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Investigation of the performance of wedge type ultrasonic transducers for excitation of Lamb waves in steel plates

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Introduction

Performing non-destructive testing of a large constructions consisting of metal plates with lateral dimensions up to 100 meters, the most effective are techniques exploiting guided waves. The main factor which limits the measurement possibilities are the signal losses due to the long propagation path, therefore low frequencies signals should be used (about 50 kHz).

In ultrasonic measuring and non-destructive testing instruments, ultrasonic waves are very often radiated by a piezoelectric transducer through a layer with non-parallel boundaries or prism. This layer is used for wave mode transformation. In the case of inspection of a metal plates wedge type transducers (with prisms) could be used for generation of Lamb waves. In this case another limiting factor is a spherical wavefront in a prism, which is caused by small lateral dimensions of the transmitting transducer at the low frequencies.

When an ultrasonic wave is radiated through the layer with non-parallel boundaries, the structure of ultrasonic field becomes complicated, because the ultrasonic field, while travelling through non-parallel boundaries, loses its axial symmetry. Generally, calculation of such fields requires application of 3D models.

The main objective of the presented research was to investigate the performance of the wedge type ultrasonic transducers used for excitation of low frequency Lamb waves in steel plates.

Therefore two different methods for simulation of ultrasonic fields radiated through the layers with nonparallel boundaries (prisms) were used. The first method is based on transformation of a multi-layered medium into a virtual one without internal boundaries. The second method solves the 2D acoustic wave equation using finite difference method.

Simulation method, based on transformation of a multilayered medium into a virtual one without internal boundaries

Objective of this part of work was to develop the method suitable for simulation of ultrasonic fields radiated through the layer with non-parallel boundaries. For this purpose the known model for calculation of the field of a single circular transducer in homogeneous medium was extended to the case of a multi-layered medium with non-parallel boundaries [1]. The proposed simulation method is based on transformation of a multi-layered medium into a virtual medium without internal boundaries equivalent to the actual one from the point of a view of the relative times of flights of direct and edge waves.

The pulsed field of the circular transducer in homogeneous media can be calculated using mathematical model based on the spatial pulse response approach, that is, response of the transducer to excitation by a very short pulse [1].

The main assumption of the proposed method is following: after refraction at the boundary between two media the ultrasonic field consists of plane and edge waves also. This means, that even after passing the boundary, the shape of the spatial pulse response remains the same, as in the case of a homogeneous medium, only the delay time of spikes in the spatial pulse response are different.

Calculating the paths along which the acoustic rays propagate, it is assumed, that each ray has to obey the Snell's and reflection laws. Usually these laws are applied to the plane waves, but after some assumptions it is possible to apply them for other types of waves also. It is assumed that the Snell's and reflection laws are valid for each ray, which is transmitted from any point of the transducer. If the trajectory of the ray from the point on the surface of the transducer to the point in the second medium has to be calculated, such a point on the boundary between two media has to be found, that the angles of incidence, reflection and refraction would satisfy the Snell's and reflection laws [1].

Calculations of the transient ultrasonic fields and waveforms in the time domain using the described method were performed for the plexiglas – steel – diesel structure with non-parallel boundary between plexiglas - steel and parallel boundary between steel – diesel (Fig.1). The calculations were performed for two different transducers excited by different driving pulses. The first calculation was performed for the circular transducer of the radius R = 10mm and with the frequency f = 50 kHz. It was assumed that the circular ultrasonic transducer was located at $z = 0, x = 0$ mm. The driving signal was assumed to be a sinus with 3 periods (Fig.2). The following parameters were used: the thickness of the first layer (plexiglas) on the central axis of the transducer z_{rb1} (Fig.1) was assumed to be 7.144 mm; the thickness of the second layer z_{rb2} (steel) was assumed to be 6 mm. The ultrasound velocity in the first layer (plexiglas) was assumed to be c_1 = 2770 m/s, in the second layer (steel) – c_{2l} = 5900 m/s (longitudinal) and c_{2t} = 3190 m/s (shear), in the third layer (diesel) – c_3 = 1250m/s. An inclination angle of the transducer was α = 30° and the shear waves in the second layer (steel) are generated (Fig.3).

The calculated pressure field is presented in figures as a spatial distribution of peak values of the acoustic pressure $p_{cs}(x,z)=\max\limits_{t}|p(x,z,t)|$. For better understanding the presented field is normalised with respect to the maximum value of the pressure in the third medium.

The presented example of the simulated field in Fig.3 illustrates, that is possible to generate the shear waves in steel plate, but the amplitude of the generated field in steel plate is quite small.

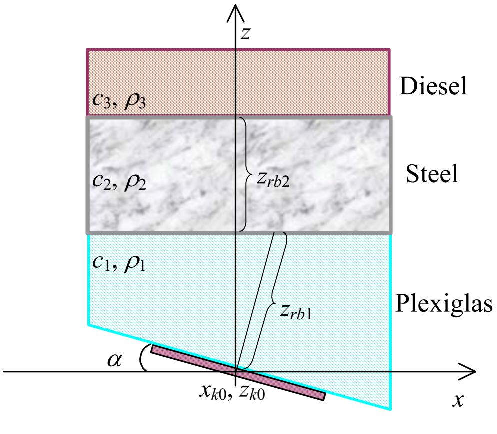

Fig.1. **Plexiglas – steel - diesel structure with parallel and non-parallel boundaries used for simulation of ultrasonic fields**

The second calculation was performed for the circular transducer of the radius R = 20 mm and with the frequency f = 66 kHz. The circular ultrasonic transducer is located at z = 0, x = 0 mm. The thickness of the first layer (plexiglas) on the central axis of the transducer z_{rb1} was assumed to be 45 mm (Fig.1). The thickness of the second layer z_{rb2} (steel) was assumed to be 8 mm.

The driving signal was approximated by [1]:

$$u(t)=\mathrm{e}^{a(t-b)^2}\sin(2\pi ft), \qquad (1)$$

where $a=k_a f\sqrt{\dfrac{-2\ln 0.1}{p_s}}$; $b=\dfrac{2p_s}{3f}$, p_s is the number of periods, k_a is the asymmetry factor, f is the frequency (Fig.4). Steepness of the front and back slopes of the pulse can be set separately selecting corresponding value of k_a. The simulation was carried out for a pulse with $p_s=5$.

The ultrasound velocity in the first layer (plexiglas) was assumed to be c_1 = 2760 m/s, in the second layer (steel) – c_{2l} = 5385 m/s (longitudinal) and c_{2t} = 3190 m/s (shear), in the third layer (diesel) – c_3 = 1250 m/s.

The calculations were performed for the two cases – when an inclination angle of the transducer is α = 30° and the longitudinal waves in the second layer (steel) are generated (Fig.5) and when an inclination angle of the transducer is α = 30° and only shear wave in the second layer (steel) is generated (Fig.6).

From the presented simulated ultrasonic fields we can see, that the amplitude of the generated wave in the second medium is very small. The amplitude of the generated field is a little bigger for the shear waves. The amplitude of the generated field does not differ very much for two different configurations (45 mm and ~7 mm of plexiglas), presented here. The presented examples of the simulated fields illustrate, that the effective generation of longitudinal waves in steel plates is not possible – the amplitude of the generated wave is too small. The reason for this is that the diameter of the transducer is smaller than the wavelength (from 1,2 to 6 times for different cases) and therefore the transducer is generating a spherical wave and, not as expected, the plane wave. Therefore, transformation of the wave components in a steel plate occurs and not only as expected the longitudinal component (S_0 mode) of the Lamb wave is generated, but also the dominant shear component (A_0 mode).

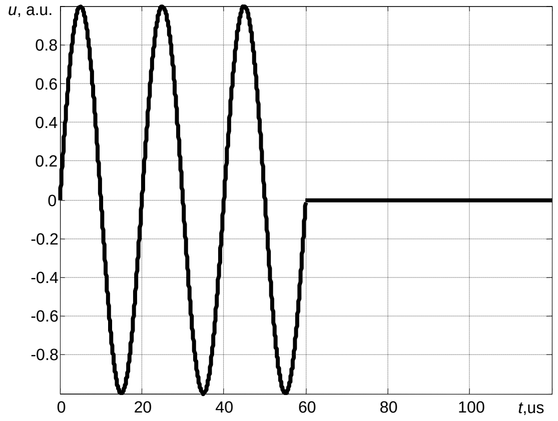

Fig.2. **Waveform of the driving ultrasonic pulse (normalised)**

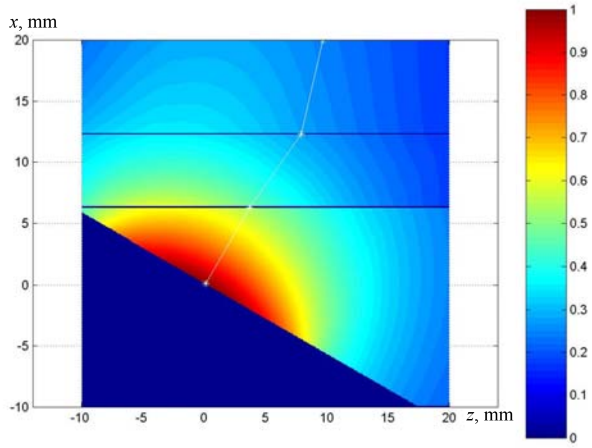

Fig.3. **Simulated ultrasonic field in the plexiglas-steel-diesel structure, for the case of shear waves in steel. The inclination angle of the transducer - 30°**

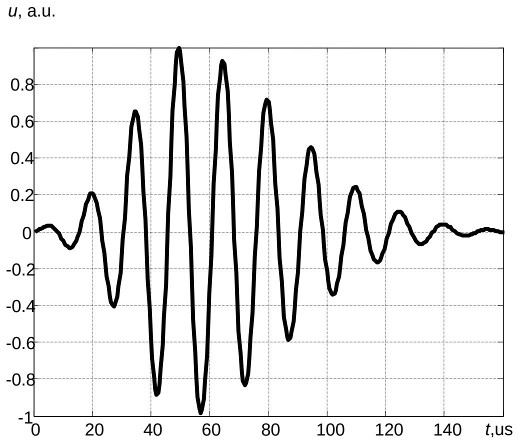

Fig.4. **Waveform of the driving ultrasonic pulse (normalised)**

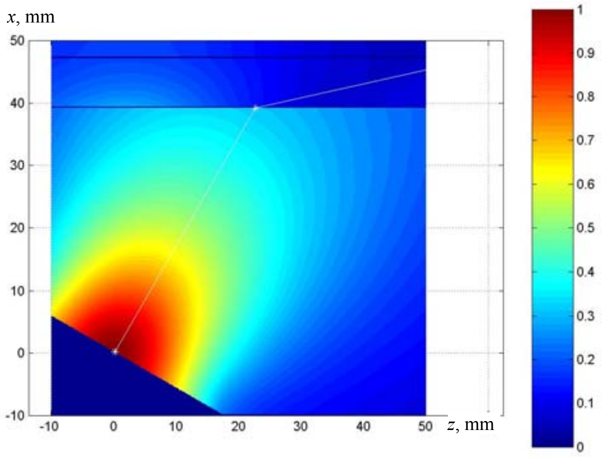

Fig.5. **Simulated ultrasonic field in the plexiglas-steel-diesel structure, for the case of longitudinal waves in steel. The inclination angle of the transducer - 30°.**

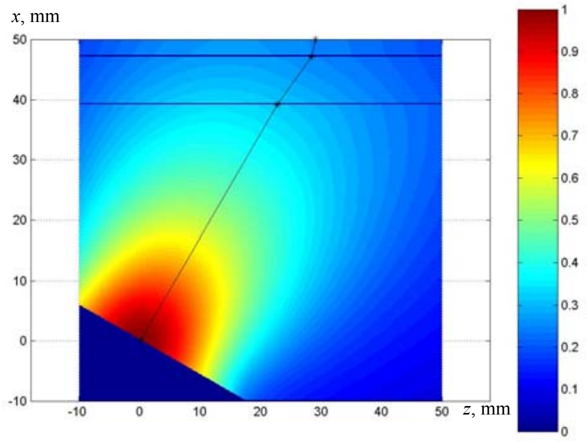

Fig.6. **Simulated ultrasonic field in the plexiglas-steel-diesel structure, for the case of shear waves in steel. The inclination angle of the transducer - 30°**

Simulation of a wedge type transducer field using finite difference method

Calculations of the transient ultrasonic fields and waveforms in the time domain were performed for the plexiglas – steel – diesel structure (Fig.7) also using the Wave2000 software. This software solves the 2D acoustic wave equation based on a method of finite differences. Wave2000 computes an approximate solution to the two-dimensional acoustic wave equation [2, 3, 4].

TFor comparison with simulated fields using analytical model of the ultrasound transducer the same parameters were assumed as in the previous part.

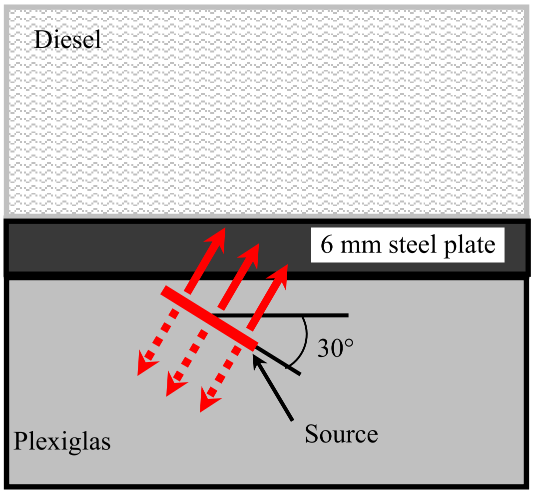

Fig.7. **Plexiglas-steel-diesel structure used for simulation of excitation of the Lamb wave S_0 mode in the steel plate using the wedge type transducer**

In Fig.8 the wavefront transformation process at different time instants is shown. Here the field is presented as:

$$F=\sqrt{U_x^2+U_y^2}\ , \qquad (2)$$

where U_x is displacement in the transverse direction of the transducer, U_y is displacement in the longitudinal direction.

From the presented figures follows that the structure of the radiated field is quite complicated. The amplitude of Lamb wave S_0 mode in a plate is smaller as the amplitude of the field in plexiglas wedge.

The numerical simulation of the S_0 mode propagation along the steel plate (wave path 400 mm) and reception with a virtual transducer Rc1 was performed too (Fig.9). From Fig.10 it is possible to see, that the received waveform of the signal at the end of the steel plate with the transducer Rc1 in Fig.9 is distorted and weak.

If to compare the amplitudes of the signal, used for excitation and the amplitude of the signal, received after propagating 400 mm distance in a steel, the amplitude of the received signal is smaller more than 500 times.

These results also show, that generation of the Lamb wave S_0 mode with a wedge type transducer at low ultrasonic frequencies (50 – 66 kHz) is not efficient.

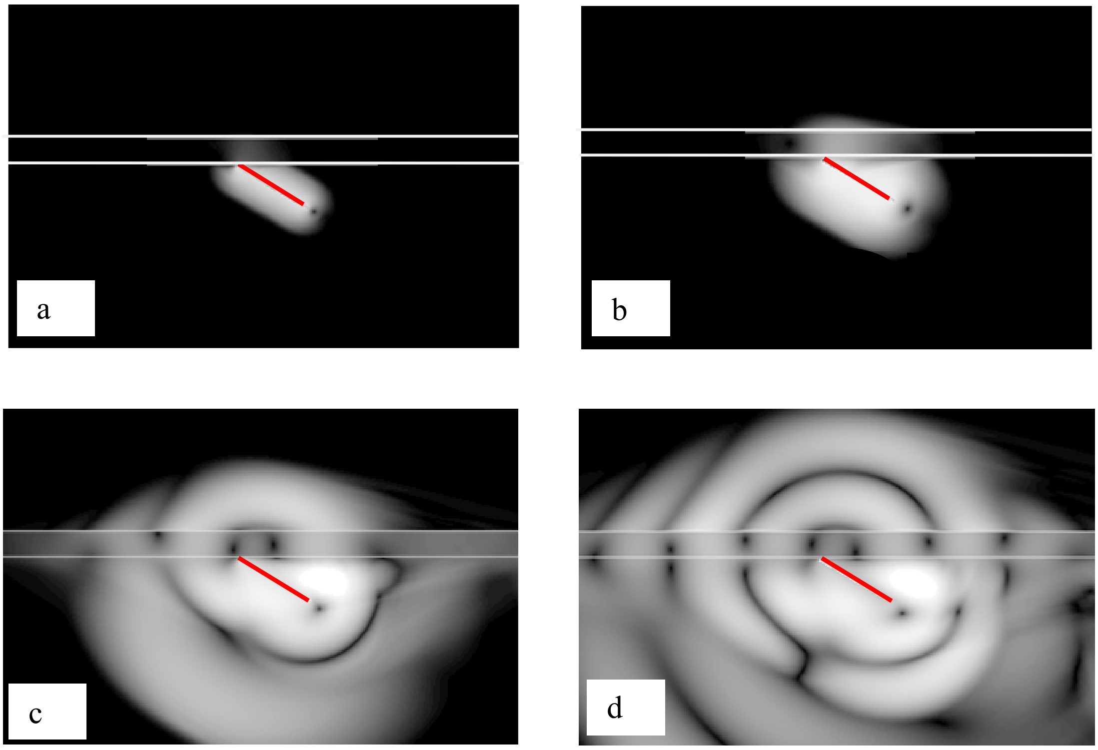

Fig.8. **Propagation of the Lamb wave S_0 mode at different time instants after excitation: a - 2.83 μs, b - 5.67 μs, c - 17.00 μs, d - 28.33 μs**

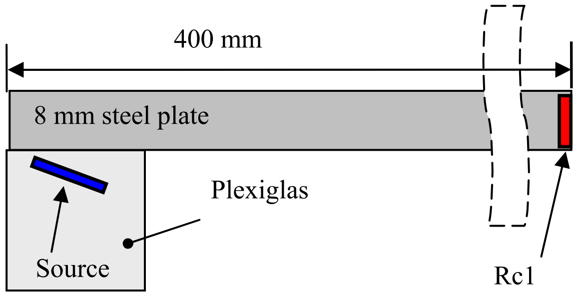

Fig.9. **Position of the virtual transducer, used for simulations by the finite difference method**

Experimental investigation

The objective of the presented part was experimental verification of the earlier presented simulation results of the ultrasonic field in pulse and transient modes.

For estimation of the performance of the wedge type ultrasonic transducers for excitation of Lamb waves in steel plates the through transmission measurement technique was used (Fig.11).

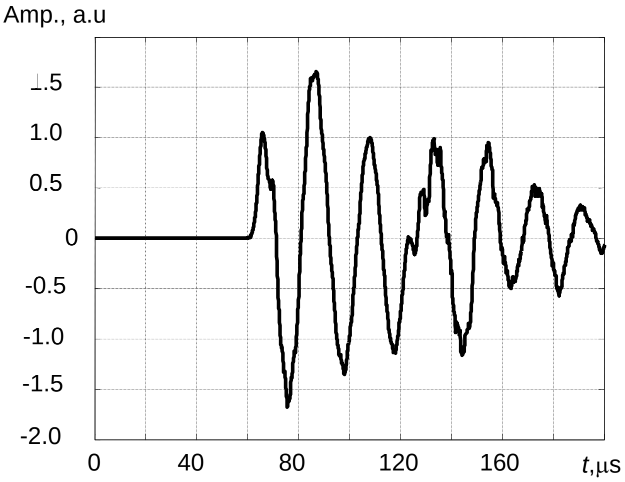

Fig.10. **Waveform of the signal at the end of the steel plate at 400 mm, received with the virtual transducer Rc1)**

For experimental investigations the contact type transducers with the 66.3 kHz central frequency and the diameter 30 mm were exploited. Data acquisition was performed by the HP54645A digital oscilloscope with averaging of 8 signals. The data were transferred to a personal computer via IEEE488 interface for a further analysis. Dimensions of the test plate were the following: length l = 1500 mm, width n = 600 mm, thickness h = 8 mm.

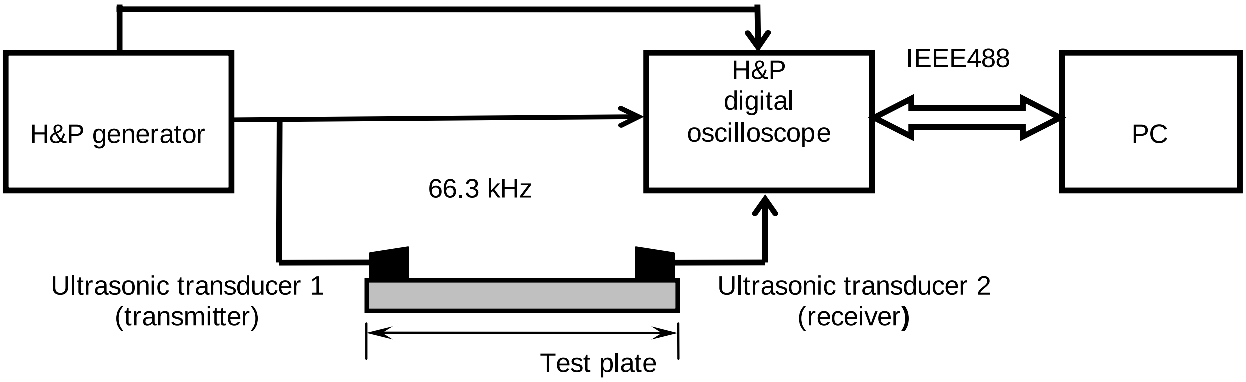

Fig.11. **Measurement configuration of the S_0 mode, when the transmitting and the receiving ultrasonic transducers are wedge type**

The optimal angle of the plexiglas prism for the wedge type transducer is given by:

$$\Theta = \arcsin\left(\frac{v_p}{v_L}\right), \qquad (3)$$

where v_p = 2760 m/s is the longitudinal wave velocity in plexiglas (value from handbook), v_L = 5351 m/s is the Lamb wave S_0 velocity in the unloaded steel plate (the value obtained from the simulation results by the global matrix method) at the frequency 66.3 kHz and the angle $\Theta = 31.05°$.

During the experimental investigation the two measurement configurations were exploited. The first measurement configuration is presented in Fig.12. The transducer was excited by the rectangular burst, consisting of 8 cycles, the repetition rate 20 Hz, amplitude of the excitation pulse was 10 V peak to peak. The distances were the following: x = 680 mm, l_1 = 60 mm and l_2 = 70 mm.

The second measurement configuration is presented in Fig.13. The excitation pulse amplitude was 10 V peak to peak, the number of the rectangular burst cycle was 5, and the repetition rate for better separation of A_0 and S_0 signals was 20 Hz. The measured ultrasound velocity was 5396±13 m/s for the S_0 mode and 1920±12 m/s for the A_0 mode. The distances were the following x = 1020 mm, l_1 = 70mm.

The waveform of the S_0 mode signal transmitted through the unloaded plate, when the transmitter and the receiver transducers are wedge type, is presented in Fig.14. The angle of the wedge Θ was calculated for the S_0 mode, but during experimental investigation transmitted S_0 mode signal was very weak, and the only strong A_0 mode signal was received (Fig.14). The reason for that was trapping of the S_0 mode in the plate which acted as the planar waveguide. The used wedge type transducer acted as the point type transmitter of the spherical wave, because the transducer diameter was close to the wavelength. The transverse component of the A_0 mode is generated better. Therefore, the S_0 mode was not generated efficiently by a wedge type transducer. The presented results are in good agreement with the simulation results using the diffraction model of the ultrasonic transducer and finite difference approach.

Fig.12. **Experimental set-up for the investigation of the S_0 mode propagation when the transmitter and the receiver are wedge type transducers**

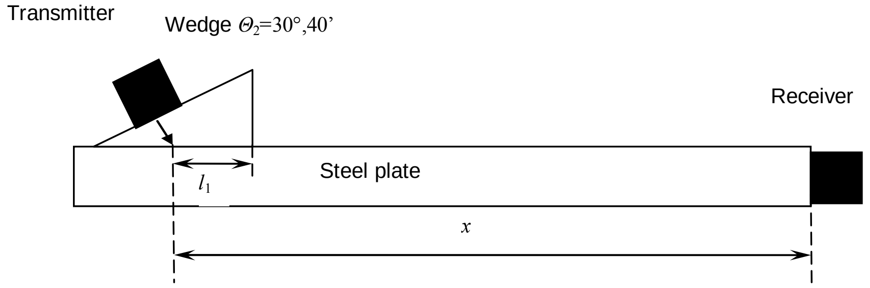

Fig.13. **Experimental set-up for the investigation of the S_0 mode propagation, when the transmitter is a wedge type transducer and the receiver is mounted on the edge of the plate**

Due to the mentioned assumption, that S_0 mode was trapped inside the planar waveguide, the receiving transducer was mounted on the plate edge. The waveform of the S_0 mode signal transmitted through the unloaded plate, when the transmitter is a wedge type and the receiver is mounted on the edge of the plate, is presented in Fig.15.

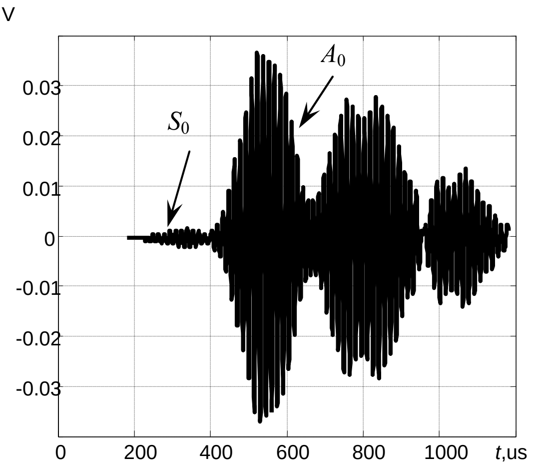

Fig.14. **The S_0 signal transmitted through the unloaded plate, when the transmitter and the receiver are wedge type transducers**

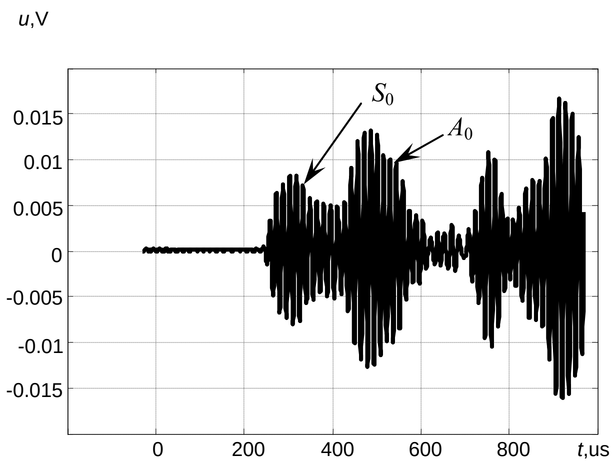

Fig.15. **The S_0 signal transmitted through the unloaded plate, when the transmitter is a wedge type transducer and the receiver is mounted on the plate edge**

It is possible to see, that S_0 mode signal is stronger more than four times in comparison with the signal, received using the wedge type transducer (Fig.14). The amplitude of the received A_0 mode signal is a few times smaller, because the receiver mounted on the plate edge is more sensitive to the longitudinal component, which is dominant for S_0 mode.

Conclusions

The presented examples of the simulated fields in pulse and transient modes illustrate, that the effective generation of S_0 mode Lamb waves in a low ultrasonic frequency range (about 50 kHz) using the wedge type transducers is not possible. The amplitude of the generated longitudinal component of the plane wave, suitable for generation of the S_0 mode, is too small. The reason for this is that the diameter of the transducer is smaller than the wavelength and therefore the transducer is generating a spherical wave and, not as expected, the plane wave. Therefore, transformation of the modes in a steel plate occurs and not only as expected the S_0 mode of the Lamb wave is generated, but also the A_0 mode.

From the experimental investigation it was verified that the used wedge type transducer, dimensions of which are small in comparison with the wavelength, acted as the point type transmitter of the spherical wave. Such wedge type transducer is not efficient for generation of the Lamb wave S_0 mode and it is exciting other parasitic modes. The transverse component of the A_0 mode is generated better. The received S_0 mode signal was very weak, and the only strong A_0 mode signal was received. The reason for that was trapping of the S_0 mode in the plate, which acted as the planar waveguide. Therefore, the S_0 mode was not generated efficiently by a wedge type transducer. The experimental results are in good agreement with the simulation results of the excited field in pulse and transient modes.

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Ultragarsinių keitiklių su prizmėmis panaudojimo Lembo bangoms žadinti plieno plokštėse tyrimas

Reziumė

Atliekant lakštinių metalo konstrukcijų neardomuosius tyrimus, naudojamos Lembo bangos. Kai reikia tirti didelių skersinių matmenų lakštines metalo konstrukcijas, tai ultragarsinis signalas yra stipriai slopinamas, dėl to reikia naudoti žemo dažnio signalus (~50 kHz).

Straipsnyje aptariamas Lembo bangų žadinimo naudojant ultragarsinius keitiklius su prizmėmis tyrimas. Sužadintasis ultragarsinio keitiklio laukas pliene buvo sumodeliuotas dviem metodais. Pirmasis yra toks, kai ultragarsinio keitiklio laukas prizmėje ir perėjus organinio stiklo prizmės ir metalo ribą pliene apskaičiuojamas remiantis daugiasluoksnės terpės pakeitimu tariamąja vienalyte terpe, įvertinant santykines plokščios ir krašto bangų sklidimo trukmes. Taikant dvimatį skaitmeninį baigtinių skirtumų metodą ultragarsinio keitiklio laukas apskaičiuojamas esant pereinamajam režimui.

Teoriniai tyrimo rezultatai buvo patikrinti eksperimentiškai. Eksperimentų metu Lembo bangų S_0 moda buvo žadinama naudojant ultragarsinius keitiklius su prizmėmis, o bangoms priimti taikyti du metodai – ultragarsinis keitiklis su prizme ir keitiklis be prizmės.

Buvo nustatyta, kad S_0 modos žadinimas ir priėmimas naudojant ultragarsinį keitiklį su prizme yra neefektyvus, kai ultragarsinio keitiklio skersmuo mažesnis už bangos ilgį.Kai dirbama žemų dažnių srityje, prizmėje generuojama sferinė banga ir tai sąlygoja parazitinių modų generavimą plieno plokštėje.

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