Detection, localization, and quantification of corrosion damage using Lamb Waves for the structural health monitoring of aluminum aeronautics structures

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Abstract: Corrosion is a major concern for the aeronautic industry and providing structures with the intrinsic ability to monitor autonomously their health state is a major actual academic and industrial challenge. In this paper, detection, localization, and quantification of a damage representative of a corrosion damage using Lamb waves emitted and received by piezoelectric elements for the purpose of structural health monitoring of aeronautics aluminum structures is addressed. Semi-spherical holes of different sizes representing a calibrated corrosion pit are manufactured on a 2024 aluminum plate with four piezoelectric sensors bonded on it. Lamb waves are then recorded with one element used as an actuator and the other ones being used as sensors. A dedicated recording system provided by Cedrat Technologies is used to acquire Lamb waves data. It is demonstrated on this representative example that by using actual algorithms from the SHM literature, it is possible to detect, localize, and quantify this damage representative of an actual corrosion damage. These preliminary results are very encouraging before monitoring actual corrosion and fatigue damages which constitutes the main objective of the COQTEL project.

Keywords: Structural health monitoring, corrosion damage, piezoelectric element, detection, localization, quantification, Lamb waves.

1 Introduction

In the transition toward condition-based maintenance (CBM), aeronautics structures are evolving in terms of monitoring processes from human-based procedures to automatic monitoring strategies. Such structural health monitoring (SHM) strategies are very appealing in the aeronautic field because they potentially allow for a nondestructive and autonomous health evaluation of the entire plane structure [1]. Lamb waves are widely used in that SHM field because they spread far away without much energy loss in materials [2]. Moreover, when encountering a corrosion damage in aluminum aeronautic structures, these waves will face a local diminution of the plate thickness due to corrosion which will generate a reflected and diffracted Lamb wave echo indicative of damage presence, position, and size [3, 4, 5].

This topic is very important in practice especially regarding corrosion since it happens to be a major issue in aeronautics field [6] even if typical aeronautic structure made of 2024 aluminum alloy are usually coated to protect the plane from corrosion coming from the operational environment. One solution to monitor corrosion damage in such a context is to equip aeronautic structures with piezoelectric elements which can act both as sensors and actuators receiving and emitting Lamb waves. Indeed, when provided with adequate voltage, piezoelectric elements can generate Lamb waves propagating in the host structure and interacting with potential corrosion damages. Due to the reversibility of the piezoelectric effect, they can also receive Lamb waves as well as damage echoes and will generate a corresponding voltage output when crossed by a Lamb wave [7].

In recent years, many researchers have explored the abilities of piezoelectric elements for SHM applications, such as impact localization, acoustic emission detection, and damage detection in composite materials. There has been substantial work achieved in the area of ultrasonic guided waves for the SHM of aeronautic structures [8, 9, 10], but additional work must be carried out to increase the acceptance by the industry of this growing technology. Detection of a corrosion damage, its localization, and the quantification of its size using Lamb waves must thus be more closely examined to have the wholesome picture of corrosion damage monitoring in SHM. The objective of the present work is to provide a first step toward a proof of concept demonstrating that existing SHM algorithms based on Lamb waves are mature enough regarding corrosion monitoring for being used in practice.

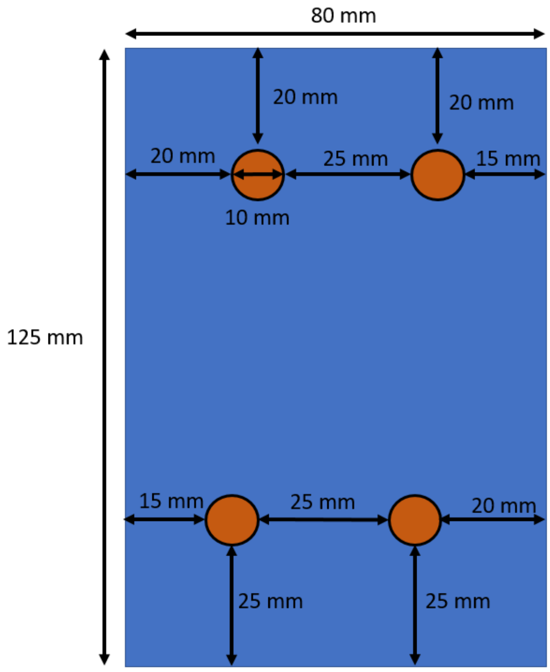
This paper is part of the COQTEL project (Corrosion Quantification Through Extended use of Lamb waves) funded by the French government. The purpose of this project is to monitor damage caused by corrosion which cannot be detected by human eyes during an inspection using both active and passive methodologies. To tackle this challenge through active methodologies, Lamb waves are being used as they were proven to be very sensitive to corrosion damage as previously stated. The objectives of this paper are consequently to demonstrate that it is possible to detect, localize, and quantify a damage representative of corrosion (hemispherical hole) using the active method based on Lamb waves emitted and received by piezoelectric elements on a 2024 aluminum plate as a first step before moving to simultaneous corrosion and fatigue experiments.

2 Experimental setup and method

In this section, details about the experimental setup are presented. The material used is 2024 Aluminum alloy with the material properties provided in Figure 1 by the company Rescoll[1]. The studied aluminum plates dimensions are 125×80 mm and 2 mm of thickness (see Figure 2a).

[1] Rescoll : www.rescoll.fr

Four piezoelectric transducers were bonded to the aluminum plates and positioned strategically (not symmetric to the center to avoid recording reflected signals) as shown in Figure 1.



Young Modulus	Poisson's ratio	Density
E (MPa)	ν	$\rho\ (kg.m^{-3})$
69 000	0.33	2700

Figure 1 : [Left] Dimensions of the aluminum plate studied within the COQTEL project with the piezoelectric elements position (orange circles). [Right] Material's properties of 2024 aluminum

The chosen piezoelectric transducers are made up of NCE51 material provided by Noliac and have a 5mm radius allowing them to measure a target frequency bandwidth contained between 50 kHz and 400 kHz using a sampling frequency of 2 MHz. These piezoelectric elements have been bonded on the aluminum coupons by Cedrat Technologies[2]. They are 1mm thick because such thickness allows them to catch more energy than larger thicknesses (like 2 or 3 mm) and not to be too brittle. A coaxial cable of length 150 mm (see Figure 2b and 2c) has been brazed directly on each element in order to optimize the signal to noise ratio. The piezoelectric elements are then bonded to the plate and made waterproof using a specific coating (see Figure 2d&e).

[2] www.cedrat-technologies.com

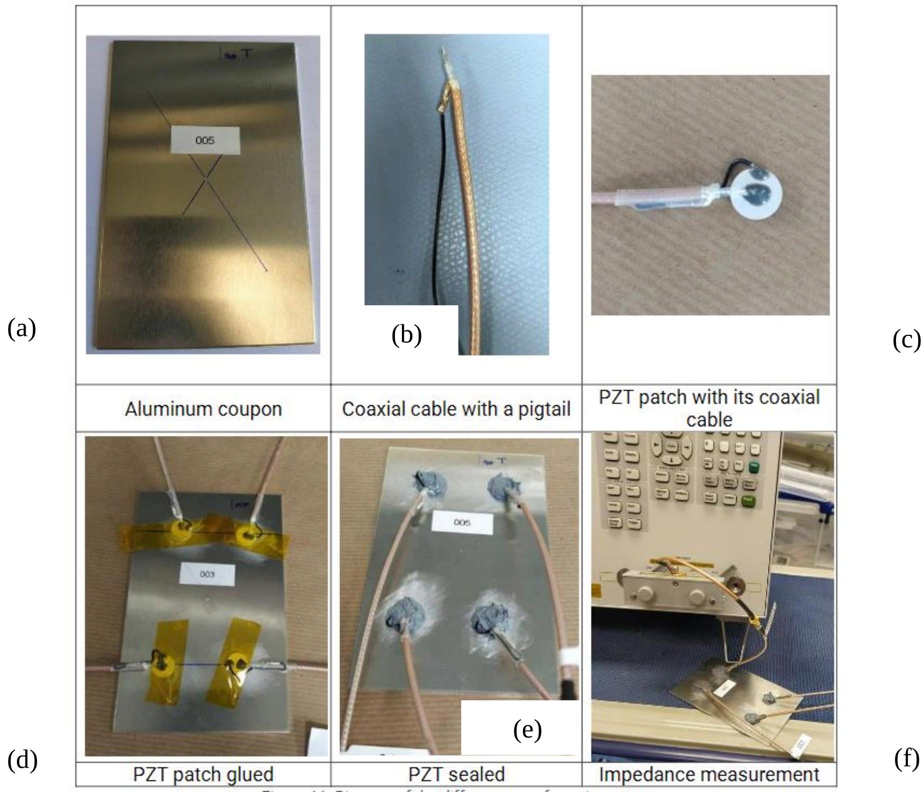


Figure 2 : Experiment set up with PWAS and aluminum plate

A Matlab script is used to acquire the data of the experiment through the Lamb Wave Detection System (LWDS) hardware provided by Cedrat Technologies[3]. Each piezoelectric element is excited and the other three are listening alternately and resulting signals are recorded.

A hole is manufactured mechanically on the plate to simulate the corrosion pit. In this paper, nine plates with increasing hole sizes were studied:

- The reference plate (with no hole, to collect reference signals)
- Seven plates with hemispherical holes with 0.15mm, 0.2mm, 0.3mm, 0.4mm, 0.6mm, 0.8mm and 1mm of diameter and depth hole
- A plate with 1mm of diameter and drilled through its whole thickness

To exploit the recorded data, a Matlab internal toolbox developed at PIMM laboratory was used: "SHM@PIMM" [11]. It allows to directly process raw experimental data using algorithms from the literature and developed by the team to perform damage detection, localization, quantification as well as signals denoising.

[3] Cedrat Technologies : cedrat-technologies.com

The following algorithms are being selected here for SHM purposes. For damage quantification the imaging post-processing (IPP) algorithm [12] has been chosen. For damage localization, a ponderated deterministic localization method based on "Time of Arrival" (ToA) [13] method is being used. For ponderation, the damage index CC defined as followed has been chosen:

$$CC = 1 - \max\left(\frac{IFFT\left[FFT\left[x_{ij(t)}\right] * FFT\left[y_{ij(t)}\right]\right]}{\sqrt{\left(E_{xij} * E_{yij}\right)}}\right)$$

Figure 3: Equation of the FFT based implementation of the maximum of the correlation

3 Damage detection, localization and quantification results

To exploit the recorded Lamb wave data, signals from the damaged plate are compared to the healthy ones. For example, below are shown the signals received and processed from the plate with the 1mm damage and at 200kHz with the piezoelectric element number 2 being active. On the left column, the signals are raw. In the middle one, the denoised and time aligned reference and current signals are presented. On the right one, the difference signals (*i.e.* the differences between the healthy and damaged signals) are shown.

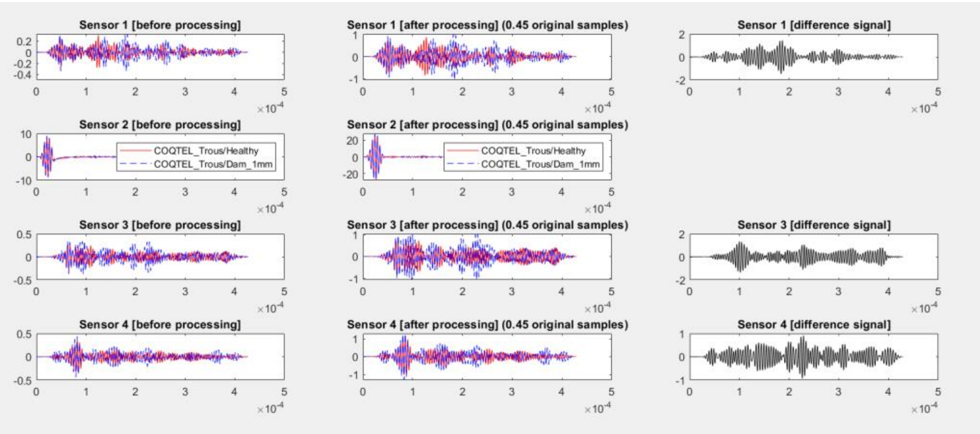


Figure 4 : Signals from plate with 1mm defect at 200kHz and with the piezoelectric element number 2 used as an actuator. On the left column, the signals are raw. In the middle one, the denoised and time aligned reference and current signals are presented. On the right one, the difference signals (i.e. the differences between the healthy and damaged signals) are shown.

Given the received signals, a clear difference between the signal associated to corrosion damage and the healthy one can be seen. The hole of 1mm radius and 1mm of depth is thus clearly detectable using Lamb waves and this is also true for the smaller holes. The detection step is thus correctly achieved using Lamb waves.

To localize the damage, the ponderated ToA method mentioned earlier is used and pictured below. The time of flight corresponds to the time taken by the wave packet to travel from an actuator to a sensor along a given path. It is a feature extracted from the scattered signal that is used for damage localization purposes as it contains information related with damage position. More precisely, the ToA method ponderated using the CC damage index is used. It means that when adding up the ellipse corresponding to each path, they are weighted by the CC value corresponding to each path. In practice, ellipses having a high DI value count more than the one with a lower CC value in the final imaging results. Like the rest of the graphs shown before, the example of the plate with 1mm hole defect is displayed and the frequency sent by the piezoelectric 2 is 200kHz. As the picture below illustrates, the estimated localization damage (green diamond) is very close, if not superimposed, to the real localization of the damage (black "x"). This algorithm also provided correct localization results for the other damage sizes thus validating its effectiveness for corrosion-like damage monitoring.

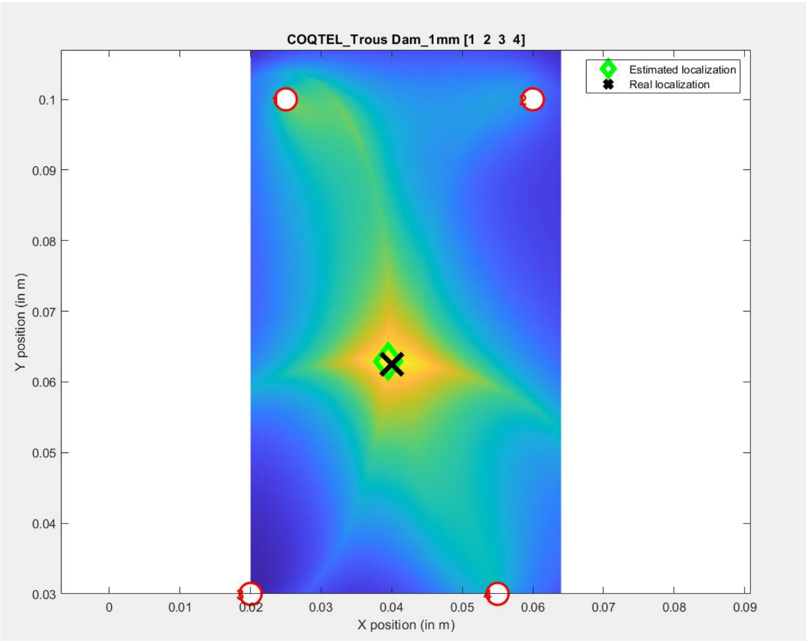


Figure 5 : Damage localization results for the damage of 1mm at 200kHz

To quantify the damage, the IPP damage quantification method was used as mentioned earlier. This method consists in computing a damage localization map and in extracting from this map the area above a given threshold (the yellow points in the above figure). When the damage size is increasing, this area is also very likely to increase and thus provide a reliable cue to damage size quantification. A polynomial regression between the area size and the actual damage size then allows to extrapolate to unknown damage sizes. A figure representing the estimated damage size versus the actual damage size is plotted. Only small damage sizes have been used for learning purposes and then the ability of the algorithm to extrapolate to larger damage sizes have been assessed. Points close to the diagonal line indicated correct damage size quantification. Learning points are shown in blue and prediction points in green. This example illustrates the fact that such algorithm is able to quantify correctly the size of corrosion-like damages.

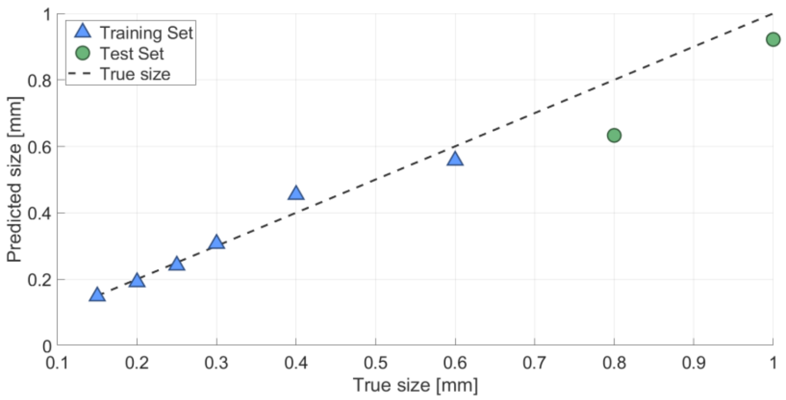


Figure 6 : Example of damage size quantification achieved by the IPP approach. The IPP algorithm has been trained on blue triangle and predicts sizes corresponding to green circles.

4 Conclusion

In this paper, a damage representative of corrosion damage using a 2024 aluminum plate with a semi-spherical hole of increasing size was studied for SHM purposes. Lamb waves were measured with piezoelectric sensors on the samples used. Detection (based on difference signals analysis), localization (using ponderated ToA method) and quantification (through IPP method) were demonstrated to be possible from a 0.15 mm to a 1 mm damage thus validating the practical ability of those algorithms to monitor corrosion-like damages.

Theses damages are however representing ideally the pits of corrosion which are not exactly hemispherical holes. Since it is not exactly corrosion, these algorithms will need to be also validated on real pits of corrosion in future work. The final objective of the COQTEL project is to combine active and passive method using piezoelectric elements. In this paper, the active method is validated on calibrated damages. The passive method needs then also to be acknowledged and paired with the active method. The final goal of the COQTEL project is to then track in real time corrosion damage during experiments of combining fatigue and corrosion using both active and passive methods. It seems to be an interesting challenge.

Acknowledgments

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