REFLECTION OF ACOUSTIC BEAM FROM THE SOLID SURFACE WITH INHOMOGENEOUS BOUNDARY CONDITIONS

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At present to increase reliability and safety of different national economy installation, they widely use materials with layered structure, where one of the layers functions as a protective coating, as a component of friction surface cohesion, of product strength growth, etc. These junctions can be made by adhesion, sputtering, welding, soldering and other techniques. There are different amplitude, spectral, phase methods of ultrasonic inspection and their combinations to evaluate quality of adhesion and cohesion of the joints of layered solid materials. [1-6]. Considerable difficulties of the former methods applied arise, when contacting materials have varied structure and ultrasonic attenuation in the volume – various properties, high roughness of the exit surface, one-sided access, etc.

To overcome previous difficulties, an idea has been suggested by Baev A. R. [7], based on peculiarities of simultaneous beam reflection from the joint surface with various boundary conditions. This paper is devoted to theoretical and experimental study of new distinctive features of elastic wave reflection from the interface *S* of two contacting materials with model inhomogeneous boundary conditions: free-rigid (1), free-slip (2), slip-rigid, rigid-slip. The first stage analyzes peculiarities of alteration of amplitude and phase characteristics of obliquely incident waves of longitudinal and lateral mode, reflected from the media joints *S* with different homogeneous boundary conditions. Calculation has been made of the modes reflection coefficient modulus $R=|R_{ll}, R_{tt}, R_{tl}, R_{lt}|$ and wave phase φ according to classical formulas [8] at different ratio of ultrasonic velocities of contacting media $n=C_2/C_1$, densities $m=\rho_2/\rho_1$. And then conditions are defined, under which phase shift Δφ of the waves reflected from different boundaries differ and are optimal.

In case when the boundary is inhomogeneous, the resulting acoustical field $F_1(\theta)$ of reflected ultrasonic waves may be expressed as a sum of acoustic fields of two or more imaginary coherent ultrasonic emitters. To calculate the field of the reflected waves at space coordinate *B*, Green integral theorem-based formula [2] has been applied

$$P_A = -\frac{iP_0}{\lambda}\sum_{i=1}^{n}\iint R_i\left(\frac{e^{i(\vec{k}\vec{r}_{iB}-\varphi_i)}}{r_{iB}}\right)\left(1+\frac{i\lambda}{2\pi r_{iV}}\right)\frac{\partial r_{iB}}{\partial z}\,dS_{ip}\ , \qquad (1)$$

where ∂/∂z – is derivative to normal vector of the imaginary emitter surface; P_0 - is amplitude of the mode incident on the boundary.

There is possible indication that there must be such conditions, including D_i, beam's incident β_1 and reflected θ angles, wave frequency ν, time duration of ultrasonic pulses τ and probe position {*x*, *y*}, at which total acoustic field of the reflected beam undergoes substantial modifications. For the sake of simplicity, the problem is assumed to be two-dimensional and phases φ_i of the waves reflected from the interface surfaces with different boundary conditions *(DBC)* are not equal to each other. As follows from the calculation data obtained (Fig. 1), we can observe substantial variations of diagram directivity $F_1=\Phi(\theta)$ vs. position of the incident beam with regard to the boundary line between reflecting spots with different boundary conditions. At that one can observe the shift of angular maximum $\Phi(\theta)$ or/and appearance of two or more additional maxima, etc. I.e. it is assumed that when inspecting the quality of surface cohesion, one can realize such conditions, at which registered acoustic field variations of the reflected waves from defective surfaces were maximal and measurement sensitivity was the highest one.

Specifically, let *i*=2, index *q* is proper to qualitative surface but *d* – with defect one, $S_d{}^*= S_d/(S_q+S_d)$, then a resulting field at the receiving probe may be presented as

$$P_A = \sim R_q S_q F_q + R_d S_d F_d \sim S_d^*\left(\frac{R_q F_q}{R_d F_d}-1\right)+1 = S_d^*(\aleph_{qd}-1)+1, \qquad (2)$$

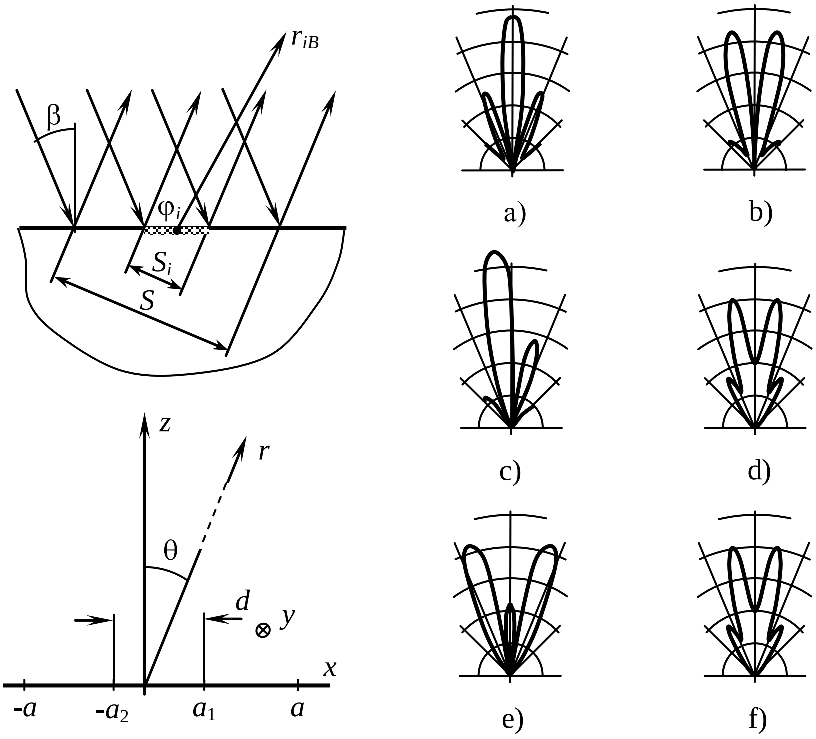

Fig. 1. Calculated data of the imaginary emitters directivity vs. location of an acoustical beam relatively *BDC* lines ⁄ and и vs. phase shift of $\Delta\varphi$ between waves reflected from different places: a) $a_1=-a$, $a_2=a$, $d=2a$, $\varphi=0$; b) – $a_1=0$, $a_2=a$, $d=a$, $\Delta\varphi=\pi$; c) – $a_1=0$, $a_2=a$, $d=a$, $\Delta\varphi=\pi/2$; d) – $a_1=-a$, $a_2=-1/3a$, $d=2/3a$, $\varphi=\pi$; e) – $a_1=-1/3a$, $a_2=1/3a$, $d=2/3a$, $\Delta\varphi=\pi$; f) – $a_1=-1/3a$, $a_2=-a$, $d=2/3a$, $\Delta\varphi=\pi/2$.

at simultaneous incidence of the acoustic beam on the surfaces with "qualitative" (S_q) and "defective (S_d) adhesiveness. One can show that when relation (2) is realized, there are such conditions, at which this expression is close to zero and $|\lg P_A| \to \infty$. That means that high sensitivity of the method to defects like "lamination" is achieved as a result of interference of the fields of neighboring "imaginary coherent sources" of the waves, rather than due to a varying reflection coefficient of the obliquely incident wave during phase transformations at homogeneous boundary [6].

Taking into account the nature of the effect under consideration, one can suppose that the influence of the material structure (in the volume), roughness of the contacting surface and its curvature on the measurement validity will be considerably less than in the known conventional techniques. To verify theoretical analysis, a setup and measurement technique shown in Fig.2-4 have been developed. Slipping boundary is realized by developing contact of plane-parallel surfaces of the materials through a thin liquid interlayer with width h. We set the latter according to relation $h^{*}<h<h^{**}<<\lambda$, where h^{**} is boundary thickness of contacting interlayer, ensuring equality of strain normal components and absolute slipping of tangential component of incident wave shift. Rigid boundary is being simulated by sticking the materials and free one – by absence of their contact. Contacting materials are plexiglass-steel, plexiglass-aluminum, plexiglass-plexiglass, as well as plexiglass-rubber, where load specimen (1) is $30\times40\times10$ m^{-3}.

From Plexiglas (specimen I) ultrasonic beam falls onto the media joint with simulated inhomogeneous boundary conditions and reflected waves are received by receiving probe, which is provided with the opportunity of moving along plane, cylindrical or spherical surface of specimen II. One can easily study the fields of the waves reflected from *DBC*. Experimental data has been obtained on the setup, which measuring circuit is assembled on the basis of standard devices. Respective units of ultrasonic flaw detector УД2-12 are the source 1 and amplifier 2 of the probing signal. The signal is given from amplifier 2 outlet to one of the screen sweeps of double-beam oscilloscope C1-13 (3) to which a reference signal from test oscillator 4 is sent at the same time to define probing signal amplitude by comparison method [9]. Simultaneously amplitude stability and pulse shape in time are controlled by sending an electrical pulse from flaw detector's oscillator 1 outlet to the second channel of oscilloscope 3 sweep (via a divider). Circuit operation is synchronized by a device И2-26 (5), which makes probing pulse delay and scanning, as well as measures time intervals.

Major results of experimental studies are given in Fig. 2–5. As follows from the data of the theoretical analysis and the experimental information, good qualitative agreement is observed between them. And quantitative difference is caused by some idealization during the present problem statement. So, it has been assumed during calculations that the probing pulse is sufficiently wide ($\tau >> \nu^{-1}$) and imaginary source aperture is small, compared to a cylindrical specimen radius modeling material, from which an acoustic beam falls, at that $a/R << 1$; $a^2/R\lambda < 3$. Note first of all that the fact (Fig. 2) that the parameters of reflected beam acoustic field considerably vary as far as *BDC* line *L* relatively "moves" along axis *x* (straight line $L \parallel y$ and $z=0$) is experimentally confirmed. To add, depending on the angle of incidence and reception of the acoustic signal, type of boundary conditions, signal amplitude at the receiver can decrease by 20 – 40 dB. So at $\beta=\alpha$, the behavior of dependence of the signal amplitude at the receiving probe on phase inversion line coordinate $P_A(x)$ considerably varies, depending on the locality of media joint surface zones with different boundary conditions.

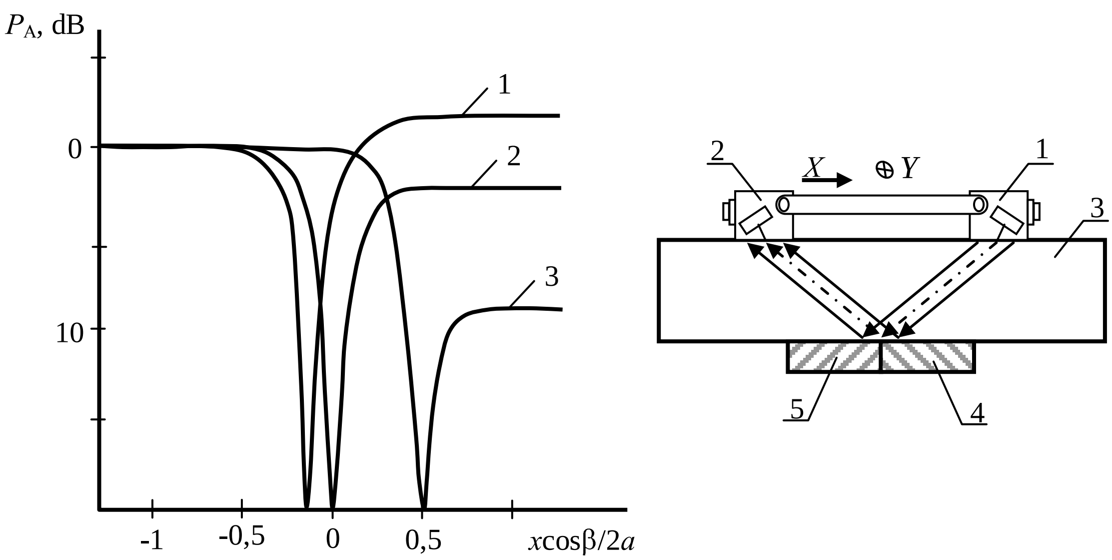

Fig.2. Amplitude of reflected wave vs. *DBC* line location relatively an acoustical beam axis when contacting materials Plexiglas-Steel and boundary free–sleep (1), free–rigid (2), sleep–rigid (3): 1, 2 – probes; 3-5 – contacting materials.

One can also observe separation (splitting) of the main lobe of acoustic field expansion into two with peak amplitude and reception angles α_1 and α_2 ($\alpha_1<\alpha<\alpha_2$) depending on *BDC* line *L* position and reflection factor difference in value (and phase shift $\Delta\varphi$ between them) – Fig. 3. The more is the difference of the reflection factors, the larger is angular shift $\Delta_{\alpha\beta}=|\beta-\beta^*|$, as well as that of coordinate x^* of *BDC* line relatively $x=0$, at which minimal signal is observed at probe (Fig. 2). If phase and amplitude characteristics of such sources are not identical, the parameters of the acoustic field also vary at reciprocal change of their location relatively line *L*. Fig. 4 gives experimental and calculated data realized in accordance with formula (2). It has been assumed during calculations that $2a = a_1+a_1 = 12$ mm, $\lambda = 2{,}7$ mm. We didn't take into account divergence of the acoustic beam falling onto the reflecting surface, insufficiently large radius of specimen I, as well as effect of wave attenuation and refraction at the boundary of solid and liquid media joint. Nevertheless, experimental results confirm suggested approach for experimental dependency description and are in good qualitative agreement with the calculated data.

It is ascertained that acoustic beam splitting in to two and more is also observed during sequential motion of the limited-width acoustic beam in parallel to *BDC* line, however at that, the

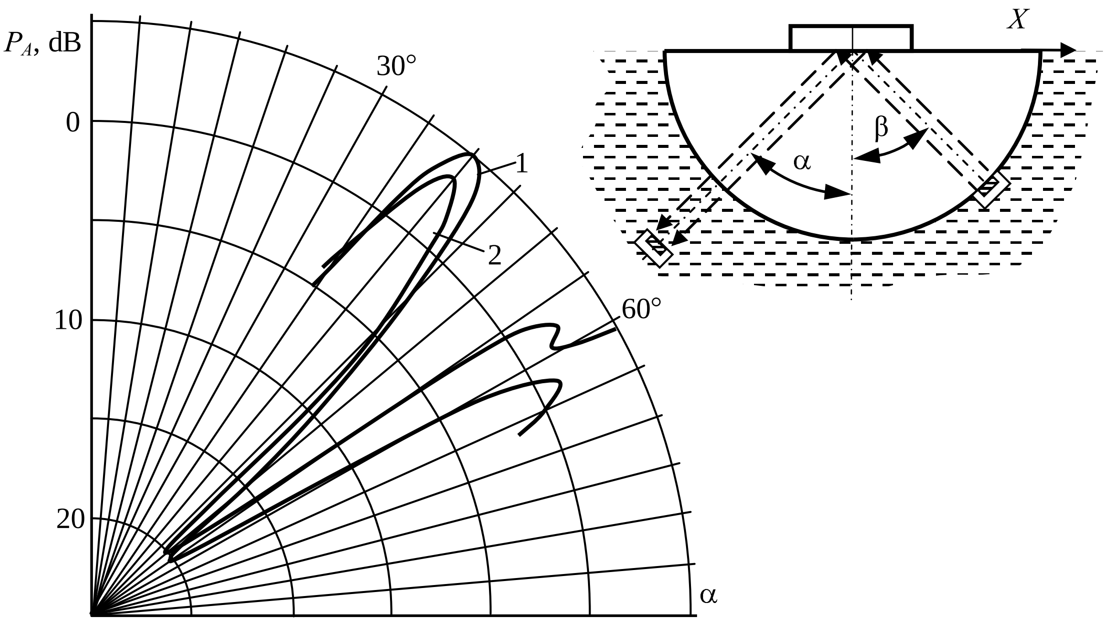

Fig. 3. Directivity characteristics of the acoustical field of reflected waves from the free–sleep boundary P_A vs. receiving angle $\alpha=\beta+\theta$, when contacting materials Plexiglas-Steel (1) and Plexiglas-Plexiglas (2).

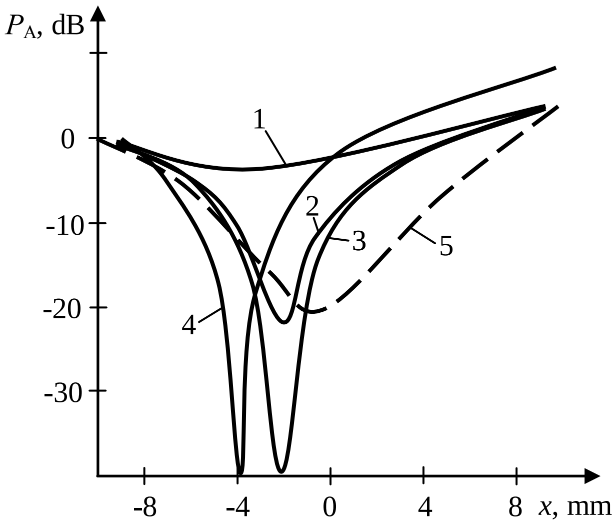

Fig.4. Theoretical (1-4) and experimental (5) dependences P_A vs. *BDC* line location *x*: conacting materials: Plexiglas-Steel; $\beta=\theta=50°$; *BDC* – free-sleep; φ, rad = 1 (1); 2 (2); 0,5π (3); π (4).

location of the main plane of longitudinal wave reflection is changed too. When the incident wave is shear, wave polarization planes are also changed after reflection. If straight *BDC* line ratites in contact plane, the generated field is also rotated relatively axis *z*. Since the main point of nondestructive method under consideration has wave nature, one should assume similarity of dependencies considered for the case of using other wave modes too, including head waves [9-10], plate waves and etc. Fig. 5 shows the effect of head wave reflection from slip-free boundary, when *BDC* line moves in two directions perpendicular to each other. As seen (dependence 3), even reflected signal multiplication is observed during specimen-reflector's motion along the normal's direction towards contacting surface, which is caused by the shift of imaginary source emission field maximum in vertical plane due to interference phenomenon. The above-presented results of the studies are of interest for higher efficiency of material adhesion quality inspection.

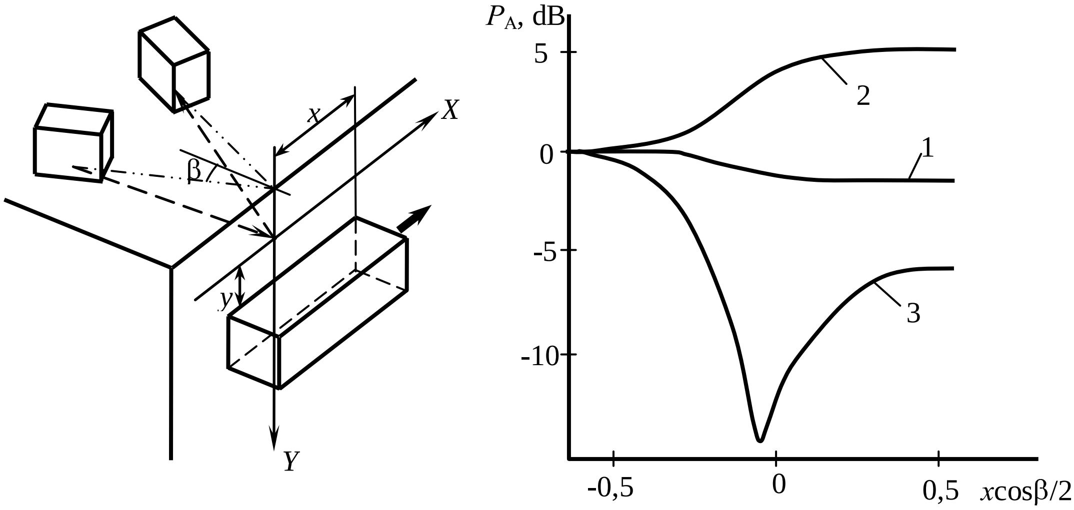

Fig. 5. Experimental scheme and amplitude of head waves reflected from BDC - boundary: free – sleep vs. x and y shift of the BDC line $\angle$: $y/2a''$= 0,5 (1); 0 (2); -1,2 (3).

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