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Comparison of several techniques of ultrasonic Lamb waves velocities measurements

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Abstract

In ultrasonic NDT the important question is how precisely the velocity of ultrasonic waves propagating in the object under investigation is known. Accurate measurements of the ultrasound velocity are necessary for estimation of the elastic properties of the object material. These properties are used in numerical modelling of propagation of ultrasonic waves and determination of the object response. In the presented study a few different ultrasonic techniques for measurement of the phase velocity of Lamb waves in metal plates are presented. The immersion measurement technique was used for estimation of the S_0 mode phase velocity in the case of contact type excitation. The air-coupled measurement technique was used for estimation of the A_0 mode phase velocity which posses high leakage losses in the case of the plate loaded by liquid. The air-coupled investigations have been carried out using both through-transmission and one-side access configurations. The measured values of the phase velocities were compared with theoretically predicted and the good correspondence has been obtained.

Keywords: elastic parameters, isotropic plate, Lamb waves, immersed, air-coupled

1. Introduction

In ultrasonic non-destructive testing (NDT) one of the most important parameters is ultrasound velocity in a material, which must be known in advance or measured precisely. In the case of ultrasonic guided waves applications in plates two fundamental symmetric S_0 and asymmetric A_0 modes are used. According to the values of the estimated phase velocities of the fundamental modes A_0 and S_0 it is possible to estimate the distance to the non-homogeneities in a material structure, to detect the internal defects and to estimate elastic properties of the material. Further, such material properties are being used in numerical modelling by finite element and finite difference techniques of the ultrasonic response of the object under a test and propagation of ultrasonic waves [1-3].

In order to estimated the phase velocities of the fundamental modes of the guided waves it is necessary to perform appropriate ultrasonic measurements based on generation and reception of the leaky ultrasonic waves. The leaky waves are radiated into surrounding medium by the direct wave which propagates in a plate-like structure. There are a few conventional techniques for estimation of phase velocities from the received leaky waves. The first one is based on the lateral shift of the receiving transducer away from the transmitter. This technique is attractive in the case of the known in advance angle of generation and reception or in the case of the immersion investigation when the generation and reception of the waves are performed using normally to the surface of the plate oriented transducers with the diameter close to the wavelength. However, the immersion investigations can be used only for measurement of the phase velocities of the S_0 mode due to low leakage losses of it (Fig.1) [4,5]. The asymmetric mode A_0 possesses high leakage losses in the case of plate loaded by liquid (Fig.1) and the signals 'disappear' quit fast with the increase of the distance between the transmitter and the receiver. Therefore, for measurement of the phase velocities of the A_0 mode the air-coupled ultrasonic technique could be used. The air-coupled set-up can be implemented in pitch-catch or through-transmission configurations. During the measurements an angular rotation of the transducers or the object situated between the transducers is performed in order to determine the dependency of the leaky wave amplitude versus angle. The angular position corresponding to the local maximum of this dependency indicates the optimal excitation/reception angle of the asymmetric A_0 mode. In the case when temperature and humidity of the surrounding medium are known, the orientation angle of the ultrasonic transducers can be recalculated to the appropriate phase velocity value using the Snell's law [4].

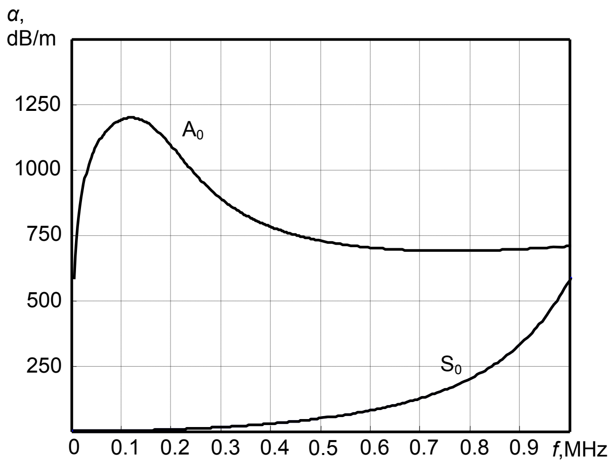

Fig.1. **The attenuation curves of the fundamental Lamb wave modes in the 2 mm aluminium plate**

The objective of the presented study was measurement of the phase velocity of the guided waves in a aluminium plate using immersion and air – coupled ultrasonic techniques and comparison of the measurement results with theoretical ones.

2. Immersion measurement technique

As the object for experimental investigations the 2mm x 620 mm x 1100 mm aluminium plate was selected. Due to low leakage losses of the symmetric mode with dominant longitudinal displacements the immersion testing can be applied. The measurements were performed using the ultrasonic measurement system 'Ultralab', which has been developed at Ultrasound Institute of Kaunas University of Technology.

The contact type transmitter with the frequency f=280 kHz of has been used. At this frequency Lamb waves in the plate under investigation posses non-significant dispersion. The transmitter was driven by one period rectangular shape pulse. The contact type transmitting transducer was permanently fixed by an epoxy glue to the opposite side of the aluminium plate (Fig.2).

The receiving transducer was placed at the distance equal to 10 mm over the plate surface and scanned along two perpendicular directions with the scanning step of 0.5 mm in order to pick-up the leaky waves.

In the case of the contact type excitation using a thickness mode piezoceramic transducer the both symmetric and asymmetric modes are being generated. However, due to large leakage losses of the A_0 mode, only the symmetric S_0 mode is being observed. In Fig.3 the B-scan image of the leaky wave obtained along x axis is presented. The leaky wave is radiated due to propagation of the direct S_0 mode. The wave generated in water is also observed (Fig.3).

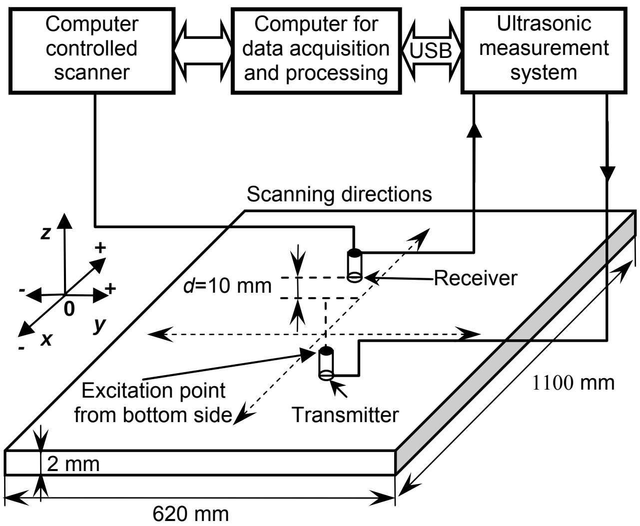

Fig.2. **The experimental set-up for measurement the phase velocity of S_0 mode in 2 mm aluminium plate**

For estimation of the phase and group velocities of guided waves from B-scan data, the optimisation technique described in [1] was used.

This technique is based on calculation of the target function according to [1]:

$$U_{ph}(\Delta t_w) = \sum_{k=1}^{N_w} u_k(t - \Delta t_w \cdot (k-1)) , \qquad (1)$$

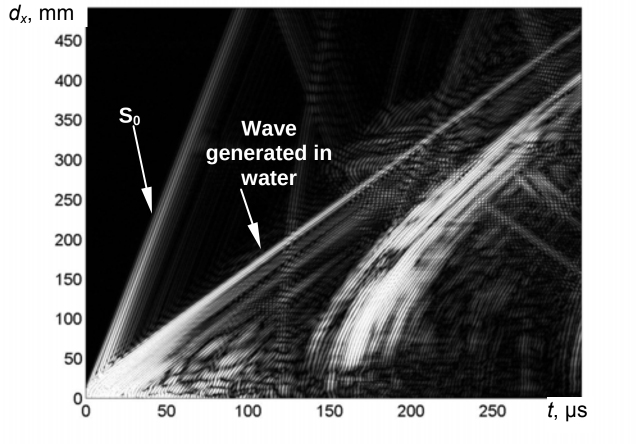

Fig.3. **The B-scan image of the leaky waves obtained along x axis**

were $u_k(t)$ is the signal measured at k-th position along x axis, N_w is the number of measurement positions, Δt_w is the value of the signal shift in the time domain, varied in the range $[0 \div 4]$ μs. In general this technique integrates the signals into one the temporal array using some additional shift in the time domain for each next signal. This function has the maximum values at time instances at which the time shift Δt_w corresponds to the time interval between two neighbouring points. The target function calculated using radio frequency signal (not envelope) will gain the maximal values corresponding to the phase velocity of the propagating wave mode.So, the phase velocity of S_0 mode of a guided wave can be calculated by [1]:

$$c_{S_0,ph} = \arg_{c_{ph}}\{\max[U_{ph}(c_{ph})]\} \qquad (2)$$

The obtained values of the S_0 wave mode along two perpendicular scanning axes (x and y) of the aluminium plate are presented in Table 1. The signs denote the forward or backward scanning directions with respect to the position of the transmitter (Fig.2).

Table 1. **Phase velocities of the S_0 wave mode at 277.8 kHz in two perpendicular directions**

Velocity in scanning direction	c, m/s
c_{x+}	5351
c_{x-}	5297
c_{y+}	5407
c_{y-}	5454

The mean value of the resultant phase velocity obtained from measurement results along two perpendicular directions is c_{S0}=5377 m/s.

3. Air-coupled measurement technique

3.1 The through-transmission set-up

In air – coupled ultrasonic technique the A_0 Lamb wave mode is more easy to generate (comparing to the S_0 mode) since its surface motion is mainly out – of – plane [4,5]. In order to excite Lamb wave in a plate - like structures, the optimal excitation angle must be known. The relationship between the excitation angle and the phase velocity of the Lamb wave can be described by the Snell's law [6-9]:

$$\Theta_m = \arcsin\left(\frac{c_{\mathrm{air}}}{c_m}\right), \quad (3)$$

where Θ_m is the excitation angle of the m–th Lamb wave mode, c_m is the phase velocity of the m–th Lamb wave mode, c_{air} is the velocity of the wave propagating in the surrounding air. And vice versa – if the optimal excitation angle is known, the phase velocity of the Lamb wave can be calculated.

The experimental set-up for determination of the optimal excitation angle of the Lamb wave is presented in Fig.4.

In the experimental investigation a pair of 500 kHz air – coupled planar ultrasonic transducers arranged in the trough transmission mode were used. Excitation and reception of the signals were carried out using the computer controlled air – coupled ultrasonic system 'Ultralab'. The transmitter was driven by 5 periods 750 V burst. Signal at the output of the ultrasonic receiver was amplified by 82dB using low noise amplifiers. In order to increase signal to noise ratio 64 signals were averaged at each scanning step. Experimentally obtained signals were stored in a PC via USB bus for a further signal processing.

The aluminium test plate was placed between the ultrasonic transducer and rotated by the computer controlled angular scanner. The angular scanning was carried out from -25° to 25° with the step 0,1°.

The experimentally obtained B – scan image, which represents dependence of the received ultrasonic wave versus the rotation angle of the test sample, is presented in Fig. 5. The shorter time of flight at the bigger angles can be explained by a longer propagation path of the ultrasonic wave in the aluminium test sample in which the velocity of the ultrasonic wave is bigger than in air.

The dependence of the normalized peak-to-peak amplitude of the experimentally obtained signals versus the rotation angle of the test sample is presented in Fig.6. The diagram shows that only one A_0 mode of the Lamb wave was excited. The angles Θ_1 and Θ_2 correspond to optimal angles of excitation of the A_0 Lamb wave mode. The mean value of the optimal excitation angle is 8.3°. The ultrasound velocity in air was 345.68 m/s at the temperature 23°C and the relative humidity was 35%. Taking the mean value of the optimal angle and using the Snell's law (Eq.3) it was found that the velocity of the A_0 Lamb wave mode is 2394.6 m/s.

In order to obtain more information about propagation of guided waves in the aluminium plate the same rotation experiment as presented above was performed using 280 kHz planar air-coupled transducers.

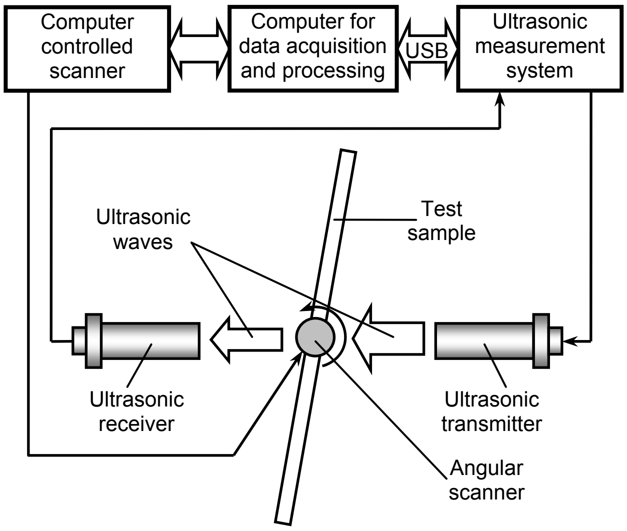

Fig.4. **Experimental set-up of though transmission air – coupled testing**

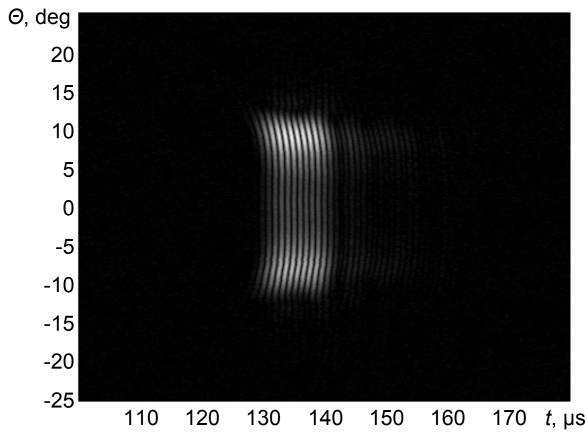

Fig 5. **The B-scan image of the received A_0 mode signals in a plate rotated by angle (-25° to 25°) at the frequency 500 kHz**

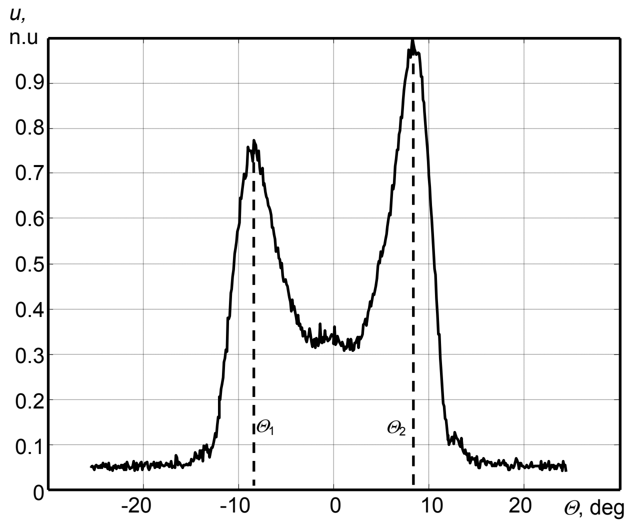

Fig.6. **The normalized maximum amplitude of the A_0 mode signals obtained versus the rotation angle of the text sample at 500 kHz: Θ_1 and Θ_2 are the optimal angles of excitation/reception (±8.3°)**

The experimentally obtained B–scan image at the frequency 280 kHz, which represents dependence of the A_0 mode wave versus the rotation angle of the test sample is presented in Fig. 7.

The dependence of the normalized peak-to-peak amplitude of the experimentally obtained signals versus the rotation angle of the test sample is presented in Fig.8. The diagram shows that only one A_0 mode of the Lamb wave was excited also. The mean value of the optimal excitation angle is 9.8°. Taking the mean value of the optimal angle and using the Snell's law (Eq.3) it was found that the velocity of the A_0 Lamb wave mode in this case is 2027.5 m/s. The ultrasound velocity in air at temperature 22°C and at relative humidity 35% was 345.1 m/s .

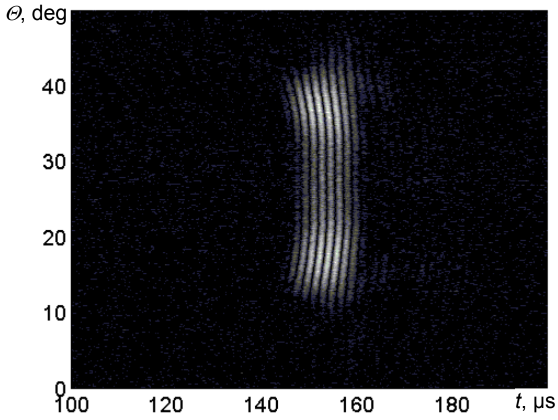

Fig.7. **The B-scan image of the received A_0 mode signals in a plate rotated by angle (-25° to 25°) at frequency 280 kHz**

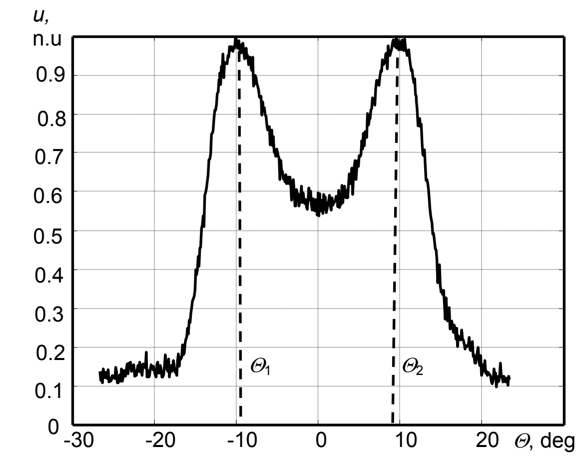

Fig.8. **The normalized maximum amplitude of the A_0 mode signals obtained versus the rotation angle of the test sample at 280 kHz: Θ_1 and Θ_2 are the optimal angles of excitation/reception (±9.8°)**

The detailed uncertainty analysis of this technique is presented in [4]. The analysis has shown that the main source of uncertainty is determination of the optimal excitation angle of the Lamb wave. The phase velocity of the A_0 Lamb wave mode can be measured with the 3.5% uncertainty using the air – coupled ultrasonic technique.

3.2. The through-transmission set-up with lateral shift of the receiving transducer

In the experiment described above it was assumed that there is no essential shift of the ultrasonic beam axis when it passes the aluminium plate. However, the generation of guided waves needs some distance in order to achieve the maximal amplitude. As a consequence, the maximal amplitude may be measured not by the receiver situated directly in front of the transmitter, but slightly shifted in the lateral direction. In order to determine at which positions the best signal to noise ratio can be achieved, the through-transmission experiments with a lateral shift of the receiving transducer away from the excitation zone were carried out.

The experimental investigation has been carried out using the same measurement configuration as described in a chapter above and the transmitting and the receiving ultrasonic transducers with the central frequency 300 kHz were used.

The angular scanning was carried out in the sector ±20° with the rotation step of 0.1°. At each angle the scanning (the lateral shift) of the receiving transducer away from the acoustic axis of the transmitter was performed in two opposite directions up to ±30 mm with the step 1mm.

During measurements the ultrasound velocity in air was 345.1 m/s, the temperature was 22°C and the relative humidity was 35%.

The C-scan image demonstrating the obtained results is presented in Fig. 9.

The dependency of the normalized amplitude of the A_0 mode signal versus the rotation angle is presented in Fig.10.

The optimal excitation/reception angle was determined using the 2nd order polynomial approximation and is 9.95° (Fig. 11). The corresponding phase velocity of the A_0 Lamb wave is 1997,2 m/s.

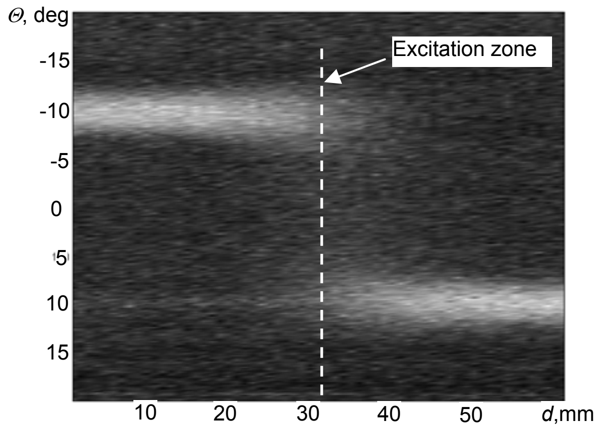

Fig.9. **The C-scan image of the received A_0 mode signals in a plate rotated by angle (-20° to 20°) at *f*=300 kHz, the lateral shift of the receiver has been performed at each rotation step**

The amplitudes of the signals corresponding to the optimal rotation angles, but measured at different lateral shifts demonstrates that bigger leaky wave amplitudes are measured in the case when the receiver is shifted approximately 15mm away from the transmitter axis (Fig.12).

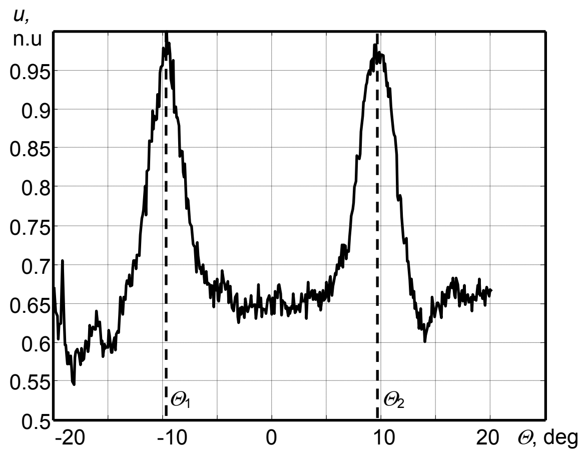

Fig.10. **The normalized mean amplitude of the A_0 mode signals obtained during a lateral shift of the receiving transducer versus the rotation angle of the test sample at 300 kHz: Θ_1 and Θ_2 are the optimal angles of excitation/reception (±9.95°)**

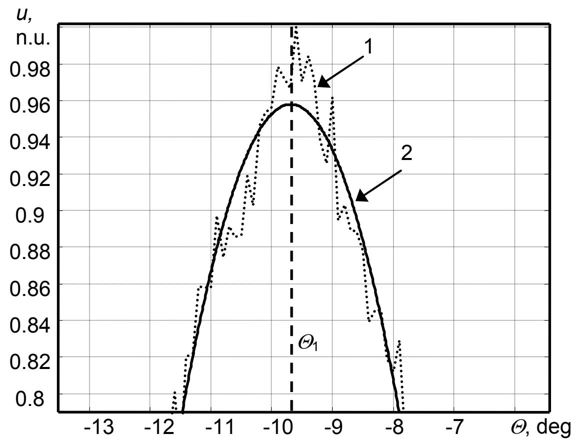

Fig.11. **The normalized mean amplitude of the A_0 mode signals obtained during a lateral shift of the receiving transducer versus the rotation angle of the test sample at 300 kHz: 1 – measured, 2- polynomial fitting of degree 2, Θ_1=9.95°is the optimal angle of excitation/reception**

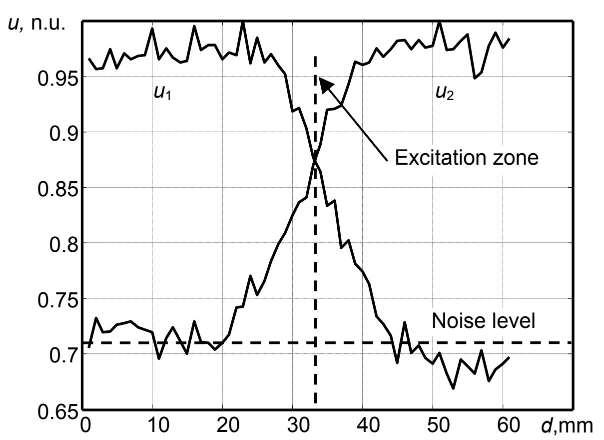

Fig.12. **The normalized mean values of C-scan regions calculated at the angular positions equal to (-5°:-15°) and (5°:15°) versus the distance away from the excitation zone**.

Therefore, at such distance the S/N ratio is higher and the measurement results are more reliable.

The ultrasonic measurement set-up based on a conventional through-transmission principle can be restricted by a complex geometry of the test sample and may not be always applied in situ inspections. In this case, the one-side access measurement principle with ultrasonic transducers mounted into a pitch-catch arrangement can be applied.

3.3. One – side access set-up

The difficulties of the one-side access set-up are related to the fact that in this arrangement not the sample, but only transducers should be rotated with respect to the surface of the sample. Also, they should be rotated simultaneously and in opposite directions. This leads to essentially more complicated adjustments and application of the necessary instrumentation.

In order to solve this task, the mechanical system kinematics sketch of which is presented in Fig.13 was developed.

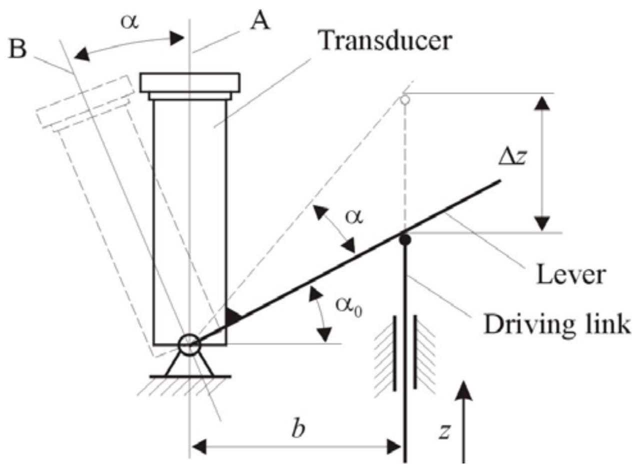

Fig.13. **The kinematic operation principle of angular positioning of the both ultrasonic transducers (transmitter and receiver): A – initial position, B – final position.**

The transfer function of the movement along the vertical axis Δz to the rotation angle α is given by (Fig.13):

$$\Delta z = b\left[\mathrm{tg}(\alpha + \alpha_0) - \mathrm{tg}\,\alpha_0\right], \tag{4}$$

$$\alpha = \mathrm{arctg}\left(\frac{\Delta z}{b} + \mathrm{tg}\,\alpha_0\right) - \alpha_0 . \tag{5}$$

The graphical representation of the transfer characteristics of the angular positioning device is presented in Fig.14.

The drawing of the device for a simultaneous angular positioning of both ultrasonic transducers deflected in opposite directions is presented in Fig.15.

The ultrasonic transducers 2, 3 (Fig.15) were mounted into the holders 4, 5. The distance between the axes of the transducers is 2*b*. It was assumed that the acoustic axes of the ultrasonic transducers at the initial position are perpendicular to the surface of the plate. Vertical movement of the driving link 6 along *z* axis simultaneously moves the levers 7 of both transducer holders. As the result, the holders of the transducers with the mounted transducers move by the angle *α*.

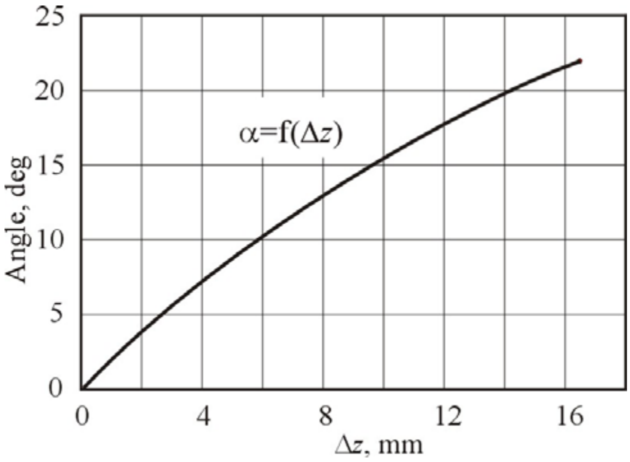

Fig.14. **Transfer function of the angular positioning device in the case of α_0=33°, *b*=21.2mm**

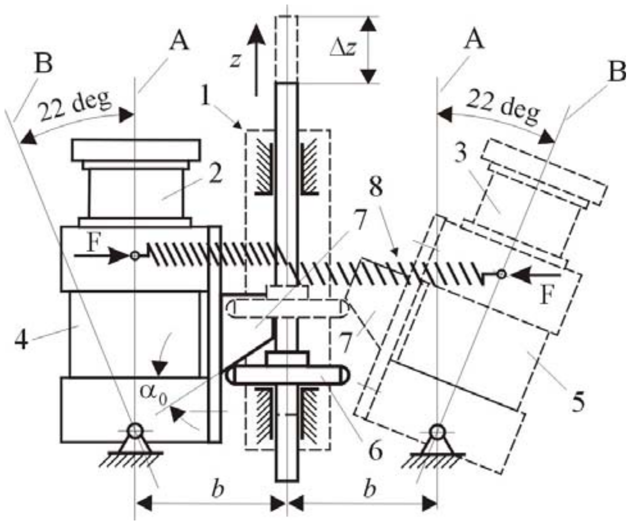

Fig.15. **The drawing of the device for angular positioning of the both ultrasonic transducers (transmitter and receiver): A – initial position, B-final position, 1-housing of the driving link, 2 and 3 – ultrasonic transducers, 4 and 5 – holders of ultrasonic transducers, 6 – driving link, 7 –levers, 8-spring**

The mechanical scanning of the driving link along *z* axis has been performed with the 50 μm step. This corresponds approximately to the angular movement equal to 0.1°.

4. Comparison of the results

In order to compare the experimentally measured results with the theoretical ones, the dispersion curves of phase velocity of the Lamb waves propagating in 2mm aluminium plate have been calculated using the global matrix technique presented in [10]. The experimentally measured values of the phase velocities of the symmetric S_0 and asymmetric A_0 modes versus the calculated theoretical curves are presented in Table 2. The measured values of the phase velocities at different frequencies are presented on the dispersion curves in Fig.16, also.

Table 2. **Phase velocities in 2 mm aluminium plate**

	Measured		Calculated	
f, kHz	$c_{ph,S0}$, m/s	$c_{ph,A0}$, m/s	$c_{ph,S0}$, m/s	$c_{ph,A0}$, m/s
280 kHz	5377	2027,5	5383	1954
300 kHz	-	1997,2	5380	1999
500 kHz	-	2394,6	5315	2323

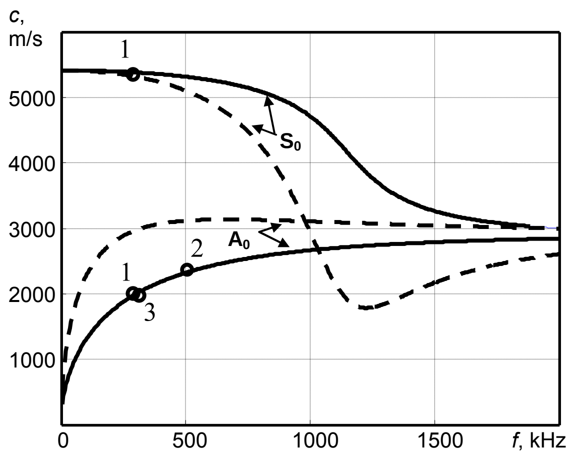

Fig.16. **Calculated dispersion curves of Lamb waves in 2 mm aluminium plate: 1 - measured phase velocity at 280 kHz, 2- measured phase velocity at 500 kHz, 3- measured phase velocity at 300 kHz, dashed curve - group velocity, solid curve – phase velocity**.

Conclusions

In the presented study a few ultrasonic measurement techniques of phase velocity of guided waves in metal plates have been described and compared. Two different techniques have been used: immersion and air-coupled. Due to large leakage losses of the asymmetric A_0 mode in the case of a plate loaded by liquid, the measurements can be performed only using the air-coupled technique.

It was determined that the most reliable results of the A_0 mode phase velocity were obtained using the air-coupled measurement technique with a lateral shift of the receiving transducer due to the better signal to noise ratio comparing to the conventional through-transmission set-up.

Using the immersion experimental set-up and the contact type excitation for generation of the longitudinal displacements the propagation of S_0 mode in plate loaded by water has been investigated.

The measured values of the phase velocities at different frequencies are in a good agreement with the theoretically calculated dispersion curves.

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Nukreiptųjų ultragarso bangų greičio matavimo plokštėse metodų palyginimas

Reziumė

Ultragarsiniams neardomiesiems matavimams svarbu turėti tikslius duomenis apie ultragarso bangų greitį tiriamame objekte. Tikslūs sklindančios bangos greičio matavimo rezultatai naudojami medžiagų elastines savybes aprašančioms pastoviosioms nustatyti. Šios pastoviosios vėliau naudojamos baigtinių elementų ir baigtinių skirtumų modeliuose nustatant objekto stiprumo charakteristikas ir ultragarso bangų sklidimo dėsningumus. Nukreiptųjų bangų fundamentinių modų (A_0 ir S_0) faziniams greičiams aliuminio plokštėje matuoti taikyti imersinis ir per oro tarpą būdai. Pateikta imersiniu būdu išmatuotos simetrinės S_0 modos fazinio greičio vertė. Be to, pateikti vienpusio ir dvipusio priėjimo metodais per oro tarpą išmatuoti asimetrinės A_0 modos faziniai greičiai esant skirtingiems dažniams. Eksperimentiniai rezultatai palyginti su teoriniais, gauta gera rezultatų atitiktis.

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