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Laser Ultrasonic Inspection System Based on Optical Multi-Channel Interferometer

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ABSTRACT

We proposed and developed two novel techniques of multi-channel laser ultrasonic defectoscopy for industrial application. They are based on and adaptive interferometers of two types: i) using refraction dynamic holograms and ii) photo-electromotion force (photo-EMF) in semiconductor crystals. In our approach acoustic waves in samples are produced by the pulsed laser beam generated with cylindrical optics and thus being cross-shaped in the form of a narrow strip. Such a form of a laser beam enables to excite shear and longitudinal bulk acoustic waves with cylindrical wavefront. In the case of defects and inhomogeneties contained within a sample volume the scattered acoustic waves arise, which cause additional vibrations of the sample surface; the phase of these vibrations in each point of the sample surface depends on the location of scattering defects. The registration of amplitude and phase of surface displacement caused by defects is made in the local areas situated symmetrically relatively to the region of laser ultrasound excitation. In the device prototype from two to four pairs of local areas are analyzed.

INTRODUCTION

One of the most promising methods in area of non-destructive testing is laser excitation of acoustic waves and non-contact registration of the useful information by various methods of modern laser interferometry. The development of non-contact methods of detecting internal heterogeneity or defects in solid-state samples is of great importance for the advance of industrial manufacturing technology. Development and creation of high-sensitive and effective system of monitoring of engineering structures and technical constructions (pipes of oil and gas pipe lines, power plants of electric power stations, dams, mines, aviation engineering, etc) is an important problem A promising nondestructive approach to solve such problems is the registration of laser-generated ultrasonic acoustic waves by means of laser-

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interferometry-based techniques. The use of ultra sensitive optical interferometric method of nondestructive testing allows one to detect required parameters of a physical field in ranges inaccessible by other methods (for example, electronic or ultrasonic ones). Capabilities of the technique have been demonstrated clearly in a number of experimental investigations [1,2].

Within the framework of these directions, adaptive informational-measuring systems are being developed. In state-of-the-art ultrasonics systems used for industrial inspection one exploits, in particular, ultrasonic diagnostics, where the detection of ultrasound is performed with the use of piezoelectric converters of pulse lasers [3]. The later approach based on remote optical methods is used at the nondestructive testing of surfaces of a complex geometry or productions at processing lines in conditions of elevated temperatures. However, until recently, the detection of ultrasound has been implemented by interferometers with passive elements, which, on the one hand, made a system complex, bulky and ineffective by virtue of necessity to use external system of stabilization. Emergence of adaptive devices of nondestructive testing based on photorefractive crystals and effect of non-stationary photo-induced EMF have been considered as a fundamental step toward the development of monitoring systems [4,5]. Adaptive devices combine both processing of a signal with its simultaneous stabilization.

In this paper, it is proposed a new approach for creating laser ultrasonic inspection system based on optical multi-channel interferometer. In such approach acoustic waves in samples are produced by the pulsed laser beam generated with cylindrical optics and thus being cross-shaped in the form of a narrow strip. Here the registration of amplitude and phase of surface displacement caused by defects is made in the several local areas situated symmetrically relatively the region of laser ultrasound excitation. With special advanced soft the processing of output signals of interferometers and reconstruction of defects position inside a sample under testing is made.

SCHEME OF PROTOTYPE DEVICE OF FOUR-CHANNEL ADAPTIVE INTERFEROMETER

Prototype device of four-channel adaptive interferometer using separate units has been assembled (Fig.1).Here the ultrasonic vibrations were excited by radiation of a solid-state $YAG:Nd^{3+}$ laser operating in the regime of Q-switching the basic frequency of lasing. The output radiation of laser passes through lens L_1 and incidents on the surface of test sample. Here in the sample acoustic waves excite, which causes mechanical vibrations of the front surface of the sample, which are to be registered further. The scheme of the interferometer (Fig. 1) includes also continuous wave laser source, which is diode-pumped solid state laser (DPSS) with the wavelength of 532 nm and output power of 100mW. The radiation from DPSS laser passes through half-wave plate ($\lambda/2$-plate) and directed on polarizing beam splitter (PBS) cube, which divides the incident beam on two orthogonal polarizations. One of the beams (signal beam) is directed on the investigated sample and the second beam is a reference beam. Signal beam passes through $\lambda/2$-plate and lens L_2, and then reflects from the surface of test sample and on the way back incident on the separating cube with the polarization turned into 90 deg. This gives the possibility of the signal beam to pass through separating cube. Then signal beam passes through the lens L_3 and is directed on *GaAs* chip of photo-EMF detector. In its turn the reference beam is reflected from the mirror and also incidents on the receiving site of the sensor. The reference beam is inclined at a small angle (typically 1.5-2 deg.) with the respect to a small angle to create a fringe pattern on the detector. The $\lambda/2$-plate placed in the radiation of CW laser's way provides optimal ratio of intensities of signal and reference beams. This allows one to obtain optimal signal-to-noise ratio at the output of sensor. Electrical signal from *CaAs* chip is intensified by amplifier and is registered by the four-channel oscilloscope Tektronix TDS 3054B. The photo-EMF sensor is arranged as part of a normal homodyne reference beam interferometer, which is to be used for detection of weak ultrasound vibrations of the test samples. Laser-acoustic methods have been developed for control of defect areas of the tested material with cracks.

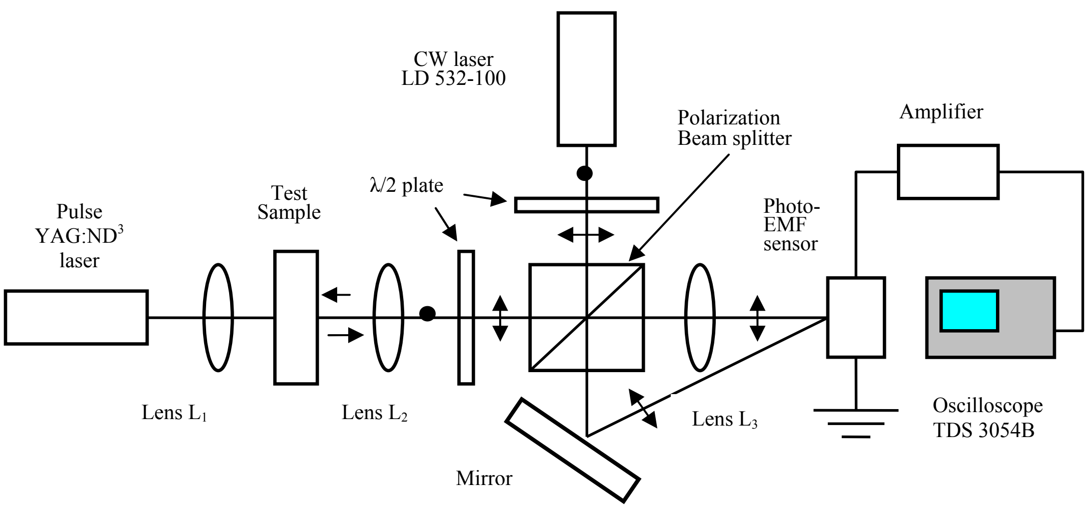

Figure 1. Schematic layout of adaptive interferometer based on photo-EMF sensor.

EXPERIMENTAL LAYOUT

In combination with laser ultrasound method the above-described four-channel adaptive interferometer was applied to detect the location of scattering defects. The scheme of placing of the laser source and the receivers of ultrasonic waves is given in the Fig.2. Here laser heterodyne or adaptive interferometers were used as the receivers. They analyzed ultrasonic vibration in four local areas (designated as 1,2,3 and 4 in Fig.2) situated symmetrically relatively to the region of laser ultrasound excitation.

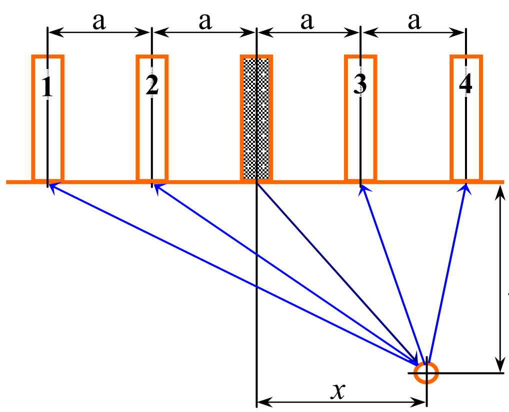

Figure 2. The scheme of placing of the region of laser ultrasound excitation and four local areas analyzed by laser interferometers. Here x and y are the coordinates of defect.

Here the acoustic waves in samples are produced by the $YAG:Nd^{3+}$ laser operating in the regime of Q-switching. The optimization of exciting the ultrasonic waves was brought about by the radiation at wavelengths of 1.064 and 0.532 μm and energies of 550 and 300 *mJ*, respectively. The pulse duration of lasing was varied from 20 to 50 *ns* at the repetition rate up to 10 *Hz*. The output laser beam formed with cylindrical optics and thus being cross-shaped in the form of a narrow strip (Fig. 3). The registration of amplitude and phase of surface displacement caused by defects is made in the four local areas situated symmetrically relatively the region of laser ultrasound excitation (Fig. 2.)

The sample (Fig. 4) is made of steel with the length L=270 mm, the width of 25 mm and the height of 70 mm. On the distance from contact surfaces h=16,5; 35; 52 mm cylindrical holes (artificial defects) with the diameter of 3mm are made, parallel to contact surfaces and directed along the short side. Additionally a pair of cylindrical holes was made, and the first one - at the distance of 35 mm from the object contact surface, and the second one - under the corner of 45 degrees and at the distance of 10mm between the centers.

Fig.2 indicates that the number of the receivers of waves is four, and they are located on the identical distance *a* from each other and symmetrically to the laser source of elastic waves. It represents the local area on the object surface where the process of transformation of light in a sound takes place. It is supposed that the "source" of elastic waves excited in the object and the receivers of the reflected signal field, located on the object surface, have the form of a long strip with the width of $d < \Lambda$ and the length of L>> d, where Λ is the wavelength of exited longitudinal mode. It is also supposed, that longitudinal mode radiation in the object is piston one, which is realized, as a rule, at the high enough laser radiation intensities $J > J_И$ where $J_И$ is a threshold of ablation laser influence on the investigated specimen. As the problem analysis shows, a piston mode of radiation of longitudinal waves can be realized at much smaller J (more than an order) by means of the additional buffer environment located between a light beam and a contact surface of the object.

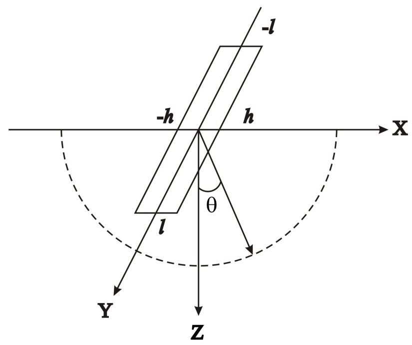

Figure 3. Schematic representation of the wave-fronts generated by a pulsed laser of narrow strip of rectangular form.

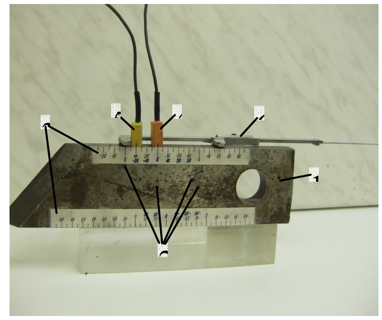

Figure 4..Experimental specimen made of steel.

The dependences of the reflected signal amplitude and time of its propagation in the specimen on the position of artificial defects have been received. The obtained data with use of four receivers are represented in Table 1.

Table 1.The specifications on the amplitude of the reflected signal P_A and the times delays of the acoustical pulse t in the sample.

Defect coordinate (x; y)	Receiver No.1		Receiver No.2		Receiver No.3		Receiver No.4	
	P_A, dB	t, μs	P_A, dB	t, μs	P_A, dB	t, μs	P_A, dB	t, μs
(0; 16,5)	9,8	7,27	0	6,12	0	6,12	9,4	7,27
(10; 16,5)	26,2	9,03	15,8	7,62	0	6,09	10,8	6,68
(20; 16,5)	-	-	-	-	12,4	7,64	9,8	7,21
(0; 35)	3,1	12,61	1	11,89	1	11,89	3,1	12,61
(10; 35)	9,8	13,87	5,1	12,86	1	11,96	3,2	12,22
(20; 35)	13,2	15,77	10	14,62	4,4	12,99	3,1	12,71
(0; 54)	8,3	18,25	6,9	17,82	6,9	17,82	8,3	18,25
(10; 54)	13,6	19,12	9,4	18,42	6,9	17,81	8,1	18,00
(20; 54)	19,5	20,62	17,1	19,60	8,3	18,46	8,3	18,29

DEVELOPMENT OF METHODS OF RECONSTRUCTION OF INTERNAL DEFECTS OF SOLIDS

The mathematical modeling has been studied of the scheme (Fig.2) of four-channel heterodyne or adaptive interferometer on the basis of photo-EMF sensors. The analysis made and mathematical description show that photo-EMF technique is well established, flexible and very suitable experimental techniques for detection of vibrating surface of various materials and specimens containing internal defects. The possibility is shown of measurement of mechanical vibration using speckle photo-EMF generated in photorefractive GaAs: Gr. The relation between the vibration amplitude, the parameters of the materials and the resulting photo-EMF current is investigated.

Temporal delays have been calculated of longitudinal and transverse ultrasonic waves for four receivers taking into account scattering from both defect and taking into account the influence of lower surface of the investigated specimen. It has been shown that in common case it is necessary to analyze sixteen acoustic signals taken by four receivers. The detailed numerical simulations have been conducted for the sample made of steel and containing cylindrical defects, which are at various depths and have arbitrary lateral shift from the center of the receiver.

Detection of defects has been proposed made according to the results of the measurements and processing of reverse acoustic signal sensing in four various places on the sample surface. Acoustic signal appears in the result of the reflection of probing cylindrical sound wave of defect surface or in the result of diffraction on the defect edges. In the first case pulse echo testing was proposed to be realized. Such testing has been shown to be characterized by the high level of acoustic signal and here the measurement of the intensity allows one to evaluate the size defect. It has been realized pulse echo testing for detection of defects with relatively large scattering section in the direction of acoustic receivers. Here the investigation of energetic and noise characteristics of photo-EMF device for receiving acoustic signals and optimization of the parameters of its functioning has been performed. For aims of comparison of measurements with the theory, the calculations of scattering of acoustic waves have been made by model defect in a form of cylinder and the coefficients of reflection and cross-polarization transformation of the power of incident acoustic wave have been determined.

For four receivers of acoustic field used in prototype device it is elaborated the following algorithm of signal processing: 4 times of delay (Δt_m, m = 1÷4) are measured between acoustic pulse reflected by the defect and 4 lateral acoustic waves propagating near the surface from the source to the receivers. Such approach allows one to exclude the influence of time of switching the probing acoustic field. Further three parameters $\tau_{1m} = \Delta t_1 - \Delta t_m$, where m = 2÷4 are calculated. The differences τ_{1m} are shown to depend only on the distance between the defect and receivers that allows one to exclude the noise influence on the line transmitter-defect on the result of measurements. In the result, there is the system of three equations, which allows one excluding the speed of acoustic wavesto determine two unknown values: depth of defect and its transverse shift relatively radiator. Here the intensity of the reflected signal gives the information on the defect size.

COMPARATIVE ANALYSIS OF TWO MEASURING SYMMETRICAL SYSTEMS OF OPTICAL-ACOUSTIC CONTROL OF SOLIDS

Comparative analysis has been made of two measuring symmetrical systems of optical-acoustic control of solids, in the basis of which there are: i) the application of spaced four acoustic-optical receivers at one source of ultrasonic waves (Scheme A) or ii) the use of one acoustic-optical receivers and the system of discreet scanning by laser beam the “long strip”-type (scheme B). Here, the probing of solids can be done not only by longitudinal but also transverse modes and their combination (two-mode acoustic regime allows one to increase sensitivity and detection of volumetric defects including subsurface zone of the object). It has been shown that in a number of cases the application of the scheme B in comparison with the scheme A allows one to simplify essentially the set-up and the measuring procedure of optical-acoustic control and to decrease the large sizes of equipment.

The development of the method of optical-acoustic control has been made and the measuring the scheme B has been realized for detection volumetric defects, where the Nd:YAG laser with the optical system of correction has been used as a source of discreet scanning and excitation of ultrasound waves in object. Moreover in the scheme of measurement the block is used for control with deviating laser beam by mirror synchronized with the block of receiving and processing information. The scheme has been proposed and realized of acoustic-optical receiver of ultrasonic waves fulfilled on the basis of holographic interferometer, which uses counter interaction of reference and signal waves in photorefractive crystal of $Bi_{12}TiO_{20}$:Fe.

CONCLUSIONS

We proposed and developed two novel techniques of multi-channel laser ultrasonic defectoscopy for industrial application. The proposed techniques have been applied to achieve accurate estimation of defects depths in steel specimen. The measurements are carried out with the use of multi-channel interferometers of two types: heterodyne and adaptive ones. With special software the processing of output signals of interferometers and reconstruction of defects position inside a sample under testing is made. It is demonstrated that based on an optical multi-channel interferometer a laser-acoustic defectoscope available for operation in industrial environment.

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