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Dynamic Monitorization of Structures with Optical Sensors

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ABSTRACT: Fiber optical sensors, namely Fiber Bragg gratings, are one the most promising technologies in several sensing systems. This sensing technology could be useful and cost effective in most civil engineering infrastructures. FBG sensors take advantage of the optical fiber properties, such us low transmission losses, immunity to electromagnetic interference, light weight and electrical isolation. But also, since the information is codified in the optical domain, they can be used in hostile environments, where electrical currents of electronic devices might pose a hazard. In this work we proposed the application of optical FBG based accelerometers to monitor two structures: a reinforced concrete building and a steel footbridge. The results show that optical monitoring schemes can be used in structural health monitorization of large structures, being a low cost solution. The two implemented acceleration systems, with different interrogation techniques allow to successfully obtaining the eigenfrequencies of structures with an error, when compared with the value obtained with a reference electronic accelerometer inferior to 0.80 %.

KEY WORDS: Structural health monitoring; optical sensors; fiber Bragg grating; accelerometer; eigenfrequencies.

1 INTRUDUCTION

Fiber optical sensors are among the most promising technologies in many sensing systems. Among a wide variety of optical sensors, FBG (Fiber Bragg Grating) based acceleration sensors can be applied in SHM (Structural Health Monitorization) of civil engineering infrastructures, in geological engineering for the monitorization of seismic activity, in military applications and in industrial applications were they could be primarily used to monitor machinery vibrations.

A FBG is a passive optical device based on the periodic modulation of the optical fiber core refraction index. The FBG sensors use the change in the center wavelength of the back-reflected light from the Bragg structure, induced by mechanical deformation or/and temperature variations [1]. FBG sensors present advantages over traditional electronic sensors due to the possibility to multiplex a large number of sensors (temperature, displacement, pressure, pH, humidity, high magnetic field and acceleration) in the same optical fiber, reducing the need for multiple and heavy cabling, used in traditional sensors. Being an in-fiber technology, FBG sensors take advantage of the properties provided by optical fiber, such us low transmission losses, immunity to electromagnetic interference, light weight and electrical isolation. But also, since the information is codified in the optical domain, they can be used in hostile environments, where electrical currents of electronic devices might cause a hazard. These sensors are usually applied for the static monitorization (deformations) of infrastructures [2]. However, this technology may provide an effective solution to measure simultaneously static and dynamic parameters at lower prices, presenting advantages even in comparison with another type of optical sensors [3].

Nowadays, the main disadvantage of this technology remains in the cost of the interrogation units, nevertheless its multiplexing capability make them a cost-effective solution for large infrastructures where a high number of different sensors could be required.

In this work we proposed the application of optical accelerometer to monitor two civil engineering structures: a reinforced concrete building and a steel footbridge. Both infrastructures are located at the Aveiro university campus. The implemented accelerometers are single-axis, based in FBG technology, providing a less expensive solution to be used in dynamic measurements of structural vibrations.

2 FIBER BRAGG GRATINGS THEORY

An FBG is a passive optical device and, in its most basic form, consists in a periodic modulation of the core refraction index along the optical fibre. When a FBG is illuminated by a broadband light source, part of the radiation, obeying to the Bragg condition, is back-reflected along the optical fibre core. The Bragg condition is the requirement that satisfies both energy and momentum conservation of the involved photons [4]. The first order Bragg condition is given by: $\lambda_B=2n_{eff}\Lambda$, where λ_B is the centre wavelength of the back-reflected light from the Bragg grating, n_{eff} is the effective refractive index of the fibre core and Λ is the period of the refractive index modulation.

From this condition becomes clear that the centre wavelength reflected by the Bragg grating will change if the grating is exposed to external perturbations. The Bragg wavelength change is due to its dependence of the refractive index modulation periodicity with temperature and mechanical deformation. Strain and temperature not only effect the period of the grating, but also the refractive index. The influence of both, in the Bragg wavelength, is given by [1]:

$$\Delta\lambda_B = 2\left(\Lambda\frac{\partial n_{eff}}{\partial l} + n_{eff}\frac{\partial \Lambda}{\partial l}\right)\Delta l + 2\left(\Lambda\frac{\partial n_{eff}}{\partial T} + n_{eff}\frac{\partial \Lambda}{\partial T}\right)\Delta T \quad (1)$$

The strain effect on the Bragg wavelength is represented by the first right hand term in equation (1). This strain dependence can be expressed as:

$$\Delta\lambda_B = S_{\Delta l}\varepsilon_z \quad (2)$$

where $S_{\Delta l}$ is the strain sensibility and ε_z the strain in the optical fibre along the longitudinal axis. The temperature dependence on the Bragg wavelength is represented by the second right hand term in equation (1) and it can also be expressed as:

$$\Delta\lambda_B = S_T\Delta T \quad (3)$$

where S_T is the thermal sensibility of the Bragg grating. For a typical Bragg grating, in a germanium-doped optical fibre, with Bragg wavelength around 1550nm, we can expect a strain sensitivity of 1.2 pm/με (1.2 pm for 1 μm stretch in a fiber with 1 m long) and a thermal sensitivity of 13 pm/ºC [1].

To be used as a sensor, an FBG must be illuminated by a broad spectrum light source and the reflected wavelength measured and related to the parameter of interest. The shift in the Bragg wavelength can be monitored by different techniques. Several interrogation techniques can be found in the literature, based on simple interferometry [5], Fabry–Perot filters [6], matched gratings [7], acoustic–optic tunable filters [8], long period gratings [9, 10], Sagnac loops based on the chirped fiber Bragg gratings [11] or multi-port fiber Mach-Zehnder interferometer for multi sensors interrogation [12]. Some provide high resolution in the measured wavelength domain, but are rather complex systems or present high implementation costs.

3 METHODOLOGY

Two similar optical accelerometers (V1 and V2) were implemented and tested. The sensor element in both versions is a Bragg grating written in a photosensitive single mode optical fiber, pre-tensioned and fixed between two points (A and B for version V1), as shown in Figure 1 and 2. The structure of the V1 accelerometer consists in a concentrated inertial mass, supported by an L-shaped cantilever beam, connected to its base by a thin plate, acting a shaped leaf spring, and a Bragg grating element. When exposed to external accelerations, the inertial mass moves in the vertical axis, imposing a contraction/expansion of the optical fiber. The movement of the inertial mass do not occur exclusively in the vertical axis, but can be considered as so. The dimensions and thickness of the square shaped leaf spring determine the sensitivity of the accelerometer and minimizes cross-axis sensitivity [13], its range and resonant frequency is dependent on the optical fiber Young modulus [14] and the thickness of the square shaped leaf spring. The main difference between these two accelerometer versions is that version V1 was assembled from discrete elements while version V2 was manufactured from a bulk brass piece.

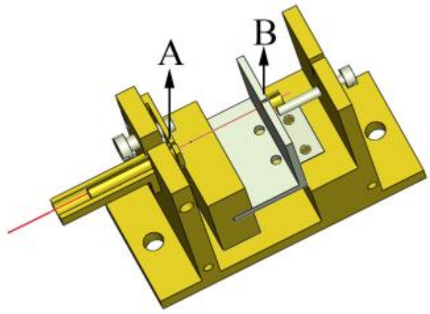

Figure 1. Optical accelerometer V1 schematics.

Accelerometer V2 principle is similar to the previous version, however, uses two FBGs fixed between points 1 and 2, for FBG 1, and between points 3 and 4 for FBG 2, as shown in Figure 2. This layout allows the accelerometer to be insensitive to environmental temperature variations.

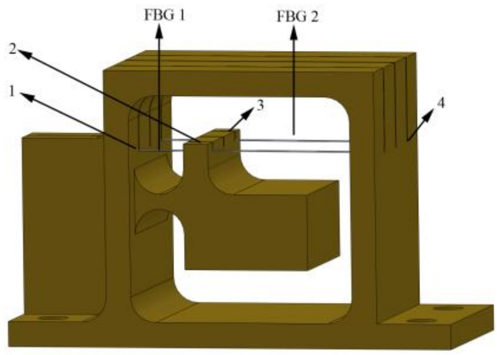

Figure 2. Optical accelerometer V2 schematics.

To measure the accelerometer response, two interrogation techniques were used: accelerometer V1 was interrogated by a commercial interrogation system from FiberSensing, model FS4200, at 200 samples per second and accelerometer V2 was interrogated using the two FBGs from the accelerometer itself to demodulate the wavelength signal codification to optical intensity [15]. The reflection spectra for the two FBG is presented in Figure 3.

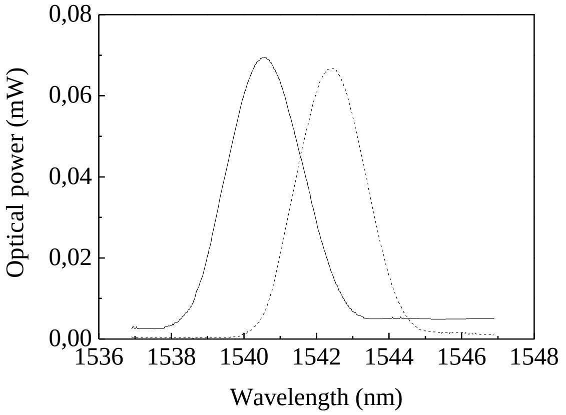

Figure 3. Reflection spectra for the two FBGs used in the accelerometer V2 (the solid line represents the FBG spectrum for the first FBG and the dashed line the spectrum for the second FBG).

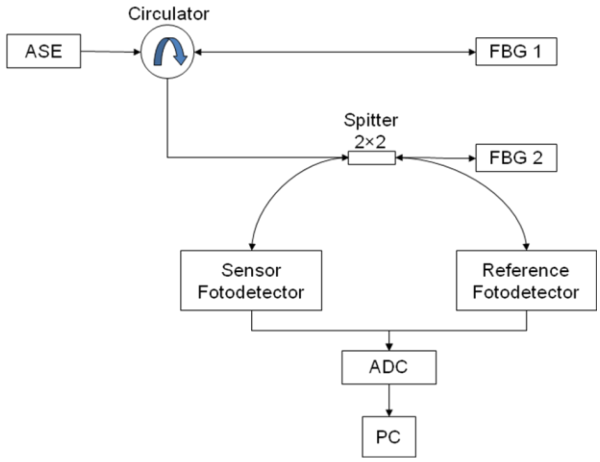

Figure 4. Building blocks for the interrogation system.

This later technique uses 2 cascaded FBGs, as displayed in figure 4, the first is illuminated by a broadband optical source (ASE - from Amonics, model ALS-CL-17-B-FA, emitting in the 1528-1608 nm spectral region, with an integrated optical power of 17 dBm), and its reflected signal is injected in the second FBG. If both FBGs are affected in the same way (temperature or rotation effects) no signal variation is noticed [16]. If the inertial mass moves, one FBG is stretched and the other suffers a contraction, causing a change in the optical intensity of the output signal. Part of the radiation reflected by the first FBG is used as a reference, allowing to compensate the optical power fluctuations at the optical power source. The reference and sensor signals are converted to the electrical domain by two InGaAs photodetectors, with a responsitivity of 0.84 A/W at 1550 nm and a cutoff frequency of 2 GHz. The signals are then converted to the digital domain by an analog-to-digital converter acquisition board (ADC), from National Instruments, model USB6008. This ADC module provides data acquisition at 10000 samples per second, with a 12-bit resolution and an input dynamic range of ±20V. After conversion, the signals are then processed in a laptop, by an application implemented in LabView®. This scheme can operate at very high sampling rates, which are only limited by the photodetectors and remaining electronics frequency response or by the ADC sampling rate.

Accelerometer V1 was used in acceleration measurements at a steel footbridge, showed in Figure 6, and for the physics department building (Figure 7) it was used accelerometer V2. Simultaneously, an electronic accelerometer was used as a reference.

The optical and electronic accelerometers were attached to a heavy (5 kg) steel plate placed over the measuring points, as showed in Figure 5. In this way, we can assume that the steel plate and the structure (footbridge or building), at the measuring point, have the same displacement and acceleration components.

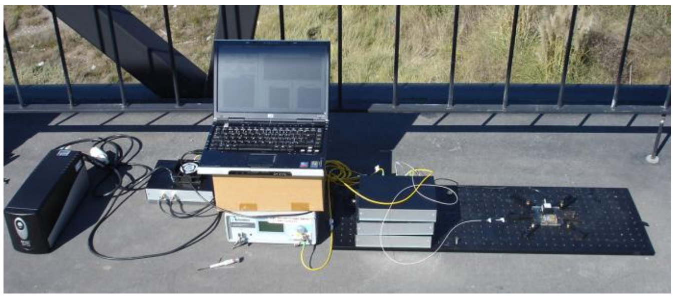

Figure 5. Experimental setup at the footbridge monitoring point.

The measuring point at the footbridge is located at the mid-span of the central bay. The measuring point at the physics department building is located at the centre of mass of the building, on the slab at the 3rd floor.

Figure 6. Photography of the characterized footbridge.

Figure 7. Photography of the characterized physics department building.

4 RESULTS

The accelerations were measured, during which three mechanical impulses were applied by the simultaneous vertical impulsion of two persons at a point close to the measuring position. Figure 8 shows the accelerograms recorded for a time-window of 10 s at the 3th floor in the physics department building with accelerometer V2 and with the electronic accelerometer.

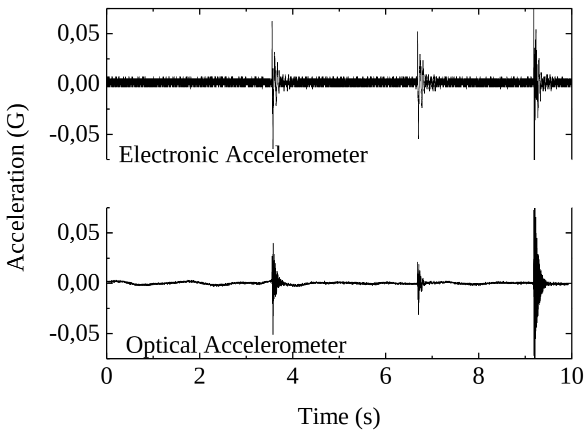

Figure 8. Accelerogram recorded from the measurements on a 3-storeys building with: electronic accelerometer and V2 optical accelerometer.

The structure eigenfrequencies are obtained by peak-picking on the frequencies spectra, obtained by FFT (Fast Fourier Transform). The frequencies spectra, for the measurements on the footbridge, with accelerometer V1 is showed in Figure 9, and for the measurements on the physics department building, measured with accelerometer V2, is shown in Figure 10. In each figure is represented, for comparison, the frequencies spectra obtained with the electronic accelerometer from Crossbow Technology, model CLX02LF1Z (LF series), with a sensitivity of 0.997 V.G^{-1} (where G stands for the gravity acceleration).

The two implemented acceleration systems, with distinct interrogation techniques allow to successfully obtain the eigenfrequencies of engineering structures with maximum errors, when compared with the value obtained with the electronic accelerometer, of 0.60 % and 0.8 %, for accelerometer V1 and V2, respectively.

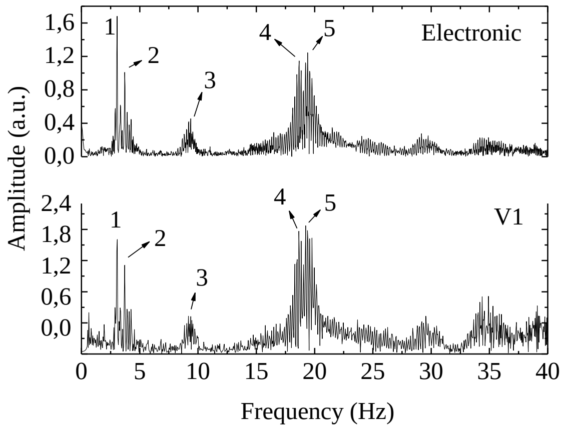

Figure 9. Frequency spectrum obtained from measurements on a footbridge with V1.

The frequencies spectra showed in Figures 9 and 10, allow the identification of some of the structure's eigenfrequencies, presented in Table 1 for the measurements on the footbridge with V1 and Table 2 for the measurements on a 3-storeys building with V2.

Table 1. Eigenfrequencies obtained from Figure 8.

Mode	Frequency (Hz)		
	Optic	Electronic	Error (%)
1	3.05	3.07	0.66
2	3.71	3.71	-
3	9.20	9.18	0.22
4	18.68	18.65	0.16
5	19.41	19.38	0.15

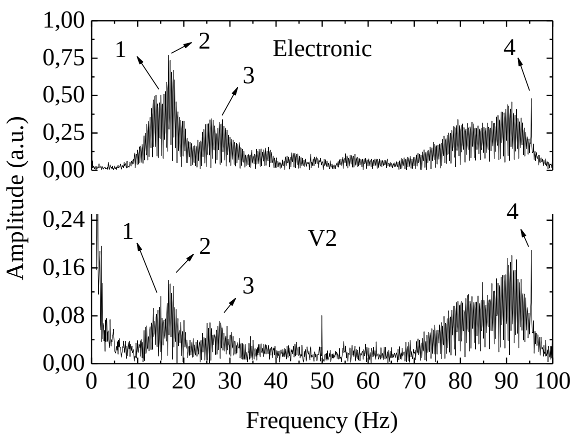

Figure 10. Frequency spectrum obtained from measurements on a 3-storeys building with V2.

Table 2. Eigenfrequencies obtained from Figure 9.

Mode	Frequency (Hz)		
	Optic	Electronic	Error (%)
1	15.04	14.92	0.80
2	16.72	16.65	0.42
3	28.12	27.96	0.57
4	95.38	95.40	0.02

5 CONCLUSIONS

The achieved results show that optical monitoring schemes can be used in SHM of large structures, being a low cost solution. Two implemented acceleration systems, with different interrogation techniques, were used, allowing to successfully obtain the eigenfrequencies of civil engineering structures with maximum error, when compared with the value obtained with the electronic accelerometer, of 0.66 % and 0.80 %, for accelerometer V1 and V2, respectively.

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