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Fiber Bragg Grating Sensors for High Frequency Damage Detection Applications

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Abstract

Damage detection is a critical issue for structural health monitoring. Between the proposed techniques, modal analysis relates the presence of structural damages to variations of the modal frequencies, retrieved from the frequency transfer function of the structure. Since greater information content is at higher frequencies, sensing systems with an adequate bandwidth are required. Here, fiber Bragg grating sensors are exploited to reveal damages on a structure by detecting variations of the frequency response between the undamaged and damaged states. As preliminary steps to verify attitudes of these sensors for this application, modal analysis tests in a wide frequency range are performed. Excitation techniques commonly used for structural health monitoring tests and state of the art sensors are used in the reported tests. Obtained experimental results confirm the excellent performances of fiber Bragg gratings, not only able to detect a damage but also to discriminate the presence of more structural alterations.

Keywords: fiber Bragg grating sensors (FBG), dynamic measurements, modal analysis, frequency response function (FRF), structural health monitoring (SHM), damage detection

1. Introduction

The high complexity and costs of modern structural systems, combined with their high operational reliability and safety needs have brought to an increasing interest in new approaches for structural health monitoring (SHM) and damage analysis aiming to assess the level of damages of a structure due to severe loading events. Current damage and crack detection systems are based on acoustic emission monitoring and active methods such as ultrasounds and modal analysis [1,2]. This latter is an experimental methodology able to retrieve the dynamic features (resonant frequencies, vibration shapes) of a mechanical structure from its frequency response function (FRF), *i.e.* the ratio between the Fourier transforms of the sensors time responses and of the excitation signals [3]. Methods correlating the presence of damage to variation of modal properties are proposed in literature [4], and high frequency modes seem more effective to detect and localize the presence of small damages [2]. For this reason, a mandatory requirement for SHM surveillance systems is a wide passing bandwidth. Moreover, a low intrusivity and an excellent multiplexing capability are necessary to provide the optimum solution in terms of reliability, robustness, repeatability and low complexity implementation for these sensing systems [1-5].

On this line of argument, optical fiber sensors, in particular fiber Bragg gratings, can represent an attractive alternative for SHM applications: an adequate bandwidth operation is warranted, joined with other features like: reduced dimensions, high resistance to corrosion and fatigue, immunity to electromagnetic interferences, compatibility with the most part of composite materials and high multiplexing capability [6 - 10].

In recent works FBGs attitude to perform modal analysis on real structures for aerospace and aeronautic applications has been showed. Modal analysis tests were carried out on a component for an artificial satellite sensorized with FBGs and accelerometers as reference sensors [11]. This class of optic devices gave satisfactory results also when embedded in a composite structure for aeronautical applications: in this case complex vibrational shapes, due to the nature of the structure, were retrieved, in good agreement with reference accelerometers [12, 13]. For the previously mentioned applications, low frequency modal shapes were retrieved.

Here, the FBGs capability to be exploited as SHM sensors is under investigation. In particular, the intent is to verify whether these devices can detect resonant modes frequencies and amplitude variations in a wide frequency range. To this aim, results of damage detection tests on an *ad hoc* steel structure are reported. Modal frequency and amplitude variations on a series of resonances belonging to the structure in the undamaged and damaged states are reported. As previous step, results of high frequencies (up to kilohertz) modal analysis tests carried out on the same structure are reported in order to verify if FBGs and their interrogation schemes are able to perform this activity in such a frequency range, as SHM specifications require. As reference sensors, a vibrometer is exploited for modal analysis tests and an accelerometer for damage detection ones. Excitation is provided by instrumented hammer's impacts for modal analysis, and by a piezoelectric element, able of a wider frequency excitation, for damage detection tests. These excitation and reference sensing systems represent the state of the art for the systems exploited for this application [3].

2. Fiber Bragg Gratings as Sensing Elements and Their Application to the Modal Analysis Method

A Fiber Bragg Grating (FBG) is a periodic or semi-periodic permanent perturbation of the refractive index of the core of an optic fiber [6]. As effect, when a grating is irradiated with a broadband optical source, a narrow band pass spectrum signal is reflected. The central wavelength of this signal, called also "Bragg's wavelength", λ_B, is related to the physical parameters of the grating by the following relationship [4]:

$$\lambda_B = 2n\Lambda \qquad (1)$$

where n is the effective refractive index of the mode propagating inside the fiber and Λ is the grating period. Each external cause, able to modify right hand terms of the equation (1), causes a shift of the Bragg's wavelength. Relative variations of λ_B induced by n or Λ changes can be obtained by differentiating the equation (1) respect to these two parameters, and substituting the relationships obtained applying the strain optic theory [6]. If an axial strain field is experienced by the FBG, a shift in the central wavelength occurs, according to the following expression [6]:

$$\frac{\Delta\lambda_B}{\lambda_B} = \left(1 - \frac{n_0^2}{2}\left[p_{12} - \nu\left(p_{11} + p_{12}\right)\right]\right)\cdot\varepsilon \qquad (2)$$

where n_0 is the effective refractive index of the unstrained optic fiber, p_{ij} is the generic element of the elasto - optic matrix, ε is a strain component co-axial to the optic fiber, ν is the Poisson's ratio. The relationship reported in equation (2) is valid for a light polarized in the plane orthogonal to the fiber axis. For bonded configuration and dynamic tests involving lower strain field amplitudes, it can be safely assumed that only the strain field parallel the fiber axis significantly affects the FBG response. Typical values of strain – optic matrix elements and Poisson's ratio for standard optic fibers are: p_{11}=0.12, p_{12}=0.27 and ν=0.17, while $S\varepsilon$=0.78 * 10-6 $\mu\varepsilon^{-1}$ [14].

For these optic devices the interrogation system adopted in the modal analysis tests relies on a low cost ratiometric technique based on optical filtering combined with broadband interrogation. By using a chirped and strongly apodized FBG, an optic filter with a response linear in wavelength can be obtained [15, 16]. In light of the passive nature of the proposed technique, system bandwidth is only limited by the electronic circuitry involved in the receiving unit. Such a system is capable of a static resolution of 1$\mu\varepsilon$ and a dynamic one of 40nε/(Hz)$^{1/2}$ @ 50 KHz [15].

According to the modal analysis approach, reported in [3], a mechanical structure is modelled with a linear vector system. It has as inputs excitation signals and as outputs sensors responses evaluated at their locations, which realize the nodes of a grid on the structure. Output values for each node can be obtained from the frequency domain representation of this system, considering the matrix where the "jk" element is the relationship between the j-th output under a excitation signal applied at the k-th input, when all other inputs are set to zero. It can be shown after simple mathematical passages, that each FRF in an around of r–th vibrational mode resonant pulsation has the following expression [3]:

$$H_{jk}(\omega\approx\omega_r)\approx\frac{\Phi_r^j\,\Phi_r^k}{\left|-\omega^2+\omega_r^2+j2\omega\omega_r\zeta_r\right|^2}(-\omega^2+\omega_r^2)+ -j\frac{\Phi_r^j\,\Phi_r^k}{\left|-\omega^2+\omega_r^2+j2\omega\omega_r\zeta_r\right|^2}2\omega\omega_r\zeta_r \qquad (3)$$

where ω_r is the resonant pulsation; ζ_r is the damping coefficient; $\Phi^r{}_j$, $\Phi^r{}_k$ are respectively the j-th and the k-th component of the related eigenvector. It can be assumed that if the structure is lightly damped (i.e. the damping coefficient tends to zero), all eigenvectors components are real quantities [3]. Moreover, natural pulsations can be evaluated from zero crossings of the real part of equation (3). Peaks of imaginary parts give both location of resonant frequencies and the amplitude of the structure response (displacement or strain) at the point where sensors are located [3]. A commonly exploited result is the Maxwell reciprocity assertion: it states that for mechanical structures, roles of sensors and excitation devices can be inverted [3], as it happened in the tests reported in the following.

In the case of FBGs, they measure strain components and so can give a strain frequency response function (SFRF), treated in the same way as the FRF to retrieve the modal features of the structure under investigation.

3. Sample Description

In order to perform the reported tests, a sample structure, obtained joining two steel beams, was exploited. One beam, called "A" in figure 1, is an AISI 4340 steel sample. It has a rectangular 2.5 x 5cm base and a height of 90cm. It is hollow and the thickness of every wall is 2mm. A second thin AISI 4340 steel beam, called "B" in figure 1, was placed perpendicularly to the first one and soldered at its midspan. Dimensions of this latter were 44 x 2.5cm and 5mm of thickness. The edges of the obtained "T" shaped structure were soldered to a heavy mount, acting as constrain. On each one of the two beams a FBG was bonded: a device with a 1.2nm FWHM bandwidth, a central wavelength of 1550.00nm was bonded on the "A" beam at 34.5cm from its upper constrain. Another FBG with a 1.2nm FWHM bandwidth, a central wavelength of 1550.00nm was glued at the centre of the "B" beam.

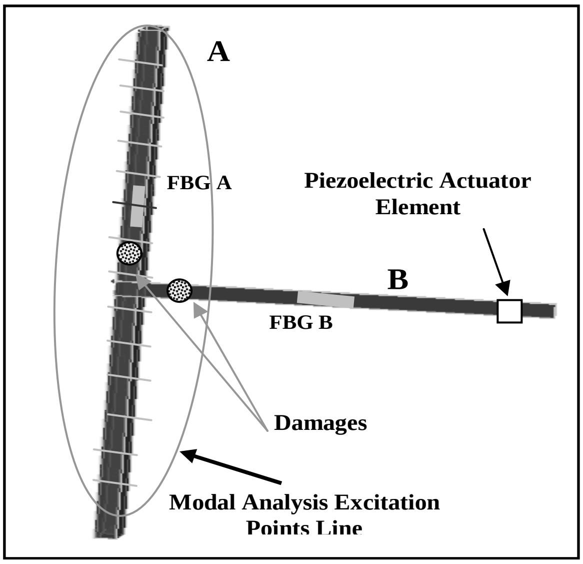


Figure 1: A scheme of the test structure.

A piezoelectric actuator, exploited for damage detection tests, was bonded on the horizontal beam too, next to the constrained edge.

4 Experimentals

4.1 Experimental Set-Up and Tests Procedure

For the carried out modal analysis tests, as reference sensor a Polytec PSV – 400 vibrometer was utilized to perform punctual measurements of the dynamic displacement component out of the plane of the front side of the "A" beam. The scanning laser beam was focused on the same location as the bonded FBG grating. As mechanical excitation system, an instrumented hammer was exploited. This device can furnish a mechanical impulsive input with frequency flat bandwidth up to 3.5kHz. It can be easily moved from an excitation point to another one, allowing the retrieving of modal shapes. An excitation line was traced on the rear side of the vertical beam, as depicted in figure 1. It was constituted by a series of 15 points, 5cm spaced among them, sufficiently to perform an efficient modal analysis. The first point was at 10cm from the upper constrain (see figure 1). For each point, five hammer impacts were performed and five excitation – output pairs signals were acquired for each sensor in order to obtain five FRF (SFRF), successively averaged for the evaluation of the dynamic features of interest.

For the damage detection tests, the "B" beam reported in figure 1 is used. Mechanical excitation was given by a piezoelectric element bonded on the right edge of the beam since this can give a wider frequency excitation than the instrumented hammer. This device was fed with a 100Hz - 10kHz frequency chirp having a of 100V peak to peak amplitude. On the rear side of the beam, in correspondence of the FBG, an accelerometer was placed. Since this latter has a resonance at about 7kHz, the range up to 5.5kHz is exploited. Damage detection tests were carried out with on only input. In this case, FRFs (SFRFs) exploited for modal parameters evaluations were an average of eight sweeps of the piezoelectric element. In order to improve the quality of the obtained SFRFs, experimental data were filtered using an algorithm based on the single value decomposition (SVD) of the Hankel matrix obtained rearranging experimental data [17]. After the first acquisition on the undamaged test sample, a clay mass was added in order to simulate the presence of a damage. Successively, a different one, located further from the sensors, was placed to simulate a second damage (see figure 1).

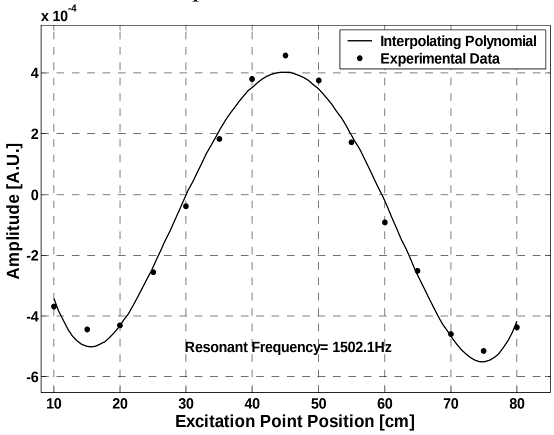
4.2 Results and Discussion

Several modes are retrieved by both sensors in the range 114 - 1502Hz. Good agreement is obtained for the vibrational shapes and related resonant frequencies values.

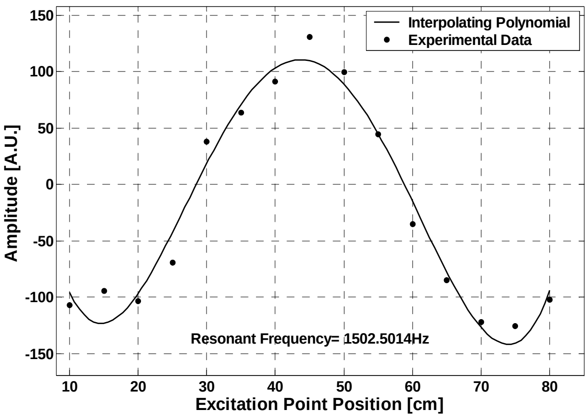
Here, shapes obtained for the highest frequency mode (1502Hz) are reported in figures 2(a) and (b).

Results obtained in this case from FBG sensors demonstrate their capability to retrieve modal parameters in a wide frequency range, being able to perform damage detection test, as described in the following.

These latter were performed on the "B" beam of figure 1. The presence of one or two damages is related to changes of resonant frequencies and amplitudes. Here results obtained from 625, 992, 1060 and 2096Hz are reported.



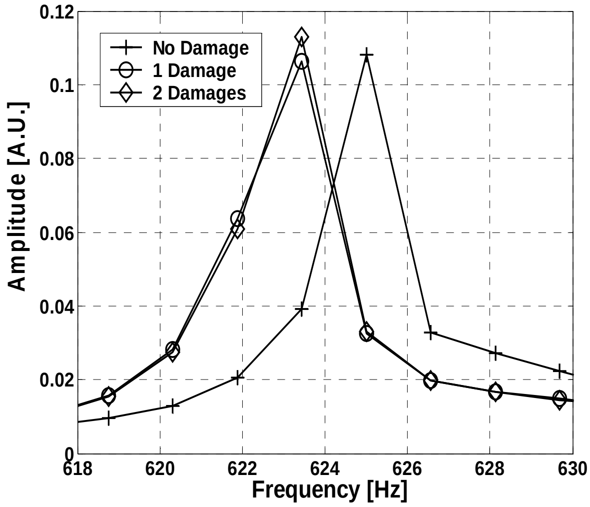
(a)



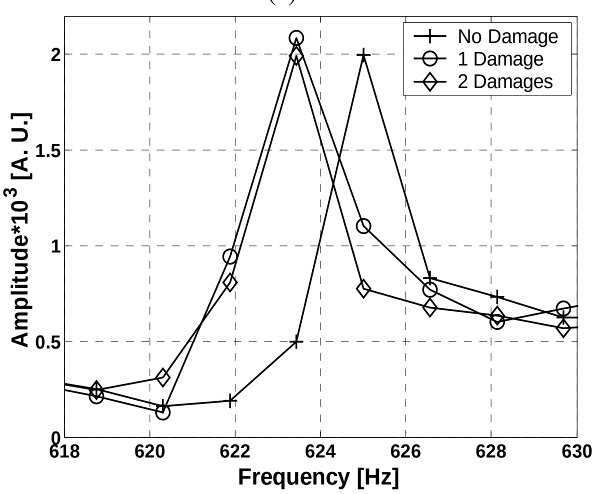
(b)

Figure 2. Comparison between vibrational shapes belonging to the mode at 1502Hz, (a) vibrometer, (b) FBG.

For the first one, reported in figures 3(a) and (b), after the first damage, the same frequency change is observed by both sensors, while no modification is observed at the second one.



(a)

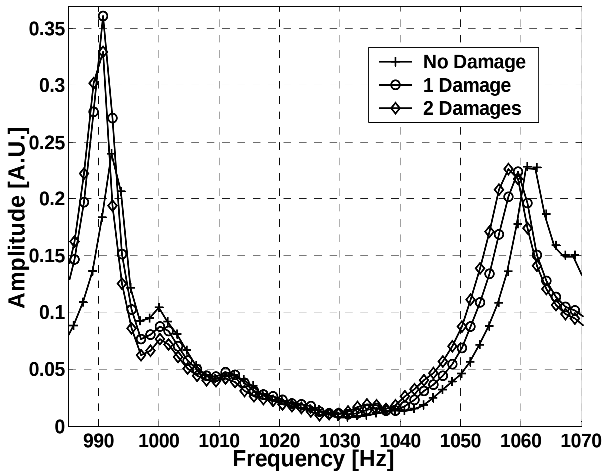


(b)

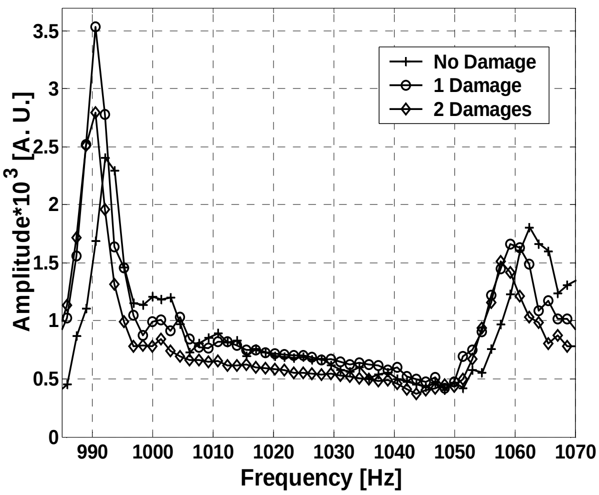
Figure 3. Comparison between the FRF's (a) and SFRF's (b) amplitudes for the 625Hz resonant frequency.

Amplitudes changes can be observed for this mode: the accelerometer demonstrates a -1.85% variation at the first damage and an increasing of 4.63% for the second one. The difference between the two damaged states is 6.60%. For the same mode, the FBG has a 4.50% variation for the first damage, and a small variation for the second one (-0.50%), while the difference between the amplitudes induced by the two damaged states is 4.79%.

Figures 4(a) and (b) show the changes in the natural frequencies for two shortly spaced modes at 992 and 1060Hz.



(a)



(b)

Figure 4. Comparison between the FRF's (a) and SFRF's (b) amplitudes for the 992 and 1060Hz resonant frequencies.

With reference to the 992Hz mode, after the first damage, the same percent frequency shift is observed by both sensors, -0.16%. Also in this case the second damage isn't sensed by both devices. About modal amplitudes, for the accelerometer, the first damage causes a strong increasing of 49.58%, respect to the undamaged structure, while for the second alteration, a difference of 36.67%, is observed. The optic sensor exhibits a 46.89% difference between the undamaged and damaged state, similar to the accelerometer's one, and also a good variation at the rising of the second damage, 16.18%, can be observed.

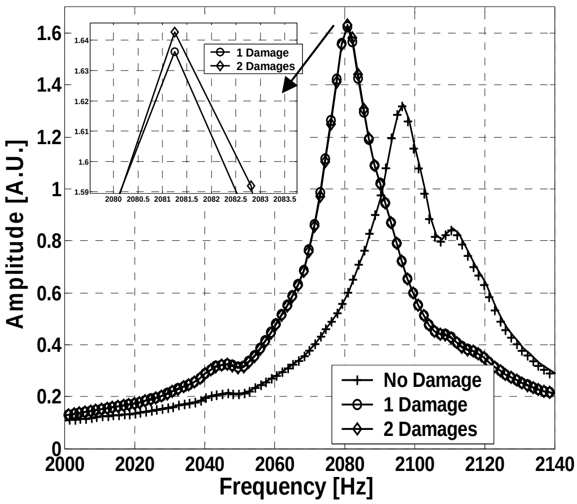
For both sensors the mode at 1060Hz, detected at 1062Hz for FBG device, is the only mode able to discriminate in frequency the presence of the second damage: the first one causes a percent change of -0.147% for the accelerometer and -0.294% for the FBG. The second structural alteration causes a -0.295% variation for the accelerometer and -0.441% for the FBG. Related amplitudes exhibit small variations between the first detected damage (-2.20%) and the second one, -0.881% for the accelerometer. The FBG presents a variation of -8.29% for the first damage, and -16.02% for the second one. As expected from the literature, higher order modes are more sensitive to the presence of damages [2].

Figures 5(a) and (b) show the changes in the strongest detected mode: 2096Hz. After the first damage, the same frequency shift is observed by both sensors (-0.745%), while no modification is observed at the second one. A variation of 23.47% can be observed in the accelerometer's peak at the first damage and 24.00% at the second one. For the FBG's resonance peak, a difference of 17.49% between the first damage and the second one can be observed while the second one introduces a 4.79% variation.

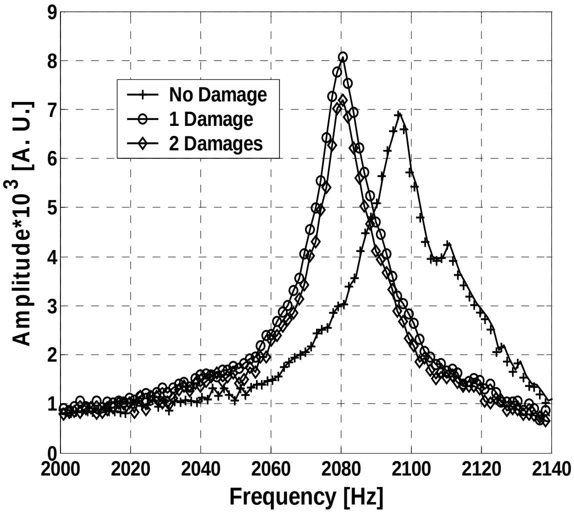
5 Conclusions

The aim of this work is to verify FBG sensors capability to detect the presence of damages in mechanical structure revealing changes of dynamic features in a wide frequency range. To achieve this goal, preliminary modal analysis tests are performed on a structure with high resonances. As result, FBGs can retrieve modal shapes in good agreement with the reference sensors up to the frequency of 2.0kHz.

As successive step, damage detection tests are performed. Presence of damages is revealed by variation of modal frequencies and amplitudes. For the modes associated to higher peaks of both FRF and SFRF amplitudes, a good agreement in frequency shifts is obtained by both sensors. For the most part of the investigated resonance, the presence of a second damage, localized further from sensor position has not been associated to a frequency shift. FBG amplitudes, as for the reference sensor, have showed variations for each one of the considered states. Results obtained during these tests witness the possibility to exploit these optic devices for SHM applications.



(a)



(b)

Figure 5. Comparison between the FRF's (a) and SFRF's (b) amplitudes for the 2096Hz resonant frequency. The inset represented in (a) is a zoom on the peak .

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