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Modulated opto-acoustical sounding of the upper ocean

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Abstract. We analyse a new optical method to detect and utilize underwater acoustic signals from above the ocean surface. The method is based on scattering of modulated laser light by natural inhomogeneities (hydrosoles, bubbles, turbulence, etc.) whose concentration oscillates in a vertically propagating sound wave. Measurement of the Doppler shifted modulation frequency in the scattered light may be used both for monitoring of the upper ocean sound speed profile and for communication with underwater objects.

1. Introduction

Current methods of air-borne and/or space-borne remote sensing can monitor large areas in the ocean, yet provide information only from the ocean surface. To explore the ocean body acoustical methods are presently being developed, based on underwater sound signals, carrying information about the ocean depths (Munk *et al.* 1996). Ocean acoustic tomography is shown to be capable of monitoring mesoscale and large-scale features in the ocean.

A major problem in a use of sound, propagating in the underwater acoustic channel for long distances, is that the sound is affected by wave and turbulent fluctuations concentrated mainly in the upper ocean layer (Flatte *et al.* 1979). Thus, monitoring the sound speed profile in the upper ocean becomes a problem of special importance for analysis and prediction of long-distance sound propagation in the ocean. This information also would be valuable for processing information, collected with sonars, because the acoustical location signal is influenced by inhomogeneous sound speed field.

A detection of underwater acoustical signals from above the ocean surface might provide an effective and practical way of direct measurement of the sound speed profile. It also could have other multiple applications, including remote monitoring of the ocean acoustic environment and communication through the ocean surface.

Numerous attempts have been made to detect underwater sound by its surface signature. Laser methods were used to 'read' ocean surface variations of acoustic frequencies. All the attempts so far have been operational failures. An obvious reason for it is the extremely high natural variability of the ocean surface, that masks weak surface signatures of the underwater acoustic signals.

In the present article we propose an alternative optical method to detect underwater acoustical signals based on light–sound interaction in the water below the ocean surface. The green-blue light can propagate inside the ocean down to 100 m depth, depending on the ocean environment and weather conditions. This upper ocean layer may serve as an operating volume for an optical detection of sound, based on the mechanism of light–sound interaction, which we describe below.

The technique we are proposing here uses the effect of the Doppler shift of the modulation frequency, that occurs when the light is scattered by natural scatterers oscillating in a propagating sound wave. We prove below that this frequency shift is proportional to the sound frequency. Measuring the light modulation frequency, while the sound wave train is propagating in the vertical direction, one can monitor the sound speed vertical profile and also extract information encoded with the sound frequency modulation.

The basic idea of this method is close to the radio-acoustical sounding of the atmosphere which was first realized in 1972 (Marshall *et al.* 1972) and continues developing at the present time (Angevine *et al.* 1994, Neiman *et al.* 1992, Masuda *et al.* 1992, Fabrikant *et al.* 1994). However a direct application of the radio-acoustical method needs the Bragg resonance, matching electromagnetic wave length with the half of the acoustical wave length. This is practically impossible in the optical range because of the fast dissipation of hypersound with such short wavelengths.

Here we discuss a technique that allows the wave envelope of modulated light to be used for sounding of the acoustic field in the upper ocean. The light modulation wave can not be scattered directly by a sound wave (except high-order nonlinear scattering effects which would be very hard to achieve in practice). However in any real ocean environment there are always lots of natural scatterers (bubbles, hydrosoles, turbulence, etc.) which act so effectively, that practically limit light's ability to penetrate the ocean. If the sound affects those natural scatterers, modulating their scattering cross-section, then intensity of the scattered light will be influenced by the sound wave. As a result, the information hidden in a sound wave will be transferred to the light intensity modulation wave.

The Bragg resonance, which this techniques is based upon, matches the sound wave length λ_a with the half of the modulation wave length Λ_0

$$2\lambda_a = \Lambda_0 \tag{1}$$

As the light carrier frequency is not involved, this method does not require a coherency in the scattered light. Neither it requires a high-frequency hypersound, because the modulation wavelength in the Bragg resonance (1) is much larger than the light carrier wavelength.

A use of modulated electromagnetic wave to measure the frequency of propagating sound has been suggested first in Fabrikant (1991) for the radio-acoustical sounding of the atmosphere by meteorological radars, radiating centimetre or millimetre radio waves.

In the next section we develop a theory of scattering of periodically modulated light in a turbid water, where the specific scattering cross-section oscillates in a vertically propagating sound wave. We prove that the scattered light contains a component with a shifted modulation frequency and analyse the amplitude of this component and the value of the modulation frequency shift.

In the conclusion we discuss feasibility of the proposed method and estimate the measurable effects for realistic ocean conditions. We also discuss potential applications, advantages, and possible extentions of this opto-acoustic technique.

An ability of hydrosoles of different sizes and density to oscillate in a sound wave is analysed in the appendix. It is shown there that most of the natural hydrosole particles can produce the desirable effect.

2. Modulation of the scattered wave

Let the light beam go in the vertical direction along the z-axis (directed down the water surface), figure 1. We assume that optical signal of the frequency ω_0 is 100 per cent modulated with the frequency Ω and has the maximum intensity I_0. Then

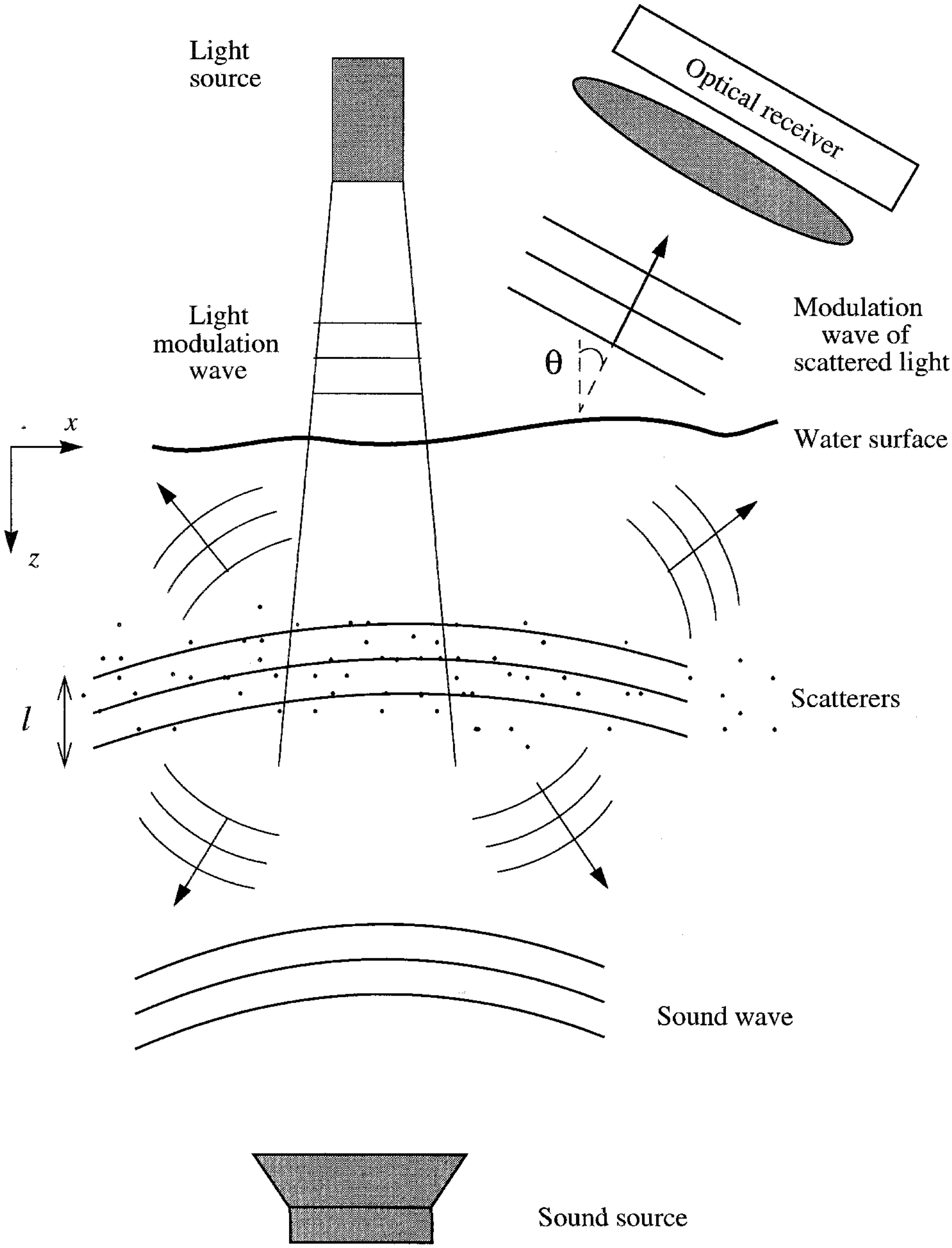

Figure 1. Modulated opto-acoustical sounding system. Incident light is modulated and goes from above the sea surface. Random scatterers in the water are concentrated in a periodic 'grating' by a propagating sound wave. Scattered light is modulated with a shifted frequency.

the intensity of the incident light propagating down the water with the light speed c_0 is

$$I = I_0\left[1 + \cos\left(\Omega\left(t - \frac{z}{c_0}\right) + \phi_0\right)\right] \quad (2)$$

where ϕ_0 is the modulation initial phase.

The sound wave train, radiated from below, propagates up to the surface in the water with the speed c_a vertically along the light beam, see figure 1. We assume that the sound wave front is close to a plane wave in the vicinity of the light beam, and so the water density perturbation due to the sound wave is

$$\rho = \bar{\rho} M \cos\left[\omega_a\left(t + \frac{z}{c_a}\right) + \phi_a\right]\Pi_r^{r+l}(z) \quad (3)$$

Here $\bar{\rho}$ is the unperturbed water density, M is the Mach number of the sound wave, ϕ_a is the initial phase of sound, and the step-wise function

$$\Pi_r^{r+l}(z) \equiv \begin{cases} 1 & \text{if } r \leqslant z \leqslant r + l \\ 0 & \text{if } z < r \text{ or } z > r + l \end{cases} \quad (4)$$

defines the shape of the sound wave train with the width l and the upper boundary located at the depth

$$r = z_m - c_a(t - t_m) \quad (5)$$

Here t_m is the time when the acoustic pulse enters into the scattering volume which extends down to the depth z_m.

We assume that light scatterers in the oceanic water oscillate with the sound wave exactly the same way as the water itself (see appendix). That means their concentration and specific scattering cross-section deviate from their mean values with the same relative amplitude as the water density does, i.e., the scattering cross-section per unit volume is

$$\eta = \eta_0\left[1 + M\cos\left(\omega_a\left(t + \frac{z}{c_a}\right) + \phi_a\right)\Pi_r^{r+l}(z)\right] \quad (6)$$

where η_0 is the undisturbed specific scattering cross-section.

If t volume contains a large number of randomly oriented small scatterers, it should disperse the incident light isotropically. Then the energy flux from the layer of the width dz does not depend on the scattering angle and equals to

$$W = I\sigma \quad (7)$$

where

$$\sigma = \eta S dz \quad (8)$$

is the total scattering cross-section of the layer dz and S is the cross-section area of the light beam.

The scattered light propagates away from the volume with the speed c_0. Therefore, at the distance R the light intensity dI_{sc} at the time t is determined by the scattering process which took place earlier, at the time

$$\tilde{t} = t - \frac{R}{c_0}$$

and we have

$$dI_{sc} = I\left(t - \frac{R}{c_0}\right)\eta\left(t - \frac{R}{c_0}\right)\frac{S}{4\pi R^2}dz \tag{9}$$

Integrating (9) over the entire enlightened volume we have the total intensity of the scattered light

$$I_{sc}(t, R) = \int I\left(z, t - \frac{R}{c_0}\right)\eta\left(t - \frac{R}{c_0}\right)\frac{S}{4\pi R^2}dz \tag{10}$$

Substituting the specific scattering cross-section from (6) into (10), we have the scattered light intensity

$$I_{sc} = \frac{1}{4\pi}\int \frac{SI_0\eta_0}{R^2}\left[1 + M\cos\left(\omega_a\left(t - \frac{R}{c_0} + \frac{z}{c_a}\right) + \phi_a\right)\Pi_r^{r+l}(z)\right] \times \left[1 + \cos\left(\Omega\left(t - \frac{R}{c_0} - \frac{z}{c_o}\right) + \phi_0\right)\right]dz \tag{11}$$

The total scattered intensity may be decomposed into four parts

$$I_{sc} = \bar{I}_{sc} + I_{sc}^{(\Omega)} + I_{sc}^{(a)} + I_{sc}^{(\Delta\Omega)} \tag{12}$$

which are

$$\bar{I}_{sc} = \frac{1}{4\pi}\int \frac{S(z)I_0(z)\eta_0(z)}{R^2}dz \tag{13}$$

$$I_{sc}^{(\Omega)} = \frac{1}{4\pi}\int \frac{S(z)I_0(z)\eta_0(z)}{R^2}\cos\left(\Omega\left(t - \frac{R}{c_0} - \frac{z}{c_0}\right) + \phi_0\right)dz \tag{14}$$

$$I_{sc}^{(a)} = \frac{SI_0\eta_0}{4\pi R^2}\int_r^{r+l} M\cos\left(\omega_a\left(t - \frac{R}{c_0} + \frac{z}{c_a}\right) + \phi_a\right)dz \tag{15}$$

$$I_{sc}^{(\Delta\Omega)} = \frac{SI_0\eta_0}{4\pi R^2}\int_r^{r+l} M\cos\left(\omega_a\left(t - \frac{R}{c_0} + \frac{z}{c_a}\right) + \phi_a\right)\cos\left(\Omega\left(t - \frac{R}{c_0} - \frac{z}{c_0}\right) + \phi_0\right)dz \tag{16}$$

The first two terms in (12) $\bar{I}_{sc}$ and I_{sc}^{Ω} represent unmodulated part of the scattered light and the signal modulated with the same frequency Ω as the incident light. Their intensity is determined by the integral over the entire enlightened volume.

A well-directed receiver can separate signals coming from different layers. If it separates the optical signal scattered just from the sound pulse area, then the reference scattered signal is

$$\bar{I}_{sc} = \frac{SI_0\eta_0 l}{4\pi R^2} \tag{17}$$

In (17) we neglected variations of the values S, I, η_0, and R over the thin layer

$r < z < r + l$ where the acoustic pulse is located, and so we placed these values outside the integrals.

The same approximation we use in the last two terms of (12). The third component in (12), I_{sc}^{a}, is the intensity of light modulated with the sound frequency. As the mean density variation in the sinusoidal sound wave train is practically zero, this term vanishes.

The fourth component in (12), $I_{sc}^{(\Delta\Omega)}$, is of the most interest for our purpose. If the sound wave train is narrow and $l \ll r$, then we can approximate the distance R to a receiver as

$$R(z) = R(r) + (z - r)\cos\theta \tag{18}$$

and write (16) in the following form

$$\begin{aligned} I_{sc}^{(\Delta\Omega)} = \frac{SI_0\eta_0 M}{8\pi R^2}\int_r^{r+l}\Bigg\{ &\cos\left[\omega_a\left(t - \frac{R(r)}{c_0} - \frac{(z-r)\cos\theta}{c_0} + \frac{z}{c_a}\right) + \phi_a \right.\\ &\left. + \Omega\left(t - \frac{R(r)}{c_0} - \frac{(z-r)\cos\theta}{c_0} - \frac{z}{c_0}\right) + \phi_0\right] \\ &+ \cos\left[\omega_a\left(t - \frac{R(r)}{c_0} - \frac{(z-r)\cos\theta}{c_0} + \frac{z}{c_a}\right) + \phi_a \right.\\ &\left. - \Omega\left(t - \frac{R(r)}{c_0} - \frac{(z-r)\cos\theta}{c_0} - \frac{z}{c_0}\right) - \phi_0\right]\Bigg\} dz \end{aligned} \tag{19}$$

After integration over z and neglecting the small terms of the order ω_a/c_0 we have from (19)

$$\begin{aligned} I_{sc}^{(\Delta\Omega)} = -\frac{SI_0\eta_0 M}{4\pi R^2}\Bigg\{ &\frac{\sin\left[\left(\frac{\omega_a}{c_a} + \frac{\Omega}{c_0}(1+\cos\theta)\right)l/2\right]}{\frac{\omega_a}{c_a} + \frac{\Omega}{c_0}(1+\cos\theta)} \\ &\times\cos\left[\omega_a\left(t - \frac{R(r+l/2)}{c_0} + \frac{r+l/2}{c_a}\right) \right.\\ &\left. + \phi_a + \Omega\left(t - \frac{R(r+l/2)}{c_0} - \frac{r+l/2}{c_0}\right) + \phi_0\right] \\ &+ \frac{\sin\left[\left(\frac{\omega_a}{c_a} - \frac{\Omega}{c_0}(1+\cos\theta)\right)l/2\right]}{\frac{\omega_a}{c_a} - \frac{\Omega}{c_0}(1+\cos\theta)} \\ &\times\cos\left[\omega_a\left(t - \frac{R(r+l/2)}{c_0} + \frac{r+l/2}{c_a}\right) + \phi_a \right.\\ &\left. - \Omega\left(t - \frac{R(r+l/2)}{c_0} - \frac{r+l/2}{c_0}\right) - \phi_0\right]\Bigg\} \end{aligned} \tag{20}$$

The signal (20) consists of two oscillating parts with frequencies shifted from Ω. If the modulation frequency is in Bragg resonance with the sound frequency so that

$$\Delta q = \left| \frac{\Omega}{c_0}(1+\cos\theta) - \frac{\omega_a}{c_a} \right| \ll \frac{\Omega}{c_0} \tag{21}$$

then the first term in (20) is small compared to the second one. The modulation frequency shift in that second part of the signal is

$$\Delta\Omega = \Omega\left(1 - \frac{1}{c_0}\frac{dR}{dt} - \frac{1}{c_0}\frac{dr}{dt}\right) - \omega_a\left(1 - \frac{1}{c_0}\frac{dR}{dt} + \frac{1}{c_a}\frac{dr}{dt}\right) - \Omega \tag{22}$$

Taking into account that $dR/dr = \cos\theta$ and substituting the formula (5), we have from (22) an approximate formula

$$\Delta\Omega = 2\Omega\frac{c_a}{c_0}\cos^2\frac{\theta}{2} \tag{23}$$

where we neglected a small term

$$\omega_a\frac{c_a}{c_0}\cos\theta$$

The frequency shift (23) is due to the Doppler effect caused by moving perturbations which propagate with the sound pulse. At Bragg resonance when $\Delta q = 0$ in (21) and for $\theta \ll 1$ this shift equals to the sound frequency.

Formula (20) yields the amplitude of modulation wave with this frequency shift

$$I_{sc}^{(\Delta\Omega)} = \frac{SI_0\eta_0 M}{4\pi R^2}\frac{2\sin(\Delta q\, l/2)}{\Delta q} \tag{24}$$

If the modulation frequency is close to the Bragg resonance and $\Delta q\, l/2 \ll 1$ then we have from (24)

$$I_{sc}^{(\Delta\Omega)} = \frac{SI_0\eta_0 M l}{4\pi R^2} \tag{25}$$

From (25) and (17) we have the relative value of the frequency-shifted modulated signal

$$\frac{I_{sc}^{(\Delta\Omega)}}{\bar{I}_{sc}} = M \tag{26}$$

Thus the component $I_{sc}^{(\Delta\Omega)}$ is proportional to the Mach number in the sound wave. Its intensity is obviously much weaker than the total intensity of scattered light. But as its modulation frequency is shifted from the incident modulation wave, it makes it possible to separate this component and measure the modulation frequency shift.

3. Conclusion

We found that scattered light contains a component with a shifted modulation frequency. Detecting this component, we can measure the modulation frequency shift relative to the modulation frequency of the incident wave. This method is feasible in the medium containing incoherent scatterers, which are small enough to oscillate with the sound wave (see appendix). Scattering particles may also move themselves under the influence of currents or as active biological units, but their velocities are negligible compared to the sound speed and the corresponding Doppler shift in the scattered signal may be obviously neglected. It utilizes the spatial resonance, where the spatial period of the acoustic 'density grating' coincides with half the period of the light modulation wave (condition (1)). Under this condition the intensity waves of the light scattered in adjacent density maxima in the sound wave are summed coherently, and the percentage modulation of the scattered light is a maximum.

If the sound frequency $f_a = \omega_a/2\pi = 30\,\text{kHz}$ and so its wavelength is about 5 cm, then at Bragg resonance the modulation frequency of the light is $F = \Omega/2\pi = 3\,\text{GHz}$, and the frequency shift is equal to the sound frequency, 30 kHz.

The relative amplitude of the modulation is equal to the Mach number in the sound wave. The Mach number M in the spherical sound wave at the distance R_a from the sound transmitter may be found from the formula

$$W = \frac{4\pi R_a^2}{G}\frac{\rho_w M^2 c_a^2}{2}c_a \tag{27}$$

where W is the power of the radiated sound, G is the sound transmitter gain, and ρ_w is the water density.

Considering sound of $W = 60\,\text{kW}$ power, transmitted with the gain $G = 30$, we have $M = 10^{-5}$ at the distance $R_a = 30$ m. Then we have to distinguish a component in the light envelope with 30 kHz frequency shift and the amplitude 10^{-5} of the total scattered light. This problem may be resolved with current optical tools.

According to the formula (23), the modulation frequency shift in the scattered light depends only on the sound frequency and local sound speed in the scattering volume. That is why, in spite of variability of the ocean parameters, the scattered signal provides unambiguous information about the ocean sound speed.

Regarding an operational technique in the real ocean, there may be other effects influencing the scattered light. For example, additional noise may appear in the received optical signal due to a strong light scattering by the waving ocean surface. This effect, however, does not change the modulation frequency, unless the laser system does not move fast enough. For an optical system, moving with the speed $100\,\text{m s}^{-1}$ with respect to a surface wave of 1 cm wavelength, the frequency of intensity variations in the scattered light due to this movement is about 10 kHz. In reality therefore, the component with the acoustically shifted modulation frequency may be still well separated from the rest of the scattered signal. Even taking into account shorter ripples which also exist in a broad spectrum of surface capillary waves we could use a latitude in the choice of the sounding system parameters (higher acoustical frequency, near-vertical sounding angle, etc.) to separate the Doppler-shifted component in the scattered signal.

There are two potential applications of the proposed method. Following modulation frequency shift due to the propagating acoustic pulse, we can monitor sound speed profile in the ocean. This is the same technology as was realized for audio-acoustical sounding of the atmosphere (Marshall *et al.* 1972). Just the light modulation frequency is going to be used here instead of the carrier frequency of radio wave. By contrast to conventional technologies of the ocean data collection this method provides an instant and direct measurement of the sound speed vertical profile. It also allows one to permanently monitor the upper ocean without expendable devices like XBTs etc.

Although this method requires radiation of powerful sound in the water, the sound source does not have to be installed on the bottom or deep in the ocean, as it is shown in figure 1. The sound may be radiated downward by a source located near the ocean surface. In this case the Doppler frequency shift of the scattered light has an opposite sign compared to the value (23), computed for the configuration on the figure 1. Obviously, this does not make any significant difference for the proposed technology.

As the proposed technique is based on a use of vertically propagating sound, it measures the vertical profile of sound speed at one local place in the ocean. With the generator installed on a ship profiling may be carried out.

Also the method can be used for communication through the ocean surface. To communicate with a receiver above the surface, an underwater object radiates a powerful sound wave upward. At the same time a modulated light beam is directed to the ocean volume where the sound is propagating. The scattered light is detected and processed by an electro-optical receiver. The information may be coded with the frequency modulation of the transmitted sound and then read from the light modulation frequency shift from above the sea surface. This method provides a communication channel from inside the ocean to planes or satellites. However, additional research with more realistic models and experimental testing is needed to practically realize this way of communication.

Appendix

A.1. *Oscillating hydrosoles*

Small particles suspended in water are dragged with the fluid displacement in the sound wave field. We assumed above that the amplitude of the particles displacement is the same as the water displacement amplitude. Here we estimate the frequency range where this assumption is valid.

A spherical particle moving through the fluid is affected by the Stokes viscous drag force (Lamb 1945)

$$F_s = -6\pi\rho_w \nu a V \tag{A 1}$$

where ρ_w is the fluid density, ν is the fluid kinematic viscosity, a is the particle radius, and V is the particle velocity relative to the fluid.

If the fluid oscillates with the frequency ω and the displacement amplitude is ξ_w, the amplitude of its acceleration is $-\omega^2\xi_w$. Then, in the frame, oscillating together with fluid, there is a gravity with the same acceleration $-\omega^2\xi_w$. A submerged particle in this frame is subject to the gravity force

$$F_g = -\frac{4}{3}\pi a^3\rho_p(-\omega^2)\xi_w \tag{A 2}$$

where ρ_p is the particle density. There is also the buoyant force which is

$$F_b = \frac{4}{3}\pi a^3\rho_w(-\omega^2)\xi_w \tag{A 3}$$

The particle acceleration in the oscillating frame is $-\omega^2(\xi_p - \xi_w)$. The inertial mass of the particle together with the added mass is

$$\frac{4}{3}\pi a^3\left(\rho_p + \frac{\rho_w}{2}\right)$$

Taking into account the forces (A 2), (A 3), (A 4), and equation (A 1) with $V = -i\omega(\xi_p - \xi_w)$, we can write the Newtons law for the particle in the following form

$$\frac{4}{3}\pi a^3\left(\rho_p + \frac{\rho_w}{2}\right)(-\omega^2)(\xi_p - \xi_w) = -6\pi\rho_w \nu a(-i\omega)(\xi_p - \xi_w) - \frac{4}{3}\pi a^3 \rho_p(-\omega^2)\xi_w + \frac{4}{3}\pi a^3 \rho_w(-\omega^2)\xi_w \tag{A 4}$$

We can find from (A 4) the squared absolute value of the relative particle displacement

$$\left|\frac{\xi_p}{\xi_w}\right|^2 = 1 - \frac{\left(1 + \frac{2}{3}(\rho_p - \rho_w)/\rho_w\right)^2 - 1}{\left(1 + \frac{2}{3}(\rho_p - \rho_w)/\rho_w\right)^2 + (3\nu/\omega a^2)^2} \tag{A 5}$$

If the oscillation frequency ω goes to zero, the particle displacement equals to the fluid displacement $|\xi_p/\xi_w| = 1$. But the particle slips the oscillating fluid environment and the particle displacement becomes different from the fluid displacement if the frequency exceeds the value

$$\omega_s = \frac{3\nu}{a^2}\left(1 + \frac{2}{3}(\rho_p - \rho_w)/\rho_w\right)^{-1} \tag{A 6}$$

For high frequencies $\omega \gg \omega_s$ the particle displacement amplitude tends to the value

$$\left|\frac{\xi_p}{\xi_w}\right|^2_\infty = \frac{1}{\left(1 + \frac{2}{3}(\rho_p - \rho_w)/\rho_w\right)^2} \tag{A 7}$$

If the particle density is bigger than the fluid density, this limit is smaller than unity. Then the particle lags the fluid and oscillates with smaller amplitude. If $\rho_p = \rho_w$ then the particle oscillates exactly the same amplitude as the fluid does, and the limit value (equation (A 7)) equals unity. For light particles (like bubbles), with the density $\rho_p < \rho_w$, high frequency oscillations have the amplitude larger than the fluid amplitude. In the limit $\rho_p = 0$ we have from equation (A 7) $|\xi_p/\xi_w|_\infty = 3$. Note, however, that for air bubbles the oscillations of their size due to compressibility may affect the light scattering as much as the bubbles displacement. We neglect here the bubble volume oscillations, regarding the sound frequency far enough from the bubble resonance frequencies (Flynn 1964).

Thus, for all practical applications, when $\rho_p \simeq \rho_w$ the particle oscillation amplitude is close to the fluid amplitude if the frequency exceeds the value (A 6). For the particles of 1 μm size and the density equal to the water density we have the frequency $f_s = \omega_s/2\pi = 500$ kHz. Hence particles of this size will oscillate with the water in a sound wave if the sound frequency is smaller than 500 kHz.

Such a small size is quite typical for many areas in the ocean. However, there may be exceptional cases where a significant amount of particles have larger size or their density significantly exceeds the water density. This may happen in a turbid water, in a plume of a river, for example. Such big and heavy particles do not oscillate as strong as the water does in a sound field. Therefore, they less effectively produce the scattered light with a shifted modulation frequency. Note, however, that even in such special case there is also some portion of smaller particles, which can produce a desirable frequency shift in the scattered signal. A possible dependence of the opto-acoustical effect on the geographical area with different particle distribution function deserves a special investigation, which is beyond the consideration of this paper.

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