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SOUND VELOCITY IN TRANSPARENT MEDIUMS MEASUREMENT BY ACOUSTOOPTICAL METHODS

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The features of a light diffraction at ultrasonic waves as applied to measurement of sound velocity in transparent mediums are considered. At some conditions (in a particular range of the attitudes of a light beam diameter to ultrasonic wavelength) practical realization of such measurement can be rather simple, ensuring, nevertheless, high precision and spatial resolution.

1. INTRODUCTION

The acoustooptical methods, which basis is the light diffraction at ultrasonic waves, primarily, are used for information processing, for modulation of laser beam parameters [1-3]. The employed frequencies of ultrasonic waves are great enough (tens and hundreds of megacycle), thus beams of different diffraction orders are separated already at rather short distances from the optical-acoustic cell. To receive reliably the signal caused by their overlap, additional precisely adjusted optical components are required, which appreciably complicates the device design. In result, the acoustooptical methods are rather rarely used in a measurement technology.

At the same time, light diffraction at waves "of intermediate frequencies" (at which wavelength is comparable to a light beam diameter) has a number of features, which can be rather useful to various problems of a measurement technology, as allow essentially simplifying the device design.

In the present work, the features of acoustooptical methods as applied to sound velocity measurement are considered.

2. RELATIONSHIPS FOR LIGHT BEAM INTENSITY

Let us consider the quantitative relationships of light diffraction at ultrasound. We assume that the light beam propagates toward 0Z. The light wave field (amplitude) E is given by: $E(x_0,y_0,0) = E_0 \exp\{i\omega t - (x_0^2 + y_0^2)/(2\sigma_0^2)\}$, where E_0 is the field on an axis of a beam; ω is its frequency; $2\sigma_0$ is the beam diameter (at the intensity level e^{-1}); x_0, y_0 are the coordinate in a plane X0Y. That is, the beam intensity profile is Gaussian, and phase front is planar at Z = 0. Let us that the acoustic wave with frequency Ω "runs" towards 0X with some velocity C. Let's assume also, that phase grid caused by the wave is "optically thin". Then for a light beam, the grid transmittance T is:

$$T = \exp\{iA\cos(\Omega t - fx_0)\} = \sum_{n=-\infty}^{\infty} \exp\{in(\Omega t - \frac{\pi}{2})\} J_n(A) \exp\{-infx_0\},$$

where $A = k\Delta(nL)$, $\Delta(nL)$ is the maximum change of an optical path caused by a wave; $k = 2\pi/\lambda$, λ is the light wavelength; $f = 2\pi/\Lambda$, Λ - is the acoustic wavelength; $\Omega = fC$, $J_n(A)$ is the Bessel function of *n*th order. For a longitudinal acoustic wave $\Delta(nL) = L\Delta n$, Δn is the maximum change in the medium refraction index caused by the wave; L is the path length of a light beam transiting through a wave. For a surface acoustic Rayleigh wave $\Delta(nL) = 2\Delta L = 2h$ (h - wave amplitude) in a case of reflected light beam.

The light wave field E_L (amplitude) at the grid output is given by: $E_L = E(x_0,y_0,0)\,T$. The field E in an arbitrary point of space is defined by Fresnel or Fraunhofer diffraction. However, the measured value is the power P defined by the intensity I = EE*. The relationships for intensity are obtained in [4, 5]. From these relationships follows, that in a particular range of the attitudes of a light beam diameter to ultrasonic wavelength the modulation of phase front of an initial light beam by the mentioned ultrasonic wave causes the intensity (power) light beam modulation at the exit of medium under study. It is important that intensity modulation is realized by a "natural manner", without any additional optical components. Therefore, the optical scheme of the acoustooptical device for sound velocity measurement may be very simple: laser - acoustooptical cell - photodetector.

In an arbitrary point of space the beam intensity consists of invariable component and a series of variable components (harmonics) with frequencies, multiple frequency of the wave. Generally these relationships are complicated enough, therefore we shall consider only first harmonic. For simplicity let that $A^2 << 1$, then $J_0 J_1 \approx A/2 >> J_1 J_2$. Let also y = 0; $x = \sigma = \sigma_0(1 + l^2)^{1/2}$, $l = z/(k\sigma_0^2)$.

Then for relative intensity $\gamma_1 = I_1 \sigma^2/(I_0\sigma_0^2))$ we shall obtain:

$$\gamma_1(x,y,z) = 2A\, U_1 \sin(\Omega t - \sigma_0 f - \phi),$$

$$U_1 = \exp\{-1 - \frac{(\sigma_0 f)^2 l^2}{2(1+l^2)}\} \sqrt{sh^2 \frac{\sigma_0 f l}{\sqrt{1+l^2}} + \sin^2 \frac{(\sigma_0 f)^2 l}{2(1+l^2)}}; \quad (1)$$

$$tg\phi = \frac{tgB}{thC}; \; B = \frac{(\sigma_0 f)^2 l}{2(1+l^2)}; \; C = \frac{\sigma_0 f l}{\sqrt{1+l^2}}.$$

Dependence $U_1(l)$ for various parameter values $\sigma_0 f$ is depicted in a Fig. 1

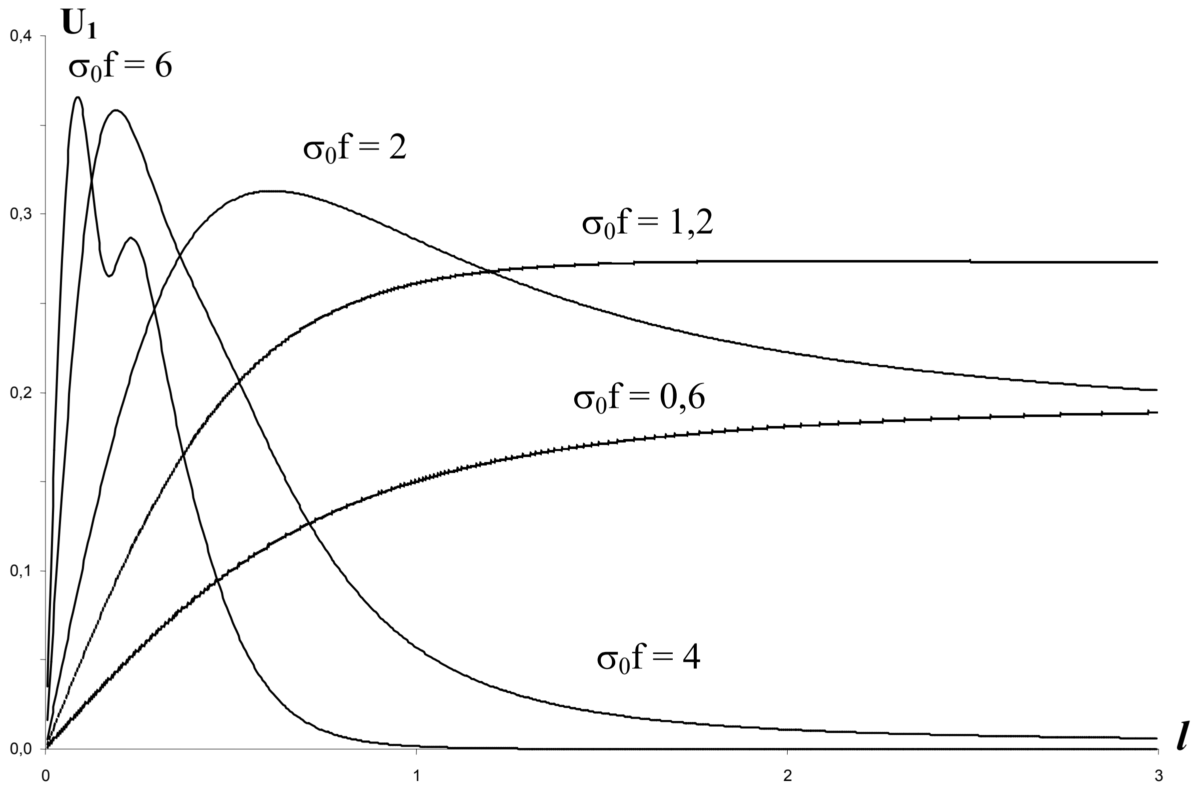

Figure 1. First harmonic relative intensity dependence on l for various values $\sigma_0 f$

One can see, that at small value $\sigma_0 f$ ($\sigma_0 f < 1.2$) value U_1 is monotony increased when l is increased. The value $\sigma_0 f = 1.2$ corresponds to the maximum U_1 when $l \to \infty$. In the case of $\sigma_0 f > 1.2$, maximum U_1 is realized at finite value l. When $\sigma_0 f$ is increased, maximum U_1 is realized at smaller value l. Thus will increase value U_1 in a maximum (in a limit - up to e^{-1} = 0,367), and maximum becomes sharper. From Fig. 1, it is visible, that at $\sigma_0 f = 6$ the secondary maximum is shaped. When $\sigma_0 f$ is increased this secondary maximum becomes increasingly sharp, and at further increasing $\sigma_0 f$, there is a second secondary maximum, etc.

3. SOUND VELOCITY MEASUREMENT

In (1) for definiteness it was assumed, that $x = \sigma = \sigma_0(1 + l^2)^{1/2}$, $l = z/(k\sigma_0^2)$. Thereof U_1 had component of a phase of a view $\sigma_0 f$. For arbitrary value x this component looks like $fx/(1 + l^2)$. It is uneasy to see, that $fx/(1 + l^2) = = 2\pi x/[\Lambda(1 + l^2)]$. That is, if to register a beam intensity simultaneously at two values x ($x = x_1$; $x = x_2$), on a phase shift $\Delta\phi$ of the relevant signals it is uneasy to find and quantity Λ: $\Delta\phi = 2\pi d/\Lambda$, where $d = (x_1 - x_2)/(1 + l^2)$.). Similar takes place and for any other harmonics.

So, if d is known, on measured value it is uneasy to find and wavelength Λ. One can see, that the response of a grid period measurement $d(\Delta\phi)/d\Lambda$ is close to zero at $l \to \infty$. At $l = 0$ response of measurement is peak. However in this case U_1 ($l = 0$) = 0.

Then, the measuring of the wavelength (definition of sound velocity) is substantially possible only in a particular range of value l. From below, this range is restricted to an acceptable level U_1, and from above - both level U_1, and acceptable measurement response. Apparently, from the practical point of view it is expedient to ensure realization of a requirement $\sigma_0 f > 2$, and to use values l, relevant to a maximum U_1 (at distances relevant to the size of the first Fresnel zone for a wavelength of a sound).

If simultaneously to measure frequency of a wave and its length, it is uneasy to calculate and sound velocity C - one of the important performances of any medium, $C = \Omega\Lambda/2\pi = \Omega d/\Delta\phi$.

It is necessary to note, that the kind of an intensity profile of an initial light beam influences only upon amplitudes of harmonics of intensity, but not on a frequency - phase characteristic of these harmonics. That is, at measuring sound velocity the kind of this profile is unessential.

The possible scheme of sound velocity measurement is depicted in a Fig. 2.

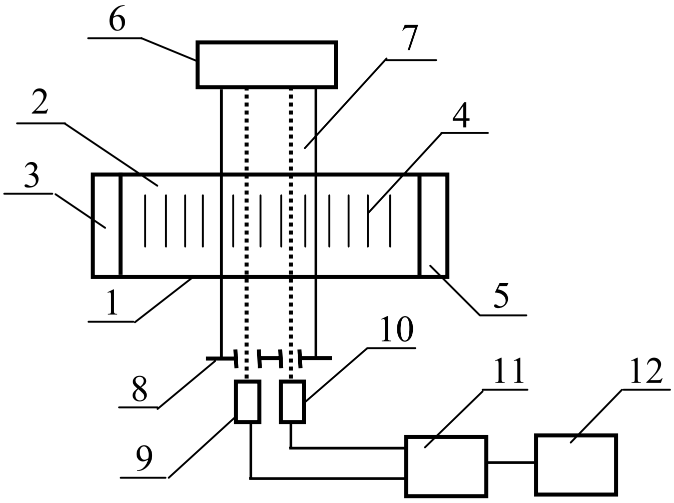

Figure 2. The scheme of sound velocity measurement

(1) acoustooptical cell, (2) medium under study, (3) emitter of ultrasonic waves, (4) ultrasonic wave, (5) suppressor of a wave, (6) light source (laser), (7) light beam,(8) diaphragm, (9, 10) photodetectors, (11) phase meter, and (12) logger

Let us give some quantitative assessments. Let us assume that the diameter of a light beam in the medium under study is approximately equal to 2 mm. For Gaussian intensity profile, this diameter (defined "on an eye") corresponds to a level e^{-2}, i.e. $\sigma_0 \approx 0{,}71$ mm. Then for values $\sigma_0 f = 1 \div 6$ ultrasonic wavelength Λ can be in limits from 0,7 up to 4,4 mm. If C = 1,5 km/s (that corresponds to sound velocity for water), the frequency range of ultrasonic waves can be $0{,}34 \div 2{,}1$ MHz. If a beam diameter to increase or to decrease in some times, then the frequency range accordingly will vary also.

The size of holes in a diaphragm 8 (in a direction of a wave propagation) should be much less beam diameter in a recording plane. Practically this size can be the tenth of millimeter and more. Distance between holes in the same direction can be close to a beam diameter. One of the important problems of practical realization of such measurements is a definition of "an instrumental constant" d. This problem can be solved by calibration of a metering circuit on a wave with a known phase velocity.

At use as a light source of the usual semiconductor laser with power only 1 mW and at low diffraction efficiency ($A \leq 0{,}5$) a first harmonic signal power ($10^{-4} \div 10^{-5}$ W) appears sufficient for recording a signal by the usual photodiode.

The phase shift of two harmonic signals at a modern level of technique can be measured with a relative error not worse 10^{-4}. Approximately with the same error can be determined and sound velocity.

It is necessary to note that in a viewed case the spatial resolution is defined by a light beam diameter and can be high enough. It allows exploring " thin structure " velocities of a sound in medium under study.

In moving fluids only by one device on frequency shift of a signal concerning frequency of a wave, it is possible to determine traveling speed of a fluid (i.e. its flow rate), and on a phase shift of signals simultaneously to determine and sound velocity in a fluid. This circumstance can be useful for different chemical technologies. In particular, for petroleum simultaneously with the check of the flow rate it is possible to check and quality of a fluid.

4. CONCLUSION

The features of a light diffraction (Fresnel diffraction) at ultrasonic waves as applied to measurement of sound velocity are considered.

At some conditions (in some range of the attitudes of a light beam diameter to ultrasonic wavelength and in some range of distances from medium under study up to a recording plane) the acoustooptical methods can be successfully usable for measuring sound velocity in transparent mediums.

From a point of view of practical realization the main advantages of these methods are the next: extremely simple optical scheme; the high spatial resolution; the possibility of measuring of sound velocity in moving medium simultaneously with measuring of traveling speed of this medium. Apart from it, in case of surface waves the measurements essentially are non-contact. These advantages can be of interest for different problems in an oceanology, hydrology, chemical technologies, etc.

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