KAUNAS UNIVERSITY OF TECHNOLOGY

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DEVELOPMENT AND INVESTIGATION OF METHOD FOR AIR COUPLED LAMB WAVE EXCITATION IN PLATE STRUCTURES USING ULTRASONIC ARRAY

Summary of Doctoral Dissertation

Technological Sciences, Electrical and Electronics Engineering (01T)

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1. INTRODUCTION

The contemporary industry manufactures a lot of items based on differently shaped plate structures. Such structures can be found in cars, trucks, boats, aircraft, wind turbines, tubing, tanks and technological vessels. Various primary shapes, such as panels, tin, foil or film elements, are used. These primary shapes can be manufactured from metals, plastics, paper, cardboard, veneer, GLARE (Glass Laminate Aluminum Reinforced Epoxy), GFRP (Glass Fiber Reinforced Plastic) or CFRP (Carbon Fiber Reinforced Polymer). In order to achieve the required quality, a number of testing methods have been developed and used.

Lamb (or guided) waves are widely applied in NDT&E (Non Destructive Testing and Evaluation) of plate structures. These waves are commonly excited by transferring ultrasonic transducer vibrations to the material under the test through the thin layer of a liquid couplant. Yet there are a lot of occasions when couplants may damage or contaminate the tested material. Some of the well-known examples are paper, cardboard, wood, plastics, composite and aerospace materials. In these cases, Lamb waves are excited without the direct contact between the transducer and the material under the test.

Non-contact Lamb wave excitation methods are frequently used in NDT & E. Vibrations may be excited by using lasers, EMATs (Electro-Magnetic Acoustic Transducer) and electrostatic methods. Air-coupled generation of Lamb waves in plate materials is becoming a very popular and state-of-the-art method in NDT. The popularity of this method is still growing up – yet its broader usage is definitely limited by a very serious drawback: the total insertion losses for the entire air-coupled system may typically be 120–160 dB, thus optimum vibration excitation in the tested material is needed.

Acoustic waves are attenuated in the air and in the tested material. The attenuation non-linearly grows when the system frequency is increased. The frequency is selected as low as possible, and it usually never exceeds 1 MHz. Excitation of low frequency Lamb waves is very important whenever the testing is performed in large structures.

Air-coupled excitation of Lamb waves can be performed in two propagation cases. Leaky Lamb waves at sonic regime can be excited when the sound velocity in the air is lower than the phase velocity. This excitation method is usually applied in composites because the leakage grows significantly in the defected area. By decreasing the system frequency, the subsonic regime can be reached. Then, the Lamb wave phase velocity becomes smaller than the sound velocity in the air. In this case, the propagating slow Lamb waves are entrapped in the structure, and the leakage field exists only in the near field zone. These vibrations are called evanescent Lamb waves. They are used in biosensors in order to measure the mass of small particles and to establish the physical parameters of the soil.

Excitation and usage of evanescent Lamb waves is very important if we want to extend the potential of NDT&E.

Objective and tasks

The main objective of the dissertation is the development and investigation of a new ultrasonic method enabling air-coupled slow Lamb wave excitation in thin isotropic plastic films using the phased array. In order to achieve this objective, the following tasks have been outlined:

1. Analysis of Lamb wave features and their excitation methods.
2. Selection of the most appropriate air-coupled Lamb wave excitation numerical model.
3. Numerical and experimental investigation of leaky Lamb waves air-coupled excitation.
4. Development of a new method for air-coupled slow Lamb wave excitation, its numerical and experimental investigation.

Scientific novelty of the work

1. A new air-coupled slow A_0 Lamb wave mode excitation method by using matched size phased ultrasonic array has been created. The pitch of the matched size phased array is equal to the Lamb wavelength in the material under the test.
2. By applying the new air-coupled method, the slow A_0 Lamb wave mode can be excited in plastic films when the A_0 Lamb wave mode phase velocity is lower than the sound velocity in the air.
3. Numerical investigation of air-coupled slow Lamb wave excitation in a clear polyvinyl chloride (PVC) film has been performed. Excitation process optimization laws have been formulated.
4. Experimental investigation of slow Lamb wave excitation has been performed in a thin clear PVC film. The velocity of the propagating ultrasonic wave has been measured and compared with the theoretical value. The obtained results confirmed the possibility of the excitation of A_0 mode in the subsonic regime by applying multielement arrays in contact and air-coupled methods.

Approbation of results

Results of the scientific research have been published in three articles. Two articles are abstracted and indexed in the main list of the Institute of Scientific Information (ISI). One article has been issued in the proceedings of an international conference. Scientific investigations have been presented in two international conferences.

Results presented for the defense

1. Performing air-coupled Lamb wave excitation in thin plastic films when the A_0 mode phase velocity is slightly greater than the sound velocity in the air and the optimum excitation angle may be calculated by using Snell's law, the relative elongation of the normal displacement impulse is obtained by comparing it with the excitation impulse.
2. Slow Lamb wave A_0 mode can be excited by being air-coupled with ultrasonic array when the A_0 mode phase velocity is lower than the sound velocity in the air and the optimum excitation angle cannot be calculated by using Snell's law. When this method is applied, the relative elongation of the normal displacement impulse compared with the excitation impulse is not obtained.
3. The optimum regime of the slow Lamb wave A_0 mode air-coupled excitation is obtained by properly selecting delay times for the array elements. These times may be established by optimizing the air-coupled excitation process according to the maximum normal displacement amplitude. By performing a newly developed algorithm, a stepped array delay scheme is obtained.

Structure and volume of the dissertation

The doctoral dissertation consists of an Introduction, 4 main chapters, conclusions, an outline of potential investigation trends for the future, a list of references and a list of scientific publications. The entire content is presented in 98 pages featuring 177 figures, 4 tables, 46 mathematical expressions and 96 references.

2. REVIEW OF LAMB WAVE EXCITATION METHODS

In this chapter, a review of Lamb wave excitation methods is presented. The methods were classified in two main groups according to the type of the mechanical contact between an ultrasonic transducer and the material under the test. Contact Lamb wave excitation methods are characterized by the direct mechanical contact between an ultrasonic transducer and the material under the test. A variety of piezoelectric and electrostatic methods is used in order to achieve this objective. Even though the main advantage of these methods is their accuracy and simplicity, still the direct mechanical contact limits their applicability in mass production. Non-contact Lamb wave excitation methods do not require direct mechanical contact between an ultrasonic transducer and the material under the test. Various thermoacoustic methods as well as electromagnetic acoustic and air-coupled piezoelectric transducers are used. The air-coupled piezoelectric Lamb wave excitation method seems to be the most universal – yet its applicability is limited by large attenuation losses typically reaching 120-160 dB for the entire air-coupled system. It seems very promising to investigate, optimize and improve the air-coupled Lamb wave excitation process by using arrays. No investigations have been previously performed where Lamb waves are excited in thin plastic films by using low frequency (< 100 kHz) air-coupled piezoelectric array.

3. MODEL OF AIR-COUPLED LAMB WAVE EXCITATION

In the case of an isotropic single layer plate, the entire air-coupled Lamb wave system can be modeled analytically. For this purpose, open source software tool *The Lamb Matlab Toolbox* (*Beta version 0.1*) has been used. The software tool was checked, and corrections were made in terms of the excitation signal generation, transducer geometry calculation, excitation and the emission zone coordinate points calculation. A new set of functions was devised for emitting the transducer-generated pressure signal visualization. Two modeling methods are used in *The Lamb Matlab Toolbox*:

1. The Impulse Response Method (IRM) is used for the calculation of acoustic pressure generated by a rectangular piston (or an array of rectangular pistons) in the air medium.
2. The Time Harmonic Solution (THS) method is used for the calculation of normal displacement signals in the plate when these signals are excited by time harmonic signals exerting pressure over a finite set of finite radius circular regions.

These methods allow performing calculations in particular spatial points; thus a variety of 2D and 3D tasks can be solved.

4. INVESTIGATION OF LEAKY LAMB WAVES EXCITATION

Air-coupled leaky Lamb wave excitation is very popular in NDT & E. This method is denoted by large attenuation losses. That is why the entire excitation process requires more detailed investigation and optimization.

Investigation of the influence of piston position on air-coupled excitation

Air-coupled leaky Lamb wave excitation was simulated in an aluminum plate of d = 2 mm thickness. In order to solve this task, a simplified 2D approach was appropriate; it was consequently used (Fig. 1.)

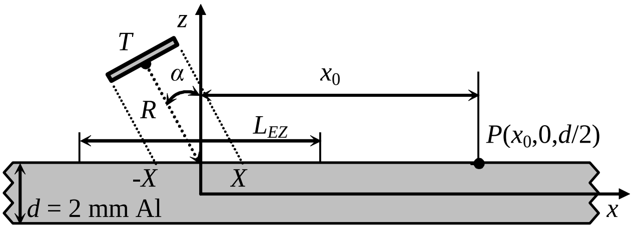

Fig. 1. A schematic diagram of air-coupled Lamb wave excitation in an aluminum plate.

The square air-coupled transducer *T* has dimensions 15 mm × 15 mm, it is located at distance *R* from the excitation zone centre on the plate surface and deflected by incidence angle *α*. The length of the *x*-line type excitation zone is set at L_{EZ} = 70 mm, the zone is filled with 176 circular excitation sub-regions of the *a* = 0.2 mm radius. The normal displacement signal is calculated at point *P* situated on the plate's surface at x_0 = 50 mm distance from the excitation zone centre.

The surface of transducer *T* radiates a narrow-band particle velocity signal of 20 cycles sinus pulse with the sinus type envelope, 1 m/s amplitude and 100 MHz sampling frequency. Two different frequencies were used: 150 kHz with the (50-500) kHz limited bandwidth and 260 µs THS time limit (Fig. 3); 500 kHz with the (300-900) kHz limited bandwidth and 180 µs THS time limit.

The structure of the transducer pressure field changes along distance *R*. Three zones constitute the researched area: the near field, the intermediate field and the far field; thus Lamb wave excitation conditions are different in the three areas. The near field limits *NFL* of the transducer *T* depend on the frequency. For 150 kHz, the value of NFL_{150} is NFL_{150} = 33.68 mm, and for 500 kHz, the level of NFL_{500} is NFL_{500} = 112.34 mm. Based on the 150 kHz frequency near field limit, three distances *R* were chosen: *R* = 10 mm for the near field; *R* = 35 mm for the intermediate field (when the transducer is deflected, one part of the excitation zone gets into the near field while the other is in the far field pressure zone), and *R* = 45 mm for the far field. Deflection angle *α* of transducer *T* was being changed from 0˚ to 30˚ at a step of 0.5˚. The normal displacement signal of the A_0 Lamb wave mode was calculated at point *P*. The value of maximum positive peak amplitude u_{max} is taken; dependencies versus deflection angle *α* and distance *R* were plotted (Fig. 2, 3).

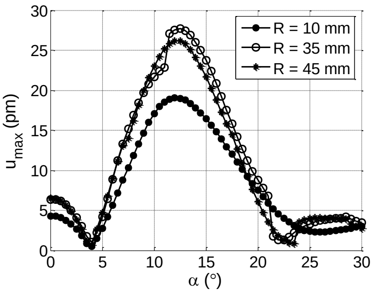

Fig. 2. The dependency of A_0 mode normal displacement amplitude maximum positive peak for 2 mm aluminum plate when using 150 kHz excitation signal.

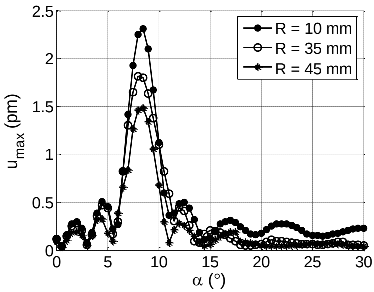

Fig. 3. The dependency of A_0 mode normal displacement amplitude maximum positive peak for 2 mm aluminum plate when using 500 kHz excitation signal.

A sharp jump in the curve (Fig. 2, R = 35 mm, α = 11º→11.5º) near the optimum excitation angle was observed. It is presumed that the jump occurs when the pressure signal amplitude and the phase spatial characteristics change in the intermediate field zone.

The experimental dependency was obtained when using two rectangular air-coupled transducers (Fig. 4.) with the dimensions of 10 mm × 20 mm. The emitter was deflected with respect to the aluminum plate; the receiver was tuned according to the signal maximum and then fixed appropriately. Five peak-to-peak dependencies were obtained which were then averaged and normalized. A reasonable degree of similarity between the theory and the experiment was obtained (Fig. 5.).

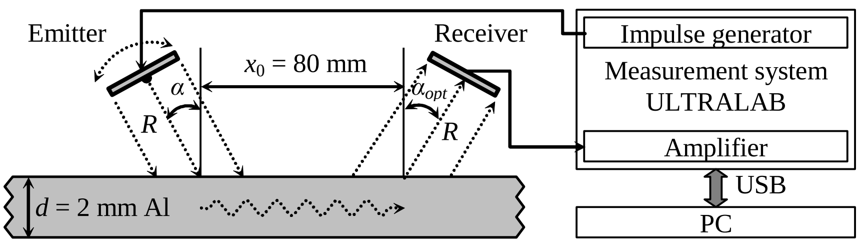

Fig. 4. A schematic diagram of the air-coupled Lamb wave excitation and reception experiment

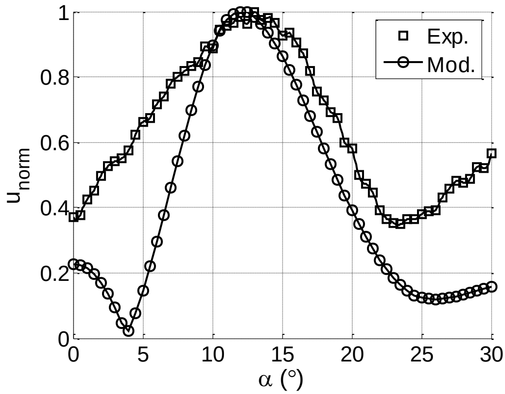

Fig. 5. Experimentally obtained and modeled normalized amplitude dependency versus the incidence angle when using 150 kHz excitation signal at R = 10 mm.

Investigation of plate thickness influence on air-coupled excitation

Air-coupled leaky A_0 Lamb wave mode excitation was simulated in a clear polyvinyl chloride (PVC) film. The square transducer T and a simplified 2D approach were used (Fig. 6). Four different PVC thicknesses d were investigated: d = 1, 0.5, 0.25 and 0.15 mm. The A_0 mode phase velocity dispersion curves were calculated by using the SAFE (Semi Analytical Finite Element) method (Fig. 7).

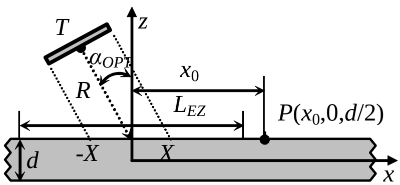

Fig. 6. A schematic diagram of air-coupled Lamb wave excitation when using transducer T

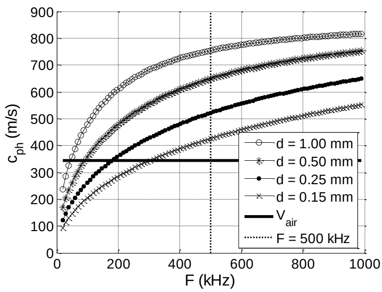

Fig. 7. Phase velocity dispersion curves for A_0 mode in clear PVC films of thickness d

Square transducer T used for excitation has dimensions 18 mm × 18 mm and is located at a distance of R = 30 mm from the excitation zone centre on the film surface and deflected by the optimum incidence angle α_{opt}. The length of the x-line type excitation zone is set at L_{EZ} = 40 mm, the zone is filled with 201 circular sub-regions of the a = 0.1 mm radius. The surface of the transducer T radiates the particle velocity signal of the 5-cycle harmonic pulse with the sinus type envelope, 500 kHz main frequency, 1 m/s amplitude and 100 MHz sampling frequency. The pulse bandwidth was limited to (303-950) kHz.

The normal displacement pulse of the A_0 Lamb wave mode is calculated at point P situated on the plate's surface at x_0 = 21 mm distance from the excitation zone centre (Fig. 8 depicts d = 1.00 mm while Fig. 9 represents the data for d = 0.15 mm).

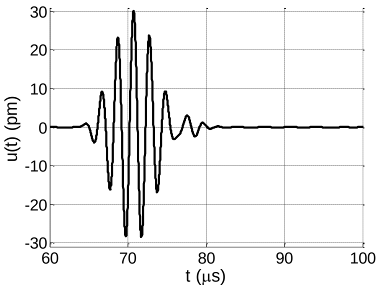

Fig. 8. Normal displacement pulse at point P when d = 1.00 mm

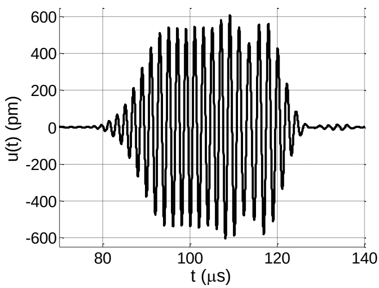

Fig. 9. Normal displacement pulse at point P when d = 0.15 mm

It was observed that the pulse duration and amplitude grows up when the PVC film thickness decreases.

5. INVESTIGATION OF SLOW LAMB WAVES EXCITATION

It is not useful to excite long A_0 mode normal displacement impulses because the interpretation of signals becomes very complex. A new method of air-coupled evanescent A_0 Lamb wave mode excitation using matched size phased array was proposed and investigated.

Air-coupled matched size phased array method

A new excitation method was proposed for the case of $c_{ph} \leq V_{air}$. It is based on the application of an air-coupled planar phased array with rectangular radiators where the array pitch p is equal to the Lamb wavelength: $p = \lambda_{Lamb}$ (Fig. 10).

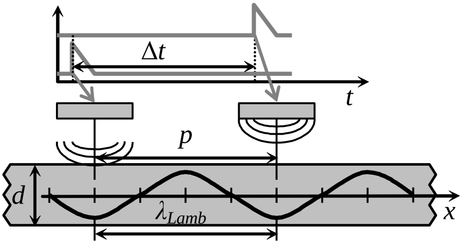

Fig. 10. The principle of air-coupled Lamb wave excitation when using the matched size phased array with rectangular radiators and delayed excitation.

By exciting array elements with appropriate delayed signals, the summation of vibrations in the plate should be achieved. The delay time step between the two elements Δt should be equal to the amount of time required to travel distance p.

Numerical simulation of air-coupled slow Lamb wave excitation

Numerical investigation was performed when simulating air-coupled A_0 Lamb wave mode excitation with the use of matched size planar phased array *A* consisting of 8 rectangular elements (Fig. 11).

As the plate material, clear polyvinyl chloride (PVC) film of d = 0.15 mm thickness was selected. The A_0 mode phase velocity dispersion curve was calculated by using the SAFE (Semi Analytical Finite Element) method (Fig. 12).

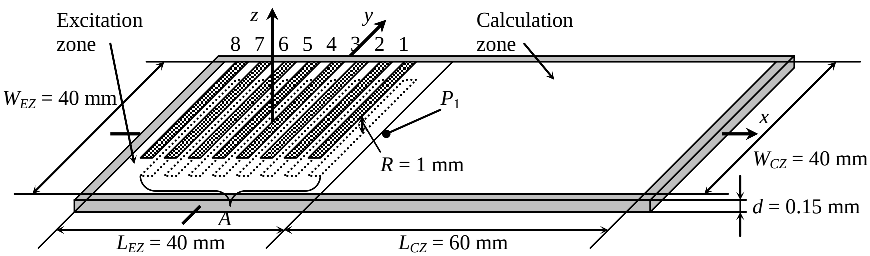

Fig. 11. A schematic diagram of air-coupled Lamb wave excitation when using phased array *A*.

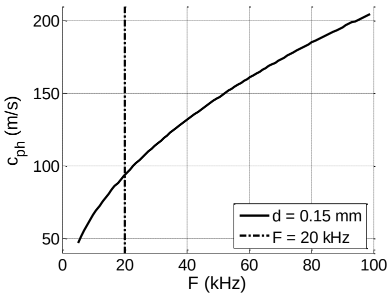

Fig. 12. Phase velocity dispersion curve for A_0 mode in d = 0.15 mm thickness PVC film

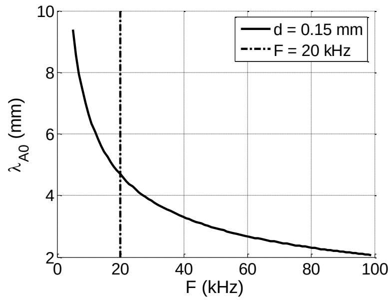

Fig. 13. A_0 mode wavelength dependency versus frequency for PVC d = 0.15 mm

Matched size phased array pitch p and the delay times are determined by the A_0 mode phase velocity (Fig. 12) and the wavelength (Fig. 13) at the selected frequency. According to the proposed excitation method as shown in Fig. 11, the width of the array element should be ≤ ½ λ_{A0}. At high frequencies, this size becomes very small, and the array element cannot be manufactured. For this reason, the main frequency of 20 kHz was chosen where the wavelength of the A_0 mode is λ_{A0} = 4.7 mm. The value of 2 mm was taken as the array element width. The matched size phased array A (Fig. 11) consists of 8 narrow rectangular elements with the dimensions of 2×30 mm and the 2.7 mm space between the elements.

The near field limit for one array element is L_{NF} = 1.1 mm. Maximum pressure values are concentrated in the near field zone; thus the distance R between array A and the PVC film has been chosen at R = 1 mm because it fits into the near field limit. The array A element surface radiates a particle velocity signal of 5 cycles sinus pulse with the sinus type envelope (Fig. 14).

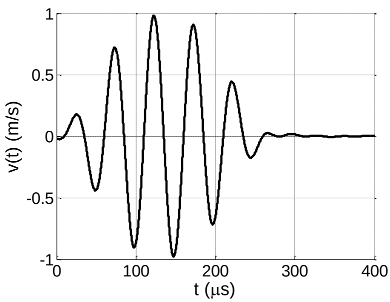

Fig. 14. Array element velocity signal: the main frequency is 20 kHz; the bandwidth equals (10-30) kHz

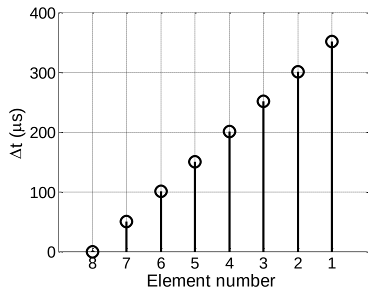

Fig. 15. Array A linear delay scheme with the delay time increased by using a Δt = 50.2 µs step

The generated pressure signal is calculated within the selected finite rectangular excitation zone located on a clear PVC film surface. The most significant pressure values are created in the array A rectangular projection zone with the dimensions of 34.9×30 mm. In order to achieve sufficiently accurate simulation results, the dimensions of the rectangular excitation zone are greater, and the length is set at L_{EZ} = 40 mm, the width measures W_{EZ} = 40 mm, and the zone is filled with 2601 circular sub-regions of the a = 0.4 mm radius.

THS method does not allow calculations of normal displacement signals at the excitation zone – hence the displacement calculation zone is positioned to the right of the excitation zone. The length of the calculation zone is set at L_{CZ} = 60 mm whereas the width is W_{CZ} = 40 mm. The zone is divided into points by using a square grid with a 1 mm step.

Signals of pressure at the excitation zone and signals of the A_0 Lamb wave mode normal displacements at the calculation zone were calculated for the two cases. Then, the maximum positive peak values were taken and plotted. In the first case (Fig. 16, 17), delays for array *A* elements were not involved. In the second case (Fig. 18, 19), the linear delay scheme was used (Fig. 15).

Superposition conditions for pressure signals generated by array *A* elements depend on the employed delay scheme. For this reason, the distribution of the pressure maximum positive peak value at the excitation zone has 4 peaks (p_{max} = 262 Pa) when array *A* elements are being excited simultaneously (Fig. 16), and it develops 14 peaks (p_{max} = 266 Pa) when the delays for the elements are being applied (Fig. 18).

Distributions of the A_0 mode normal displacements maximum positive peak value at the calculation zone acquire virtually the same shape in both cases; however, the delays give about 1.2 times greater normal displacement values (Fig. 17) comparing to the simultaneous excitation (Fig. 19).

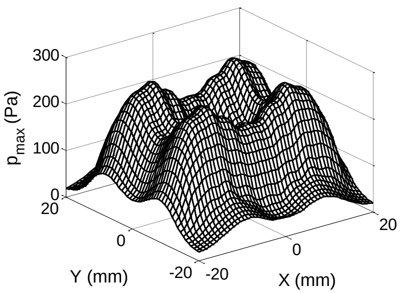

Fig. 16. Distribution of the pressure maximum positive peak value at the excitation zone. No delays for array *A* elements are observed

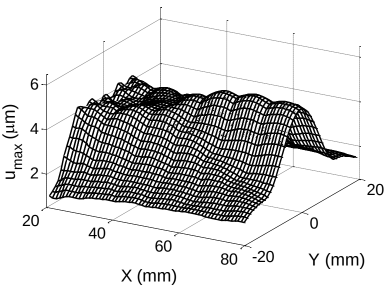

Fig. 17. Distribution of the normal displacement maximum positive peak value at the calculation zone. No delays for array *A* elements are observed

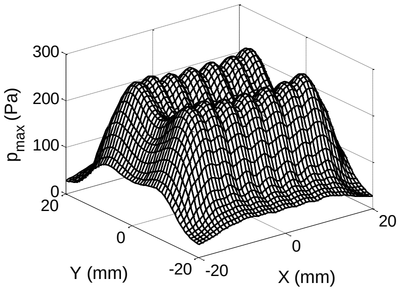

Fig. 18. Distribution of the pressure maximum positive peak value at the excitation zone. The linear array *A* elements delay scheme was being used

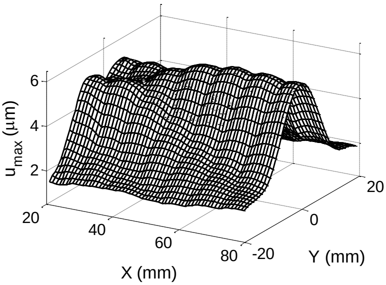

Fig. 19. Distribution of the normal displacements maximum positive peak value at the calculation zone. The linear array *A* elements delay scheme was being used

One point was selected at the calculation zone for the comparison of normal displacement signals in the time domain. Point P_1 (20.5; -0.5; d/2) was picked from the calculated normal displacement distributions because it represents the location which is the nearest to array A and *x*-axis (Fig. 11).

The impulse of the normal displacements signal when all the elements are being excited simultaneously is displayed in Fig. 20. The case of delays being applied is depicted in Fig. 21.

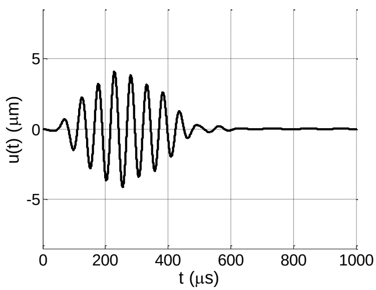

Fig. 20. Impulse of normal displacements at point P_1; no delays for array *A* elements are observed

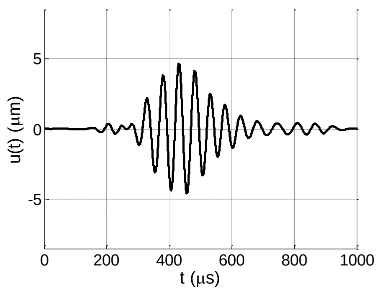

Fig. 21. Impulse of normal displacements at point P_1. Linear array *A* elements delay scheme was being used

When all array *A* elements are being excited simultaneously, the impulse of normal displacements arrives at point P_1 with almost no delay. The use of timings between array *A* elements results in the ≈ 160 μs delayed signal with ≈

1.2 times greater amplitude, and it affects the shape of the signal in the time domain as clear trails are visible at the beginning as well as at the end. The maximum amplitude of these trails is about 20 times lesser than the maximum amplitude of the main pulse.

The trails in the normal displacement signal are being excited by distorted pressure impulses. From the calculated distribution, point *S* (-16.8; 0) was picked which is the nearest point to the center of element No. 8 (-16.45; 0). The total distorted pressure signal is displayed in Fig. 22. The distorted pressure signals are getting formed due to the acoustic cross-talk effect between array elements (Fig. 23).

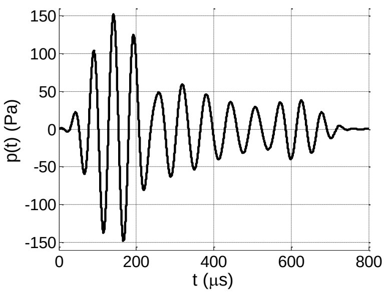

Fig. 22. Total pressure signal at point *S*

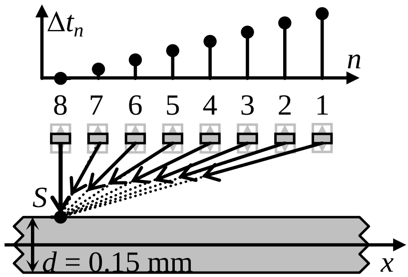

Fig. 23. Formation of a distorted pressure signal under element 8

Distorted pressure signals excite normal displacement signals with trails at the beginning as well as at the end. Analysis was performed with the objection to estimate how the impulse of normal displacement signals is being formed. The signal at point P_1 (Fig. 21) was chosen. It is the superposition of 8 normal displacement signals generated by exerted pressure impulses created by separate air-coupled array elements. Normal displacement signals were added up, the maximum amplitude was detected, and the dependency versus the number of elements was plotted (Fig. 24).

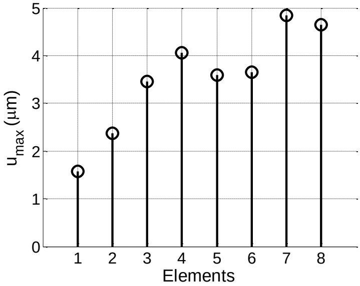

Fig. 24. Dependency of maximum displacement amplitude versus the number of elements

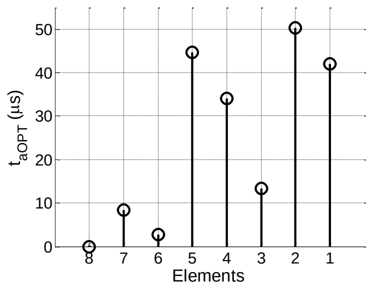

Fig. 25. Advance times for normal displacement signals

A signal generated by using 5 and 6 array elements has an approximately ≈ 1.1 times smaller maximum amplitude when compared to the signal generated by using only 4 array elements. It is clear that the normal superposition process of displacement signals is not optimal and that the impulses are suppressing each other.

It was presumed, that the optimisation of normal displacement signals can be performed by applying additional time shifts for partial displacement signals and by seeking the maximum value of the sum. The recorded advance times are shown in Fig. 25. The dependency of the maximum displacement amplitude versus the number of elements at point P_1 after applying advance times is shown in Fig. 26.

By subtracting advance times (Fig. 25) from the linear delay scheme (Fig. 15), a stepped delay scheme was obtained (Fig. 27).

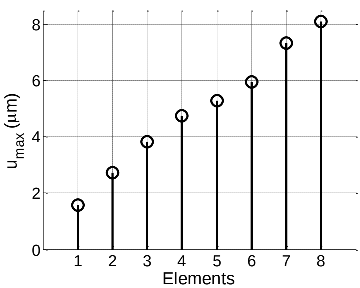

Fig. 26. Dependency of the maximum displacement amplitude on the number of elements at point P_1 after applying advance times

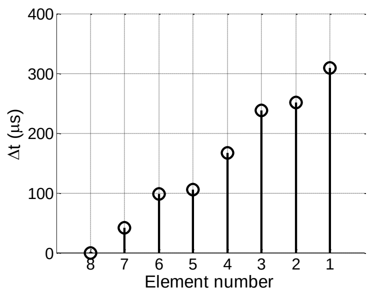

Fig. 27. Array *A* stepped delay scheme

The entire process of excitation was modeled by using a new stepped delay scheme (Fig. 27), and then by obtaining the maximum positive peak values of pressure (Fig. 28); then, the normal displacement maximum positive peak value (Fig. 29) was taken and plotted.

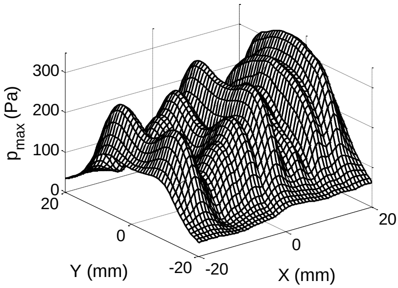

Fig. 28. Distribution of the pressure maximum positive peak value within the excitation zone. Stepped array *A* elements delay scheme was being used

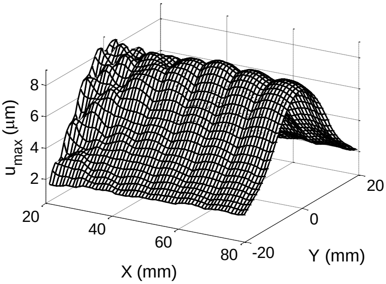

Fig. 29. Distribution of the normal displacement maximum positive peak value within the calculation zone. Stepped array *A* elements delay scheme was being used

The application of the stepped array *A* delay scheme strongly changes the distribution of the pressure maximum positive peak value within the excitation zone (Fig. 28). The absolute maximum value (p_{max} = 367 Pa) is concentrated to the side, next to the calculation zone; it is about 1.4 times greater than the value obtained by using the linear delay scheme. The distribution of normal displacement maximum positive peak values within the calculation zone (Fig. 29) shows about 1.5 times greater maximum amplitudes than in the case of using the linear delay scheme (Fig. 19).

Experimental air-coupled slow Lamb wave excitation

Air-coupled matched size array was produced for slow Lamb wave excitation experiments. Active array elements were manufactured from piezoceramics *Pz29* (company: Ferroperm Piezoceramics A/S). The plates of piezoceramics have the dimensions of 60×60×1 mm.

The main resonance mode of a long and narrow piezoelement is determined by its length. For that reason, eight long and narrow piezoelements with the dimensions of 60×7×1 mm were used. One element had the main resonance frequency *F* = 23.3 kHz, which was 3.3 kHz higher than the value of 20 kHz used in numerical simulations.

A gap between the matched size array elements depends on the A_0 mode phase velocity and the wavelength. In the experiment, a sample of clear PVC film was used. The sample was of *d* = 0.15 mm thickness and A4 size (i.e. 210×297 mm). The obtained simulated dispersion curves are given in Fig. 30.

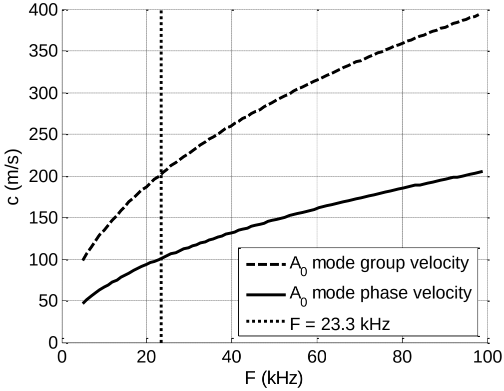

Fig. 30. Simulated phase and group velocity dispersion curves for the *d* = 0.15 mm thickness clear PVC film.

The manufactured matched size air-coupled array is shown in Fig. 31. The array frame was manufactured from glass textolite with double-sided copper foil laminate, and the piezoelements were fixed by using a double-sided bonding tape.

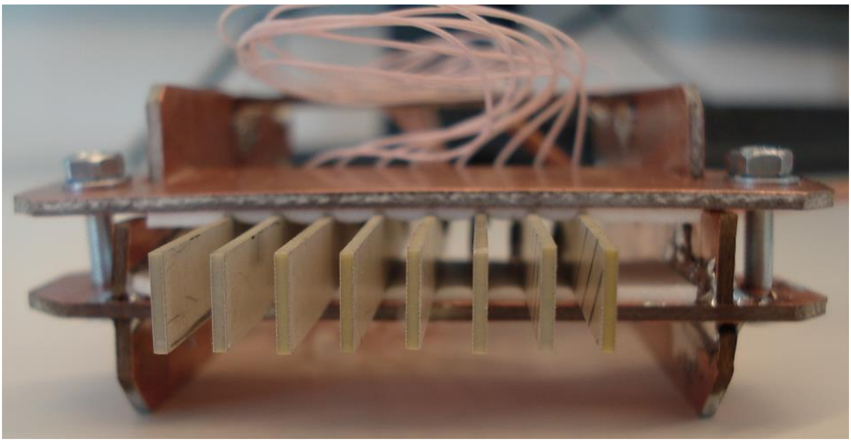

Fig. 31. Manufactured matched size air-coupled array

The array generates pressure signals whose propagation velocity is greater than the Lamb wave propagation velocity. In order to eliminate the influence of pressure signals, a *Polytec* laser interferometer was used for signal reception (Fig. 32).

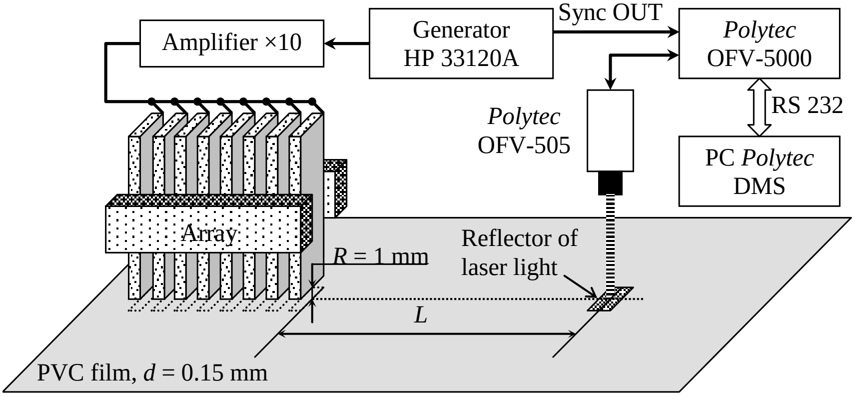

Fig. 32. A schematic diagram of the air-coupled Lamb wave excitation experiment conducted by using a phased array

The matched size phased array is fixed at a R = 1 mm distance from the surface of the clear PVC film. The array is excited with F = 23.3 kHz harmonic voltage pulse. The features of the pulse were as follows: 40 V amplitude, 40 cycle duration and 100 Hz repetition frequency (Fig. 33). In order to improve the reflection of light, a small rectangular 5×4 mm-sized reflector was glued onto the clear PVC film surface.

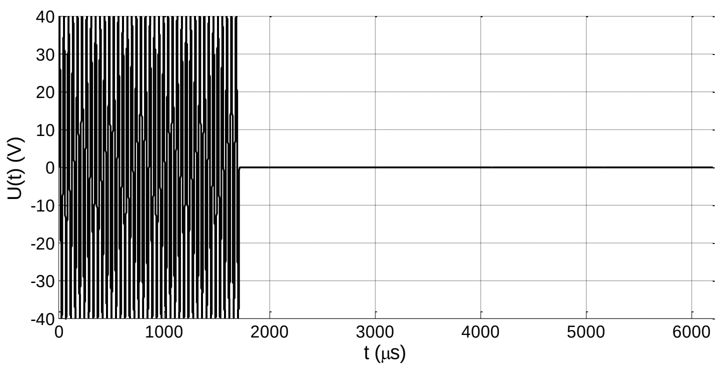

Fig. 33. Voltage pulse for air-coupled array excitation

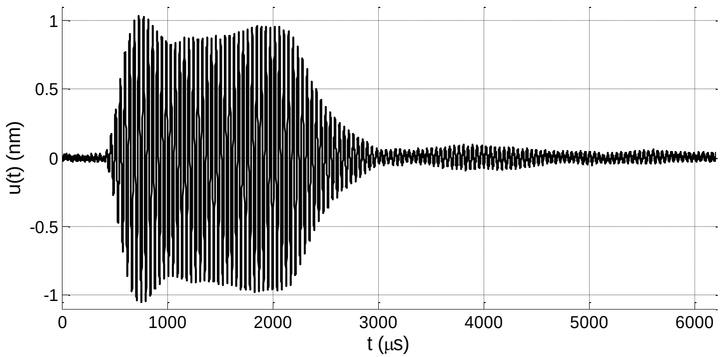

Fig. 34. Normal displacement signal; distance L_1 = 63 mm

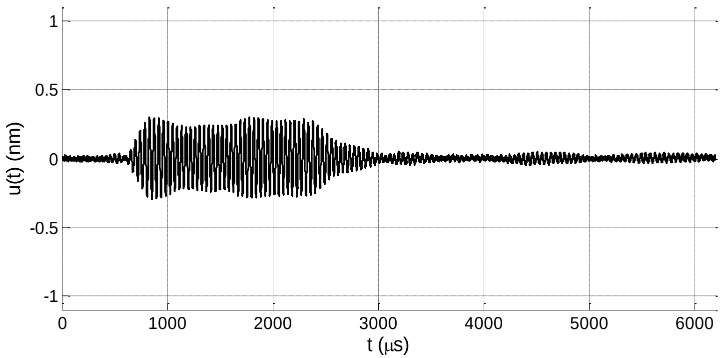

Fig. 35. Normal displacement signal; distance L_2 = 94 mm

Vibrations can be identified by measuring the velocity; hence two signals were obtained at different distances: L_1 = 63 mm (Fig. 34), and L_2 = 94 mm (Fig. 35.). The measurement process was extremely noisy, and the above depicted signals were obtained by averaging 500 measurements.

The delay time between the two signals was obtained by calculating the cross-correlation function $r(t)$ (Fig. 36).

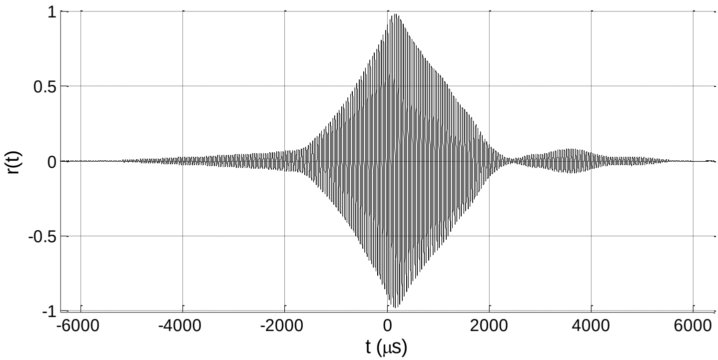

Fig. 36. Cross-correlation function

The maximum of the function stands for the greatest signal similarity and represents the delay time between the two signals. The time is Δt = 144.5 μs

In the practical measurements, the group Lamb wave velocity is obtained. The simulated group velocity is v_{sim} = 201.9 m/s, the obtained in the experiment group velocity is v_{exp} = 218.9 m/s. The relative error equals σ = 8.4 %. Any mismatch may stem from the difference between the real material properties and the properties used in the calculation of dispersion curves.

6. CONCLUSIONS

1. A new method for the excitation of slow Lamb waves by using the air-coupled matched size phased array was devised and investigated in this dissertation. The method allows non-contact excitation of guided waves when the phase velocity is lower than the velocity of sound in the air and Snell's law cannot be applied.
2. Air-coupled Lamb wave excitation in non-destructive testing and evaluation is the most universal method because it is suitable for all materials and does not influence the mechanical properties and the structure of the sample under the test. Yet the wider application of the method is limited due to the great 120-160 dB loss in the measurement system. Improvement and optimization of the excitation process was suggested.
3. The air-coupled Lamb wave excitation process was improved, and the obtained results were compared by using numerical modeling. The Impulse Response Method (IRM) was chosen to model the acoustic pressure created by a vibrating rectangular piston or by an array of rectangular pistons. The Time Harmonic Solution (THS) method was selected in order to calculate the normal displacement signals of the propagating Lamb waves.

4. The excitation of air-coupled leaky Lamb waves in an isotropic homogeneous plate shows that the optimum excitation angle does not depend on the distance between the piston and the plate. The value of the angle is virtually the same in comparison with the value calculated according to Snell's law for the plane wave. Air-coupled excitation of Lamb waves should be avoided in the intermediate zone because it determines sharp changes in the maximum amplitude of normal displacements. The excitation of air-coupled leaky Lamb waves in thin PVC films is problematic concerning non-destructive testing and evaluation because when the phase velocity of the A_0 mode is slightly greater than the velocity of sound in the air, the value of the optimum excitation angle increases, and the relative duration of the normal displacement impulse increases as well.
5. Air-coupled excitation of the slow A_0 Lamb wave mode by using the matched size phased array shows that the duration of the normal displacement impulse is close to the duration of the excitation impulse. The use of the linear delay scheme results in a delay to the normal displacement impulse as well as to the trail signals at the beginning and at the end with the consequence of an unevenly growing dependency of the maximum displacement amplitude versus the number of array elements. In order to solve these drawbacks, an optimization algorithm according to the maximum amplitude was proposed and applied for the normal displacement components. As a result, the stepped array delay scheme was obtained. Due to the application of the stepped delay scheme, the maximum amplitude of normal displacement signals increased by 1.5 times, and the trail signals at the beginning as well as at the end of the normal displacement pulses became approximately 24 times weaker than the main impulse maximum amplitude.

LIST OF SCIENTIFIC PUBLICATIONS ON THE TOPIC OF DISSERTATION

ARTICLES

In the journals from the ISI (Institute of Scientific Information) list

1. Vilpišauskas, Almantas; Kažys, Rymantas Jonas. Numerical investigation of air-coupled generation of Lamb waves in isotropic plates // Elektronika ir elektrotechnika = Electronic and electrical engineering. ISSN 1392-1215. 2014, vol. 20, no. 1. p. 33-36. [ISI Web of Knowledge; INSPEC; VINITI; EBSCO Publishing].
2. Vilpišauskas, Almantas; Kažys, Rymantas Jonas. Investigation of air-coupled generation of asymmetric Lamb waves using rectangular phased arrays // JVE = Journal of Vibroengineering. ISSN 1392-8716. May 2014, vol. 16, no. 3. p. 1397-1404. [ISI Web of Science; SCOPUS; COMPENDEX; EBSCO; INSPEC; VINITI].

In the journals of conference proceedings

1. Vilpišauskas, Almantas; Kažys, Rymantas Jonas. Numerical investigation of air-coupled generation of Lamb waves using rectangular phased arrays // Vibroengineering PROCEDIA. ISSN 2345-0533. September 2013, vol. 1. p. 97-102. [INSPEC; COMPENDEX].

REPORTS IN SCIENTIFIC CONFERENCES

1. Vilpišauskas, Almantas; Kažys, Rymantas Jonas. Numerical investigation of air-coupled generation of Lamb waves in isotropic plates // 17th International Conference ELECTRONICS 2013: June 17-19, 2013, Palanga, Lithuania.
2. Vilpišauskas, Almantas; Kažys, Rymantas Jonas. Numerical investigation of air-coupled generation of Lamb waves using rectangular phased arrays // International Conference VIBROENGINEERING – 2013: September 17-19, 2013, Druskininkai, Lithuania.

REZIUMĖ

Darbo aktualumas

Šiuolaikinė pramonė sukuria daugybę gaminių, kurių pagrindas yra skirtingai suformuotos lakštinės struktūros, pagamintos iš skardos, folijos arba plėvelės tipo pradinių ruošinių. Tokių struktūrų galima rasti automobiliuose, laivuose, lėktuvuose, vėjo elektrinėse, vamzdynuose, cisternose, rezervuaruose, įvairiausiuose technologiniuose induose. Minėtųjų pradinių ruošinių gamybai naudojamos įvairios medžiagos, pavyzdžiui, metalai, plastikai, popierius, kartonas, fanera, stiklo pluoštu armuoti aliuminio kompozitai, stiklo pluoštu armuoti kompozitai, anglies pluoštu armuoti kompozitai. Reikiamai gaminių kokybei užtikrinti kuriami ir taikomi skirtingi tyrimo metodai.

Lembo bangos plačiai taikomos atliekant neardomuosius bandymus ir kontrolę lakštinėse struktūrose. Dažniausiai jos sužadinamos ultragarso keitiklio virpesius tiriamajam gaminiui perduodant kontaktiniu būdu per ploną skysčio tarpą. Tačiau daugybe atvejų skysčių panaudoti negalima, nes bus užterštas, sugadintas arba kitaip neigiamai paveiktas pats tyrimo objektas. Tai aktualu naudojant popierių, kartoną, medį, plastikus, kompozitus bei kosmoso ir aviacijos pramonės medžiagas. Šiuo atveju Lembo bangos sužadinamos nesant tiesioginio kontakto tarp keitiklio ir tiriamojo objekto.

Bekontakčiai metodai dažnai taikomi Lembo bangoms sužadinti atliekant įvairius tyrimus. Virpesiai gali būti sukurti naudojant lazerius, elektromagnetinius akustinius keitiklius, taikant elektrostatinius metodus. Lembo bangų sužadinimas per orą tapo labai populiariu ir šiuolaikišku metodu atliekant neardomuosius tyrimus. Didėjant metodo taikymo poreikiui tampa aktualu pašalinti pagrindinius trūkumus – sumažinti sistemos nuostolius, siekiančius 120–160 dB. Vienas iš būdų tai atlikti – optimizuoti virpesių sužadinimą tiriamojoje medžiagoje.

Akustinių bangų slopinimas ore ir tiriamojoje medžiagoje didėja netiesiškai augant darbiniam sistemos dažniui, todėl jis parenkamas kiek įmanoma žemesnis, ir paprastai neviršija 1 MHz. Žemojo dažnio Lembo bangų sužadinimas per orą tiriamosiose struktūrose aktualus esant dideliems testuojamųjų objektų matmenims.

Lembo bangas per orą tiriamajame objekte galima sužadinti esant dviem sklidimo režimams. Garsinis (angl. *sonic*) režimas gaunamas tada, kai akustinių virpesių greitis ore yra mažesnis už fazinį Lembo bangų greitį bandinyje. Tada egzistuoja akustinių virpesių kritimo iš oro į plokštelę optimalusis kampas, kuriam esant plokštelėje sužadinami didžiausios amplitudės virpesiai. Šis kampas apskaičiuojamas pagal Snelio dėsnį. Plokštelėje sklindantys Lembo bangų poslinkiai aplinkos ore sukuria toli sklindantį virpamąjį akustinį slėgį. Dėl tokios savybės šios Lembo bangos dar vadinamos ištekančiosiomis (angl. *leaky*

Lamb waves). Toks režimas paprastai taikomas kompozicinių medžiagų defektams aptikti, nes nuotėkis labai išauga defekto vietoje. Mažinant sistemos dažnį galima pasiekti ikigarsinį (angl. *subsonic*) režimą, kai Lembo bangų fazinis greitis tampa mažesnis už garso greitį ore, o akustinių virpesių kritimo iš oro į plokštelę optimaliojo kampo neįmanoma apskaičiuoti pagal Snelio dėsnį. Tada sklindančios lėtosios Lembo bangos uždaromos testuojamoje struktūroje ir gali nukeliauti didelius atstumus, nes ištekėjimas į orą yra silpnas ir egzistuoja tik artimajame lauke. Tokio tipo Lembo bangos dar vadinamos silpstančiosiomis (angl. *evanescent Lamb waves*).

Lėtosios Lembo bangos naudojamos atliekant įvairius matavimus. Aukštųjų dažnių bangos taikomos skysčių biologiniuose jutikliuose, o žemųjų dažnių bangos pasitelkiamos dirvožemio paviršiaus parametrams matuoti.

Siekiant praplėsti neardomųjų bandymų galimybes tampa aktualu sužadinti lėtąsias Lembo bangas ir panaudoti jas tyrimams.

Darbo tikslas ir uždaviniai

Darbo tikslas – sukurti ir ištirti naują ultragarsinį metodą, kurį taikant būtų galima gardele per orą sužadinti lėtųjų Lembo bangų A_0 modą izotropinėse plastikinėse plėvelėse. Tikslui pasiekti buvo suformuluoti šie uždaviniai:

1. Lembo bangų savybių ir joms sužadinti taikomų metodų analizė.
2. Lembo bangų sužadinimo per orą modelio pasirinkimas.
3. Ištekančiųjų Lembo bangų sužadinimo per orą teorinis ir eksperimentinis tyrimas.
4. Lėtųjų Lembo bangų sužadinimo per orą metodo sukūrimas, jo teorinis ir eksperimentinis tyrimas.

Mokslinis naujumas

1. Sukurtas ir ištirtas naujas lėtųjų Lembo bangų A_0 modos sužadinimo per orą suderintųjų matmenų ultragarsine gardele metodas, kai atstumas tarp dviejų gretimų gardelės elementų centrų lygus Lembo bangos tiriamajame bandinyje ilgiui.
2. Taikant naująjį metodą galima per orą selektyviai sužadinti lėtųjų Lembo bangų A_0 modą izotropinėse plastikinėse plėvelėse, kai A_0 modos fazinis greitis yra mažesnis už garso greitį ore.
3. Atliktas lėtųjų Lembo bangų A_0 modos sužadinimo per orą plonoje skaidraus polivinilchlorido (PVC) plėvelėje proceso teorinis tyrimas ir nustatyti sužadinimo proceso optimizavimo dėsningumai.
4. Atlikti eksperimentiniai lėtųjų Lembo bangų sužadinimo plonoje skaidraus polivinilchlorido (PVC) plėvelėje tyrimai. Juos atliekant išmatuotas sklindančios ultragarso bangos greitis. Jį palyginus su teoriškai apskaičiuota

verte patvirtinta galimybė sužadinti A_0 modą ikigarsiniu režimu daugiaelementėmis gardelėmis tiek kontaktiniu, tiek bekontakčiu metodu per orą.

Rezultatų aprobavimas

Doktorantūros studijų metu atliktų tyrimų rezultatai buvo paskelbti 3 straipsniuose: 2 straipsniai išspausdinti leidiniuose, įrašytuose į Mokslinės informacijos instituto (ISI) pagrindinį sąrašą, 1 straipsnis išspausdintas Lietuvos mokslo tarybos patvirtinto sąrašo tarptautinėse duomenų bazėse referuojamame leidinyje. Tarptautinėse mokslinėse konferencijose perskaityti 2 pranešimai.

Ginamieji teiginiai

1. Lembo bangas žadinant per orą plonose plastikinėse plėvelėse, kuriose A_0 modos fazinis greitis yra nedaug didesnis už garso greitį ore, o optimalusis kritimo kampas apskaičiuojamas pagal Snelio dėsnį, gaunamas santykinis normalinių poslinkių impulso trukmės pailgėjimas, palyginti su žadinančiuoju impulsu.
2. Lėtųjų Lembo bangų A_0 modą galima sužadinti ultragarsine gardele per orą, kai A_0 modos fazinis greitis yra mažesnis už garso greitį ore ir optimaliojo kritimo kampo neįmanoma apskaičiuoti pagal Snelio dėsnį. Taikant šį metodą santykinis normalinių poslinkių impulso trukmės pailgėjimas, palyginti su žadinančiuoju impulsu, nepasireiškia.
3. Optimalusis lėtųjų Lembo bangų A_0 modos sužadinimo režimas gaunamas tinkamai parinkus gardelės elementų suvėlinimo laikus. Šiems laikams rasti pasiūlytas naujas sužadinimo per orą proceso optimizavimo pagal normalinių poslinkių maksimaliąją amplitudę algoritmas, kurį įvykdžius gaunama laiptuotoji suderintųjų matmenų gardelės fazavimo schema.

Disertacijos struktūra ir apimtis

Daktaro disertaciją sudaro įvadas, 4 skyriai, išvados, tolesnių tyrimų kryptys, literatūros sąrašas ir mokslinių publikacijų disertacijos tema sąrašas. Darbo apimtis – 98 puslapiai, kuriuose pateikiami 177 paveikslai, 4 lentelės, 46 matematinės išraiškos ir 96 pavadinimų literatūros sąrašas.

IŠVADOS

1. Disertacijoje sukurtas ir ištirtas naujas lėtųjų Lembo bangų sužadinimo suderintųjų matmenų gardele metodas, leidžiantis jas bekontakčiu būdu generuoti per orą plonose plastikinėse plėvelėse. Garso greičiui ore esant

didesniam už nukreiptųjų bangų fazinį greitį to padaryti įprastais metodais neįmanoma, nes pasiekiama Snelio dėsnio galiojimo riba.

2. Atliekant neardomąją diagnostiką Lembo bangas patogiausia sužadinti pjezoelektriniu keitikliu per orą, nes šis būdas tinka visoms medžiagoms ir nedaro įtakos tiriamojo bandinio savybėms ar struktūrai. Tačiau metodo platesnį taikymą riboja dideli (120–160 dB) slopinimo nuostoliai sistemoje, todėl pasiūlyta tobulinti ir optimizuoti patį sužadinimo procesą.
3. Lembo bangų sužadinimo procesui tobulinti ir gautiems rezultatams palyginti taikytas matematinis modeliavimas. Ore virpančių stačiakampių spinduolių akustinio slėgio laukas skaičiuotas difrakciniu impulsinės reakcijos metodu, o izotropinėje homogeninėje plokštelėje sklindančių Lembo bangų normaliniai poslinkiai modeliuoti harmoninių sprendinių metodu.
4. Izotropinėse homogeninėse plokštelėse per orą sužadinant ištekančiųjų Lembo bangų A_0 modą optimalusis kritimo kampas nepriklauso nuo atstumo tarp plokštelės ir spinduolio, o jo vertė sutampa su apskaičiuotuoju pagal Snelio dėsnį. Nustatyta, kad netikslinga Lembo bangas sužadinti pereinamojoje keitiklio akustinio lauko zonoje, nes tai lemia netolygius normalinių poslinkių signalo amplitudės pokyčius. Ištekančiąsias Lembo bangas problemiška naudoti plonų plastikinių plėvelių neardomajai diagnostikai, nes A_0 modos faziniam greičiui esant nedaug didesniam už garso greitį ore gaunama didelė optimaliojo kritimo kampo vertė, o sužadintojo normalinių poslinkių impulso trukmė tampa daug didesnė už sužadinančiojo impulso trukmę.
5. Lėtųjų Lembo bangų A_0 modą sužadinant suderintųjų matmenų gardele per orą normalinių poslinkių impulso trukmė yra artima sužadinančiojo impulso trukmei. Tačiau tiesinės elementų suvėlinimo schemos panaudojimas lemia pašalinius signalus normalinių poslinkių impulso pradžioje ir gale bei netolygią jo amplitudės augimo priklausomybę nuo gardelės elementų skaičiaus. Šiems trūkumams pašalinti pasiūlytas optimizavimo pagal normalinių poslinkių maksimaliąją amplitudę algoritmas, kurį įvykdžius randama laiptuotoji suvėlinimo schema. Pritaikius šią schemą normalinių poslinkių amplitudė išauga 1,5 karto, o pašalinių virpesių impulso pradžioje ir gale maksimalioji amplitudė gaunama 24 kartus mažesnė už pagrindinio impulso maksimaliąją amplitudę.

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Padėka

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