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Multi-type sensor placement and response reconstruction for structural health monitoring of long-span suspension bridges

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Abstract This study is devoted to the experimental validation of the multi-type sensor placement and response reconstruction method for structural health monitoring of long-span suspension bridges. The method for multi-type sensor placement and response reconstruction is briefly described. A test bed, comprising of a physical model and an updated finite element (FE) model of a long-span suspension bridge is also concisely introduced. The proposed method is then applied to the test bed; the equation of motion of the test bed subject to ground motion, the objective function for sensor location optimization, the principles for mode selection and multi-type response reconstruction are established. A numerical study using the updated FE model is performed to select the sensor types, numbers, and locations. Subsequently, with the identified sensor locations and some practical considerations, fiber Bragg grating (FBG) sensors, laser displacement transducers, and accelerometers are installed on the physical bridge model. Finally, experimental investigations are conducted to validate the proposed method. The experimental results show that the reconstructed responses using the measured responses from the limited number of multi-type sensors agree well with the actual bridge responses. The proposed method is validated to be feasible and effective for the monitoring of structural behavior of long-span suspension bridges.

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1 Introduction

Many innovative long-span suspension bridges have been built throughout the world to meet the social needs for efficient and convenient transportation systems. Because they are key components of national transportation network systems and require immense capital investment, the safety and functionality of the bridges become an important issue. Hence, the installation of comprehensive structural health monitoring (SHM) systems on such civil structures has become a trend [1–4]. The main objectives of the SHM for a long-span suspension bridge are to monitor its loading and response in real time, assess its operational performance under various service loads, verify or update design rules and assumptions, detect damage or deterioration, and guide its maintenance or repair work [5–7]. To reach these objectives, an in-depth understanding of the behavior and performance of the entire bridge is required. However, owing to the cost associated with data acquisition and the huge size of a long-span suspension bridge, sensors are often installed only at a few locations and the number of sensors are much less than the total degrees of freedom (DOFs) of the bridge structure. However, to successfully monitor the performance of a bridge structure, responses are often required at all its key locations, including the desired locations but not accessible for measurements during its operation. Thus, accurate response reconstruction at all the key structural locations using the measured responses from limited sensors is essential to achieve the SHM objectives.

Numerous techniques have been developed for optimal sensor placement (OSP). Information-based OSP methods have been studied by many researchers, in which the optimal sensor locations are so selected that they maximize the norm of the Fisher information matrix or its variants to provide maximum information on the state of a structure [8–10]. Barthorpe and Worden [11] provided a comprehensive review on OSP methods.

Nevertheless, the sensor network in the SHM system of a long-span suspension bridge has become increasingly complex in the past 10 years because of the practical demand for the SHM of long-span suspension bridges and the rapid advances in sensor technology. Some sensors (e.g., accelerometers and displacement transducers) are global sensors that measure global structural responses, whereas some sensors (e.g., strain gauges) are local sensors that monitor local structural responses. Although various sensors provide more comprehensive information and advanced features, their distinct properties and limitations considerably complicate the design procedure of sensor systems. Studies on the development of effective methods for the optimal placement of multi-type sensors that can integrate the information from both global and local sensors for better SHM are very limited. In this regard, we recently proposed sensor placement methods for the optimal configuration of dual-type and multi-type sensors [12–14]. The number and location of multi-type sensors were selected simultaneously through an optimization procedure with the aim of accurately reconstructing the multi-type responses. However, these studies were performed with respect to a simply supported beam only other than a long-span suspension bridge, in which many practical considerations have to be included. First, the geometric size of a long-span suspension bridge is significantly larger than that of a simple structure. The finite element (FE) model of the test bed of a suspension bridge investigated in this paper has a total of 23,700 DOFs, whereas the simply supported overhang beam used in Refs. [12–14] has 123 DOFs only. Second, the FE model of the suspension bridge test bed comprising deck, cable, and tower components has more element types than simple structures. The FE model of the suspension bridge test bed has beam, link, and shell elements, but the simply supported overhanging beam used in Refs. [12–14] has only beam elements. Moreover, the mode shapes of the suspension bridge test bed, including vertical, lateral, longitudinal, and torsional vibration modes, are more complex than those of simple structures. The vibration modes of the suspension bridge test bed are distributed in a manner that is close to one another. In addition, the suspension bridge test bed is supposed to be subjected to ground motion, making the objective function for the sensor location optimization and response reconstruction equation different from those used in Refs. [12–14]. Finally, structural responses of the suspension bridge test bed at some locations are extremely small that they are overwhelmed by noise. These responses are insignificant in the evaluation of the bridge performance and, thus, shall be ignored. There are also some locations where sensors are difficult to be installed. As a result, the implementation procedure of the multi-type sensor optimal placement and multi-scale response reconstruction method presented in Refs. [12–14] is reconsidered in this paper.

This study first briefly introduces the method for multi-type sensor placement and response reconstruction and the test bed of a long-span suspension bridge developed by the writers. The proposed method is then applied to the test bed; the equation of motion of the test bed subject to ground motion, the objective function for sensor location optimization, the principles for mode selection and multi-type response reconstruction are established. A numerical study using the updated FE model is performed to select the sensor type, number and location. Subsequently, with the identified sensor locations from the numerical study and some practical considerations, FBG sensors, laser displacement transducers, and accelerometers are installed on the physical bridge model. Finally, experimental investigations are conducted to examine the accuracy of the selected multi-type sensor locations by comparing some of the reconstructed responses with the measured responses at locations where additional sensors are installed. The experience obtained from this exercise can shed light on the application of the proposed method to real long-span suspension bridges.

2 Methodology

A brief review of the method for multi-type sensor placement and response reconstruction proposed by Zhu et al. [14] is given below.

2.1 State-space equation

The dynamics of a structure with the observation of some responses can be described by the following state-space equation [15]:

$$\begin{cases} \dot{\boldsymbol{z}} = \boldsymbol{A}_{\mathrm{c}}\boldsymbol{z} + \boldsymbol{B}_{\mathrm{c}}\boldsymbol{u}, \\ \boldsymbol{y} = \boldsymbol{C}\boldsymbol{z} + \boldsymbol{D}\boldsymbol{u}, \end{cases} \tag{1}$$

where $\boldsymbol{z}$ is the state vector; $\boldsymbol{A}_{\mathrm{c}}$ and $\boldsymbol{B}_{\mathrm{c}}$ are the state matrix and input matrix, respectively; $\boldsymbol{u}$ is the external excitation vector; $\boldsymbol{C}$ and $\boldsymbol{D}$ represent the output matrix and direct transmission matrix, respectively; and $\boldsymbol{y}$ is the observation vector. In reality, the measurement data are discretely sampled and the measurement noise and processing noise