SUBSURFACE WAVES IN SOLIDS WITH CURVED SURFACE AND ACOUSTICAL IMPEDANCE ON IT

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Abstract: This paper presents the results of a study of the peculiarities of subsurface longitudinal (head) waves (SLW) and transverse waves (STW) propagation in solids with wavequide surface of different geometry. Studying an acoustical path of SLW propagation along axis of metallic cylindrical solid of radius R we established, that dependence of pulse amplitude vs. distance r can be approximated by function $\sim r^{-n}$, where $n\approx 1,8\div 1,9$ for dimensionless curvature $\varepsilon=0\div 0,36$ and $n\approx 1,8\div 2,1$ for $\varepsilon=-(0\div 0,48)$. Much more amplitude wave decrease vs. r is when $\varepsilon<0$ and wave vector is perpendicular to cylindrical axis.

As follows from laboratory finding, the fluid layer of length l, contacting with a solid (waveguide) surface between two probes, causes P_A increase by 2–4 dB and more. Function $\Delta P_A \sim log P_A$ is nonlinear one and increasing vs. l: $\delta = | d(\Delta P_A)/dl |$ has absolute maximum at $l=\{0, l_{max}\}$; but minimum at $l=0,5 l_{max}$. This effect is more significant for STW than for SLW mode.

If a solid waveguide surface has rectangular projection, we observe substantial amplitude growth by 10–15 dB and more. As a result of diffraction effect, the top part of the directivity lobe is increasing one. If STW used, the directivity lobe has two maximums, caused by base mode and secondary one (surface waves). It is shown that the former effects must be taken into account when methods using STW and SLW are applied.

Introduction: Subsurface longitudinal (SLW) ore head waves and vertically polarized transverse waves (STW) are excited at critical angles of incidence β_i of ultrasonic beam, and are propagating in solids along its surface (waveguide). Here $\beta_i=\arcsin(C_1/C_{2p})$; C_1 and C_{2p} are ultrasonic velocities in the layers of contacting materials; index $p\equiv\{l, t\}$ refer to the used wave mode [1].

Group of scientists led by I. Ermolov has obtained significant experimental and theoretical data on excitation and propagation SLW in steel, which are important for development methods and instruments of ultrasonic flaw detection [2–4]. It should be noted, that the former and known laboratory finding [5–7], as a rule, have been obtained in simplified experimental conditions when SLW mode excitation and propagation been in solids with free and plane waveguide surface.

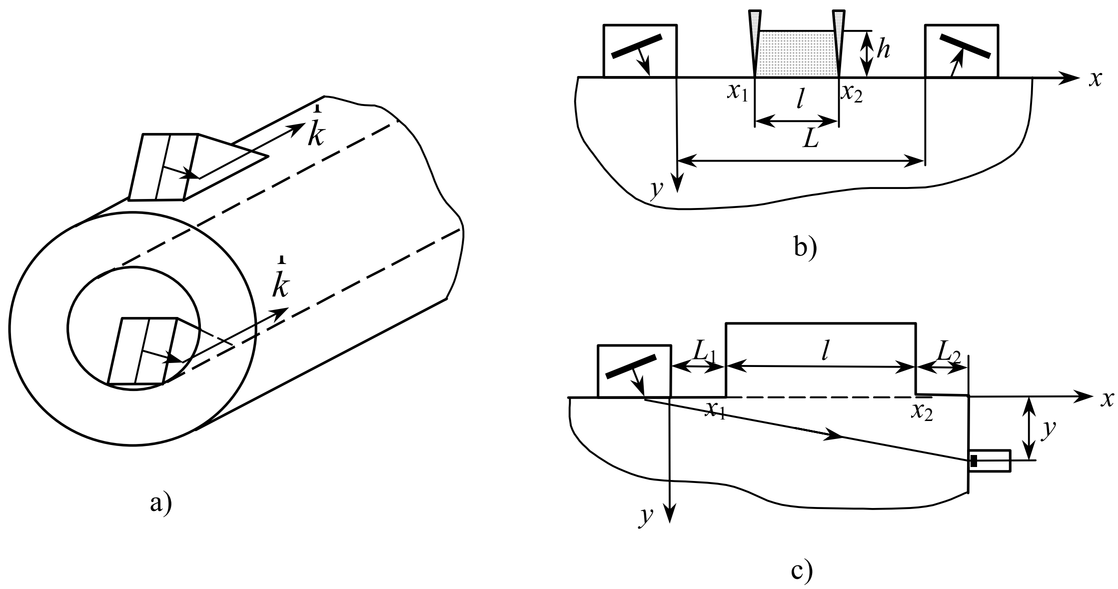

Figure 1. Schematic diagram of ultrasound generation and receiving.

It should be noted that the more specific area of the interaction, reflection and refraction of stress waves (of the former type) at an interface between two different materials, in the known works are almost entirely in the field of geophysics. Much of the theoretical work is concerned with waveforms due to line ore point sources, which involves wave propagation under the conditions of plane strain. Experimental work has concentrated on point-by-point observations (with piezoelectric or similar types of transducers) on the free surfaces of two- or three-dimensional models [1, 5, 7–9].

Taking into account wide possibilities of the former type of waves application and real output problems, we could conclude that it is necessary to study the laws of SLW and STW mode excitation and propagation in the solids of different geometry and boundary conditions at interface surface. The solids of cylindrical geometry; solids, which waveguide surface made of with rectangular projection; solids with fluid layer on its waveguide surface.

There are perspective ways of subsurface waves application in ultrasonic NDT: flaw detection; tensometric and structure measurements, etc.

Results and discussion: The experimental data have been obtained by using the basic devices for ultrasonic defectoscope, voltmeter V7-23, oscilloscope C1-71 and device I2-22 for the time delay measurements with an accuracy of 5 ns. In all measurements we used acoustic pulses of the “belt” form. Working frequency of the probes is ν=(0,6÷5) MHz. Solid materials to be tested are: steel; Aluminum; Plexiglas. An experimental study of the main parameters of sound fields, generated by angle probes, has been carried out.

The angle probes with plane working surface were used to excite (to receive) waves in cylindrical solids through “immersion bath” and contoured probes - through thin contact fluid layer. Probes with cone sound reflector installed axially in its corp. or without reflector were used to excite SLW in cylindrical canals of solids. Waves, reflected from cone reflector, propagate in solid in axial planes. Some results and the main schemes of experimental research are illustrated in Figure 1 – 8].

Figure 2 illustrates dependence of SLW pulse amplitude vs. distance between generator and receiving probes, put on cylindrical surface of metal body with positive $(\varepsilon=\lambda/R>0)$ and negative $(\varepsilon<0)$ radius R of the cylinder curvature ε . Formula, descrying effective pulse amplitude

$P_A'=P_A\Phi^{-1}(\varepsilon)$ vs. distance between probes, its constructive parameters, solid curvature ε and another parameters, have been derived, where

$$F(\varepsilon)=\Delta D[1-\alpha(\varepsilon)^m]^{-1}[W(\varepsilon)/W(\infty)]^{0,5} \quad (1)$$

Here $[1-\alpha(\varepsilon)^m]^{-1}$ – is complex coefficient, depending on "defocusing" characteristics of the system: probe-, coupling medium surface of cylinder; α=0,7, m=0,3 - when sound input in solid is contact, but α=1,3, m=0,5 – immersion one; $W(\varepsilon)$ – integral coefficient of the sound transmission from probe into the solid.

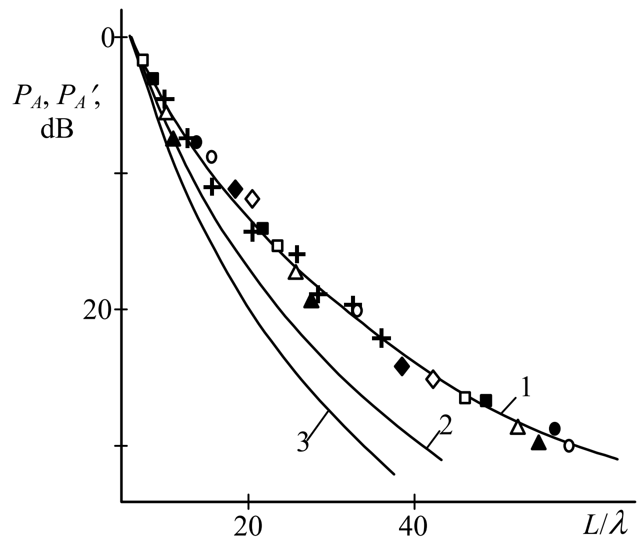

Figure 2. Amplitude of SLW propagating along cylindrical surface vs. distance between probes: ε=0 (1); -0,13 (2); -0,27 (3, +); probe with cone reflector (+); P_A'=$P_A\Phi^{-1}(\varepsilon)$: ε=0,07 (○, ●); 0,13 (?, ?); 0,22 (□, ■); 0,36 (? ,◆).

It is necessary to note, that for 0<ε<0,36 $P_A \sim l^{-n}$, where n=1,8÷1,9. For ε<0 n=2÷2,1 (probes with a cone reflector have not been used). As seen in figure 2, for ε=0÷0,36 maximum divergence between basic curve (ε=0) and modified function $P_A'\Phi(\varepsilon)$ is not more than 2 dB. Much more amplitude wave decrease vs. R is when ε<0 and wave vector is perpendicular to cylindrical axis. It was established that function $f(y)$, characterizing the SLW probe′s diagram directivity $\Phi(\alpha)$ in plane of beam incidence, is not varying substantially vs. ε, when ε=0÷-0,27. And $f(y)$, practically, does not depend on probe construction.

The results of study of fluid layer influence on propagation SLW and STW modes, are in Figures 3 – 5. There are boundary conditions for normal and tangential components of tensions (σ_{ni}, $\sigma_{\tau i}$) and displacements (ξ_{ni}, $\xi_{\tau i}$) at the interface fluid–waveguide solid surface:

$$\sigma_{n1}=\sigma_{n2},\ \sigma_{\tau 1}=\sigma_{\tau 2}=0;\ \xi_{n1}=\xi_{n2},\ \xi_{\tau 1}\neq\xi_{\tau 2}. \quad (2)$$

It was established that dependence $\Delta P_A(l)=20\log(P_A/P_{A0})$ is nonlinear and increasing one vs. fluid layer l, where $P_{A0}=P_A$ for l=0. But $P_l=|\partial\Delta P_A/\partial l|$ is symmetrical function in regard of the middle point between probes $l=l_{max}/2$. It has maximums at $l=\{0, l_{max}\}$ and minimum at $l=l_{max}/2$.

Experimental data show, the lesser the difference between acoustical impedance of the contacting mediums $R'=(\rho C)_f/(\rho C_{2p})$ and the lesser the wave frequency the more the pulse amplitude is. So, if ν=1 MHz, R'≈1 and λ/h_f <<*1*, than ΔP_A can be ~6 dB. (In this case, function *f(y)* increases with fluid layer length and its addition is more at $y\to 0$). This result is unexpected and distinguished from the known classic data in line of surface wave propagation [5]. There are amplitude of surface wave P_A~exp(-$\alpha x/\lambda$), P_l =const. and P_l~ν.

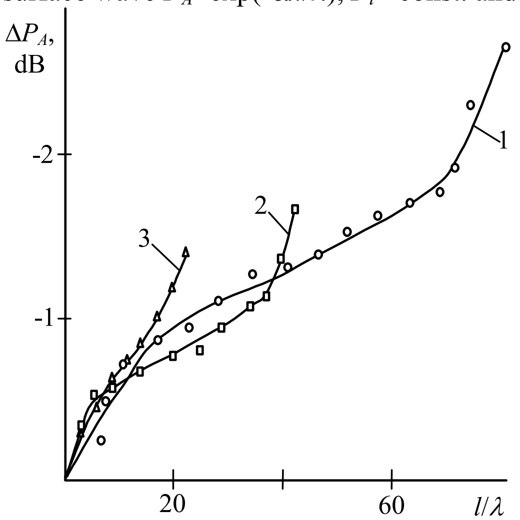

Figure 3. ST (1) and SL (2,3) modes in Aluminum (h/λ>>1). *L*, m=0,15 (1,2); 0,08 (3).

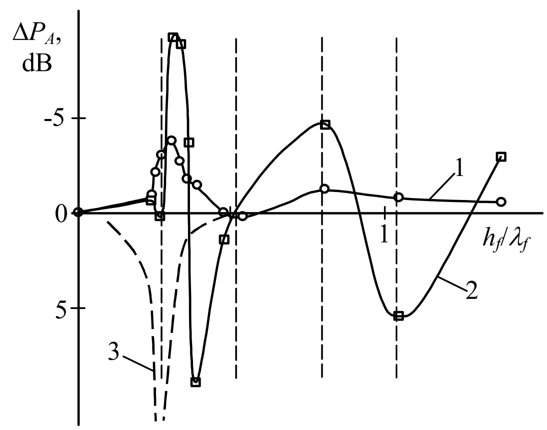

Figure 4. Amplitude oscillation in pulse of SLW (1, 2) and surface mode (3) [5] vs. fluid heigth h_f. Number of oscillation in pulse: 2 (1); 5 (2).

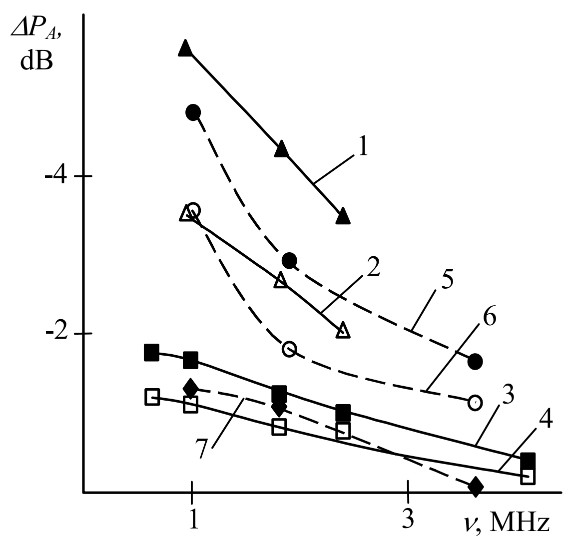

Figure 5. Pulse amplitude of SLW (1-4) and STW (5-7) vs. freequency when fluid layer put on wavequide surface. Solid: Plexiglas (1, 2); Aluminium (3-6); steel (7).

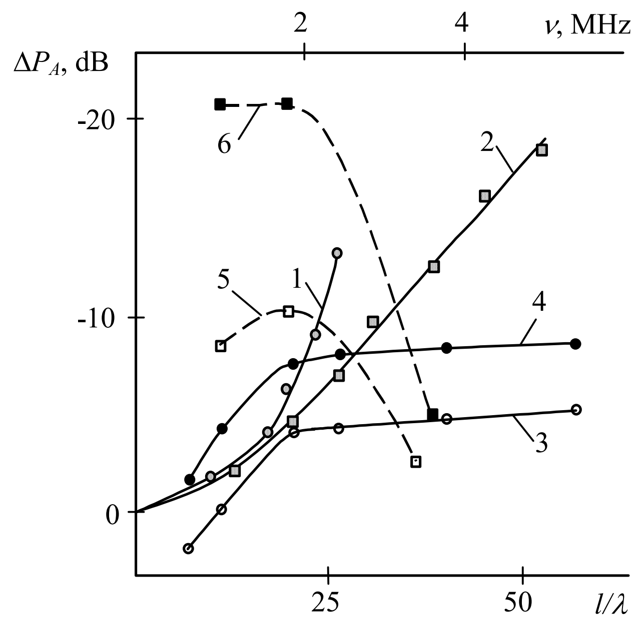

Figure 6. SLW (1, 3, 4) and STW (2,5,6) modes in steel specimen with rectangular projection vs. *l* (1, 2) and ν (3 - 6). *l*,m=0,035 (3, 5); 0,07 (4, 6).

If a fluid layer height is $h_f<\lambda$ and defined, the pulse amplitude and its shape may be changed substantially at some h_f (Figure 4). And ΔP_A can be up to 10dB, while R'≅0,09<<1.The former effect could be explained on the base of interference phenomena, caused by the basic SLW and additive mode generated in fluid. (Phenomena like that takes place when surface wave propagates at the interface solid-fluid [5]). Formula for calculation resonance fluid height h_f* and frequency ν*, at which P_A is maximum or minimum have been derived:

$$h_f^*/\lambda=0,25(2k+1)(1+\Delta)[1-(C_1/C_{2p})^2]^{0,5} \quad (3)$$

Here P_A is maximum (k=1) and minimum (k=0). As seen in Figure 4, there is satisfactory agreement between experimental and calculated data. (Vertical lines are proper to calculated magnitudes of h_f*). So, fluid layer on the solids may cause pulse amplitude increase or decrease up to 10 dB or more though ratio R' is small.

If a solid surface has rectangular projection (Figure 1c, 6-8), we found out that, as against the former case, increasing function $\Delta P_A(L)$ has not symmetry, and ΔP_A effect is the more when projection height h>(2÷3)λ. Partially, ΔP_A can be ~10÷15 dB and more for L/λ>20. Frequency dependence $\Delta P_A(\nu)$ is increasing one when SLW mode is to study. But $\Delta P_A(\nu)$ dependence is more complicated at some $\nu>\nu^*$ when STW mode used. Amplitude function $f(y)$, characterizing sound field of the SLW and STW probes, shows that the lobe of their diagram directivity is more than in the case when waveguide surface is plane(Figure 6, 7).

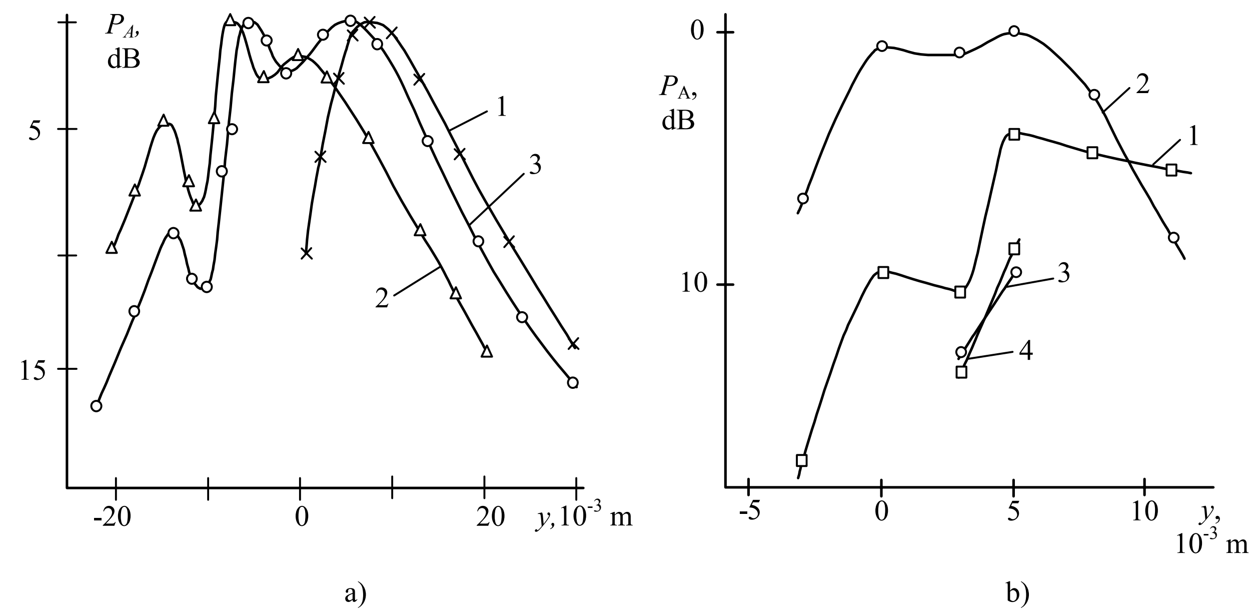

Figure 7. Sound field of STW probe (a) and detection of reference reflectors (b) in steel specimens with having rectangular projection. (a) Waveguide surface is plane (1) and with projection (2, 3); 2 - transverse mode conversed from the surface mode; 3– summary field. (b) Waveguide surface with projection (1, 2) and is plane (3, 4); l/λ=8,4 (1); 22,3 (2); 0 (3, 4).

It is interesting that the angle of amplitude maximum of sound field is single and, practically, its angle position does not depend on the geometry of waveguide surface, when SLW mode used and L_2=0. There are two angles, at wich diagram directivity has maximums, when STW mode used: the former one is lower and another one is higher than plane y=0. These effects could be explained by diffraction phenomena of acoustic beams at the projection wedges, which coordinates are: y=0, $x_1=L_1$ and y=0, $x_2=L_1+l$ [1, 7].

It is known that the law of SLW and STW amplitude variation vs. distance ~r^{-n} where n.=1,75÷2 [[1, 4]. But for SLW and STW modes, conversed at the projection edge ($x=x_1$, y=0) and propagating in the solid volume ($x_1<x<x_2$), index $n\leq1$. So, that is why $\Delta P_A>0$.

Effect of SLW amplitude growth vs. wave frequency (Figure 6) is connected with peculiarities of amplitude variation in near field and far [5] field. According to [6], magnitude of near field is $L_N = 4a_1a_2/\lambda$, where a_i is radius of piezoelectric transducers It is known, that amplitude decreasing in near field much lower than in far field ($L_F > L_N$). But the more the wave frequency the more the $\{L_N , L_F\}$ and the lesser the sound beam attenuation for fixed acoustical path between a sound generator and receiver is.

Double maximum of curves describing sound field of the STW probe arises in the result of addition of the sound fields of two "imaginary sources" of transverse waves, conversed at the projection wedge from surface [7] and STW modes. As Figure 7 illustrates, amplitude of the sound field of the first "imaginary source" has one maximum at $y<0$, but the second one – at $y>0$. Therefore, a flaw detection function $P_A(y)$ has two maximums – lower and higher than plane $y=0$ is (Figure 7a).

Conclusions: A further development of the physical principles of excitation and propagation of ultrasonic head and vertically polarized transverse waves in solids with curved surface and different boundary conditions has been made. Formula describing pulse wave amplitude vs. curvature of cylindrical body, acoustical path between probes and etc. has been derived. The influence of the fluid layer length l, by wetting a solid surface between probes, on pulse amplitude of subsurface waves P_A variation was discovered. The amplitude function ΔP_A is increasing and nonlinear vs. the layer length; the lesser the difference between elastic properties of contacting mediums the higher ΔP_A will be. When a thickness of the layer is resonance, than ΔP_A varying can be ~8÷10dB though an acoustical-impedance′s ratio of contacting mediums R' is ~0,1.Effect of ΔP_A increase is about 10÷15 dB and more when SLW and STW waves propagate along the surface of the continuous solid with rectangular projection. Peculiarities of the sound fields of the SLW and STW probes vs. projection length and height, wave frequency and type of mode are caused by diffraction phenomena and mode′s conversion near the edges of rectangular projection. The former effects must be taken into account to develop new method of ultrasonic testing on the base of SLW and STW modes.

References:

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