytoplankton thickenings and their part in acoustical effects. Until that, only blue-green algae (procariotes) were known to possess of gas hollows (vacuoles). Nevertheless it was found that during the phytoplankton bloom (ordinary eucariotes algae) the concentration of big gas bubbles (radius a > 10 μ) is increased, but such bubbles were not generated in phytoplankton cultures in the laboratory [7,8]. But the special experiments testified that the cells of almost all groups of phytoplankton possessed of small gas cavity (radius a < 2 μ).

Our experiments included both volumetric and acoustical measurements. The latter were the measurements of the sound velocity dispersion and the volume reverberation [8].The measurement of sound velocity was made with standart cycle method for f_1=7.5 Mc and f_2=0.75 Mc. It had a sensivity $4*10^{-6}$. For all measurements we used alive cultures of phytoplankton, cell concentration was 1-10 times of natural cell populations in phytoplankton thickenings.

The measurement of sound velocity shows two effects. The first is the rise of the velocity on both frequencies 7.5 Mc and 0.75 Mc. This effect may be very large in some phytoplankton cultures ($\Delta c/c \sim 1*10^{-2}$) and we attribute it primary to hardening the structure of water at the vicinity of cells. This effect does almost not depend on the presence of gas hollows in phytoplankton cells and will be examined by us later. The second effect of phytoplankton is the dispersion of the sound velocity. When the culture with phytoplankton stayed in the darkness at two days, sound velocity on low frequency (0.75 Mc) is larger than on high frequency ($c_1/c_2 = 1 - 1*10^{-4}$). But the ratio c_1/c_2 was greater than 1 for all cultures used by us when they every day stayed on light (see Table 1). The latter was truth also for measurements in situ and for laboratory measurements, when the probe was taken in situ during a phytoplankton bloom.

Table 1. Ratio of the sound velocity for f_1=7.5 Mc and f_2=0.75 Mc (c_1/c_2) in the medium with phitoplankton of concentration N (cell/cc). V - the accounted volume of gas hollow (μ^3/cell).

N	Specimen	c_1/c_2-1	$N*10^{-5}$	V_{gh}
1.	*Olistodiscus luteri*	$1*10^{-4}$	1.0	$2-5*10^{-2}$
2.	*Phaeodactilum tricornutum*	$3-10*10^{-5}$	2.2	$1-4*10^{-2}$
3.	*Dunaliela salina*	$1.2*10^{-4}$	4.0	$1-5*10^{-2}$
4.	The mixture of 2 and 3	$5*10^{-5}$	2+1	$1-2*10^{-2}$
5.	*Dunaliela salina**	$5-7*10^{-6}$	2.8	$1-9*10^{-3}$

* The measurement on the culture after compression.

Such behavior of the ratio c_1/c_2 may be expected if it is caused with gas bubbles of varing dimensions. The gas hollows have minimal dimensions when the phytoplankton cells stayed in darkness for a long time. Under illumination the dimensions of the hollows increased to their normal sizes which depending on the type of cells. The mean radius of hollows found by sound dispersion are 0,2 - 0,4 μ. The reverberation measurements were made in glass vessel (3 l), where the ceramic tranducer-reciever was mounted. The frequency of ultrasonic was 6,5 Mc, the impulse duration 10 μsec, and echo-signal from 0,1 cc of water in center of vessel was analysed. The back scattering crossing for one specimen was calculated by dividing of the measured scattering by a number of cells. The cell concentration was 10^3 -10^6 1/cc. Nevertheless there was a linear relation between scattering and concentration and therefore we supposed that the level of coherent scattering was relatively low. During the measurements the medium could be compressed with an outer pressure up to 4 atm.

The results of measurement are given at Table 2. Here the measured and theoretical data are compared. For all cases the former are 10^2-10^4 times higher. There were common assumption for a calculation of scattering: the densities of cells are 1,1 times higher than water and their compressibilities are the same. This is very important experimental result. All phitoplankton specimens can be divided in two groups. For the first group the outer pressure up to 4 atm has not influenced on scattering. But for the second group of plankton the signal of scattering diminishes sharply under outer pressure > 0,15 atm. The resulted scattering crossing per one cell becames close to theoretical ones. It is important to note, that the primary value of scattering are restoring after 2-30 hours of light illumination of the vessel as under atmospheric pressure and so under condition of compression. These experiments were made with laboratory cultures of phytoplankton and also with samples of water taken in situ and examined on the ship.

It is worth of noting that the same specimen show also the decrease of the differential compressibility under outer pressure 4 atm, while for specimen from the first group the altering of the compressibility under the pressure is reversible. All these observations on alive phytoplankton together with some results of volumetric measurements are an evidence for us that all examined specimens of phytoplankton possess gas hollows. As it follows from reverberation measurements the equivalent radius of gas hollows is $a < 2$ μ. Different experiments give various equivalent

Table 2. The scattering crossing of the phytoplankton cells: σ_t - theoretical, σ_m - measured, σ_p - measured under the the outer pressure 4 atm (in units μ^2/cell), D - dimentions of the cell (μ), V_{gh} - the accounted volume of gas hollws (μ^3/cell), N - concentration (μ^3/cell).

N	D	$N*10^{-5}$	σ_t	σ_m	σ_p	V_{gh}
1	17×12×6	0.35	$5\text{-}50*10^{-5}$	$1\text{-}8*10^{-1}$	$\sigma_p = \sigma_m$	0.5-8
2	23×15×15	1.2	$1\text{-}10*10^{-4}$	$1\text{-}8*10^{-1}$	-- " --	0.5-8
3	45×30×20	≃0.3	$1\text{-}1*10^{-2}$	5-15	-- " --	2-10
4	13×8×5	2.0	$5\text{-}50*10^{-6}$	0.5-0.9	0.1-0.2	0.6-3
5	11×7×3	4.0	$1\text{-}10*10^{-6}$	0.1-0.5	$1\text{-}10*10^{-5}$	0.5-0.7
6	6×5×2	≃3.0	$1\text{-}10*10^{-6}$	$4\text{-}9*10^{-2}$	$1\text{-}10*10^{-3}$	0.4-1

Specimen : 1 - *Olistodiscus luteri*, 2 - *Peridinium tricvetrum*, 3 - *Prorocentrum micans (in situ)*, 4 - *Platimonas veridis*, 5 - *Dunaliela salina*, 6 - *Phaedactilum tricornutum (in situ)*

values of the radius but the latter seems the most concrete. Then on the thickenings ofphytoplankton the sound of low-frequency (<100 kc) can undergo the varyation of velocity $\Delta c/c \sim 1*10^{-3}$ and give a reflection of order -60 db as it was estimated by Weston [4]. The possible display of phytoplankton on the acoustical fields in the ocean is determined by the depth of the thickenings and their configuration. It is known from bottle samples and fluorimetric profiles that phytoplankton thickenings have sufficiently homogeneity in the horizontal direction (few tens kilometers) and a layer structure in the vertical direction (tens centimeters - ten meters). The depth of thickenings is located from zero meters to a low boundary of thermocline (0-150 m). They takes part in the inner motion of the water. In this case the phytoplankton can be a noticeable factor of the variation of the sound level going in an underwater sound channel. The influence can be estimated with a model spectrum of the finescale inner formations:

$$B(\bar{æ};\ æ_z, z) = \pi^{-1} \langle\mu^2\rangle\ L_z\ L_r^2\ F(æ_z\ L_z) * \exp\ (-æ^2\ L_r^2\ )$$

where L_z and L_r -vertical and horizontal scales of the correla tion of unhomogeneities, F - arbitrary function, æ and $æ_z$ - horizontal and vertical wavenumber.

The parameter $\langle\mu^2\rangle$ was set as a function of z:

$$\langle\mu^2\rangle = \begin{cases} \mu^2; & 0 < z < h \\ 0; & z > h \end{cases}$$

The approximated solution gives for the attenuation decrement of channel mode γ_p [9]:

$$\gamma_p = \begin{cases} A\sqrt{(P-P_h)}\ ; & P_h \leqslant P \leqslant P_o \\ A\left(\sqrt{(P-P_o)+(P_o-P_h)} - \sqrt{(P-P_o)}\right); & P_o < P \leqslant P_{cr} \end{cases}$$

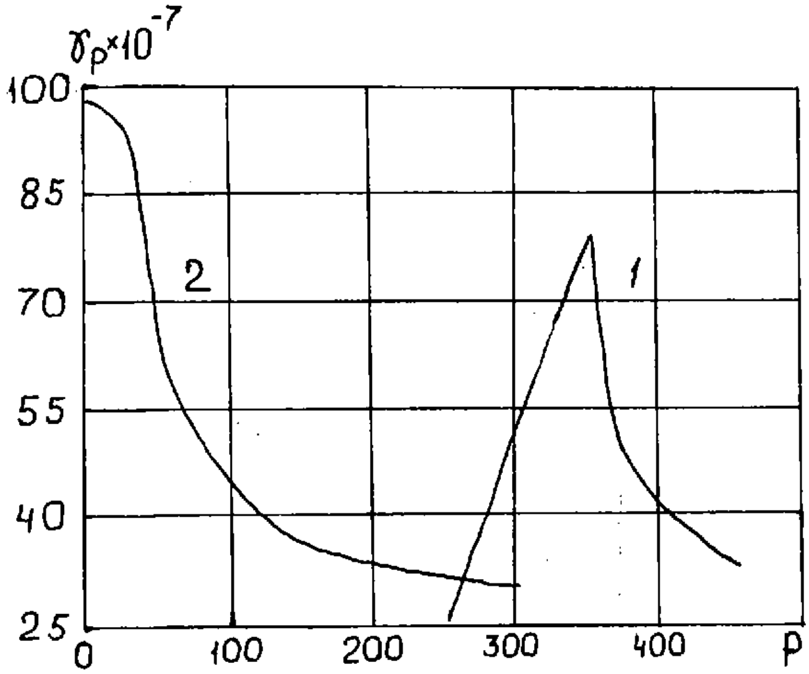
there $$A = \frac{4\ \pi\ \sqrt{2}\ \Gamma(1.25)\ F(0)\ L_z\sqrt{L_r}\ \omega^2\ \mu^2}{\nu^+\ c_o\ L_o^{3/2}},$$

$$P_o - P_h = \frac{\nu^+\ h\ \omega\ Lo}{2\pi\ c_o}\ ;$$

$$\nu^+ = \left.\frac{dco(z)}{dz}\right|_{z=h};$$

the function $F(æ_z, L_z) = \sqrt{2}\ \pi^{-1}(1+2\ æ_z^2\ L_z^2\ )^{-1}$; Γ - is the gamma function, L_o- the length of the beam cycle touching tangentially the surface, P_{cr} - is the highest number of the mode in the channel.

The dependence of γ_p on the mode number p is given on the Figure (curve 1). Here it is used the type profile $c_o(z)$ for a



middle latitude when the depth of the axis of the sound channel is 1 km, the characteristic length of the beam cycle L_o=60 km and the values of other parameters are: ν^+=0.15 s, h=100 m, $\omega/2\pi$=240 c, L_z=5 m, L_r=1000 m. Curve 2 represents an ordinary form of γ_p for usial finescale thermohaline structure of the ocean [9]. It is clear that the phytoplankton thickenings can cause the noticeable sound attenuation in the ocean for high modes in contrary to the thermohaline structure causing in general attenuation of lower modes.

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REFERENCES

[1] R J URICK,'Principle of Underwater Sound', 2-nd ed. N.Y. McGrow-Hill (1975)

[2] D E WESTON, In:'Underwater Acoustics and Signal Processing', Eds. Leif Bjørnø & D Reid, Publishing Company,p95 (1980)

[3] D H CUSHING A J LEE & J D RICHARDSON,'Echo Traces Associated with Thermoclines', *J Mar Res*, 15 p1 (1956)

[4] W E WESTON,'Observation on a Scattering Layer at the Thermocline', *Deep Sea Res*.5 p44 (1958)

[5] J D WATSON & R MEISTER,'Ultrasonic Absorption in Water Containing Plancton in Suspension', *JASA*,35 p1584 (1963)

[6] C S Clay & H Medwin, 'Acoustical Oceanograhy: Principles and Application', N Y, Willy (1977)

[7] B M SANDLER, D A SELIVANOVSKY & A YU SOKOLOV,' ', *Dokladj Academy of Science USSR*, 260 p1474 (1981)

[8] B M SANDLER, D A SELIVANOVSKY & P A STUNZHAS,'Bubbles in the Ocean and Phytoplankton', Reports of the Conference: Metrological Problems of Hydrophysical Measurements, Moscow (1990)

[9] V V ARTELNY, N S GORSKAY & M A RAEVSKY,'The Statistical Chareсteristics of the Normal Waves in Occasional Nonhomogeneous Channel in Ocean', Preprint of Institute of Applied Physics (1988)