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Strain flexibility identification of bridges from long-gauge strain measurements

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ABSTRACT

Strain flexibility, defined as the strain response of a structure's element to a unit input force, is import for structural safety evaluation, but its identification is seldom investigated. A novel long-gauge fiber optic sensor has been developed to measure the averaged strain within a long gauge length. Its advantage of measuring both local and global information of the structure offers an excellent opportunity of developing the strain flexibility identification theory. In this article, the method to identify structural strain flexibility from long-gauge dynamic strain measurements is proposed. It includes the following main steps: (a) macro strain frequency response function (FRF) estimation from macro strain measurements and its feature characterization; (b) general strain modal parameter identification; (c) scaling factor calculation, and (d) strain flexibility identification. Numerical and experimental examples successfully verify the effectiveness of the proposed method.

1. Introduction

Structural health monitoring (SHM) aims at providing in-time information concerning structural safety condition by installing sensors and processing measured data [1,2]. Operational modal analysis (OMA), a technology to process the accelerations from ambient vibration tests, has been developed over 50 years [3–7]. Modal identification results (frequencies, damping ratios and mode shapes) from the OMA technology have direct relations with structural intrinsic parameters (mass, stiffness, damping), but they are too global to detect structural local damages. More detailed structural parameters, for instance, structural flexibility/stiffness, are much more useful for structural safety evaluation. Even there were investigations to identify structural flexibility from ambient vibration data [8,9], the more reliable way is to perform multiple-reference impact tests for flexibility identification [10,11]. Both accelerations and impacting forces are simultaneously measured during the impact test, thus the magnitudes of estimated frequency response functions (FRFs) are comparable to the analytical ones calculated from structural intrinsic parameters. In contrast, the FRF magnitudes estimated from ambient vibration test data are different with the analytical values [12]. This unique feature of the impact test method guarantees the flexibility characteristic be accurately identified. Brown and Witter [13] reviewed the multiple-reference impact test methods and the related flexibility identification theory. Aktan et al. [14] identified the flexibility matrices of a few short/middle span bridges by performing impact tests. Zhang et al. [11] successfully developed a flexibility identification

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method corresponding to mobile impact testing. Their results illustrated that the predicted static deflections from the identified flexibility agreed well with the measured deflections from static tests. The identified flexibility is important for bridge owners/engineers to understand stiffness distribution of the structure. It can also be used to predict structural deflection under any static load. Flexibility-based indexes have also been proved to be effective for structural damage detection [15,16].

The value of identifying flexibility from acceleration measurements has been realized by researchers and engineers, however, identifying the strain flexibility from strain measurements was rarely investigated. Strain gauge plays an important role in structural monitoring by providing direct-viewing strain responses [17], and strain measurements have been realized to be sensitive to local damages [18–20]. However, traditional strain gauges are point-type sensors which are only able to reveal structural local information. This limitation hinders the development of strain modal theory for global modal parameter identification.

The long-gauge fiber optic strain sensor developed recently [3,4,21,22] provides an excellent opportunity of developing the macro strain modal identification theory. It measures the averaged strain within a designed long-gauge length (e.g. 1–2 m), thus it has the feature of measuring both local and global information of the structure. The long-gauge sensor can also be connected in series for distributed sensing. Taking the advantage of the long-gauge FBG sensor as an opportunity, the theory of strain flexibility identification will be investigated by processing dynamic macro strain measurements. The proposed strain flexibility identification method will be an original contribution to the strain modal identification theory. It will also have clear engineering application potential for instance damage detection and safety evaluation of civil infrastructures.

In this article, the concept of the long-gauge fiber optic sensor is first presented. Then, the procedure of identifying strain flexibility from dynamic macro strain measurements is theoretically derived. This section includes strain FRF estimation and its feature characterization, strain modal parameter identification, scaling factor calculation, and strain flexibility identification. Numerical and experimental examples are investigated to verify the effectiveness of the proposed method for strain flexibility identification even in the mass unknown condition. Finally, conclusions are drawn.

2. Concept of the long-gauge FBG sensor

Traditional point-type strain gauges are limited to local measurements, thus they are not suitable for strain modal analysis for which aims at identifying global modal parameters. A kind of long-gauge FBG sensor as shown in Fig. 1(a) has been developed [22,23] to overcome that limitation. By designing the FBG sensor with a long gauge (e.g., 1–2 m) and fixing its two ends (Fig. 1(a)), the in-tube fiber has the same mechanical behavior of the structure, and hence the strain transferred from the shift of Bragg center wavelength represents the averaged strain over the long gauge length. An improved packaging design has also been developed to enhance the measuring sensitivity by utilizing composite materials to package the optic fiber and to impose deformation within the gage length largely on the essential sensing part of the FBG (Fig. 1(b)). The designed package also has the function to protect the sensor from high temperature, corrosion and humidity in a harsh environment. Due to its long gauge length, the developed sensor has the merit to measure the averaged strain in a large area of structural critical elements. It is much more suitable for strain modal analysis than the traditional point-type strain measurement from traditional strain gauges. The longer the sensor gauge length, the impact measurement within the gauge length will be more averaged. Moreover, the long-gauge sensors can be connected in series to make an FBG sensor array (Fig. 1(c)) for area sensing. The above features offer the developed sensor the advantage of measuring both local and global information of the structure. Therefore, it provides an excellent opportunity for developing the strain modal identification theory, for instance, identifying strain flexibility investigated in this article.

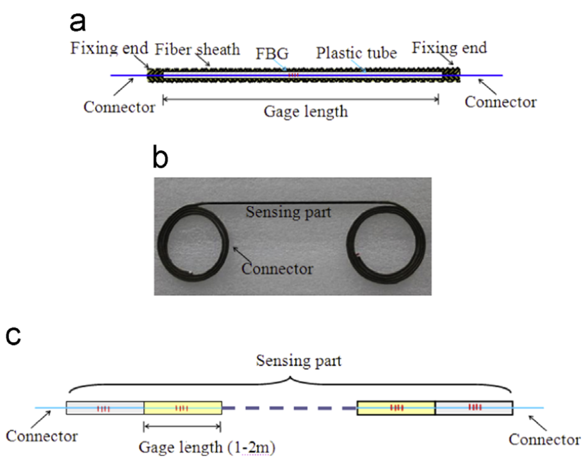

Fig. 1. Packaged long-gauge FBG sensor: (a) schematic picture, (b) actual sensor, and (c) sensor arrays.