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Abstract

Structural health monitoring (SHM) consists in embedding sensors in a structure in order to monitor its health status throughout its lifetime. The implementation of SHM systems is restricted in many situations by the necessity to store or to harvest the electric energy necessary to emit the waves which give information about the health of the structure.

A promising way to tackle this constraint is to take advantage of the elastic noise naturally present in the structure in order to avoid the emission of the elastic waves by the SHM system. The complexity of the embedded SHM system is therefore reduced.

We present here studies of a passive technique - the ambient elastic noise cross-correlation - applied to guided wave tomography. Experimental results which come from usual time-of-flight tomography as well as passive tomography will be described.

1. INTRODUCTION

The Structural Health Monitoring (SHM) consists in the embedding of sensors in a structure such as an aircraft or a naval ship in order to detect defects (for example cracks or corrosion in metallic materials or delamination in composite materials) before a serious fault occurs in the structure. Guided elastic waves emitted by a sensor and propagating to another one are often used as the physical way to detect flaws. In aeronautics, the classical approach generally aims at minimizing the number of sensors to limit the embedded mass as well as the sensors intrusiveness within the structure. Comparisons between current signals and baseline signals are often performed in order to reveal the presence of defects [1]. However, this method may not be robust under certain conditions such as changes in temperature, stress, sensors aging between the two measurements.

A possible strategy to avoid the use of baseline signals consists in increasing the number of sensors to perform guided wave tomography. This way, the physical information obtained from the structure is more relevant, making the diagnosis more robust. Moreover tomography algorithms produce images that are much easier to interpret than temporal signals. However, SHM systems based on piezoelectric transducers might be too intrusive when the number of measurement points becomes important. Optical fiber sensors using Fiber Bragg Gratings (FBGs) for dynamic strain measurements allow multiplexing capabilities and low intrusiveness in the structure. However, FBGs can only be used as sensors but not as a source of elastic waves. A promising way to tackle these constraints is to use passive techniques such as cross-correlation of the ambient acoustic noise present in the structure. It has been shown that, under certain conditions, transient response between two sensors can be passively estimated from the cross-correlation of such noise [2–4]. The idea is to take advantage of the elastic noise naturally present in the structure (due to engine vibrations or aero-acoustic turbulences on the fuselage of an aircraft for example) in order to avoid the need for the SHM system to emit elastic waves.

Previous works have shown that the use of FBGs seems to be promising within the framework of passive guided wave tomography [5]. Indeed, [5] shows comparisons between active signals and passive signals - obtained with the ambient elastic noise cross-correlation method - with the use of piezoelectric transducers as well as Fiber Bragg Gratings. The fact that passive and active signals are adequately superimposed gives confidence on the possibility to obtain images of good quality using passive tomography and confirms that this technique is highly promising.

This paper presents a study of a passive method - the ambient elastic noise cross-correlation - applied to guided wave tomography. In Section 2, the tomography algorithm as well as the ambient elastic noise cross-correlation method are presented. In Section 3, the devices - composing the experimental setup - used to acquire the data necessary to obtain active and passive images of Section 4 are described.

2. METHODS

Generally, the input data for guided wave tomography is a set of signals which are measurements of the propagation field generated by acoustic sources located around the zone under inspection. In this paper, we call this kind of data "active signal". Conversely, if there is no emission of guided waves by the array of sensors, it is possible to use measurements of the ambient noise present in the structure. Then, the idea is to process this noise with a "passive method" - called ambient noise cross-correlation - in order to get the same information as given by active signal. Here, we call "passive signal" the output of a passive method. The purpose of this paper is to prove the feasibility of guided wave tomography using only passive signals. Also called "passive tomography".

This Section presents the methods which are used to obtain results of the Section 4. The ambient elastic noise cross-correlation method is used to collect the necessary input data for passive tomography. Section 2.1 presents this method based on cross-correlation and Section 2.2 presents the tomography algorithm used in this paper.

2.1 Ambient elastic noise cross-correlation method

Passive tomography is performed through the determination of Greens functions between two arbitrary points, A and B. In order to achieve this, the ambient noise is measured simultaneously in A and B during the necessary amount of time. The cross-correlation of the two measurements converge towards Greens functions [4]. Equation 1 shows the cross-correlation formula. Here $\overrightarrow{u}$ is the displacement field at the point $\overrightarrow{A}$ and $\overrightarrow{v}$ is the displacement field at the point $\overrightarrow{B}$.

$$\underline{\underline{C}}_{\overrightarrow{u},\overrightarrow{v}}(t,\overrightarrow{A},\overrightarrow{B}) = \lim_{T\to+\infty} \frac{1}{T}\int_0^T \overrightarrow{u}(\tau,\overrightarrow{A})\overrightarrow{v}(t+\tau,\overrightarrow{B})^T d\tau. \quad (1)$$

After the cross-correlation computation, signal processing is performed to get the set of time-of-flights necessary for the tomography algorithm.

2.2 Time-of-Flight Tomography

In this paper, we use a guided waves tomography algorithm to image flaws, in plate-like structure, such as corrosion. This kind of flaws induces local losses in thickness. The fact that Lamb waves are dispersive - their group velocities change with the product $frequency \times thickness$ - means that if there are local losses in thickness, the time-of-flight of a guided wave changes if the wave crosses the flaw. The algorithm used in this paper is based on this principle.

Images shown in Section 4 are obtained with a time-of-flight tomography algorithm which uses the Simultaneous Algebraic Reconstruction Technique (SART) [6]. Straight ray assumption is taken within this framework. Straight ray tomography takes into account neither refraction nor diffraction. By ignoring diffraction, only defects bigger than the first Fresnel zone [7] and varying slowly are correctly reconstructed. By ignoring refraction the algorithm is limited to low contrast flaws. Better algorithms that take into account refraction and diffraction exist [8] and will be studied in future work.

3. EXPERIMENTAL SETUP

The purpose of this Section is to present the experimental setups allowing to obtain the data for active and passive tomography of Section 4.

3.1 Experimental Setup for Active Tomography

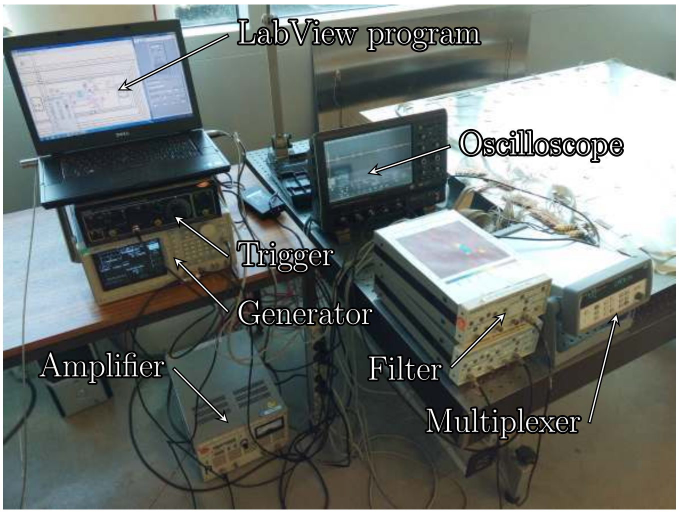

Figure 1 : Material composing the bench

Figure 1 shows the experimental setup used to perform active tomography. This setup is composed of a computer running LabView which controls an oscilloscope and a multiplexer; a generator which is synchronized with the oscilloscope by a trigger; an amplifier; two filters and finally the piezoelectric transducers glued to the 2 mm thick aluminum plate that is presented on Figure 2.

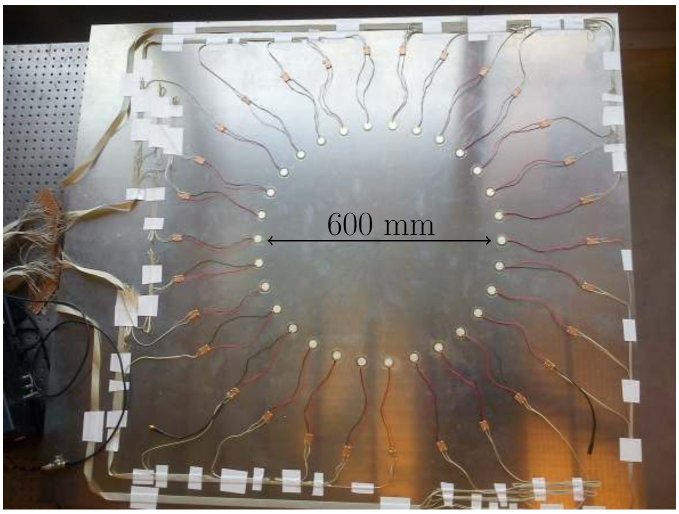

Figure 2 : 30 piezoelectric transducers (∅ 18 mm) glued on the 2 mm thick aluminum plate

The acquisition of data is completely automatic. Each pair of sensors in the array emits and measures guided waves until the end of the acquisition.

Phenyl salicylate (SALOL) is used to bond localized thin calibrated aluminum layers on the plate.

For experimental purposes, these layers serve as easily removable defects with an effect somehow similar to the one of corrosion on wave velocity due to thickness change.

3.2 Experimental Setup for Passive Tomography

Figure 3 : Experimental setup for passive tomography

The experimental setup for passive tomography of Figure 3 is quite different from the one for active tomography. Actually, there is no guided wave emission by the array of sensors. Ambient noise has to be generated in the 2 mm aluminum plate to perform passive tomography. Figure 3 shows a jet of compressed air mounted on a robotic arm which travels along the plate. This way, ambient noise is generated and can be measured by the array of sensors which is underneath the plate to prevent damage. The flaw is a thin calibrated aluminum layer bonded with SALOL. This passive setup is composed of two filters and a computer running LabView which controls an oscilloscope, a multiplexer and an other program which commands the robotic arm.

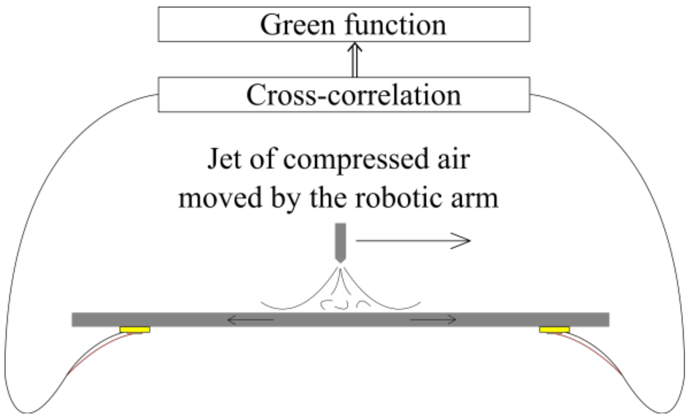

Figure 4 : Process of acquisition for passive tomography

The process of acquisition for one pair of sensors is presented on Figure 4. The multiplexer chooses one pair of sensors that measures the ambient noise during an adequate amount of time. While the robotic arm travels along the plate, the cross-correlation is calculated in real time by the oscilloscope. Once the robotic arm stops moving, the oscilloscope saves data for the pair of sensors activated. The multiplexer then chooses the following pair of sensors for the next acquisition.

4. EXPERIMENTAL RESULTS

Active tomography is presented in Section 4.1 to illustrate the fact that it is possible to avoid baseline signals with this technique and in Section 4.2, this paper presents a first passive tomography result which proves that this method is viable.

4.1 Active Tomography

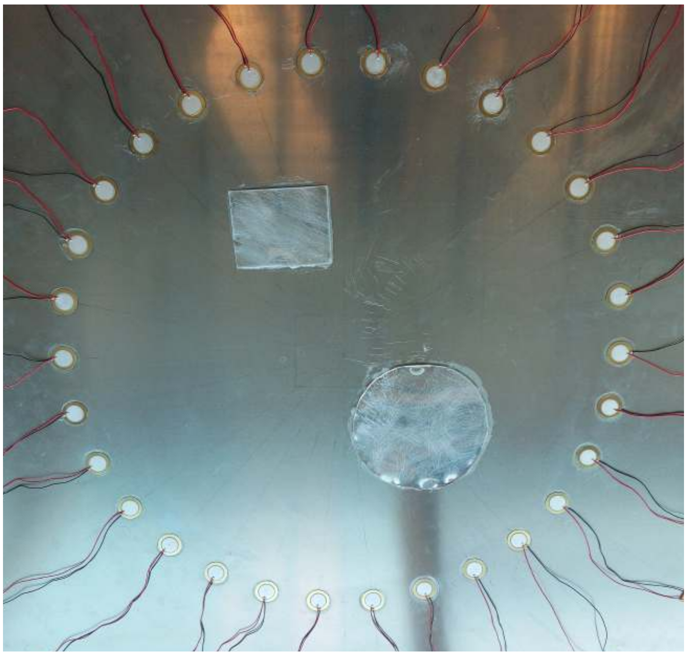

Figure 5 : The flaws of the active time-of-flight tomographies of Figure 6

The flaws to image are presented on Figure 5. These are thin aluminum plates glued (with SALOL) on the plate to be inspected. This process was chosen because it is possible to test different configurations without damaging the plate.

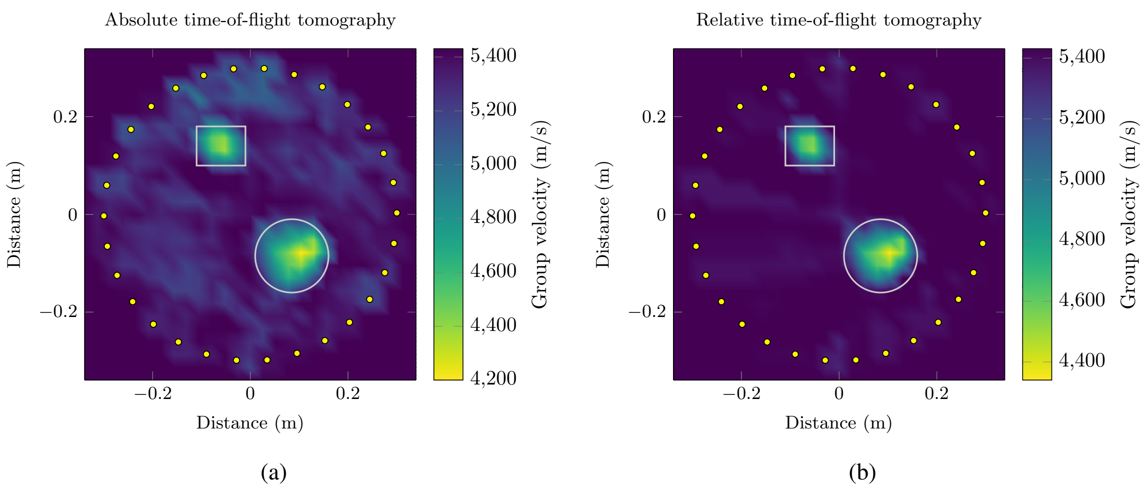

Figure 6 : Active time-of-flight tomography using the Simultaneous Algebraic Reconstruction Technique (SART [6, page 275])

Figure 6 shows experimental active time-of-flight tomography images which result from the algorithm mentioned in Section 2.2. Input data was obtained by emitting a 1.5 cycle tone-burst at 177.5 kHz through the piezoelectric transducers. Time-of-flights from first S0 wave packet were identified by the algorithm for each pair of sensors. On Figure 6(a) is presented the result of an absolute tomography and on Figure 6(b) the result of relative tomography. The term “absolute tomography” means that data only comes from current signals whereas for “relative tomographies” the baseline signals are also used. The two flaws are easily distinguishable in both cases even if on Figure 6(a) the image contains more noise than on Figure 6(b). With relative tomography, experimental uncertainties are reduced. However, Absolute tomography is more interesting because the method is more robust as baseline signals are never used.

Experimentally, there were local adhesive disbonds between aluminum plates, zones with poor SALOL adhesion and fluctuations in the thickness of the SALOL. All of those reasons partly explain why the reconstructed defects do not fit exactly the real lines of the flaws.

4.2 Passive Tomography

This Section presents a first passive tomography in order to image the flaw of the Figure 7. The flaw is once again a thin aluminum plate glued on the plate to be inspected. The 30 piezoelectric transducers are depicted by yellow points.

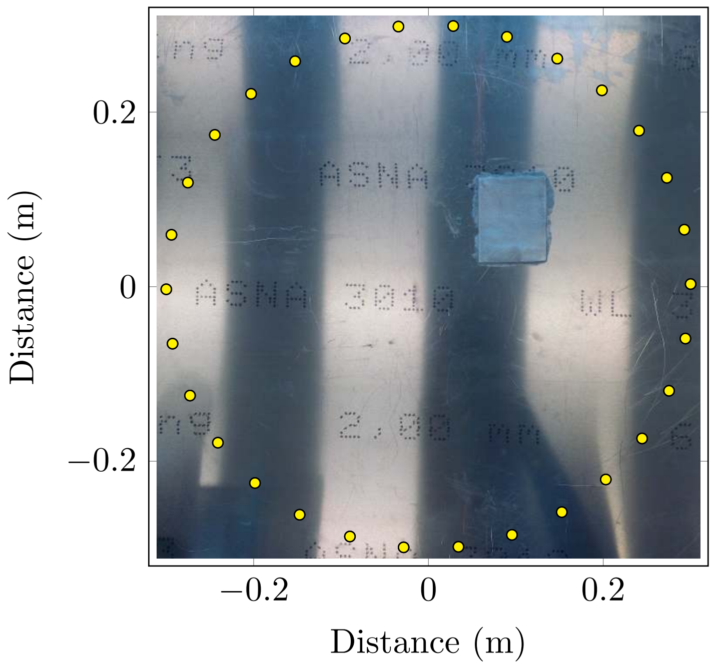

Figure 7 : The flaw of the passive time-of-flight tomography of Figure 8

Figure 8 shows experimental passive time-of-flight tomography images which results from the algorithm described in Section 2.2. The input data was obtained using the method presented in Section 2.1 with fifteen seconds of ambient noise acquisition for each pair of sensors. After signal processing, passive responses were obtain. Time-of-flights of the first S0 wave packet at 150 kHz were identified by the algorithm for each pair of sensors. On Figure 8 the flaw is distinguishable. This result demonstrates the potential of passive tomography. Experimentally, there were local adhesive disbonds between aluminum plates. This partly explains why the reconstructed defect does not fit exactly the real lines of the flaw. Future works will study passive tomography on more realistic flaws - real losses in thickness - in order to be more quantitative than qualitative.

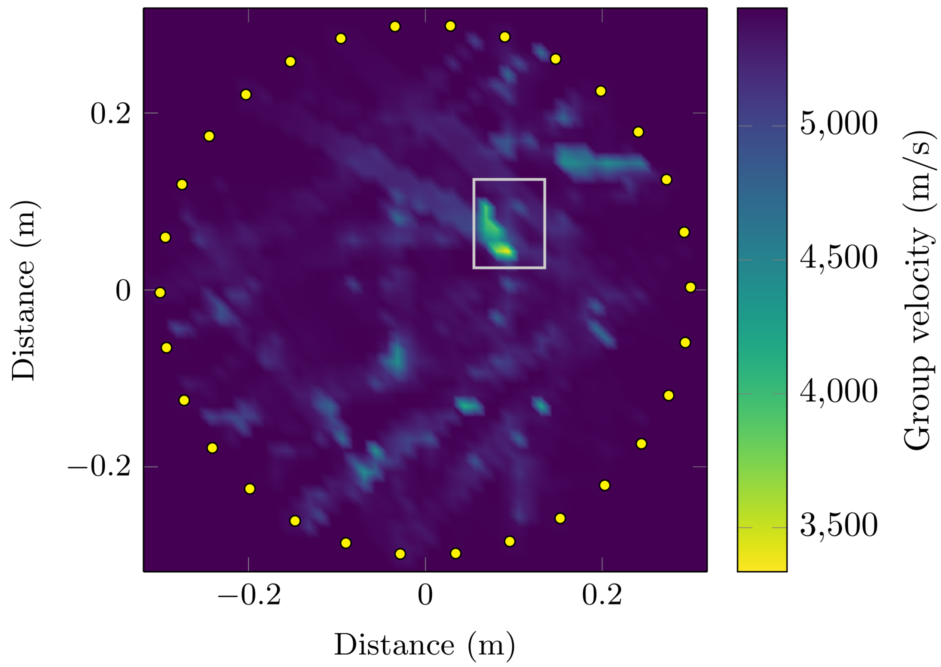

Figure 8 : Passive time-of-flight tomography using the Simultaneous Algebraic Reconstruction Technique (SART [6, page 275])

5. CONCLUSION

Avoiding the need of baseline signals is a major problem in structural health monitoring. This paper has shown a way to avoid this problem, using guided waves tomography algorithms which allows to image defects such as corrosion.

The implementation of such Structural Health Monitoring systems are restricted by the necessity to store or harvest the electric energy necessary to emit waves. A promising way to avoid this necessity is to use ambient noise. This paper explains how to use such noise with passive tomography. A first passive guided wave tomography image is exhibited. This work is a proof of passive tomography feasibility.

Future works will go further in passive tomography studies in order to be more quantitative. Better tomography algorithms will be studied to image a greater variety of flaws.

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