Investigation of multi-layer structures by the use of angular ultrasonic transducers

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Abstract:
Practical aspects of application of angular ultrasonic transducers for measurement parameters of multi-layered structures are analyzed. The algorithms for determination of thickness of every separate layer in the multi-layered structure, by the use of angular ultrasonic transducers as well as by the use of longitudinal or shear waves, are proposed. It is shown that the ratio of thickness of the first layer to the transversal dimensions of angular ultrasonic transducers is very important when the angle of incidence is selected and the parameters of multi-layered structures are determined. The algorithms for determination of minimal thickness of the first layer, which may be determined by the use of angular ultrasonic transducers with a given transversal dimensions, are developed. The modeling of dependence of the ratio of minimal thickness of the first layer to the transversal dimensions of angular transducers in the plane of incidence was performed, when the angle of incidence and propagation velocity of ultrasound signals in the first layer of structure are changed. The results of modeling are presented and analyzed.
Keywords: ultrasound velocity, angular ultrasonic transducer, layered structure, longitudinal wave, shear wave, thickness of layer.

Introduction

Recently ultrasonic methods are widely used for investigation of multi-layer structures [1-4]. They are especially useful when only one-side access to a particular multi-layer structure is possible [5, 6]. In this case difficulties occur because the acoustical properties of materials of different layers can not be known exactly in advance. For that reason the measurement of thickness and other parameters of separate layers is more complicated. The problems occur because the propagation velocities of acoustic waves of different types in the separate layers are unknown. In such a case the determination of thickness of the separate layer and propagation velocity of longitudinal or shear waves in it is possible only by the use of two separate measuring channels [5, 6]. At least in one channel the layer must be irradiated at an angle to its surface and the angular transducers must be used [7]. When the plane acoustic wave is radiated at an angle α to the layered structure, this wave is transformed to the reflected and refracted longitudinal and shear waves at every boundary of structure. For that reason many pulses of shear and longitudinal waves may be received, when the distance between the angular transducers is changed [7]. The displacement of reflected waves in the distance scale is different from their displacement in the time scale [7]. Therefore in practice it is difficult to determine the type of the wave received at a given distance and at a given instant. With the purpose to minimize the number of ultrasonic waves, appearing due to mode conversion, the angle of incidence α of the ultrasound longitudinal wave, excited by the angular transducer, is chosen between the first and second critical angles to the first layer. Therefore, only the shear waves may be excited in the first layer. However, for realization of this case in practice, the velocity propagation of shear and longitudinal ultrasound waves in the first layer of structure must be approximately known in advance. Therefore, when using the angular transducers, it is very important to know the basic parameters of angular transducers more precisely. The most important of them is the angle of the wedge of a transducer and the propagation velocity of longitudinal ultrasonic waves in the wedges. These parameters of transducers predetermine the types of ultrasound waves, which may be excited in the first layer of a multi-layer structure. Except that, these parameters predetermine the spatial and temporal resolution of ultrasound waves received on the surface of the layered structure. In that case, when the parameters of wedges of angular transducers are known, the first and the second critical angles may be calculated and the radiation angles of transducers may be selected. However, the separation of different modes of waves depends not only on the angles of wedges of angular transducers. The transversal dimensions of angular transducers in the plane of incidence are very important too. Besides that, the transversal dimensions and the angles of radiation of transducers determine the minimal thickness of the first layer, which may be determined by the separate pair of angular transducers. But in analysis presented in [5-7] the relationship between the angular and transversal dimensions of transducers and propagation velocity of waves in the layered structure and in the wedges of transducers are not revealed. Therefore, the objective of this paper is the evaluation of the relationship between the parameters of angular transducers and the measured parameters of the layered structure.

Theoretical investigation

Investigation of a layered structure using the angle beam transducers gives attractive information about the layers if longitudinal and shear ultrasonic waves are used. The excitation of these waves can be carried out by the use of transducers of longitudinal waves or shear waves. The background of this investigation is a knowledge of parameters of angular transducers. Main of them are the delay time in the wedge, the angle of the wedge and the acoustical path of ultrasonic waves in the wedge. The values of these parameters can be determined from the analysis of transducers design or by the experimental investigation. The delay time t_0 in the wedge of transducer is given by

$$t_0 = \frac{d_0 \tan \alpha_0}{c_0}. \quad (1)$$

Here d_0 is the distance between the center of piezoelement and the lower boundary of the wedge; α_0 is the angle of the wedge; c_0 is the velocity of a longitudinal wave in the wedge.

The scheme of measurement of the delay time in the layered structure is shown in Fig.1.

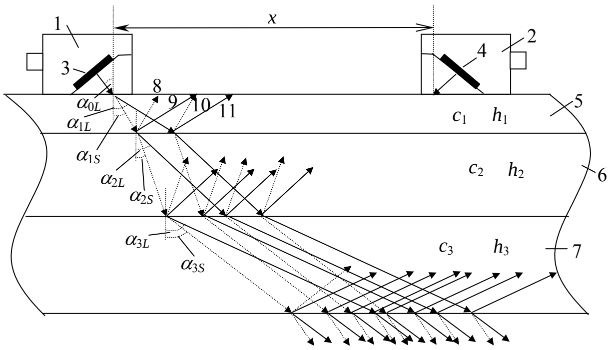

Fig.1. **The measurement scheme of the delay time in the layered structure**

It consists of two transducers placed on the surface of the layered structure. The piezoelement 3 of the transducer 1 radiates the longitudinal wave into the wedge. Two refracted ultrasound waves are excited in the first layer: the longitudinal wave and the shear wave. After the reflection from the boundary with the second layer and after the mode conversion there will be four waves: two longitudinal (11), two shear (8) and (after the mode conversion) longitudinal – shear (10) and shear – longitudinal (9) waves. The delay time in the wedges of both transducers ($2t_0$) and the time of a full skip (t_{1w}) for the shear (t_{1S}) and longitudinal (t_{1L}) waves in the first layer will be

$$t_{1w} = 2t_0 + \frac{2h_1}{c_{1w} \cos \alpha_{1w}}, \quad (2)$$

where $t_{1w}=t_{1L}$ and $t_{1w}=t_{1S}$ are the sums of the delay times of waves propagating in the wedges of the transducers and in the first layer for longitudinal or shear waves, correspondingly; $c_{1w}=c_{1L}$ and $c_{1w}=c_{1S}$ are the velocities of longitudinal or shear waves in the first layer; $\alpha_{1w}=\alpha_{1L}$ and $\alpha_{1w}=\alpha_{1S}$ are the refraction angles of longitudinal or shear waves in the mentioned layer, respectively. The angle α_{1L} as well as the angle α_{1S} are defined by the Snell's law

$$\frac{\sin \alpha_0}{c_0} = \frac{\sin \alpha_{1w}}{c_{1w}} \quad (3)$$

Then the thickness of the first layer can be calculated for longitudinal or shear waves

$$h_1 = \frac{(t_{1w} - 2t_0) c_{1w} \cos \alpha_{1w}}{2}. \quad (4)$$

Ultrasonic waves after the mode conversion (longitudinal – shear and shear – longitudinal) were not considered here. The delay time of ultrasonic waves in the wedges of the transducers and in the first and second layers of the structure is given by

$$t_{2w} = 2t_0 + \frac{2h_1}{c_{1w} \cos \alpha_{1w}} + \frac{2h_2}{c_{2w} \cos \alpha_{2w}}, \quad (5)$$

where $t_{2w}=t_{2L}$ and $t_{2w}=t_{2S}$ are the sums of the delay times of longitudinal or shear waves in the wedges of the transducers and in the first and second layers, correspondingly; $c_{2w}=c_{2L}$ and $c_{2w}=c_{2S}$ are the velocities of longitudinal or shear waves in the second layer; α_{2L}, α_{2S} are the refraction angles of longitudinal and shear waves in the second layer, respectively. The thickness of the second layer for both types of waves is

$$h_2 = \frac{(t_{2w} - 2t_0 - \Delta t_{1w}) c_{2w} \cos \alpha_{2w}}{2}. \quad (6)$$

Here $\Delta t_{1w}=\Delta t_{1L}$ and $\Delta t_{1w}=\Delta t_{1S}$ are the delay times of longitudinal or shear ultrasound waves in the first layer, respectively. In the same manner the thickness of the third layer may be determined. Then the thickness of the k-th layer may be determined as

$$h_k = \frac{\left(t_{kw} - 2t_0 - \sum_{i=1}^{k-1} \Delta t_{iw} \right) c_{kw} \cos \alpha_{kw}}{2}. \quad (7)$$

The subscripts kw and iw must be changed to kL and iL for longitudinal waves and to ks and is for shear waves, respectively. The accuracy of this method highly depends on the accuracy of measurement of parameters of the first layer. Therefore, a more deep investigation of interaction of ultrasonic waves with a layered structure and especially with the first layer is necessary.

For that reason let us suppose that we have two identical angular ultrasound transducers, the dimensions of which in the plane of incidence is d, the angle of incidence is α, and the distance between the external edge of the transducer and the boundary of external enclosure of the transducer is l (Fig.2).

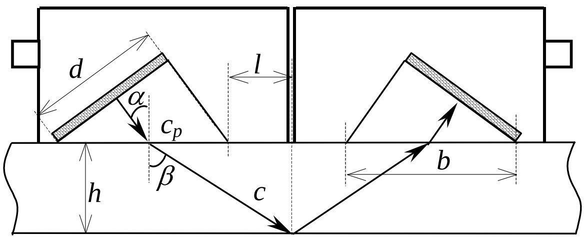

Fig.2. **Displacement of angular transducers for realization of the pitch-catch of ultrasound signals**

Let us determine the minimal thickness h of the layer, which may be measured by the use of the first skip of ultrasound wave, excited by the angular transducer. How one can see from Fig. 2, the minimal thickness of the first layer may be fixed, when the housings of the ultrasound transducers are pressed close together.

Then one can obtain

$$h = \frac{b + 2l}{2} \cot(\beta). \quad (8)$$

Here b is the length of the surface of the wedge, which is contacting the layered structure in the plane of incidence; β is the angle of the propagation direction of ultrasound wave in the first layer of the structure. After the trigonometric reconstruction may be written

$$h = \frac{(b+2l)}{2}\frac{\sqrt{1-\sin^2(\beta)}}{\sin(\beta)}. \tag{9}$$

If c is the velocity propagation of ultrasonic waves in the layer under investigation and c_p is the velocity propagation of ultrasound waves in the wedge of the angular transducer, then, after the use of Snell's law and geometrical relation $s = d/\cos\alpha$, from Eq. 2, one can obtain

$$h = \frac{[d+2l\cos(\alpha)]\sqrt{c_p^2 - c^2\sin^2(\alpha)}}{c\sin(2\alpha)}. \tag{10}$$

In order to reduce the number of variables the relative quantities $n=c/c_p$, $m=l/d$ were introduced. Then the relative thickness h/d may be obtained:

$$\frac{h}{d} = \frac{[1+2m\cos(\alpha)]\sqrt{1-n^2\sin^2(\alpha)}}{n\sin(2\alpha)}. \tag{11}$$

This expression describes the minimal thickness of the layer, which may be measured by the use of ultrasonic transducers with the specific parameters, when the first pitch-catch signal is fixed. When analyzing this expression one can determine the optimal parameters of angular ultrasonic transducers, which may be used for investigation of layered structures of specific materials.

The analysis of the obtained expression showed that in an ideal case the distance between the external edge of the transducer and the boundary of its housing should be l=0. Then the first pitch-catch signal may be fixed on the surface of the first layer with the thickness not less than the normalized value

$$\frac{h}{d} = \frac{\sqrt{1-n^2\sin^2(\alpha)}}{n\sin(2\alpha)}. \tag{12}$$

Mathematical modeling

With the purpose to reveal the possibilities of the proposed algorithms, the mathematical modeling was carried out. The modeling of change of the ratio of the minimal thickness of the first layer to the transversal dimensions of angular transducers in the plane of incidence was performed. During modeling the angle of incidence and the propagation velocity of waves in the layered structure were changed. The results of modeling are presented in Fig. 3.

How one can see from Fig.3, when the velocity of ultrasonic waves in the layered structure is bigger than the propagation velocity in the wedges of angular transducers ($n=c/c_p<1$), the minimal thickness of the layer in comparison with the dimensions of transducers, is rapidly decreasing, when the angle of incidence is increased. In that case the angle of incidence α of longitudinal waves may be increased only till the first critical angle. By analogy, the angle of incidence of the shear waves may increase only till the second critical angle too.

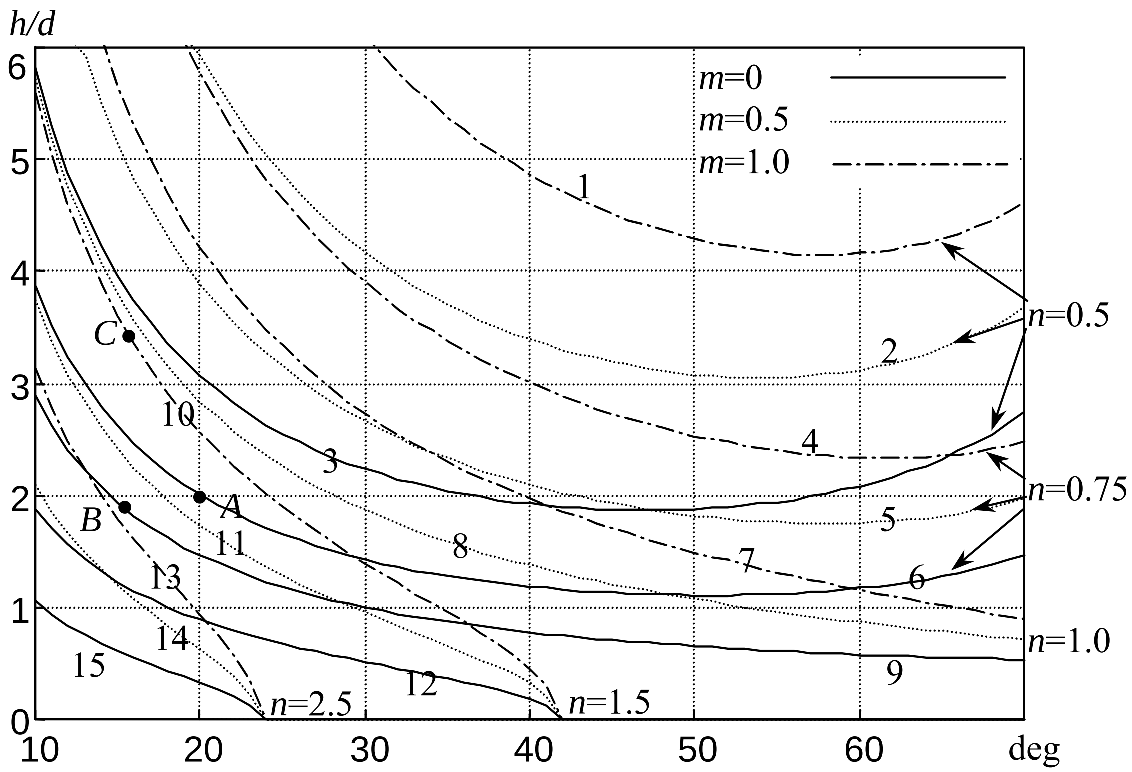

Fig.3. **Angular dependencies of the relative minimal thickness *h/d* of the first layer at different relations of propagation velocities c/c_p in the layered structure and in the wedges of transducers**

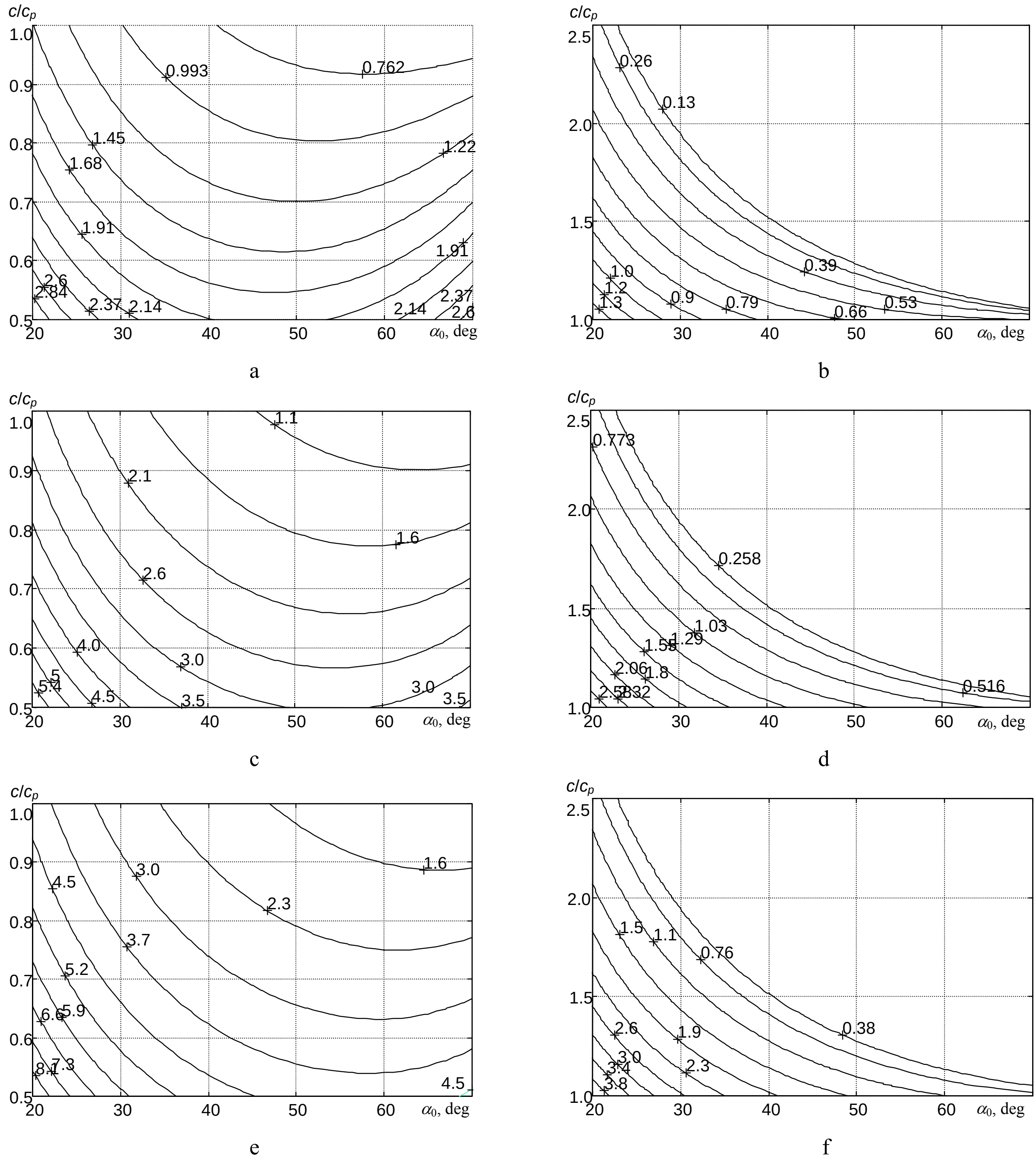

Fig.4. **The dependence of the relative thickness *h/d* of the first layer on the angle of incidence and on the relative c/c_p velocity propagation of signals at different relations *m*: a, b – *m*=0; c, d – *m*=0.5; e, f - *m*=1.0; a, c, e - the ratio $c/c_p< 1$; b, d, f – the ratio $c/c_p> 1$**

When the velocity of ultrasonic waves in the first layer of the structure is less than the velocity in the wedges of angular transducers ($n=c/c_p<1$) and the angle of incidence $\alpha<20°$, the measurements of thickness are possible only when the thickness of the layer is considerably bigger than the diameter of the piezoelement of the transducer (curves 1-6, Fig.3). This condition is often satisfied, when the shear waves are applied, but the thickness of the layer must be at least twice bigger than the diameter of the transducer (point *A*, Fig.3). The minimal thickness of the first layer, which may be measured by the angular transducers with the given transversal dimensions, is decreasing with the angle of incidence. But this decrease continues till the optimal value of the angle of incidence is achieved. In this case the minimal thickness of the first layer may be fixed. After that the minimal thickness, which may be measured by the use of angular transducers with the given parameters, begins to increase with the angle of incidence.

On the other hand, the possibilities of measurement of a thickness of a separate layer depend on the distances between the wedges of transducers and their housings (distance *l*, Fig.2). In the best case, when $m=l/d=0$ and $n=c/c_0=1$ (curve 9, Fig.3), the thickness of the first layer can be smaller than the diameter of the transducer if the incidence angle α_0>30°. Therefore the distance *l* in the ultrasonic transducer should be minimized. When the incidence angle is between the first and second critical angles (for example α_0=20°), longitudinal and shear waves may be excited in the layer and may be used for measurement of its thickness. However, the minimal thickness of the first layer may be fixed when longitudinal waves are used and the incidence angle is α_0=15° (point *B* on the curve 9, Fig.3). In this case the same transducer, located on the surface of the first layer, will receive longitudinal and shear waves, but at different time instants. Slow shear waves in the first layer cause difficulties to receive waves of other types, reflected from different layers of the layered structure. Within the range of the incidence angles from 40° to 70° shear waves can be used with the best advantage. In this case, when *n*=1.0, the thickness of the layer may be less than the diameter of the piezoelement (curves 7-9). When the velocity of ultrasound waves in the layer is more than the velocity in the wedge, the angle of incidence is restricted (curves 10-15). For example, when $n=c/c_0$=1.5, the angle of incidence can not be bigger than 42° (the second critical angle for longitudinal waves). Inside the range of the angles of incidence from 10° to 42° the distance *l* influences significantly. The possibilities of measurement of the layer thickness depend considerably on the incidence angle. Near the critical angle it is possible to measure the thickness of the layer which compile 0.1…0.5 from the diameter of transducer. This condition can be easily fulfilled by exiting the shear waves and using the angles of the wedges between α=30° and α=40°.

The dependencies of the minimal relative thickness *h/d* of the layer on the angle of incidence and on the relative velocity c/c_p of sound velocity in the layer and in the wedges of transducers at different relations *m=l/d* are presented in Fig.4. How one can see from Fig.4, when the ratio c/c_p is constant, the relative minimal thickness of the layer, in comparison with the transversal dimensions of transducers, is rapidly decreasing with the angle of incidence. Especially it is evident when the propagation velocity of signals in the layered structure is bigger than the velocity of waves in the wedges of angular transducers (Fig.4 b, d, f). When the velocity of ultrasound waves in the first layer of structure is less than the velocity in the wedges of angular transducers, the minimal thickness of the first layer is decreasing, when the angle of incidence is increased. However, this decrease continues only till the optimal value of the angle of incidence is achieved. In this case the minimal thickness of the first layer may be fixed at given ratios c/c_p and *l/d* (Fig.4 a, c, e).

Conclusions

The analysis of practical aspects of application of angular transducers shows that when measuring parameters of layered structures the ratio of thickness of the first layer to the transversal dimensions of angular transducers is very important, when the angle of incidence is selected.

The algorithms for determination of a minimal thickness of the first layer, which may be determined by the use of angular transducers, with given transversal dimensions, are proposed and modeling is performed.

When the velocity of ultrasonic waves in the layer structure is bigger than the velocity propagation in the wedge of an angular transducer, the minimal thickness of the first layer, in comparison with the transversal dimensions of the transducers, is rapidly decreasing when the angle of incidence is increased.

When the velocity of ultrasound waves in the first layer of structure is less than the velocity in the wedges of transducers, the optimal radiation angle of transducers may be selected and the layers of minimal thickness may be investigated.

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Daugiasluoksnių struktūrų tyrimas naudojant ultragarsinius kampinius keitiklius

Reziumė

Analizuojami ultragarsinių kampinių keitiklių naudojimo daugiasluoksnių struktūrų parametrams matuoti praktiniai aspektai. Pasiūlyti algoritmai kiekvieno sluoksnio storiui daugiasluoksnėje struktūroje nustatyti naudojant ultragarsinius kampinius keitiklius ir išilgines arba skersines ultragarso bangas. Parodoma, kad, matuojant daugiasluoksnių struktūrų parametrus ir pasirenkant bangų kritimo kampą, labai svarbu yra pirmojo sluoksnio storio ir kampinio keitiklio skersinių matmenų santykis. Pateikiami pirmojo sluoksnio mažiausio storio, kuris gali būti išmatuotas naudojant tam tikrų skersinių matmenų kampinius keitiklius, nustatymo algoritmai. Atliktas pirmojo sluoksnio mažiausio storio santykio su kampinio keitiklio skersiniais matmenimis kritimo plokštumoje modeliavimas, kai keičiamas ultragarsinių signalų kritimo kampas ir signalų sklidimo greitis pirmajame struktūros sluoksnyje. Pateikiami ir analizuojami modeliavimo rezultatai.

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