Feasibility of Passive SHM for Corrosion Detection by Guided Wave Tomography

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Abstract. Guided elastic waves emitted by a sensor and propagating to another one are often used as the physical way of detecting the defect in Structural Health Monitoring (SHM) systems of plate-like structures. However, 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.

A promising way to overcome this constraint is to use passive techniques such as cross-correlations of the ambient noise in place in the structure. 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 emission of the elastic waves by the SHM system. The complexity of the embedded SHM system is therefore reduced.

We present here studies of noise cross-correlation techniques that have been conducted with the aim of doing passive guided wave tomography of extended defects (such as corrosion) using an array of piezoelectric (PZT) transducers. Noise is generated by spraying compressed air on the surface of a thin aluminum plate. Passive measurements are compared to active signals to demonstrate the effectiveness of the cross-correlation technique. Experimental results which come from tomographic time-of-flight imaging algorithms will also be described. Finally, an extension of this technique using Fiber Bragg Gratings (FBG) optic sensors will be presented.

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 defects. 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, etc.

A possible strategy to avoid the use of baseline signals can consist in increasing the number of sensors and perform guided wave tomography. Indeed, more relevant physical
information is obtained from the structure, making the diagnosis more robust. Moreover, tomography algorithms produce images that are much easier to interpret than temporal signals. Implementation of SHM systems with a large number of sensors might be intrusive with the use of piezoelectric transducers. Optical fiber sensors using Fiber Bragg gratings (FBGs) for dynamic strain measurements should allow multiplexing capabilities with low intrusiveness in the structure. However, FBG are used only 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 ambient noise [2, 3, 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 emission of the elastic waves by the SHM system. Moreover, passive techniques can be used for the ranges of frequencies for which active techniques are destabilized because of ambient noise.

This paper shows an active tomography image which has been performed with a time-of-flight tomography algorithm using experimental data produced by piezoelectric transducers. Furthermore, a comparison between active signals and passive signals which comes from cross-correlation of ambient noise produced by spraying compressed air on an aluminum plate shows that it is possible to detect time-of-flight passively. In a first section the tomography algorithm used in this work is presented. Then, the devices - composing the experimental setup - used to acquire the data necessary to obtain the tomography images are described. Finally, experiments are presented showing that it is possible to use cross-correlation of ambient noise present in the plate-like structure to get the data required for the tomography algorithm. Several configurations of sensors were studied using piezoelectric transducers, Fiber Bragg Gratings and a combination thereof.

2. Time-of-Flight Tomography Algorithm

Images shown in this paper are obtained with a time-of-flight tomography algorithm which uses either the Simultaneous Iterative Reconstructive Technique (SIRT) or the Simultaneous Algebraic Reconstruction Technique (SART) [5]. For the SIRT, the weighting factors that represent the contributions of the pixels to the ray integrals are the lengths of intersections between rays and pixels whereas for the SART, the traditional pixel basis is abandoned in favor of bilinear elements.

Straight ray assumption is taken within this framework. Straight ray tomography does not take into account refraction and diffraction. By ignoring diffraction, only defect bigger than the first Fresnel zone [6] 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 [7] and will be studied in future works.

A simulation respecting these assumptions (i.e. no refraction and diffraction) and using the SIRT has been made (see Figure 1). The configuration on Figure 1a shows 30 sensors (which are depicted by yellow points) and three different defects. The image values matrix has a size of 23 x 23 pixels. The set of time-of-flight - input of the tomography algorithm - comes from the theoretical dispersion curves of A0 mode at 30 kHz propagating in a 2 mm thick plate. The absolute group velocity is 1447 m/s when waves propagate in the healthy part of the plate and 1300 m/s, 1200 m/s and 1056 m/s when they propagate in flawed regions (i.e. zones of reduced thickness which can illustrate corrosion phenomenon). In practice, image smoothing is interesting since corrosion and pixels will unlikely be superimposed on each other. That is why Figure 1b and the experimental images on Figure 3b and Figure 3c are smoothed by performing interpolation.
3. Experimental Setup

The simulation of the previous section helped, among others things, to design an experimental setup (see Figure 2). The setup is composed of a computer with a LabView program which controls an oscilloscope and a multiplexer; a generator which is synchronized with the oscilloscope by a trigger; an amplifier; a filter and finally the piezoelectric transducers stuck on a 2 mm thick aluminum plate. Phenyl salicylate (SALOL) is used to bond localized thin calibrated aluminum layers on the plate. For experimental purposes, these layers will serve as an easily removable defect with a somewhat similar effect than corrosion on wave velocity due to thickness change.

4. Active experimental image

Figure 3 shows experimental active absolute time-of-flight tomography images which result from the SIRT on Figure 3b and the SART on Figure 3c. In practice, reversible flaws (Figure 3a) were used by adding a thin aluminum plate glued (with SALOL) on the plate to be inspected. The term 'Absolute tomography' notifies that data only comes from current signals. This way, the method should be quite robust as baseline signals are never used. Input data was obtained by emitting a 1.5 cycle tone-burst at 177.5 kHz. Arrival times from first S0 wave packet were identified by the algorithm for each couple of sensors. The two flaws of Figure 3a are easily distinguishable on Figure 3b and 3c. Experimentally, there were local adhesive lacks between aluminum plates, zones with poor adhesion of SALOL and fluctuations in the thickness of the SALOL. All of those reasons partly explain why the reconstructed defects do not fit exactly the real key lines of rectangular and circular aluminum plates.
5. Passive experimental results

Input data necessary to obtain the tomography images presented in previous sections was a set of time-of-flight. This Section aims at assessing the retrieval of this kind of data from ambient noise. The passive signals shown and discussed in this Section results from cross-correlation of ambient noise recorded during the amount of time necessary (10 seconds in our experiments) for it to converge towards Green’s functions. Equation 1 shows the cross-correlation formulation. Here $\vec{u}$ is the displacement field at the point $\vec{x}$ and $\vec{v}$ is the displacement field at the point $\vec{x}^\prime$.

$$
C_{\vec{u},\vec{v}}(t, \vec{x}, \vec{x}^\prime) = \lim_{T \to \infty} \frac{1}{T} \int_0^T \vec{u}(\tau, \vec{x})\vec{v}(t + \tau, \vec{x}^\prime)^T d\tau
$$

5.1 Piezoelectric sensors (PZT)

A comparison between active signals and passive signals resulting from cross-correlation of ambient elastic noise, is presented on Figure 4.
8 cycles tone-burst at 20 kHz were generated in order to obtain the active signals. The elastic noise used for the cross-correlation was produced by spraying compressed air on the aluminum plate surface. The absolute values of those signals are plotted on Figure 4 for several distances between sensors. This way, the first wave packet represents the propagation of the $A_0$ mode between emitter (fixed position) and receiver (moving position). The theoretical arrival times of $A_0$ mode correspond to the first wave packet for each distances. On Figure 4 it can be seen that the cross-correlations and the active signals are adequately superimposed. This indicates a satisfactory reconstruction of Green's functions. It is therefore possible to get time-of-flight from passive signals. This result gives confidence on the possibility to obtain images of good quality by passive tomography and confirms that this technique is highly promising. We can notice on passive signals some parasite wavelets caused by the spatial distribution of the ambient noise [8, 9]. Indeed, the more the ambient noise in structures is spatially uniformly distributed the better the convergence towards Green’s functions will be good.

Figure 5 shows that it is possible to obtain time-of-flight on passive signals for higher frequency, of at least 250 kHz (for the ambient noise created by spraying the air on the aluminum plate). Here, $S_0$ as well as $A_0$ modes can be detected on Figure 5 but it is not possible to identify correctly the time-of-flight for $A_0$. Indeed, $S_0$ reflections arrive at the same time as $A_0$ first wave packet.
5.2 Fiber Bragg Gratings (FBG)

It has been demonstrated that FBGs are able to detect guided waves emitted by piezoelectric transducers [10, 11]. Here we perform passive experimental measurements using only fiber Bragg gratings sensors. With such passive measurements PZT transducers for elastic wave emission would no longer be necessary, reducing the intrusiveness of the sensors in the structure.
Elastic noise is generated in the structure using the same setup than in previous sections: by spraying compressed air on the aluminum plate surface. Figure 6 shows the cross-correlation of ambient noise measured by two FBGs bonded on the surface of a 2 mm thick aluminum plate and spaced 400 mm apart from each other. This demonstrates the feasibility of passive reconstruction using FBGs only. Indeed, theoretical time-of-flight of $A_0$ mode perfectly matches the maximum of the first wave packet.

![Figure 6. Cross-correlation of ambient noise measured by two FBGs bonded on the surface of a 2 mm thick aluminum plate and spaced 400 mm apart from each other.](image)

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Figure 7 shows the cross-correlation (in red) between a FBG and a PZT for several distances between both sensors. The PZT is used here only as sensor of the elastic noise, not to emit the guided waves. It has been chosen by convenience in this experiment because it is easier to move than the FBG. It confirms that the first wave packet is well reconstructed and that it is possible to correctly identify its time of flight with passive measurements using FBG. On Figure 7, in the same way as on Figure 4 we can say that the cross-correlations and the active signals are adequately superimposed.

### 6. Conclusion

This paper shows that it is possible to image defects by using piezoelectric transducers thanks to a time-of-flight tomography algorithm without the need of baseline signals. Active experimental tomography using guided waves was performed in this paper. It is also shown that it is possible to obtain time-of-flight by using cross-correlation of ambient noise with piezoelectric transducers as well as with fiber Bragg gratings. The next step of our study is to obtain experimental images from passive tomography.
References