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Modal analysis and damage detection by Fiber Bragg grating sensors

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Abstract

Damage detection and localization are critical issues for structural health monitoring. To this aim, many techniques have been proposed relating, the presence of damage to variations of its dynamic features between the undamaged and damaged states. Since a greater information content is localized at higher frequencies, sensing systems with adequate bandwidth and resolution are required. Here, Fiber Bragg grating sensors with an adequate interrogation system are exploited to reveal the presence of damage on a structure. As preliminary step, modal analysis tests in a wide frequency range are performed in order to verify the performances of these optic devices to retrieve high frequency structural dynamic features. As reference sensors, laser Doppler vibrometers and accelerometers, representative of the state of the art for this application field were exploited. Experimental results confirm the excellent performances of Fiber Bragg gratings, not only able to detect damage but also to discriminate between different damage levels.

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 from both industrial and academic world. Current corrosion and crack detection systems are based on acoustic emission monitoring and active methods such as ultrasound and modal analysis [1,2]. This latter is an experimental methodology able to retrieve the dynamic features (resonant frequencies, vibration shapes and modal damping ratios) 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]. Based on this line of arguments, Schultz et al. proposed SHM methods classifying the structures in various damage states based on the differences between vibration features extracted from the measured responses of the structure in the undamaged and damaged states [4]. Since high frequency modes are more effective to detect and localize the presence small damage [2], one of the mandatory requirement for SHM surveillance systems is a wide bandwidth, joined to a very low intrusivity and, in order to simplify the overall architecture, high multiplexing capability [1–5]. Actually, as sensing systems for these applications, non-contact systems like laser Doppler vibrometers or in situ electric devices like accelerometers are widely utilized.

A valid alternative for SHM applications can be represented by fiber optic sensors, and in particular by Fiber Bragg gratings (FBGs). Key points of this technology are reduced dimensions combined with the intrinsic capability to measure several parameters simultaneously; the high resistance to corrosion and fatigue, good compatibility with the most advanced composite materials exploited in the aeronautic and aerospace field, immunity to electromagnetic interferences, the wide bandwidth operation, an excellent multiplexing capability [6–10].

In recent works FBGs attitude to perform modal analysis on real structures for aerospace and aeronautic applications has

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been demonstrated. Experimental modal analysis tests were carried out on the aluminum mock up of a component for an artificial satellite. In this case both FBGs and reference accelerometers were bonded on the lower surface of this structure and optic devices were able to detect resonant frequencies and planar vibrational shapes for the first two flexural modes, located at about 72 and 120 Hz, in good agreement with preliminary numerical simulation and reference sensors outputs [11].

Moreover, FBG sensors performances as embedded sensors in a real composite structure for aeronautical applications were tested: these devices were deployed in the spar of the wing of a composite materials aircraft model. In this case a complex strain field, due to their position, was expected. Accelerometers were exploited as reference sensors. Several modes, also with a complex shape, were retrieved. Also in this case a good agreement with numerical simulations and results obtained by reference sensors was obtained. Retrieved modes for this test article belonged to range up to 170 Hz [12,13].

In this work the attention is focused on the FBGs capability to be exploited as SHM in situ sensors. In particular, the intent is to verify whether these device can detect resonant modes frequency 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 described. As previous step, results of high frequencies (up to kilohertz) modal analysis tests carried out on the same structure are reported.

2. Fiber Bragg gratings as sensing elements and their application to the modal analysis method

A Fiber Bragg grating 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 wavelength”, λ_B, is related to the physical parameters of the grating by the following relationship [14]:

$$\lambda_B = 2n\Lambda \tag{1}$$

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 (1), causes a shift of the Bragg wavelength. In particular, when the FBG is subjected to strain fields, relative variations of λ_B induced by n or Λ changes can be obtained by differentiating (1) respect to these two parameters, and substituting the relationships obtained applying the strain-optic theory [6]. If complex strain is experienced by a FBG, shift in the central wavelength taking into account polarization effects occurs according to the following expression:

$$\left(\frac{\Delta\lambda_B}{\lambda_B}\right)_i = \frac{\Delta\Lambda}{\Lambda} + \frac{\Delta n}{n} = \varepsilon_1 - \frac{n_0^2}{2}\sum_{j=1}^{3} p_{ij}\varepsilon_j \tag{2}$$

where n_0 is the effective refractive index of the unstrained, not birefringent optic fiber, p_{ij} is the generic element of the elasto-optic matrix, where $i=2, 3$ is the polarization axis of the light propagating along the optic fiber. 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. This means that the transverse strain is uniform ($\varepsilon_2 = \varepsilon_3$), and related to the axial one by the Poisson’s ratio. In this way, by exploiting also the symmetry properties of the p_{ij} for the optic fibers [6], (8) becomes independent of the polarization of the light and the Bragg wavelength relative shift is proportional to axial strain:

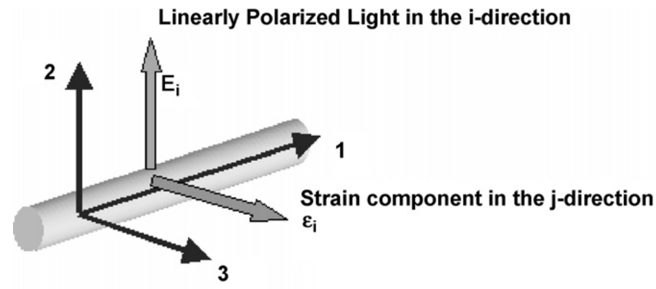

Fig. 1. Schematic co-ordinate systems used for strain-optic calculation.

$$\frac{\Delta\lambda_B}{\lambda_B} = \left\{1 - \frac{n_0^2}{2}[p_{12} - \nu(p_{11} + p_{12})]\right\}\varepsilon_1 = S_\varepsilon \varepsilon_1 \tag{3}$$

where ν is the Poisson’s ratio and S_ε is FBG strain sensitivity. 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 $\nu=0.17$, while $S_\varepsilon = 0.78 \times 10^{-6}\ \mu\varepsilon^{-1}$ [6] (Fig. 1).

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]. The block diagram of this system is shown in Fig. 2, while the transmitted spectrum of the involved filter are shown in Fig. 3.

With reference to the scheme in Fig. 2, each voltage signal, v_T and v_R, converted by the photodetectors is related to the convolution between the sensing grating spectrum and, respectively, the transmission and reflection responses of the optical filter involved in. The electronic processing of these two detected signals consists of taking the ratio of the difference and the sum of the outputs as follows [15]:

$$v_n = \frac{v_T - Kv_R}{v_T + Kv_R} \tag{5}$$

The v_n can be called “normalized voltage”. In this procedure an additional coefficient K is introduced in order to compensate the asymmetry in the receiving scheme due the additional coupler used for the reflected signal v_R, the optical losses introduced by the filter and to equalize the filter slope in transmission and reflection modes. In the case of linearly varying filter, the so generated normalized signal is a good measure of the centroid of the sensing grating spectrum, and as a consequence, also of Bragg wavelength [15]. Moreover, it is not dependent on the intensity