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# RECENT DEVELOPMENT IN THE STRUCTURAL HEALTH MONITORING IN THE GRAVI GROUP IN UFMG

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***Abstract.*** *The group of GRAVI of UFMG has been implemented two techniques to damage detection in structures using Lamb wave approach. The first method is based on the construction of the wave propagation map calculated using the group velocity of the wave propagation and the Hilbert Transform. The second method is based on the comparison of the Power Spectrum Density of the signal measured by the sensors. The Methods were tested in a simple squared composite plate and in a curved reinforced metallic plate composed by three plates jointed by bolts. The results are presented using the Probability of Detection (POD) curves based on hit/miss data.*

***Keywords:*** *Structural Integrity, Structural Health Monitoring, Damage Detection*

## 1. INTRODUCTION

Nowadays, SHM (Structural Health Monitoring) has been gained interest, where can be cited some dedicated journals such as “NDT&E International” and “Journal of Structural Health Monitoring”, some commercial products such as the Acellent technologies and some prototypes such as Finzi Neto et al. (2010) and Overly et al. (2009).

In this scenarios, the group of GRAVI (Grupo de Acústica e Vibração) of UFMG has been working since 2010 in SHM using Lamb waves to detect damage in structures in which has been working in the development of a software so named “LaWade$_{UFMG}$” (Lamb Wave Detection), the software was part of a project sponsored by Embraer and FINEP, developed in Matlab to control the generation, acquisition, storing, and processing of Lamb Waves using a PXI modular hardware composed by an arbitrary wave generator up to 100 MHz, two acquisition board with 8 channel each up to 60 MHz and a relay commutation matrix with 31 channels.

## 2. GENERAL DESCRIPTION OF DAMAGE IDENTIFICATION SOFTWARE “LAWADE$_{UFMG}$”

The LaWade$_{UFMG}$ software was developed to perform the process of damage location in any kind of structures by the Lamb wave inspection. Thus, in the software can be defined,

- **Geometry** of the structure analyzed such as the bounds of the structure and the position of the PZTs informing if the PZT acts only as a sensor, only as an actuator or both of them;
- **Acquisition** setup such as to generate the Lamb wave as base frequency of the signal, amplitude, number of periods, the window, and the symmetry. And the general setup to the acquisition of the signal measured by the PZTs such as the sample frequency, the time of acquisition, average number, and the form of perform the measurement;
- **Auto diagnosis** to verify the cable and PZTs conditions in terms of the background noise and the amplitude of the measured signal;
- **Analysis method** defining such as threshold to positive identification in between the baseline and the verification, and what method are being used, and other information necessary to perform the verification;

Besides the functions below, the LaWade$_{UFMG}$ is able to import and export to several files formats such as **.xml*, **.m*, **.dat*, **.lvm*, and generate a final report including the complete checkup of a data test performed.

## 3. DAMAGE DETECTION METHODOLOGIES

In the LaWade$_{UFMG}$ were implemented two techniques used to damage detection. The first method is based on the construction of the wave propagation map calculated using the group velocity of the wave propagation and the Hilbert Transform, Konstantinidis et al. (2006). The second method is based on the comparison of the Power Spectrum Density of the signal measured by the sensors, Lee et al. (2011), Sohn et al. (2004), and Ihn et al. (2004).

The two methodologies were chosen because both of them are simple to be implemented, requiring the same baseline and the most important is that they use the same configuration of the actuators and sensors. Besides, the use of more than one methodology provides a comparison between then.

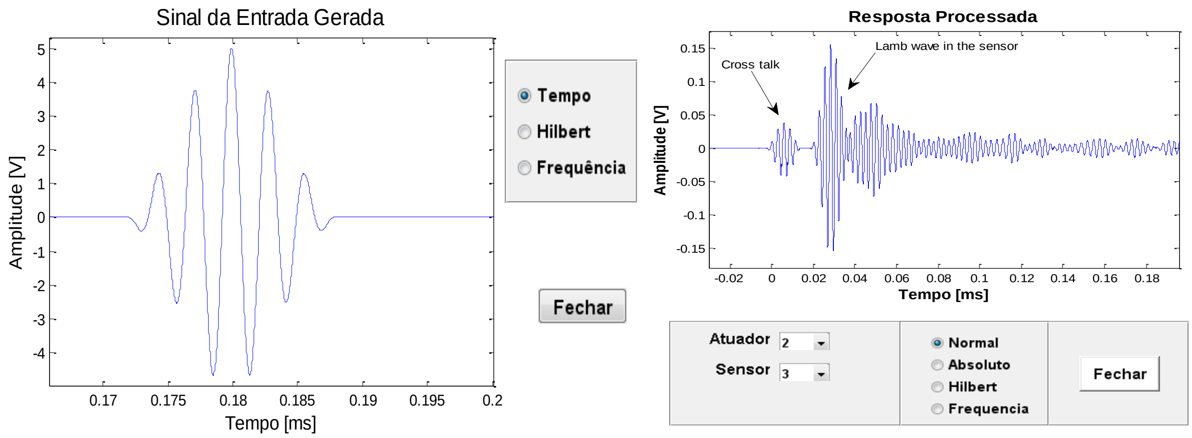
The methodologies are based on a mesh of piezoelectric (PZT) spread over the structure being the sensing system. To inspect the structure, one of them is being used as actuator and the others as sensors, so working usually called pitch-catch configuration where it has one PZT generating the lamb wave and one or more sensors receiving the signal. Then, the actuation point is changed until all the PZTs had being worked as actuator to perform the entire inference in the analyzed structure.

### 3.1 Lamb wave Generation and Acquisition

The process of Lamb wave generation can be done taking a base frequency windowed by hanning window, Konstantinidis et al. (2006). In order to implement the generation, it was chosen construct the signal using three parts, the first part containing only zeros to observe the presence of vibration from the past signal, the second part containing the base frequency multiplied by the hanning window and the third part containing only zeros and long enough to assure that the structure vibration had been vanished.

This methodology of constructing the excitation was chosen because the system continuously generates the input and the software acquires using trigger in the input signal. Figure 1(a) shows an example of input signal to generate Lamb waves in the structure, observe that in this case it was chosen 0.2 ms as a length in time.

The process of measurement was performed using STMR (Single-Transmitter, Multiple-Receiver), and it was used repetitive measurements to perform averages in the data to eliminate noise. An example of measured data can be seen in Fig. 1(b).




(a) input signal (b) measured signal

Figure 1: Example of input and measured signal

### 3.2 Hilbert Envelop methodology

The HE (Hilbert Envelope) methodology consists in apply the Hilbert transform in the signal measured by the sensor. The transformation allows estimating the TOF (Time of Flight) of the travelling wave from the actuator to the sensor. With this information it is possible to construct a propagation map of the wave in the structure using the velocity group of the wave and the relative position of points in the structure. This procedure is performed to all pair of actuator and sensor in the structure. Summing the maps over the actuators and sensors, a general map of propagation is generated.

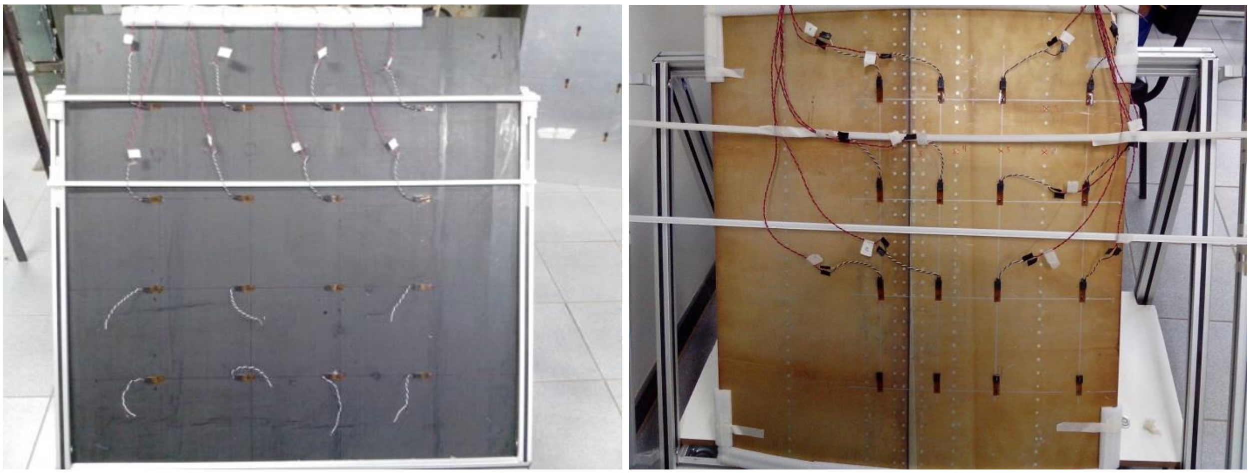
Subtracting the general propagation map of the verification from the propagation map generated by the baseline, it is possible to identify the damage location. For more details see Konstantinidis et al. (2006). The threshold of 1% was considered to indicate that there is damage. This methodology gives indication of the exact location of the damage in the structure.

### 3.3 Power Spectrum Density methodology

The PSD (Power Spectrum Density) methodology consists in calculating the power density using the welch method of the signal measured by the sensor, so representing the PSD in between the actuator and the sensor. The same process is performed to the baseline. The threshold of 1% was considered as difference to indicate that there is damage in the path. For more details see Lee et al. (2011), Sohn et al. (2004), and Ihn et al. (2004).Therefore, the PSD indicates a region where is possible to have damage and not the true location.

## 4. EXPERIMENTAL SETUP

The location of the damage were been chosen to validate de system. Thus, the majority of situation found in practice application were used here, for example, near the sensor, in between sensors, and out of the sensors. Figure 2 shows both panels using to evaluate the methods.



(a) Composite plate (b) Metallic plate

Figure 2: Composite and metallic plate used in the experimental analysis

### 4.1 Composite plate

The first experiment was performed in a simple squared composite plate of 1m x 1m made using 16 layers in a 45° configuration. It was used 12 PZTs according to Fig. 3 and introduced 10 positions to the simulated damage.

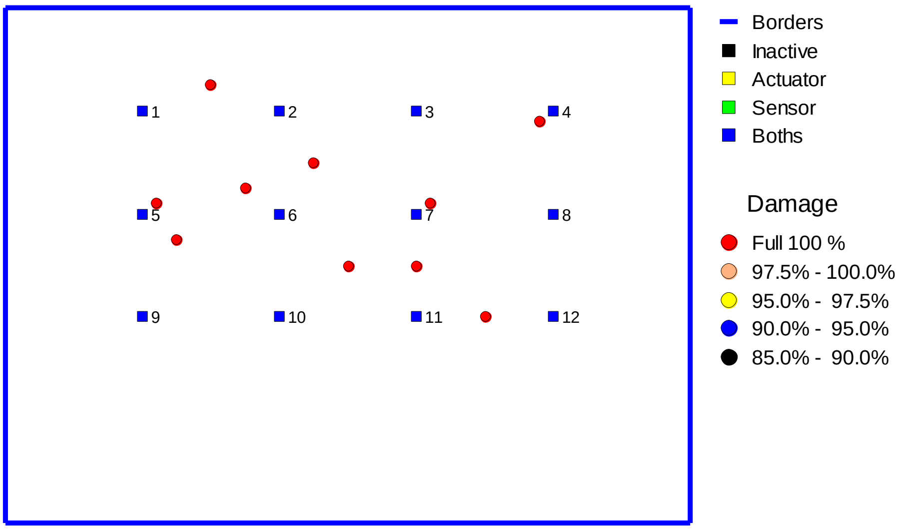


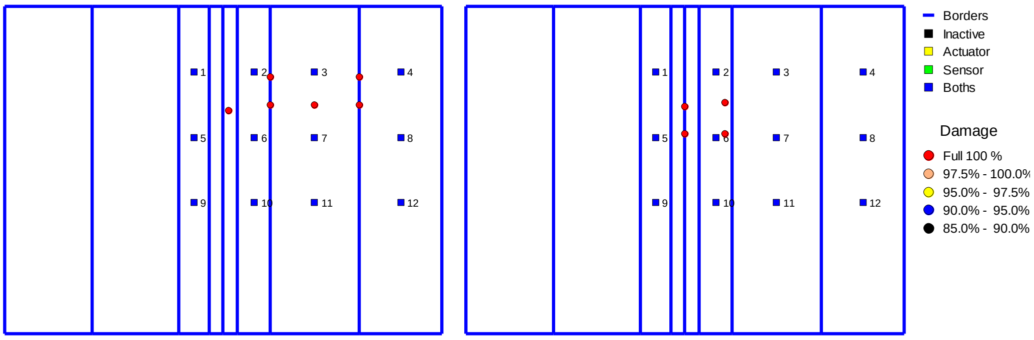

Figure 3: Schematic diagram of the PZTs positions and the simulate damages

The input signal was generated using sample frequency of 60MHz, base frequency of 300 kHz with 6 periods windowed by hanning window, 5 Volts of amplitude during 4 ms. The signal is zero in between 0 and 0.2 ms and in between 0.22 ms and 4 ms.

### 4.2 Metallic plate

The second experiment was performed in a curved metallic plate with reinforcements made of three plates jointed by bolts. Figure 1(b) shows the metallic plate with two plates are joined by another plate using two bolts columns and a glue material. The reinforcements are in “Z” using bolts to each plate.

As the system is symmetric, it is considered only one side in the analysis. The 6 first damages were located in the front side of the Figure 1(b) and are seen in Figure 4(a), all locations are exactly in the bolts position, that is the suppose position where can have damages. The other 4 damage locations were located in the back side of the plate in Fig. 1(b) and located in the reinforcements and the joint plate in the location shown in Fig. 4(b).




(a) front side (b) back side

Figure 4: Position of the damage in the metallic plate

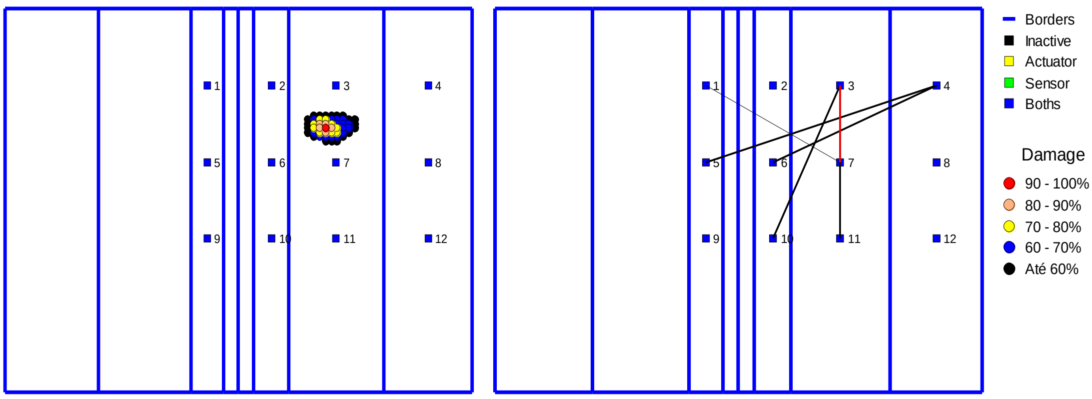
The input signal was generated using sample frequency of 60MHz, base frequency of 400 kHz with 6 periods windowed by hanning window, 5 Volts of amplitude during 32 ms. The signal is zero in between 0 and 0.2 ms and in between 0.22 ms and 32 ms.

## 5. RESULTS

The identification analyses were performed using the hit/miss methodology according to MIL-HDBK-1823A (2009). First of all, the identification is performed for each damage position. If the damage is detected in the true position it represented by “1”, otherwise by “0”, that means if the results is a false positive or if the damage location produced by the analysis is far from the true position, it is represented by “0”. Once having the whole verification performed, the POD can be evaluated using the software developed for the calculation of POD.

The POD indicates how reliable the identification a given methodology is, and when using hit/miss data a “0”, meaning not identified, into the upper side of the POD graphic is much worse than a positive identification in the lower side. The most important result from the POD is the $a_{90/95}$ indicator that means the damage size capable of being identified with 90% of time with 95% of reliability.

In the experiments below, it was measured only once to each damages position and the measured data were applied to both identification methodologies. An example of positive identification to each methodology can be seen in Fig. 5.




(a) Composite plate (b) Metallic plate

Figure 5: Example of identification generated by the HE and PSD methodologies

## 5.1 Hit/miss evaluation

Table 1 shows the hit/miss results for the composite plate verified using the Hilbert Envelope and the Power Spectrum Density. It is possible to notice that the position 01, positon out of the PZTs net, did not identified the damage, besides, the size of 0.25 inches were not identified also.

Table 1: Identification Matrix using the hit/miss methodology for the composite plate
HE – Hilbert Envelop Methodology; PS – Power Spectrum Density methodology

| **Size inches** | **0.25** | | **0.50** | | **0.75** | | **1.0** | | **1.50** | | **2.0** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Position** | **HE** | **PS** | **HE** | **PS** | **HE** | **PS** | **HE** | **PS** | **HE** | **PS** | **HE** | **PS** |
| 01 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| 02 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 03 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 04 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 05 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 06 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 07 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 08 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 09 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 10 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

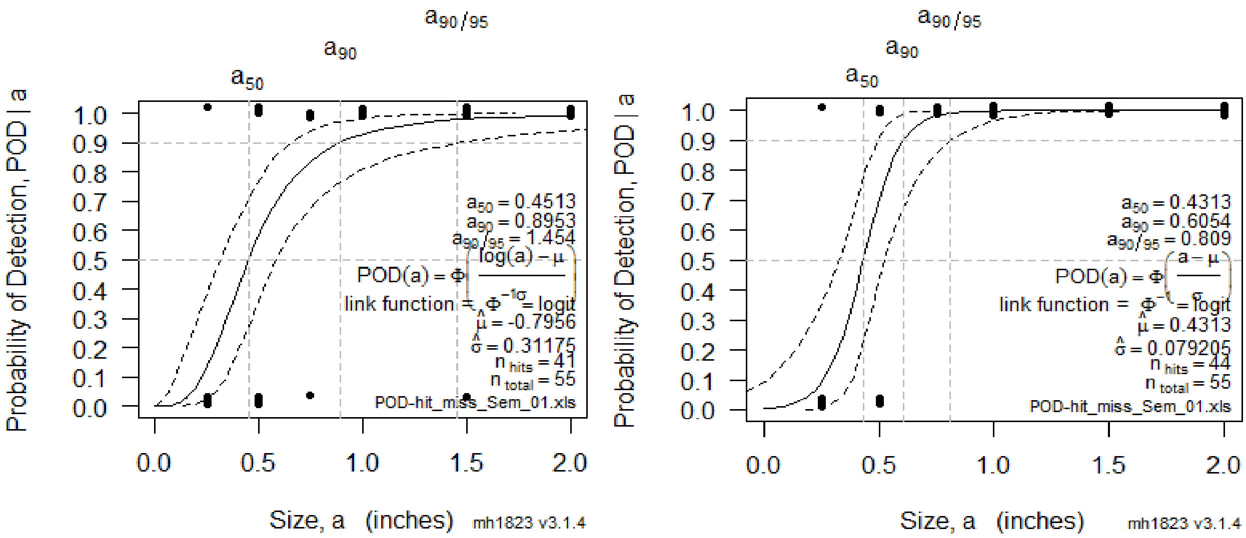
Table 2 shows the hit/miss results for the metallic plate verified using the Hilbert Envelope and the Power Spectrum Density. It is possible to notice that the positions 07 to 10, positon in the back face of the PZTs net, did not identify the damage, which are the position in the back side of the metallic plate.

Table 2: Identification Matrix using the hit/miss methodology for the metallic plate
HE – Hilbert Envelop Methodology; PS – Power Spectrum Density methodology

| **Size inches** | **0.5** | | **0.75** | | **1.0** | | **1.25** | | **1.50** | | **2.00** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Position** | **HE** | **PS** | **HE** | **PS** | **HE** | **PS** | **HE** | **PS** | **HE** | **PS** | **HE** | **PS** |
| 01 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 02 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 03 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 04 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 |
| 05 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 06 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 |
| 07 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 08 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 09 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

## 5.2 POD analysis

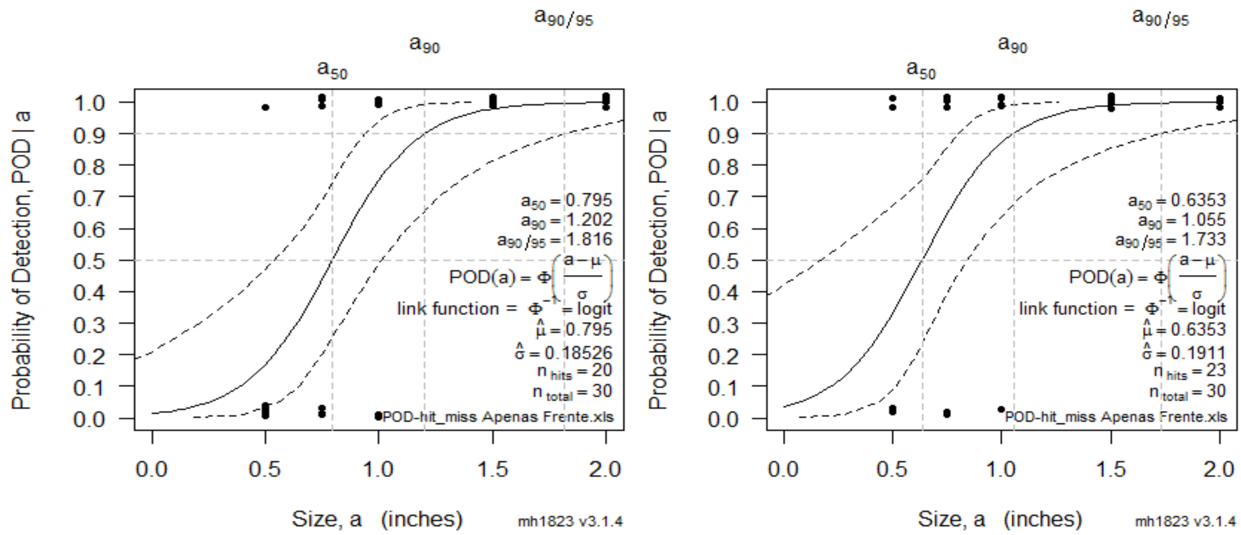
The results from the POD for both methodologies applied to the composite plate can be seen in Fig. 6, were can be observed the $a_{90/95}$ for the Hilbert Envelop was 1.45 inches while for the Power Spectrum Density was 0.809 inches. The difference in size is basically due to damage size of 1.50 inches that was not identified by the Hilbert Envelope in the position 05.




(a) Hilbert Envelope (b) Power Spectrum Density

Figure 6: POD to the composite plate

The results from the POD for both methodologies applied to the composite plate can be seen in Fig. 7, were can be observed the $a_{90/95}$ for the Hilbert Envelop was 1.816 inches while for the Power Spectrum Density was 1.733 inches. The difference in size is basically due to damage size of 1.50 inches that was not identified by the Hilbert Envelope in the position 05.




(a) Hilbert Envelope (b) Power Spectrum Density

Figure 7: POD to the metallic plate

## 6. FINAL REMARKS

The experimental results described above indicates that the Lamb wave technic to identify damage in structure is promising, however several studies must be performed before the implementation of the methodologies in structure such as airplanes.

The LaWade$_{UFMG}$ seem to be a useful tool to automatize the experimental analysis but it is still far from a commercial product because the communication in between the software and hardware is not fulfil complete.

## 7. ACKNOWLEDGEMENTS

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