A COMPARATIVE ANALYSIS BETWEEN LAMB-WAVE AND IMPEDANCE BASED SHM METHODS APPLIED IN RIVETED STRUCTURES

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Abstract. *The present contribution is devoted to studying two well-known structural health monitoring (SHM) techniques to detect damage in typical metallic riveted structures, such as beams and panels such as those found in various types of industry: automotive, aeronautic and civil. For this aim, a comparative analysis between the methods based on Lamb Waves and Electromechanical Impedance is presented. The evolution of the damage is observed by using a specially defined Damage Metrics that is able to detect damage as caracterized by revet losses. The monitoring signals are obtained from PZT patches bonded to the structure as electromechanical sensors and actuators by using the indirect and direct piezoelectric effect, respectively. A signal processing tehcnique based on the wavelet transform was used together with the pitch-catch approach to detect the damage for the Lamb wave technique. Finally, the main objective of the present work is to determine if the methods proposed can effectively identify incipient damage in the above-mentioned types of structures, aiming at incorporating the studied techniques in real-time SHM strategies.*

Keywords*: lamb wave based health monitoring, impedance-based health monitoring, riveted structures.*

1. INTRODUCTION

Maintenance of mechanical structures has been considered a key point in engineering since it is strongly related to the operational cost of machines, vehicles and equipment and also to safety. It is desirable to know the location of the damage and how the structure is affected by this damage before starting the maintenance procedure. Besides, in our days, the remaining life of the damaged structure is a very important issue both from the economic and technologic viewpoints. Besides, smart material technology is able to offer self-healing solutions in some applications (Park and Inman, 2001). The simplest way to detect defects on a given structure is by performing a visual inspection, however this methodology is very time consuming and depends on the human factor. Besides, it is very common that the access to mechanical components that are subjected to flaws is quite difficult and lead to a complete stop of the system and its operation is interrupted for long periods of time.

To overcome this problem, Farrar et al (2005) defines Structural Health Monitoring (SHM) as the process of damage detection for engineering structures involving the observation of a system over time using various response measurements from an array of sensors. These acquired signals load damage-sensitive information that can be extracted and analyzed in such a way that it is possible to obtain a pattern of the structural degradation along its useful life.

Typically, up to date evaluation techniques store a signature of a signal obtained from the healthy structure and compares it with a given signal that may represent damage in this system. After statistical analysis, the damage can be confirmed or not, depending on how different the compared signal is from the signature of the healthy one. More than this, many other signatures can be obtained from different types of damages and, with a proper algorithm, the damage can be classified. The application of all these techniques provides to the system reliability, security and reduces both operating and maintenance costs.

This study presents a comparison between two branches of SHM techniques, namely the electromechanical impedance and Lamb-waves techniques. These non-destructive evaluation techniques explore the capacity of the piezoelectric materials to play the role of sensors and actuators simultaneously, when bonded to the surface of a monitored structure. In this case, an aluminum beam and a panel were tested and damage was characterized by missing rivets in the structure. For both the techniques used, measurements were made before and after removing rivets.

2. STRUCTURAL HEALTH MONITORING METHODS

A structural health monitoring system basically consists of a structure to be analyzed, an onboard network of sensors, – and actuators, depending on which technique is used – and some processing hardware employing algorithms to evaluate data from structure health (Raghavan and Cesnik, 2005). Lamb-waves and Electromechanical Impedance based techniques are sensitive to small structural changes and they are briefly revisited in the following.

2.1 The Electromechanical Impedance-Based Method

The mechanical impedance can be defined as the complex relationship of the force applied to and the velocity achieved by a given structure. This function is associated with the parameters of mass, stiffness and damping of the structure (K, C, M_m, respectively). As any change in these parameters lead to a modification in the impedance value, measuring the mechanical impedance signal can give indication of possible damage in the structure. In this way, the impedance signal can be used as tool for structural health monitoring. It is worth mentioning that measuring the impedance can be quite difficult in practical cases.

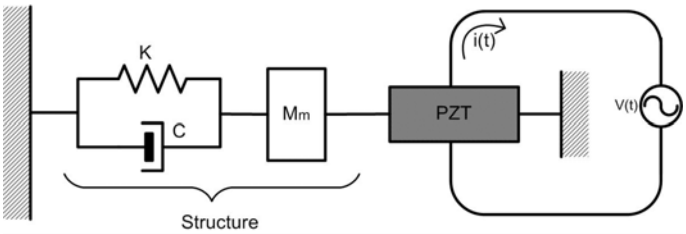


Figure 1. Simplified 1D model used to represent the impedance coupling systems. (Park, 2005)

To overcome this problem, a piezoelectric element can be used to couple the mechanical parameters with the electrical properties of the PZT patch by the coupling coefficient and obtain a complex electrical impedance that is related to the mechanical impedance of the structure as shown in the figure 1. Since the mechanical properties of the piezoelectric material do not vary with the time, the electrical impedance of the PZT patch can be linked with the electromechanical impedance of the structure. Through monitoring this function and by comparing it to a value measured under healthy conditions (called baseline), it is possible to determine how damaged is the structure (Park, 2003) making this a suitable NDE (Non Destructive Evaluation) method.

The sensitivity of this technique depends on the frequency range selected for electromechanical impedance measurement. This sensitivity range can be determined by trial and error and typically is located in the range of ultrasonic frequencies between 30 kHz and 250 kHz.

After the measurement of the electromechanical impedance function the use of a statistical algorithm is necessary to provide a quantitative assessment of the damage, called damage metrics. One of the most widely used damage metric is the RMSD (root mean square deviation) is given by equation (1).

$$RMSD = \sum_{i=1}^{n} \sqrt{\frac{\left[\mathrm{Re}(Z_{i,1}) - \mathrm{Re}(Z_{i,2})\right]^2}{n}} \tag{1}$$

where:

- Re() stands for the real part of the given complex number;
- $Z_{i,1}$ is the impedance of the PZT measured at healthy conditions (baseline);
- $Z_{i,2}$ is the impedance of the PZT measured for comparison;
- n is the number of frequencies taken in the range.

The value of the damage metrics simplifies the interpretation of this technique and can be used in a number of applications.

2.2. The Lamb-Wave Based Method

Lamb-waves are elastic waves that propagate in solid media and they were first predicted by Lamb (1917). However, he was unable to produce these waves experimentally due to technical limitations at that time. In the last decade the study of the Lamb-waves has progressed due to its possible practical application in the field of non destructive evaluation.

As the Lamb-waves propagate in the structure they can provide information regarding its healthiness along the path of propagation. The usual diagnostic methods associated with the lamb-waves are the so-called pulse-echo method and the pitch-catch method. On both methods the actuator excites the structure with a pulse signal, usually a tone burst. In the pulse-echo method the same actuator is used as a sensor to monitor the echoes of this signal along the path of propagation. In the pitch-catch approach the pulse signal is generated by an actuator and propagates across the structure; then, a sensor located in a different location of the structure receives the signal (Raghavan and Cesnik, 2005).

Each technique provides different characteristics that can be extracted from the received signal. It is important to observe that basically the lamb-waves method uses a time-domain analysis. Since the approach used in the present work is the pitch-catch, this methodology will be described below.

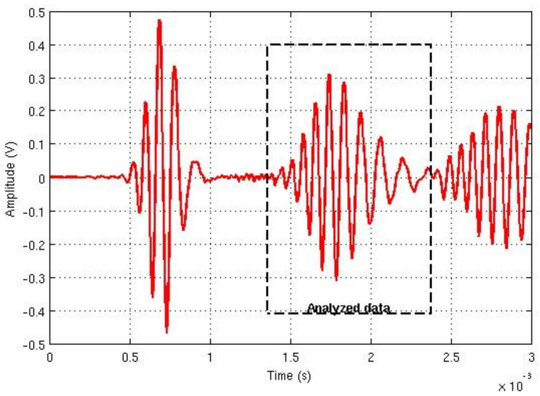


Figure 2a. Typical response of a Lamb-wave experiment.

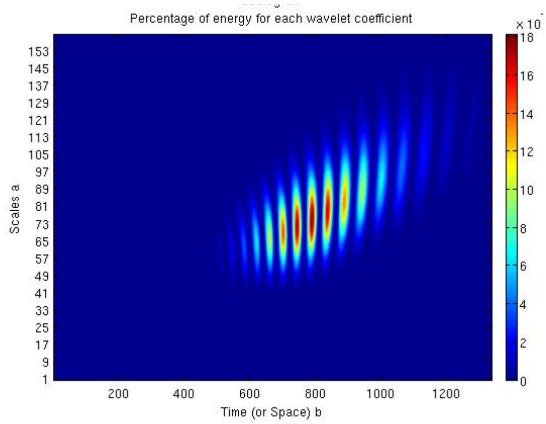


Figure 2b. Scalogram of the analyzed region.

In the figure 2a the original signal acquired from a PZT patch sensor bonded to a structure which is excited by an actuator through a sinusoidal burst is shown. It represents a typical response obtained by the pitch-catch method. The highlighted area represents the part of the data that is used for the analysis. It corresponds to the reflected signal that is traveling along the structure.

Looking at the analyzed data window and searching for the peak of the signal, we can define the time it occurs – called TOF (Time of Flight) – and the peak's value given at this time. Moreover, the energy of the signal can be used to characterize it (Sohn, 2005). By the fact that this signal is classified as transient, transient-analysis tools such as the Continuous Wavelet Transform (CWT) is used to extract more information of the data acquired, especially to isolate the input frequency (Wang and Chang, 2000; Lind et al, 2001; Abbate et al, 1997).

The figure 2b shows the analyzed data after CWT and the corresponding data is plotted as a scalogram. Note that CWT returns a Scale x Time plot. Since the scales of CWT are associated with the frequencies of the signal, the input frequency corresponds to a specific scale of the plot and is analyzed as described earlier.

Once again data that provides information about the structure`s health is obtained. It is possible to establish a quantitative value of the damage in this case. One of the most reliable indexes is considered to be the so-called Damage Index (Sohn, 2005) that uses a comparison between the energy of the baseline and proofed CWT processed signals. The formulation for this metrics is given by equation (2).

$$DI = 1 - \frac{\int_{u1}^{u2} Wft(u, s_0)du}{\int_{u1}^{u2} Wfb(u, s_0)du} \tag{2}$$

where:

- $Wf_b()$ stands for the wavelet transform of the baseline signal;
- $Wf_t()$ stands for the wavelet transform of the tested signal;
- u represents the translation of the wavelet used on CWT;
- s represents the dilatation of the wavelet used on CWT;
- u2, u1 are the interval of translation (linked to time) analyzed by CWT.

Similarly to the impedance method, the sensitivity of this technique depends on the selected excitation frequency. However, this method uses only one input frequency to generate the tone burst and after this the signal is analyzed. Moreover, the Lamb-wave technique uses lower frequencies as compared with the Impedance-based one (in the present work, since metallic materials are used in the tests). This makes the required hardware (data acquisition board, computer memory) less sophisticated. The excitation frequency is affected by the attenuation along the propagation path and is usually determined by trial and error testing.

2.3. Summary of the Methods

As commented above both the techniques presented have their own characteristics: Table1 summarizes the main differences between the lamb-waves method and the Impedance-based.

Table 1. Comparison between the main characteristics of the methods.

	Electromechanical Impedance	**Lamb Waves**
Frequencies used	Wide range	Single tone burst
Analysis	Frequency-based	Time-based

3. EXPERIMENTAL TESTS

To illustrate the application of the two methods used, experiments have been performed using two types of structures. Free-free boundary conditions have been assured for the structures. An Impedance Analyzer (HP4194A) was used to obtain the impedance curves and a Labview® based acquiring board (adjusted accordingly) was set to obtain the Lamb-waves signals for the excitation frequency.

3.1. Aluminum Beam Experiment

The first specimen tested was the aluminum beam depicted in the figure 3a; the geometry and the arrangement of the PZT patches are shown in the figure 3b. The damage was simulated by taking a single rivet off the structure.

First the baseline signals for both techniques were acquired by considering the structure as healthy (the rivet is intact). For the impedance technique the bandwidth analyzed was 40 kHz to 50 kHz measured at PZT1 with 20 repetitions. For the Lamb-wave, the frequency used was 10 kHz tone burst, the signal was acquired by the two PZT patches, and for each PZT patch 50 repetitions were performed.

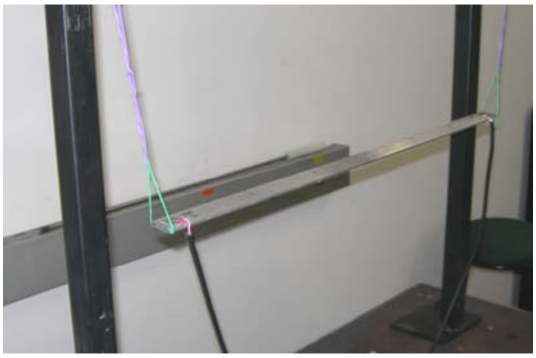


Figure 3a. Aluminum beam used on the experiments.

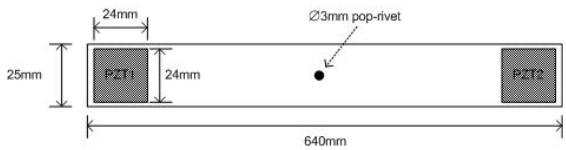


Figure 3a. Geometry of the set-up.

The signals obtained from the two methods were analyzed by using the equation (1) for the impedance method and equation (2) for the Lamb-wave. The results obtained are shown in the figures 4a and 4b for the impedance and the lamb- wave techniques, respectively.

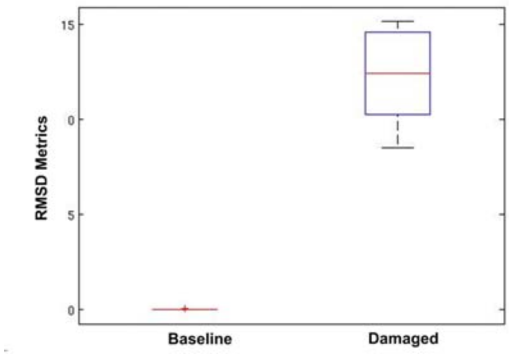


Figure 4a. RMSD for the beam.

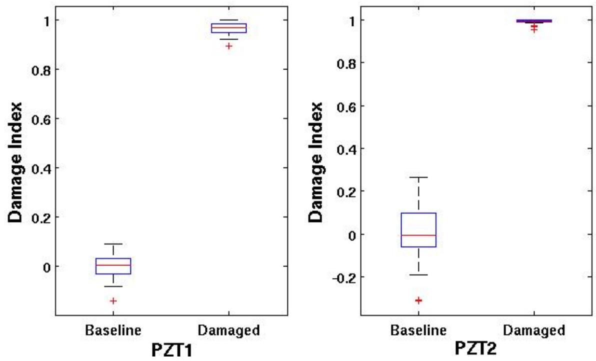


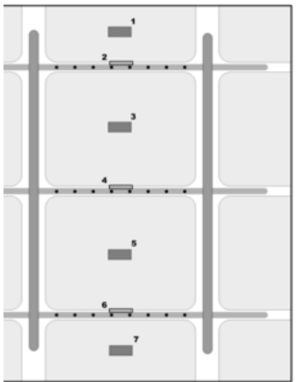
Figure 4b. Damage Index for the beam.

The metrics used clearly indicate the effect of the loss of the rivet as represented by quantitative values. Note that the pattern differs from each case studied, while for the impedance technique the value of the metrics decreases and for the Lamb-wave method the metrics value increases. These tests demonstrated the potential use of both techniques for SHM purposes in riveted structures.

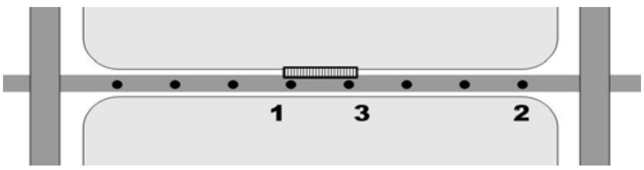
3.2. Aeronautic Panel

This experiment proposes a more complex structure to evaluate the studied techniques. It consists of an aeronautic panel (figure 5a) measuring 810 mm x 810 mm and the arrangement of the PZT patches bonded to the structure is shown in figure 5b. During the test, three rivets of the central part of the panel were taken off as illustrated by figure 5c. The configuration of the experiment was as follows: bandwidth from 35 kHz to 45 kHz measured at PZT3 for the impedance-based test and a single tone burst of 8.3 kHz pitched on PZT1 and acquired at PZT5 for the lamb-wave method. In this set of experiments, 50 repetitions were made for the impedance measurements and 500 for the lamb-waves.

(a)



(b)



(c)

Figure 5a. Aeronautic fuselage component used. Figure 5b. Positions of PZT patches on the structure.
Figure 5c. Detailed view of loosen rivets.

Figures 6a and 6b show the results from these sets of experiments and it can be noticed that there is a region in the plot that is shared by all the metric values that correspond to the damaged state of the structure. It is worth mentioning that as the Lamb-waves technique is based on time-domain analysis it requires a larger number of repetitions as compared with the impedance based. This procedure is necessary because time-domain analysis is very sensitive to noise and to low quality data acquisition.

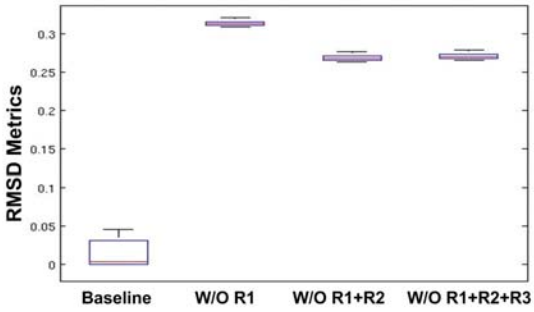


Figure 6a. RMSD values obtained from the plate.

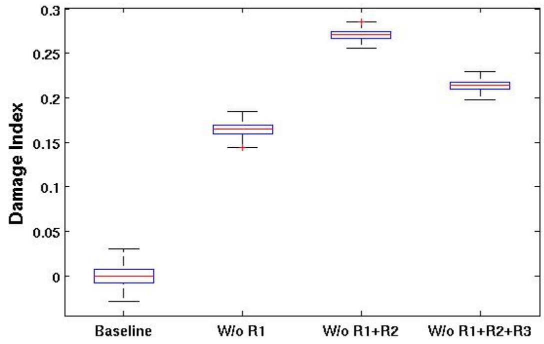


Figure 6b. Damage Index obtained.

It is not simple to represent the phenomenon studied above mathematically. For this reason, a meta-model can be built by using the available data. For this aim, the curves which represent the metrics obtained from the tests are fitted to the state of the structure as the damage increases (Moura and Steffen, 2006). This meta-model can be implemented by a hardware-based SHM monitoring system to verify the damage condition; however this approach is not the focus of the present work. Figures 7a and 7b show the fitted curves (impedance-based and Lamb-wave techniques, respectively) where the Y_{lamb} and Y_{imp} variables stand for the damage condition of the structure where 0 corresponds to the healthy condition and 1, 2, 3 have to do with the successive rivet losses, respectively.

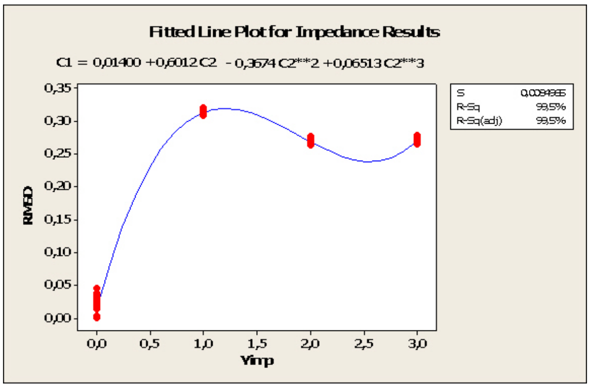


Figure 7a. Curve fitting for the impedance method.

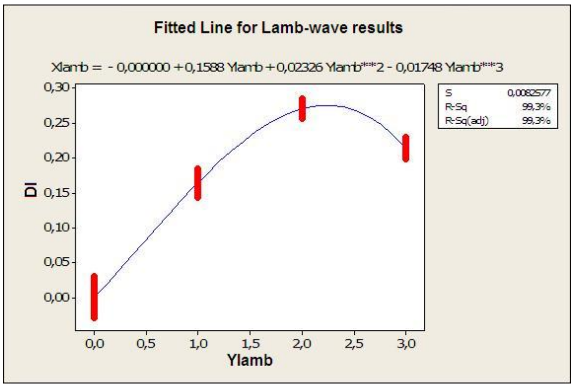


Figure 7b. Curve fitting for the lamb-wave.

4. CONCLUSIONS

In this paper, two state-of-the-art SHM approaches were developed for detecting incipient damage on metallic structures. For this aim, a comparative analysis between the methods based on Lamb Waves and Electromechanical Impedance was presented. The evolution of the damage was observed by using a specially defined Damage Metrics that was able to detect damage as characterized by rivet losses. The monitoring signals were obtained from PZT patches bonded to the structure as electromechanical sensors and actuators. The wavelet transform was used together with the pitch-catch approach to detect the damage for the Lamb wave technique. After processing the data obtained by using Lamb Waves and Impedance-based techniques, it was possible to conclude that both of them are capable of detecting the loss of one or more rivets on the structure.

Regarding the choice of the most appropriate technique, this is a very delicate decision. In most cases it depends on the available hardware and the quality of the signal obtained from the PZT patches, since some parameters of both the techniques used are chosen from trial and error tests.

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