Damage Identification and Localization in an Aluminium Plate Based on Lamb Waves

Laura Țîrle, Ioan Ursu, and Daniela Enciu

***Abstract*—The article presents a method for identifying and locating damages in an aluminum plate using Lamb waves. For this, a network of PZT wafer type actuators/sensors is used to generate and detect Lamb waves. The damage location algorithm is sketched taking into account the network configuration of PZT sensors. The experimental results confirm the calculation procedure.**

***Index Terms*—Tructural health monitoring, Lamb waves, PZT sensors/actuators, aluminum plate specimen.**

I. Introduction

In the aerospace field, as well as in many other engineering areas, the Predictive Maintenance techniques, also called Condition Based Maintenance (CBM) are designed to preserve the structures in their functional parameters with reducing the huge costs related to their maintenance. As an example, NASA spent $2.16 billion in 2019 for the maintenance of the structures [1]. By intelligently associating the actuators and sensors in a complex network connected to computer systems, a significant economy can be reached [2]. As a result, the overall lifecycle cost of an aircraft, for example, can be reduced with the use of a Structural Health Monitoring (SHM) system as a part of a CBM approach.

SHM is a complex process of monitoring the 'health' status of structures usually online or whenever it is necessary [3]. It consists in acquisition, validation and analysis of technical data to facilitate life-cycle management decisions.

Several methods are well-known and used as a non-destructive SHM techniques for damage identification, each of them having its own potential and being suitable for different types of applications. The most used methods in literature are represented by electromechanical impedance [4]-[7], and by ultrasonic guided waves [8]-[13]. Among the types of the transducers, one can mention the piezoelectric wafer active sensors [14] or the vast class of fiber optics [15].

The SHM techniques are sensitive to every change that appear in the physical properties of the structure [16], [17]. For this reason, the structure is continuous monitored and the data are constantly compared with a baseline corresponding to a pristine state of a structure, an initial state without damage.

The type of damage, crack, corrosion, delamination, etc. requires a change or adaptation of the identification methodology. This methodology could be one of Big Data. For a given active sensor and actuators network, a series of digital damage fingerprints (DDF) can be established for all the signals captured by the sensor network, using the same principle [18]. One particular damage case is uniquely defined with one set of DDF. The entire amount of patterns obtained is stored in a damage parameter database (DPD). Then, through pattern recognition techniques that use artificial neural networks [19], [20], this DPD is used to confront and identify the concrete situation of defect analyzed.

In this article, a know-how is used to illustrate the identification and localization of a defect in an aluminum plate specimen based on guided waves. In the second Section of the paper, a short description of the method is presented. The third Section is dedicated to the experimental setup and to the research findings.

II. Lamb Waves Based SHM for Damage Identification and Localization Methodology

The Lamb waves are ultrasonic waves which, as soon as they are generated by a device, are intrinsically guided between two parallel free surfaces, such as the upper and lower surfaces of a plate [8], [18], [21]. Their great advantage is that the waves can travel relatively long distances without a significant loss of energy, thus providing a large coverage area [22], [23]. Lamb waves are used in diverse applications because of their high sensitivity at damage identification. The disadvantage refers to the fact that this SHM method can be applied to plate and cylindrical structures [22], [24].

Active piezoelectric sensors mounted on aluminium plate were used to identify and localize damage by means of the Lamb waves. Piezoelectric lead zirconate titanate (PZT) sensors offer excellent performance at generating and collecting Lamb waves being suitable for integration on a structure as generators and/or as sensors, due to their negligent mass, excellent mechanical strength, high operating frequency, low energy consumption and low costs. The information is obtained by analysing the parameters of the reflected and transmitted waves resulting from the interaction between the incident wave and damage [25].

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In the case of a sufficiently thin structure, for example a plate whose thickness is of the order of the wavelength, surface waves degenerate into Lamb waves.

There are two types of Lamb waves, symmetrical and antisymmetric, which satisfy the equation of the elastic wave and the boundary conditions and propagate independently of each other. Their characteristic equations, named Rayleigh-Lamb (R-L) equations, one for each mode, are given by [9]

$$\frac{\tan(qd)}{\tan(pd)} = -\left[\frac{4k^2 pq}{\left(k^2 - q^2\right)^2}\right]^{\pm 1} \tag{1}$$

corresponding to the symmetric mode when the exponent is $+1$ and to the antisymmetric mode for -1. The coefficients p and q are

$$p = \sqrt{\frac{\omega^2}{c_L^2} - k^2},\ q = \sqrt{\frac{\omega^2}{c_T^2} - k^2},\ k = \frac{\omega}{c_p}, \tag{2}$$

with ω the angular frequency, k the wavenumber, c_p the phase velocity, and d the specimen half-thickness. c_L represents the velocity of longitudinal wave and c_T is the velocity of the transverse wave

$$c_L = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}},\ c_T = \sqrt{\frac{E}{2\rho(1+\nu)}} \tag{3}$$

where E is the Young's modulus and ν is the Poisson's ratio of the material. Solving R-L equations provides the dispersion curves of symmetric S_i and antisymmetric A_i Lamb modes defined in both the plan $\left(c_p, \omega\right)$ and the plan $\left(c_g, \omega\right)$. c_g is the group velocity with which the overall shape of the amplitudes of the wave (known as the modulation or envelope of the wave) propagates through space; this is the actual velocity captured in experiments (the velocity of wave energy transportation). The phase velocity c_p is the propagation velocity of the wave phase of a particular frequency contained in the overall wave signals, which can be linked with the wavelength λ_w by the relation $c_p = \lambda_w \omega / \left(2\pi\right)$. Thus, we are approaching an important parameter in locating a defect, namely the time-of-flight (ToF) of the wave packet propagating along a sensing path, defined as

$$t = \frac{l}{c_g} \tag{4}$$

where l is the propagation distance between transmitter and receiver. ToF represents the time required that the wave travel from the actuator to the sensor.

There are a few methods to localize the damage. One of them is the triangulation method. The method used in this paper is based on [22]. This method is briefly described below.

A coordinate system originating in $A(0,0)$, which represents the position of the actuator A, is considered. Cartesian coordinates of the sensors are expressed as $S_i(x_i, y_i)$, with $i = 1, \ldots, n$, indicating the sensor number, and the coordinates of the damage are denoted by $D(x_d, y_d)$. In real-time SHM applications, the coordinates of the sensors are known but not the damage location. Consider r the radial distance between the actuator A and the damage D, and θ the angle made by the radial axis with the x -axis. The objective is to find the Cartesian coordinates (x_d, y_d) of the damage. Also, consider t_i the total time that the Lamb wave requires to propagate from the actuator A to the sensors S_i via the damage by the shortest direction d_i. Thus, the polar coordinates of the radial distance and the angle are given by

$$r = \frac{\alpha}{2\left(x_i \cos\theta + y_i \sin\theta\right)},\ \theta = \varphi + \arccos K \tag{5}$$

where

$$\begin{gathered} \alpha = x_i^2 + y_i^2 - d_i^2,\ \beta = x_{i+1}^2 + y_{i+1}^2 - d_{i+1}^2 \\ K = \alpha d_{i+1} - \beta d_i,\ \varphi = \arctan\left(\frac{\alpha y_{i+1} - \beta y_i}{\alpha x_{i+1} - \beta x_i}\right). \end{gathered} \tag{6}$$

The Cartesian coordinates are simply obtained by using the relations

$$x = r\cos\theta,\ y = r\sin\theta. \tag{7}$$

III. Experimental Setup and Results

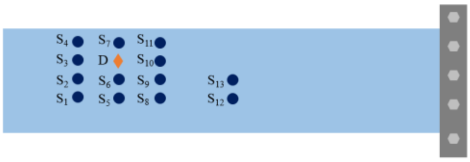
An aluminium plate with the dimensions 1000 mm x 200 mm x 2 mm instrumented with 13 PZT sensors was chosen as a specimen, see Fig. 1. The coordinates of each sensor can be found in Table 1. The sensors were bought from STEMiNC and had a diameter of 10 mm and a thickness of 0.4 mm.

TABLE I: The Cartesian Coordinates of the Sensors on the Aluminum PLATE [mm]

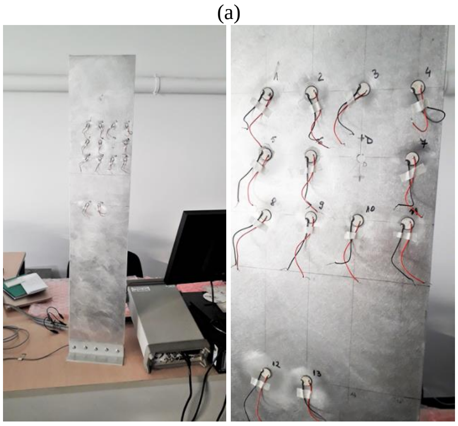
S_1(200, 60)	S_5(250, 60)	S_8(300, 60)	S_{12}(450, 60)
S_2(200,100)	S_6(250,100)	S_9(300,100)	S_{13}(450,100)
S_3(200,140)		S_{10}(300,140)	
S_4(200,180)	S_7(250,180)	S_{11}(300,180)	

The simulated damage consisted in a drill hole of 6 mm and a cut through-the-thickness of 30 mm x 1mm located at half of the distance between the sensors S_6-S_7, respectively S_3-S_{10}. Using a 33120A Hewlett Packard signal generator a three cycle Hanning modulated sinusoidal tone burst signal was generated at 100 kHz frequency. The amplitude of the signal was 10 VPP (peak-to-peak voltage). The Lamb wave signals were collected by a DSO-X-3034A Agilent Technologies InfiniVision oscilloscope.

In the paper, the damage was simulated as a simple drilled hole, of diameter compatible with the frequency of the generated Lamb wave. It is known that the wavelength of Lamb waves that propagates in thin plates is of the order of magnitude of plate thickness, the upper and lower surfaces of the plate serving as guides for their propagation. On the other hand, the half wavelength of a chosen wave mode must be at most equal to the damage size to allow the wave to interact with the damage. In these correlations one can evaluate the influence of plate thickness, or Lamb wavelength in the investigation of the damage. In all these approaches, the transducer noise must keep the same characteristics, so as not to compromise the results.



(a)



(b)

Fig. 1. The distribution of PZT sensors on aluminium plate (a) drawing (b) the aluminium specimen with PZT and damage.

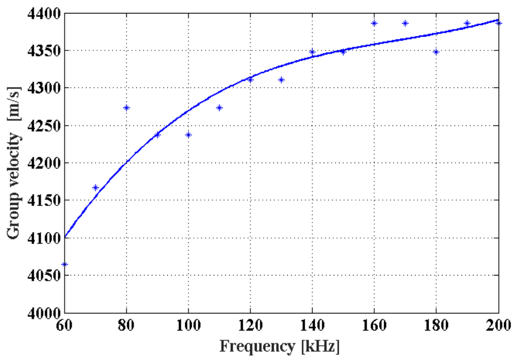


Fig. 2. Experimental identification of the group velocity.

Locating defects in a structure with a complex geometry is difficult to achieve. This involves the design of a well-defined network of sensors and their optimal bonding on the tested specimen. Moreover, the guided Lamb waves are dispersive leading to a strong dependency between the group and phase velocities and the product fd of the frequency f and the plate half-thickness d. For a given frequency-thickness product, for each solution of the R-L equation, the corresponding Lamb wave velocity and the corresponding Lamb wave mode are found. In Fig. 2 is depicted the variation of the group velocity with the frequency.

Signal measurements were performed for a wide range of frequencies, starting from 60 to 200 kHz to establish the optimal frequency. It was observed that the signal amplitude decreases as the frequency increases (Fig. 3), and the identification of wave packages becomes difficult to perform.

The measurement frequency was chosen as 100 kHz because the signal has a high amplitude and the wave packets are clearly delimited. The optimal oscillation frequency is influenced by the frequency characteristic of the transducers and the material.

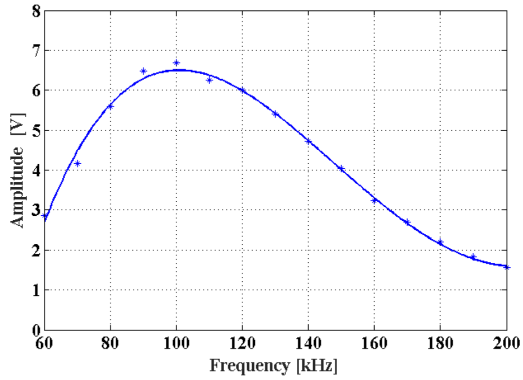


Fig. 3. Maximum amplitudes of Lamb waves depending on frequency.

The theoretical velocities were calculated using the aluminum material properties: Young modulus - 72×10^9 Pa, Poisson's ratio - 0.33 and density - 2800 kg/m^3. According to (3), the longitudinal velocity is equal with 5071 m/s, and the transverse velocity is equal to 3109 m/s.

Three transducers from the configuration in Fig. 1 were chosen as it follows: transducer 7 as actuator and 6 and 11 as sensors. In Fig. 4 one can see the response recorded by the sensors for the pristine case.

In order to identify the damage, the signals recorded before and after the defect in the aluminum plate were compared. It was observed a decrease in amplitude, a change of *ToF*, and appearance of new wave packets as shown in Fig. 5. Also, to highlight these changes, the Hilbert transform was applied.

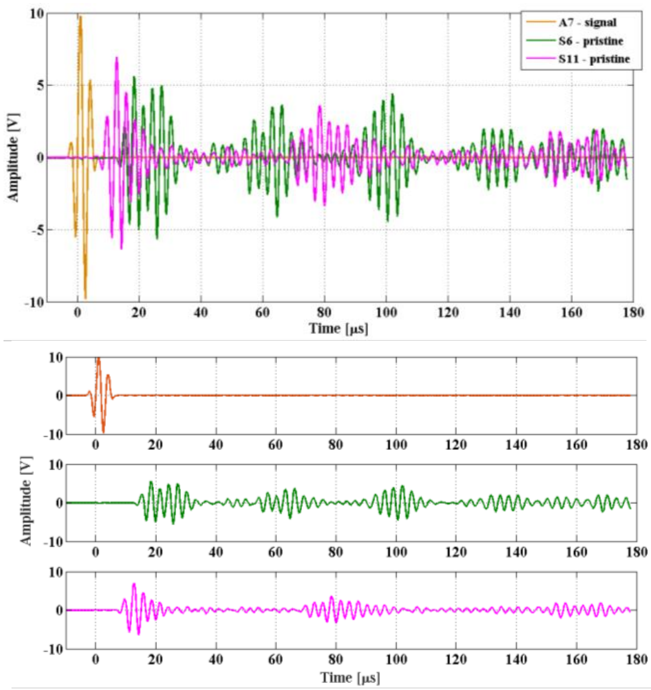


Fig. 4. Signal recorded by sensors S_6 and S_{11} on pristine specimen. Excitation signal generated by actuator A_7: (up) overlapping signals and (down) individual signals.

The next step of the experiment was to locate the position of the damage. For that, the method described above by (5)-

(7) was applied. In order to identify the Cartesian coordinates of the defect, the geometric scheme from Fig. 6 is considered.

The distance between actuator A_7 and sensor S_{11} is denoted by d, and by d_1 the distance from A_7 to the damage position D. The distance from the actuator to the sensor S_{11} via the damage is $d_2 = r + d_1$. According to the experimental set-up from Fig. 1a, r = 39.5 mm, d =50 mm and d_2=103.22 mm.

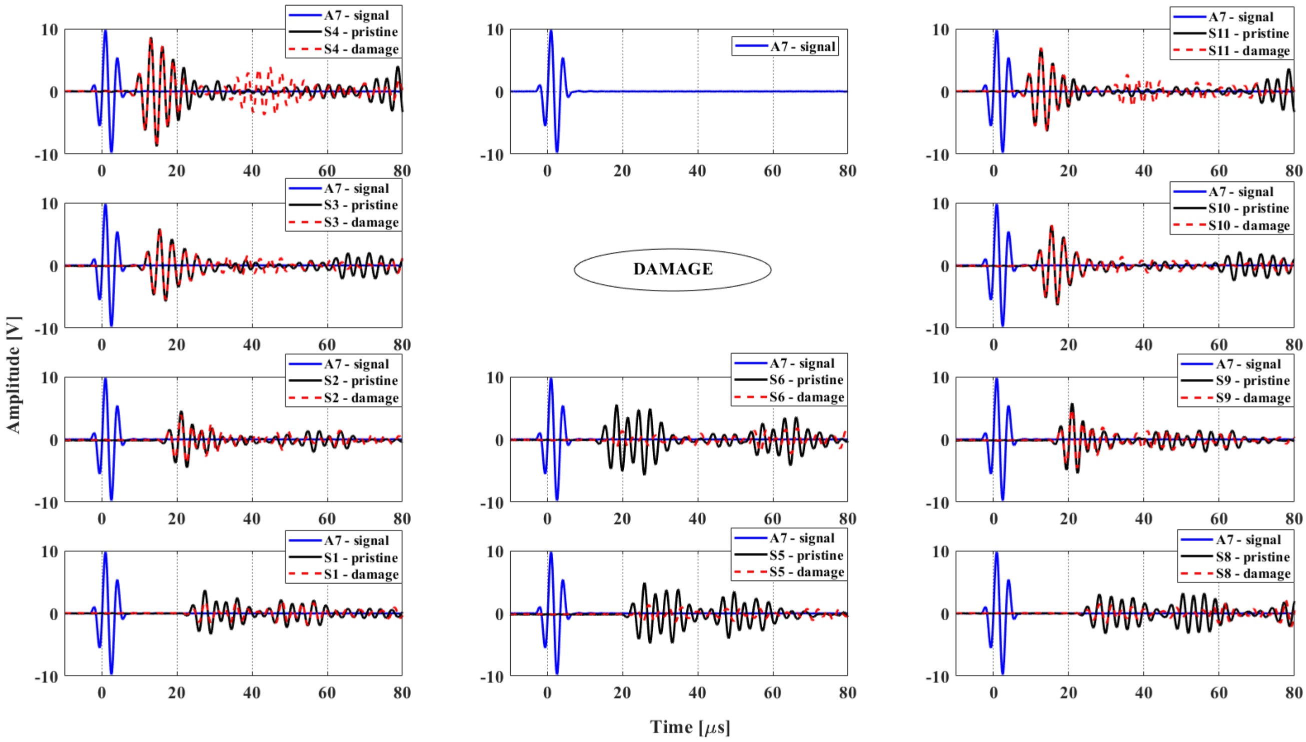


Fig. 5. The signal response of the sensors S_1-S_{10} on pristine and damage specimen. The signal was generated by transducer A_7

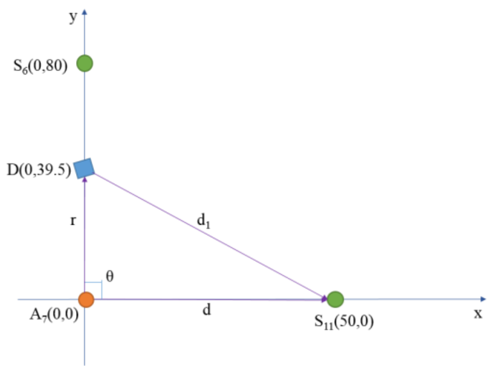


Fig. 6. Lamb wave propagation scheme

The polar coordinate *(r,θ)* are determined according to (5). In this case $m(\widehat{\theta}) = 90^\circ$. Thus, replacing with numerical values it is obtained $r = 39.49999$. Therefore, the Cartesian coordinates of the damage D are $D(0,39.49999)$ which correspond to the real position where the damage was made on the aluminium plate.

IV. Conclusion

The method presented for detecting a simulated damage, for a chosen configuration of sensors-actuators bonded to an aluminum specimen, is the triangulation method. This method provides, in principle, a good accuracy. The Hilbert transform of the wave packet was used to measure the group velocities of the Lamb waves. Solving the Rayleigh-Lamb equations, otherwise difficult, has been avoided by experimentally identifying the basic frequency of the propagation modes. A method of accurately locating defects in a structure has been substantiated.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Formulation of the study and experimental design: D. Enciu; analysis of the methodology: I. Ursu; acquisition of data: L. Ţîrle; analysis and/or interpretation of data: all authors; drafting the manuscript: L. Ţîrle; critical revision of the article: I. Ursu, D. Enciu; final approval of the version to be published: all authors.

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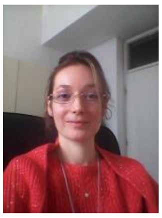

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