



**HAL**  
open science

# Ultrasonic guided wave monitoring of composite structure: impact detection and localization with Fiber Bragg Grating sensors

Guillemette Ribay, Rudy Desmarchelier, Nicolas Roussel, Arnaud Recoquillay, Guillaume Laffont, Oscar d'Almeida

## ► To cite this version:

Guillemette Ribay, Rudy Desmarchelier, Nicolas Roussel, Arnaud Recoquillay, Guillaume Laffont, et al.. Ultrasonic guided wave monitoring of composite structure: impact detection and localization with Fiber Bragg Grating sensors. OFS 2023 -28th International Conference on Optical Fiber Sensors, Nov 2023, Hamamatsu, Japan. paper Th6-95, 10.1364/OFS.2023.Th6.95 . cea-04790053

**HAL Id: cea-04790053**

**<https://cea.hal.science/cea-04790053v1>**

Submitted on 19 Nov 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Ultrasonic guided wave monitoring of composite structure: impact detection and localization with Fiber Bragg Grating sensors

Guillemette Ribay[1], Rudy Desmarchelier[1], Nicolas Roussel[1], Arnaud Recoquillay[1], Guillaume Laffont[1], Oscar d'Almeida[2]

*1 Université Paris-Saclay, CEA, List, F-91120, Palaiseau, France,  
2 Safran Tech, Rue des Jeunes Bois, Châteaufort, 78114 Magny-Les-Hameaux, France  
Author e-mail address: guillemette.ribay@cea.fr*

**Abstract:** Fiber Bragg Grating sensors record the ultrasonic signature of impacts on aeronautic composite structures. Experiments with 4 FBG sensors show proper localization of impacts with around 1cm precision using an algorithm based on time of arrivals of guided waves.

## 1. Introduction

Aeronautical equipment are subjected to numerous stresses throughout their lifetime, in particular via impacts. While high energy impacts induce damages that are easy to detect, low energy impacts may result in undetectable precursor damage that reduces the component strength in the long term [1]. Impact monitoring is thus of great interest. This paper focuses on the monitoring of these impacts, particularly on composite parts of aircraft, using the vibrations created by an impact to retrieve its location with a precision of the order of a centimeter. Fiber Bragg grating (FBG) sensors can be used to measure ultrasonic elastic waves [2]. Their low weight and good embedding in composite material makes them a viable solution for in-flight monitoring. In this study, a curved carbon fiber composite panel with a thickness ranging from 2 to 12 mm is monitored with surface-glued FBG sensors. The properties of ultrasonic waves generated by an impact in such a structure depend on frequency, local thickness and propagation direction (anisotropy of composite). A suitable localization algorithm is first determined. The choice of an interrogation system is established by taking into account the constraints imposed by the physics of waves in our material. Impact localization experiments were then carried out with four FBGs using an interrogation system based on the edge filtering technique.

## 2. Impact monitoring via ultrasonic guided waves

### 2.1. Impact localization algorithm

Various strategies can be found in the literature for source localization, with applications as various as impact localization on industrial components or finger localization on tactile interfaces. Post-processing of measured acoustic or ultrasonic signatures usually include time-of-flight extraction or correlation with a reference database of signals [3]. Among time-of-flight based algorithms, triangulation is the simplest solution with low numerical cost. However, anisotropic materials or dispersion, such as for guided waves in plate-like structures (as in this study), cause a complex relationship between the energy velocity, the frequency and the incidence angle, to which triangulation techniques are not robust [4]. As for algorithms based on correlation with reference data sets, they are not adapted to structural health monitoring. Indeed, while they may be robust to the varying nature of impact (soft or solid) or to varying temperature [3,5], they are sensitive to the variations of boundary conditions of the component during service. Other strategies are based on the extraction of amplitude or energy of signals together with advanced post processing tools after calibration (see for instance [6]). Localization is then possible using FBG sensors sensing waves at acoustic frequencies. However, the characteristics of the measured signals depend on the boundary conditions when the incident and reflected wave packets are likely to overlap in time; the calibration would have to be carried out directly on the part in its real environment, which is not always possible.

In this paper, we chose instead a different time-of-flight-based algorithm called grid search [7]. It consists in defining a grid of points (pixels) at which a cost function is estimated; the estimated point of impact corresponds to the minimum of this cost function. Let  $x_0$  be a point in the grid ;  $t_i$  the time of flight extracted from signal measured by sensor  $i$  ;  $x_i$  the position of sensor  $i$ ,  $v_g$  the energy velocity in the component, and  $d_{x_i, x_0}$  the distance between sensor  $i$  and  $x_0$ .

For each receiver  $i$ , if an impact occurred at point  $x_0$ ,  $d_{x_i, x_0} = v_g(t_i - t_0)$  ( $t_0$  being the unknown time of impact). Consequently, for a pair of receivers  $i, j$ ,  $\{v_g(t_i - t_j) - (d_{x_i, x_0} - d_{x_j, x_0})\}$  would be zero. The chosen cost function for  $N_s$  sensors is then defined as:

$$E(x_0) = \sum_{i=1}^{N_s-1} \sum_{j=i+1}^{N_s} \{v_g(t_i - t_j) - (d_{x_i, x_0} - d_{x_j, x_0})\}^2 \quad (1)$$

## 2.2. Choice of FBG interrogation system

First experiments were performed using a commercially available interrogator system AeroGator (PhotonFirst), with which acoustic signals can be sampled up to 19.23 kHz. Acoustic signals below approximately 10 kHz can thus be retrieved. Various impacts on a composite panel were detected. The system was also found robust to typical noise created by in-flight conditions.

However, with time-of-flight-based algorithm, localization precision depends on the typical wavelength of ultrasonic guided waves propagating in the component. As shown in Table 1, in our composite panel, wavelengths vary with the wave propagation direction due to anisotropy, as well as with the local thickness of the panel. At low frequencies (1 to 10 kHz), the wavelength is about ten centimeters. Hence, the precision will be of this order, which is not sufficient in our case.

	1 kHz	10 kHz	20 kHz	50 kHz
<i>wavelength</i>	170 to 400 mm	52 to 111 mm	36 to 66 mm	18 to 32 mm
<i>group velocity</i>	338 to 774 m/s	986 to 1705 m/s	1270 to 1800 m/s	1585 to 1800 m/s

Table 1: Maximum and minimum value of wavelength and group velocity at different frequencies in our composite panel (depending on local thickness and wave propagation direction).

Experiments with the Aerogator (not shown here) confirmed the need for high frequency monitoring of FBG reflected peak, as ultrasound of at least 20 kHz are necessary to achieve centimeter-like localization.

The achievable localization precision at frequencies higher than 20 kHz was checked on non-noisy signals simulated using CIVA software [8] in a simplified configuration (where the well-known directivity of FBG was not taken into account). The simulations also allowed the determination of proper sensor positions to avoid boundary effects and limit the influence of varying group velocity in the structure on the localization efficiency.

## 3. Experiments with FBGs on a composite panel

Experiments were then performed on carbon-fiber composite panel; the experimental set-up is shown in figure 1. Four FBG sensors were attached to the panel. Each FBG is illuminated by a dedicated external cavity wavelength tunable laser source (OSICS TLS-AG, EXFO). An optical circulator leads each laser light to its corresponding sensing FBG and the reflected light to a photodiode. The resulting electric signal is then high-pass filtered. Additional high pass filtering is performed on each channel by a preamplifier (Stanford Research Systems, reference SR560) to get rid of the very low frequency component of impact signature, which would overload the acquisition system and prevent us from getting the high frequency components enabling a precise localization. For a given Bragg peak wavelength, the emitted lasing wavelength is adjusted to the midpoint of one edge of the Bragg peak. Any shift of the Bragg wavelength will modulate the transmitted/reflected optical power. This demodulation scheme is commonly referred to as "edge filtering" technique [9] and is illustrated in figure 1. In our experiment, FBG reflected optical power is thus recorded. The Bragg Grating length was chosen between 10 and 14mm. Sensors are attached close to the panel borders (see orange crosses in figure 3), and tilted by 45° (thus with maximum sensitivity to impacts located in the center of the rectangle drawn by the four FBG sensors). Signals are digitized by a four-channel Lecroy oscilloscope at a sampling rate of 500 kHz.

With this set-up, ultrasonic wave signals are digitized with the sampling frequency of the oscilloscope (here 500 kHz). Before each experiment, the lasing wavelength is tuned as described above, to avoid any drift due to possible temperature fluctuations. Impacts are performed on various places on the composite panel, either by pencil-lead break

or with a 1cm diameter steel ball. The spectrum of typical recorded ultrasonic signals (figure 2) contains information at ultrasonic frequencies above noise level until at least 50 kHz. For optimal time-of-flight extraction of the first wave packet, signals are then de-noised using wavelet transform and lastly fed into the grid search algorithm. The mean group velocity at the central frequency was used in equation (1). As shown in figure 3, the impact positions are retrieved with a precision of around 1cm.

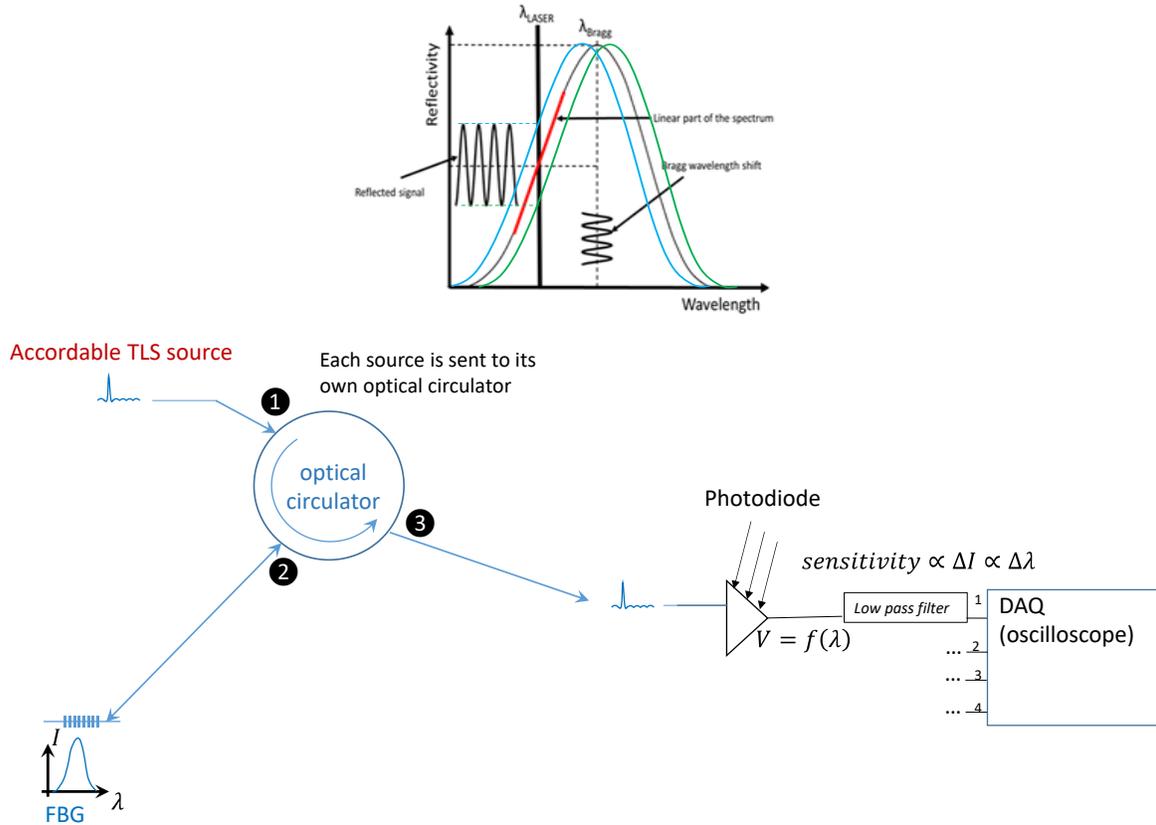


Figure 1: Experimental set-up for Fiber Bragg Grating sensor measurements of ultrasonic guided waves.

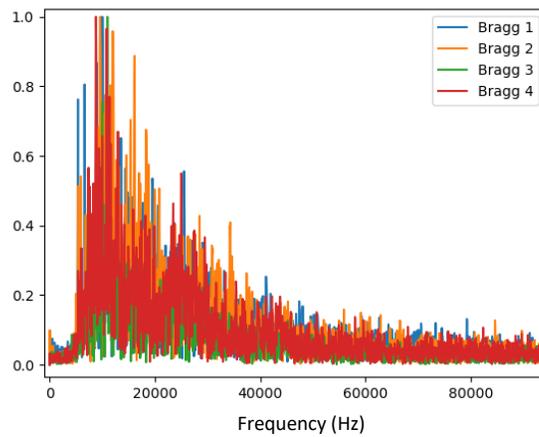


Figure 1: Modulus of Fast Fourier Transform of recorded ultrasonic signals

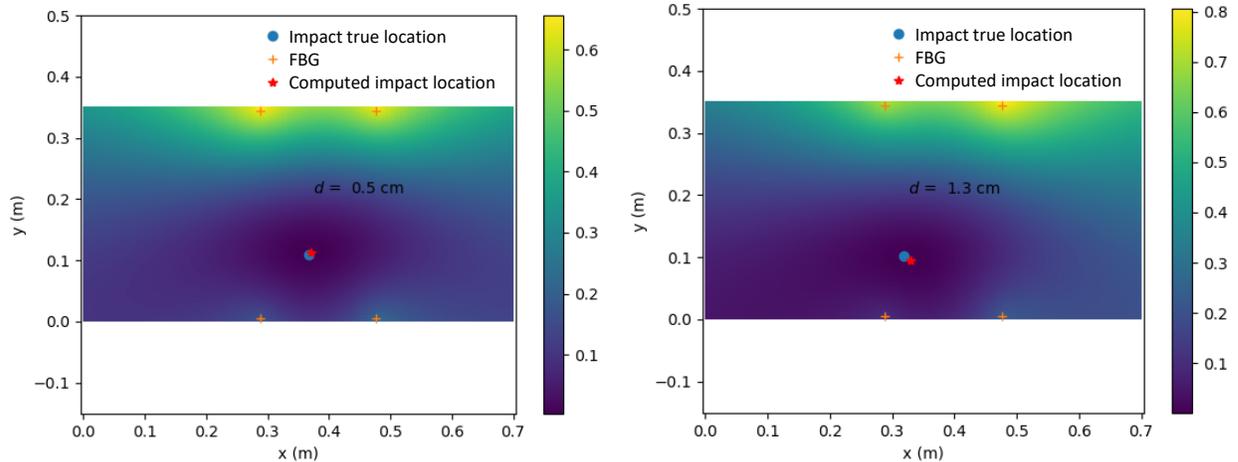


Figure 3: Localization of pencil-lead breaks at two different impact locations on a 70cmx35cm composite panel.

#### 4. Conclusion

In this paper, impacts on a composite panel were monitored using FBG sensors. Detection of impacts is efficient with Bragg reflected peak tracking (using Aerogator) able to retrieve vibrations at acoustic frequencies (<10 kHz). Interrogation with edge-filtering technique was used to extract high frequency signature of impacts (above 20 kHz). Simulations with CIVA software helped design the experiment (sensor locations, identification of some influential parameters) and validate the localization algorithm in our specific component. Pencil lead breaks and steel ball impacts were localized with a precision of around 1cm (around half the wavelength of the ultrasonic guided wave in this composite panel).

Future works will focus on the determination of the influence of FBG orientation using both simulations taking into account FBG directivity and further experiments will be carried out.

#### 5. Acknowledgements

Research presented in this paper was partially funded by Safran-Tech.

#### 6. References

- [1] A. Güemes, et al. "Structural health monitoring for advanced composite structures: a review." *J. Compos. Sci.* 2020, 4(1), 13.
- [2] A. Recoquillay, T. Druet, S. Nehr, M. Horpin, O. Mesnil, et al.. "Guided wave imaging of composite plates using passive acquisitions by fiber Bragg gratings". *J. Acoust. Soc. Am.*, 2020, 147 (5), pp.3565-3574.
- [3] R. K. Ing, N. Quieffin, S. Catheline, M. Fink; "In solid localization of finger impacts using acoustic time-reversal process". *Appl. Phys. Lett.* 14 November 2005; 87 (20): 204104. <https://doi.org/10.1063/1.2130720>
- [4] T. Kundu, S. Das, Kumar V. Jata; "Point of impact prediction in isotropic and anisotropic plates from the acoustic emission data". *J Acoust Soc Am* 1 October 2007; 122 (4): 2057–2066. <https://doi.org/10.1121/1.2775322>
- [5] G. Ribay, S. Catheline, D. Clorennec, R. Kiri Ing, N. Quieffin and M. Fink, "Acoustic impact localization in plates: properties and stability to temperature variation," in *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 54, no. 2, pp. 378-385, February 2007, doi: 10.1109/TUFFC.2007.251.
- [6] J. Yu, D. Liang, X. Gong, X. Song, "Impact localization for composite plate based on detrended fluctuation analysis and centroid localization algorithm using FBG sensors", *Optik* 167 (2018) 25–36
- [7] T. Kundu, S. Das, S.A. Martin, K.V. Jata, "Locating point of impact in anisotropic fiber reinforced composite plates", *Ultrasonics*, 48 (3) (2008)
- [8] O. Mesnil, A. Recoquillay, T. Druet, V. Serey, H.T. Hoang, A. Imperiale, and E. Demaldent, "Experimental Validation of Transient Spectral Finite Element Simulation Tools Dedicated to Guided Wave-Based Structural Health Monitoring." *ASME. ASME J Nondestructive Evaluation*. November 2021; 4(4): 041003. <https://doi.org/10.1115/1.4050708>
- [9] S. M. Melle, K. Liu, and R. Measures, "A passive wave length demodulation system for guided-wave bragg grating sensors," *IEEE Photonics Technology Letters* 4(5), 516–518, (1992).