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Measurement of thickness of layer and sound velocity in multi-layered structure by the use of angular ultrasonic transducers

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Abstract:

The possibilities of measurement of thickness of layer and the velocity propagation of ultrasound signals in layered structures by the use of the angular electroacoustical transducers with known parameters are analyzed. It is shown that, when the velocity propagation of ultrasound signals in the separate layer of structure is unknown, the thickness and the velocity propagation of signals in them may be measured by the use of the single measuring channel with angular ultrasonic transducers. The algorithms for determination of thickness of separate layers and ultrasound velocity in them are developed, when the layered structure is iradiated at a known angle to the surface of structure. The modeling of a measuring channel with the angular ultrasonic transducers is performed. When modeling the propagation and reflection of ultrasound signals in duralumin – plexiglass layered structure and the spatial and temporal distributions of them on the surface of layered structure are revealed. The variation of temporal and spatial distributions of received signals is investigated when the angle of incidence to the layered structure is changed. It is shown that temporal and spatial distributions of shear and longitudinal waves do not coincide to each other and alter differently, when the angle of incidence is changed. The results of experimental investigation are presented.

Keywords: ultrasound velocity, angular ultrasonic transducer, layered structure, shear wave, longitudinal wave.

Introduction

Ultrasonic measuring methods of thickness and other physical parameters of layered structures are widely used in industry and non-destructive testing [1-4]. But at present the multi-layered structures become more complicated, consisting of materials with different mechanical and acoustical properties, such as plastics and metals or metals, liquids and plastics. Difference of mechanical impedances of these materials causes many problems. Especially it is evident when the measuring information must be obtained only from one side of the layered structure [5,6]. In this case not always it is possible to obtain the measuring information about parameters of all layers or some of them. This is stipulated by the losses of ultrasound signals in separate layers as well as by loses of ultrasound signals in the boundaries between them. These loses depend on the differences of acoustical impedances and on the acoustical properties of the materials of different layers. Other difficulties occur because the acoustical properties of the materials of different layers often cannot be exactly known. For that reason the measurement of thickness and other parameters of the separate layers is problematic. The problems are related to the fact that the velocities of propagation of acoustic waves of different types in the separate layers of structure are unknown. In such a case the determination of thickness of separate layer is possible only by using of two separate measuring channels. At least in one channel the layer must be irradiated at an angle to its surface. Though, when sounding at the angle to the surface of the layer structure, the longitudinal, shear and other types of ultrasound waves are excited [1]. It allows increase the measurement possibility by the use of ultrasound wave mode conversion. The velocity propagation of shear waves is about two times less than the velocity of longitudinal waves. In this case the time of propagation of acoustical signals in the layer becomes almost twice longer. It enables improve the resolution and accuracy of measurement of thickness. But often in multi-layer structures the velocities of propagation of different types of waves in separate layers are unknown, especially for ultrasonic shear waves. In that case the angles of propagation and reflection of ultrasound waves of different types are not known too.

An oblique incidence method for excitation of longitudinal and shear waves is very convenient for measurement of an unknown ultrasound velocity and thickness by the use of two measuring channels [6,7]. In both cases two measurements are performed for different distances and delay times. But in analysis presented [6,7] there is no information about ultrasound wave mode conversion and about propagation of shear waves in separate layers of the layered structure. In these articles no information about the use and selection of different types of waves and information about the use of angular transducers for that purpose is given. Therefore the objective of this paper is analysis and verification of a new method for thickness and ultrasound velocity measurement in multi-layer structures using information about parameters of angular transducers.

Theoretical investigation

Suppose that we have a medium, which consists of *n* parallel layers with different physical properties. The plane acoustic wave is radiated to this structure at an angle α_0 by the use of angular ultrasonic transducer. The velocity of longitudinal wave propagation in the wedge of the transducer is c_0. This wave at every boundary of layers is transformed to the reflected and refracted longitudinal and shear waves (Fig.1). With the purpose do not overburden Fig.1 by information only one from the refracted waves is shown in it. The angle α_I of propagation of any wave in the *i* layer is determined by the Snell's law

$$\frac{\sin\alpha_0}{c_0} = \frac{\sin\alpha_i}{c_i}, \qquad (1)$$

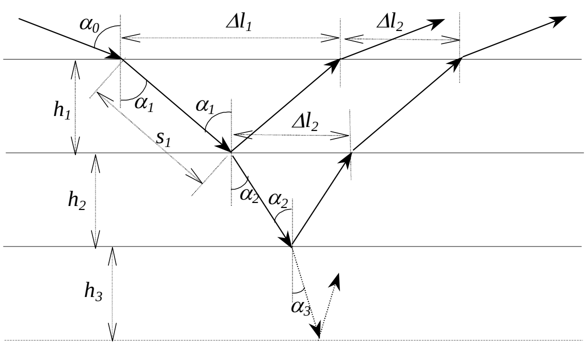

Fig.1. **Propagation and reflection of ultrasonic waves in a multi-layered structure**

where c_i is the velocity of propagation of ultrasound waves in the i medium. Let us consider that the velocity of propagation of ultrasound waves c_0 and the angle α_0 of radiation of waves by the wedge of transducer are known. Then the parameter k, characterizing the transducer wedge, may by introduced

$$k = \frac{\sin \alpha_0}{c_0}. \qquad (2)$$

By the use of Fig.1, equation $\sin\alpha_I = \Delta l / 2s$ and Eqs.1 and 2 we can obtain the expression for signal path s_i in the i layer

$$s_i = \frac{\Delta l_i}{2kc_i}, \qquad (3)$$

where Δl_i is the displacement of an acoustical signal in the i layer during the one pitch-catch (Fig.1). On the other hand, the path s_i of the acoustical signal in the i layer may by determined

$$s_i = \frac{\Delta t_i c_i}{2}, \qquad (4)$$

where Δt_i is the propagation time of the ultrasound signal during the one pitch-catch. From Eqs.3 and 4 one can obtain the velocity c_i of propagation of the acoustical signal in the i layer

$$c_i = \sqrt{\frac{\Delta l_i}{k\Delta t_i}}. \qquad (5)$$

From Fig.1 it is seen that the thickness h_i of the i layer

$$h_i = \frac{\Delta l_i}{2}\cot\alpha_i. \qquad (6)$$

By the use of Eqs.1, 2 and Eq.5 we can obtain

$$\alpha_i = \arcsin\sqrt{\frac{k\Delta l_i}{\Delta t_i}}. \qquad (7)$$

Then the thickness h_i of the i layer may be described by equation

$$h_i = \frac{\Delta l_i}{2}\cot\left(\arcsin\sqrt{\frac{k\Delta l_i}{\Delta t_i}}\right). \qquad (8)$$

In practice usually the time of propagation t_i of an acoustical signal from its transmission to reception is measured. This time consists of the time of propagation of the ultrasound signal t_0 in the wedges of electroacoustical transducers and the times of propagation of the acoustical signal in the layered structure during which the signal propagates, i.e.

$$t_i = \Delta t_0 + \Delta t_1 + \Delta t_2 + \cdots + \Delta t_{i-1} + \Delta t_i. \qquad (9)$$

The distance l_i it is convenient to measure between the centers of acoustic axes of transducers

$$l_i = \Delta l_1 + \Delta l_2 + \cdots + \Delta l_{i-1} + \Delta l_i. \qquad (10)$$

By the use of expressions (9) and (10), Eq.5 and.8 become like as

$$c_i = \sqrt{\frac{l_i - l_{i-1}}{k(t_i - t_{i-1})}}, \qquad (11)$$

$$h_i = \frac{l_i - l_{i-1}}{2}\cot\left(\arcsin\sqrt{\frac{k(l_i - l_{i-1})}{t_i - t_{i-1}}}\right). \qquad (12)$$

The results obtained show that, when knowing the parameters k and t_0 of transducer wedges and using the developed algorithms, one can determine the thickness of a separate layer as well as the velocity of propagation of acoustical signals in it.

Modeling of signal propagation

With the purpose to reveal possibilities of the obtained algorithms in practice the modeling of spatial and time distributions of ultrasound signals, propagating in layer structure, was performed. For derivation of mathematical equations Fig. 1 was used. How one can see from Fig.1, an acoustical signal, when propagating through the n-th layer, is delayed in time by the value

$$t_{nm} = \frac{h_n c_0}{c_{nm}\sqrt{c_0^2 - c_{nm}^2 \sin^2\alpha_0}}. \qquad (13)$$

Here n=1, 2, 3,… is the number of the layer; m denotes the type of wave (l-longitudinal, s-shear). During this time the ultrasound signal is propagating in the layer and passes along the surface of the layer the distance

$$l_{nm} = \frac{h_n c_{nm}\sin\alpha_0}{\sqrt{c_0^2 - c_{nm}^2\sin^2\alpha_0}}. \qquad (14)$$

By the use of algorithms (Eq.13 and 14) modeling of signal propagation in the two layer duralumin-plexiglass structure was performed. The thickness of each separate layer was 5mm. The excitation and reception of ultrasound signals was performed from duralumin side of the layered structure. With the purpose to minimize the number of ultrasound waves, appearing due to mode conversion of waves, the angle α_0 of incidence of the ultrasound longitudinal wave excited by the angular transducer was chosen between the first and second critical angles in duralumin. In our case this angle was changed between 30° and 50°. For that reason only the shear waves may be excited in the first (duralumin) layer. The material of the wedge of the angular transducer, from which the ultrasound wave was radiated, was plexiglass. The velocity of longitudinal waves in it is c_l =2650 m/s [8]. The first layer was the duralumin with the velocity of shear waves c_{ds}=3100 m/s. The second boundary of the duralumin layer

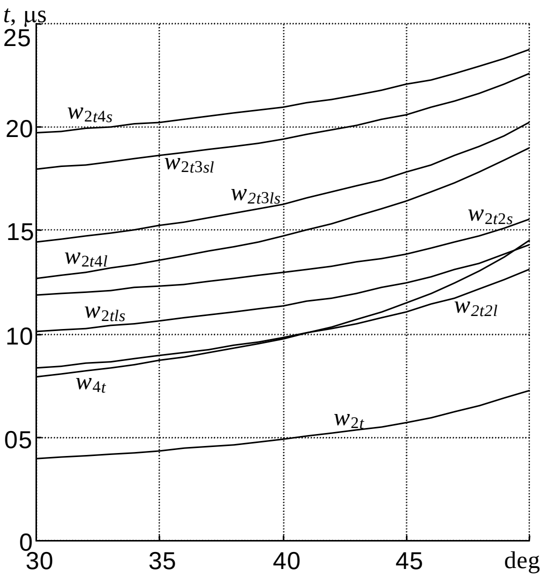

Fig.2. **Variation of propagation time of ultrasound signals in two layer duralumin-plexiglass structure when the angle of incidence is changed**

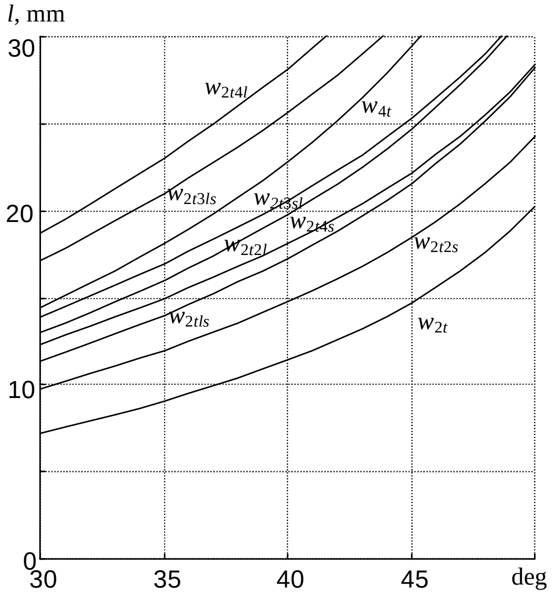

Fig.3. **Variation of distance between the points of transmission and reception of ultrasound waves on the surface of layered structure when the angle of incidence is changed**

is the interface with the plexiglass, with the velocity of longitudinal waves c_{pl}=2650 m/s and the velocity of shear waves c_{ps}=1335 m/s [8].

The results of modeling, which show spatial and temporal distribution of ultrasound signals propagating in the two-layer structure, when the angle of incidence α_0 is changed between 30° and 50° are shown in Fig.2 and Fig 3. With the purpose to simplify the designation of ultrasound signals, propagating in the layered structure, the shear wave in duralumin was labeled by the index *t*. The shear and longitudinal waves in the plexiglass layer were labeled by indexes *s* and *l* correspondingly. The number before the index shows the number of transitions of corresponding wave through the layer. The first two symbols in index concern the first layer (duralumin) and two subsequent the second – plexiglass layer.

How it was mention above only the shear wave is excited in the duralumin layer. Part of its energy is reflected from the interface duralumin-plexiglass and the shear wave w_{2t} returns to the receiving transducer (the first pitch-catch in Fig.4). The shear waves in Fig.4 are shown by solid lines and the longitudinal waves - by the dotted lines. Another part of energy of this wave on the boundary duralumin-plexiglass is transformed to the shear and longitudinal waves, transmitted to plexiglass. During the reflection from the interface plexiglass-air the part of energy of the shear wave is transformed to a longitudinal wave. By analogy the part of energy of the longitudinal

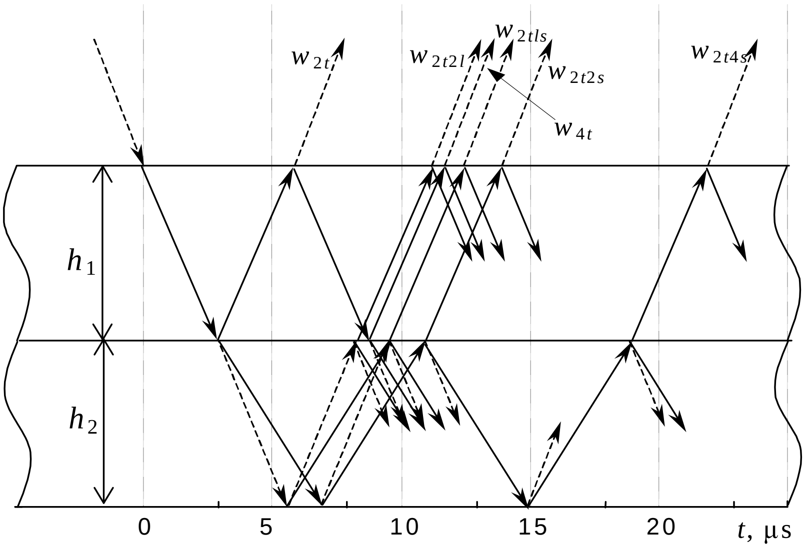

Fig.4. **Spatial distribution of ultrasound waves in two layer duralumin-plexiglass structure**

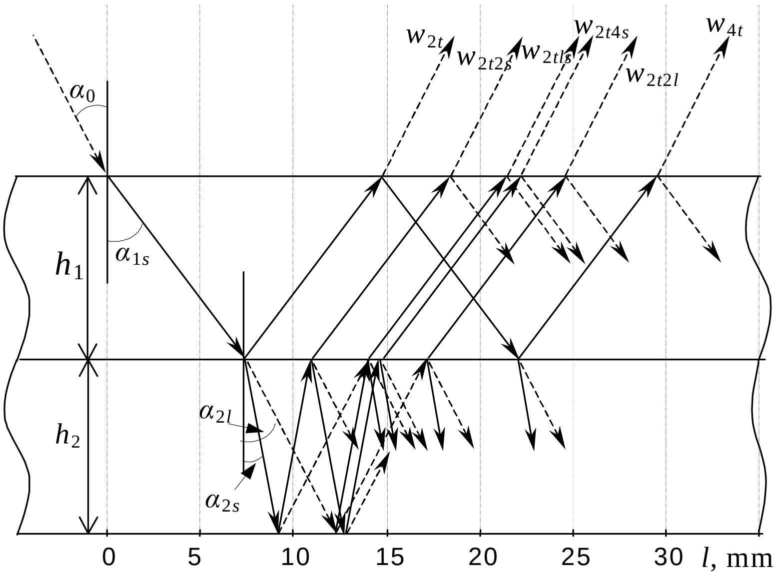

Fig.5. **Temporal distribution of ultrasound waves in two layer duralumin-plexiglass structure**

wave is transformed to the shear wave. After the refraction on the interface plexiglass-duralumin these waves are received at a different distances from the point of transmission (the waves w_{2t2s}, w_{2tls} and $w_{2ts}l$ in Fig.4). The part of energy of the longitudinal wave, reflected from the plexiglass-air interface, on the boundary plexiglass-duralumin is converted to the shear wave and is received as w_{2t2s} wave. But the shear wave in the plexiglass layer, between the duralumin and gas media, may be reflected two or more times and is received as w_{2t4s} wave. In the similar way the shear wave in duralumin, between the boundaries with plexiglass and angular transducer, may be reflected 3 or more times and received at a sufficiently big distances (the wave w_{4t} after the second pitch-catch in Fig.4). In the time scale (Fig.5) like as in the distance scale (Fig.4) the first received wave is the shear wave w_{2t} reflected from the duralumin-plexiglass interface. But the displacement in the time scale of other reflected waves is different from their displacement in the distance scale. For that reason in practice it is difficult to determine the type of wave received at a given distance or at a given instant. Therefore, the modeling of signal propagation in multi-layer structure is necessary before the measurements in real conditions.

Experimental results and discussion

An experimental investigation of the measuring method was performed using angular transducers with an angle of incidence of signal to the layer structure $\alpha_0=44.7^0$. The wedges of ultrasound transducers were made of plexiglass. The velocity of longitudinal waves in the wedges of transducers was $c_{pl}=2650$ m/s [8]. For calibration of the measuring channel the wedges of transducers were pressed face to face to each other and maximal amplitude of the signal was received. During this experiment the delay time of the ultrasonic signal in the wedges of the transducers $t_0=6.90\mu$s and the distance $l_0=10$mm between the acoustical axes of transducers were determined.

The frequency of the broadband ultrasonic transducers was 5.0 MHz. The thickness of the first duralumin layer, to which the transducers were pressed, was 5.14 mm. The second layer was plexiglass glued to the first layer by epoxy resin. The thickness of the plexiglass layer was 4.90 mm and thickness of glue – 20×10^{-6} mm.

The results of calculations and experimental investigations are presented in Table 1. Six impulses of shear and longitudinal waves were received when the distance between the transducers was changed. By the use of the results of measurement the delay time and the ultrasound velocity in the layers were calculated. Every measurement of the delay time and the distance between ultrasonic transducers was performed in a skip position according to the impulse amplitude. The parameter k of the transducer wedges, for the angle α_0 =44.7° and the ultrasound velocity in them c_p=2650 m/s, was $0.2654*10^{-3}$.

Table 1. **The delay time and the distance between acoustical axes of transducers**

Reflected wave	Theoretical		Experimental	
	t, µs	l, mm	t, µs	l, mm
w_{2t}	5.84	14.9	5.97	15.0
w_{2tsl}	13.85	18.5	13.80	18.6
w_{2t4s}	12.46	21.3	12.62	21.8
w_{2t2l}	21.86	22.2	22.71	22.7
w_{2t2s}	11.06	24.6	11.12	24.8
w_{4t}	11.67	29.8	11.80	30.4

For calculations of the thickness of layers and the ultrasound velocity in it the Eqs.11 and 12 were used. The results of calculations of thickness of layers and the velocities propagation of shear and longitudinal waves are presented in the Table 2.

Table 2. **The ultrasound velocity and the thickness of layers**

	Shear wave		Longitudinal wave	
	c, m/s	*h*, mm	*c*, m/s	*h*, mm
First layer	3137	5.18	-	-
Second layer	1303	4.95	2634	4.95

Conclusions

By the use of angular transducers with known parameters of wedges the new measurement method of the thickness of layers and the velocity propagation of ultrasound signals in it is presented. The method is based on the measurement of the distance between the acoustical axes of transducers (on the surface of a layer) and the delay time of signals in skip.

The modeling of propagation of ultrasound signals in a two-layer duralumin-plexiglass structure is performed. The peculiarities of temporal and spatial distributions of ultrasound signals and dependencies of these distributions on the angle of excitation of waves are analyzed. The results of modeling show that the sequence of received ultrasound signals on the distance axis not coincide with the sequence of corresponding signals on the time axis. For that reason the difficulties occur, when measuring the thickness of the layer and the ultrasound velocity in multi-layered structures.

With the purpose to increase the possibilities of measurement and facilitate the selection of measuring signals it is expedient to minimize the transformations of ultrasound waves in the first layer. They depend on the acoustical properties of a layer as well as on the angle of the wedge of electroacoustical transducers, which must be chosen between the first and second critical angles of the layer.

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Sluoksnio storio ir ultragarso greičio matavimas daugiasluoksnėje struktūroje naudojant kampinius ultragarsinius keitiklius

Reziumė

Ištirtos galimybės sluoksnių storį ir ultragarsinių signalų sklidimo greitį sluoksniuotose struktūrose matuoti naudojant žinomų parametrų kampinius elektroakustinius keitiklius. Parodyta, kad, esant nežinomam ultragarsinių signalų sklidimo greičiui struktūros sluoksniuose, šių storį ir garso greitį juose galima išmatuoti naudojant vieną ultragarsinį matavimo kanalą ir žinomų parametrų kampinius elektroakustinius keitiklius. Sukurti algoritmai sluoksnių storiui ir ultragarso greičiui juose nustatyti, kai sluoksniuotoji struktūra zonduojama ultragarsinius signalus spinduliuojant žinomu kampu į jos paviršių. Be to, sumodeliuotas toks ultragarsinio matavimo kanalas su kampiniais ultragarsiniais keitikliais. Modeliuojant akustinių signalų sklidimą ir atspindžius diuraliuminio-organinio stiklo sluoksniuotoje struktūroje, atskleistas laikinis ir erdvinis signalų pasiskirstymas sluoksniuotos struktūros paviršiuje, ištirtas jo kitimas dėl sluoksniuotos struktūros zondavimo kampo pokyčio. Parodyta, kad laikinis ir erdvinis skersinių ir išilginių bangų pasiskirstymas neatitinka vienas kito ir skirtingai kinta keičiantis sluoksniuotos struktūros zondavimo kampui. Pateikiami eksperimentinio tyrimo rezultatai.

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