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PROBABILITY OF DAMAGE IN STRUCTURES BY THE USE OF LAMB WAVES AND RAPID ALGORITHM

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Abstract. *With recent development of new composite materials, the mechanical structures demand the use of lightweight and high resistance to fatigue in aircraft and engineering applications. However, damage detection in composite materials is a very difficult task by using traditional vibration methods. This contribution uses the Lamb Waves SHM method in an aluminum beam for damage detection purposes with a low cost experimental apparatus. Three simulated damages (added mass) were proposed and identified by the Wavelet Transforms for feature extraction and the reconstruction algorithm for probabilistic inspection of damage (RAPID) algorithm to quantify the probability of occurrence of damage, locating it from the sparse matrix of the patches. Results can illustrate good results of the experimental setup associated to the proposed mathematical tools in order to identify and quantify the damage.*

Keywords: *Lamb Waves, Structural Health Monitoring, RAPID algorithm, CWT*

1. INTRODUCTION

In general, a mechanical system works on critical conditions concerning to the failure considering design assumptions (Santos, 2016). Based on this design aspect, studies of health monitoring of such structures are increasing in the past decades.

Some SHM (Structural Health Monitoring) methods are based on the fact that any damage in the structure can promote dynamic response changes in the system. Then, it is possible to identify the damage by the comparison of the signatures of the dynamic responses in both states (Leucas 2009, Moura Júnior 2008, Palomino 2012 e Sohn *et al.*, 2003).

On the other hand, composite materials have been used in new aircraft and engineering designs due to the lightweight and higher resistance to the fatigue (Lemistre *et al.*, 1999). Also, some SHM techniques are very efficient to composite materials because some troubles regarding the incipient damage detection.

In this scenario good results can be obtained by the use of Lamb Waves in composite materials once this high frequency evaluation is able to detect small defects in layers of the structure (Franco 2009, Moura *et al.* 2008 e Dalton *et al.* 2000). This method can identify and quantify damages by the use of mechanical waves that attenuates and deflects inside the structure.

Some advantages of the Lamb Wave technique is the capacity to be used in long shape structures, high sensitivity to small damages and low cost of implementation. However, due to the dissipation of the waves along the structure and multimodal response aspects, such implementation demands mathematical models for feature extraction. The RAPID

algorithm (Reconstruction Algorithm for Probabilistic Inspection of Damage) is also an important tool in this aspect, once it can correlate the signature obtained by different sensors in a network.

There is two feature extraction for the damage detection procedure: based on physical modeling and based on statistical modeling of the experimental data (Lemistre et al 1999, Raghavan and Cesnik 2005, Moura Junior, 2008). This contribution uses the experimental approach associated to feature extraction based on CWT (Continuous Wavelets Transforms) (Leucas, 2009 and Moura Júnior, 2008).

In this contribution is proposed a low cost process of damage detection in composite structures by the Lamb Waves technique in UFG (Federal University of Goias), by using the Wavelets for feature extraction and RAPID algorithm to identify the place and severity of the damages.

2. DEVELOPMENT

2.1 Lamb Waves SHM Method

The Lamb Waves technique is based on the superposition of two different vibration modes: longitudinal and transverse waves (Cardoso, 2012).

The longitudinal wave has the movement of the particles in parallel to the direction of the applied force. The transverse wave occurs in a perpendicular direction of the longitudinal wave. Then, the coupling of the two vibration modes gives the ability to cover an area of inspection. Also, the coupling of these two vibration modes can be symmetric and asymmetric patterns.

In a symmetric pattern the particles move along the material in a symmetric shape to the middle plane of the structure. This kind of pattern is more applied to metal structures. Asymmetric waves have particles moving in alternate points related to the middle plane and this kind of pattern is more suitable to composite structures. Figure 1 illustrates both patterns.

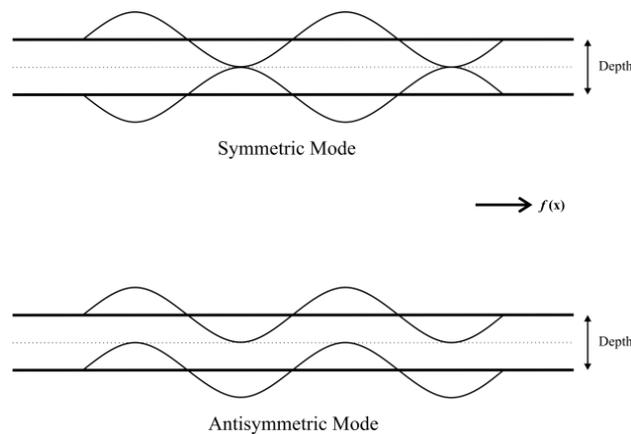


Figure 1: Two patterns of Lamb Waves

There are infinite modes of wave propagation in different frequencies, considering symmetric and asymmetric pattern.

2.2 RAPID Algorithm to correlation analysis

Some Lamb Waves techniques use power reduction and phase speed variation of the experimental signatures to identify damages in the system. Some of them are Delay-and-sum beam-forming (Wang, 2004 e Sharif-Khodaei, 2014), time-difference-of-arrival method (Michael, 2007) and energy arrival method (Michael, 2007).

However, due to the multimodal aspect and high dissipation of the waves in the structure, these parameters can be difficult to be found. Then, the RAPID algorithm is an important way to identify and map structural damages because it considers the changes of the signatures and the relative distance between the sensor-actuator couple (Liu, 2015). Also, this algorithm can incorporate other tools as CWT used in this contribution to improve the precision of evaluation.

RAPID algorithm uses the concept of the SDC (Signal Difference Coefficient), which represents the difference between the damage and baseline signatures. Then, it is done the probabilistic linear sum of the sparse matrix of the patches (Hettler, 2015). This correlation coefficient is obtained in two steps, defined by Eq. (1) and (2).

$$\rho_{ij} = \frac{Cov(B, D)}{\sigma_B \sigma_D} = \frac{\sum_{k=1}^n (B_k - \mu_B)(D_k - \mu_D)}{\sqrt{\sum_{k=1}^n (B_k - \mu_B)^2} \sqrt{\sum_{k=1}^n (D_k - \mu_D)^2}} \quad (1)$$

$$SDC_{ij} = 1 - |\rho_{ij}| \quad (2)$$

where B_k and D_k are, respectively, baseline and damage signatures after Wavelet Transform extraction, considering the path from the actuator i to the sensor j . The variables μ_b e μ_d are the averages of each data set and SDC can change from 0 to 1. Minimal values of SDC means absence of damage and SDC closer to 1 represent its presence (Wang, 2014).

After the dissimilarity parameter for damage and baseline signatures of the system, it is defined an elliptic area between actuator and sensor. This area uses the SDC values to delimitate the probability of occurrence of damage (Keulen, 2014). Thus, the function of the SDC values found can be defined by the Eq. (3).

$$\begin{cases} s_{ij} = \frac{\beta - R_{ij(x,y)}}{1 - \beta} & \text{for } \beta > R_{ij(x,y)} \\ s_{ij} = 0 & \text{for } \beta \leq R_{ij(x,y)} \end{cases} \quad (3)$$

where β defines a control factor of the maximum size of the ellipse (greater than 1), and $R_{ij(x,y)}$ defines the maximum radius of the ellipse, considering the i actuator and j sensor positions, following the Eq. (4).

$$R_{ij(x,y)} = \frac{\sqrt{(x_i - x)^2 + (y_i - y)^2} + \sqrt{(x_j - x)^2 + (y_j - y)^2}}{\sqrt{(x_j - x_i)^2 + (y_j - y_i)^2}} \quad (4)$$

From the values obtained to the probabilistic distribution function s_{ij} and the obtained $R_{ij(x,y)}$ and β , it can be defined an area which the method can find the presence of damage for a specific path ij . An illustration of this area is represented in Fig. 2.

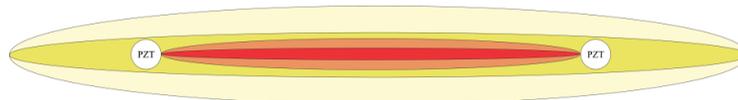


Figure 2: Probabilistic distribution area of the damage

Then, each evaluation of the probability of occurrence of damage of each inspection path will indicate the vertical presence of damage between each actuator-sensor. To obtain the correct prediction, it is necessary to sum all inspection paths according to Eq. (5) (Sheen, 2012).

$$P = \sum_{i=1}^n \sum_{j=1}^n SDC_{ij} * s_{ij} \quad (5)$$

In order to apply this method in bi-dimensional structures (plates), it is necessary to build a network of patches working as sensors/actuators. In beam studies there is only one inspection path, which the PZT patches are placed at the focus of the ellipse.

3. EXPERIMENTAL PROCEDURE

3.1 Experimental setup

This contribution aims the identification of damages in an aluminum beam (300x25x3mm). The simulated damage was done by mass addition (10x10x10mm magnet applied on the surface of the structure). The added mass was positioned in three different places and can be illustrated by the Fig. 3 (50, 100, 150 mm far from PZT A, respectively).

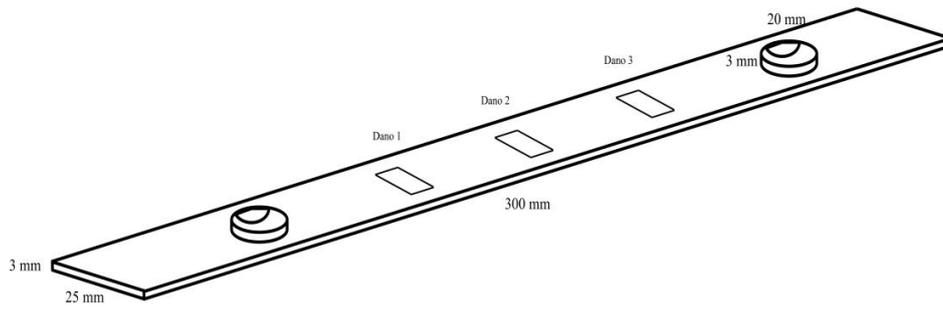


Figure 3: Structure, added masses (damages) and PZT patches.

The low cost acquisition system used in the experiment was composed by: one wave generator UDB110x (S) series DDS Signal Generator, one B&K Precision 2530 Digital Storage Oscilloscope 25 MHz Bandwidth and two PZT patches with 20mm of diameter and 3mm of thickness (each one bonded at 50mm from the tip of the beam).

3.2 Experimental simulation

Initially, each PZT patch was excited individually while the response of the structure was gathered in another one. Thus, the setup patch catch was used in the experiment to obtain each path of inspection (Leucas, 2009). The Fig. 4 illustrates the averages of the waves obtained from the experiment.

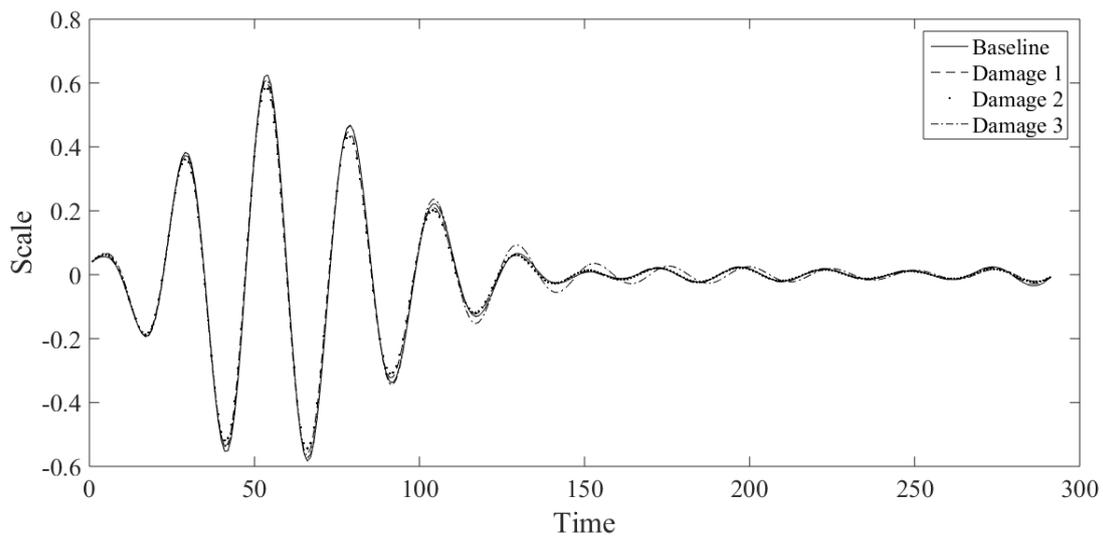


Figure 4: Averages of the samples (baseline and damages).

Figure 4 illustrates that the Wavelet Transform can be used to separate the data sets, resulting in SDC values closer to zero for all paths of detection.

From the sample data sets it was implemented the RAPID algorithm in a virtual environment in order to obtain the probability of damage occurrence in the analyzed structure. Next session will present the results of this implementation.

4. RESULTS AND DISCUSSION

The frequency of excitation used in the experimental procedure was 20kHz with a sampling of 291 points, after features extraction both sample sets were able to detect the damage in a probabilistic area of inspection limited by two PZT patches. This probability distribution of the damage occurrence obtained by the method is illustrated in the Fig. 5.

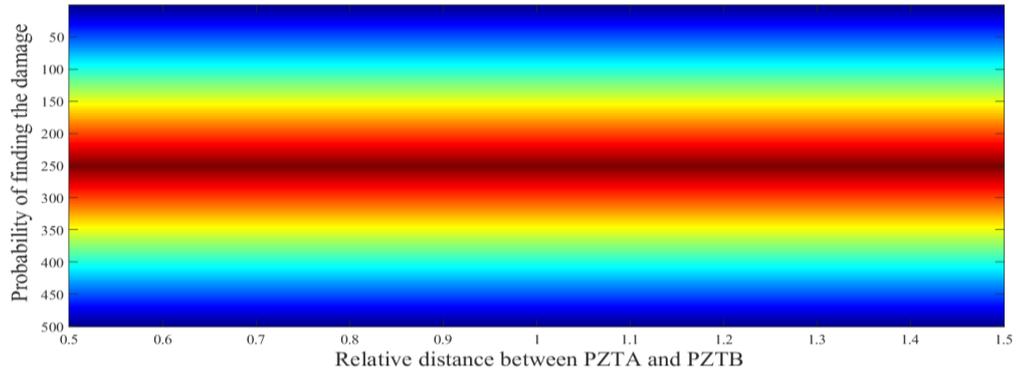


Figure 5: Probabilistic distribution of the damage analysis of the beam (with and without damage).

Once there is only one path of inspection, the application of the method can define only the vertical distribution of the damage between two sensor/actuators. However, the method was able to identify with success the presence and severity of the damage.

In order to make a quantitative mapping of the damage related to the piezoelectric sensor/actuators, it was conducted the correlation coefficient analysis and the damage distribution related to each applied position of the damage, illustrated in Fig. 6.

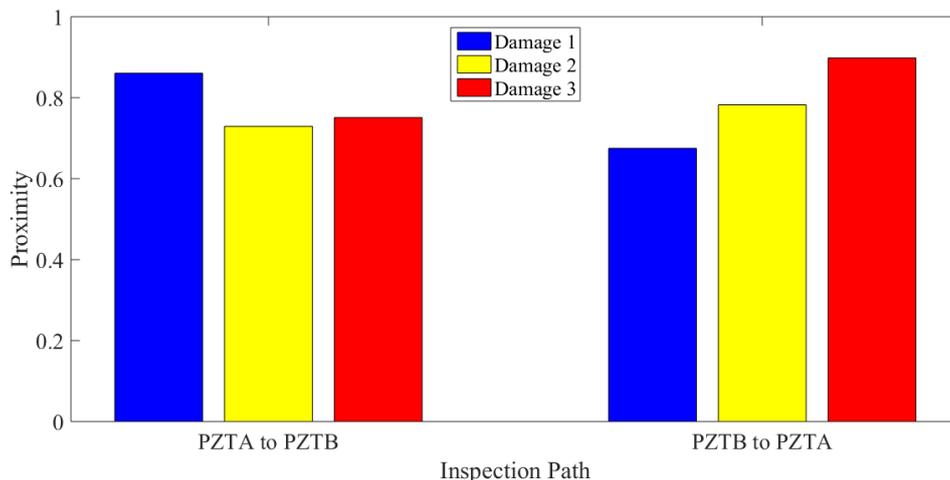


Figure 6: Quantitative mapping of the damage.

Thus, the method was able to define the relative position of the damage in each condition, describing the damage condition 1 closer to the PZT patch A and the damage condition 3 closer to the PZT patch B.

5. CONCLUSIONS

In this contribution it was used the Lamb Wave technique for damage detection in an aluminum beam. It was applied the Wavelet Transform in order to extract sensible features of the signatures from the data amount. Thus, it was possible to show the use of the method in structural analysis by the use of low cost devices.

Also, the result illustrates the good precision in the quantitative analysis due to the RAPID algorithm (Probabilistic Inspection). However, once the experiment has only one inspection path, the damage mapping was not completely efficient. Concluding, it is planned to apply the same procedure for a two-dimensional aircraft structure to validate the approach in more complex systems.

6. ACKNOWLEDGEMENTS

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