SELECTION OF PIEZOCERAMIC SENSOR PARAMETERS FOR DAMAGE DETECTION AND LOCALIZATION SYSTEM

Andrzej KLEPKA, Łukasz AMBROZIŃSKI

Department of Robotics and Mechatronics AGH - University of Science and Technology,
Al. Mickiewicza 30, 30-059 Kraków, tel. 12 6173128
andrzej.klepka@agh.edu.pl, lukasz.ambrozinski@agh.edu.pl

Summary

Damage detection method based on Lamb waves propagation phenomena are increasingly used as a tool for Structural Health Monitoring (SHM) and Nondestructive Testing and Evaluation (NDT/E). Phenomena connected with wave propagation and interaction with damages are very complex and complicated. In many cases depends on sensors/actuators location, electronic system design, sensor shape, frequency range of excitation or sensors properties. Actuator/sensor selection based only on specification sheet can be insufficient, so time and frequency analysis have to be applied to signals acquired when an examined transducer was attached to a plate. In this paper sensor study on the transducer used for Lamb waves generation and acquisition has been presented. Robustness of the array consisting of chosen transducers has been verified with the scanning vibrometer.

Keywords: lamb waves, damage detection, piezoceramics transducers, phased array technique.

DOBÓR PARAMETRÓW PRZETWORNIKÓW PIEZOCERAMICZNYCH
DO SYSTEMU DETEKCJI I LOKALIZACJI USZKODZEŃ

Streszczenie

Metody detekcji uszkodzeń oparte o zjawiska propagacji fal Lamba są coraz częściej używane w systemach SHM oraz do nieniszczących metod badań i oceny stanu konstrukcji. Zjawiska związane z propagacją fali oraz jej interakcji z uszkodzeniami są złożone i skomplikowane. W wielu przypadkach zależą od rozmieszczenia nadajników/odbiorników, układu elektronicznego i jego parametrów elektrycznych, kształtu elementu piezoceramicznego, zakresu częstotliwości wymuszenia czy właściwości samego przetwornika piezoceramicznego (PZT). Wybór elementów PZT tylko na podstawie danych zawartych w specyfikacji nie zawsze jest wystarczający. Konieczne jest przeprowadzenie analiz układu składającego się z badanej struktury oraz przetwornika. W artykule przedstawiono analizę czujników wykorzystywanych do wymuszania struktury oraz do akwizycji sygnałów odpowiedzi. Poprawność przeprowadzonych testów została zweryfikowana z wykorzystaniem wibrometru laserowego.

Słowa kluczowe: fale lamba, detekcja uszkodzeń, przetworniki piezoceramiczne, technika phased array.

1. INTRODUCTION

A variety of means can be used as Lamb waves actuators and sensors such as ultrasonic probes, lasers, piezoelectric element, interdigital transducers, optical fibers. Brief description of transducers can be found in [2]. A selection of the transducer used in a system depends on many factors like a size and a shape of a monitored element, its material properties and signal processing applied to a damage detection algorithm. In this paper a SHM system based on piezoelectric transducers used to the damage detection method based on the phased array technique was presented. Giurgiutiu in [1] showed that piezoelectric active wafers can be used in this method with good results.

Lamb waves are dispersive and multimode – many modes can exist at one frequency. It means, that Lamb waves excited by PZT contains multiple modes. However when excitation frequency is limited below so called cut-off frequency only two: A_0 and S_0 modes exist. Moreover it is possible to enhance one mode and reduce the other by mode tuning technique based on a transducer size and an excitation frequency selection [3].

Phased array technique is very often used as a non-destructive damage detection method based on ultrasound waves. Main idea of that method is to steer of wavefront shape, generated by a matrix of piezoelectric transducers [5,6,12]. The selection of transducer size, and the excitation frequency is essential for the phased array technique. Time delays calculation for each transducer is based on the phase velocity and transducers spacing so exact material properties of examined structure are necessary to calculate the phase and the group velocity. The excited wavelength should be at least twice as long as transmitters spacing, in another case the side lobes and additional false ghost damages could be disclosed. The size of a PZT determinates the lowest wavelength and the highest excitation frequency.

2. HARDWARE

In all experiments Phased Array Non Destructive Testing System (PAS-8000)(fig. 1) was used. The system enable sinusoidal signal generation with frequencies between 40 – 500kHz. Additionally many types of windows can be applied (square, triangle or Hanning). 8 channels wave used for signal sending with simultaneous phase shifting generation between generated signals. Data acquisition was performed by PAQ-16000D at 2.5 MHz sampling frequency.

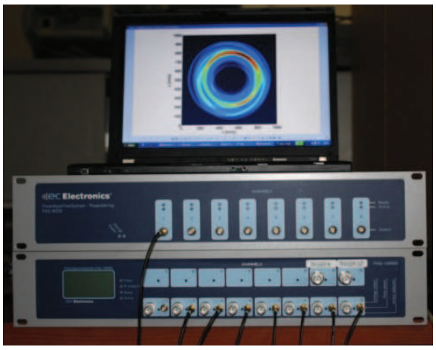


Fig. 1. PAS-8000 and PAQ-16000 used in experiments.

3. SENSOR STUDY

3.1. Time and frequency domain test

As mentioned above many factors affect the wave propagation so transducers attached to the aluminum plate were tested rather than unbounded ones. Three types of multilayer Noliac PZTs transducers were examined: a ring actuator CMAR03 of the diameter 12 mm and two plate actuators: CMAP07 and CMAP12 of the size 5x5x2 and 2x2x2 respectively. All transducers were made of material NCE57 with frequency constant 1950 m/s, so resonance frequencies corresponding to the largest transducer dimension was calculated as 166 kHz, 390 kHz and 975 kHz for CMAR03, CMAP07 and CMAP12 respectively.

Examined transducers were placed on the 2 mm thick plate in a pitch-catch setup (Fig.).

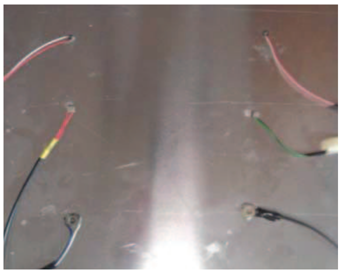
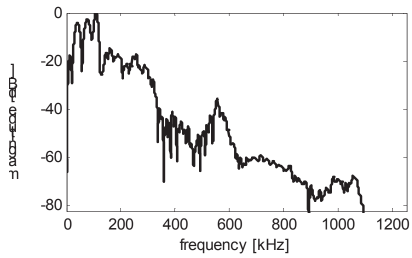


Fig. 2. Three types of Noliac PZTs transducers:

Wax was used as a coupling agent. The actuator-sensor distance was 150 mm. In the first step transducers were excited with a broadband square pulse. Frequency responses presented in the Fig. 3. reveal resonance frequencies calculated above.

a)



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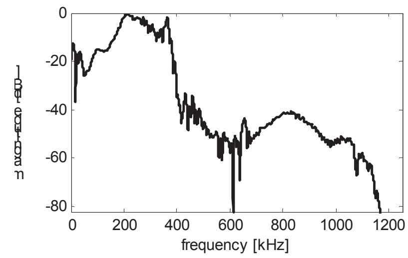

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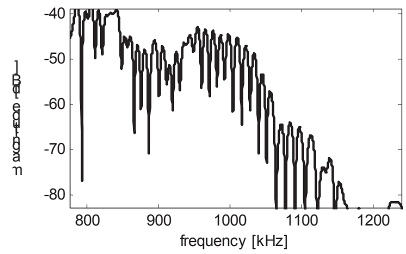
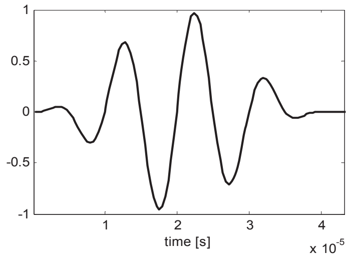


Fig. 3. Frequency responses of transducers excited with a broadband square signal a) CMAR 03 b) CMAP07 c) CMAP12.

In the second step transducers were excited with a tone-burst signal – 4 cycles of sinusoid with the centre frequency 100 kHz, modulated with Hanning window. Comparisons of the excitation pulse to the time responses, presented in the 4, reveals that the best representation of the excited signal can be found in the signal acquired with the CMAP 12. The CMAP 7 response distinctly contain high frequency components, for the CMAR03 it was impossible to isolate the excited pulse. In the next experiments only CMAP 7 and CMAP 12 have been used.

a)



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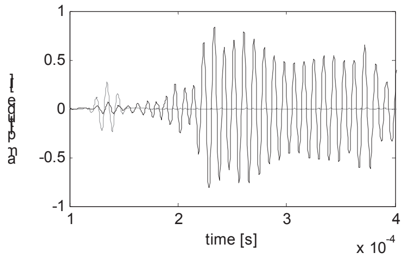

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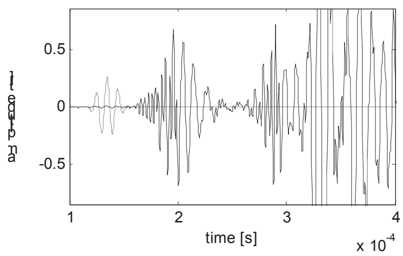

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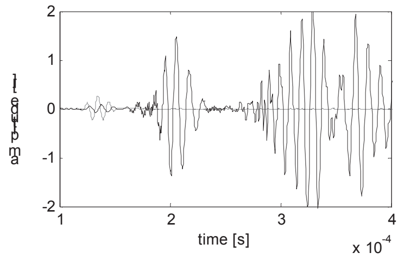
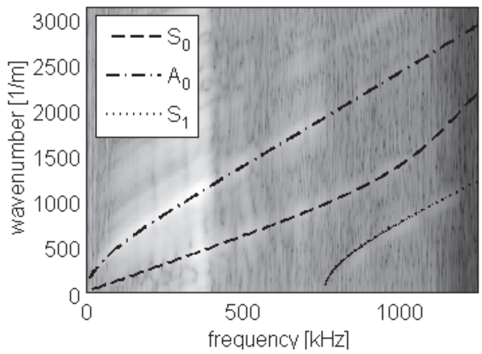


Fig. 4. Time responses acquired at 100 kHz narrowband pulse excitation a) excitation signal b) CMAR 03 c) CMAP07d) CMAP12.

3.2. Dispersion curves validation

In the phased array technique time delays calculation based on the phased velocity of excited mode. To validate the analytically calculated curves by comparing them with the experimental ones and to assess the sensitivity of the transducer to the particular Lamb mode, the 2D Fourier transform method for the measurement of propagating multimode signals was used [4]. In Fig. 5a. can be seen that the S_0 mode is hardly recognizable for signals acquired by CMAP07 at lower wavenumber-frequency range. In the response from CMAP12 A_0 (Fig. 5b.)mode is even more dominant for whole frequency range.

a)



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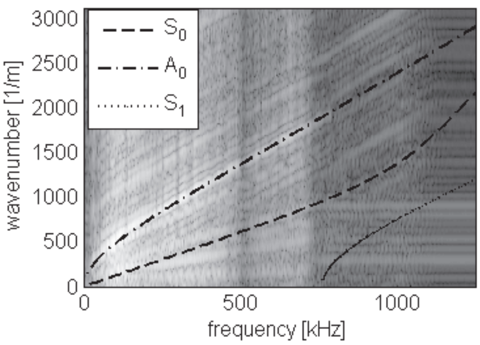

Fig. 5. Theoretical and measured wavenumber vs. frequency plot obtained for signals acquired by a) CMAP07, b) CMAP12.

When a mode with different wavenumber is generated with a PZT element an additional beam is formed in the unintentional direction. Generated signal contains multiple frequency components with significant amplitude. It may affect more unwanted beams. The least of the tested transducers (CMAP12) allows for narrowband excitation without high frequency components, moreover in the tested plate it generated enhanced A_0 with reduced S_0 mode.

3.3. Experimental results for Damage imaging technique

Damage localization algorithm is based on time domain responses analysis of the structure. The responses are acquired from the distributed actuators – sensors grid, placed on the structure. First step in this method is estimation of the group velocity for given plate geometry. It can be done in two ways: solving dispersion equation or measure the group velocity experimentally. Position in time domain of the incident wave and scatters from edges can be estimated using time of flight parameter[13].

Damage localisation process consist in representing investigated area as an image, where values of the pixel $S(i,j)$ are calculated using equation [13]:

$$S(i,j) = \sum_{m}^{N} A_m f_{wg}(t_{mij}) f_m(t_{mij}), \qquad (1)$$

$$t_{mij} = \frac{R_m^a + R_m^s}{c_g}, A_m = \frac{10}{max|f_m|}$$

where $S(i,j)$ – value of the given pixel, R_m^a, R_m^s is the distance from damage to actuator and sensor respectively, f_m – envelope of the recorded signal, c_g – group velocity of the wave, f_{wg} – is windowing function. Typical structure response signal is presented in figure 6.

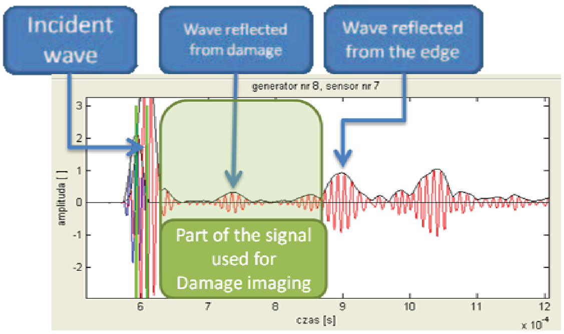

Fig. 6. Example of structure response signal with damage.

For each actuator–sensor path one image can be obtained. The final result is achieved by summing images from all paths. Comparison of results obtained with use CMAP 7 and CMAP 12 transducers are presented in figure 7. As can be noticed that in case of use CMAP 12 transducers damage area is showed correctly. In case CMAP 7 transducer, results are not clear.

3.4. Experimental results for phased array

The second method is based on the phased array technique. This technique creates the possibility of forming and steering the front wave generated from a set of transducers. The beam forming is realized by delay generation during excitation of particular transducers, using equation [6,10,11].

$$t = \frac{l_x \cdot \sin(\alpha)}{c} \qquad (2)$$

a)

b)

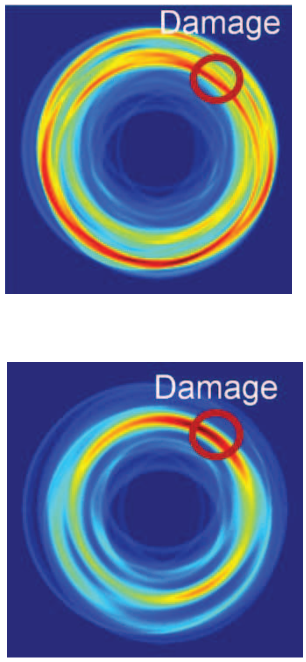

Fig. 7. Comparison of damage identification process with use different types of PZT: a) CMAP 7, b) CMAP 12

where l_x is the distance between transducers, c is phase velocity, α is the angle between the actuator line and wave front. The acquisition process is performed with the same delay as during excitation of the structure. Due to the complexity of the phenomena appearing during the interaction between waves and the damage, some methods of signal processing have been proposed, such as wavelet filtration and envelope estimation.

Main parameters of the phased array technique are distance between transducers and angle resolution (width of the main lobe). If the some restriction connected with wave length, sensor or actuators placement or frequency component of the excitation signals are not fulfill, the result of the identification algorithm which based on the response signal processing can be incorrect. In case when side lobes have dominant influence, the effects like ghost damages or false damage can appear (Fig.8)

Eight CMAP12 plate actuators of the size 2x2x2 mm were used to built an linear array. The distance between PZTs centers was equal to 5 mm. The array was set in the centre of an aluminum plate with size 1000x1000x2 mm. As a coupling agent a wax was used. Disadvantages of this coupling method is irregular wax layer for all transducers. In the end the amplitudes of the signal sending to the plate can be different for particular elements. Before the experiment a calibration procedure was performed. Each actuator one by one generated signals captured by one PZT element. Output amplitude gains for all channels were adjusted so the linear and Hamming apertures was achieved. This problem is not investigated in the current paper but detailed information about apodization and effective aperture can be found in[7 – 9,12].

Time delays calculation was based on theoretical dispersion curves presented in Fig. 5.

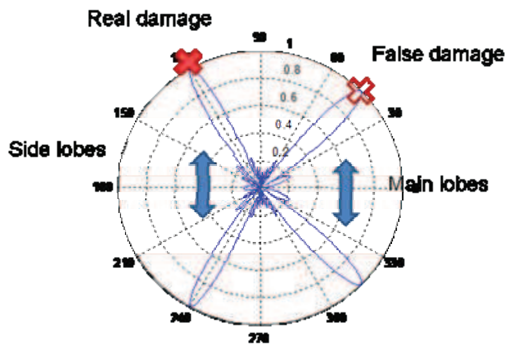

Fig. 8."False damage" effect.

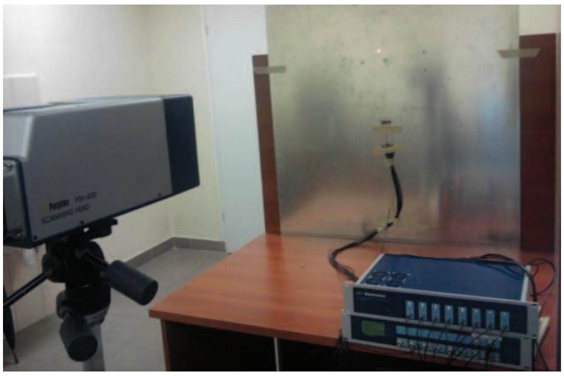

Fig. 9. Experimental setup for phased array testing.

During experiment assumed excitation frequency equal to 100kHz. It is correspond wavelength equal 13.57mm. This parameters provided "half wavelength" condition fulfill (half of the wavelength should be grater then transducer spacing). The steering direction was 120 degrees. To validate the performance of steering the wavefront a scanning laser vibrometer POLYTEC PSV 400 was used (Fig. 9). The signals generated by the array were captured by the vibrometer. The device enabled noncontact measurement of the out of plane perturbation velocity. Examined points were distributed in a circle shape so distances between the measurement points and the source of the wave were equal. Time signals were acquired in the arc shaped grid points, the maximum value of the first arrival wave packet has been used to create the beam patterns. Two methods of an apodisation have been used during the experiment.

The results of the experiment can be seen above. The highest vibration amplitude was appeared in the desired direction. Fig. 10a,b presents measured beam pattern in polar plot. It represents the normalized maximum amplitude in all directions for a specified array configuration. A theoretical beam pattern was added to Fig 10c,d. It showed good agreement with a measured signal and theoretical calculation. A slight difference of steering angle is caused by a small error in the theoretical disperse curves estimation. The array used in experiments was linear so an additional, symmetric beam is expected at direction 240 degrees.

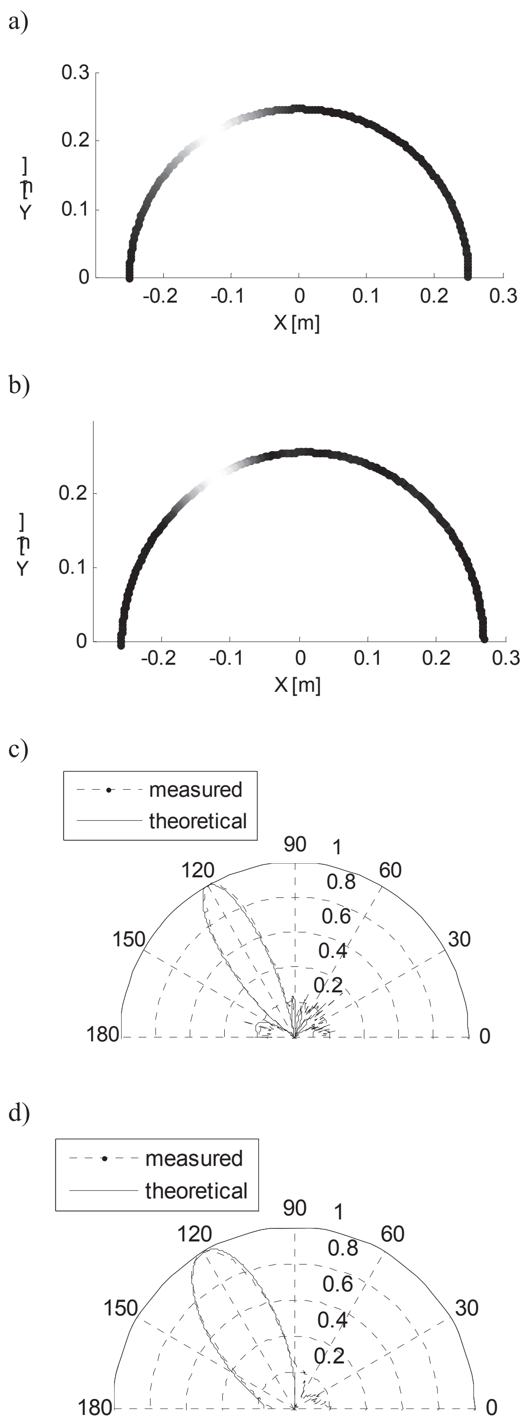

Fig. 10. Measurement points and amplitude values- a) linear apodization b) Hamming apodization. Theoretical and experimental normalized results of wave amplitudes in measured direction. - c) linear apodization d) Hamming apodization

4. CONCLUSIONS

Performed test showed that shape and dimensions of transducer can have significant impact of damage detection algorithm results. The smallest transducers have better properties but their power sometimes can be unsatisfactory.

The geometrical resonant frequency can be determined, but their influence on results during narrowband excitation can be significant. Resonant frequency of the PZT elements can have influence on results in spite of frequency of excitation is selected definitely outside the resonance.

Selection of proper transducers and their parameters is key for Phased Array technique and apply together with apodization technique allow to decrease of sidelobs, enable better directionality and prevent „false damage" and „ghost damage" effects.

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Andrzej KLEPKA Ph.D. is an assistant proffessor at the Department of Robotics and Mechatronics of AGH University of Science and Techmnology. His scientific interests focus on signal processing, nonlinear systems and Structural Sealth Monitoring

Łukasz AMBROZIŃSKI M.Sc. is PhD student at the Department of Robotics and Mechatronics of AGH University of Science and Techmnology. His works are connected with damage detection and localisation and Structural Health Monitoring.