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Optical measurement of the liquid surface wave amplitude with different intensities of underwater acoustic signal

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ABSTRACT

A simple measurement system is developed to study the optical effect of the low-frequency liquid surface wave excited underwater acoustic source. The high stability and clear diffraction patterns were observed experimentally. The relationship between the diffraction patterns divergence angle and the distance of the acoustic signal was derived. Furthermore, with the increase in distance, the diffraction patterns divergence angle will decrease. The damping characters of the liquid surface wave were theoretically obtained when underwater acoustic wave spread to the liquid surface. The analytical expression between the diffraction patterns divergence angle and the liquid surface wave amplitude was theoretically derived. It was found that the surface wave amplitude is exponently attenuated with the change of the horizontal distance. The attenuation coefficients are dependent on the frequency of the liquid surface acoustic wave, and the greater the frequency, the smaller is the attenuation coefficient.

1. Introduction

Optical techniques have been available for the investigation of surface acoustic wave (SAW) since 1960s. In order to obtain larger diffraction angle distribution, in acoustic-optical diffraction technology, ultrasonic wave was usually adopted in a solid surface with smaller amplitude [1–3]. At the same time, the optical detection methods have been widely applied to the study of properties of liquid surface including laser slope scanning technology, laser imaging detection technology, laser interference measurement technology, laser phase scanning for detecting technology, and so on [4]. The liquid surface wave can be regarded as the optic grating which was used to study the liquid surface tension which has been first reported by Weisbuch in 1979 [5]. Although Barter adopted the imaging analyzer for SAW [6], the image was formed by the light transmitted through the liquid medium and the liquid had to be dyed to produce the absorption in his study. It means that their method is not suitable for the transparent liquid such as water. We not only studied SAW at a few tens Hertz frequencies and obtained the clear diffraction pattern, but also avoided the shortcoming of imaging analyzer that the liquid must be dyed [7–14]. However, most of the reports aforementioned about the liquid surface acoustic wave are stimulated with a surface excited source. There are few papers that have reported the liquid surface wave stimulated by underwater acoustic signal, particularly in the range of dozens to hundreds Hz. Lee and Fletcher have used the laser sensor technique to detect underwater acoustic signal [15,16]. Lagution and Chunine as well as Lynn researched the laser scattering in the underwater environment [17].

In this paper, we have established a simple setup to study the optical effect of low-frequency liquid surface wave excited by an underwater acoustic source. The clear and high stable diffraction pattern was observed experimentally when the laser beam illuminates on the liquid surface that was stimulated by an underwater acoustic signal. We find that if the distance of the laser beam incident point to the underwater acoustic signal changed, the width of the diffraction pattern also changed. It was found that the distribution of the diffraction pattern was dependent on the horizontal distance between the illuminated spot and the underwater acoustical source. By carefully analyzing the experimental results, the attenuation coefficient of the liquid surface wave versus the horizontal distance was obtained theoretically. The results can be applied to study the properties of liquid surface wave, particularly with an underwater excited acoustic source.

2. Description of experiment

A schematic diagram of the apparatus is shown in Fig. 1(a). A low frequency sinusoidal generator is used to produce an output at a few hundred Hertz, which is amplified by a power amplifier. The output of the amplifier is used to drive the underwater

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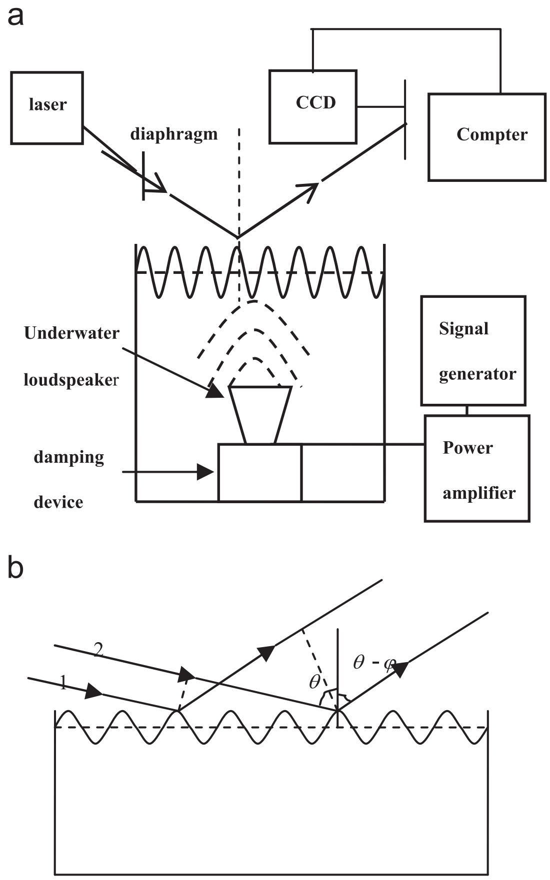

Fig. 1. Schematic diagram of the experimental setup (a) and principle (b).

loudspeaker which is placed on top of the damping device. The distance of the speaker upper surface to the liquid surface is about 6.5 cm.The underwater loudspeaker is of a delicate plastic frame with its holding wire connected to the power amplifier. The underwater loudspeaker generates a quasi-plane SAW on the liquid surface. It is reasonable to assume that the frequency of SAW is the same as that of the underwater loudspeaker (driven by a signal generator). The frequency of SAW is monitored directly from the frequency readings of the signal generator. A laser beam ($\lambda = 632.8$ nm) is incident on the liquid surface where SAWs are propagating. For reference, the diameter of the laser beam cross section is about 2.3 mm. For an oblique incidence of the laser beam, the shape of the illuminating area on the liquid surface is an ellipse whose major axis and minor axis are about 70.3 and 2.3 mm, respectively. The major axis is parallel to the SAW direction of travel on the liquid surface. In order to increase the diffraction efficiency, the incidence angle θ is chosen to be as large as possible. The depth of the water tank is about 16.7 cm, the location of damping device can be adjusted. The distance from observed screen to the liquid surface wave is far away, the light diffraction on the liquid surface can be regarded as the Fraunhofer diffraction or farfiled diffraction. The separation of the diffraction spots becomes greater with the increase of distance between the liquid surface and the screen. The CCD (model MTV-1881EX) is used to detect the light distribution. The data detected by the CCD are input to a computer. The CCD size is $7.95 \times 6.45\ \text{mm}^2$ and the signal to noise ratio is better than 48 dB. The diffraction spot can be subsequently displayed, stored, and processed by the computer. In order to reduce the influence of environmental vibration as far as possible, the entire experimental setup including the optical system is set on an optical table.

3. Theoretical analysis

Though the surface particle motion is actually somewhat more complex in nature, SAW propagation can be adequately approximated as a traveling sinusoidal disturbance and can be written as

$$Y = A\cos(\omega t - kx) \tag{1}$$

where Y is the displacement of the surface particle in the vertical direction, x is a variable along the SAW propagation direction, A is the SAW amplitude, ω is the SAW frequency, k is the wave vector, and $k = 2\pi/\Lambda$, where Λ is the SAW wavelength. It is assumed that a plane light wave is incident upon a liquid surface, which is modulated by a SAW at a few tens Hertz frequencies, and the illuminated area on the liquid surface along the SAW traveling direction just contain double surface wave shape. Consider now the problem of the reflected light filed from the adjacent acoustic wave shape. As illustrated in Fig. 1(b), the corresponding point with same phase on adjacent wave shape, such as the reflected light of rays 1 and 2, will propagate in the same direction marked by the angle $\theta - \varphi$ because the surface wave slopes at these two point are equal. Since the light velocity is much greater than that of the SAW, the surface wave shape can be assumed to be unchanged while calculating the path difference between these two beams. According to the principle of geometrical optics and by analyzing Fig. 1(b), one can easily obtain the reflected filed expression. The corresponding intensity can be written as

$$I_r(\varphi) \propto \cos^2\left\{\frac{\pi\Lambda}{\lambda}[\sin\theta - \sin(\theta - \varphi)]\right\} \tag{2}$$

where $I_r(\varphi)$ represents the reflected light intensity on the observation plane which is a function of angle φ, φ is the angle width of diffraction pattern from one bright fringe to the central bright fringe, λ is the light wavelength, θ is the light incident angle and $\theta - \varphi$ describes the reflection direction. It is obviously know from Eq. (2) that the diffraction fringes will be formed on the observation plane in the far region. The angular separation $\Delta\varphi$ of adjacent bright fringes relative the light incident point can be written as

$$\Delta\varphi = \frac{\lambda}{\Lambda\cos(\theta - \varphi)} \tag{3}$$

Since the angle φ is much smaller than the incident angle θ, the equation above can be approximated as

$$\Delta\varphi = \frac{\lambda}{\Lambda\cos\theta} \tag{4}$$

here the wavelength of the surface wave at a few ten Hertz is much greater than that of the incident light. In order to acquire a higher angle separation $\Delta\varphi$, the incident angle θ should be reasonably chosen to be as large as possible.

The reflection ray's direction represented by the angle $\theta - \varphi$ as shown in Fig. 1(b). The direction of the reflected light depends on the gradient of this point. From Eq. (1) we can obtain $dY/dx = kA\sin(\omega t - kx)$. The normal direction must turn $\varphi/2$ when the reflected light turn by an angle φ at the same incident point. The surface gradient of the incident point shown in Fig. 1(b) can be expressed as $dY/dx = \tan(\varphi/2)$. And then

$$\tan\left(\frac{\varphi}{2}\right) = kA\sin(\omega t - kx) \tag{5}$$

From Eq. (5), the maximum $\varphi_{\max}$ will be obtained, that is,

$$\varphi_{\max} = 2\arctan(kA) \tag{6}$$

Eq. (6) indicates that the reflection filed is certainly confined to the region between the angle $\theta - \varphi_{\max}$ and the angle $\theta + \varphi_{\max}$. If the