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Structural identification of cable-stayed bridge under back-to-back typhoons by wireless vibration monitoring

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ABSTRACT

In this paper, structural identification of a cable-stayed bridge under back-to-back typhoons is performed using vibration responses measured by a wireless sensor system. Firstly, a cable-stayed bridge with the wireless monitoring system is described. Wireless vibration sensor nodes are utilized to measure accelerations from the deck, pylon and stay cables of the bridge. Secondly, dynamic responses of the cable-stayed bridge under the attack of two consecutive typhoons, Bolaven and Tembin, are analyzed under various wind speeds. Stochastic subspace identification method and short-time Fourier transform analysis are selected to examine wind-induced variations of the bridge's responses based on the field measurements under the two typhoons. Finally, the structural identification of the bridge is performed under various wind velocities to examine the typhoon-induced variations of the bridge's structural properties. The variations of dynamic characteristics due to the typhoons are turned into the changes of the bridge's stiffness (or flexibility) via the fine-tuning process.

1. Introduction

For the safety and serviceability designs of the long-span cable-supported bridges, the bridge aerodynamic is regarded as a critical concern [5,9,15,43,44,50]. To ensure the design assumptions and to monitor the structural performance, structural health monitoring (SHM) systems have been commonly installed in the bridges [1,22,31,59,60]. Recently, great developments in smart sensing technologies have led to a new paradigm for the SHM field. Many research attempts have been made to develop wireless sensor systems that can allow autonomous operation and cost-efficient implementation for SHM applications [8,17,21,24,26,37,41,48,53].

Hwamyung Bridge, a cable-stayed bridge with the prestressed concrete box girder in Busan, Korea, has been monitored by adopting the smart sensing technologies [18,45]. The long-term performance of the wireless monitoring system of the bridge has been evaluated for the vibration measurement, the wireless communication, the capacity of solar-powered supply, and the survivability of sensors [18]. By the end of August 2012, two consecutive typhoons named Bolaven and Tembin passed through the Korean peninsula and affected the site of the bridge. During the attack of the typhoons, the acceleration response of the bridge was wirelessly recorded from a few survived sensor nodes. Kim et al. [29] and Park et al. [49] have reported the performance of the wireless monitoring system and the wind-induced variation of the bridge's dynamic characteristics during the typhoons.

The aerodynamics (e.g., turbulence, vortex, buffeting, galloping) are often coupled with the dynamic responses of the cable-supported bridges [4,33,39]. It has been

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reported that the natural frequencies of the cable-supported bridges decrease as the results of increasing the structural flexibility when the wind velocity increases [14,29]. One important issue in the bridge aerodynamic is the non-stationary dynamic responses due to the vortex shedding during the typhoon. To extract the instantaneous changes in modal parameters induced by the typhoon, therefore, non-stationary random vibration responses should be dealt appropriately. As another remaining issue, the relationship between the wind velocity and the structural flexibility (or stiffness) of the bridges should be quantitatively proved by estimating the wind-induced variation of the structural stiffness. The above-mentioned issues could be solved when identifying the structural properties of the bridges under the change of wind velocities.

Over the past decades, many research efforts have been made for various aspects of system identification and model updating [13,20,23,40,54,57,60]. A process to fine-tune the structural and geometrical parameters of the numerical model (e.g., finite element (FE) model) to reproduce the measured structural responses of the real structure is usually known as structural system identification [2]. The fine-tuned numerical model can be used as the reference for the future assessment of the structure's health status. The structural system identification methods could be classified into non-iterative methods and iterative parameter updating methods [3,13,23]. The non-iterative methods usually refer to one-step process that can directly determine the structural properties (e.g., mass and stiffness matrices) of the numerical model. Meanwhile, the iterative methods use multi-step procedures to identify the structural parameters which are sensitive to the dynamic behaviors of the updating structure. In practice, the iterative updating methods are usually preferred since they can maintain the structural connectivity and provide the physically meaningful fine-tuning results in most cases.

A number of iterative updating algorithms have been developed for the area of structural system identification [13,23,35,36,54]. Among those methods, modal sensitivity (or flexibility)-based algorithms have been popularly applied and successfully identified baseline numerical models of various types of structures [7,19,28,32,34,56]. By using the modal sensitivity-based approach, Zhang et al. [61] updated the FE model of the Kap Shui Mun Bridge (Hong Kong), Brownjohn and Xia [6] updated the initial FE model of the Safti Link cable-stayed bridge (Singapore), and Kim et al. [28] identified structural parameters of the Hwamyung cable-stayed bridge (Korea) under ambient excitation conditions. Despite those research attempts, the structural identification of cable-stayed bridges under strong wind conditions has not been studied so far.

In this paper, the structural identification of a cable-stayed bridge under back-to-back typhoons is performed using vibration responses measured by a wireless monitoring system. Firstly, a cable-stayed bridge with the wireless monitoring system is described. Wireless vibration sensor nodes are utilized to measure accelerations from the deck, pylon and stay cables of the bridge. Secondly, dynamic responses of the cable-stayed bridge under the attack of two consecutive typhoons, Bolaven and Tembin, are analyzed under various wind speeds. Stochastic subspace identification method and short-time Fourier transform analysis are selected to examine wind-induced variations of the bridge's responses based on the field measurements under the two typhoons. Finally, the structural identification of the bridge is performed under various wind velocities to examine the typhoon-induced variations of the bridge's structural properties. The variations of dynamic characteristics due to the typhoons are turned into the changes in the bridge's stiffness (or flexibility) via the fine-tuning process. Then, the relationship between the wind velocity and the structural stiffness of the deck and pylon is examined to identify an appropriate modal analysis method for investigating the dynamic behaviors of the cable-stayed bridge under the typhoons.

2. Wireless monitoring of cable-stayed bridge under typhoons

2.1. Hwamyung cable-stayed bridge

Hwamyung Bridge, completed in 2011, is located on the Nakdong River to connect Gimhae-si, Gyeongnam province with Hwamyeong-dong, Busan, Korea (see Fig. 1). The bridge has a total length of 1414 m, a width of 17.9–27.8 m (four lanes), and a design speed of 80 km/h. The bridge consists of a two-pylon concrete cable-stayed bridge with a length of 500 m, five steel box girder bridges with a total length of 834 m, and a ramp bridge with a length of 80 m. As a cable-stayed bridge with the prestressed concrete box girder in Busan, Korea, the two-pylon cable-stayed bridge has three spans including a 270 m long mid-span and two 115 m long side-spans, and total 72 multi-strand type stay cables. More detailed information of the bridge can be found in Ho et al. [18].

2.2. Wireless monitoring system

Based on the design of Imote2-platformed vibration measurement system [18,42,52], a typical wireless sensor node was designed, as shown in Fig. 2. A solar panel (SPE-350-6) and a rechargeable battery (Powerizer 3.7 V, 10,000 mA h) were used to harvest the solar-power energy for each sensor node (see Fig. 2(a) and (b)). The sensor prototype consists of a battery board, an Imote2 sensor platform provided by Memsic Co. [38], and a SHM-H or a SHM-A sensor board (see Fig. 2(c)).

The SHM-H sensor board was utilized to measure the acceleration responses of the deck and pylons of the cable-stayed bridge. This sensor board was designed with a SD1221 accelerometer for high-sensitivity channel, the input range ±2*g*, the sensitivity 2 V/*g* and the output noise 5 $\mu g/\sqrt{\text{Hz}}$ [25]. For the cable's acceleration measurement, the SHM-A sensor board was used. The SHM-A board was designed with a tri-axial LIS344ALH accelerometer which has relatively lower sensitivity and higher output noise than the SHM-H board. Its core component is the 16 ADC with digital filter, QF4A512 ADC, for signal conditioning with customizable sampling rates. A 2.4 GHz surface