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Investigation of influence of edge on the excitation of Lamb waves

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Abstract

In applications of guided waves for non-destructives testing usually it is recommended to attach transducers not close to the edges, boundaries or joints of the object under investigation, because it influences the received signals and as a consequence complicates interpretation of the results. However, there are many objects access to which is limited and there is no other possibility then to perform inspection from the position close to the edge of the object. The objective of the work presented is to investigate the regularities of the excitation of guided waves from positions close to the boundaries of the object.

The regularities of excitation of guided waves in a rectangular steel plate using transducers attached near the edges were investigated. The differences between excitation at far and close distances from the boundaries were demonstrated using a finite element modelling. The experimental investigations using an 8 element transducer array have been carried out and the obtained data were compared with the modelling results.

Keywords: Wave reflection, edges, transducer array, Lamb waves, directivity pattern, modelling.

Introduction

The guided waves propagate in elongated or planar structures such as plates, tube and etc. Such objects at least in one direction are mach longer than in another one. Presence of edges or ends of the object on the way of propagating guided waves educes reflection and mode conversion. In the case when the transmitter is positioned close to the boundaries of the object under investigation the reflected and mode converted waves overlap with directly propagating waves and essentially complicates or makes impossible analysis and interpretation of the results. Even more, the mode conversion may create different undesirable mode waves. Due to this problem in most applications of guided wave inspection, for example, inspections of the pipes, ultrasonic transducers are fixed to the object at some distance from the closest edge [1-2]. However, on some objects it is impossible to keep this distance sufficiently big. The example of such an object is sheet piles, significant part of which is hidden into the ground or under water and is inaccessible.

The objective of the work presented was to investigate the differences of the excitation of guided waves at close and far distances from the edges in a rather simple steel plate case.

The shear displacement point source on the edge

In our previous work [3] it was demonstrated by modelling that in the case of the shear type excitation attached to the middle of the steel plate three zero order wave modes are generated: A_0, S_0 propagating in front and backward directions and S_H propagating in side directions. It was also shown that directivity patterns possess symmetry with respect to the excitation point. So, in the case when the excitation point is close to the boundaries the waves generated in a backward direction will be reflected and will overlap with the waves propagating in the front direction. In order to investigate the regularities of the guided wave excitation under conditions close to the edges the numerical experiment was carried out. The set up of the experiment is shown in Fig.1.

The investigations were performed using a finite element 3D model of the d=10mm thickness steel plate. The dimensions of plate are 0.5x0.5m. The parameters of the steel used in the modelling are the following: density ρ_{Al} = 7800 kg/m^3, the Young modulus E_{Al}, = 203 GPa, the Poisson's ratio ν = 0.29.

The waveform of the excitation signal possessing the central frequency 100kHz is presented also in Fig.1b. The point source of a shear excitation force was added at the edge of the steel plate oriented along y axis. The propagation of the excited waves was analysed in the time interval up to 200µs and for each time instance the all three components of particle velocities v_x, v_y, v_z at points corresponding to the lines A and B (Fig.1) were recorded.

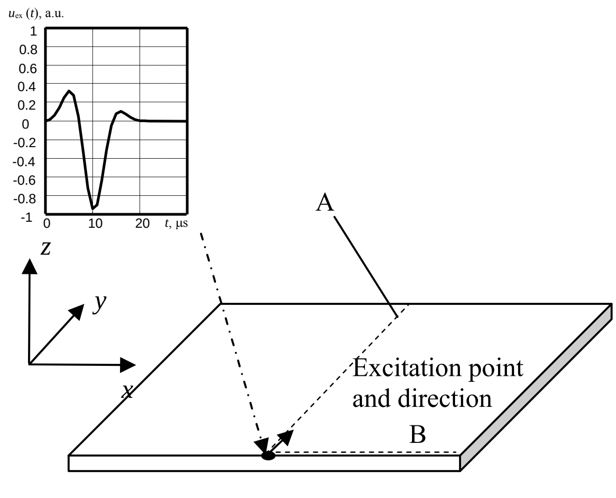

Fig.1. Set up of the modelling. The applied shear excitation force is denoted by arrow. Two dashed lines A and B denotes points at which the signals were recorded.

The obtained distribution of the particle velocity modulus

$$v_{t=50}(x,y)=\sqrt{v_{x,t=50}^2(x,y)+v_{y,t=50}^2(x,y)+v_{z,t=50}^2(x,y)}$$

on the surface of the plate at time instance 50μs is presented in Fig. 2. The several modes of guided waves can be observed. However, accurate determination of the wave mode and propagation velocity can be obtained using the signals, measured at the lines A and B. The B scan images presented in Fig. 3-4 show the distribution of components of the particle velocity along the lines A and B at different time instances. Different propagating waves can be observed in these images as a linear pattern oriented at some angle with respect to horizontal axis. The patterns of S_0 and A_0 modes of the Lamb waves can be seen in Fig.3. These modes contain both *y* and *z* components of a particle velocity. However, the *x* component of these waves is equal to zero due to the symmetry of the task. In the B scan images obtained from the data measured along *x* axis (line B) one dominating wave mode can be observed. In the case when a shear type excitation is attached to the middle of the plate, in the lateral direction propagates the shear horizontal mode of the Lamb wave. However, when the excitation point is on the edge, some mixed guided wave mode S_{HE} is generated and propagates along the plate edge. The weak pattern of some faster guided wave mode S_{0E} can be observed also.

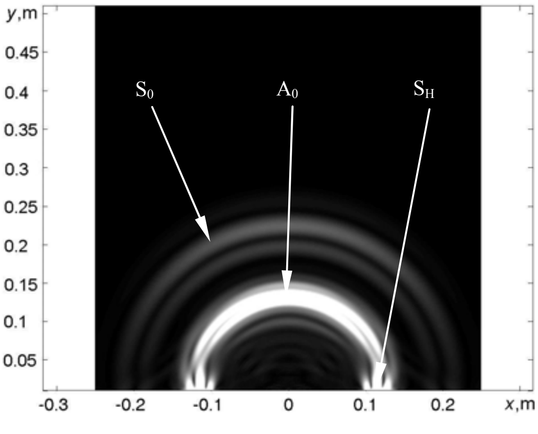

Fig.2. **The distribution of the modulus of the particle velocity *v* of at the time instance 50 μs after the excitation**

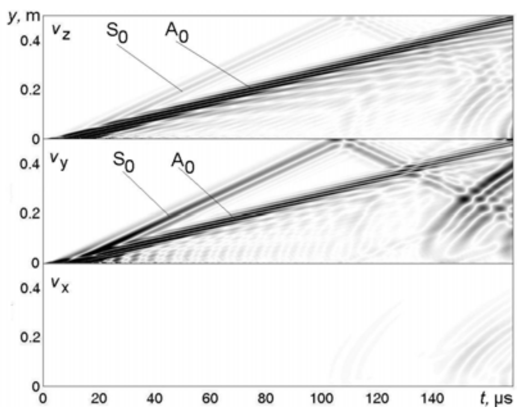

Fig.3. **The distribution of the components of a particle velocity v_x; v_y; v_z along the line B**

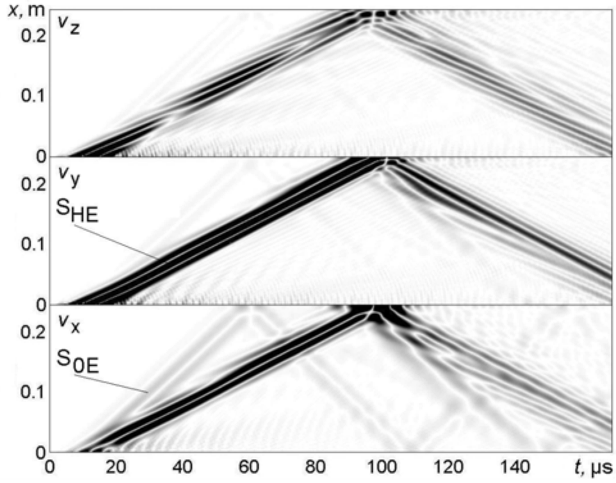

Fig.4. **The distribution of the components of particle a velocity v_x; v_y; v_z along the line A**

In order to determine the propagation velocity of all discussed above modes of guided waves from the B-scan data, optimisation technique was used. This technique is based on calculation of the target function according to

$$U_{ph}(\Delta t_w)=\sum_{k=1}^{N_w} v_k\left(t-\Delta t_w\cdot(k-1)\right), \tag{1}$$

$$U_{gr}(\Delta t_w)=\sum_{k=1}^{N_w}\left|\mathrm{H}\left[v_k\left(t-\Delta t_w\cdot(k-1)\right)\right]\right|, \tag{2}$$

where $v_k(t)$ is the component under analysis of the particle velocity, calculated along the line A or B, N_w is the number of analysed points, Δt_w is the value of the signal shift in the time domain, varied in the range $[0\div 4.0]\,\mu\mathrm{s}$, H denotes the Hilbert transform. In general this technique integrates the signals into one array using some additional shift in the time domain for each next signal. This function should have the maximum values at time instances at which the time shift Δt_w corresponds to the time interval necessary for propagation of the wave under analysis between two neighbouring points. The target function calculated using radio frequency signal (Eq. 1) will gain the maximal values corresponding to the phase velocity of the propagating wave mode and the target function calculated using the signals envelop (Eq. 2) – the group velocity. So, taking into account that

$$c_{ph}=\frac{\Delta xy}{\Delta t_{ph}},\qquad c_{gr}=\frac{\Delta xy}{\Delta t_{gr}}, \tag{3}$$

where Δxy is the distance between neighbouring points, the target functions can be expressed as

$$U_{ph}(c_{ph})=\sum_{k=1}^{N_w} v_k\left(t-\frac{\Delta xy}{c_{ph}}\cdot(k-1)\right), \tag{4}$$

$$U_{gr}(c_{gr})=\sum_{k=1}^{N_w}\left|\mathrm{H}\left[v_k\left(t-\frac{\Delta xy}{c_{gr}}\cdot(k-1)\right)\right]\right|. \tag{5}$$

The example of the function calculated according to Eq. 4 and using the data of the particle velocity component v_y obtained along the line B is presented in Fig.5.

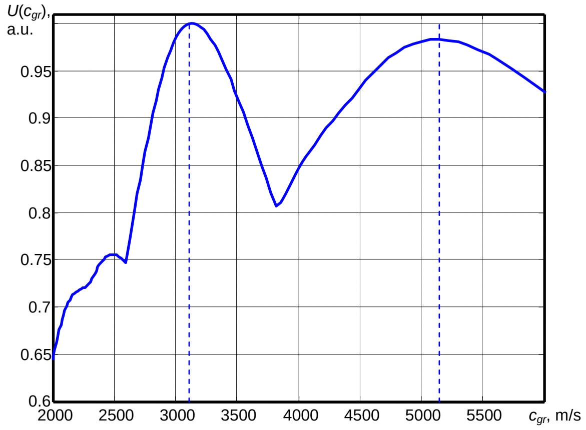

Fig.5. **The dependency of the target function versus a group velocity of the propagating guided wave**

As can be seen two local maximums of the target function can be observed. The first one corresponds to the propagating A_0 mode of Lamb wave, the second one to S_0 mode. Using the dependency obtained according to Eq. 4 and Eq. 5, the phase and group velocities of any propagating *M* mode of guided waves can be calculated:

$$c_{M,ph} = \arg\left\{\max_{c_{ph}}\left[U_{ph}\left(c_{ph}\right)\right]\right\}, \quad (6)$$

$$c_{M,gr} = \arg\left\{\max_{c_{gr}}\left[U_{gr}\left(c_{gr}\right)\right]\right\}. \quad (7)$$

The obtained values of propagating A_0 and S_0 modes of guided waves are presented in Table 1 and they are exactly the same as in the case of excitation in the middle of the plate [1].

Table 1. **Phase and group velocities of propagating Lamb wave modes calculated using simulation data in the case of the shear type excitation attached to the edge of the plate**

	S_0, m/s	A_0, m/s	S_H, m/s
Group velocity	5147	3115	3157
Phase velocity	5223	2400	3157

The results obtained along the line B (Fig. 4) demonstrates that in a lateral direction propagates one dominating wave mode containing all three components of a particle velocity v_x, v_y, v_z. It is named as a shear horizontal on edge S_{HE} mode and possesses the propagation velocity 2841 m/s. So, the results are essentially different from the case of the excitation in the middle of the plate, where a pure shear horizontal mode of the Lamb wave are generated and propagates with the velocity 3147m/s (Fig. 6).

Comparison of the amplitude of different guided wave modes in the cases of excitation at the centre and the edge of the plate (Table 2) shows that excitation at the edge generates wave possessing essentially higher amplitudes. Moreover, the generated very strong guided wave propagating along the edge is many times reflected between sidelateral boundaries of the plate.

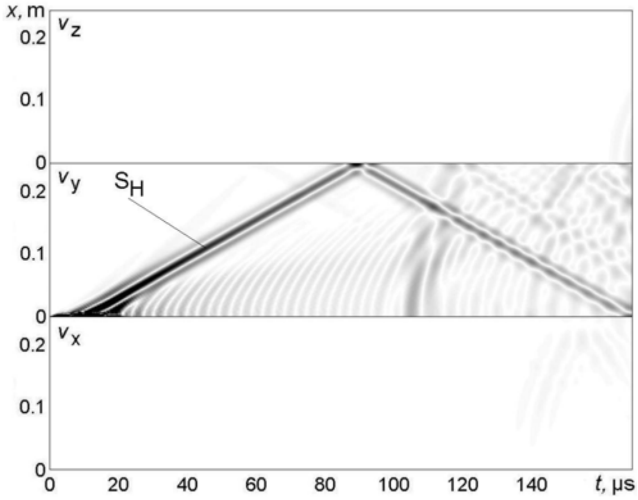

Fig.6. **The distribution of the components of a particle velocity along *x* axis in the case of excitation in the middle of the steel plate**

Table 2. **Amplitudes of the modulus of a particle velocity of different guided waves modes, normalized with respect to the amplitude of the modulus of shear horizontal mode wave**

	A_0	S_0	S_H	S_{HE}
Excitation at centre	0.5	0.4	1	
Excitation at edge	2.3	0.8		5.9

Experimental investigations

In order to verify the regularities obtained using modelling, the experimental investigation has been carried out. The set up of the experiment is presented in Fig. 7. The 8 element transducer array was attached to the upper surface of the 10mm thickness steel plate at the position close to the edge. The array elements are shear type, e.g., they are designed for excitation of shear horizontal type waves propagating in a lateral (*x* axis) direction. The distance between elements along *x* axis is half wavelength of S_0 mode of Lamb wave. The distance along *y* axis is equal to the wavelength of the A_0 mode wave. The excitation frequency is 100 kHz. Such spacing should essentially reduce the S_0 mode waves propagating in front direction. Additionally the single transducer (receiver) was positioned close to the opposite edge of the plate (Fig. 7).

The experimental estimation of the group velocities can be obtained using the signal recorded by the transducer attached to the opposite side of the plate. The signal is presented in Fig. 8 and the zoomed part of the signal corresponding to the arrival of S_0 mode is presented in Fig. 9.

The obtained values of group velocities are 5130 m/s for S_0 mode and 3205 m/s for A_0 mode of Lamb wave. The signal received by the transducer array is presented in Fig.10. The signals many times reflected in lateral direction can be observed. The estimated group velocity is 3180 m/s.

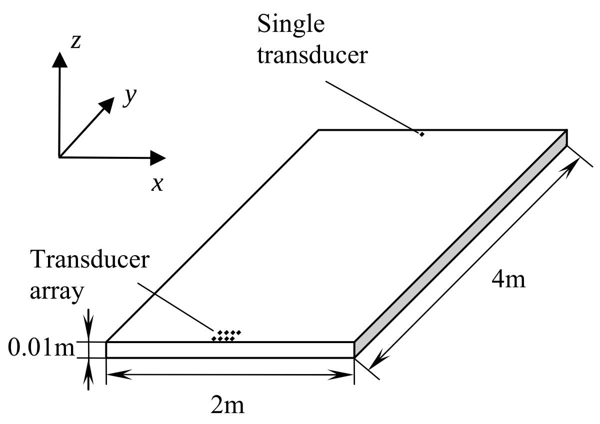

Fig.7. **Set up of the experiment**

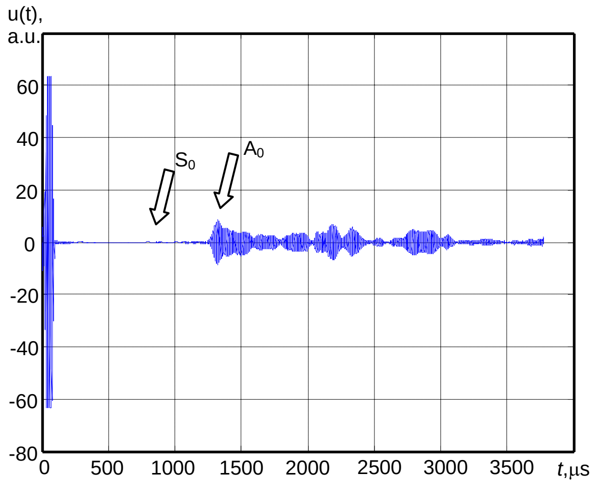

Fig.8. **The signal measured at the opposite side of the plate**

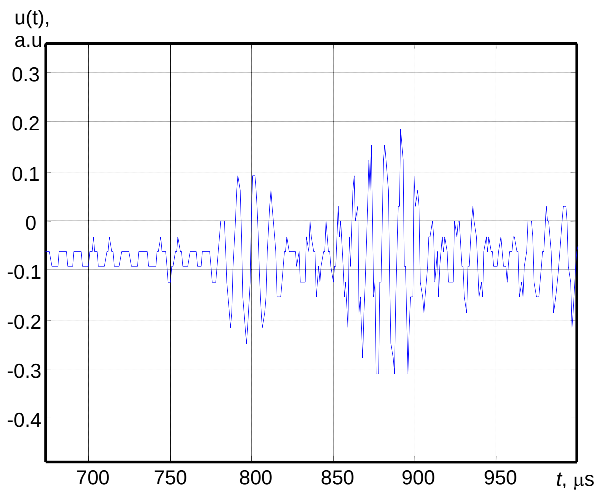

Fig.9. **The segment of the signal measured at the opposite side of the plate corresponding to the arrival of the S_0 mode wave**

Conclusions

The modeling and experimental investigation have demonstrated that in the case of the excitation of guided wave using transducers attached close to the boundaries of a plate the specific guided waves propagating along edges are generated. These waves do not possess clearly expressed dispersion, possess low attenuation and as consequence creates multiple reflections in a lateral direction.

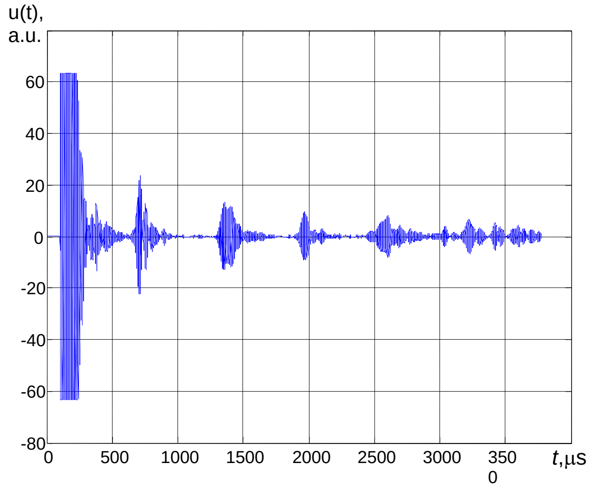

Fig.10. **The signal measured by the transducer array**

Also, it was found that excitation on the very edge of plates enables to increase the amplitudes of the S0 and A0 modes of Lamb waves propagating in the front direction.

Acknowledgements

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Krašto įtakos Lembo bangų žadinimui tyrimas

Reziumė

Plačiausiai nukreiptosios bangos naudojamos vamzdžių neardomiesiems bandymams atlikti, tačiau ir šiuo atveju vengiama statyti keitiklius arti vamzdžio krašto, nes tai apsunkina rezultatų interpretaciją. Tačiau atliekant kitokių objektų tyrimus, pavyzdžiui, metalinių lakštinių polių, iš tikrųjų nėra kitos keitiklių statymo vietos, išskyrus arti krašto. Šio darbo tikslas yra ištirti, kuo gali skirtis Lembo bangų žadinimo dėsningumai naudojant to paties tipo ultragarsinius keitiklius, bet statant juos skirtingose krašto atžvilgiu padėtyse. Buvo tiriami Lembo bangų žadinimo stačiakampėje plieno plokštėje ypatumai statant keitiklius arti krašto. Baigtinių elementų metodu parodyti skirtumai tarp žadinimo ant krašto ir plokštės viduryje. Modeliavimo rezultatams įvertinti eksperimentuota naudojant skersinių bangų aštuonių elementų gardelę. Gautųjų signalų analizės rezultatai palyginti su teoriniais duomenimis.

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