# Comparison of modelling and experimental results of the phase velocity measurement of Lamb wave in aluminium plate

**L. Mažeika, L. Draudvilienė, A. Vladišauskas, A. Jankauskas**

*Ultrasound Institute, Kaunas University of Technology,*

*Studentu Str. 50, Kaunas, LITHUANIA. Phone: +370 37 351162. Fax: +370 37 451489.*

*E-mail: ulab@ktu.lt*

**Abstract**

The analysis of the phase velocity measurement using zero-crossing technique presented in previous our articles revealed some regularities which can be exploited for mode identification in the complicated signals of guided waves. However the investigations were carried out using the signals obtained by a finite element method. The objective of the work presented is to carry out similar investigation using experimental signals and to determine is it possible to measure a needed parameter with accuracy sufficient for mode identification. The experiments were carried out on the 2mm thickness aluminium plate with dimensions 1100 mm x 620 mm. The guided waves were excited and recorded using the contact type wide band transducers. The waveform of the excited waves is the 300 kHz burst with Gaussian envelop. The receiver was scanned on the plate in the distance ranges 60-260 mm from the excitation point with the step 0.1 mm. The analysis has shown that scattering of results is almost three times bigger then in the case of the simulated signals. Comparison of the modelling and the experimental results also revealed some differences which partially can be explained by different excitation condition, however the experimental investigation proved main regularities obtained using simulated signals. So, in general the experimental investigation demonstrated the possibility of mode identification based of the phase velocity measurement using the zero-crossing technique.

**Keywords:** guided wave, phase velocity, symmetric mode, asymmetric mode, dispersion curves.

## Introduction

The Lamb waves are very attractive for different non-destructive testing and monitoring applications due to their property to propagate relatively long distance with small attenuation. The other properties of them such as dispersion and presence of multiple modes make them very informative. That means that they carry much information about condition of the object. However extraction of this information is a complicated task. Even identification of the segments of the signal corresponding to different guided wave modes is an ambiguous task. The phase velocity measurement technique based on the zero-crossing approach proposed in the [1-3] enables to identify at least some of the modes and in such a way simplifies the mentioned above tasks. However, the results presented in [1-2] were obtained using simulated signals. So, at least two questions arise. The first one is: will be the same regularities obtained by experimental measurements also? The second one – will be the accuracy of experimental measurements sufficient to enable identification of different modes.

The objective of this work was to investigate experimentally the phase velocity measurement technique based on the zero-crossing method technique and to compare the results with regularities obtained using modelling.

## The set-up of the experiment

The experiments were carried out on the 2mm aluminium plate with dimensions 1100 x 620 mm. The Lamb waves were excited and received using the wide band contact type transducer. The transmitter was attached at a fixed position to the top surface of the plate. The receiver was scanned in the distance range 60-260 mm from the excitation point (Fig.1) with the step 0.1mm. The transmitter was excited by the rectangular pulse with duration 1,67 μs, what corresponds to excitation of 300 kHz frequency waves. For the data acquisition and scanner control the ultrasonic system “Ultralab” developed in the Ultrasound Institute of Kaunas University of Technology was used. The measured signals in the form of B-scan image are presented in Fig.2.

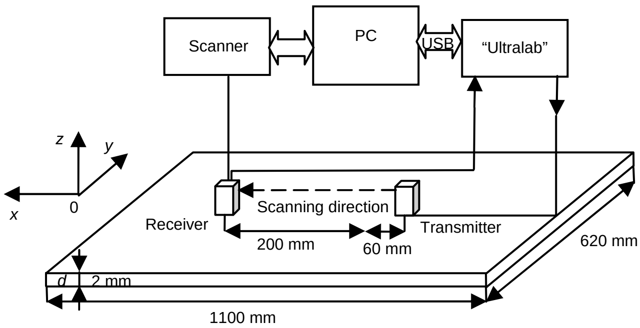


Fig.1. **The set-up of experiment for investigation of the phase velocity measurement techniques of the $A_0$ and the $S_0$ modes of Lamb waves**

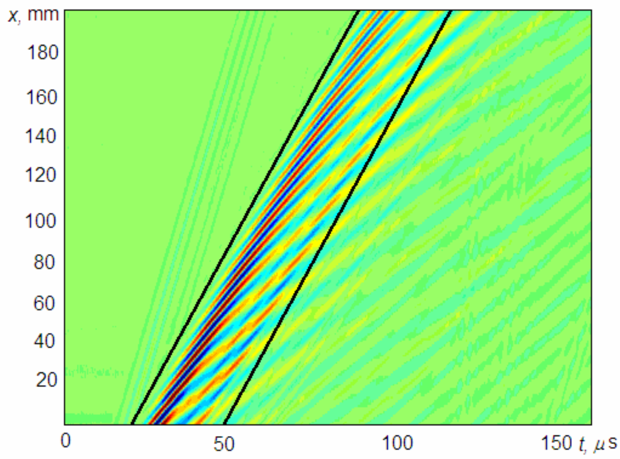


Fig.2. **The B-scan image of the Lamb wave signals measured on the aluminium plate with selected $A_0$ mode**

The propagating $A_0$ mode can be clearly observed in the presented figure. The weak pattern of symmetric $S_0$ can be observed also.

## The phase velocity of $A_0$ mode in aluminium plate

The first difference between the experimental measurements and modelling which can be observed in the B-scan is in the fact that the waves of each of the modes to be analysed can not be generated separately. As can be seen in Fig.2 both modes propagate from the excitation position. Of course, the amplitude of the symmetric mode is much smaller because this mode is not excited efficiently using a direct type longitudinal wave transducer. So, in order to measure the phase velocity of the slower $A_0$ mode it should be filtered using a moving time window. The boundaries of this window are shown in the Fig.2 by solid lines. Another feature of the generated $A_0$ mode waves which can be observed in Fig.2 is presence of different frequency component in the signal. The frequency spectrum of $A_0$ mode signal is presented in Fig.3. In the same figure the spectrum of the signal used in the modeling is presented also. The essential difference of the spectra can be observed especially in a low frequency region. The waveform of the signal corresponding to the $A_0$ mode is presented in Fig.4.

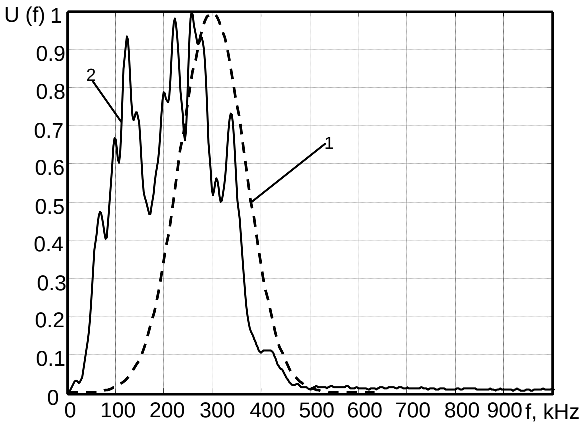


Fig.3. **The normalized frequency spectrums of the $A_0$ mode signal measured at the distance 160 mm (2) and the signal used in the modelling (1)**

The four zero-crossing instants were measured in each signal recorded at different distances. Using this data and exploiting the technique described in [1, 2] the durations of different half periods were estimated (Fig.5). As can be seen the dependency of these durations versus a distance possess the same character defined by modelling as typical for the $A_0$ mode. The dependency of the averaged phase velocity and the averaged equivalent frequency on the distance obtained using the same technique as described in [1-2] are presented Fig.6 and Fig.7. The values of the phase velocity obtained using the zero-crossing points which are closer to the front of the signal (first and second) are higher comparing to the phase velocities obtained using later ones. This regularity fits well with the dependency of the equivalent frequency which demonstrates that half periods in the front of the signal are slightly shorter in time. As the phase velocity of the $A_0$ mode of Lamb waves increases with a frequency, the measurement of the phase velocity using these half periods should give higher values. The obtained values of the phase velocity and corresponding equivalent frequencies enable to overlap the experimental results on the theoretical dispersion curve (Fig.8). A very good coincidence of experimental and theoretical results can be observed. The relative errors of the experimentally measured phase velocity with respect to the theoretical one are presented in Fig. 9 and does not exceed 2%.

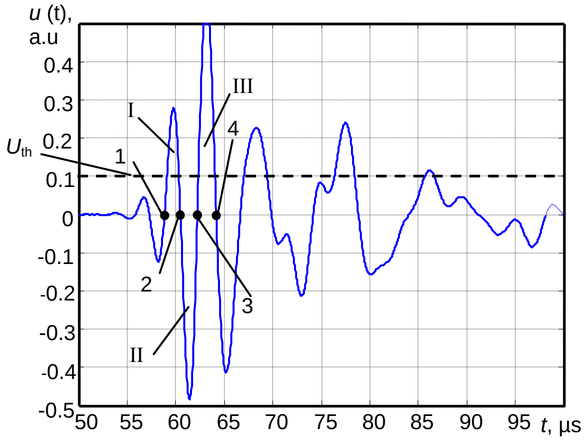


Fig.4. **The waveform of the $A_0$ mode signal measured at distance 160mm from transmitter.**

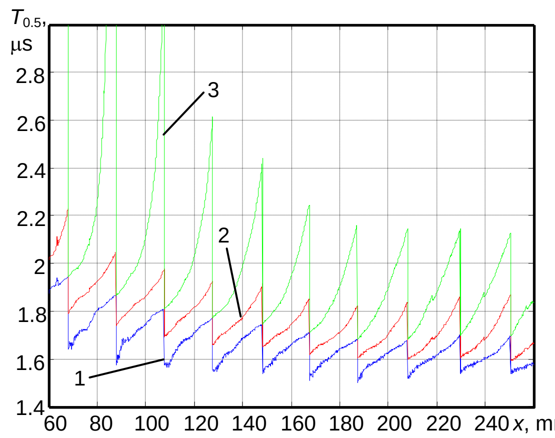


Fig.5. **Duration of different half periods versus distance: 1,2,3 are the numbers of half periods in the burst of the signal**

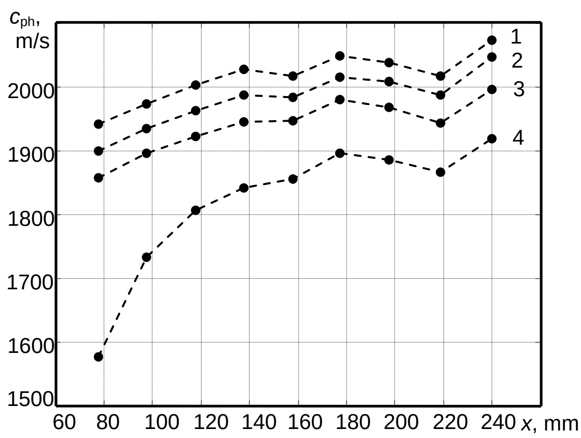


Fig.6. **The phase velocity of $A_0$ mode of Lamb wave versus distance from transmitter obtained using different zero-crossing instances in the measured experimental signals.**

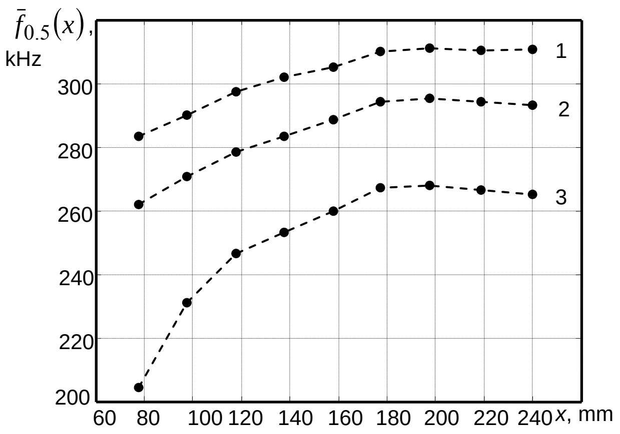


Fig.7. **The equivalent frequencies of different half periods of the $A_0$ mode signal versus distance from transmitter obtained using different zero-crossing instances in the measured experimental signals**

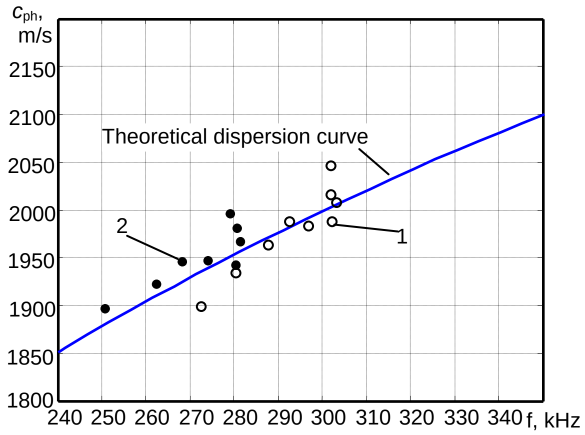


Fig.8. **The phase velocities of $A_0$ mode of Lamb (dots and circles) wave obtained using first two zero-crossing instance in the measured experimental signals overlapped on the theoretical dispersion curve (solid line)**

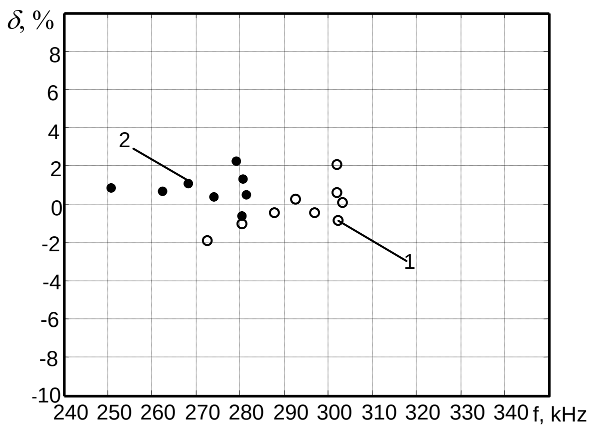


Fig.9. **The relative errors of measured phase velocity of $A_0$ mode of Lamb waves with respect to theoretical dispersion curve.**

## The phase velocity of $S_0$ mode in aluminium plate

In similar way the signals corresponding to the propagating $S_0$ mode of Lamb wave were analysed. The B scan image with zoomed colour coding scale and denoted boundaries of moving time window for selection of necessary signal is presented in Fig.10. As can be seen, at closer distance from transmitter it is impossible to filter $S_0$ mode signals completely - they are interfering with $A_0$ mode wave. However at longer distances these two modes do not interfere with each other. The waveform of the $S_0$ mode signal and it frequency spectrum are presented in Fig.11 and Fig.12. The signals of both modes were measured during the single experiment and as consequence

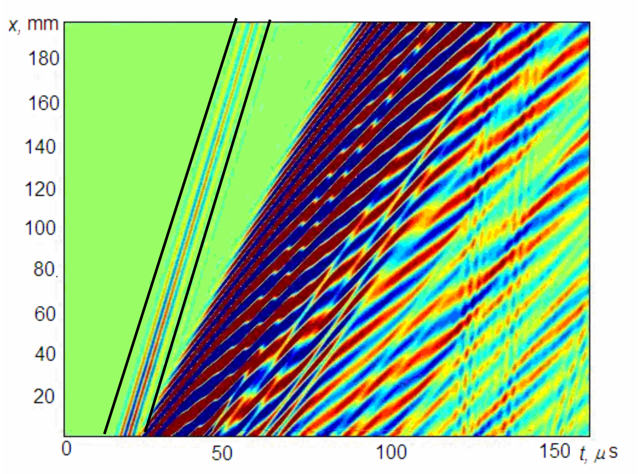


Fig.10**. The B-scan image of the signals measured on the aluminium plate with selected $S_0$ mode signals**

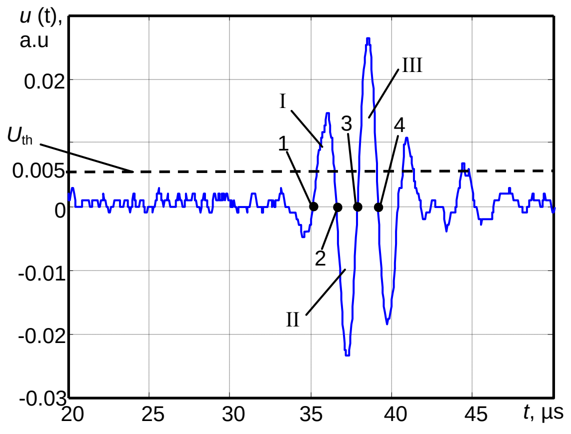


Fig.11. **The waveform of the $S_0$ mode signal measured at the distance 160mm from transmitter.**

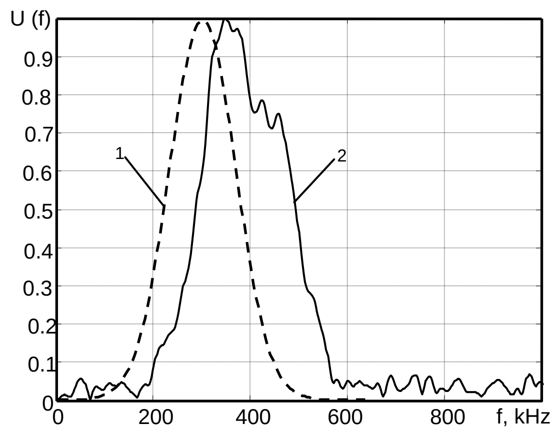


Fig.12. **The normalized frequency spectra of the $S_0$ mode signal measured at the distance 160 mm (2) and the signal used in the modelling (1)**

the signals of $S_0$ mode are acquired on the limits of the dynamic range and contain significant numerical noise. It can be noted that the signal of generated $S_0$ mode possess higher frequency comparing with $A_0$ mode.

The obtained averages values of the phase velocity and equivalent frequency are presented in Fig.13 and 14. In this case some mismatch between experimental and measured results can be observed also. In the case of modelling with increase of the distance the difference between the phase velocities obtained using different zero-crossing points increases also [3]. In the case of the presented experiments the difference between corresponding phase velocity values reduces with distance.

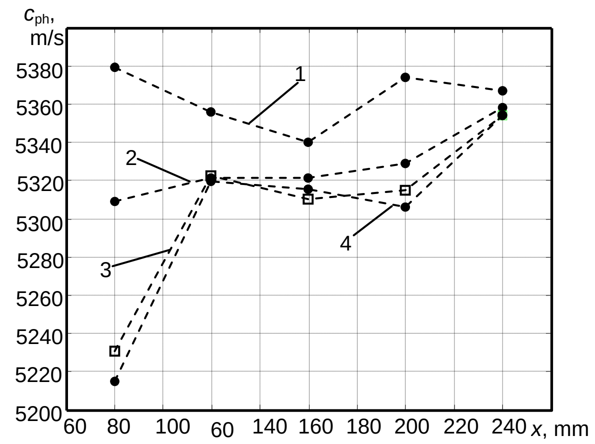


Fig.13. **The phase velocity of $S_0$ mode of Lamb wave versus distance from the transmitter obtained using different zero-crossing instants in the measured experimental signals**

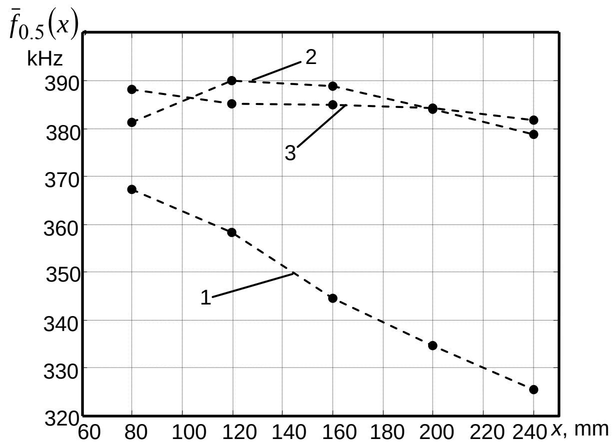


Fig.14. **The equivalent frequencies of different half periods of the $S_0$ mode signal versus distance from the transmitter obtained using different zero-crossing instants in the measured experimental signals**

The clear explanation can not be obtained from the presented investigations due to difference of wave excitation and measurement conditions in the modelling and experiment. The strong scattering of the results obtained at close distances can be due to interference between two propagating waves. The dependencies of the equivalent frequency versus a distance are more regular and demonstrate similar dependencies typical for $S_0$ mode as in the modelling that is, the equivalent frequencies of the half periods of the signal with bigger numbers are bigger. The obtained variations of the equivalent frequency depending on the number of half period both for $A_0$ and $S_0$ modes are presented in Fig.15. The experimentally measured values of the phase velocity of the $S_0$ mode overlapped on the theoretical dispersion curve and relative deviation between them are presented in Fig.16 and 17.

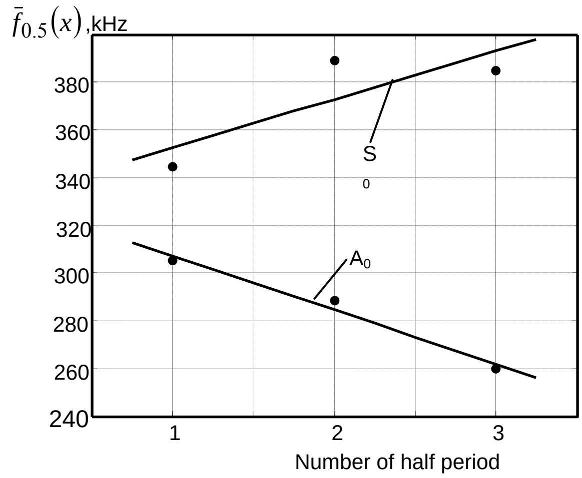


Fig.15. **Variations of the equivalent frequency of the different half periods in the case of $A_0$ and $S_0$ mode signals at the distance 100mm obtained using experimental signals**

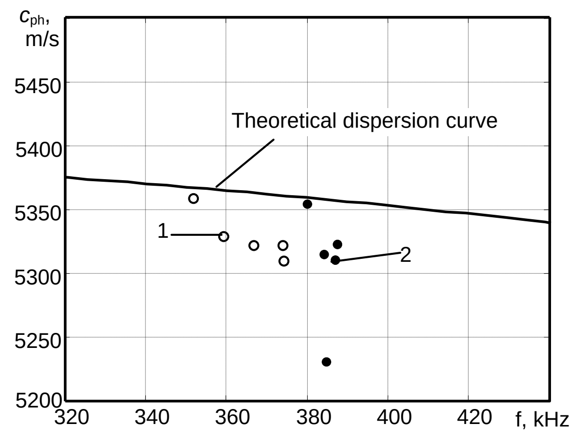


Fig.16. **The phase velocities of $S_0$ mode of Lamb wave (dots and circles) obtained using the first two zero-crossing instants in the measured experimental signals overlapped on the theoretical dispersion curve (solid line)**

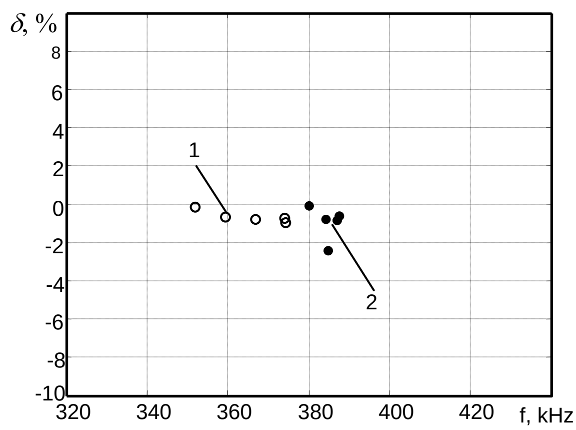


Fig.17. **The relative errors of measured phase velocity of $S_0$ mode of Lamb waves with respect to the theoretical dispersion curve.**

## Conclusions

Comparison of the modelling and experimental results revealed some differences which partially can be explained by different excitation and measurement conditions, however the experimental investigation proved the main regularities obtained using simulated signals. In general, the experimental investigation demonstrated that the estimation of the equivalent frequencies of different half periods in the signal can be used for mode identification.

**References**

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**Eksperimentinių ir modeliavimo rezultatų, gautų matuojant Lembo bangų fazinį greitį, palyginimas**

Reziumė

Atlikus Lembo bangos $A_0$ ir $S_0$ modų, taip pat fazinio greičio matavimo tyrimus naudojant signalus, gautus modeliavimo metu, buvo nustatyti tam tikri dėsningumai, įgalinantys atpažinti modas. Šio darbo tikslas buvo eksperimentiškai patikrinti dėsningumus, gautus palyginus modeliavimo ir teorinių skaičiavimų rezultatus. Eksperimentiškai buvo tiriamas Lembo bangų sklidimas aliuminio lakšte, kurio matmenys 1100 mm x 620 mm, o storis 2 mm. Bangoms žadinti ir priimti buvo naudojami kontaktiniai mažo skersmens keitikliai. Signalai buvo registruojami nuo 60 mm iki 260 mm atstumu nuo siuntiklio 0,1 mm žingsniu. Matavimai buvo atliekami 300 kHz dažnio aplinkoje. Nustatyta, kad eksperimento metu gautų fazinio greičio verčių sklaida beveik tris kartus didesnė, palyginti su modeliavimo rezultatais. Palyginus eksperimentų rezultatus, išryškėjo tam tikri skirtumai, greičiausiai sąlygoti skirtingų bangų žadinimo sąlygų, tačiau pagrindiniai dėsningumai, būdingi tam tikrai modai, išliko. Taigi eksperimentiniai tyrimai patvirtino skirtingų modų atpažinimo pasiūlytuoju metodu galimybes.

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