Analysis of the zero-crossing technique in relation to measurements of phase velocities of the S_0 mode of Lamb waves

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Abstract

It was demonstrated by previous works that the regularities obtained in phased velocity measurement of A_0 mode of Lamb waves using zero-crossing technique creates possibilities for identification of the modes. The objective of the work presented was to investigate the similar approach on the S_0 mode of Lamb waves and to determines if difference of regularities is sufficient or strong enough to be used for mode identification. The signals obtained by finite element modelling of S_0 mode in 2mm thickness aluminium plate were analysed. The excitation signal was 300 kHz burst with the Gaussian envelop It was demonstrated that the distribution of lower and higher frequency components in the signals are different for A_0 and S_0 modes, what can be exploited as criteria for mode identification

Keywords: Lamb wave, symmetric mode, asymmetric mode, dispersion curves, phase velocity, zero-crossing technique, measurement.

Introduction

The phase and group velocities are main parameters of Lamb waves, the measurements of which are exploited in various industrial fields. However, the measurements of these parameters are complicated due to their dependence on frequency and presence of infinite number of modes. Even excitation of guided waves is affected by presence of the edges of the object at close distance from excitation point [1]. In the case of real objects the propagating waves are reflected by non-uniformities and converted to other modes. These factors lead to signals complicated for analysis. As consequence mainly faster, in most cases symmetric S_0 mode, are only used in measurements. So, there is need of signal processing techniques which enables to identify the signal segments corresponding to different modes of propagating guided waves.

The analysis if the signals of the A_0 mode of Lamb waves propagating in aluminium plate using the zero–crossing technique demonstrated that there is some regularities which can be related exclusively to the A_0 mode [2-3]. Presented in [2-3] results create the background for mode identification. However, the similar investigations should be carried out on the mode guided waves in order to determine if the obtained regularities differs sufficiently to enable identification.

So, the objective of this work was to measure the phase velocity of the symmetric S_0 mode Lamb waves using the same measurement technique based on the zero-crossing method.

Object of the investigation

The general view of the dispersion curves of the symmetric S_0 and the asymmetric A_0 modes Lamb waves propagating in the 2 mm aluminium plate are presented in Fig.1. The dispersion curves were calculated using analytical method assuming that the propagation velocity of the longitudinal waves is $c_L = 6350$m/s and the velocity of the shear waves is $c_T = 3100$ m/s.

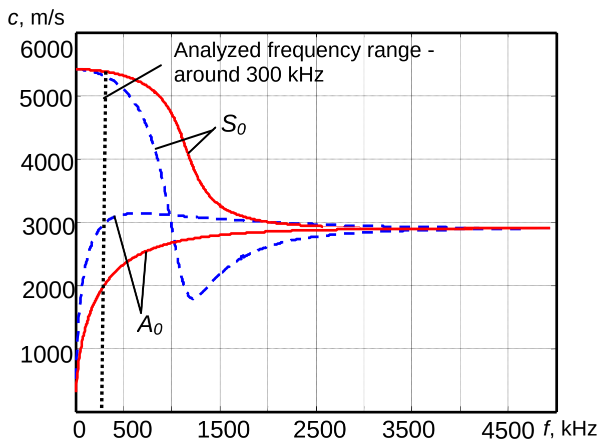

Fig.1. **The theoretical dispersion curves of the symmetric S_0 and the asymmetric A_0 modes Lamb waves propagating in 2 mm aluminium plate: solid line -the phase velocity; dotted line - group velocity**

As can be seen from the graph the frequency range with strong dispersion for the asymmetric A_0 mode is 0-1000 kHz and for the symmetric S_0 mode is from 500 up to 1500 kHz. It can be noted that in the frequency ranges under investigation (around 300 kHz) the phase and group velocities of A_0 mode increases with a frequency and the both velocities of S_0 mode possess opposite feature – decreases with a frequency. The zoomed part of the dispersion curves corresponding to the frequency ranges under investigation is presented in Fig.2. The other differences between A_0 and S_0 modes is that the group velocity of the S_0 mode is slightly smaller then the phase velocity and the group velocity of the A_0 mode is essentially bigger then the phase velocity. At the frequency the phase velocity of the A_0 mode is approximately 2000 m/s and the group velocity – 3000 m/s. More detailed values of phase and group velocities in the frequency ranges under investigations are presented in Table 1.

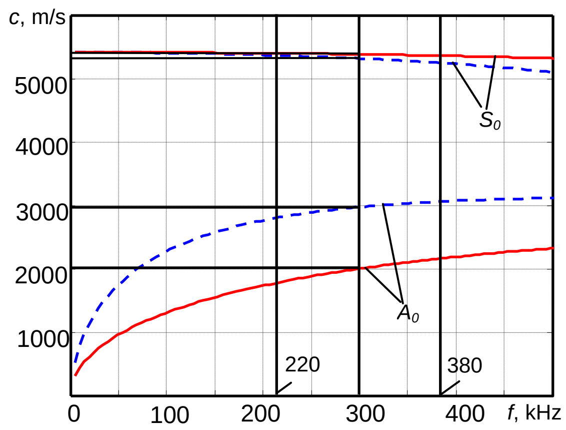

Fig.2. **The zoomed part of the phase velocity and the group velocity dispersion curves of A_0 and S_0 modes of the Lamb wave in 2mm aluminium plate**

Table 1. **The phase and the group velocities of A_0 and S_0 modes of the Lamb waves propagating in 2mm thickness aluminium plate at different frequencies**

Frequency, KHz	Phase velocity , m/s		Group velocity, m/s	
	A_0	S_0	A_0	S_0
220	1794	5395	2817	5360
300	1999	5380	2972	5314
380	2153	5360	3056	5248

The analysis of the phase velocity of the asymmetric A_0 mode was carried out and it was determined that the components of the signal corresponding to higher frequencies are faster because the phase velocity of A_0 mode increases with a frequency. As a consequence they should arrive earlier and more concentrates in the first part of the signal [6]. So, it can be stated that the distribution of the components of different frequency in the burst of the signal change during Lamb wave propagations. These changes are dependent on the shape of the dispersion curve of the mode under analysis. As a consequence they are unique for some mode as finger prints and can be used for mode identification. However this is only assumption followed from the A_0 mode analysis. In order to prove this assumption the signals of other modes should be investigated.

As it was discussed above, the features of the dispersion curves of the S_0 mode are quite different. So, during wave propagation it should to lead to different distribution of the different frequency components in the burst of the signal.

The finite element model of the aluminium plate

In order to obtain signals of propagating S_0 mode for analysis the same 2D finite element model of the aluminium plate was used (Fig.3). The symmetric S_0 mode of Lamb wave propagating in the 2 mm thickness and 200 mm length aluminium plate was investigates.

The parameters of the aluminium plate were the same as the investigation of asymmetric A_0 mode: density ρ = 2780 kg/m^3, Young modulus E = 73.78 GPa, the Poisson‘s ratio ν = 0.3435. The sampling step in the spatial domain was dx = 0.1 mm and dt = 0.15 µs in the time domain. The S_0 mode was excited by attaching a normal force to one of the plate edges (Fig.3).

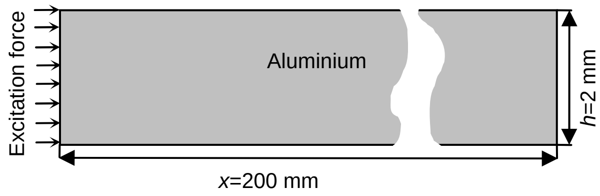

Fig.3. **The finite element model for investigation of propagation of the S_0 mode Lamb wave in aluminium plate**

The waveform of the excitation signal and frequency spectrum of it is also the same as in the A_0 mode analysis and is presented in [3]. The propagation of the S_0 mode was modeled during 100 µs time interval and the obtained the B-scan image of the normal component of particle velocity on the top surface of the plate is presented in Fig.4. The normal component was selected in order to have in future experimental verification. Measurement of the tangential component of a particle velocity of propagating waves is much more complicated.

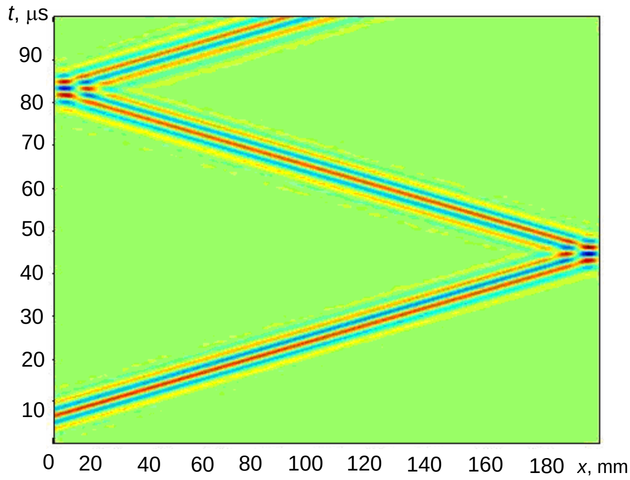

Fig.4. **The B-scan image of the normal component of the (dashed line) particle velocity on the surface of the plate**

It can be seen that faster S_0 mode is reflected several times by the boundaries of the plate during the same modelling time. In the previous modelling of the A_0 propagation it was reflected only once during the same modelling time.

The typical signal of the S_0 mode of Lamb wave propagating in aluminum plate is presented in Fig.5. The fixed threshold level equal to 0.02 was set for signals measured at different distance and time instance corresponding to six zero-crossing points (Fig.5) were measured. As the results for each measurement position x_n the six time instance are obtained $t_m(x_n)$, where $m = 1 \div 6$ $n = 1 \div N$, N is the total number of the measurement positions. Then the phase velocity at any point x_n along aluminium plate surface is estimated according

$$c_{ph,m}(x_n) = \frac{x_n - x_{n-1}}{t_m(x_n) - t_m(x_{n-1})} \quad (1)$$

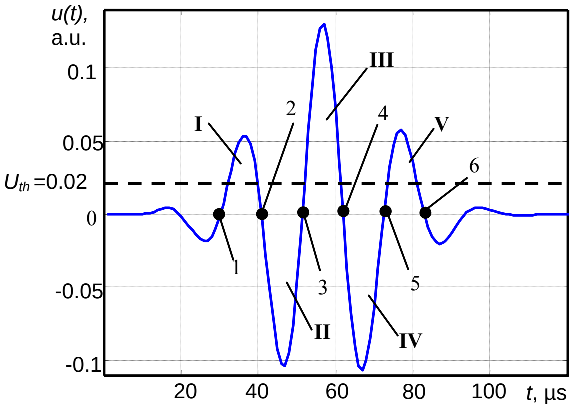

Fig.5. **Explanation of zero-crossing technique, 1, 2, 3, 4, 5, 6 are the zero crossing points used for estimation of the phase velocity of S_0; I, II, III, IV, V are half periods of the signal used for frequency analysis; U_{th} is the threshold level**

As the result of these calculations the matrix $\mathbf{C}_{nm}$ is obtained, the elements of which represents the phase velocity estimated at different positions of the plate and calculated using different zero-crossing points. However, due to the small distance between the measurements points (0.1 mm) there is big scattering of results. In order to obtain more accurate values they were grouped for each 20 mm and averaged. The obtained results are presented in Fig.6. As can be seen the velocities obtained using different zero-crossing points do not differ so strongly as in the case of A_0 mode especially if to take into account the fact that the phase velocity of S_0 mode is almost 3 times higher then the phase velocity of the A_0 mode. It can be observed also that the phase velocity obtained using the first and the second zero-crossing points demonstrate small increase with a frequency, when other almost do not depend on a frequency and are concentrated between values 5390m/s and 5410m/s.

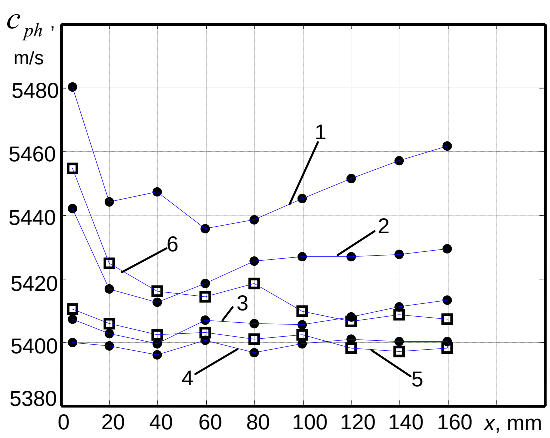

Fig.6. **The phase velocities of S_0 mode of Lamb wave versus distance measured at different distances using different zero-crossing point: 1, 2, 3, 4, 5, 6 correspond to the number of zero-crossing point in the burst of the signal**

The same zero-crossing instances $t_m(x_n)$ are used for estimation of the frequencies to which the presented above values of phase velocity should be related. At first the duration of each of half period in the signal is estimated

$$T_{0.5,k}(x_n) = t_{k+1}(x_n) - t_k(x_n)\,, \tag{2}$$

where $T_{0.5,k}(x_n)$ are duration of the k^{th} half periods of the signal, $k = 1 \div 5$ The obtained durations $T_{0.5,k}(x_n)$ are converted to the equivalent frequency

$$f_{0.5,k}(x) = 0.5 / T_{0.5,k}(x)\,. \tag{3}$$

In order to reduce errors these values were averaged for each 20 mm also. The obtained frequencies are presented in Fig.7. It can be stated that the distribution of the components corresponding to different frequencies posses similar ranges however possess opposite regularity. As can be see in Fig.7 the frequency of the first, the second and the third half period decreases with distance, whereas the fifth increases. Most stable results are obtained using the fourth zero-crossing point. It can be explained by the fact that the components of the low frequency are concentrated in the first part of the signal as they are faster and arrive earlier then the components of the high frequency which dominates at the end of the signal. So, this regularity is completely opposite comparing with the signals of A_0 mode [6]. The deviation of the frequency of the 5^{th} half period at distance 180 mm can be explained by the interference of the direct and the reflected by the edge waves.

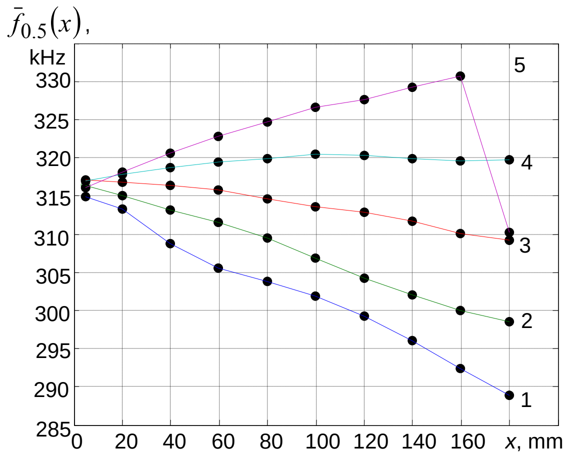

Fig.7. **The equivalent frequencies of the different half periods of the signal versus distance. 1, 2, 3, 4, 5 are the numbers of the half period**

The interference can be clearly observed in Fig.8 where the B-scan image with zoomed colour coding scale is presented. The comparison of variations of the equivalent frequency in the case of A_0 and S_0 mode is presented in Fig.9.

The obtained values of phase velocity related to the corresponding equivalent frequency enables to reconstruct segment of the dispersion curve. Such results together with the theoretical dispersion curve are presented in Fig.10. In general the results fits into some curve, however there is some systematic deviation, approximately 40 m/s with respect to the theoretical curve.

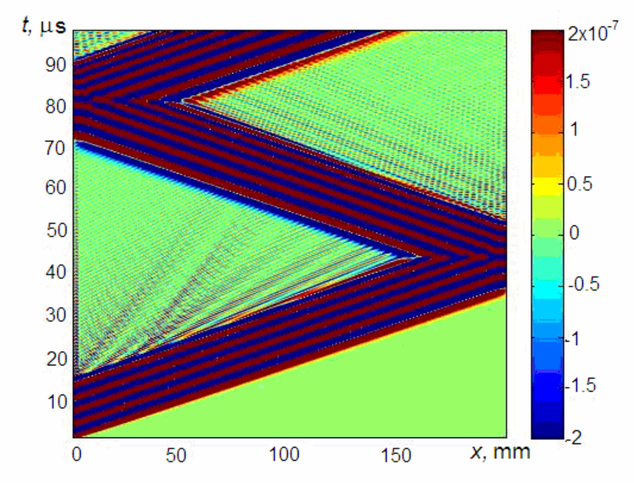

Fig.8. **The B-scan image of the normal component of the particle velocity on the surface of the plate with zoomed colour coding scale**

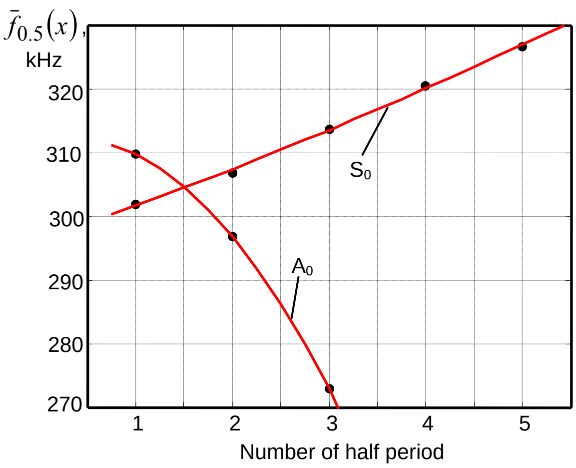

Fig.9. **Variations of the equivalent frequency of the different half periods in the case of A_0 and S_0 mode signals at distance 100mm**

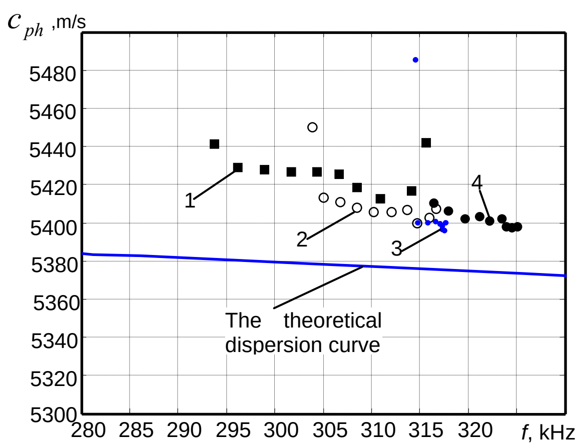

Fig.10. **The theoretical dispersion curve (solid line) and the phase velocity versus frequency obtained using proposed approach:**

1- $\overline{c}_{ph,2}$, **2 -** $\overline{c}_{ph,3}$, **3-** $\overline{c}_{ph,4}$, **4 -** $\overline{c}_{ph,5}$

Conclusions

Summarising the results obtained using numerical experiments it can be stated:

1. Analysis of the signals of S_0 mode proves assumption that the redistributions of the different frequency components in the burst take place when the guided wave propagates;
2. It was demonstrated that this redistribution depends on the shape of the dispersion curve of the mode under analysis and it parameters can be exploited for different mode identification in the signal;
3. It was demonstrated also that the distribution of the components of different frequency of the asymmetric A_0 and symmetric S_0 Lemb wave's modes posses opposite character and can be a reliable parameter which enables to identify them.

References

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Lembo bangų S_0 modos fazinio greičio matavimo signalo perėjimo per nulį metodu dėsningumų tyrimas

Reziumė

Ankstesni Lembo bangų asimetrinės A_0 modos fazino greičio atavimai signalo perėjimo per nulį metodu atskleidė tam tikrus dėsningumus. Jie sudaro prielaidą modoms atpažinti. Šio darbo tikslas buvo atlikti analogiškus tyrimus - išmatuoti simetrinės S_0 modos fazinį greitį ir nustatyti, ar gaunami dėsningumai yra pakankami skirtingoms modoms atpažinti. Tyrimo metu buvo naudojami signalai, gauti baigtinių elementų metodu modeliuojant Lembo bangos S0 modos sklidimą 2 mm storio ir 200 mm ilgio aliuminio plokštelėje. Bangos buvo žadinamos 300 kHz Gauso gaubtinės signalu. Tyrimais nustatyta, kad nukreiptųjų bangų A_0 ir S_0 modų fazinio greičio sklidimo skirtumus lemia ne tik skirtingas sklidimo greitis, bet ir aukštojo bei žemojo dažnio sandų pasiskirstymas signale. Sukurtas nukreiptųjų bangų fazinio greičio matavimo duomenų analizės metodas įgalina atpažinti signalo segmentus atitinkančias sklindančių Lembo bangų asimetrinę A_0 ir simetrinę S_0 modas.

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