# Structural Health Monitoring of Road Infrastructures Based on FBG Sensor Network


Maha Sliti
Communication Networks and Security Research Lab.
University of Carthage, Tunisia
Email: slitimaha@gmail.com

Noureddine Boudriga
University of Carthage
Email: noure.boudriga2@gmail.com



***Abstract*—We present an architecture for road vibration monitoring based on Fiber Bragg Grating (FBG) sensor interrogation. The deployed network of FBG sensors allows the estimation of fiber elongation and sensor displacement in the presence of an external factor like strain. The Brown Road Bridge is used as a real-world study case to examine the designed vibration monitoring architecture's performances. In our simulation, we use real fbg sensor displacement signals collected from sensors during an earthquake.**



*Keywords*: Vibration Monitoring, FBG displacement, Structure Health Monitoring.


## I. Introduction

Public roads are frequently seen as a structure that is exposed to daily vibration, strain, and temperature impacts. Underdesign of the road pavement might result in permanent deformation and even collapse of the road. Because road damage is not always visible, it is critical to discover the damage in its early phases of development. The structure health monitoring (SHM) concept is increasingly being used for the monitoring of civil infrastructures like roads, buildings, and bridges, in the objective to save money and offer longer-lasting infrastructure. Within the SHM framework, it is feasible to identify damage or particular parameters of interest, allowing to react before the occurrence of any major structural damage.

Nowadays, Fiber optical sensors are increasingly used in several applications including civil, mechanical, and aerospace domains [1], [2], [3], [4]. When compared to traditional electronic sensors [5], [6], [7], optical sensors offer various benefits such as multiplexing capabilities, resilience, ease of integration, compact size, and resistance to electromagnetic interference. Because of their numerous benefits, fiber Bragg gratings (FBGs) are widely used by several SHM applications in recent years. Indeed, FBG sensors allow to measure numerous physical and chemical characteristics in several industrial sectors, based on its great sensitivity to various factors such as strain and temperature.

In this research, We propose a vibration monitoring architecture based on FBG. To this end, sensors are deployed along the road in critical positions to detect mechanical damage, such as that caused by earthquakes or heavy traffic. Then, the deployed sensor arrays are interrogated by the transmission of series of optical pulses. The installed sensors respond by changing the reflected signals' wavelength in response to an external factor (strain, traffic load, etc) applied to the road. Based on the reflected signals, a data acquisition unit assesses sensors' displacements and fiber elongations in a particular road position. The performance of the provided vibration monitoring system is evaluated using a real-world case study, the Brown Road Bridge. Real displacement signals obtained by sensors during an earthquake are considered for simulation purposes.

The current research work contributions consist on the following:

- We use a real-world case study, the Brown Road Bridge, to evaluate the performance of the proposed vibration monitoring system. Real displacement signals measured by sensors during an earthquake are considered for simulation purposes.
- The presented vibration monitoring system allows for real-time vibration monitoring, which improves structural protection. This is accom-

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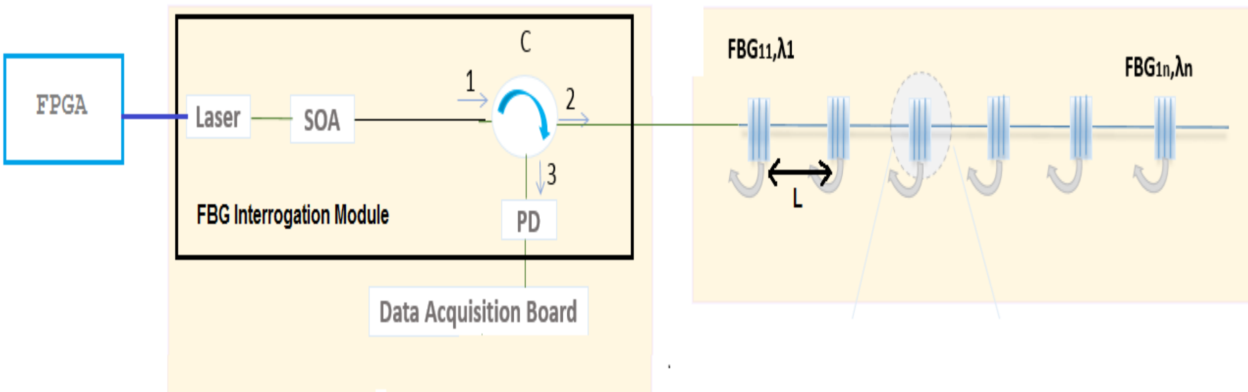



Figure 1: Proposed Vibration Monitoring System

plished by sending a series of laser pulses to the installed sensor arrays. The acquisition module computes the instant sensor displacement and average vibration using the reflected signals.

- The presented vibration measurement method makes advantage of the physical properties of the FBG, which change depending on the applied strain. When there is strain, the wavelength of the reflected signal changes. As a result, this wavelength shift is utilized to calculate fiber elongation, FBG displacement, and average vibration.

The paper is organized as follows. Section 2 studies the proposed architecture for vibration monitoring. Section 3 covers the proposed method for calculating sensor displacement. Section 4 presents the results of the simulations. Section 5 concludes the paper.

## II. Vibration Monitoring Architecture Based on FBG

Figure 1 illustrates the proposed FBG-based vibration monitoring architecture. We deploy one or more FBG arrays in this architecture. The sensor reflects the wavelength defined as $\lambda_B$ (Bragg wavelength), while emitting the remainder of the spectrum. A FBG is constructed of parallel semireflecting plates distant by $\Lambda$. The bragg wavelength $\lambda_B = 2n\Lambda$, where $n$ is the effective refractive index of the fiber core and $\Lambda$ corresponds to the grating period $L$ is the distance between two neighboring sensors in each sensor array. The number of deployed sensor arrays and the number of sensors in each array depends on the length and form of the controlled structure.

An FBG Interrogation unit, which consists of a light source (laser), an optical amplifier (SOA), and a circulator, interrogates the deployed sensor arrays. Therefore, the laser generates $n$ synchronized pulses with $n$ wavelengths. Each wavelength is associated with a sensor. The FPGA unit controls the pulse generator by setting the following parameters: $V_{max}$ (maximum structural vibration), $A_{max}$ (maximum displacement), and time slot. The pulse train will then be fed into the sensor array via the circulator.

The DAQ (Data acquisition unit) collects the reflected signals from the deployed sensors. The latter handles the correspondence between the received optical pulse and the relevant sensor. The pulse delay must not be longer than the time it takes for the next optical pulse to arrive. To that aim, the $n$ reflection wavelengths for FBG sensors must be selected correctly. The average vibration $V$ and amplitude $A$ (FBG displacement) will then be tracked over time by the analysis module. If these parameters reach certain levels, actions must be made to prevent structural damage.

## III. Calculation Method of Sensors' Displacement

This section describes a method for estimating fiber elongation and sensor displacements under strain. The reflected wavelength change indicates the FBG's reaction to strain. As a result, the effective refractive index and grating period of the FBG are altered. As a consequence, the signal wavelength shift may be used to quantify strain intensity as explained by Equation (1):

$$\frac{\Delta\lambda}{\lambda_B} = (1 - p_e) * \epsilon \tag{1}$$

where $\Delta\lambda$ represents the signal wavelength shift, $\lambda_B$ represents the bragg wavelength, $p_e$ indicates the strain-optic coefficient, and $\epsilon$ denotes the grating strain.

Therefore, the strain imparted to a sensor may be calculated using Equation(2) ([8]):

$$\epsilon_i = \frac{E_i}{L_i} \tag{2}$$

As seen in Figure 2, $E_i$ represents the total elongation of the fiber from source to sensor $i$, and $L_i$ represents the initial distance between the source and the sensor $i$.

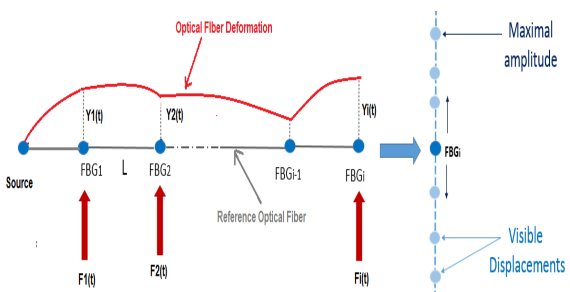



Figure 2: Fiber elongation

As previously indicated, signal wavelength shift is affected by external strain. As a result, using the signal wavelength shift, the DAQ module determines the strain experienced by a sensor. Then, the elongation $E_i$ experienced by the fiber is estimated. Because the direction of the external force and the fiber are perpendicular, the fiber deformation follows the direction of the force. Indeed, the displacement $y_i(t)$ of the sensor is given by the equations below.

$$y_1(t) = \sqrt{E_1^2 - L^2} \tag{3}$$

Whether the external force's strength rises, $y_i(t)$ is estimated as follows:

$$y_i(t) = y_{i-1}(t) + \sqrt{(E_{i+1} - E_i)^2 - L^2} \tag{4}$$

Whether the external force's strength decreases, $y_i(t)$ is estimated as follows:

$$y_i(t) = y_{i-1}(t) - \sqrt{(E_{i+1} - E_i)^2 - L^2} \tag{5}$$

For each sensor, a sequence of wavelength shifts are collected in observation instants. To approximate the real sensor displacement signal, the gathered displacements are interpolated (Figure 3). In order to anticipate probable structural damage, the predicted sensor displacement is utilized to determine the peak to peak sensor displacement, the elongation of the fiber, and the average vibration of the sensor.

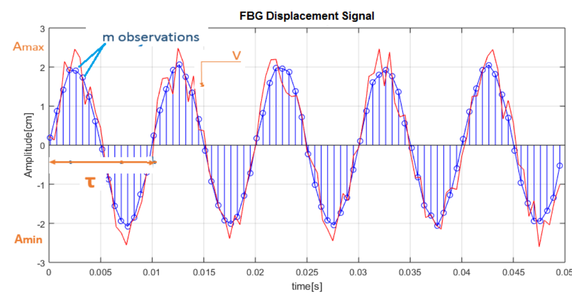


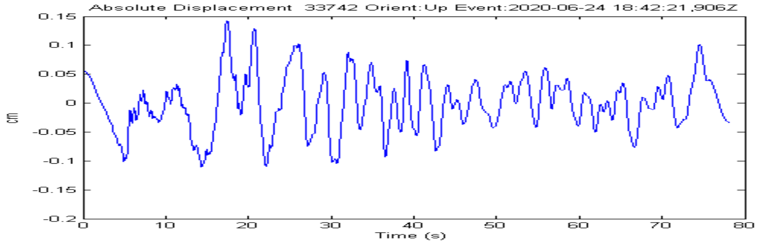

Figure 3: Observation scheme.

We emphasize that a slotted time is considered while calculating the sensor displacement $y_i(t)$ under the influence of external forces. The slot length is significant because it influences the observed sensor displacements. In fact, when the slot time is shortened, the number of observations increases. Moreover, the maximum sensor displacement is estimated more precisely.

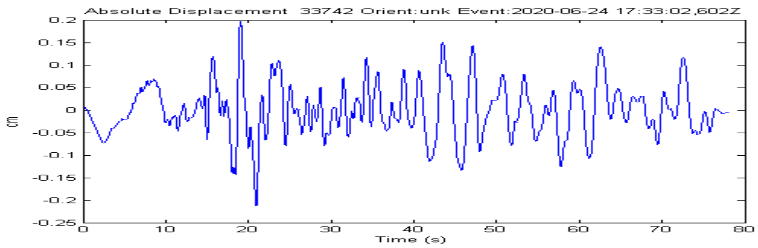
We compute the average period $\tau_{avg}$ by measuring a number of periods $\tau$ in the interpolated displacement signal across an observation time. The average vibration is then calculated, which equals: $1/\tau_{avg}$.

## IV. Simulation Results

This section assesses the proposed Vibration Monitoring System performances. To this purpose, we study the Brown Road Bridge (Figure 5) as a real case study. The 282-meter-long bridge was constructed in the early 1960s. It features four spans




(a)

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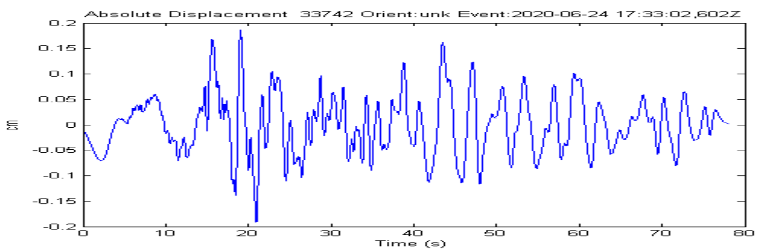


(c)

Figure 4: FBG Sensors Displacements.

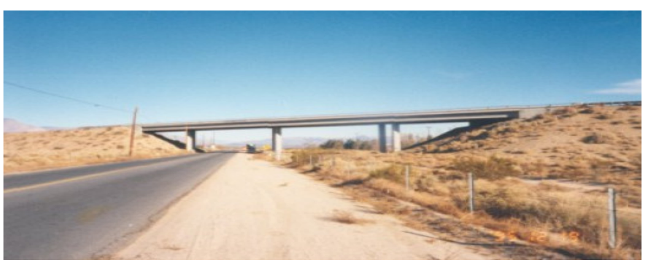

Figure 5: The Brown Road Bridge.

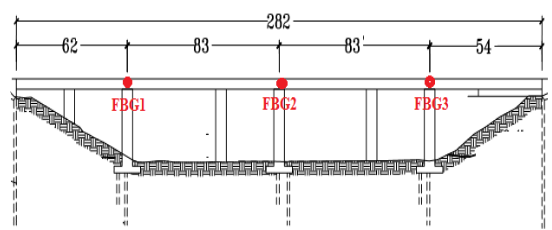


Figure 6: Deployed FBG sensor network on the Brown Road Bridge.

that range in length from 16.5 to 25.3 meters. Figure 6 displays the installation of a vibration monitoring system on the Brown Road Bridge.

The following values were utilized in the simulation:

- Number of deployed FBGs: 3.
- Inter-FBG distance $L$: 83m.
- Number of FBG arrays: 1.
- Minimal period: 0.02 seconds.
- Maximal vibration $V_{max}$: 1/0.02.
- Maximal amplitude $A_{max}$: 0.194 cm.

Furthermore, real displacement signals from the Brown Road Bridge during the 2020 SearlesValley earthquake are used. Figure 6 depicts the real sensors displacement signals acquired from sensor nodes mounted on the Brown Road Bridge. The $FBG_2$ sensor, which is located in the bridge's mid-span, has the maximum displacement amplitude of 0.12 cm. However, for the $FBG_1$ sensor (0.15 cm) and the $FBG_3$ sensor, the displacement amplitude decreases.

The estimated peak to peak displacement for the three sensors is shown in Figure 7. The difference between the largest and smallest displacement values over time is defined as the peak to peak displacement. As can be noticed, the mid-span sensor ($FBG2$) has the highest peak-to-peak displacement.

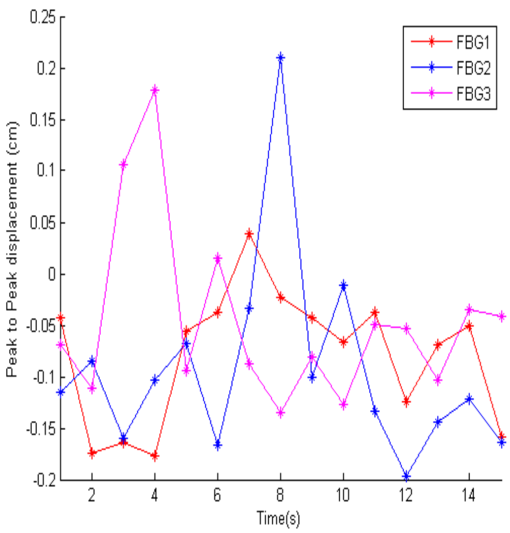


Figure 7: Peak to Peak sensor displacement.

Figures 8 and 9 show the estimated $FBG1$ displacements with $m$=4 and $m$=6, where $m$ is the number of observations. As we can notice, with $m$=6, we get a more reliable estimated displacement signal $y_i(t)$. Consequently, the amplitude estimation error is reduced if the observations' number $m$ during a period is increased.

Figure 10 shows the amplitude approximation error as a function of the number of observations $m$ per period $\tau$. To accomplish this, we calculate the area between the real and estimated extrapolated displacement signals. This is achieved with the matlab function trapz(X, Y), which uses trapezoidal integration to get the integral of Y in respect to X. As we can see, as the number of observations $m$ increases, the amplitude estimation error reduces considerably.

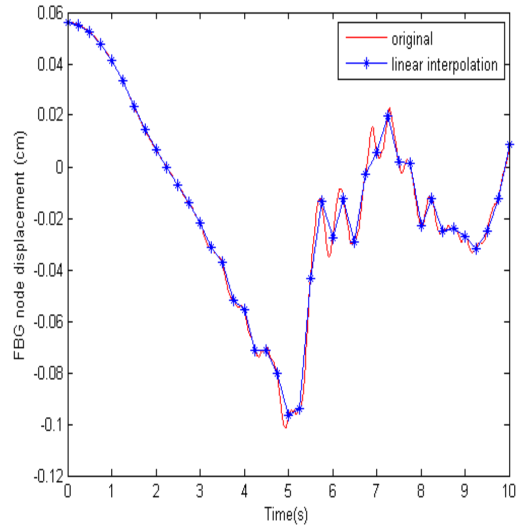


Figure 8: FBG1 Estimated Displacement signal (m=4).

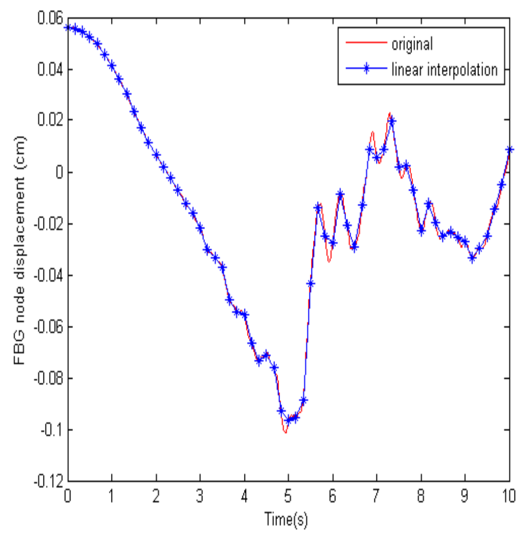


Figure 9: FBG1 Estimated Displacement signal (m=6).

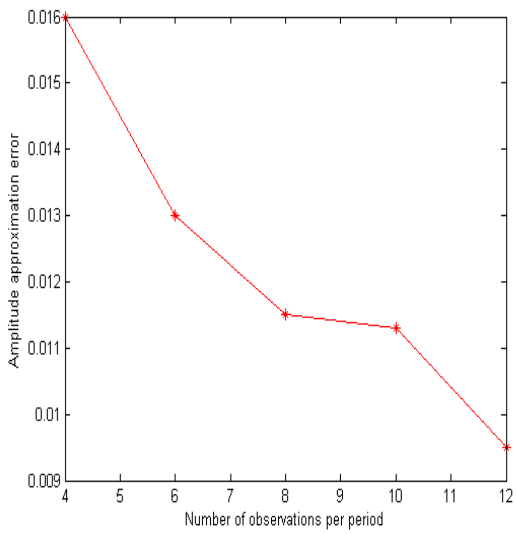


Figure 10: Amplitude approximation error.

## V. Conclusion

We discuss in this paper a vibration monitoring system based on FBG sensors that allows real-time vibration monitoring, which improves structural safety. We present a method for computing fiber elongation, sensor displacement, and average sensor vibration based on this design. The proposed vibration monitoring approach makes use of the physical FBG sensor characteristics, which change substantially depending on the applied external factors.

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