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FEATURES OF LASER DETECTION OF ELASTIC WAVES WITH CONCAVE REGIONS OF WAVEFRONTS

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Features of optical detection of acoustic fields of longitudinal elastic waves with concave regions of wavefront were investigated with the use of laser interferometry technique. The simple model describing the process of such nonmonotonic wavefront propagation in elastic media and variation of their projections on the detection surface in time was formulated. The results obtained could be used for estimation the radii of the local wavefront curvature.

Wavefront, which is a locus of points oscillating in the same phase, has plain, cylindrical or spherical form in simple cases. In real terms the wavefront profile can be essentially distorted due to finite sizes of excitation sources and diffraction effects sufficient in the near-field zone. When travelling through the media such wavefront of elastic waves sustains even greater deformation and as a result it acquires complicated form to describe which it's necessary to use sophisticated mathematical equations. Meanwhile, the investigation of wavefront structure and it's local curvature together with estimation of diffraction losses resulted from ultrasound beam divergence is an important aspect of studying of acoustic fields excited with ultrasound sources of different types and sizes.

The problem of wavefront form distortion with interchangeable concave and convex regions appearing due to diffraction of elastic waves was described by R. Truell, C. Elbaum and B. Chick in [1]. There were described the wavefront profiles, which were dependences calculated by using integration over receiver's surface which diameter was much smaller than ultrasonic wavelength. It's interesting to obtain two-dimensional wavefront images and investigate the features of wavefront structure using instruments capable of measuring the field parameters with high spatial resolution not limited by ultrasonic wavelength.

Optical detection of acoustic fields by using laser interferometry technique became one of the perspective methods for wavefront structure visualization and investigation. There, a laser beam which diameter is much smaller than the ultrasonic wavelength is used for scanning along the detection surface what makes it possible to obtain spatial distributions of elastic displacements or particle velocities with high spatial resolution. Thus detailed information about the features of space-time structure of acoustic field can be acquired. Studying snapshots of the field of elastic displacements obtained within time intervals much smaller than ultrasonic wave period it is possible to trace the dynamics of phase variation of a vibration process on the specimen surface at various instants [2].

The objective of this paper is to investigate variation of the structure and curvature of propagating through the elastic media piston source wavefront with the use of laser interferometry technique.

Typical scheme of laser detection of the field of elastic displacements used in interferometry technique is shown in Fig. 1a. The piezoelectric transducer, placed on one of the plane-parallel sides of the sample, was used for exciting ultrasonic vibrations. The other side, opposite to the surface of ultrasonic waves input, was thoroughly polished and used for laser detection of acoustic fields. When ultrasound beam wavefronts corresponding to various phases of the vibration process intersect the detection surface one can see several concentric circles on the obtained acoustic field distributions. The radii of the circles grow with time as it is shown in Fig.1b, what corresponds to the propagation of phase of vibration process along the detection surface. It is obvious that the pattern of diverging circles appears due to the curvature of the acoustic wavefront propagating in the sample, which is in its turn results from the finite sizes of the ultrasound transducer. The analysis of the wavefront propagation velocity along the detection surface depending on the parameters of the heterogeneous elastic media was described in detail in [3].

During subsequent investigation of the acoustic fields of longitudinal elastic waves in specimens which were made of high-temperature resistant steel, the concentric circles which radii decreased with time (Fig. 2) were detected simultaneously with the diverging circles described above. The time moments corresponding to the snapshots of acoustic fields with such converging and diverging circles appearing are shown in the type A-scan in Fig. 3.

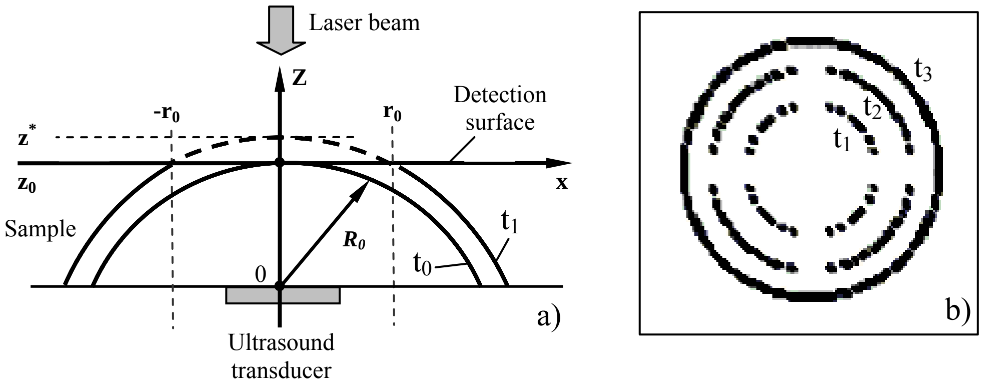

Fig. 1. Scheme of laser detection of acoustic fields of longitudinal elastic waves (a); several concentric circles (b) detected at instants $t_1<t_2<t_3$.

As it can be see from Fig. 3 the detection of such converging circles corresponds to the first echo-pulse, i.e. the wave that has traveled through the sample once in the forward direction.

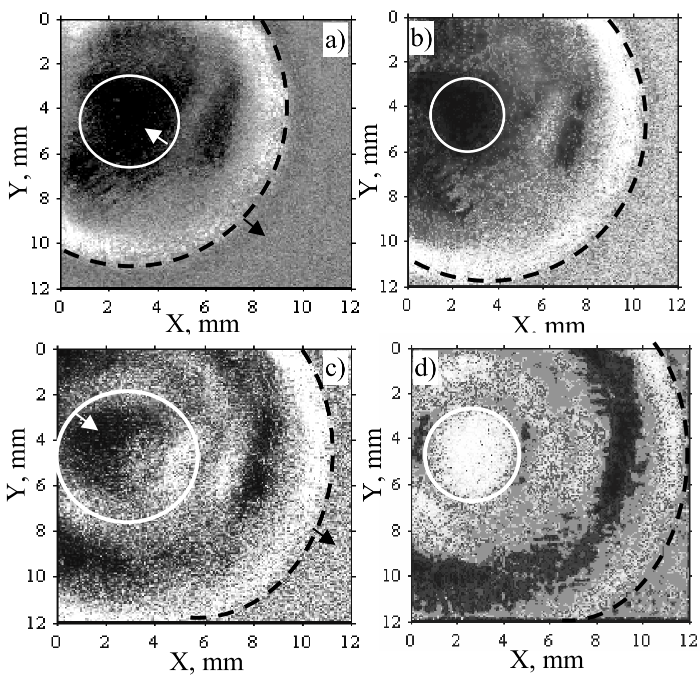

Fig. 2. Converging (white solid line) and diverging (black dotted line) circles detected on snapshots of acoustic fields corresponding to instants: (a) t_1=1.61 µs, (b) t_2=1.7 µs, (c) t_3=1.79 µs, t_4=1.86 µs.

As the transducer aperture was 2a=5 mm in diameter and centre frequency of ultrasound was 5 MHz the near field region will be $x_N = \frac{a^2 \cdot f}{c_l} \approx 5.2$ mm, where c_l=5900 m/s is longitudinal wave length in steel sample. The tested sample was of about 5 mm thickness. Thus, the detection of such “collapsing” circles corresponds to the boundary between near and far field region.

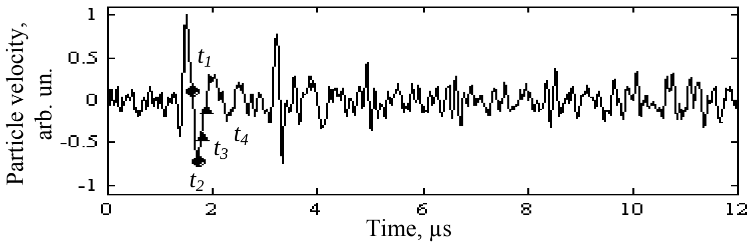

Fig. 3. Time moments corresponding to snapshots of acoustic fields with converging and diverging circles detected.

The only explanation of such “collapsing” circles formation on snapshots of acoustic fields can be nonmonotonic wavefront curvature, i.e. the presence of concavity of wavefront profile. The formation of such concave region arises from the finite sizes of ultrasonic transducer and diffraction effects sufficient in intermediate-field zone. In this case there could be convex and concave regions of wavefront profile [1].The simplest way to describe wavefront with concave region is to approximate its surface by the 4th order paraboloid with the following equation of surface:

$$Z(r) = ar^4 + br^2 + d\,, \tag{1}$$

where *a, b, d* – numerical coefficients; *a*<0, *b*>0 – determine the degree of concavity, variation of *d* describes wavefront propagation along Z axis. The profile of such nonmonotonic wavefront is shown in Fig. 4a.

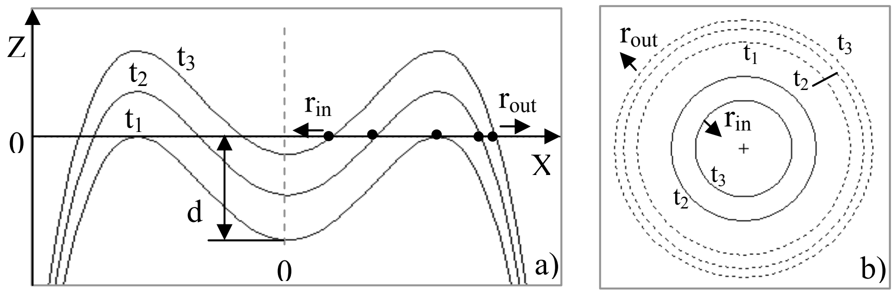

Fig. 4. Wavefront profile with concave region (a) and its projection on the detection surface at time moments: $t_1<t_2<t_3$ (b): solid lines correspond to converging circles, dotted lines – to diverging circles.

When such wavefront intersects the detection surface several converging (solid lines, Fig.4b) and diverging (dotted lines, Fig. 4b) concentric circles could be simultaneously detected on snapshots of acoustic fields obtained with the use of interferometer. To describe variation of values of converging and diverging circles radii with time it’s necessary to set equation (1) equal to zero. Then the roots of an equation (1) will be:

$$r_{in}(d)=\sqrt{\frac{-b+\sqrt{b^2-4ad}}{2a}}\ ,\ r_{out}(d)=\sqrt{\frac{-b-\sqrt{b^2-4ad}}{2a}}\ ;$$

where r_{in} – converging circle radius, r_{out} – diverging circle radius.

Taking into account that d describes wavefront propagation along Z axis: $d = \frac{b^2}{4a} + c_l t$, mentioned equations for radii are the following:

$$r_{in}(t)=\sqrt{\frac{-b+\sqrt{-4ac_l t}}{2a}}\ ,\ r_{out}(t)=\sqrt{\frac{-b-\sqrt{-4ac_l t}}{2a}}\ ;$$

where $t \geq 0$ – time after wavefront touching the detection surface.

The time dependences of radii of converging and diverging circles calculated on the basis of described simple model of nonmonotonic wavefront for the following coefficient values: $a = -1.7 \cdot 10^6$ m^{-3}, $b = 25$ m^{-1}, $d = -9 \cdot 10^{-5}$ m are presented in Fig. 5a. Also, the calculation of radii of osculating circles for concave and convex wavefront regions (Fig.5b) was performed with the use of this model. Radii of curvature for these regions were determined by the following equation: $R = \frac{\left(1+\left(Z(r)'\right)^2\right)^{3/2}}{Z(r)''}$ [4]. Here, positive sign of curvature will be when wavefront is concave upward $\cup$ and negative sign of curvature will be when wavefront is concave downward $\cap$. By model calculation values of radii $R_{\cup}$=2.53 mm and $R_{\cap}$=-1.25 mm corresponding to concave and convex regions were obtained.

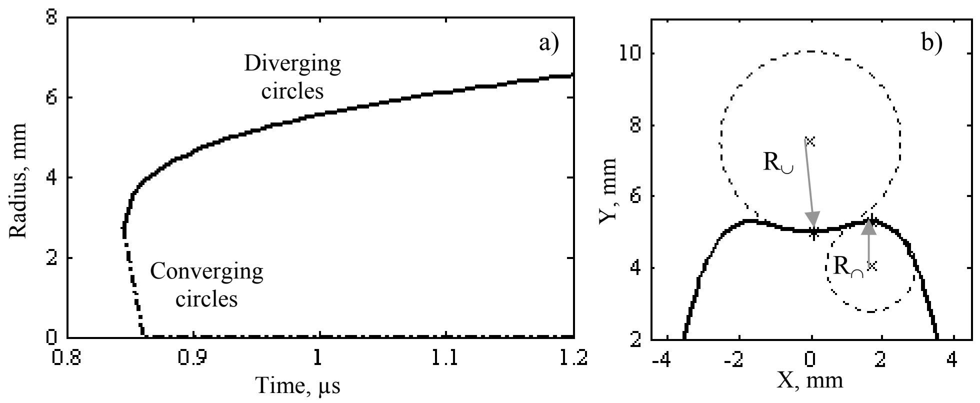

Fig.5. The time dependence of radii of converging and diverging circles (a); osculating circles for concave and convex wavefront regions together with their radii of local curvature (b).

Thus, the use of instrument capable of measurement of acoustic fields with high spatial resolution such as laser interferometer makes it possible to detect and visualize "collapsing" circles which point at the presence of concave region on the wavefront profile. Simple model described above allows quantitative estimation of the features of such nonmonotonic wavefront with concave region.

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