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CORROSION DETECTION IN AERONAUTICAL STRUCTURES USING LAMB WAVES SYSTEM FOR SHM

A. K. F. Tamba*, L. C. Vieira*, G. O. C. Prado*, F. Dotta*, R. P. Rulli*, P. A. da Silva*, R. R. Cunha*, J. P. Costa*

***Embraer S.A., Brazil**

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Abstract

Structural Health Monitoring (SHM) can modify the current procedures of aircraft maintenance with new technologies, concepts and philosophies. When compared to current Non Destructive Inspection (NDI) technologies, SHM can reduce the amount of time and workload of inspection tasks and consequently reduce costs because it has less complex and less time consuming processes. Reliable SHM systems are able to automatically evaluate structural conditions and inform the maintenance company of the presence and the location of a structural flaw.

For years Embraer has investigated different SHM technologies for damage detection with possible application scenarios. Embraer understands that SHM can provide without great effort the structural diagnosis in restricted access areas with early detection of structural damages and reduction of maintenance costs, besides minimizing the effects of "human-factors" during an inspection due to automated damage detection.

In aircraft maintenance sometimes it is necessary to disassemble aircraft parts to reach the inspection location, and after that process, the aircraft must be reassembled. All these steps can be costly and favorable to induce flaws when incorrect executed. Embraer has an incentive to explore ways of reducing maintenance costs and increasing efficiency of its services.

Aircraft in service are susceptible to corrosion and these structural damages can be detected during a scheduled maintenance. Non Destructive Test (NDT) methods for rapid and reliable corrosion detection in complex metallic assemblies are an on-going challenge due to practicalities of inspection and geometric complexity. The Embraer's R&D team has dedicated studies for corrosion damage detection using Lamb Waves (LW) Technology.

This work demonstrates further Lamb Waves results for detecting corrosion in aluminum alloys for aircraft structures. These studies were performed using Acellent Technologies Lamb Waves system with different types of specimen configurations.

1 Introduction

Embraer has been studying SHM technologies and application scenarios for structural damage detection. Technologies such as Comparative Vacuum Monitoring (CVM), Electro-Mechanical Impedance (EMI), Acoustic Emission (AE) and LW are under investigation [1]. For Embraer, SHM can provide facilitated damage detection in areas with restricted access with early detection of structural damages and reduction of maintenance costs for current and future aircrafts, besides minimizing the effects of "human-factors" during an inspection [2]. Typically, corrosion damage are in difficult access areas, hidden by the lavatory or galley and LW technology can assist in the implementation of these inspection tasks following the ideology of SHM adopted by Embraer. This paper presents complementary studies based on some results of the tests performed by Embraer with the Acellent Technologies Lamb Waves system for detection of corrosion damage with the use of artificially induced damage on test specimens.

Figures 1 and 2 shows examples of specimen configurations used in the tests and the Acellent Technologies software screen.

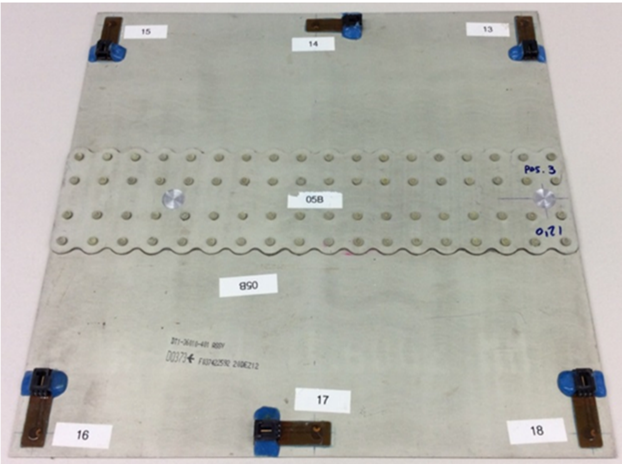

Fig. 1 Test Specimens Example

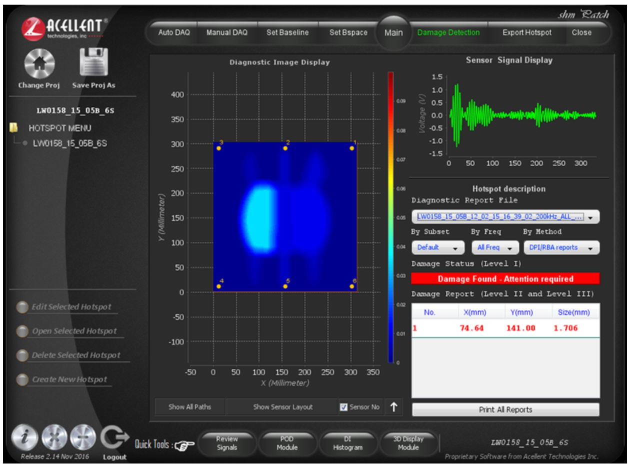

Fig. 2 Damage Detection on Software

The corrosion damage was induced artificially with a series of thinning in the test specimens. These lab tests provide data that can be used for generating Probability of Detection (POD) curves for LW systems. The experimental results indicate that Lamb Waves technique is accurate and it is shown as a promising technology for the application of corrosion damage detection.

1.1 Corrosion Damage

Corrosion is a natural and costly phenomenon and cannot be avoided, but aircraft manufacturers and operators spend time and money to keep it in control. According to (NACE), in the year of 1996 the total annual direct cost of corrosion to the U.S. aircraft industry is estimated at $2.2 billion, which includes the cost of design and manufacturing ($0.2 billion), corrosion maintenance ($1.7 billion), and downtime ($0.3 billion) [3]. Corrosion protection in aircraft structures is a well-established technology, both to prevent and to inhibit corrosion damage. However, there is a high probability of failure of these protection methods on older aircraft, with long periods of service.

The surface corrosion in its early stages can be detected visually through signs such as discoloration, faint markings of dust, bubbles and paint damage. On the other hand, it is very difficult to detect hidden corrosion damage since the characteristics do not allow for identification methods or conventional NDT. In many cases, the damage reaches a very advanced stage before it is detected, requiring dismounting of the structure, which leads to a very high maintenance cost. Therefore, it becomes interesting to use a sensor system that effectively monitors the corrosion damage of the structure and allows obtaining data regarding the problem severity. A preliminary study was conducted to assess the use of LW system to detect thickness reduction and the results were promising [4].

2 LW Approach for Damage Detection

The fundamental of this technique is based on the assumption that structural damage changes the physical dynamic response of the structure, such as natural frequencies, mode shapes and damping, frequency response, etc. [4]. Lamb waves represent two-dimensional wave propagation in plates or shells, which are described by known mathematical equations originally formulated by Horace Lamb in 1917 [5]. A structure with a damage like thickness reduction (corrosion) exhibits non-linear vibrations due to the stiffness change under load variation [6].

The accuracy of relating changes in modal parameters to flaws such as cracks becomes quite poor when the aspect ratio between the size of the structure and the size of the flaw is larger than 10 [6, 7]. Lamb waves are two groups of waves, the symmetric waves and the anti-symmetric waves, that satisfy the wave equation and the boundary conditions. The general solutions can then be split into two modes: symmetric (S_0) and anti-symmetric (A_0) [8] as shown in Figure 3. The Lamb wave modes are considered to be sensitive to fatigue cracks and can be used in metallic or composite material structures to detect a wide range of damages types.

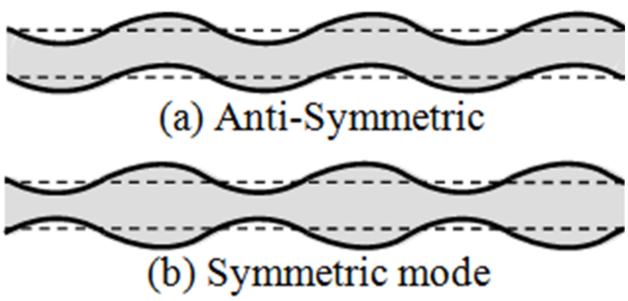

Fig. 3 Wave modes: (a) Anti-symmetric, where a peak at one surface corresponds to a trough at the other surface; (b) Symmetric, where the wave peaks or troughs occur simultaneously at the same in-plane location

3 Probability of Detection

POD is a means of describing how well an inspection procedure can detect the required defects. Based on data statistic, the POD have a focus on measure the chance or probability of detecting a defect. By assigning POD values to a procedure, it is possible to compare the effectiveness of different inspection techniques. Alternatively, POD values can be used as a target which procedures have to be shown to be able to achieve.

Basically the POD is calculated using statistical methods for analyzing these data to produce a curves that provides a quantitative and graphical relationship between probability of detection and those factors that control it, such as target size. The Figure 4 exemplifies a POD curve.

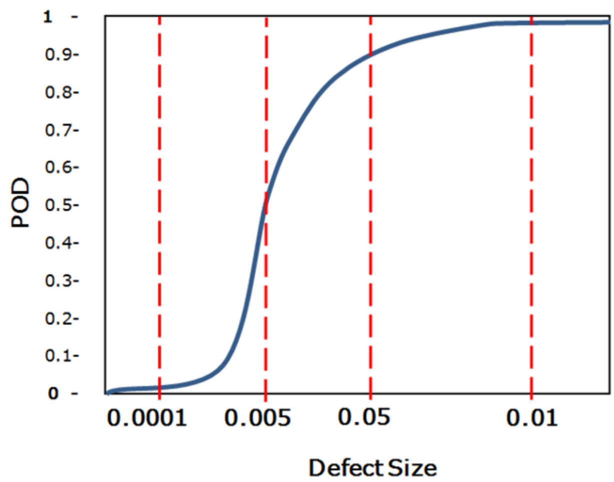

Fig. 4 POD Curve Example

To uses a POD curve or values, it is important to understand how it was obtained, the procedure used, kind of defects its applied and any other assumptions have been made during the experimental program. The POD is estimate based on results with representative significant statistical sampling.

3.1 MIL-HDBK-1823: Nondestructive Evaluation System Reliability Assessment

The MIL-HDBK-1823[9] is a document of Department of Defense of United States provides Non Destructive Evaluation (NDE) procedures for inspecting flight propulsion system (gas turbine engines and rockets) components, airframe components, ground vehicle components, either new or in-service hardware. The NDE methods can be Eddy Current (EC), Fluorescent Penetrant (PT), Ultrasonic (UT), Magnetic Particle (MT) testing, Radiographic testing, Holographic testing, and Shearographic testing, provided they produce an output similar to those listed herein and provide either a quantitative signal, â, or a binary response, hit/miss. This document provides uniform guidance requirements for establishing NDE procedures used to inspect new or inservice hardware for which a measure of NDE reliability is required.

One of the focuses of this MIL Handbook is present a guidance (for planning, conducting, analyzing, and reporting reliability evaluations) for assessing the capability of an NDE system in terms of the POD as a function of target size to quantitatively determining NDE system capability.

4 Corrosion Damage Detection Evaluation

This session presents the experimental program for this study and the POD results. As previews explained in this study the POD approach used was the MIL-HDBK-1823[9].

4.1 Test Summary

The test were performed in three types of test specimens with different shapes for verification of corrosion damage detection with LW technology as showing in Figure 5. All specimens were manufactured with aerospace aluminum alloy 2000 series for plates and splices and the aluminum alloy 7000 series are used for stiffeners.

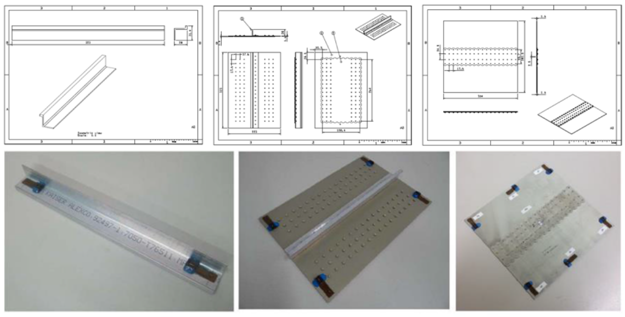

Fig. 5 Specimens: (a) SHM-C02: Stiffener, (b) SHM-C04: Reinforced Panel and (c) SHM-C05: Spliced Panel.

Four progressive stages of thickness reduction were elaborate to simulate the corrosion. The first stage (a) starts the simulated corrosion on structure with a punching tool that reduces 0.21 mm of thickness. The next stages were performed by machine with a milling cutter tool. In the second stage (b) a reduction of 0.08 mm of the thickness with a diameter of 6 mm is performed, followed by the third stage (c) with a reduction of 0.16 mm of the thickness with the same diameter from previous stage and the fourth stage (d) enlarges the hole diameter to 13 mm and keeps the hole depth. All stages described above and each manufactured damage locations are shown on Figure 6.

The Figure 7 shows the detail of machining thickness reduction for specimen 5B for damage on position 03.

The SHMPatch software was used for damage detection analysis. The default software procedure was used for damage detection. Figure 7 shows the damage detection results from Acellent software, which the damages were detected on manufactured damages DF02, DF03 and DF04. No damage was detected for manufactured damage DF01.

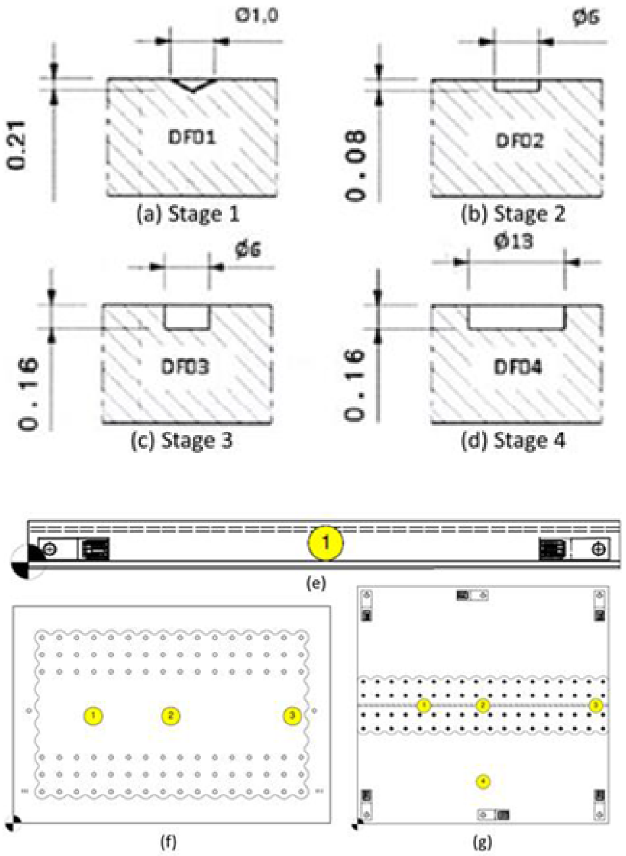

Fig. 6 Thickness reduction stages: (a) DF01, (b) DF02, (c) DF03 and (d) DF04 and Damage Positions: (e) SHM-C02, (f) SHM-C04 and (g) SHM-C05.

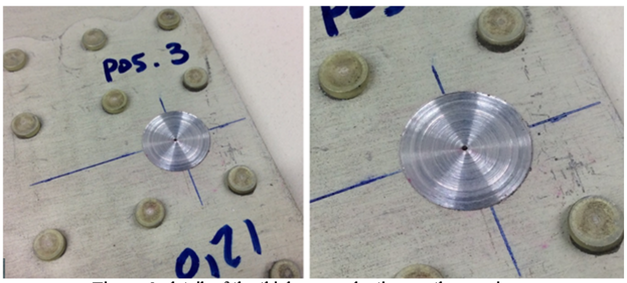

Fig. 7 Detail of the thickness reduction on the specimen.

4.2 Test Results

Embraer conducted the test with three configurations of specimen but for POD study will be used only one configuration: Configuration SHM-C05.

For each coupon the damages are manufactured and the data were collected using the Acellent Technologies System. All test results data [10] are organized and the damage detection functionality of SHM Patch Software was used to diagnosis and evaluate if the system detect or not detect the defect in each step of test.

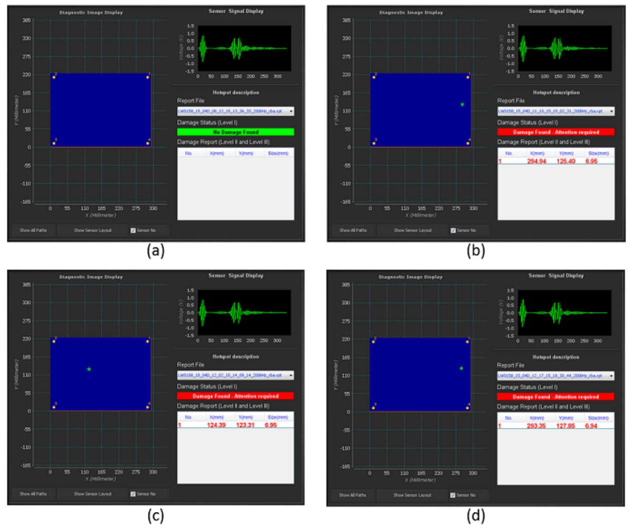

Fig. 8 Damage Detection on SHMPatch

For this specimen configuration were installed 6 Lead Zirconate Titanate (PZT) sensors and software was configured 2 frequencies (200KHz and 250KHz) to evaluate the specimen in analysis. The use of these two frequencies results in 96 interrogations of the system to analyze if detect or not detect the damages in the specimens. During the test one specimen has a problem (05J) and it was eliminated from test set and reduced the total valid data points to 88.

For POD analysis the Hit/Miss approach can be used because the test were done with fixed damage sizes steps and the system returns detection or no detection the damage in other words the test results in binary response. The large number of interrogations is other factor that contributed to choice this approach, justifying use of Hit/Miss methodology to POD study.

The Table 1 presents the test results for Hit/Miss approach. In table are the frequency used to run damage detection, the specimens identification and values for Hit (1) when the system detected the damage or Miss (0) when the not detected for each damage size.

Table 1 Configuration SHM-C05 Hit/Miss Data

Frequency (kHz)	Specimen	DF01	DF02	DF03	DF04
200	5	0	0	1	1
	05A	0	1	1	1
	05B	0	0	1	1
	05C	0	0	1	1
	05D	0	0	1	1
	05E	0	0	1	1
	05F	0	1	1	1
	05G	0	0	1	1
	05H	0	1	1	1
	05I	0	0	0	0
	05K	0	0	0	1
Frequency (kHz)	Specimen	DF01	DF02	DF03	DF04
250	5	0	1	1	1
	05A	0	1	1	1
	05B	0	1	1	1
	05C	0	1	1	1
	05D	0	1	1	1
	05E	0	1	1	1
	05F	0	1	1	1
	05G	0	0	1	1
	05H	0	1	1	1
	05I	0	0	0	1
	05K	0	0	0	1

The data in table is used as input data for mh1823 POD software [11] to calculate and generate the POD curves for this test. The system obtained a total of 50 detections and 38 not detections. All valid data were input in mh1823 software and the Acellent's system obtained value of 8.498mm^3 of volume loss with 90% of POD for this test.

For some NDE inspections included the aeronautical area is used the called POD 90/95 that corresponds 90% of probability of detection with 95% of confidence in this probability. For this test the system obtained a value of 21.79mm^3 of volume loss with 90% of POD and 95% of confidence. Figure 9 shows experimental data POD's curve from mh1823 software [11].

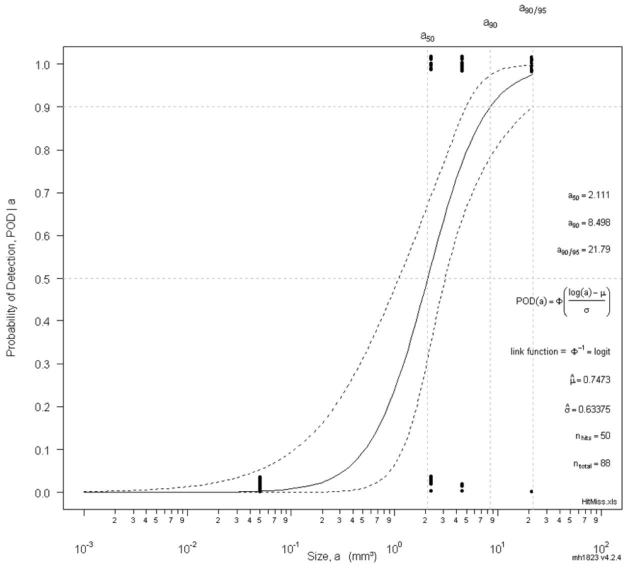

Fig. 9 POD Curve from mh1823 Software

5 Conclusion

Embraer have tested 12 specimen of Configuration named SHM-C05 (Spliced Panel) with 4 damage sizes manufactured step by step. The evaluate have done with Acellent Technologies system using 6 sensors installed on each specimen.

The system was configured to evaluate the sensor mash with 2 different frequencies (200KHz and 250KHz) resulting in 24 data points for each size manufactured and 96 data in total. During the test one specimen presented problem and was eliminated of the test and reduced the data points to 88 in total.

The Hit/Miss methodology was used in this test to obtain the Probability of Detection for Acellent's system. This POD study is valid only for these configuration of specimen, sensor mash and system configurations to detect mass loss.

The results and POD study show the capability of Acellent Technologies System to detect corrosion damage based on loss mass. The values of POD obtained in this study show quantitatively the system sensitivity and reliability to detect corrosion. In the future, other tests will be conducted by Embraer to evaluate the SHM systems capability based on MIL-HDBK-1823[9] and others POD approaches.

6 Contact Author

For further information please contact andre.tamba@embraer.com.br.

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