Optical-acoustic diagnostics of cracks on the surface of solid bodies

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Abstract. The features of optical-acoustic diagnostics of defects in the form of cracks on the surface of solid bodies in a pulsed mode are investigated. It has been established that pulsed surface Rayleigh waves should be used to detect cracks. The largest amplitude of the scattered surface acoustic wave is achieved at the optimum width of the laser spot, directed to the center of the crack.

1. Introduction
Optical-acoustic (OA) sources of ultrasonic (US) waves have several advantages over traditional (piezoelectric and electromagnetic-acoustic), including the absence of contact with the medium, the ability to easily change the geometric parameters of an acoustic antenna, diagnose objects moving at any speed [1]. For the excitation of short acoustic pulses, the application of OA methods under pulsed laser exposure is promising [2, 3]. The excitation of a Rayleigh SAW upon absorption of nanosecond laser pulses in a fused silica material was studied in [4]. The features of diagnostics of inhomogeneities in the form of strips of gold on the surface of fused quartz are considered.

2. Theoretical results and discussion
The surface defect in the form of a crack has a width l and is located at a distance of ρ from the center of the laser beam and at a distance of ρ’ from the receiver of the scattered SAW. The excitation region of the US wave has the shape of a rectangle with the area $S_f = ab$, where a is the width of the rectangle, b is its length. In our case $a < b$ [5]. A laser pulse propagates along the Z axis and excites high-frequency ultrasonic waves of different polarization and spatial-angular distribution. Suppose that OA excitation is carried out in a linear mode [1], and the laser pulse has a Gaussian amplitude distribution in time $f(t) = \exp(-t^2 / \tau^2)$. Then the Gaussian acoustic pulse has a duration of $\tau_a$ exceeding the duration of the laser pulse. The pulse of ultrasonic SAW displacements has a width of the spectrum
\[ \Delta \Omega \sim 1/\tau_a \] and a central frequency \( \Omega \sim \Delta \Omega \). The frequency spectrum of a Gaussian acoustic pulse excited on the surface of a solid body has the form \( F(\Omega) = \tau_a \sqrt{\pi} \exp(-\tau_a^2 \Omega^2 / 4) \), where \( \Omega \) is the circular frequency of the ultrasonic wave. The frequency spectrum of the components of the scattered Rayleigh SAW polarized along the Z and X directions has the form [5]

\[
\tilde{U}_{R_z}(\Omega) = \frac{P_f \rho_{\text{sa}} F(\Omega) \eta^2}{4\mu} \sqrt{\frac{2k_R}{\pi \rho}} \sqrt{1-\gamma^2 \eta^2} \sin(A_R) \sin(B_R) e^{i \phi},
\]

(1)

\[
\tilde{U}_{R_x}(\Omega) = \frac{\tilde{U}_{R_z}(\Omega)(1-\eta^2/2)}{\sqrt{1-\gamma^2 \eta^2}}, \quad A_R = ak_R/2, \quad B_R = b(k_R \sin \alpha)/2,
\]

(2)

where \( S_f = ab \), where \( a \) (b) is the size of the excitation strip along the X (Y) axis; \( \alpha \) is the azimuth angle measured from the X axis (in the XY plane); \( P_f \) is the pressure on the surface of a solid in the region of laser irradiation; \( \rho \) is the distance from the excitation region to the crack; \( \phi_R = (k_R \rho^2 - \Omega + \pi / 4) \); \( k_R = \Omega / \nu_R \), \( \nu_R \) is the phase velocity of the SAW; \( \eta = (0.87 + 1.12 \nu)/(1 + \nu) \) and \( \nu \) is Poisson's ratio; \( \gamma = \mu / (\lambda + 2\mu) \); \( \lambda \), \( \mu \) are the constant Lame; \( C_0 = 2(2-\eta^2) - C_1 / C_2 - C_2 / C_1 - 2C_1 C_2 \). Note that the frequency-angular distribution of the surface ultrasonic waves excited by laser pulses is determined by the diffraction function on the rectangular excitation region and the frequency spectrum of the incident acoustic wave, i.e. \( \{ F(\Omega) \sin(A_R) / A_R, \sin(B_R) / B_R \} \).

The incident Rayleigh ultrasonic wave with frequency \( \Omega \) is directed to the defect and scatters on it in the forward direction. Using the two-dimensional Green function in the Y1X2 plane (in the X1X2X3 coordinate system), the amplitude of the scattered SAW can be found from the expression [6]

\[
U_{R_i}^{\mu}(r') = -\int n_p(r') C_{\text{pmm}} \frac{\partial}{\partial x_n} G_{\text{in}}(r', r)[U_{R_i}(r)] |dS_r|,
\]

(4)

where \( n_p \) are the components of the unit vector normal to the crack surface (CR), \( C_{\text{pmm}} \) are the elastic moduli of the material; \( [U_{R_i}(r)] \) – components of displacement in the region of an open crack, induced by Rayleigh SAW; the Green function for displacement in the excited wave has the form [6]

\[
G_{\text{in}}(r, r') = \sum_{\alpha=L,T} \left( \frac{i}{4\pi \mu} \right) k_\alpha \left( \frac{k_\alpha}{k_T} \right)^2 \int_{-\infty}^{\xi'} \left( 1 - \xi^2 \right)^{1/2} d' \tilde{\mu}^\alpha(\xi) \tilde{a}^\alpha(\xi) e^{i(\pi \rho(-r-r'))} d\xi,
\]

(5)

where \( k_L, k_T \) are the wave numbers of the longitudinal and shear bulk ultrasonic waves in the material; \( \tilde{d}^\alpha = \hat{d}^\alpha = [\hat{e}_z, \hat{p}] \), where \( \hat{p} = \left( \hat{e}_z \sqrt{1-\xi^2} \right) \hat{e}_z \parallel X_3 \).

After completing the asymptotic estimate of the integral (5) and substituting the resulting expression in (4), we can integrate over the inner surface of the defect by obtaining the expression for the components of the displacement vector of the scattered SAW of the form

\[
U_{R_i}^{\mu}(r) = -\frac{2}{\pi \rho k_L} e^{-\pi \rho / 4} |U_{R_i,t}^{\mu}| Q_{LT} I_{LT},
\]

(6)

where \( Q_L = -k_L^3 \lambda / 4k_T^3 \mu, \quad Q_T = k_T / 4, \quad I_{LT} = \sin[(k_L + k_T)/2]/(k_L + k_T), \)

moreover, \( \rho' \) is the distance from the scattering center to the receiver of ultrasonic waves.

The temporal form of the scattered acoustic pulse is determined by the integral [1], [3]
where $\tilde{r}_R = t - \rho' / \eta \nu_s$. Substituting expressions (6) into (7), and, completing the integration by numerical methods, we obtain the temporal form of the longitudinal and transverse components of the scattered acoustic pulse of Rayleigh ultrasonic waves in the receiver region. The fast Fourier transform method was used in the numerical calculations. The calculations were performed for the Rayleigh SAW propagating along the free surface of a material made of steel (Fe). It was assumed that $P_f = 100$ MPa, $\nu_f = 5900$ m/c, $\nu_s = 3200$ m/c, $\alpha = 0^\circ$, $\lambda = 4.9 \times 10^{10}$ Pa, $\mu = 7.84 \times 10^{10}$ Pa. It was assumed that a model defect in the form of a crack of width $l$ has a flat boundary and is oriented along the axis $OX$. It is shown that for small widths of the laser spot, the shape of the SAW pulse in the form of a “kink” takes place for the incident pulse of the Gaussian shape. For large spot widths $a \sim 6$ mm, the pulse shape has the form close to S-shaped with the presence of a “precursor” with small amplitude of oscillations in time. The oscillograms of the scattered SAW in the forward direction for the normalized amplitude when scattered on a defect in the form of a crack is investigated. It follows that the form of the oscillograms changes with a change in the spot width of the laser spot $a$. The amplitude value of the scattered SAW pulse varies significantly with increasing laser spot width $a$. The greatest amplitude in time is achieved by a pulse with a laser spot width $a = 2.5$ mm. The width of the laser spot is a multiple of the integer number of SAW wavelengths that fit on it.

Figure 1 shows the dependences of the amplitude of the $Z$ component of the scattered SAW on the position of the laser excitation source $x_1$. It was assumed that there is a small deviation $\Delta x_1$ due to the experimental features imposed on the accuracy of the orientation of the center of the laser spot.

![Figure 1](image_url)

**Figure 1.** Dependence of the amplitude of the transverse component of the pulse of Rayleigh SAW when the position of the excitation point $x_1$ is changed relative to the crack at different widths of the laser excitation $a$: 1-0.25, 2-2.5, 3-5.5 mm (Fe, $\tau_c=12$ ns, $\alpha = 0$, $\rho' = 10$ mm, $l=0.2$ mm, $b=30$ mm, $\Delta x_1 = 0.01$ mm).

As can be seen from figure 1, when the laser beam moves relative to the crack, there is a pronounced maximum reached when the center of the laser beam is located in the vicinity of the crack ($x_1 \approx 0$). It is determined that the amplitude of the scattered SAW in the receiver region increases with increasing width of the excitation strip. An increase in the pulse amplitude with increasing US frequency $f$ is associated with the dispersive properties of a scattering crack for the transverse component of the incident Rayleigh SAW. With increasing frequency $f$ the frequency of oscillations increases significantly with a simultaneous increase in the amplitude of the SAW reaching the receiver. When $a = 5.5$ mm amplitude $U_{Rz}^{sc} \approx 4.5$ nm.
3. Conclusion
Registration surface defects in the form of a crack can be detected using scattering effects of Rayleigh surface acoustic wave in the pulsed mode and the second measurement time pulse shape scattered by a surfactant defect. A significant decrease in the amplitude of the scattered SAW takes place when the receiver location area deviates from the crack location area. By choosing the spot width of the laser spot is possible to achieve the maximum value of the signal of the scattered SAW in the receiver region.

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