High-Velocity Impact Detection and Localization Enabled by 10 MSa/s Sample-Rate FBG Interrogation

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ABSTRACT

Real-time structural health monitoring (SHM) systems for airborne structures can help detect and predict damage to critical components. This study demonstrates a system for real-time detection and evaluation of high-velocity foreign object impacts on composite structures using fiber Bragg gratings (FBGs). A set of fiber Bragg gratings were applied to a composite helicopter blade, and by using high-speed and wide frequency-band FBG interrogation, we demonstrate object impact detection made by projectiles of various materials and weights, with speeds from 100 m/s up to 200 m/s and their respective elastic wave propagation along the blade. Early impact damage detection has the potential to reduce the chance of critical failure and decrease aircraft downtime caused by rigorous and time-consuming non-destructive inspections.

INTRODUCTION

SHM is a critical field in aerospace engineering that focuses on detecting and diagnosing damage in structural components. For helicopters, SHM has become increasingly important. Critical components like helicopter blades are susceptible to damage over time. In addition to fatigue and wear, helicopter blades can also be damaged by impacts from hail, stones, birds, and other objects. These impacts can cause dents and cracks, sometimes invisible to the naked eye, leading to severe damage and safety concerns if undetected. SHM systems that use embedded sensors can detect damage to helicopter blades caused by impacts and other factors, allowing maintenance personnel to perform preemptive maintenance and prevent critical failure.

Implementing SHM systems on helicopter rotor blades for continuous monitoring can reduce maintenance costs and downtime, improve safety and performance, and enhance the design and operation of helicopters. However, the development and implementation of SHM systems for helicopter blades also present significant challenges, including sensor placement, data analysis, and system integration [1].

Fiber Bragg gratings (FBGs) are optical sensors that have become increasingly popular in the field of SHM [2]. An FBG is a periodic modulation of the refractive index along the length of an optical fiber, which creates a wavelength-

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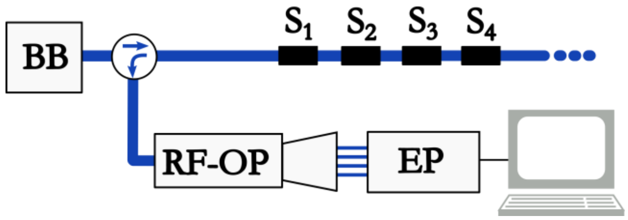

Figure 1. PerCiv FBG interrogator schematic. BB - broadband light source, RF-OP - RFphotonic stage, EP - electronic processing.

selective reflection band. The center wavelength of the FBG can be defined as

$$\lambda_B = 2n_e\Lambda, \tag{1}$$

where n_e is the effective refractive index of the grating in the fiber core and Λ is the grating period. When the FBG is experiencing strain, the period Λ of the refractive index modulation changes, therefore λ_B also experiences a shift [3]. When a light signal is transmitted through the fiber, the change in the reflected wavelengths of light can provide information about the changes in strain or temperature that the FBG experiences. The wavelength shift can be defined as

$$\frac{\Delta\lambda_B}{\lambda_B} = (1-\rho_e)\varepsilon, \tag{1}$$

where ε is the longitudinal strain and ρ_e the photoelastic coefficient of the fiber core material. For an FBG in the 1550 nm wavelength region using a standard SMF fiber, sensitivity to strain is 1.2 pm/$\mu\varepsilon$ [3].

FBG sensors have been gaining increasing interest in manifold applications and various fields [3–6]. They are immune to electromagnetic interference, minuscule, lightweight, not susceptible to corrosion, and can operate in harsh environments [3], which makes them ideal for embedding directly into composite or metal structures. For these reasons, they are particularly interesting for SHM applications because they offer several advantages over traditional sensors. FBGs can also be used to monitor various parameters such as strain, temperature, vibrations, humidity [7], and pressure. In particular, FBGs are used to measure strain in composite materials, which are increasingly used in aerospace and other industries due to their high strength-to-weight ratio. FBG sensors can therefore be used for monitoring critical structural components, such as aircraft wings, wind turbine blades, and bridges. Composite materials in particular suffer from cracks and delamination of composite layers, which, if detected preemptively, can prevent structural failure.

In this study, FBG sensors were used for SHM in composite helicopter blades. By using PerCiv's FBG interrogation system's ability to simultaneously sample several FBG sensors at 10 MSa/s, we show the effects of impacts of projectiles at speeds ranging between 100 and 200 m/s. High-speed sampling not only allows detection of high-speed impacts and recovery of most of the information about the impact's strength but also a 100 ns time resolution, which permits easy differentiation

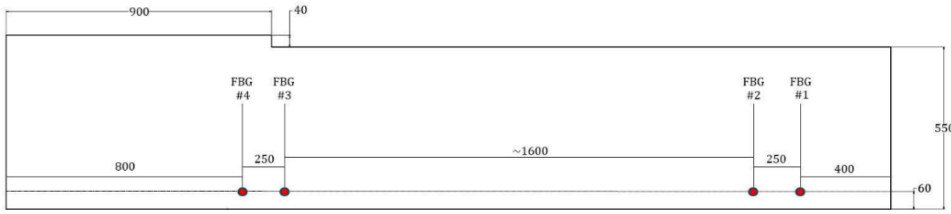

Figure 2. FBG sensor placement on the blade section. Measurements are in mm.

between sensors. This high-speed resolution enables precise tracking of elastic wave propagation along the blade following an impact.

EXPERIMENTAL SETUP

The experimental setup for this study was based on the PerCiv FBG interrogator. The working principle has been described in detail in ref. [8]. A schematic of the interrogator is presented in fig. 1. It features a broadband light source (BB) that illuminates all the sensors simultaneously and routes the back-reflected light into the RF photonic processing (RF-OP) stage, where the wavelength information is converted to RF phase-shift. Each sensor is detected by its respective photodiode, which converts the optical signal to an electrical one. The phase-shift information is extracted, filtered, and transferred to a computer for further analysis. The interrogator is a robust, solid-state solution with no moving parts. The use of broadband light permits sampling the sensors at very high speeds, limited by the system's analog-to-digital converters at 100 MSa/s, and further curtailed by the communication protocol to 10 MSa/s for the experiments described herein. The interrogator configuration has the potential for significant miniaturization to further be used as an on-board continuous monitoring device.

To test an application for high-speed FBG interrogation for composite structures, four FBG sensors were installed on the upper skin of a 3-meter-long section of a helicopter's main rotor blade. The placement of the FBG sensors on the blade section is depicted in fig. 2.

Two sets of FBG sensors were placed along the blade, at the beginning of the blade section, and towards its end. The distance between the FBGs in each set was 250mm, while the distance between the two sets was 1600mm. The FBGs had a length of 5mm, FWHM of 0.5 nm, and were coated in polyimide. The test was conducted in a certified ballistic lab. Fig. 3 shows the chosen projectiles for the impact detection test, which were 7g steel balls, 2.54g silicon carbide balls, and compacted stone pellets weighing approx. 2.5g.

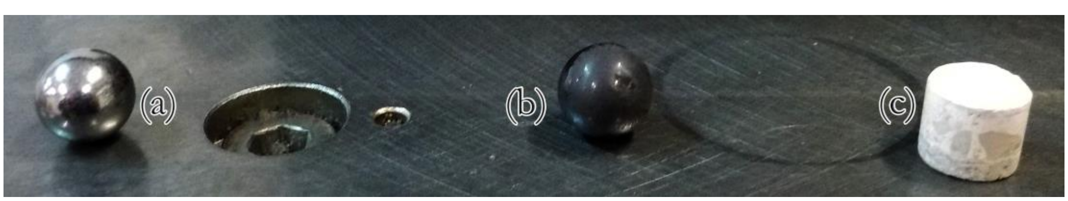

Figure 3. Projectiles: (a) 7g steel ball, (b) 2.54g silicon carbide ball, and (c) 2.5g. stone pellet.

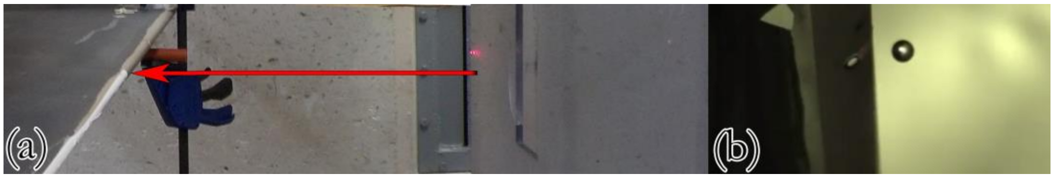

Figure 4. (a) wing placement relative to the cannon (marked by red arrow), (b) high-speed camera shot of the projectile in flight.

The blade was set with the leading edge towards the firing cannon (fig. 4) since this is the susceptible area for potential high-speed impacts. The projectiles were fired with a calibrated gas cannon. The projectile speed was measured by a high-speed camera that was placed close to the impact location.

RESULTS AND DISCUSSION

During one of the experiments, the third FBG sensor was dislodged from the blade, which led to oscillations at that sensor. Therefore, the results of experiments do not show this sensor on the graphs so only sensors one, two, and four will be presented. The highest projectile speed achieved for the 2.95g silicon carbide ball impact was 193.6 m/s, and the measurement of the resulting impact is presented in fig. 5 as

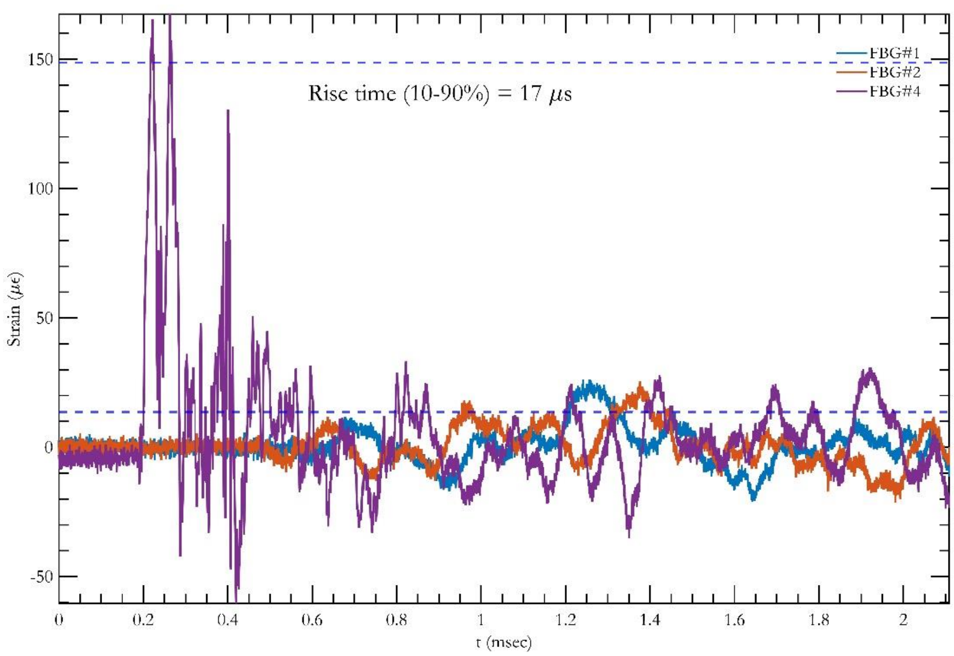

Figure 5. Impact measurement for the 2.95g silicon carbide ball projectile at 193.6 m/s. Dashed blue line - 10-90% rise time of the impulse.

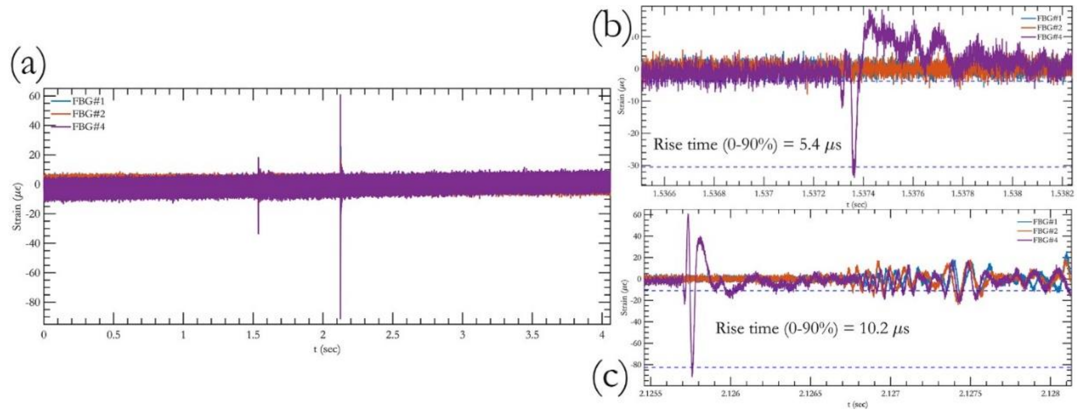

Figure 6. Double impact by debris and silicon carbide projectile. (a) 6 second measurement, (b) zoom-in on the first impact, (c) zoom-in on the second impact.

recorded μstrain vs. time. The blue dashed lines mark the 10-90% rise time of an impulse, on which we are basing our calculations. To detect, and thereafter accurately measure the rise time and recover most of the impulse amplitude we are assuming at least 5 samples per rising edge, therefore, for this event, a sampling speed of, at least, 294 kSa/s is required to fully define the impact severity.

These measurements present a case where the strain due to impact was both fast and high. The higher the strain, the longer the rise time, which lowers the required sampling speed. Another example where high sampling speed is crucial is for lower strain impact detection, where the impact might have been enough to cause damage, yet weak and fast enough to remain undetected by slower systems. An example of this situation is presented in fig. 6, where the blade experiences two impacts - the first one is relatively weak, most likely due to debris from a previous experiment firing together with the new projectile, followed by a stronger impact by the main projectile. The recorded speed of the main projectile was 149 m/s. To capture and accurately characterize the first impact that produced a weaker strain, which had a rise time of only $5.4\ \mu s$, a sampling speed of at least 925 kSa/s is required. The second, stronger impact still requires a minimum of 490 kSa/s for accurate representation.

CONCLUSION

PerCiv's high-speed FBG interrogation system demonstrated in this experiment pro- vides a powerful tool for fast impact detection for use in continuous SHM in composite helicopter blades. The system was able to detect strains of different magnitude, e.g. fast and weak events that would have been otherwise missed, or high energy impacts which require fast sampling to accurately represent the severity of the damage. These experiments show a clear advantage to sampling speeds upwards of 1 MSa/s.

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