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Modeling of speckle metrology technique of detecting the medium acoustic oscillations

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To describe the speckle metrology technique of detecting the medium acoustic oscillations, the acousto-optic modulator circuit was assembled. It is based on the process of double laser beam propagation through a medium with regular phase changes induced by the acoustic wave. Spectral analysis of photocurrent, obtained by direct photodetection of the laser radiation, allows us to detect frequency of acoustic oscillations in the medium. According to presented scheme the computer model is developed. The simulation results, obtained for the various parameters of the acoustic wave, are described. The case of excitation of two acoustic waves with different frequencies is partially considered.

Key words: *speckle metrology, acoustic oscillations, retro-reflector, phase transparent.*

Для опису спеклометричного методу виявлення акустичних коливань середовища було зібрано схему акустооптичного модулятора. Він заснований на процесі дворазового поширення лазерного випромінювання крізь середовище з регулярними змінами фаз під дією акустичної хвилі. Спектральний аналіз фотоструму, отриманого шляхом прямого фотодетектування лазерного випромінювання, дозволяє визначити частоту акустичних коливань середовища. Згідно представленої схеми розроблено комп'ютерну модель. Описано результати моделювання, отримані для різних параметрів акустичної хвилі. Частково розглянуто випадок збудження двох акустичних хвиль з різними частотами.

Ключові слова: *спеклометрія, акустичні коливання, ретрорефлектор, фазовий транспарант.*

Для описания спеклометрического метода обнаружения акустических колебаний среды была собрана схема акустооптического модулятора. В его основе лежит процесс двукратного прохождения лазерного излучения через среду с регулярными изменениями фаз, вызванными действием акустической волны. Спектральный анализ фототока, полученного путем прямого фотодетектирования лазерного излучения, позволяет определить частоту акустических колебаний среды. Согласно представленной схеме разработана компьютерная модель. Описаны результаты моделирования, полученные для различных параметров акустической волны. Частично рассмотрен случай возбуждения двух акустических волн с разными частотами.

Ключевые слова: *спеклометрия, акустические колебания, ретрорефлектор, фазовый транспарант.*

1. Introduction

Methods of studying medium acoustic oscillations by means of light beams were widely used before the invention of lasers [1]. Acousto-optic interaction theory [2] and its application in various fields of technology [3] relate to a situation where the acoustic wavelength is much smaller than the diameter of the associated optical beam. As a result, in that case, the light diffraction effect by ultrasonic waves arises. In the opposite situation, when the diameter of light beam is less than the acoustic wavelength, the diffraction effect does not occur. Therefore, it is necessary to use other physical phenomenon to study the properties of acoustic waves (their amplitude, frequency, etc.). One of such approaches is based on analysis of the speckle image resulting from the laser beam passing through the acoustic barrier and scattering on the rough surface.

Speckle metrology, i.e. the spatial structure analysis of laser light scattered on the rough surface and its time history, is currently commonly used tool for a wide range of applications. For example, using this method is carried out measuring local deformations and displacements of objects [4, 5]. Laser speckle velocimeters allow us to measure the lateral objects velocity against the beam direction [6, 7]. By means of analysis of the speckles change dynamics in space the vibration of local areas of objects surface can be measured [8, 9].

One of the significant limitations when using the speckle measurement method is a wide angular spectrum of the laser light scattered on the rough object surface. This leads to a rapid decrease in power of the received radiation with an increase of measurement range. By covering the object surface with retro-reflecting arrays (RRA) a significant increase of spatial concentration of the scattered radiation can be achieved. These coatings are currently widely used, for example, to enhance the visibility of the road signs, clothing, vehicles, etc. They consist of a large number of glass microspheres or microprisms [10] with characteristic dimensions ranging from tens to hundreds of micrometers and disposed on a substrate in random manner (microspheres) or relatively regular (microprisms). When the laser radiation falls on such surface, the light field is transformed in accordance with the laws of beam pass in each element of the RRA. The transformed radiation propagates in the direction of the laser source within a small angle of a few degrees. That process creates the speckle image within the receiving plane as a result of interference of waves re-emitted by each element. Use of RRA significantly increases the laser radiation capacity observed in a receiver plane. That allows us to increase observation distance and precision of measurements. In some applications, such devices are called retro-reflective laser sensors (RRLS) [11].

The possibility of using RRA in speckle metrology techniques are discussed, for example, for vibrometry [12] and speckle velocimetry [13] issues solving. The analysis of dynamics of the speckle pattern allows us not only to determine the behavior of the object surface, but also to detect changes in the state of the environment of the laser radiation between the laser and the object. For example, a technology of detecting random phase distortions generated from the heat source using the previously described method is discussed in [14]. The phase inhomogeneities of medium may be a random, caused by atmospheric turbulence, and regular, caused by acoustic oscillations of the acoustic generator. The paper [15] shows how random and regular variations in density of air can be detected by direct detection of scattered laser radiation. This spatial heterogeneity of the scattered laser light in the plane of observation (speckle pattern) is a key factor. Devices built on this principle can be called ARRLS (acoustic retro-reflective laser sensors).

Regular medium density fluctuations are created due to the excitation of a acoustic wave in the direction perpendicular to the laser beam crossing it, together with an acousto-optical interaction. The effectiveness of this interaction depends on several factors: the radiation power, the aspect ratio of the beam and acoustic wavelength, the location of the beam along its path, etc. The study of such characteristics of this acousto-optical interaction type is conveniently carried out using the method of computer simulation.

2. Detector description

The simulation was performed for the conditions corresponding to the experimental setup (fig. 1) as described in [15].

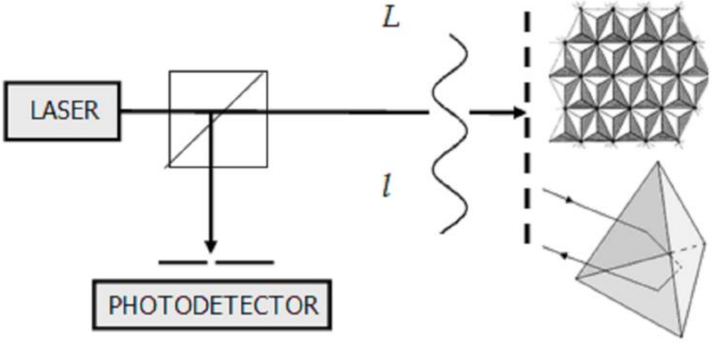


Fig.1. Acousto-optic modulator diagram.

It consists of the laser, the beam splitter, the phase transparent created by the travelling acoustic wave at a distance *l* from the laser. Laser beam diameter is *d*. The acoustic wavelength is Λ.

The RRA is situated behind the phase transparent, created by acoustic wave. It consists of tetrahedral retro-reflectors with characteristic dimension of element - σ. Photodetector with a square aperture of side *D* detects the scattered radiation.

3. Theoretical formulation

The initial structure of the beam was set in the form of a plane wave with a Gaussian distribution of the amplitude (1)

$$E_1\left(x,y,0\right)=A_{light}\exp\left(-\frac{x^2+y^2}{2\omega^2}\right). \tag{1}$$

It shall be noted that the approach to creating a computer model is described in [14]. There the phase transparent is formed by turbulent layer with a random two-dimensional phase distribution. In this paper, one-dimensional sinusoidal phase grating with phase distribution described by equation (2) was used as a phase transparent

$$\psi_{\text{ac}}(y)=A\cdot\sin\left(\frac{2\pi y}{\Lambda}-\Delta\phi\right), \tag{2}$$

where *A* is an amplitude of the acoustic wave, $\Delta\phi$ is a phase shift, which provides a simulation of a change of a travelling acoustic wave.

Thus, the structure of the field of laser radiation passing through this transparent is calculated by:

$$E_2(x,y,l)=E_1(x,y,l)\,T_{\text{ac}}(y), \tag{3}$$

where $T_{\text{ac}}(y)=e^{i\psi_{\text{ac}}(y)}$ is the transmission function of the phase transparent.

Since conditions of modeling assumed that $d >> \Lambda$ patterns of change in amplitude and phase in the area from transparent to RRA determined by the laws of geometrical optics, which do not change the phase ratio within the light beam.

The transformation behavior of the amplitude-phase distribution of the light wave in the RRA is described by a function $K_{\text{RRA}}(x, y)$. Detailed description of the method of its calculation can be found in [14]. In calculating this function we take into account the reflection features from each of the three faces of the elementary retro-reflector, which lead to a change in amplitude, phase, and direction of propagation of the beam.

The light wave with an amplitude-phase distribution described by (4), propagates onto the opposite direction:

$$E_3(x, y, L) = E_2(x, y, L)\, K_{\text{RRA}}(x, y)\,. \tag{4}$$

At the same time as a result of diffraction the light wave described by (5) is ensued in the phase transparent plane:

$$E_4(x, y, l) = \frac{k}{2\pi i}\frac{e^{ik(L-l)}}{(L-l)}\int_{S'} E_3(x', y')\exp\left\{\frac{ik[(x-x')^2 + (y-y')^2]}{2(L-l)}\right\}dx'dy'\,. \tag{5}$$

Repeated passage of the light wave through a phase transparent with a transmission function $T_{\text{ac}}(y)$ changes its structure.

Further, the light wave propagates in the direction of the laser and forms a light wave, defined by (6) in the receiving plane.

$$E_5(x, y, 0) = E_4(x, y, l)\, T_{\text{ac}}(y)\,. \tag{6}$$

There is carried out the photodetection of the obtained intensity distribution, and its integration within the receiving aperture with dimensions *D* (fig. 2).

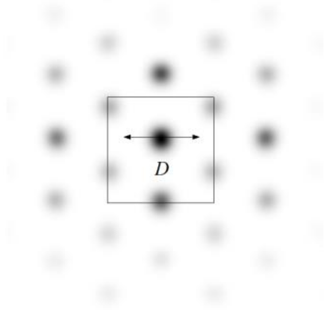
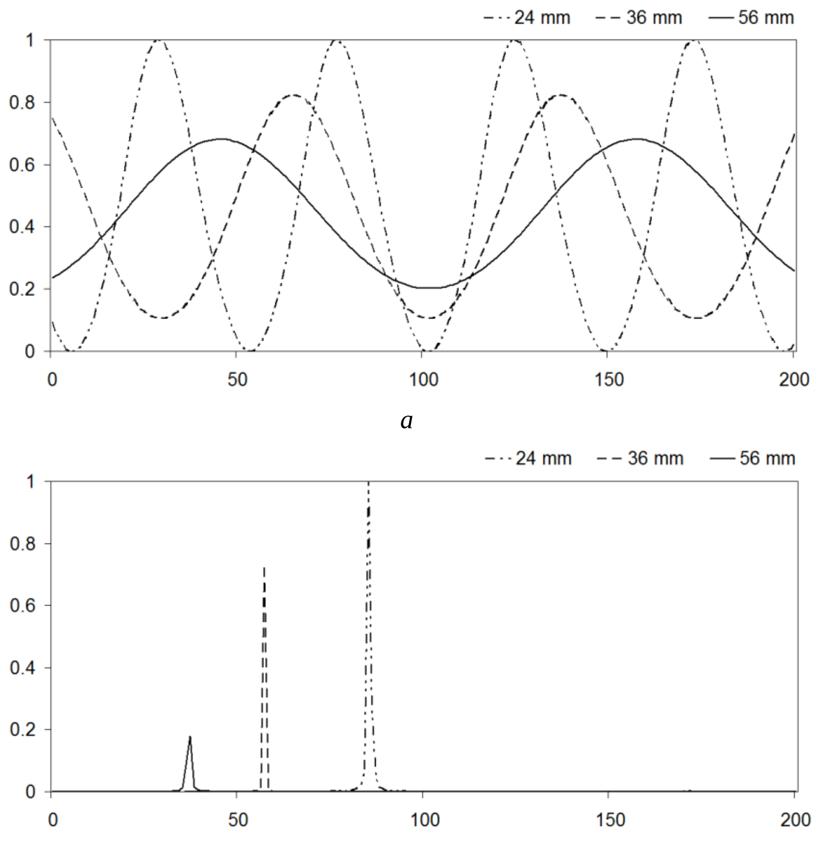


Fig.2. Receiving aperture.

4. Simulation results and analysis

Simulation data represents that the travelling acoustic wave leads to the harmonic displacement of the diffraction pattern formed in the receiving plane in accordance with the laws of the changes of the acoustic wave. Since the diaphragm is fixed, at the photodetector output harmonic oscillations of the photocurrent are generated.

Spectral analysis of these fluctuations shows the adequacy of the laws of changes in air density in the acoustic wave.



a

b

Fig.3. Photocurrent fluctuations.

Fig. 3(*a*) shows the trend in the photocurrent when the acoustic wave values Λ equal to 24mm, 36mm and 56mm. Spectral analysis of these fluctuations is shown in fig. 3(*b*). It illustrates the presence of monochromatic components, which corresponds to changes in sound frequency. It also shows that the oscillation amplitude of the photocurrent varies. It increases with decreasing the acoustic wavelength.

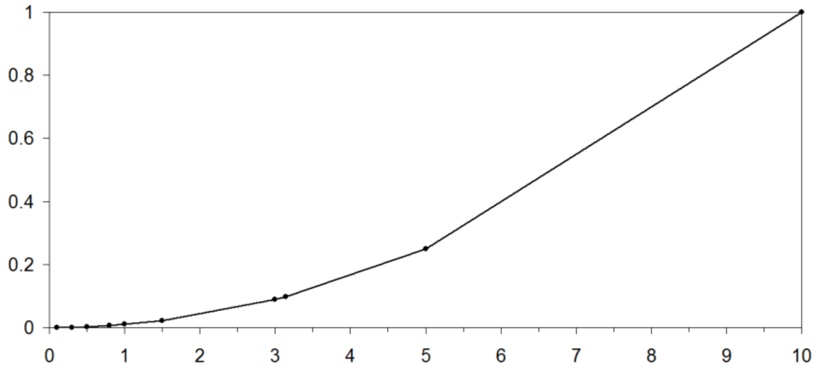


Fig.4. Dependence of photocurrent amplitude on the acoustic wave amplitude.

Fig. 4 shows the trend of change in the amplitude of the photocurrent oscillations when the amplitude of the acoustic wave *A* is changed. This dependence shows a monotonic increase in the oscillation amplitude with increasing power of the sound.

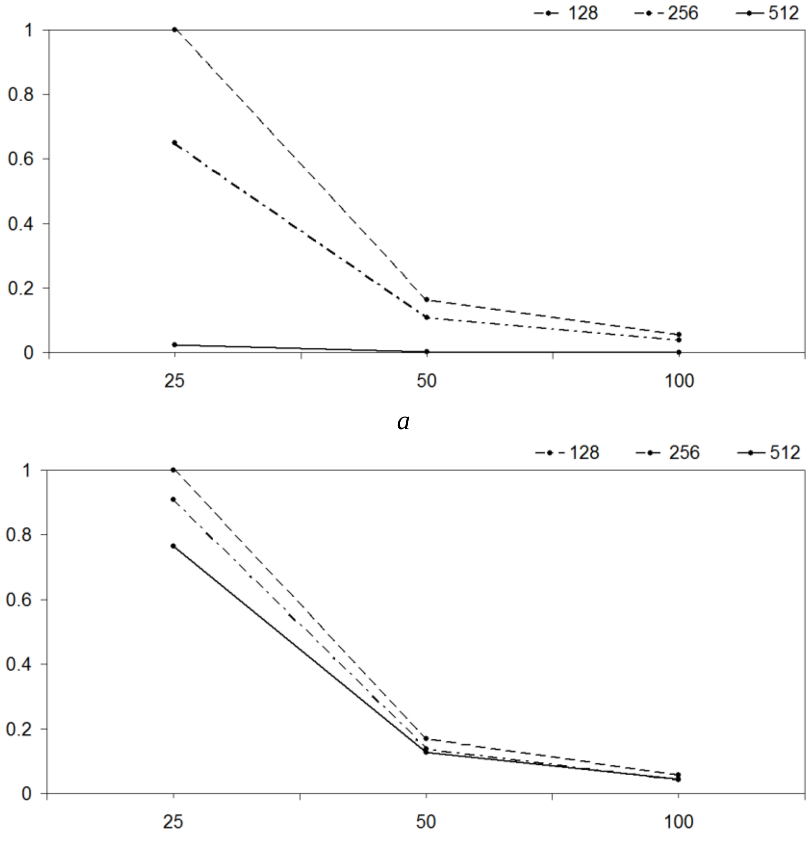


Fig.5. Dependence of photocurrent oscillation amplitude on the acoustic wavelength for different detection aperture.

Fig. 5(a) and 5(b) show the photocurrent oscillation amplitude changes depending on the acoustic wavelength Λ and the detection area size of D. The dependencies are shown for different phase transparent location on the propagation path of the beam. Fig. 5(a) corresponds to l = 1m, fig. 5(b) - l = 2m.

These curves show that the effectiveness of this method of detecting acoustic oscillations considerably depends on the ratio of the beam diameter *d*, and the acoustic wavelength Λ. The greater acoustic wavelength is, the lower sensitivity of method is.

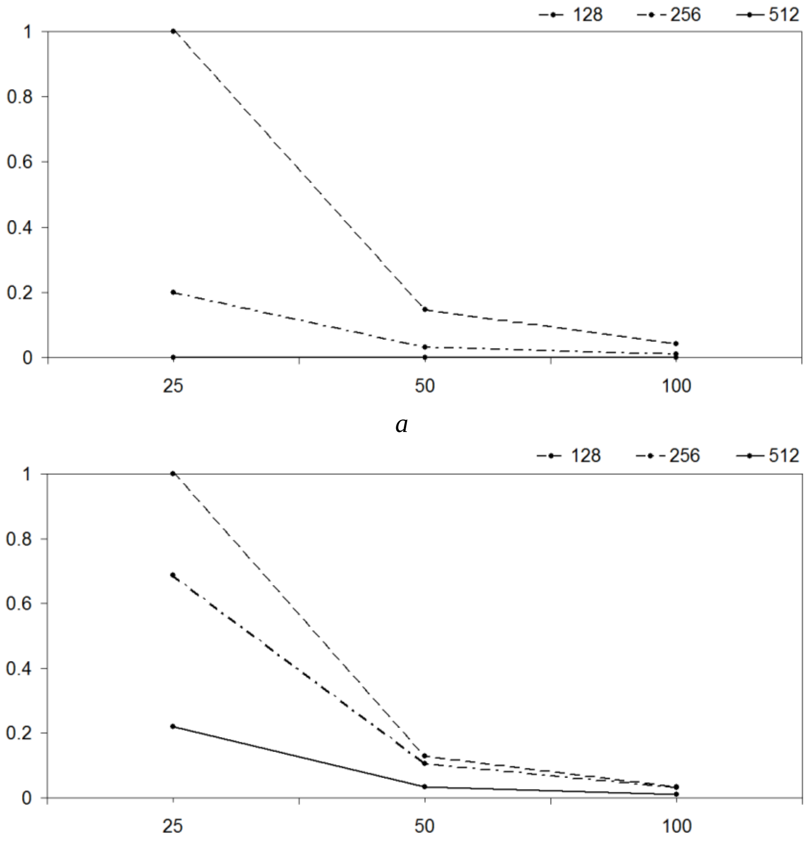
It can also be noted that the closer phase transparent is located to RRA (larger *l*), the less difference between amplitudes of oscillations is expressed for all wavelengths of acoustic waves and the integration area size *D*.

It may also be noted that a very important parameter in determining the efficiency of detection of oscillations is the size of detection region defined by the value *D* (fig. 5(*a*) and 5(*b*)).

From the analysis of dependencies in fig. 5, we can conclude that the value D is more significant in the case where an acoustic wave is located close to the radiation source. The value of D is less significant as approaching the acoustic transparent to the RRA.

Results obtained with two excitation airborne acoustic waves at different frequencies are also interesting. The simulation results showed that under the same vibration amplitudes $A_{1,2} = 1$ the superposition principle holds, i. e. there is no interference of one wave to another and vibrations can be detected independently for each frequency.

The photocurrent obtained by integrating the light power within the receiving aperture (fig. 2) contains constant and variable components. The constant component is not information, as opposed to the variable one, which is of interest to detect vibrations in the medium.



a

b

Fig.6. Dependence of variable and constant photocurrent components.

Fig. 6(*a*) and 6(*b*) show the ratio dependence of variable component to the constant one for different acoustic wavelengths and sizes of the integration range for two cases, the transparent location on the track: $l = 1$ m (fig. 6(*a*)) and $l = 2$ m (fig. 6(*b*)). These diagrams determine the following: the relative value of a useful variable component increases with decreasing the acoustic wavelength. This is obviously a result of a significant change in air density with changes in the acoustic wavelength, which leads to considerable shifts of the diffraction pattern in the receiving plane. It may also be noted that the ratio of the constant and variable components increases with decreasing the detection area. This causes, apparently, a reduction in the constant component, which is determined by the average power of laser radiation that is detected.

The simulation results for the case of detecting the amplitude of two acoustic waves $A_1 = A_2 = 1$ at different frequencies f_1 and f_2 are also of interest. The results are shown in fig. 7.

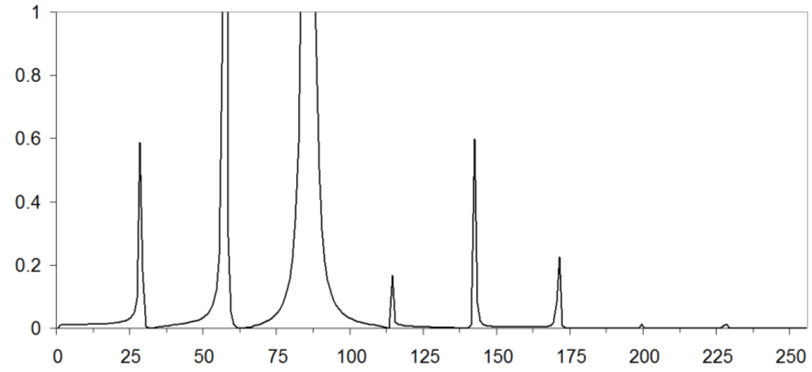


Fig.7. Computer spectral analysis of two superimposed acoustic waves.

The figure, in addition to reference frequencies, clearly shows the detection results of frequency components that are harmonics of the reference frequency $2f_1$, $2f_2$, and combination frequencies (f_2 - f_1) and (f_2 + f_1). The presence of such spectral components in the variable component of photocurrent is evident of the nonlinearity of acousto-optical interaction of this mode. This non-linearity is the subject of further research.

5. Conclusion

A computer simulation model of the speckle metrology method of detection of medium acoustic oscillations was created. It is based on the propagation of the laser beam through a medium with acoustic oscillations, on reflection from a RRA, on the back-propagation and direct photodetection of the laser radiation. Spectral analysis of photocurrent allows us to detect the frequency of acoustic oscillations in the medium.

The simulation shows that the effectiveness of this type of interaction rises with an increase of the sound power, decreases depending on the wavelength and decreases according to the detection area to a size comparable to speckle size. The amplitude also increases as the phase transparent, generated by the acoustic wave, nearing the receiving plane.

At large amplitudes of acoustic oscillations in the case of excitation of two acoustic waves in the photocurrent spectrum the harmonics of the fundamental frequency and combination frequencies appears.

The latter circumstance requires further additional research.

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