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Simultaneously identifying displacement and strain flexibility using long-gauge fiber optic sensors

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ABSTRACT

The method of simultaneously identifying displacement and strain flexibility matrices of the structure is proposed by performing the multiple reference impact test and using long-gauge (LG) fiber optic sensors. This method has the following promising features: (1) The impact test is performed in which not only structure responses but also the input force are measured, which ensures the consistency between the identified Frequency Response Function (FRF) and the analytical one, thus it has the advantage of identifying structural flexibility. In contrast, the ambient vibration test cannot output FRF magnitudes. (2) The long-gauge fiber optic sensors are used to measure structure strain responses, which has the merit of reflecting both the macro and micro characteristics of a structure. Both strain and displacement flexibility are identified simultaneously by establishing the relation between LG strain and displacement through an improved conjugate beam method. (3) The subspace identification method in the time domain is developed for structural flexibility identification. It has the merit to deal with the test data with multi-reference multi-peak impacting forces which can better excite the dynamic characteristics of the structure, while traditional frequency domain methods generally are difficult to do that due to the leakage problem. Numerical and experimental examples have been studied to verify the validity and demonstrate the promising features of the proposed method.
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1. Introduction

Structural identification (St-Id) encompasses over decades of multidisciplinary research and development in structural dynamics, signal processing, mathematics, and engineering, and they still remain an active area of research [1]. The vibration-based SHM technology is commonly used for structure identification [2,3]. Operational modal analysis (OMA) could estimates structural modal parameters from ambient vibration test data [4,5]. Its limitation is that the magnitudes of the structural frequency response functions (FRFs) estimated from ambient vibration data are incorrect [6]. Thus, it is difficult to identify deep-level structural parameters such as flexibility. Impact testing has the advantage of estimating exact structural FRFs, including their magnitudes, by measuring both input and output data, giving it the potential to identifying structural flexibility.

Structural flexibility could predict the structural deflections under any static load, and it was also shown that the modal flexibility was a sensitive diagnostic indicator compared with the natural frequency or mode shapes [7]. So impact testing

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have more potential to directly support decision-making of bridge maintenance and management. In the traditional understanding, it is very difficult to apply impact testing to field tests. But with the development of large, powerful and autonomous impacting devices, the rapid impact testing of civil structures, especially small and medium span bridges, is of increasing interest to researchers and engineers. For instance, DeVitis et al. [8] proposed the rapid impact test methodology by developing a vehicle equipped with a mobile impacting device for convenient structural vibration tests. Zhang et al. [9,10] subdivided the structure into sub-structures for rapid impact testing, in which the experimental data of sub-structures were integrated for flexibility identification of the entire structure. Zhang et al. [11,12] firstly put the exciter in the truck to excite the bridge while moving and then a moving exciter is proposed by installing a tire pressure sensor on the car's tires and building the relationship between the tire pressure and the contact force between the tire and the bridge.

The structural identification method should be investigated to adapt the rapid impacting test. Many structural identification methods exist for impact testing [6,9], but two main categories can be defined, according to the data processing method used in the algorithms: the frequency domain method and the time domain method. The frequency domain method, such as the complex mode indicator function (CMIF) method [13], suffers from the leakage problem when the impacting force has multiple peaks. But such kind of input force are preferred for sufficiently exciting the bridge to obtain enough dynamic characteristic. In this sense, the time domain method is more suitable for the field-testing. The subspace identification technology is a classical time-domain identification method [14]. Input–output subspace identification has been less investigated in the past than its output-only counterpart, cause only system matrix A and C are needed when modal parameters are estimated. In the present paper this complete system matrix identification has been used. Once the complete system matrix are identified, not only the modal parameters can be identified but also the modal scaling factors can be identified at the same time [15]. Then the structural flexibility can be assembled with the identified modal parameters and the modal scaling factors.

However, modal identification results from acceleration measurements are too global to directly support decision-making of bridge maintenance and management [10]. As an alternative way of measuring structural responses, strain gauge has the capacity to monitor structural local information. Traditional strain gauges are point-type sensors while civil structures generally are large-scale and complex. To overcome the shortcomings of accelerometers and point-type strain gauges, the long-gauge strain sensing technique have been developed recently [16,17]. The long-gauge Fiber Bragg Grating strain sensor developing recently provides a great opportunity for further development of the long-gauge (LG) strain modal identification theory. Strain flexibility, defined as the strain response of a structure's element to a unit input force, is important for structural safety evaluation, but its identification is seldom investigated [6]. Zhang et al. [6] extended the CMIF method to identify structural strain flexibility by processing the measured strain response and the single-peak impacting force. But it still suffer the limitation as mentioned above: the frequency-based flexibility identification methods are sensitive to the input force type and suffer from the leakage problem, which is not adaptive to the field-testing.

In this paper, the method of simultaneously identifying displacement and strain flexibility matrices of the structure is proposed by performing the multiple reference impact test and using LG fiber optic sensors. Firstly, the time domains strain flexibility identification method is proposed through the establishment of the state-space model for long-gauge strain output. Then, using the merit of reflecting the macro and micro characteristics of a structure, both strain and displacement flexibility are identified simultaneously by establishing the relation between LG strain and displacement through an improved conjugate beam method. This article is structured as follows. In Section 2, the idea of simultaneously identifying displacement and strain flexibility is proposed by using the advantages of the impact test extracting FRF magnitudes and the LG strain measurement reflecting both the macro and micro characteristics of a structure. In Section 3, a state-space model for long-gauge strain output is built. In Section 4, displacement and strain flexibility are identified simultaneously by using the improved conjugate beam method to establish the relation between LG strain and displacement mode shapes. In Sections 5 and 6, the validity of the proposed method is verified by a numerical example of a three-span prestressed concrete bridge and an experiment example of a simply supported beam respectively. Finally, the conclusion is drawn in Section 7.

2. Idea of the bridge rapid impact test with long-gauge FBG sensors

Bridge rapid impact testing using the moving vehicle equipped with the exciting force generator has been studied [18,19], in which accelerometers are used to measure structure responses. In this paper, the method of bridge impact test using long-gauge fiber optic sensors is proposed as shown in Fig. 1, in which long-gauge FBG sensors are connected in series to make a sensor network to record the long-gauge strain response of the structure during the impact testing.

The above idea has two promising features. Firstly, multiple reference impact test is performed on the bridge during which both the input force and the strain response are measured, thus the estimated Frequency Response Function (FRF) is consistent with the analytical one as shown in Fig. 1(b). In contrast, FRF amplitudes cannot be estimated from OMA. This feature guarantees that deep-level structural information such as flexibility can be estimated. Secondly, the LG sensor utilized in the proposed method provides the opportunity to identify both the strain and displacement flexibility characteristics. The scheme of a packaged LG fiber optic sensor is shown in Fig. 1(c). Its principle feature is that the handling of an embedded tube inside which a bare optic fiber with FBG is sleeved and fixed at two ends to ensure the measured value representing the averaged strain over the gauge length. The effective sensing gauge length can be extended to several centimeters or meters through special design and manufacturing. Long-gauge strain sensors can be connected in series to make a

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