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ELASTIC WAVES IN SOLIDS WITH PROTECTIVE LAYER

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There are many papers belonging to the layered objects and actually it is necessary to inspect the contacting materials structures and detect volume discontinuities and cracks in them. In our work new distinctive features of elastic wave propagation in solids with protective layer (*PL*) have been experimentally studied and the results are considered for application in ultrasonic testing. The first part of the work is devoted to experimental research of the acoustic path of ultrasonic echo-method, volume defect (a reflector) is under protective layer – in steel base. The second part considers the possibilities of detecting cracks, coating thickness and of measuring acoustic properties of object base on the basis of techniques applying subsurface waves in steel and laser equipment application.

1. Defect is under protective layer..

1.1. Analysis of the acoustical path. Let an angle probe with wedge angle β is moving in direction *x* along the article surface with protective layer (*PL*) and the defect is under the protective layer in steel base. In this case some problems of flaw detection are to appear, when the magnitude of the protective layer thickness h is nearly of the wavelength $\lambda_p=\nu^{-1}C_p$ in it, where ν is wave frequency and C_p is sound velocity in *PL*. If we neglect the effect of the contacting layer, then according [1, 2] acoustic path function *N* for this case can be described as in formula (1)

$$N \sim \tilde{D}^{*}_{02}\,\tilde{D}^{*}_{02}\,F_p F_D R_d S_d\, f(r)\,, \tag{1}$$

where $\tilde{D}^{*}_{02}$ and $\tilde{D}^{*}_{20}$ are the coefficients of sound transmission from the probe into the steel body base (through *PL*) and back, F_p and F_D are the directivities of the probe and the reflector in steel, R_d is the sound reflection coefficient and S_D is its effective sound reflection surface, *f*(*r*) is the function of sound attenuation.

It is clear that if $h^*=h/\lambda_p<<1$ or $h^*>>1$, then $\tilde{D}^{*}_{20}$ and $\tilde{D}^{*}_{02}$ can be evaluated by using known formulas [3]. But if $h^*\sim 1$ and is varied, some difficulties arise. Let us consider peculiarities of the interference phenomena manifestation and take into account $\tilde{D}^{*}_{20}$ and $\tilde{D}^{*}_{02}$ behavior vs. h^* and influence of the directivities F_p and F_D on the sound propagation function *N*. One should note that during probe operation, an acoustic pulse passes *PL* twice, and each time interference effects can be manifested in a different way, since they depend on acoustic beam angle of incidence on the *PL* from the probe wedge and on the angle of incidence α_i of the signal reflected from the defect to the boundary metal-*PL*. For interference effect to manifest completely, it is necessary that pulse duration, $\tau=\dfrac{m}{\nu}\dfrac{2h}{\sqrt{1-n^2\sin^2\beta}}$ where *m* is a number of oscillations in pulse, $n=C_p/C_w$, where C_w is sound velocity in the wedge. Conditions of resonance manifestation in the contacting layer, at which the signal acquires extreme values – $\{h_{\max}, h_{\min}\}$ - are defined by formulas:

$$h_{\min}=\frac{1}{4}(1-n^2\sin^2\beta)(2k+1+\frac{\phi}{2\pi})\,; \quad h_{\max}=h_{\min}(1+\frac{\phi}{2\pi})(1+\frac{\phi+4\pi}{2\pi}]^{-1}\,, \tag{2}$$

where ϕ - a phase shift of wave reflected from boundaries: Steel-*PL*-wedge; k=0,1, 2...

As follows from (2), when ultrasonic inspection input angle to coating increases, values $h_{\max}$ and $h_{\min}$ decrease, and vice versa. On the other hand, if *h* is a constant value and only wedge angle β is changed (as well as input angles α_p into the coating and α into the object base), $P_A(\beta)$ has extremes at $\beta_{\max}$ and $\beta_{\min}$.. As acoustic path analysis shows (1), the member $\Xi_1=D_{02}F_p$ will depend on the protective layer thickness *h* during probe motion along axis *x*. And the member $\Xi_2=K_D D_{20}$ is defined by both the coating thickness and the probe coordinate location *x*, since value D_{20} is the function of reflected wave angle of incidence to the boundary metal-*PL* α_1 (Fig. 1).

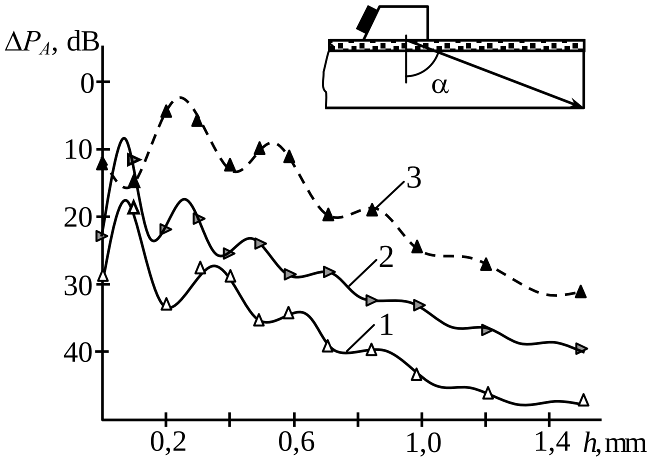

Fig. 1. Dependence amplitude of reflected wave vs. protective layer thickness: α = 65° (1); 50° (2); 0° (3).

Let D_{02} acquire minimal value at some $\{h, \beta, \alpha\}$. It is easy to show that D_{20} and N are also minimal, when $\alpha_i=\alpha$. Then it is obvious that D_{20} and N as the functions of AP location on the object x at $x_1<x<x_2$ will be growing, reaching the maximum at some typical $(x_i)_{max}$. Thus, one should conclude that during the inspection of the objects with varying thickness of PL, validity and reliability of the control are not high due to both signal amplitude pulsation and difficulties related to “correct” location of angle probe relatively the reflector to estimate its dimension and spatial location.

1.2. Experimental results and discussion. To confirm the results of the conducted analysis of the acoustic path and to reveal the opportunities of leveling the interference effect influence, we carried out experimental studies according to conventional technique [4]. To make research, an enamel coating with 0,1 mm pitch was applied to the steel specimen surfaces, a non-directed reflector being made in metal and parallel to contacting plane. We have obtained dependencies of the echo-signal amplitude P_A vs. PL thickness, wave frequency f=1,8–5 MHz, exit angle in the steel base of the specimen α=0–60°.

The obtained data show that the dependence of P_A on $h^*=h/\lambda_p$ for longitudinal, transverse and head waves, excited and propagated in the steel, have substantial oscillations (up to 10-12 dB) caused by interference phenomena. Earlier predicted effect of available two maximums of passage function $N(x)$ was also confirmed (Fig. 1). Taking the results of theoretical analysis of the acoustic path and experimental study data into account, a method of the acoustic path stabilization, when interference phenomena in the protective layer are to appear, has been developed. To diminish oscillation of P_A vs. h^*, we suggest to use the additional acoustic echo-channel (path) created by another probe with wedge angle β^* installed in a common case (Fig. 2). An optimal frequency ν_1 of the second probe is determined from the derived formula

$$\nu_1 = \nu\sqrt{\frac{1-n^2\sin^2\beta^*}{1-(\sin\beta)^2 n^2}} - \frac{C_n\Delta\varphi}{4\pi h}\sqrt{1-n^2\sin^2\beta^*}\,, \qquad (3)$$

2. Subsurface waves for ultrasonic inspection of materials with protective layer. Analysis and experimental data.

The second part of our work is devoted to the method of head waves development [4-6] applied to measure cracks depth H_0 , h, and acoustic properties of contacting materials with protective layers. To increase this method sensitivity and accuracy, small aperture probes (as receiving ones) have been developed [7] and used. For the same purposes, we have considered the possibilities of applying laser acoustic method, as well as mechanism of opto-acoustical transformation has been analyzed and optimal circuits of ultrasonic control reception excitation have been considered. Figs. 3 – 4 show suggested schemes of determining crack depth and bimetals separation depth, measuring ultrasonic sound velocity under the coating and measuring the thickness of the latter. On the basis of

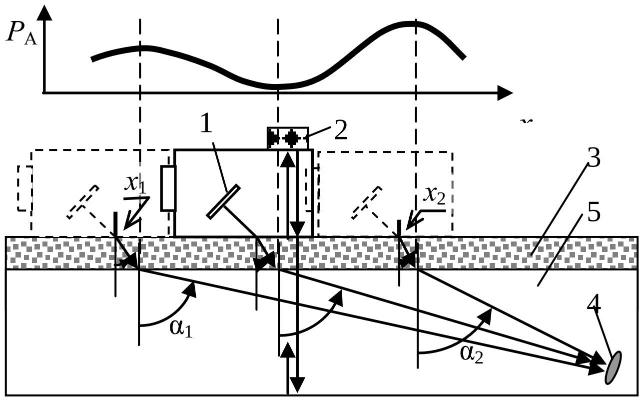

Fig. 2. Suggested sheam of the object inspection and dependence P_A vs. probe location: 1, 2 – piezoelectric elements; 3 – protective layer; 4 – defect; 5 – object's base.

beam acoustics methods, expressions (4, 5) were obtained to evaluate crack depths by using three (one emitting and two receiving) *AP*, which in their turn, can be both contact and contact-free:

$$\Delta\tau = \frac{\sqrt{\left(\ell_0 + \Delta\ell - htg\beta\right)^2 + H_0^2} + \sqrt{H_0^2 + x_0^2} - l_0 + 2htg\beta}{C_m} + \frac{\sqrt{\left(\ell - \Delta l - x_0\right)^2 + h^2} - htg\beta}{C_p} \tag{4}$$

$$\frac{C_m}{C_p}\frac{x_0}{\sqrt{x_0^2 + H_0^2}} = \frac{\ell - \Delta l - x_0}{\sqrt{h^2 + \left(\ell - \Delta l - x_0\right)^2}}. \tag{5}$$

As it follows from the function $\Delta\tau(l_0, l, H_0, \Delta l, h, C_p, C_m)$ analysis, if h □ H_0 and recieving probes are simmetrically in regard with a crack′s plane then $H_0 = \left(\frac{4C - A^2}{A - B}\right)^{1/2}$, where $A = \left(\ell_0 + 0.5\ell\right)^2 - 2\ell_0 C_m \Delta\tau - C_m^2 \Delta\tau^2; B = \left(\ell_0 + 0.5\ell\right)^2 + \ell_0^2;\ \mathrm{C} = \left(\ell_0 + 0{,}5\ell\right)^2 \ell_0^2$.

Let $x_1 = \Delta l + l_0$, $x_2 = \Delta l$, $x_3 = l - \Delta l$. Then, if $x_3 > x_1 > 0$, $x_2 < 0$, the highest sensitivity and accuracy of H_0 measurement is attained, when $\{x_3, x_1, |x_2|\} \to 0$. And for this case $\frac{d\tau}{dH_0} \to \frac{\tau}{H_0} \approx 1/C_m$ if $h=0$. But when $x_3 > 0$, $x_2 < x_1 < 0$ the maximum sensitivity is when $\{x_3, |x_1|\} \to 0$, $|x_2| \to \infty$, and $\frac{d\tau}{dH_0} \to 1/(2C_m)$. In either case laser source is the most suitable one of ultrasonic control due to compactness and opportunity of localizing emission (reception) zone. Slight increase of measuring accuracy can be achieved owing to emitting transverse mode having sonic velocity almost two times less than the head wave. If the object under study is bimetal and their adhesive interface surface (and lamination) is perpendicular to the operating surface, then the most optimal measurement alternative is the one at which emission source is in the material with more high sonic velocity.

Subsurface wave diffraction effects can be used too to define thickness and sound velocity under protective layer, which most often correlates well with physical and mechanical and structural properties of the base [1]. As it follows from (4, 5), there is dependence $\Delta\tau$ vs. $\left(h, C_p, C_m\right)$ using which it is possible to find sound velocities in materials or the layer thickness. For example, if h=const - $C_m = l/\Delta\tau$. But if $h \neq$ const – it is necessary make additive "sounding of the object" by changing the direction of sounding. In this case we have two equations to define C_m more exactly.

The results of the made analysis were experimentally verified according to the scheme given in Fig. 3, when a steel 400 mm thick parallelepiped had been used as a pattern two-layer specimen, on which surface a “protective coating” in the form of 2,5 mm thick plexiglass sheet was applied. The latter was stuck to the steel specimen surface, on which in its turn, a 0,5 mm wide cut of various depth was made. Operating probe frequency was 2,5 MHz. By using a standard scheme of measurements [4] and the developed designs of small aperture probes [7] acoustic pulse propagation time and its amplitude were determined, depending on reciprocal probe. At that, usual angle probes (contact) and experimental pulsed laser with efficient 30 ns pulse duration was used as an ultrasonic source. In the latter case, УЗ-33 was applied as an amplifier of the oscillations received.

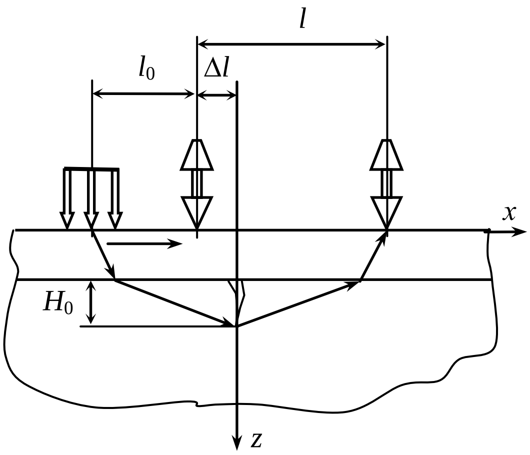

Fig. 3. Scheme of the crack's depth measuring with using opto-acoustic and acoustic method.

Some experimental data are given in Fig. 4, which shows dependencies of time difference of acoustic signal arrival to receiving probe, when the location of one of them is fixed (in the vicinity of the crack) and the coordinate x of the second one is a variable value. The present measurement conditions are characterized by the manifestation of diffraction effects conditioning oscillating nature of signal amplitude variation versus x without the coating. Interesting is the fact that availability of a thin protective layer practically smoothens this effect (curve 2). As far as dependencies $\Delta\tau(x)$ at

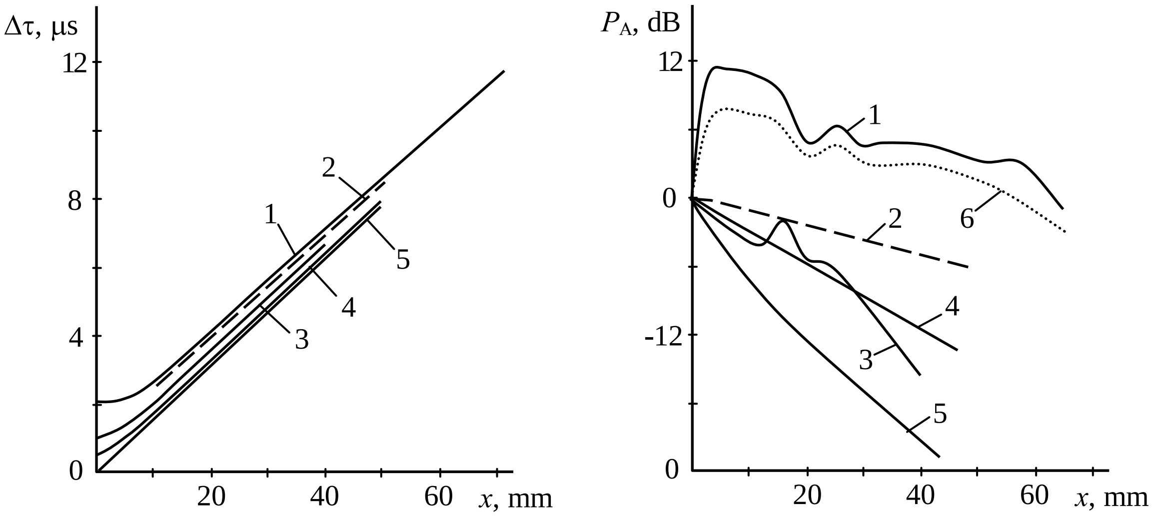

Fig.4. Time $\Delta\tau$ and wave amplitude P_A vs. probe II location (1-5) and vs. crack’s depth (7): crack’s depth H_0, 10^{-3} m = 10 (1, 2, 6); 5 (3); 3 (4); 0 (5); 4 - protective layer is; 6 – $\Delta l + l_0 = x_1(6) > x_1(1\text{-}5)$.

different h and H_0 are concerned, they monotonously increase and at $x/H_0>>5$ degenerate into straight lines with the slope angle tangent close in magnitude to reverse velocity of the wave in metal $(C_m)^{-1}$.

Research data confirms that the informative dependence is that of time $\Delta\tau(h, H_0, x)$, rather than $P_A\ (h, H_0, x)$. Experimental dependencies $\Delta\tau(h, H_0, x)$ obtained for different location of the receiving small aperture probe are found to be in good agreement with the calculated data (formulas 4, 5) and practically coincide within in accuracy of measurements. As calculated and test data shows, applying the proposed technique allows defining crack and separation depth from 1-2 mm to 10-20 mm and more with an error les than 5-10 %.

Plate mode s_0 having the largest velocity C_{s0} of all modes is an analog of the head wave in thin sheet materials, its energy being concentrated mainly in longitudinal shift component. On the basis of theoretical analysis of the set of equations describing propagation of elastic disturbances in a two-layer plate [8], we obtained the expression giving sufficiently simple connection between the relation of the thickness of contacting materials h_p/h_m , Young module E_i, and Puasson coefficients χ_i , and sound velocity: $C_{s0}=C_{s0}(E_i, \chi_i, h/h_m)$. Taking this into account, one can show that in a number of cases $(h/h_m=const)$, there is a possibility of estimating the area of separation of the zone under study, if it is sounded in series , determining signal pass time at *i-th* segment with some constant acoustic base L. It is obvious that the highest efficiency of such measurements can be achieved by using opto-acoustic methods and devices.

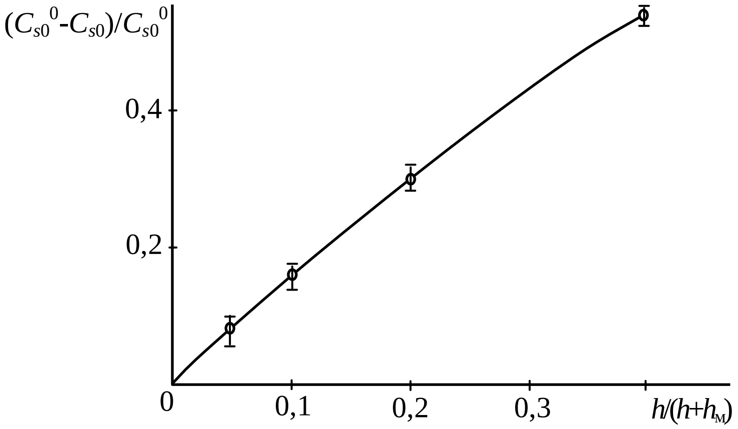

Fig.5. Sound velocity of the plate wave vs. protective layer depth h: $c_{s0}^0=c_{s0}$ if $h_p=0$.

Using the former methods we have obtained experimental dependencies $C_{s0}=C_{s0}\{h/(h_m+h)\}$, when contacting materials are: alloy (Pb-St) and copper. Fig. 5 gives calculated and experimental dependencies of sound velocity on relation of contacting material thickness, which are in good quantitative agreement. (Pulsed laser is used as ultrasonic source in this experiment).

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