Lamb Waves Tunning on Aluminium Plates for Structure Health Monitoring

Tiberiu Adrian SALAORU*[,1], Adrian TOADER[1], Minodor ARGHIR[1],
Marina ANDREI[1], Mihai TUDOSE[1], Ioana POPESCU[1], Cristiana DONCIU[1]

*Corresponding author
*[,1] INCAS – National Institute for Aerospace Research “Elie Carafoli”
B-dul Iuliu Maniu 220, Bucharest 061126, Romania
salaoru.tiberiu@incas.ro*

DOI: 10.13111/2066-8201.2014.6.1.7

Abstract: *The method for defects detection inside the mechanical structures, namely aerospace structures, using the Lamb waves is widespread because of its benefits: it is nondestructive, may reveal the presence and size of defects with high accuracy and does not require any expensive equipment for application. One of the ways to implement this method consists in mechanically exciting a point of the plate using a piezoelectric actuator followed by the signal collection by means of a piezoelectric transducer located in another point of the same plate surface. By interpreting the shape, the phase and amplitude of the collected signal the presence of a defect, its type and size can be highlighted.*

As a specimen of mechanical structure, a rectangular aluminum plate has been used. The generation of the Lamb waves in the plate was performed with a signal of certain optimal frequency values that need to be determined in advance.

The procedure for determining the optimal frequency values is called tuning and consists in measuring and processing the signals amplitude values for multiple frequencies of the excitation signal, ranging between 10-800 kHz. The article deals both with the procedure description and the relevant results obtained for aluminum plates of different sizes.

Key Words*: mechanical structures, piezoelectric actuator, optimal frequency values, aluminum plates, signals amplitude values*

1. INTRODUCTION

One of the main ways to monitor the health of structures (SHM) is the guided waves due to lower energy losses during propagation through structures even of large dimensions.

These waves can be successfully used for ultrasonic testing of bridges, airplanes, ships, missiles or pipes.

The method takes advantage of the energy transfer through the entire thickness of the plate, allowing the detection of internal defects at different depths.

The Lamb waves [1] fall into two categories: symmetric and anti-symmetric wave modes [2].

The symmetric wave mode (Fig. 1a) is denoted by S0 (basic symmetric mode), S1, S2 ... Sn and the waves have the maximum amplitude at higher frequencies (130-400 kHz).

The anti-symmetric waves mode (Fig. 1b) is denoted by A0 (basic anti-symmetric mode), A1, A2 ... An, and the waves have the maximum amplitude at lower frequencies of the excitatory signal (20-130 kHz) [3].

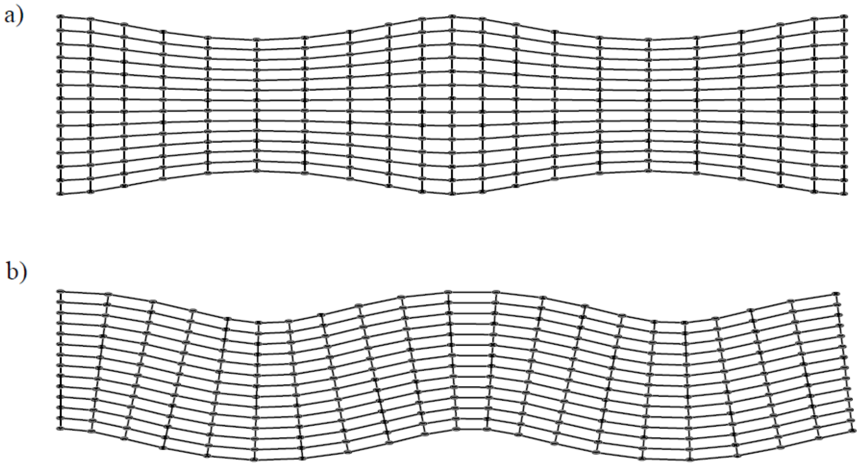


Fig. 1 Lamb wave types: symmetric mode (a) and anti-symmetric mode (b)

The difficulties of using Lamb waves lie in the fact that a) different propagation modes propagate at different velocities at a given frequency [4] and b) they are dispersive, that is, the propagation velocity varies with the frequency of each mode [5].

For simplicity, the commonly used modes are basic modes S0 and A0 as higher modes can overlap making it difficult to identify them. For this purpose operating frequencies up to 800 kHz are utilized.

To establish the optimal interrogation frequencies in order to highlight more clearly the signal due to a defect found in a rectangular aluminum plate a tuning operation is required to be performed in advance [6]. This is done on aluminum plate identical both in size and physical and mechanical properties to the damaged one, using two PWAS transducers (Piezoelectric Wafer Active Sensors); one is utilized as a transmitter and the other as a receiver.

Note that this operation is not an issue of absolute and relative positions of these two transducers on the plate, the only important thing being that they should be placed at a sufficient distance from each other. This is necessary for the basic symmetric mode waves to be separately received from those of the corresponding basic anti-symmetric mode.

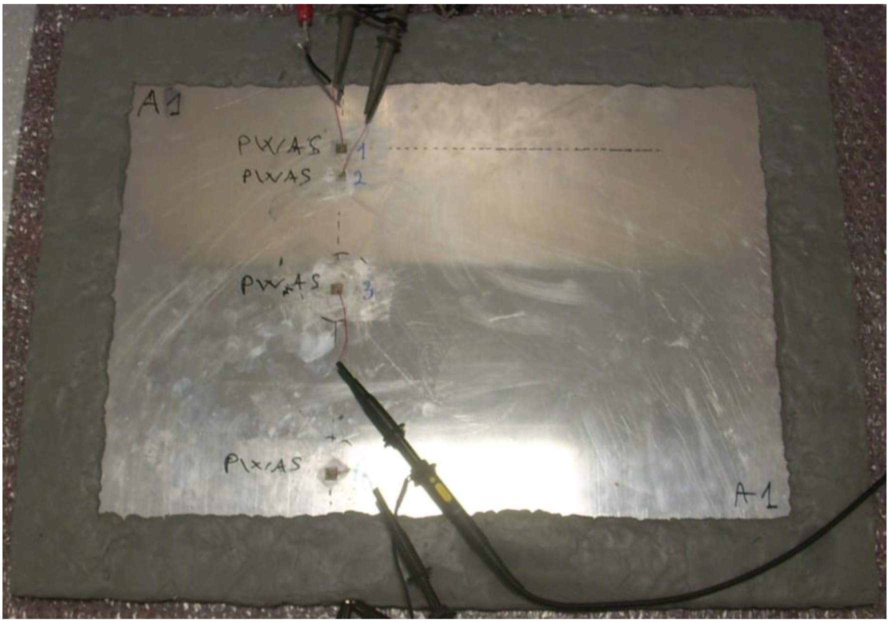
Otherwise, the two signals emitted by the transducer used as a receiver may overlap. In order to distinguish between the two received basic propagation modes in the case of a defective plate it is required that only one of these two modes be dominant. Therefore, the purpose of this operation is to establish two optimal frequencies for interrogation, one corresponding to the symmetric dominant basic mode and the second corresponding to the anti-symmetric dominant basic mode.

2. DESCRIPTION OF EXPERIMENTS

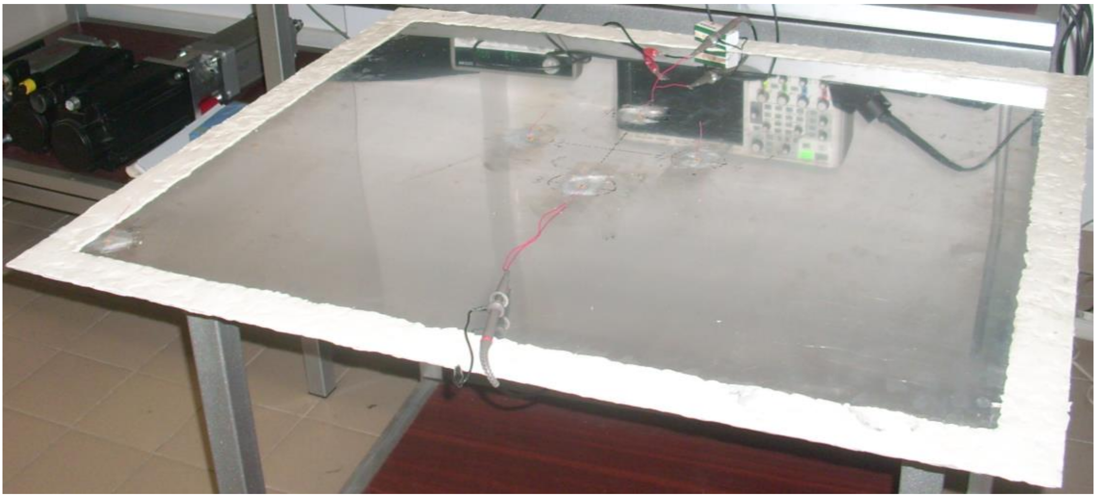
2.1. Experimental system

There have been manufactured a number of 4 rectangular aluminum plates (A1, A2, A3 and A4) of 530 x 400 mm (A1 and A2) and of 1000 x 850 mm (A3 and A4), respectively. Each of the plates A1 and A 2 has attached four PWAS devices (Wafers Active Piezoelectric Sensors), while A3 and A4, have attached five of such devices. Plates A1 and A3 are free of defects and plates A2 and A4 are structurally defective. The tuning procedure was applied only to free of defects plates, A1 and A3, respectively.

To perform the tuning it is first necessary to identify the signals corresponding to the basic modes, the symmetric and the anti-symmetric one, respectively. To this end, they should not overlap with other signals caused by other disturbing factors. One of the main disturbing factors is represented by the signals caused by multiple reflections on the plate edge. Thus, an overlap of signals caused by multiple reflections could occur which will make it difficult to identify the basic vibrational modes.



(a) A1 Plate



(a3) A3 Plate

Fig. 2 The layout of PWAS on the test plate

To avoid this issue, a wave absorbent strip of 50 mm was applied along the perimeter and on both sides of the plate. In this case we chose a material that is readily available, namely plasticine.

Such reflections on the edges of the plate being removed, it behaves like an infinite plate, for which only the direct waves reach the receiver, if free of defects plates. It is true that this situation is not realistic, if we have in view structures such as aircraft or spacecraft where there are many other centers of interaction of waves, but it is a first step in understanding of the Lamb waves propagation in structures.

In the considered SHM specimen the Lamb waves are travelling from the transmitter PWAS to receiver PWAS. If there are not occurring any reflections on the plate's edges or on other discontinuities, the signal is received without any other additional oscillations to the two propagating modes.

This happens in the study model in Fig. 2.1 but it happens also in all cases where the direct path from transmitter to receiver is much shorter than any other indirect path from transmitter to receiver via any other discontinuity in the material.

The excitation signal applied to one of the PWAS actuators is a sinusoidal pulse type signal (tone burst) with 20V peak to peak amplitude and with a Hanning window type amplitude modulation generated by an Agilent 33120 signal generator. This type of pulse modulation includes the exact number of 3 periods (Fig. 3).

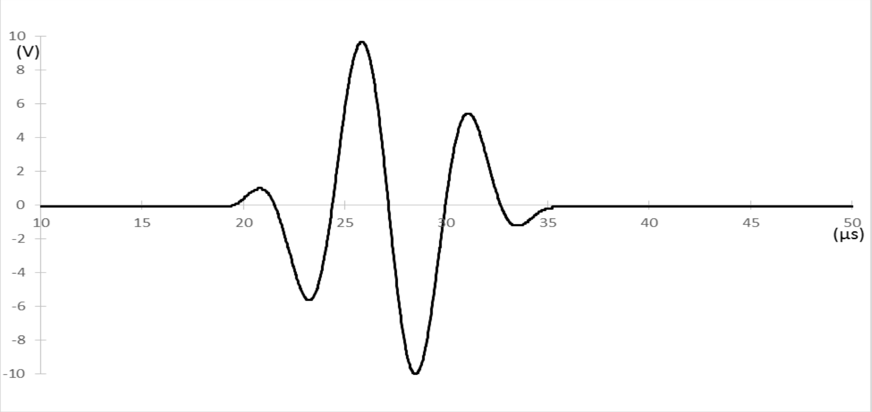


Fig. 3 Sinusoidal pulse having a Hanning window type modulation

After investigating several forms of signal this type of demodulation has been chosen, being usually used by one of the prestigious groups in the scientific community working in the SHM (Structures Health Monitoring) field such as the LAMSS group from South Carolina University.

One of the main reasons for using this type of modulation is the need for gradual excitation with progressive amplitudes of the mechanical structures.

To achieve an optimal tuning it is necessary to have an optimal value of the distance between the transmitter and the receiver.

Thus, the received signal amplitude is better at short distance and hence the signal / noise ratio is good, but short distance can also lead to overlapping of incoming waves corresponding to the two basic modes of propagation.

On the other hand, a large distance leads to a decrease in the amplitude of the received signal, so as to a decrease of the measurement accuracy, but also results in a very good separation of the two received signals of the waves corresponding to the two basic modes of propagation.

The signal taken over from one of the PWAS transducers is received by an oscilloscope of Agilent DSO-X 3034 type and forwarded via USB to a PC that performs automatically the tuning procedure in the system shown in Fig. 4.

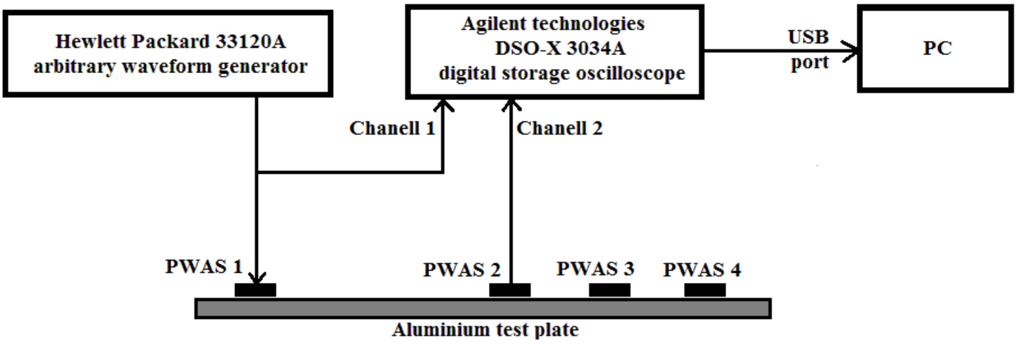
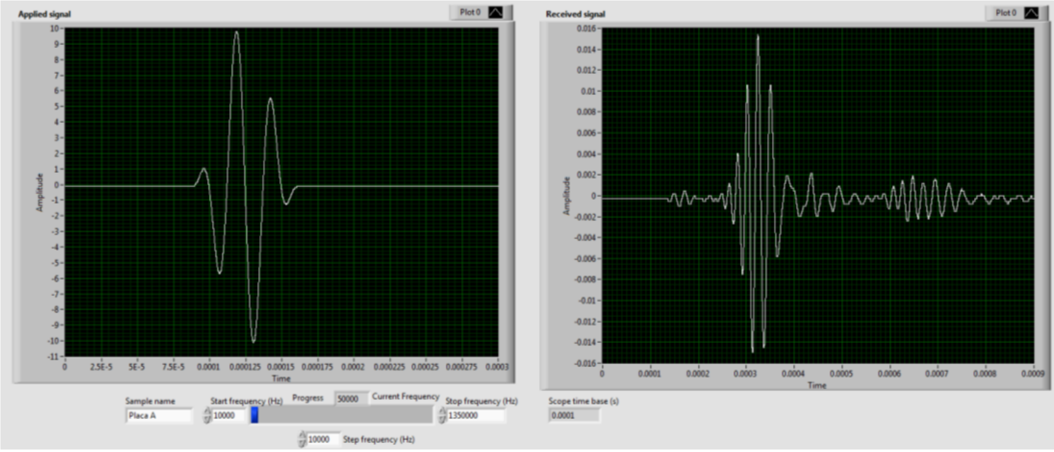


Fig. 4 Block diagram of the acquisition system

The control of the whole system and data acquisition and storage are managed using a program developed in Labview whose control panel is shown in Fig. 5.

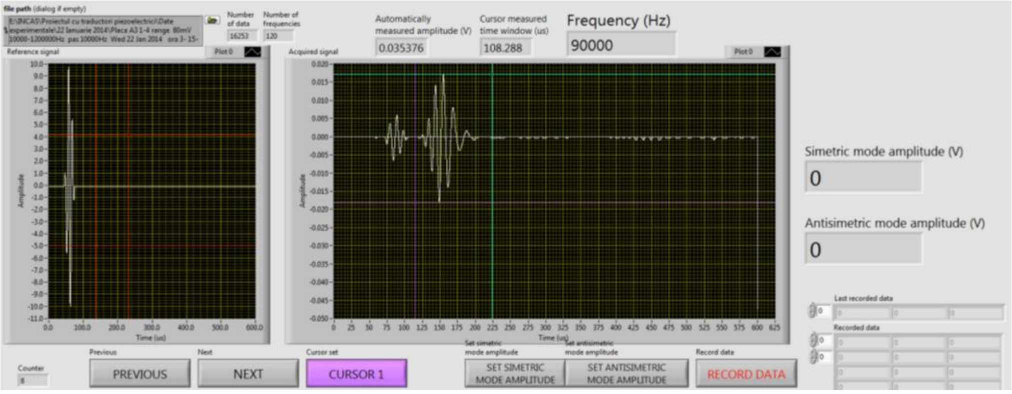


Sample name: Placa A
Start frequency (Hz): 10000
Progress: 50000
Stop frequency (Hz): 1350000
Scope time base (s): 0.0001
Step frequency (Hz): 10000

Fig. 5 Control Panel of the Labview data acquisition program

The waveform of the excitatory signal collected from channel 1 of the digital oscilloscope and applied to PWAS is displayed on the left while the waveform collected from one of the other PWAS (2, 3 or 4) used as receptors is displayed on the right.

The extraction of the amplitude of signals acquired for each frequency was made using a Labview program whose panel is shown in Figure 6.



file path (dialog if empty): E:\INCAS\Proiectul cu traductori piezoelectrici\Date \experimentale\22 Ianuarie 2014\Placa A3 1-4 range 80mV 10000-1200000Hz pas 10000Hz Wed 22 Jan 2014 ora 3- 15-
Number of data: 16253
Number of frequencies: 120
Automatically measured amplitude (V): 0.035376
Cursor measured time window (us): 108.288
Frequency (Hz): 90000
Simetric mode amplitude (V): 0
Antisimetric mode amplitude (V): 0
Counter: 8

Fig. 6 Control Panel of the data processing program

2.2. Tuning procedure

The basic frequency of the carrier signal applied to PWAS1 and PWAS2 devices was varied in the range 10-800 kHz with a 10 kHz step and the amplitude of signals collected by the PWAS receiver, corresponding to the two symmetric and anti-symmetric basic modes, was registered for each frequency value of this interval.

Recording of the signal picked up from the PWAS3 and PWAS4 receiving devices located on the plates A1 and A3 was done by performing a mediation of a number of 1000 waveforms acquired for noise reduction. In parallel the excitatory signal on another channel of the oscilloscope was also collected. The recorded signal (Fig. 7) shows a delay relative to the applied signal determined by the time needed for the wave to cover the distance from the transmitter to the receiver.

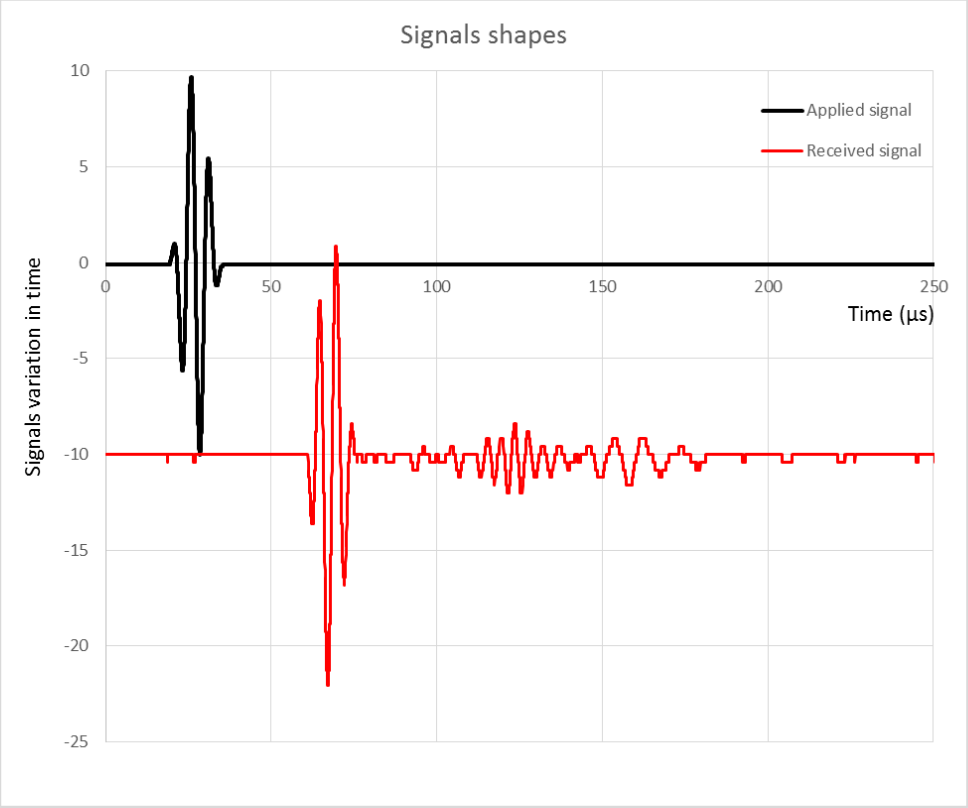


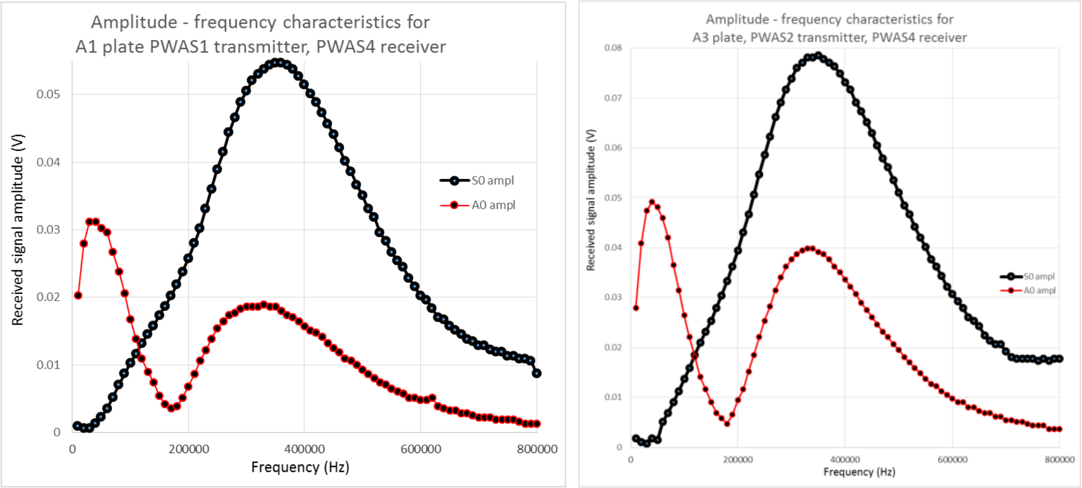
Fig. 7 Waveforms of the excitatory and the received signal

It is noted that the received signal is composed of two groups of oscillations: the first corresponds to the basic symmetric S0 propagation mode and the second corresponds to the basic anti-symmetric A0 mode (symmetric mode waves propagate at a speed greater than those of anti-symmetric mode).

In this way the two signals are identified and separated in order to measure their maximum amplitude.

It is necessary to measure the amplitude of each mode of propagation to determine which of them is dominant and at what frequencies. For each operating frequency the amplitude of each mode of propagation is determined and while storing these values on the control panel of the Labview program the variation of these amplitude values with frequency is displayed point by point.

Thus, the graphs in Fig. 8 corresponding to A1 and A3 plates were obtained.

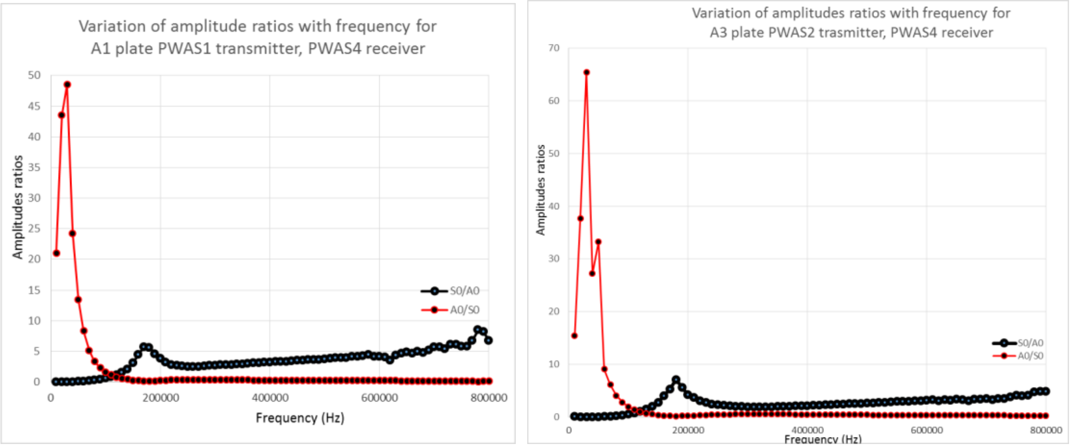


(a) (b)

Fig. 8 The amplitude-frequency characteristics of the S0 and A0 modes corresponding to A1 (a) and A3 (b) plates

The Optimal frequency values for each of the two dominant modes of propagation are those for which the ratio between the two amplitudes at each frequency from the measuring domain has maximum value.

Thus from the variation of these ratios with frequency (Fig. 9) the followings were obtained: f_{S01} = 180 KHz frequency corresponding to the basic dominant symmetric mode and f_{A01} = 30 KHz corresponding to the basic dominant anti-symmetric mode.

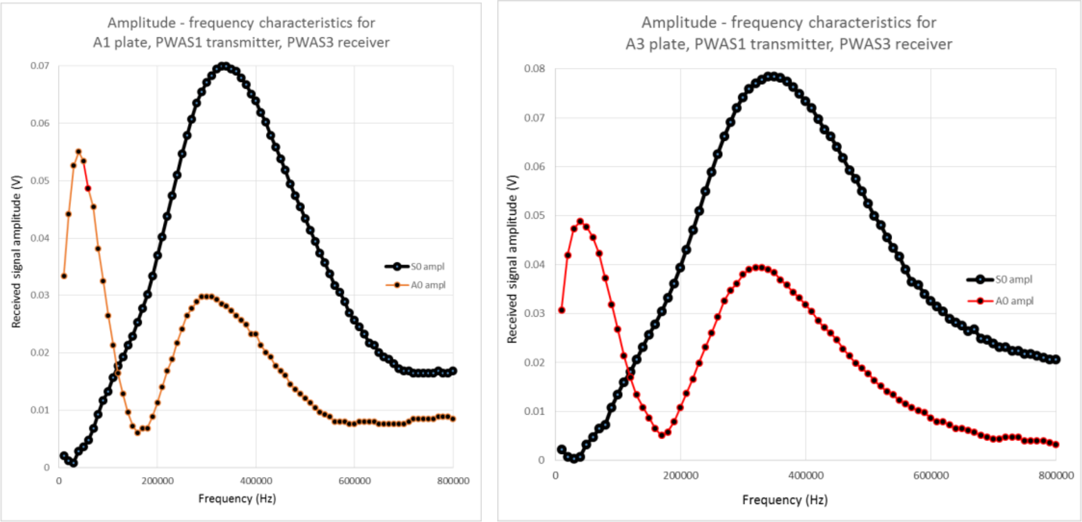


(a) (b)

Fig. 9 Variation of S0/A0 and A0/S0 signals amplitudes ratios with frequency corresponding to A1 (a) and A3 (b) plates

To check the accuracy of the tuning the entire set of operations from above was repeated using PWAS1 on plates A1 and A3 as a transmitter and PWAS3 on plates A1 and A3 as receivers.

The graphs of the received wave amplitude variations with frequency, corresponding to the two modes of propagation for each of the two plates are shown in Fig. 10.



(a) (b)

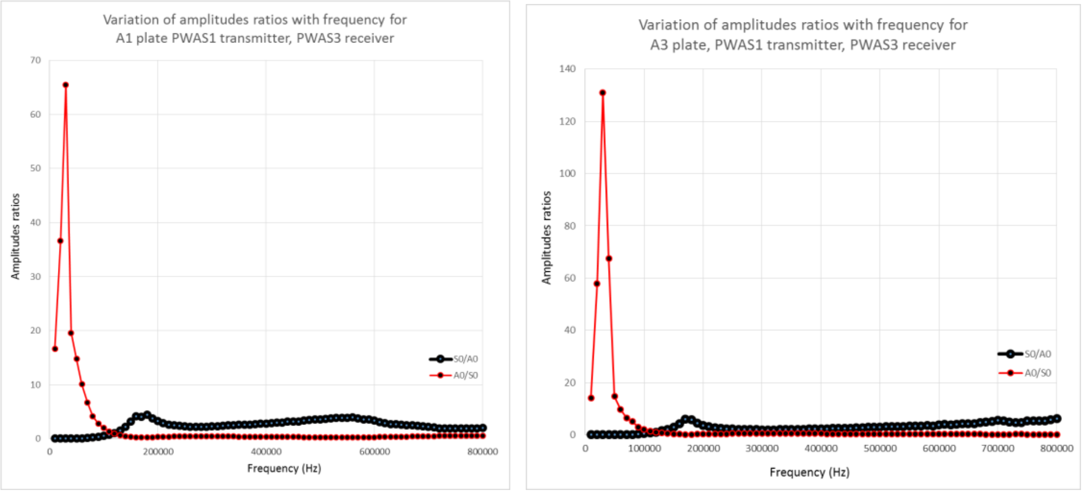
Fig. 10 The amplitude-frequency characteristics of the S0 and A0 modes corresponding to A1 (a) and A3 (b) plates

From the amplitudes ratios dependency with frequency (Fig. 11) the followings were obtained: f_{S02} = 180 KHz frequency for the basic dominant symmetric mode and f_{A02} = 30 KHz for the basic dominant anti-symmetric mode.

It is noted that the frequencies corresponding to the basic symmetric mode S0 for all plates and all combinations of PWAS as emitters and receivers are of 180 KHz. The same aspect was also found for the basic anti-symmetric mode frequencies that have the same value: 30 KHz.

The coincidence of these frequencies is explained as follows: the frequencies at which one mode is dominant depend neither on the plates plan size nor on the position of the PWAS transducers on the plates.

These frequencies depend only on the plates' thickness and their material characteristics.



(a) (b)

Fig. 11 Variation of S0/A0 and A0/S0 signals amplitudes ratios with frequency

3. CONCLUSIONS

Making a clear distinction between the two wave signals corresponding to the two propagation modes, an accurate measurement of the optimum testing frequencies for the plates was performed. This is also proved by the close correlation between the frequency values obtained through tests using the pairs PWAS1 - PWAS4 and PWAS2 - PWAS4 on the one hand, and PWAS1 - PWAS3 pairs on the other hand, in the case of the two plates of different sizes.

This clearly shows that the precision with which the measurements were made was sufficiently high. This constancy of the two measured frequencies corresponding to the two basic modes of propagation is also due to the fact that all these measurements were made at about the same temperature (room temperature). It is expected that these frequencies also vary with plates temperatures due to changes in plate thickness, speed of wave propagation and because of the mechanical characteristics of the material.

ACKNOWLEDGMENTS

The support from the Romanian Space Agency STAR project ID 188 Space SHM is thankfully acknowledged. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the funding agencies.

REFERENCES

[1] H. Lamb, *On Waves in an Elastic Plate*, Proceedings of the Royal Society, Mathematical, Physical and Engineering Sciences, Vol. **93**, no. 648, doi:10.1098/rspa.1917.0008, pp. 114 – 128, 1917.

[2] V. Giurgiutiu and J. Bao, *Embedded Ultrasonic Structural Radar with Piezoelectric Wafer Active Sensors for the NDE of Thin-Wall Structures*, ASME International Mechanical Engineering Congress, New Orleans, USA, 2002.

[3] V. Giurgiutiu, *Lamb Wave Generation with Piezoelectric Wafer Active Sensors for Structural Health Monitoring*, SPIE vol. **5056**, San Diego, CA, paper # 5056-17, 2003.

[4] V. Giurgiutiu, Tuned Lamb-Wave Excitation and Detection with Piezoelectric Wafer Active Sensors for Structural Health Monitoring, *Journal of Intelligent Material Systems and Structures*, Sage Pub., Vol. **16**, No. 4, Print ISSN 1045-389X, Online ISSN 1530-8138, pp. 291-306, April 2005.

[5] I. A. Viktorov, *Rayleigh and Lamb Waves: Physical Theory and Applications*, Plenum Press, New York, USA, ISBN-10: 0306302861, ISBN-13: 978-0306302862, 1967.

[6] M. Gresil, L. Yu, Y. Shen and V. Giurgiutiu, Predictive model of fatigue crack detection in thick bridge steel structures with piezoelectric wafer active sensors, *Smart Structures and Systems*, Vol. **12**, No. 2, ISSN 1738-1584 (Print), ISSN 1738-1991 (Online), pp. 097-119, 2013.