

PZT ARRAY FOR PASSIVE GUIDED WAVE TOMOGRAPHY OF EXTENDED DEFECTS USING AMBIENT ELASTIC NOISE CROSS- CORRELATIONS

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Abstract. Structural health monitoring (SHM) consists in embedding sensors in a structure like 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 of detecting the defect. 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 tackle this constraint is to use techniques based on the cross-correlations of the ambient acoustic noise in place in the structure. It has been shown that, under certain conditions, transient response between two sensors can be estimated from cross-correlation of ambient noise, with purely passive measurements.

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 tomography of extended defects (such as corrosion or delamination) using an array of piezoelectric (PZT) transducers. Noise is generated by spraying compressed air on the surface of an aluminum plate. Passive measurements are compared to active signals to demonstrate the convergence of the cross-correlation technique to the Green function of the system. Experimental results which come from tomographic time-of-flight imaging algorithms will also be described. Finally, an extension of this technique using purely passive guided wave sensors such as Fiber Bragg Grating (FBG) will be presented.

Introduction

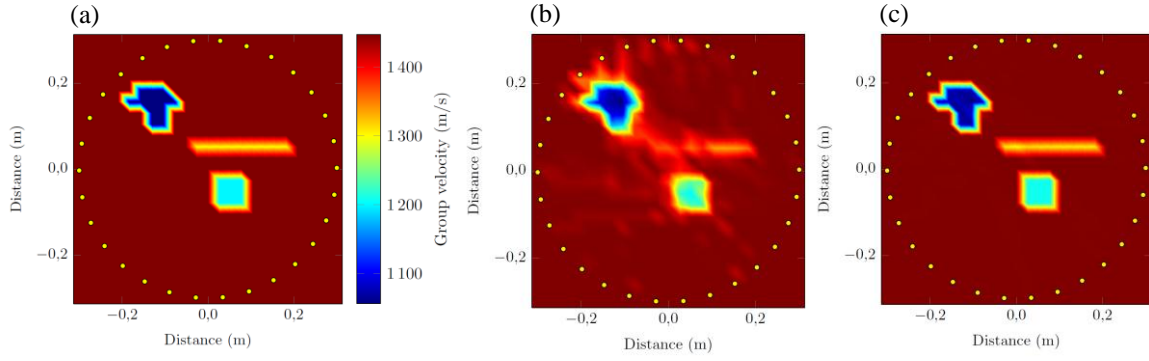
The Structural Health Monitoring (SHM) consists in the embedding of sensors in a structure such as an aircraft or a naval ship in order to detect defects (for example cracks or corrosion in metallic materials or delamination in composite materials) before a serious fault occurs in the structure. Guided 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 could 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 generally used only as sensors but not as a source of elastic waves. A promising way to tackle these constraints is to use techniques based on 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.

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.

1. Time-of-Flight Tomography Algorithm

Images shown in this paper are obtained with a time-of-flight tomography algorithm which uses the Simultaneous Iterative Reconstructive Technique (SIRT) [5]. 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.

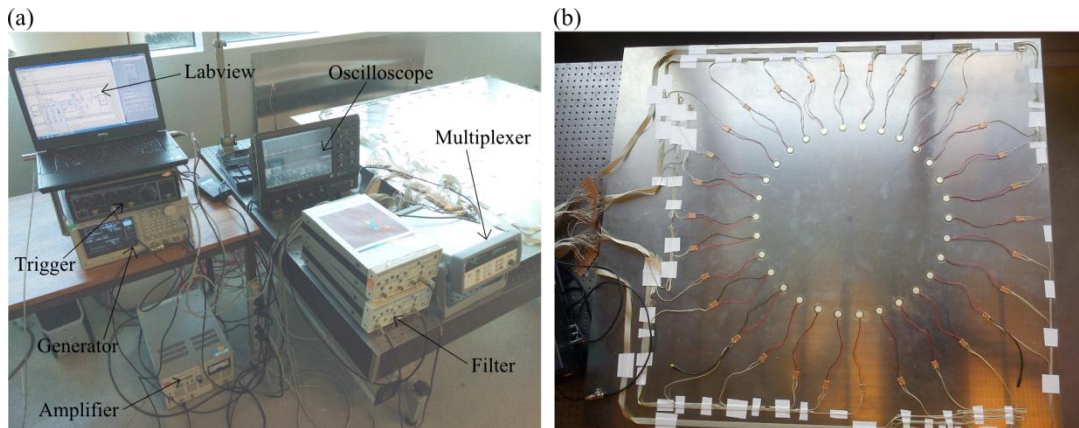


Pic. 1. (a) Configuration; (b) Result after 1 iteration; (c) Result after 15 iterations.

A simulation respecting these assumptions (i.e. no refraction and diffraction) has been made (see Picture 1). The configuration on Picture 1a shows 30 sensors (which are depicted by yellow points) and three different defects. The image values matrix has a size of 23×23 . Input data is a set of time-of-flight deduced from dispersion curves of A_0 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 defects (i.e. zones of reduced thickness which can illustrate corrosion phenomenon). Picture 1b and 1c show that when the number of iterations increases, the time-of-flight tomography algorithm converges better towards the exact velocity map. In practice, image smoothing is interesting since corrosion and pixels will unlikely be superimposed on each other. That is why Picture 1 and the experimental image on Picture 3b is smoothed by performing interpolation.

2. Experimental Setup

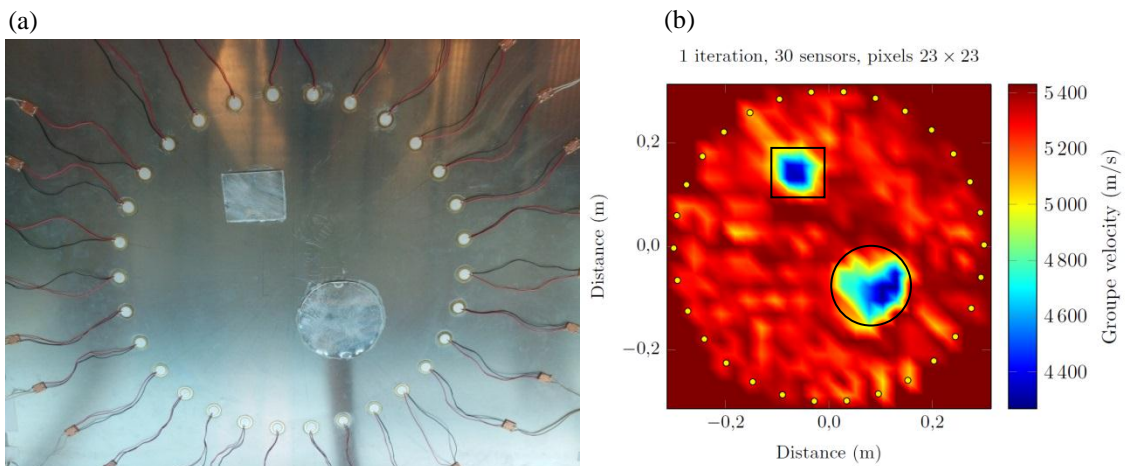
The time-of-flight algorithm in previous section helped, among others things, to design an experimental setup (see Picture 2). The setup is composed of a computer with a LabView program which controls an oscilloscope and a multiplexer; a generator which is synchronized with the oscilloscope by a trigger; 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.



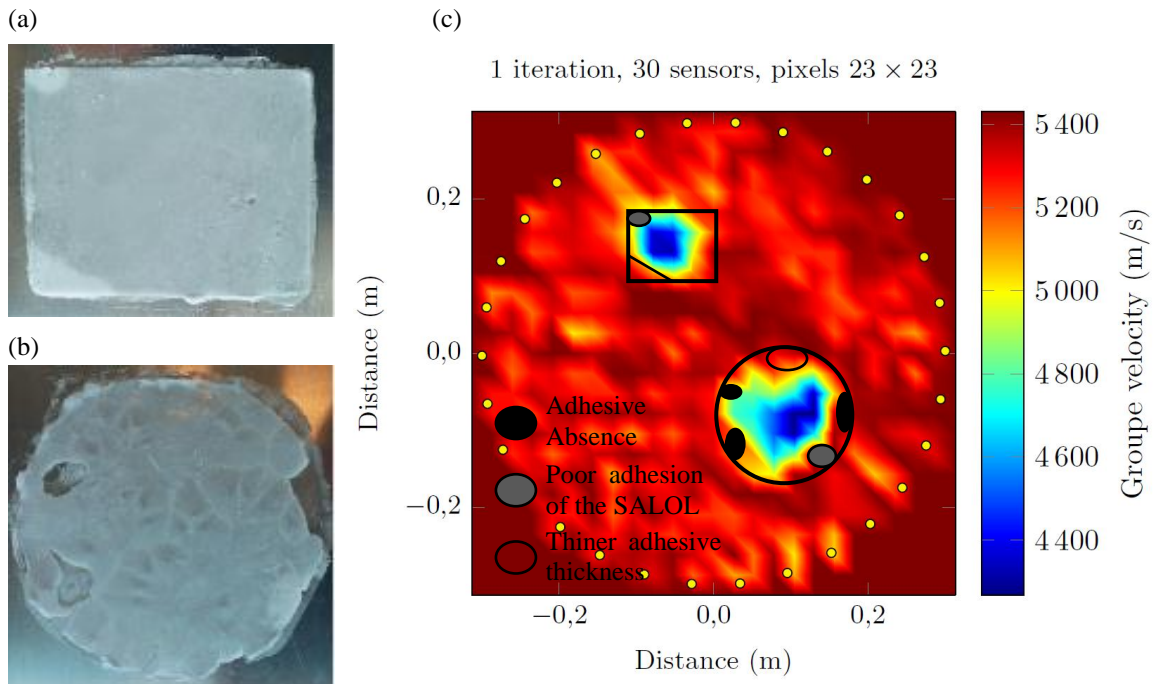
Pic. 2. (a) Experimental setup; (b) 30 piezoelectric transducers (\varnothing 18 mm) stuck on the 2 mm thick aluminum plate.

2. Active Experimental Image

Picture 3 shows an experimental active absolute time-of-flight tomography image (Picture 3b) which results from the algorithm of previous. In practice, reversible flaws (Picture 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. Time-of-flights from first S0 wave packet were identified by the algorithm for each couple of sensors. The two flaws of Picture 3a are easily distinguishable on Picture 3b. Experimentally, there were local adhesive lacks between aluminum plates, zones with poor adhesion of SALOL and fluctuations in the thickness of the SALOL (Picture 4). All of those reasons partly explain why the reconstructed defects do not fit exactly the real key lines of rectangular and circular aluminum plates.



Pic. 3. (a) Experimental configuration; (b) Absolute time-of-flight tomography (smoothed velocity map).



Pic. 4. (a) Coupling part of the rectangular flaw; (b) Coupling part of the circular flaw; (c) Absolute time-of-flight tomography with identified areas which have a coupling problem.

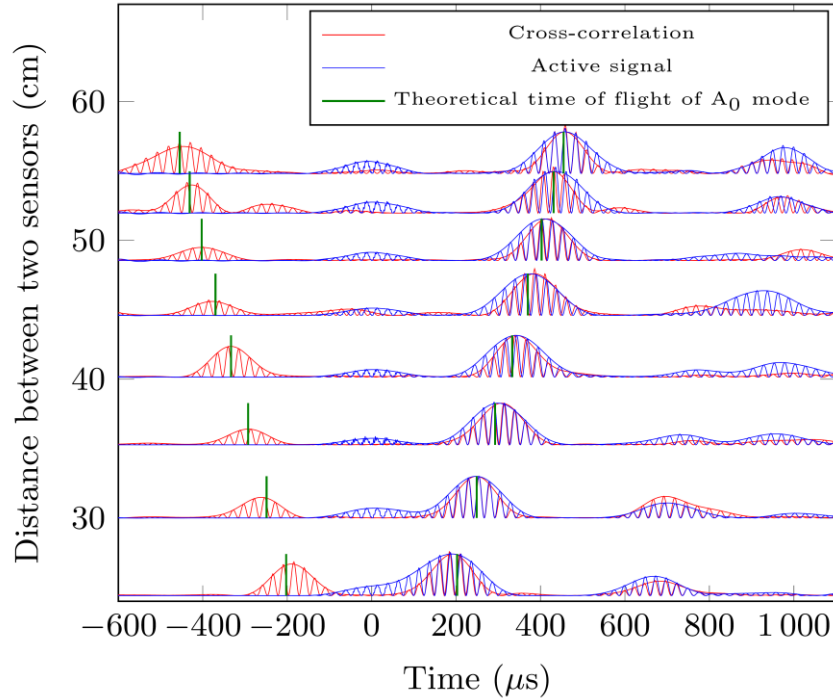
3. Passive Experimental Results

Input data necessary to obtain the tomography images presented in previous sections was a set of time-of-flights. This Section aims at assessing the retrieval of this kind of data from passive signals. Equation 1 shows the cross-correlation formulation with \vec{u} the displacement field at the point \vec{x} and \vec{v} the displacement field at the point \vec{x}' . Every passive signal obtained 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.

$$\underline{\underline{C}}_{\vec{u},\vec{v}}(t, \vec{x}, \vec{x}') = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T \vec{u}(\tau, \vec{x}) \vec{v}(t + \tau, \vec{x}')^T d\tau \quad (1)$$

3.1 Piezoelectric Sensors (PZT)

A comparison between active and passive signals, obtained thanks to cross-correlation of ambient elastic noise, is presented on Picture 5.

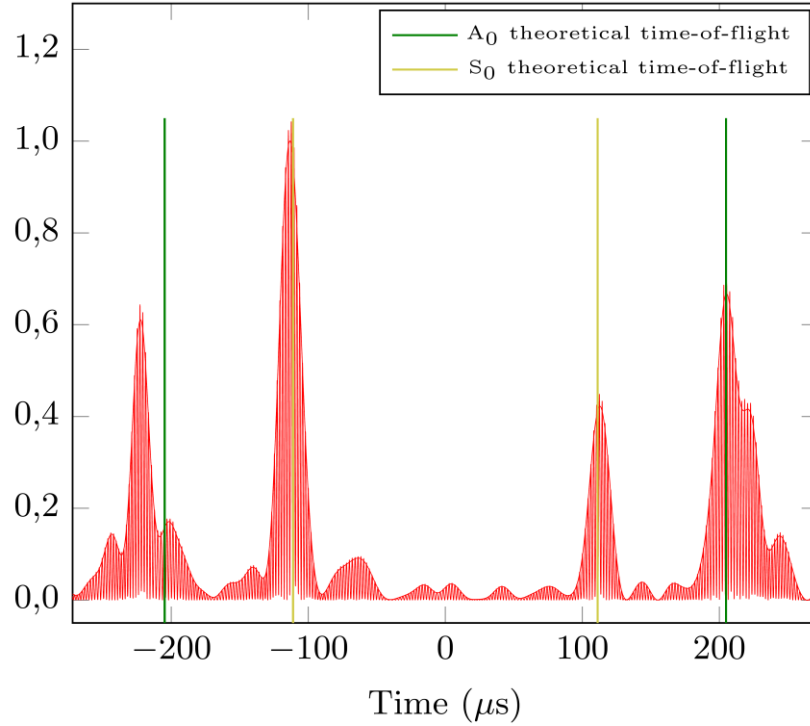


Pic. 5. Comparison between active and cross-correlation signals.

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 Picture 5 for several distances between sensors. This way, the propagation of the first wave packet is shown for each active signal. Passive signals show a satisfactory reconstruction of Green's functions at least for the first wave packet. Indeed, the result is symmetrical (because of acoustic reciprocity between the two observation points) and first wave packets are adequately superimposed on passive and active signals. It is therefore possible to get time-of-flight from passive signals. This is a reason to think that passive tomography is 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.

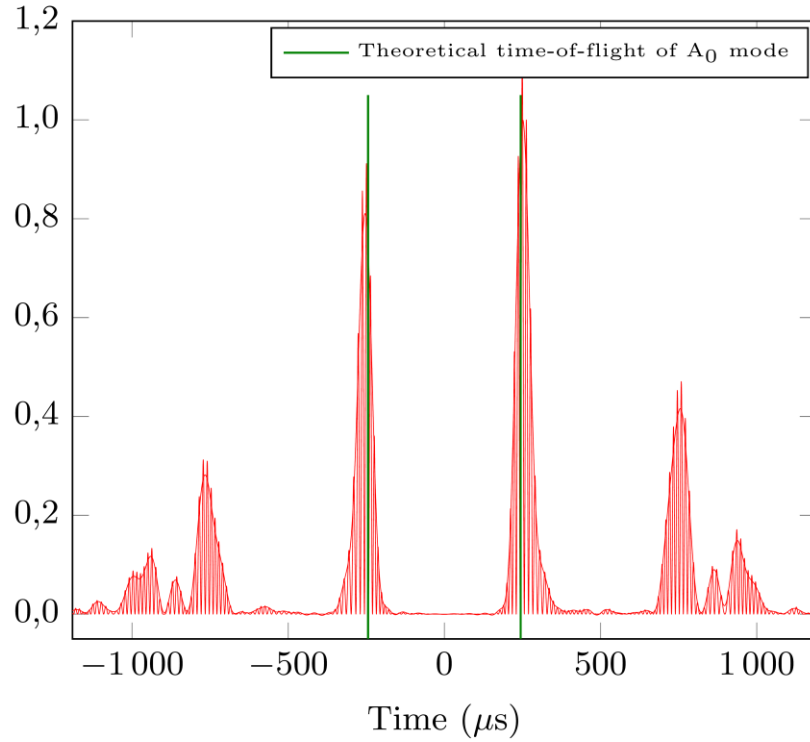
Picture 6 shows that it is possible to obtain time-of-flight on passive signals for higher frequency, of at least 250 kHz (for the ambient noise created by spraying the air on the aluminum plate). Here, S_0 as well as A_0 modes can be detected on Picture 6 but it is not possible to identify correctly the time-of-flight for A_0 . Indeed, S_0 reflections arrive at the same time as A_0 first wave packet.



Pic. 6. Reconstruction of passive signal for high frequency – theoretical time-of-flights for S_0 and A_0 at 250 kHz.

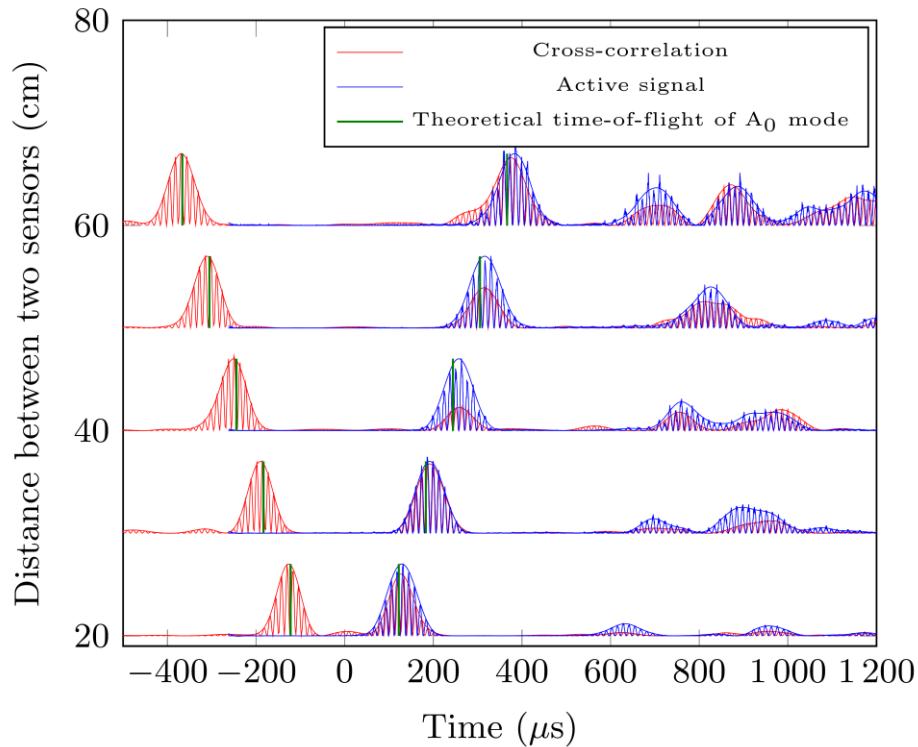
3.1 Fiber Bragg Gratings (FBG)

It has already 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.



Pic. 7. Reconstruction of passive signal with 2 fiber Bragg Gratings bonded on the surface of a 2 mm thick aluminum plate.

Elastic noise is generated in the structure using the same setup than in previous sections: by spraying compressed air on the aluminum plate surface. Picture 7 shows the passive reconstruction of A_0 mode at 40 kHz between FBGs bonded on the surface of a 2 mm thick aluminum plate and spaced 400 mm apart from each other.



Pic. 8. Reconstruction of passive signals between a piezoelectric transducer and a fiber Bragg grating. Comparison between active and cross-correlation signals.

This demonstrates the feasibility of passive reconstruction using FBGs only. Indeed, theoretical time-of-flight perfectly match the maximum of the first wave packet (A_0 mode). Picture 8 shows the passive reconstruction (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 Picture 8, in the same way as on Picture 5 we can say that first wave packets are adequately superimposed on passive and active signals.

Conclusion

This paper has shown that it is possible to image defects experimentally by using piezoelectric transducers thanks to a time-of-flight tomography algorithm without the need of baseline signals. Active experimental tomography using ballistic guided waves data was performed in this paper. It was also shown that it is possible to detect time-of-flight by using cross-correlation of ambient noise with piezoelectric transducers as well as with fiber Bragg gratings. That is why passive experimental tomography seems to be promising and could be incorporated within the framework of SHM.

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