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GUIDED WAVE IMAGING OF A COMPOSITE PLATE USING PASSIVE ACQUISITONS BY FIBER BRAGG GRATINGS ON OPTICAL FIBERS

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ABSTRACT

In this work are presented imaging results of defects in composite panels using guided wave imaging algorithms with Fiber Bragg Gratings (FBG) receivers and no piezoelectric actuation. Guided wave imaging is commonly applied to active data: each sensor acts successively as a source whereas other sensors measure the propagated signals. Here the imaging is obtained from passive data, that is, the signal corresponding to each emitter-receiver couple is reconstructed thanks to the cross-correlation of the ambient noise measured simultaneously by every couple of sensors. The passive imaging approach allows the use of sensors unable to generate guided waves, namely FBG in optical fibers. FBGs present a much smaller intrusiveness compared to traditional piezoelectric sensors while allowing dense multiplexing and are much more robust to harsh environments. Results are shown for two instrumentations, the first one using piezoelectric transducers for actuation and FBG for reception while the second one uses FBG sensors only. The imaging results presented here show the feasibility of passive imaging in composite panels and the possibility of using FBG at ultrasonic frequencies, reducing the intrusiveness of the sensors integrated in the structure in the context of Structural Health Monitoring (SHM).

Keywords: Passive imaging, Fiber Bragg Gratings, elastic guided waves, Structural Health Monitoring

1. INTRODUCTION

Structural Health Monitoring (SHM) relies on the permanent integration of sensors. As such, the sensors must be particularly efficient, resilient and lightweight. In Guided Wave (GW) SHM, piezoelectric sensors are very often used because of their affordability and simplicity of use. Piezoelectric sensors are fairly light due to their size but as each must be cabled individually, the wiring quickly leads to non-negligible masses. Moreover, piezoelectric sensors work with a limited range of temperatures and even though high-temperature piezoelectric material do exist, significant maturation of the technology remains to be done.

One of the most promising approach to overcome these limitations is to replace the piezoelectric sensors by Fiber Bragg Gratings (FBGs) on optical fibers. FBGs are short periodic inscription made inside the optical fiber core reflecting a specific wavelength. While stretched or compressed, the reflected wavelength changes, thus creating a strain sensor. Because of this highly dynamic phenomenon and a high sensitivity, FBGs can be used to measure elastic waves with sampling frequencies of the order of the mega-hertz [1, 2].

The main downside of the FBGs compared to the piezoelectric sensors is their inability to generate a strain; the ultrasonic energy must therefore come from elsewhere for GW-SHM inspection. Hybrid piezoelectric – FBG systems have been proposed to limit the number of piezoelectric sensors (therefore the mass of the instrumentation), but fully passive systems using only FBGs are also possible. Passive systems in SHM relies on the interpretation of the vibrational noise naturally present in a structure to conduct the inspection. Under some assumptions, GW wavepackets equivalent to active signals (that is, the signal that would be generated by a transducer) can be reconstructed.

In this paper, a fully passive GW-SHM system is presented, first hybrid with piezoelectric sensors and FBGs and second with FBGs only. To generate uncontrolled vibrational noise in the inspected systems representative of an inflight inspection, compressed air is sprayed on the surface of the studied composite panel. Imaging is conducted with the Excitelet algorithm [3, 4]

2. Passive acquisition by cross-corelation of ambient noise

In this section, the method to reconstruct active-like signals from passive measurements is summarized. As a reminder, the passive acquisition is defined by the signals acquired by the sensors while the system is exposed to an uncontrolled solicitation, in our case air flow. Because it contains very little relevant information, a passive acquisition is much longer than an active one, of the order of the second.

In the following, the ambient noise φ is a space-time stationary random field that is also delta correlated in space and time. Consider a plate as a 2D domain and consider two sensors placed at positions x and y. Let us denote V_x , respectivelyV_y, the passive signals acquired by the sensor at x, respectively y, on the time interval $[0, T]$, $T > 0$. The cross-correlation C_T of these two signals is given by:

$$C_T(t,x,y) = \frac{1}{T}\int_0^T V_x(\tau)V_y(t+\tau)\,\mathrm{d}\tau. \quad (1)$$

One can then show [5] that

$$\frac{\mathrm{d}\,C_T}{\mathrm{d}t} \propto H_{xy}(t) - H_{xy}(-t), \quad (2)$$

where H_{xy} is the impulse response of the system formed by the plate and the sensors, the sensor at x acting as a source while the one at y acts as a receiver. Note that if the domain is reciprocal, which is the case for composite plates, then $H_{xy} = H_{yx}$. As the impulse response is causal, the positive time part of (3) corresponds to the impulse response for x as a source and y as a receiver and the negative part to the time-reversed impulse response for y as a source and x as a receiver.

In other words, the time derivative of the correlation between the passive signals measured at both sensors is proportional to the impulse response from one sensor to the other. By doing this operation, virtual sources are created at the position of each sensor, and GW Imaging (GWI) algorithms can be used. This process is conducted for the whole frequency spectrum of the uncontrolled excitation.

3. Imaging results

To create signals for the imaging process, the passive signals are deconvolved over a frequency band of interest. In the configuration presented herein, the deconvolution is conducted to reconstruct signals equivalent to five-cycle and two-cycle tone burst centered at 30 kHz. The experiment was carried out on a 1010x610x2.2 mm^3 carbon fiber reinforced polymer flat panel with 8 plies all oriented in the same direction. It is instrumented on both sides, one side with piezoelectric sensor and one side with FBGs, both distributed on the same 30 cm diameter circle, so that FBGs and piezoelectric sensors are superimposed on either side. The wave sensing by the FBGs being directionally dependent, these sensors are here disposed radially to ensure maximal sensitivity to the area within the circle of sensors. The defect is simulated with a pair of circular magnets of radius 16 mm to emulate a guided wave scatterer. The GWI method is Excitelet [3, 4] and relies on the residual signals, defined as the difference between the pristine signals and the signals acquired in the unknown state. The residual signals between every pair of sensors are then compared for every combination of sensors to the theoretical ones for every possible position of the defect. Excitelet assumes the defect to be a point-like omnidirectional defect and requires the knowledge of the dispersion curves. Because the dispersion is taken into account, a wider frequency spectrum brings better resolved results than a narrow frequency spectrum.

The imaging is conducted for both the hybrid configuration with piezoelectric sensors as emitters and FBGs as receivers as reported in Figure 1 and in the passive configuration with the FBG sensors only as reported in Figures 2 and 3. In the active hybrid configuration (Figure 1), the piezoelectric sensors are excited by a 5-cycle tone burst. In the passive configuration of Figures 2 and 3, the passive signals are deconvolved over a 5 and 2-cycle 30 kHz tone burst respectively.

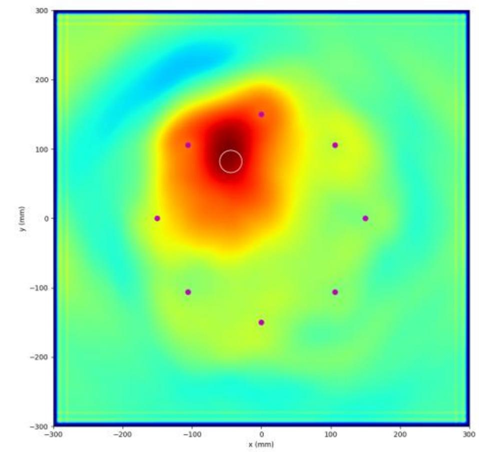

FIGURE 1: Active hybrid imaging (Emission by piezoelectric, reception by FBGs) of a defect represented by the white circle in a CFRP plate using the Excitelet algorithm and 8 piezoelectric sensors. The excitation is a 5-cycle tone burst at 30 kHz.

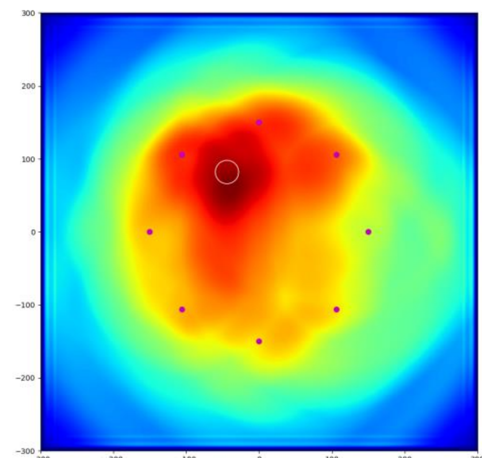

FIGURE 2: Passive imaging (vibration generated by compressed air, reception by FBGs) of a defect represented by the white circle in a CFRP plate using the Excitelet algorithm and 8 FBG sensors. Passive signals are deconvolved to reconstruct a 5-cycle tone burst at 30 kHz

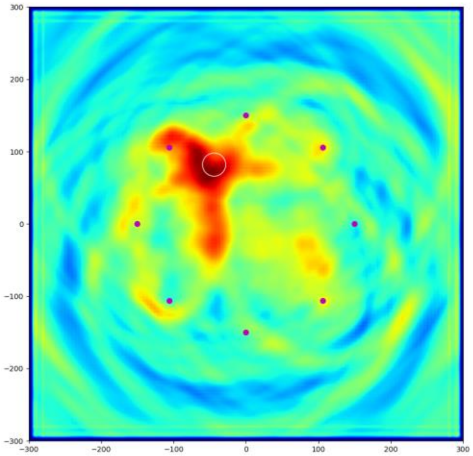

FIGURE 3: Passive imaging (vibration generated by compressed air, reception by FBGs) of a defect represented by the white circle in a CFRP plate using the Excitelet algorithm and 8 FBG sensors. Passive signals are deconvolved to reconstruct a 2-cycle tone burst at 30 kHz

In the active configuration, 56 signals are measured sequentially (8 piezoelectric emitters and 7 FBGs receivers, the FBG corresponding to the emitter being left out for each emission). In the passive configuration, since the signals must be acquired at the same time to conduct the correlation, the number of channels of the acquisition chain is a limit. In our case, the FBG acquisition system was limited to 4 channels in parallel. In practice, the passive acquisition was conducted twice for 4 FBGs sensors. This means that only 24 couple of FBG sensors are available, against 56 for the active acquisition, therefore the quality of the two images is not directly comparable.
This is why even though the defect is properly detected and located in both Figures 1 and 2, the spot for the defect in the image obtained by the FBGs is bigger. Figure 2 however demonstrates the feasibility to obtain excellent GWI results for this configuration with FBGs only and an uncontrolled vibrational solicitation. Figure 3 shows also detection and localization with a thinner spot on the true defect position. This is due to the fact that a broader frequency spectrum is used for the Excitelet imaging therefore better resolution is obtained. The vertical and horizontal lines in Figure 3 are mainly due to the fact that 2 pairs of 4 FBGs are measured in parallel, creating these imaging artifacts. The artifacts are expected to disappear if 8 FBGs could be measured in parallel leading to 56 pairs of sensors instead of 24.

4. Conclusion

This paper demonstrates the feasibility to conduct GW-SHM inspections with FBG sensors only and without any controlled GW excitation. It is demonstrated that similar results are obtained with a controlled GW excitation by piezoelectric transducers and uncontrolled GW excitation with compressed air sprayed on the surface.

The ambition is to be able to conduct in-service inspections using the natural vibration of the structure during its exploitation. For aerospace for example, the aerodynamic flow or the rotating motors would provide the necessary vibrations for the inspection. The use of FBGs is a significant breakthrough in SHM as they reduce significantly the added mass and intrusiveness of the overall system, and expand the field of application of such technologies to higher temperatures or radioactive environments.

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