ISSN 1392-2114 ULTRAGARSAS (ULTRASOUND), Vol. 66, No.4, 2011.

Measurement of the group velocity of Lamb waves in aluminium plate using spectrum decomposition technique

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crossref http://dx.doi.org/10.5755/j01.u.66.4.1026

Abstract

In the previous our article the technique for measurement of the group velocity using spectrum decomposition was proposed and demonstrated on the signals obtained from the finite element modelling. The objective of this work is to check this technique using experimental signals. The experiments were carried out on the 2mm thickness aluminium plate with dimensions 1100mm x 620mm. The guided waves were generated using a wide band contact type transducer. The excitation signal was 300 kHz, 3 periods burst with the Gaussian envelop. The signals were processed using the proposed spectrum decomposition algorithm and corresponding segments of the group velocity dispersion curves of the A_0 and the S_0 modes of Lamb waves were obtained. The analysis demonstrated that scattering and errors of the results essentially depends on the bandwidth of the filter used for decomposition. So, it is necessary to select parameters of the filters separately for each mode under investigation. The obtain results were compared with the theoretical dispersions curve and good correspondence was obtained.

Keywords: Lamb wave, dispersion, group velocity, spectrum decomposition, experiment.

Introduction

The spectrum decomposition technique was already used for investigation of the velocities of non-dispersive ultrasonic waves [1, 2]. However the phase and the group velocities of the Lamb waves are dependent on the frequency and their measurements are more complicated. Therefore conventional ultrasound velocity measurement methods are not completely suitable to measure the velocities of guided waves. In the previous our article [3] the technique for measurement of the group velocity of Lamb waves using the spectrum decomposition technique was proposed. It was demonstrated using the modelled signals that the spectrum decomposition technique enables with some uncertainties to reconstruct the segments of the group velocity dispersion curves.

The objective of this work was to test proposed the group velocity measurement technique based on the spectrum decomposition method using the experimentally measured signals of the asymmetric A_0 and symmetric S_0 modes of Lamb waves propagating in a plate.

The set-up of the experimental measurements

The aluminium plate was selected as an object for verification of the proposed phase velocity measurement technique. The experiments were carried out on the plate with dimensions 1100 x 620 mm and thickness 2 mm (Fig.1). The guided waves were generated by contact type transducers fixed at one position. The receiver was scanned along the distance 60-260mm from the transmitter (Fig.1). The signals were recorded with the step 0.1mm. The transmitter was excited using a single rectangular pulse with the duration 1.67 µs what corresponds to excitation of 300 kHz frequency waves. For the data acquisition, the scanner was control and data acquisition using the ultrasonic system "Ultralab" developed in the Ultrasound Institute of Kaunas University of Technology was used.

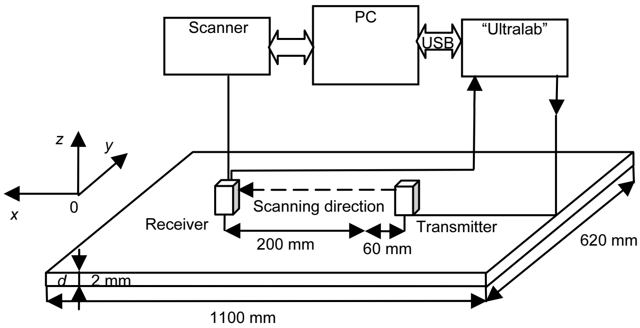

Fig.1. **The set-up of the experiment measurement of the signals of the A_0 and S_0 modes of Lamb waves propagating in aluminum plate [3]**

The results of group velocity estimation

The obtained the B-scan image of the asymmetric A_0 and symmetric S_0 modes propagating in aluminium plate of Lamb waves is presented in Fig.2. As can be seen they can be easily separated in the time domain due to different propagation velocities. In order to simplify analysis they were filtered separately using a rectangular time window. The filtered B-scan images of the both modes are presented in Fig.3 and 4.

The A_0 and S_0 modes signals obtained by experiments were processed using the same spectrum decomposition proposed and described in [3].

The waveforms of the A_0 mode signals measured at two different distances are presented in Fig.5 and the waveform of the S_0 mode in Fig.6. As can be seen, the S_0 mode signals are shorter in the time domain comparing with the A_0 mode signals. The latter posses a long trail of reverberation at the end of the main signal. This fact is probably related to a stronger dispersion of the A_0 mode in the frequency bandwidth.

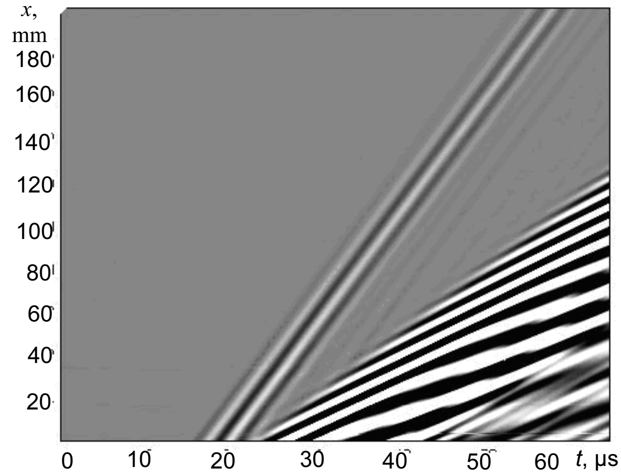

Fig.2. **The B-scan image of the asymmetric A_0 and symmetric S_0 Lamb waves modes propagating in aluminium plate**

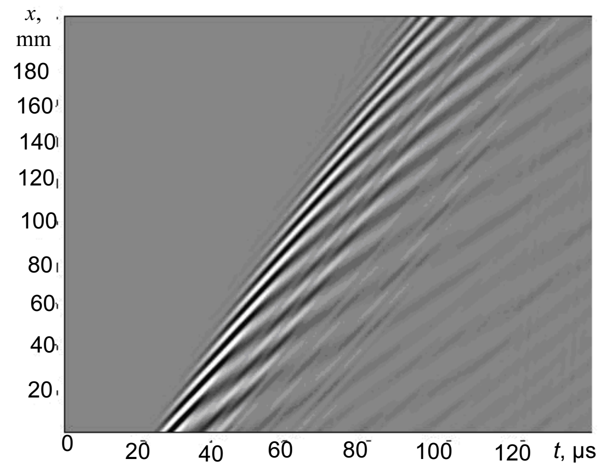

Fig.3. **The B-scan image of the Lamb wave signals measured on the surface of the aluminium plate of A_0 mode**

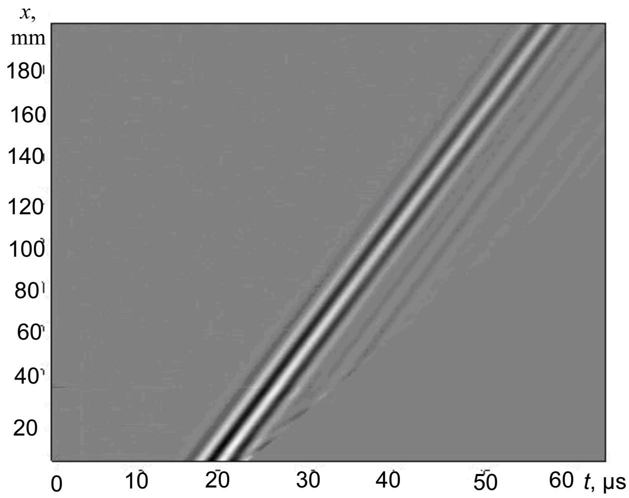

Fig.4. **The B-scan image of the Lamb wave signals measured on the surface of the aluminium plate of the S_0 mode**

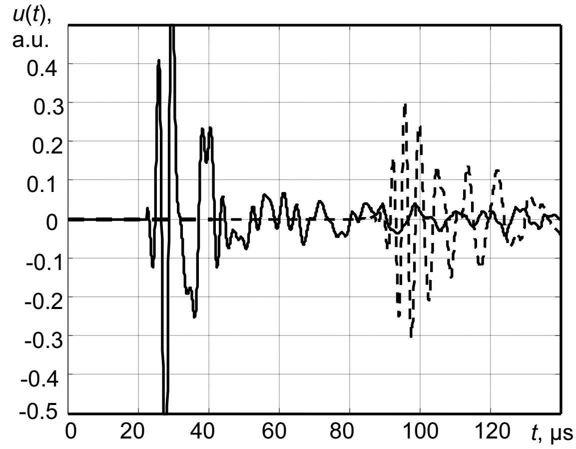

Fig.5. **Two waveforms of the A_0 mode signals measured at distances 60 mm (solid line) and 260 mm (dashed line) from the transmitter**

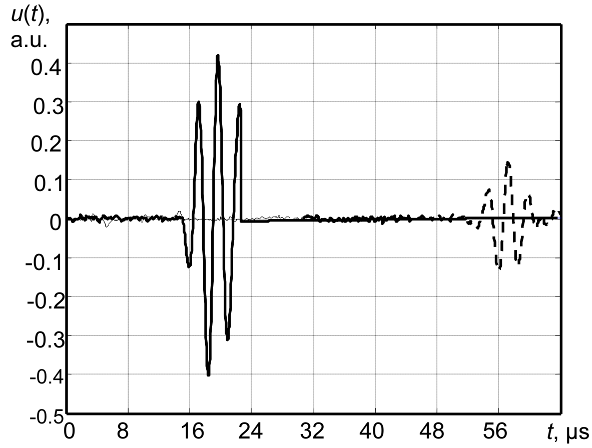

Fig.6. **Two waveforms of the S_0 mode signals measured at distances 60 mm (solid line) and 260 mm (dashed line) from the transmitter**

The frequency spectrums of the A_0 mode experimental signals are presented in Fig. 7 and the S_0 mode in Fig.8. From these graphs can be seen that the frequency spectrums of the first and the last signals of the A_0 mode possesses almost the same bandwidth from 50 kHz up to 350 kHz, whereas the frequency spectrums of the S_0 mode is more narrow and corresponds to the higher frequency bandwidth - from 300 kHz up to 500 kHz at the level -6dB.

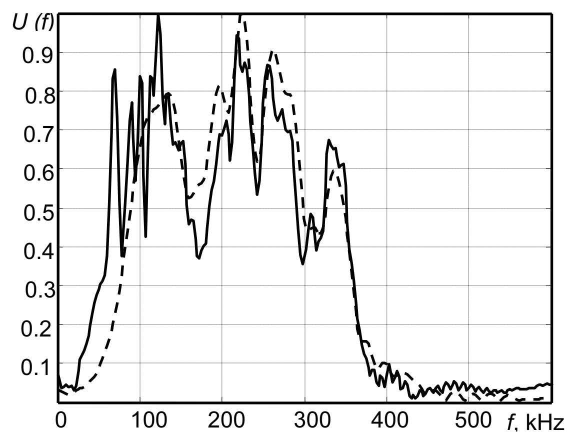

Fig.7. **The frequency spectrums of the A_0 mode experimental signals measured at distances 60mm (solid line) and 260 mm (dashed line) from the transmitter**

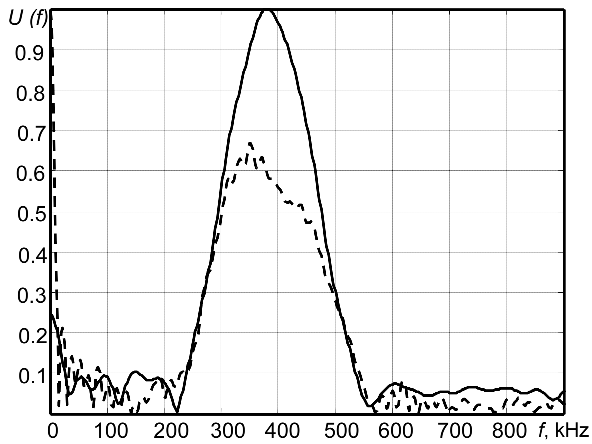

Fig.8. **The frequency spectrums of the S_0 mode experimental signals measured at distances 60mm (solid line) and 260 mm (dashed line) from the transmitter**

According to the spectrum decomposition technique the filters with central frequencies from 100 kHz up to 500 kHz with step 20 kHz were used.

In order to investigate how the bandwidth the filter affects the scattering and errors of the group velocity estimation the bandwidth was varied from 20 kHz to 170 kHz with the step 10 kHz. For group velocity estimation the signals measured at the distance 260 mm and 60 mm were used. It correspond to the first and the last signals in the B-scan data set. It means that the distance between measurement points was 200mm. After processing of the signals using the proposed the spectrum decomposition technique the set of the group velocity values $\{c_{gr,k}; f_k\}$ corresponding to the segment of the dispersion curves were obtained, where $k = 1 \div K$, K is the total number of the obtained values in one frequency bandwidth. The obtained results were compared with the theoretical group velocity dispersion curves and the mean values of the absolute Δ_c, the relative δ_c errors and the standard deviation σ_c were estimated

$$\Delta_c = \frac{1}{K}\sum_{k=1}^{K}\left(c_{gr,k} - c_{gr,k}^T\right),$$

$$\delta_c = 100\% \cdot \frac{1}{K} \cdot \sum_{k=1}^{K}\frac{\left(c_{gr,k} - c_{gr,k}^T\right)}{c_{gr,k}^T},$$

$$\sigma_c = \sqrt{\frac{\sum_{k=1}^{K}\left(c_{gr,k} - c_{gr,k}^T\right)^2}{K-1}},$$

where $c_{gr,k}^T$ are the group velocities at the frequencies f_k according the theoretical dispersion curve.

The obtained results are presented in Table 1 and 2.

The presented results demonstrate that the relative error of the estimated group velocity of A_0 mode using the different filters bandwidth are in the range up to 2.2%, however the best results were obtained using the filter with the bandwidth 70 kHz (Fig.9). Whereas the S_0 mode best results were obtained using the filter of the wider bandwidth equal to 160 kHz (Fig.10). Probably the difference of the optimal bandwidths is related to the different dispersion character of the A_0 and S_0 modes. In the investigated frequency range around 300 kHz the dispersion of the A_0 mode is bigger than the dispersion of the S_0 mode.

Table 1. **The errors and deviations of the A_0 mode group velocity dependences from the different filters bandwidth**

Filter bandwidth, *kHz*	Absolute errors, Δ_c *m/s*	Standard deviation, σ_c *m/s*	Relative errors, δ_c %
20	57.9	38.4	2
30	44.2	25.3	1.56
50	46.3	26.3	1.64
70	**38.1**	**30.8**	**1.39**
90	41.7	42.2	1.5
110	41.6	53.7	1.5
130	49.2	68.1	1.8
150	61	84	2.2

Table 2. **The errors and deviations of the A_0 mode group velocity dependences from the different filters bandwidth**

Filter bandwidth, *kHz*	Absolute errors, Δ_c *m/s*	standard deviation, σ_c *m/s*	Relative errors, δ_c %
20	462	235	7.94
50	88	112	1.6
90	56	52	1.05
110	48.6	36	0.91
130	56.7	44	1.06
150	51.5	33.3	0.96
160	**50.2**	**29.8**	**0.942**
170	50.28	26.2	0.945

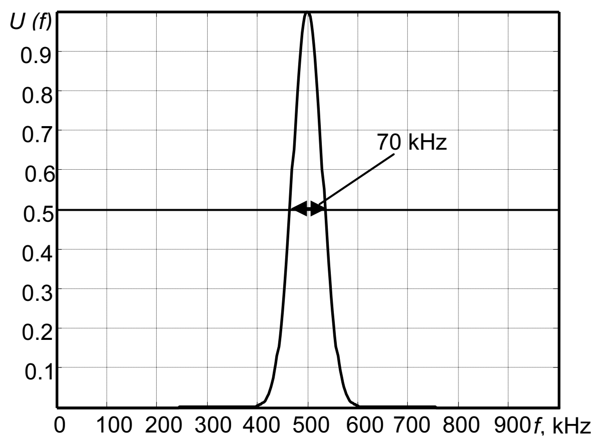

Fig.9. **The frequency spectrum of the filter**

The values of the group velocity of A_0 mode experimentally measured using the filter with the optimal 70 kHz bandwidth overlapped on the theoretical dispersion curve are presented in Fig.11.

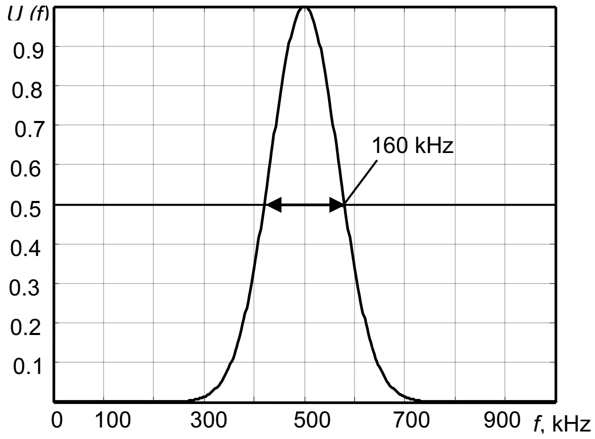

Fig.10. **The frequency spectrum of the filter**

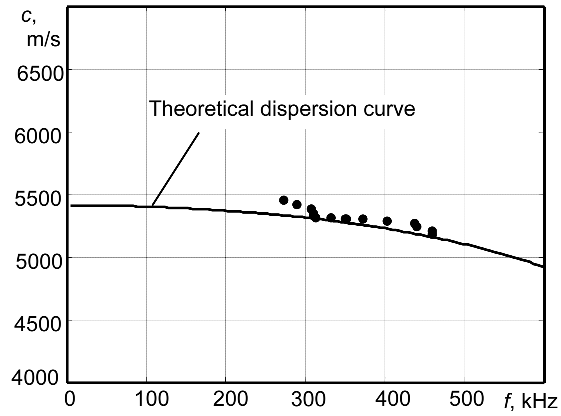

Fig.13. **The group velocities of S_0 mode of Lamb wave obtained using experimental signals and theoretical dispersion curve**

The corresponding relative errors are shown in Fig.12. In most cases the relative errors of the group velocity estimation do not exceed 2%. The similar graphs of the S_0 mode estimation are presented in Fig.13 and 14. In this case the relative errors are scattered in the range 0-2%.

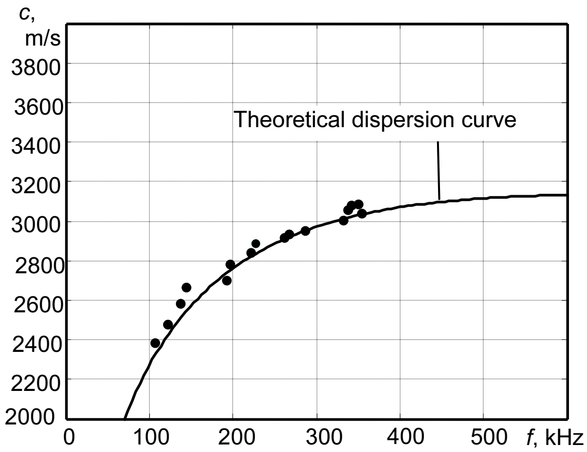

Fig.11. **The group velocities of the A_0 mode of Lamb wave obtained using experimental signals and theoretical dispersion curve**

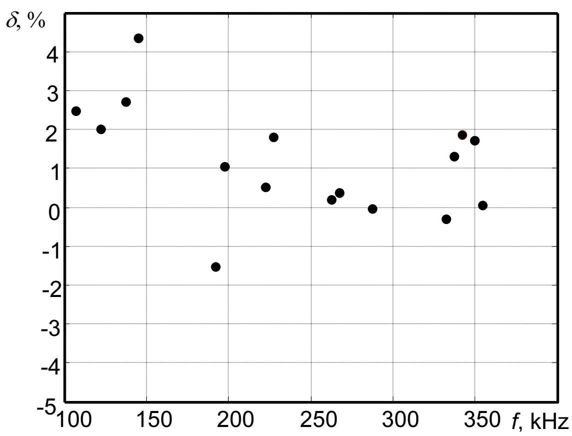

Fig.12. **The relative deviations of the measured group velocity of the A_0 mode of Lamb waves with respect to the theoretical dispersion curve**

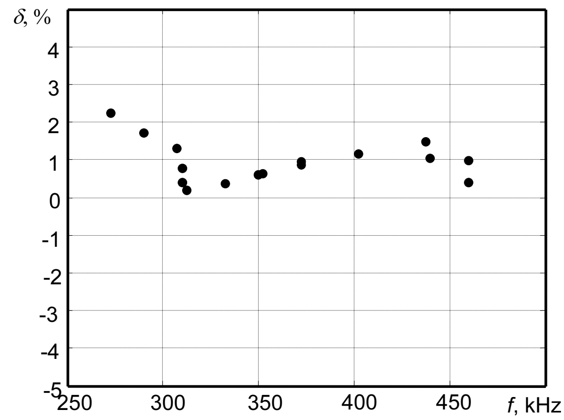

Fig.14. **The relative errors of the measured group velocity of S_0 mode of Lamb waves with respect to the theoretical dispersion curve.**

Conclusions

The experimental investigation demonstrated that the proposed group velocity measurement technique based on the spectrum decomposition enables reconstruction the segments of the dispersion curves of the fundamental modes with relative errors around 2% It was shown also that in order to obtain smaller errors the bandwidth of the filter used for decomposition should be optimised separately for different modes.

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Lembo bangų grupinio greičio aliuminio plokštelėje matavimas dažnių spektro skaidymo metodu

Reziumė

Lembo bangų grupinio greičio priklausomybei nuo dažnio nustatyti buvo pasiūlytas dažnių spektro skaidymo metodas. Ankstesniame darbe šio metodo galimybės buvo tiriamos naudojantis modeliavimo metu gautais signalais. Šio darbo tikslas buvo eksperimentiškai patikrinti grupiniam greičiui matuoti pasiūlytą dažnių spektro skaidymo metodą. Bandymo metu buvo tiriamas nukreiptųjų ultragarso bangų asimetrinės A_0 ir simetrinės S_0 modų sklidimas 1100 mm x 620 mm matmenų, 2 mm storio aliuminio lakšte. Lembo bangos buvo žadinamos įprastiniu ultragarsiniu 300 kHz Gauso gaubtinės trijų periodų signalu. Eksperimentinio tyrimo rezultatai patvirtino pasiūlyto nukreiptųjų ultragarso bangų grupinio greičio matavimo metodo galimybes atkurti skirtingų modų dispersinių kreivių segmentus.

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