Towards Passive Fiber Bragg Grating-Based Measurement of Ambient Elastic Noise for SHM Under Varying Environment

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ABSTRACT

We explore here the use of fiber Bragg Gratings (FBG) transducers in optical fibers to create a minimally intrusive structural health monitoring (SHM) system. Piezoelectric transducers, commonly used for SHM, are often intrusive, so FBG transducers offer an interesting alternative thanks to their multiplexing capabilities. However, FBG can only be used as acoustic receivers and cannot emit elastic waves like piezoelectric transducers. It has ever been demonstrated in the past years that it is possible to use ambient structure-borne elastic noise, present in the structure, to retrieve the impulse response between two sensors, known as the "ambient noise cross-correlation" method. However, passive signals are of very low amplitude, which requires a specific care in the FBG interrogation scheme, especially in realistic environment where temperature or strain variations can affect the sensing sensitivity.

We present here an optimization of an optoelectronic FBG interrogation setup to measure elastic waves at ultrasonic frequencies. The system demonstrates excellent sensitivity in active signal measurements in a varying environment thanks to the real-time tracking of the setting point. Later work will present passive measurements of impulse responses under different sources of elastic noise.

INTRODUCTION

Guided elastic waves emitted by a piezoelectric transducer and propagating to another one are often used as the physical way of detecting a defect in a structure being monitored by a structural health monitoring (SHM) system. However, the implementation of such SHM systems is restricted in many situations by the intrusiveness of piezoelectric transducers. An interesting possibility is to design a guided wave-based SHM system with minimal intrusiveness thanks to the use of fiber Bragg Gratings (FBG) transducers in optical fibers.

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FBGs also offer high multiplexing capabilities (Time Division Multiplexing - TDM & Wavelength Division Multiplexing - WDM) and resistance to harsh environments (extreme temperatures, ionizing radiations, electromagnetic environments, and capability to operate safely in explosive environment). However, these transducers cannot emit elastic waves, thus they can only work as receivers. Therefore, they are generally associated with piezoelectric transducers, in hybrid configurations [1], which limit the potential interest of the technology.

In the past years researchers have shown that it is possible to use ambient structure-borne elastic noise instead of actively emit the waves in the structure in order to retrieve the impulse response of the medium between two sensors (passive approach called "ambient noise cross-correlation") [2]. The idea is to take advantage of the elastic noise naturally present in the structure in operation (due to vibrations of engines, fluid turbulences etc.) in order to avoid the emission of the elastic waves by the SHM system. The complexity of the embedded SHM system can therefore be reduced since only FBGs in optical fibers are deployed on/within the structure, while maintaining the fine diagnosis capability allowed by guided waves.

We present here current work performed at CEA to optimize an optoelectronic interrogation setup to measure elastic waves at ultrasonic frequencies, ultimately in passive mode. A specific care has been taken to offer a good sensitivity to such very low amplitude elastic waves, especially under varying Environmental and Operational Conditions (EOC, *e.g.*: temperature and/or strain of the structure). In this paper we present only active signals, to confirm the capability of the system to offer excellent sensitivity, passive measurement of impulse responses of metallic plates and pipes under different sources of elastic noise will be shown later.

PRINCIPLE OF EDGE FILTERING

Fiber Bragg Gratings are the result of local variations of the refractive index of the core of a singlemode optical fiber, leading to the reflection of light in a narrow-band, around a center wavelength, the so-called Bragg wavelength λ_B. More precisely, for the simplest FBGs, *i.e.*: with Λ-periodic variations of this refractive index, λ_B is given by the Bragg relationship:

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

where n_{eff} is the effective refractive index of the waveguide, and Λ is the grating pitch. The ultrasonic measurement principle can easily be understood from (1): an incident wave will induce a change in the grating pitch Λ, leading to a shift $\delta\lambda_B$ of the Bragg wavelength. It is however possible to lock a narrower light source, such as a laser, on one edge of this peak, and in particular around its half maximum. The light source must be of constant power, so that when the edge of the peak shifts due to the elastic waves, the reflected power varies proportionally, the spectrum being quite linear around its half maximum (Figure 1). A photodiode is then used to convert the optical power into a voltage, which can then be digitalized at a convenient sampling rate using an Analog-to-Digital Converter.

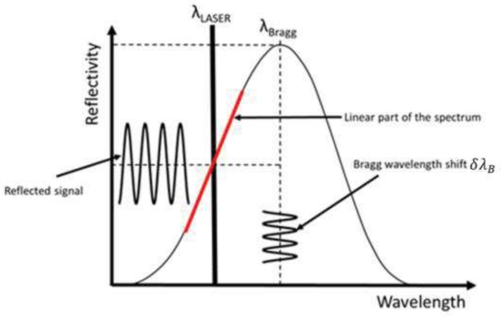

Figure 1. Principle of edge filtering

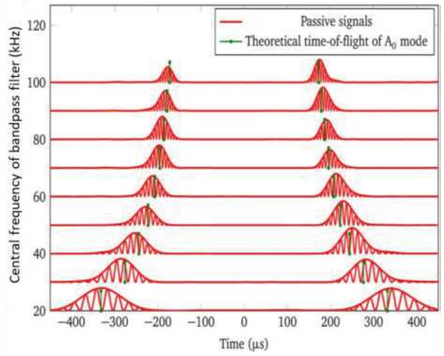

Figure 2. Cross-correlation of ambient noise generated by compressed air jet sprayed at the surface of an aluminum plate measured by 2 FBG transducers spaced 40 cm apart from each other. Filtering the impulse response at different center frequencies allows identifying the propagation of A0 mode between the two sensors [3].

Figure 2 illustrates typical passive (*i.e.* ambient elastic noise correlation) signals obtained on an aluminum plate with this approach with a first optoelectronic setup developed a few years ago [3]. The work presented aims to improve the sensitivity of the initial setup (ambient elastic noise is in general an order of magnitude below active signals), and, more important, to keep this sensitivity at an acceptable level under Environmental and Operational Conditions that may result in important shifts of the Bragg wavelength λ_B, which takes the laser out of the quasi-linearity zone of the FBG.

ULTRASONIC MEASUREMENTS USING FIBER BRAGG GRATINGS UNDER DYNAMIC ENVIRONMENTAL CONDITIONS

The principle of edge filtering was successfully used in many laboratory applications until now [4-6]. However, as mentioned above, FBGs are also sensitive to many EOCs such as temperature or strain changes. More specifically, the changes of the Bragg wavelength with respect of EOC are given by the following relationship [7]:

$$\frac{d\lambda_B}{\lambda_B} = (\kappa_T + \kappa_\varepsilon \Delta\alpha)dT + \kappa_\varepsilon d\varepsilon_{struct} \qquad (2)$$

where κ_T and κ_ε are respectively the sensitivities to temperature and longitudinal strain of the FBG, $\Delta\alpha$ is the difference in thermal expansion coefficients between the optical fiber and the host structure, and $d\varepsilon_{struct}$ is the mechanical strain variation component of the host structure in the orientation of the FBG transducer.

From (2), variations in EOCs lead to wavelength shifts in the position of the peak, resulting in a loss of sensitivity of the system as the peak drifts away from the laser wavelength, up to a null sensitivity for important EOC changes if the laser wavelength, supposed to be locked on one edge of the FBG spectrum, is not corrected.

The variations in EOCs are supposed to occur at lower frequencies than the ultrasonic frequencies. In edge filtering, ultrasonic waves are measured through small oscillations of the output voltage around a constant value, which is directly linked to the setting point, that is the relative position of the laser wavelength to the FBG wavelength. This setting point can hence be tracked through the control of the DC output of the photodiode.

More precisely, a DFB (Distributed FeedBack) laser source is used in this application: its emitting wavelength can be tuned through a thermal effect with a Peltier device controlled by a PI control loop on the output DC component.

EXPERIMENTAL VALIDATIONS

The setup was tested during a 4-points bending test. The two bottom external supports are 22 cm apart while the two top internal supports are 16 cm apart. A Fiber Bragg Grating was glued at the center, on the bottom surface of a flat composite sample. During the test, the maximum vertical displacement of the two center points was set at 32 mm, leading to a Bragg wavelength shift slightly smaller than 1 nm. The displacement speed varied between 0.5 mm/min and 7 mm/min, with a 0.5 mm/min increase between each step. By doing so, the capacity of the system to stay tuned under increasing strain rates could be tested. A 10 mm diameter piezoelectric transducer was coupled using shear gel at one end of the plate to act as an actuator. It is actuated using a low frequency generator, which emits a 5 cycles Hann burst of center frequency 40 kHz and amplitude 10 Vpp, with a burst period of 100 ms to enable several acquisitions during the bending test. An analog first order band-pass filter between 10 kHz and 300 kHz is also used in reception to limit noise outside the ultrasonic frequencies. A reference FBG, on another optical fiber, was also glued alongside the first FBG, to get an image of the sample deformation.

The optoelectronic system was set so that the maximum output voltage of the photodiode was 10 V, inducing an optimum setting point at 5 V. The area without tuning is set empirically between 4 V and 6 V. During the experiment, the DC voltage V_{DFB} is acquired as our tuning parameter. The wavelength of the reference FBG λ_{ref} is measured using a Micron-Optics™ Si255 monitoring system. The corresponding data are plotted in Figure 3.

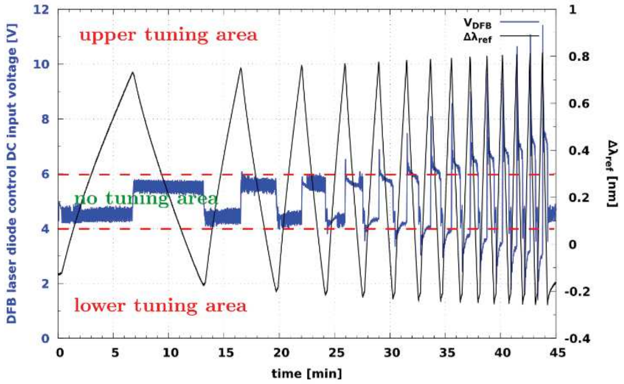

Figure 3. Evolution during the 4-points bending test of the DFB laser diode control DC input voltage $\boldsymbol{V_{DFB}}$ and the wavelength shift $\boldsymbol{\Delta\lambda_{ref}}$ of a control FBG transducer glued on the flat composite sample.

In Figure 3, the control FBG gives an image of the endured deformation by the flat sample at increasing speeds, its variations being in the prescribed range. We can see that the DC voltage remains between the prescribed boundaries for the first steps, with small corrections occurring continuously to adjust in real-time the DFB laser wavelength. As the speed increases, an overshoot appears as the solicitation direction changes: as our system is based on a thermal effect, it presents some inertia, leading to the system still shifting the laser source in a direction while the solicitation already goes in the opposite. Note however that this overshoot is mainly due to the selected solicitation shape, and may not be representative of field applications. The system is then able to go back into the “no tuning area”. For fastest solicitations, the system is not able anymore to compensate, resulting in a DC voltage that remains most of the time within the tuning areas.

From this test, we estimate that the tracking has been performed without any sensitivity degradation up to a strain rate of 17 (μm/m)/s for the sample under test. Ultrasonic signals were acquired to assess the good quality of the data. Examples of such signals are plotted in Figure 4.

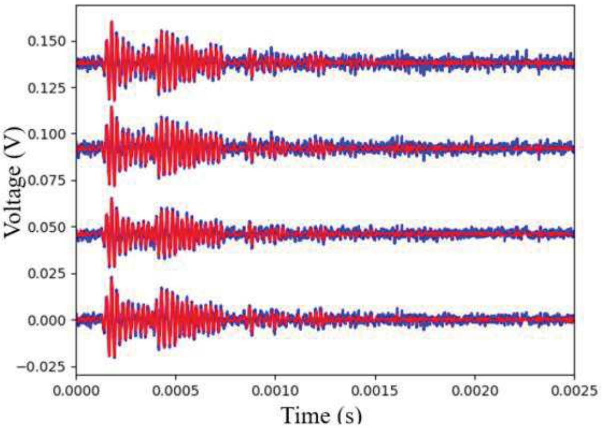

Figure 4. Acquired ultrasonic signals during the 4-points bending test. Each line is an acquisition at a different instant, the top one being without dynamic loading. Blue: raw signal. Red: band-pass filtered signal.

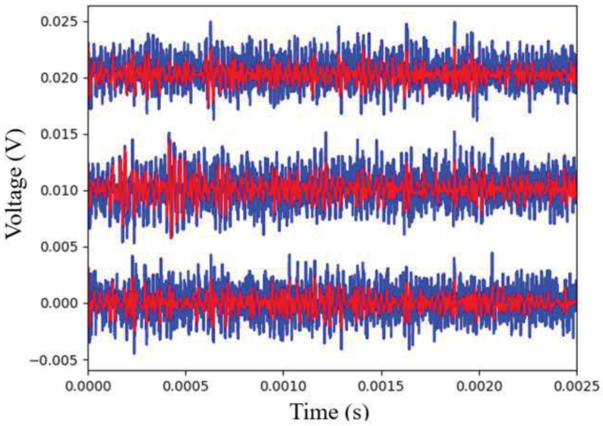

Figure 5. Residual signals using the data acquired in the static case as a reference. Each line is an acquisition at a different time, the top one being without dynamic loading. Blue: raw signal. Red: band-pass filtered signal.

In this figure, each line corresponds to a signal acquired during the test, at different times, the top one being acquired in static conditions as a reference. Raw data are plotted in blue, and numerically filtered data around the center frequency are plotted in red. Note that in this figure and for the remaining of the section, the data are not normalized, so that the amplitudes can be compared between figures. No qualitative difference can be observed between signals, with a good signal to noise ratio even though no averaging was performed. We then computed the residual signals between each acquisition and the reference one, acquired in static conditions. The corresponding signals are plotted in Figure 5.

The order of magnitude of the residuals is close to 10% of the magnitude of the original signals, with no clear evolution versus time: this shows that the residuals result mainly from measurement noise. These results demonstrate the excellent sensitivity of the setup and capability of the system to operate under Environmental and Operational varying Conditions.

CONCLUSION AND PERSPECTIVES

This paper described the approach recently developed at CEA to capture ultrasonic guided elastic waves using Fiber Bragg Gratings (FBG) in optical fiber with excellent sensitivity, under Environmental and Operational Conditions (EOC). The variations in EOCs are supposed to occur at lower frequencies than the ultrasonic frequencies, which is a reasonable assumption in most of the situations. The system uses a DFB (Distributed FeedBack) laser source whose emitting wavelength is tuned through a thermal effect with a Peltier device. The Peltier device is controlled by a PI control loop in order to track the setting point, on the edge of the FBG. The setup has been tested during a 4-points bending test in order to demonstrate the capacity of the system to stay tuned under increasing strain rates. It has been estimated that the tracking has been successful without any sensitivity degradation up to a strain rate of 17 (µm/m)/s for the sample under test.

The next step of the study will consist using this setup to perform passive acquisitions of elastic waves through the measurement of ambient noise on structures (pipes and plate-like structures) in operation. The ultimate aim is to offer a dense multiplexing of FBG deployed on/within the structure in order to be later combined with guided waves imaging algorithms able to detect and to characterize defects as described in [8-9]. This approach will combine the low intrusiveness of optical fibers with the fine diagnosis capability allowed by guided waves.

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