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Use of fiber Bragg grating array and random decrement for damage detection in steel beam

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ABSTRACT

A growing trend in the use of fiber Bragg grating array to detect structural damage has been observed in recent years. This paper describes the use of fiber Bragg grating optical sensors in an array to identify the location and assess the extent of damage on steel structures. A fiber optical sensing array with eight sensing elements has been designed, fabricated, and applied to measure the time history of strain at different points on a simply supported beam subjected to random loading. The wavelength shifts of the sensors are used to calculate the strain distribution along the beam. The random decrement at each point, for different modes, is extracted from the time history of the responses. The random decrements are compared at different damage ratios to an intact case to identify the existence of damage. Multichannel random decrement is applied to extract excited mode shapes. The mode shapes are then used to determine the location of the damage. The results show that the fiber optical sensor array is a reliable, fast, and accurate tool for the identification and localization of damage by using strain measurements.

1. Introduction

Applications of fiber optical sensors in structural health monitoring have been increasing for many years [1]. The approach allows structures to be continuously monitored without interrupting operations or affecting stiffness. Fiber optical sensors that have small diameters are used for the structural health monitoring of aerospace composite structures [2]. Linearly birefringent single-mode optical fibers embedded into woven glass epoxy composites have been used to measure strains in a 1-point loading specimen [3]. Embedded optical fibers with a simple signal attenuation measuring system are used as an inexpensive method to detect significant fatigue damage in composite material [4]. The potential of using plastic optical fibers in conjunction with high-resolution photon counting to detect and estimate the location of cracks in a single fiber glued to a tubular member is studied [5]. The effect of the presence of optical fibers on the structural fatigue behaviors of a host of carbon epoxy laminates has been quantitatively studied, in which optical fiber cables were placed in mid-plane and near the surface of the laminate subjected to loading [6]. A system of thin optical fibers integrated into a composite structure during its manufacturing process is suggested as a reliable automatic and remote long-term monitoring means for structural damage [7]. The influence of optical fiber orientation and depth on the sensitivity of a fiber optical system to detect impact damage in composite materials is reported and the optimal configuration has been determined for both orientation and depth [8].

Fiber optic sensor is classified as local, quasi-distributed and distributed sensors, related to the range that will be sensed. Local fiber optic sensors are based on detecting the optical phase change induced in light along the optical fiber. Fiber Bragg grating (FBG) sensors is a kind of quasi-distributed sensors, it has a unique property is encoding the wavelength which has been successfully employed in several civil engineering applications. These FBG sensors could be theoretically wavelength multiplexed up to 64 FBGs gratings in single fiber [9]. FBG sensors are used to evaluate damage in unidirectional carbon fiber/composites that results from both low and high velocity/energy impacts [10]. A distributed fiber optical monitoring methodology based on optical time-domain reflectometry has been developed for the seismic damage identification of steel structures [11]. The use of long FBGs to provide strain measurements is investigated with the purpose of achieving better structural health monitoring as opposed to the use of classical accelerometers because they provide low noisy data [12]. A

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gradient-based optimization algorithm is utilized to update the finite element model of a composite simple structure by using the output from fiber optical sensors and strain modal analysis [13]. A technique for damage detection has been introduced based on continuous strain data obtained from distributed fiber optical sensor arrays and neural networks [14]. An overview of the major types of fiber sensor arrays and their applications in civil structures has been reviewed by Fidanboylu and Efendioğlu [15]. Distributed fiber optical sensing has been used in an effort to detect structural damage in steel connections from direct strain measurements. It is found that the technique can be successfully applied in static analysis, but has a limited application in dynamic analysis, as data collection is too slow [16]. Lopez-Higuera et al. used Fabry–Perot interferometric sensors and neural networks to predict the size and location of delamination in laminated glass/epoxy composite beams [17]. Reviewed research and development activities on the use of fiber optical sensors in the health monitoring of various structures, including buildings, piles, bridges, pipelines and tunnels, in which existing problems and promising research efforts are also discussed [18]. An application of using FBG sensors which is the smart FBG weighbridge; traffic are weighted from the deflection of reinforced concrete beam with FBG strain sensors embedded [19]. FBG sensors used to monitor early age deformations and temperature for various materials as high performance concrete [20].

In this paper, an FBG sensor array is used to measure the time history of strains on the surface of a beam subjected to random loading. An FBG sensor array with eight FBG sensors on a single fiber is surface mounted onto a steel beam. The testing is not affected by electromagnetic noise or other sources of noise in the laboratory with different kinds of machineries. Analysis of the modal damping ratio and mode shape can clearly locate and identify structure damage. Random decrement (RD) signatures can be used to describe the free decay response of the system. The advantage of this approach is that one can obtain a free response from the stationary random response of the system. To obtain the RD from a stationary random response, the response is divided into a number of segments, N, each with a length of τ and determining the average of this segments to eliminate the random component and resulting the deterministic component introducing the random decrement signature [21].

2. Random decrement and mode shape extraction techniques

2.1. Random decrement

The response of a single degree of freedom linear system is governed by the equation of motion:

$$[M]\{\ddot{X}(t)\} + [C]\{\dot{X}(t)\} + [K]\{X(t)\} = \{F(t)\} \tag{1}$$

where M is the mass, C is the damping, K is the stiffness and $F(t)$ is the excitation force. And after normalizing the equation relative to the mass:

$$\ddot{X}(t) + 2\omega\varepsilon\,\dot{X}(t) + \omega^2\,X(t) = F(t) \tag{2}$$

ω is the natural frequency, ε is the damping ratio and $X(t)$ is the response of the system. Random decrement response extracted from Eq. (2) represents the free decay of the system, assuming that the analyzed response is realization of a zero mean stationary Gaussian stochastic process. By changing the variables indications used in the previous equation to be $y_1 = x$ and $y_2 = \dot{x}$

$$\dot{y}_1 = y_2 \tag{3}$$

$$\dot{y}_2 = -2\omega_o\xi y_2 - \omega_o y_1 + f(t) \tag{4}$$

By substituting in the probability density function and multiply the two sides with y_1 and y_2 then integrating the equation with respect to y_1 and y_2, where μ_1 and μ_2 are the mean values of displacement and velocity,

$$\ddot{\mu}_1 = \dot{\mu}_2 = -(2\omega_o\xi y_2 + \omega_o^2 y_1) \tag{5}$$

The free decay for the structure is derived from the stationary random response,

$$\ddot{\mu} + 2\xi\omega_o\dot{\mu} + \omega_0^2\mu = 0 \tag{6}$$

The technique is based on the classical RD technique, which averages the time history segments of random vibration responses in a time domain. The triggering condition is used to determine the starting point of each time segment. It is assumed that if the structure is subjected to a wideband load, the response will be composed of two components: a random and a deterministic component (free decay). By averaging the response, the random component is cancelled out and the deterministic component is obtained.

$$x(\tau) = \sum_{i=1}^{N} x_i(t_i + \tau) \tag{7}$$

The triggering values are

$$\begin{aligned} &x_i(t_i) = x_s \quad \text{for } i = 1, 2, 3, \ldots, N \\ &\dot{x}_i(t_i) \geqslant 0 \quad \text{for } i = 1, 3, 5, \ldots, N-1 \\ &\dot{x}_i(t_i) \leqslant 0 \quad \text{for } i = 2, 4, 6, \ldots, N \end{aligned}$$

In the current study, multichannel RD [21] is used to extract the excited mode shapes of the tested beam. Multichannel RD extends the approach by applying it at multiple points on the structure at the same time [20].

$$\mathrm{RD}_L = \frac{1}{N}\sum_{i=1}^{N}\{\{X_L(t_{\mathrm{isL}} + \tau)|X_L = X_S\} \tag{8}$$

$$\mathrm{RD}_{\mathrm{NL}} = \frac{1}{N}\sum_{i=1}^{N}\{\{X_{\mathrm{NL}}(t_{\mathrm{iNL}} + \tau)|t_{\mathrm{iNL}} = t_{\mathrm{isL}}\} \tag{9}$$

where RD_L is the random decrement at leading channel, X_L is the triggering conditions of the leading channel, t_{isL} is the time corresponding to the triggering conditions, and $\mathrm{RD}_{\mathrm{NL}}$ is the random decrement for the non-leading channels. To keep the phase angle between different points, one channel is used as a leading channel and the triggering condition is applied only to this channel. The times that correspond to the triggering condition in the response are used to extract RDs in other channels. A FORTRAN code was written to extract both single and multi-channel RDs. The code allows the use of constant level crossing as a triggering condition as well as the use of a time interval that is different from that used to record the original data. This capability is needed in some cases for extracting higher mode shapes. Fig. 1 shows the multichannel signals, triggering condition, and times that correspond to the triggering levels. For more details about the approach, the reader may refer to [22,23]. Fig. 2 shows the RD results for each channel. The triggering condition at Channel 1 (Y1) is used as the base triggering value for all of the other channels. The values shown in Fig. 2 are used to extract the mode shape.

A fast Fourier transform (FFT) analysis helps to determine the number of modes excited. The mode shape of the structure is composed of a set of numbers at the same time lag as shown in Fig. 2; in this work, the first set of values (RD_1, RD_2, … , RD_n) are used. However, the other points still have the same information on the mode shape.