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Damping Identification of Bridges Under Nonstationary Ambient Vibration

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ABSTRACT

This research focuses on identifying the damping ratio of bridges using nonstationary ambient vibration data. The damping ratios of bridges in service have generally been identified using operational modal analysis (OMA) based on a stationary white noise assumption for input signals. However, most bridges are generally subjected to nonstationary excitations while in service, and this violation of the basic assumption can lead to uncertainties in damping identification. To deal with nonstationarity, an amplitude-modulating function was calculated from measured responses to eliminate global trends caused by nonstationary input. A natural excitation technique (NExT)-eigensystem realization algorithm (ERA) was applied to estimate the damping ratio for a stationarized process. To improve the accuracy of OMA-based damping estimates, a comparative analysis was performed between an extracted stationary process and nonstationary data to assess the effect of eliminating nonstationarity. The mean value and standard deviation of the damping ratio for the first vertical mode decreased after signal stationarization.

1. Introduction

The damping ratio is known to have a strong correlation with the occurrence of vortex-induced vibration in long-span bridges [1,2]. To estimate the damping ratios of long-span bridges, many researchers have utilized output-only operational modal analysis (OMA), instead of using heavy exciters that would require the temporary closure of bridges in use. One of the important assumptions of output-only OMA is that a structural system should be under stationary ambient vibration. However, nonstationary loads such as earthquakes, extreme winds, and traffic are the main sources of excitation in civil infrastructures, and these loads cause nonstationary responses [3–5]. Thus, the violation of excitation conditions for the basic assumption of a classic OMA could be one of the reasons for poor estimation of damping ratios.

Traffic loads are the main loading source for bridges [6,7], and can be expressed as a stationary random process since the roughness of a road is modeled as a zero-mean stationary Gaussian random process [8]. However, when traffic volume is low, an ambient vibration signal at the sensor position is seen as an envelope as a vehicle approaches and fades away. The traffic-induced vibration (TIV) observed at a specific position can be read as a nonstationary process that is expressed as a product of stationary white noise and an envelope-like function [9]. As a result, the accelerations of loads across a bridge subjected to traffic loads were localized [8] for specific positions.

Traffic loading usually excites the structural modes that correspond to vehicle frequencies. The *Ontario Highway Bridge Design Code* [10] recommends increasing the amplification factor when the dominant natural frequencies of a structure range from 2 Hz to 5 Hz, and the American Association of State Highway and Transportation Officials (AASHTO) specifies that the frequency of general trucks should be 2.5 Hz [11]. Bartos [11] also suggested that the dynamic amplification effect could exceed limitations when the structural frequencies are between 1.5 Hz and 5 Hz. The vehicle-bridge interaction is also distorted by driving frequencies, which are dependent on the duration of a vehicle crossing a single stringer [12,13]. Brewick [14] discovered that these distortions of modal information increase the uncertainty of a damping estimation based on OMA schemes.

This study focuses on nonstationarity due to traffic loading, and its effect on OMA-based damping estimation. The effect of traffic loading was examined via the field-measured data from a

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suspension bridge. A signal stationarization algorithm was proposed by introducing an amplitude-modulating (AM) function, and was applied to the operational monitoring data obtained from a suspension bridge for damping estimation.

2. Investigating the TIV of a suspension bridge

2.1. The Sorok Bridge

The Sorok Bridge (Fig. 1) is a self-anchored mono-cable suspension bridge in Korea connecting Sorok Island with the mainland. The bridge has a total length of 470 m, which consists of a 250 m main span and two symmetric side spans of 110 m. The total width of its steel box girders is 15.7 m, which provides two traffic lanes. The bridge was opened to traffic in March 2009. Since then, a series of dynamic tests have been carried out for detailed inspections and model updates for maintenance. Table 1 summarizes the modal frequencies of the bridge, as identified by OMA using frequency domain decomposition (FDD) of the data obtained from ambient vibration testing (AVT). Table 1 also includes the calculated natural frequencies obtained from the updated finite element model based on manual tuning and a parameterized sensitivity-based model updating approach [15,16]. The coincidences between the measured and calculated frequencies are shown in Table 1.

2.2. Data acquisition from AVT

Two accelerometers deployed at the center of the main span were utilized to measure the vertical acceleration of the deck with a sampling frequency of 100 Hz. The corresponding displacement of the deck was simultaneously measured using a laser displacement transducer equipped as a built-in sensor for the monitoring of the operational behavior of the bridge. Wind direction and wind velocity were recorded via an ultrasonic anemometer installed on the bridge deck. The available data were divided into 10 min intervals for an in-depth investigation.

Even though the field tests were basically planned to secure data from AVT, a heavy truck was also prepared to create the high-level excitation of an operating condition. A series of measured accelerations from the suspension bridge were analyzed to confirm the properties of the TIV. In particular, two types of testing—a truck-loading test and an ambient vibration test using normal vehicles—were considered in order to investigate the characteristics of TIV according to different types of vehicles. The truck-loading test was performed using a three-axle truck with a total mass of 25 t at speeds of 25 $km \cdot h^{-1}$ and 40 $km \cdot h^{-1}$. The bridge was not closed to normal traffic, but the latter would have been relatively minor in weight compared with the truck and would have been of little value in investigating truck-induced vibration.

Fig. 1. The Sorok Bridge.

Table 1
The modal frequencies of the Sorok Bridge.

Mode	AVT (Hz)	Calculated (Hz)
1st vertical	0.406	0.403
2nd vertical	0.478	0.463
3rd vertical	0.839	0.829
1st lateral	0.521	0.521
1st torsional	1.550	1.530

2.3. Nonstationary characteristics in TIV

To examine the nonstationary effect caused by traffic loading, a stationary response was utilized as a reference, which satisfied the assumptions of classic OMA. To select a stationary response from among the set of operational monitoring data, the kurtosis value was evaluated for a series of vibration data. The kurtosis value data were lower than 10 and contained no peak responses that could be classified as stationary [17]. In particular, the highest wind velocity was selected to represent the stationary data in order to secure a high signal-to-noise ratio.

The TIV data statistics are summarized in Table 2. In Table 2, the TIV data induced by the truck loading are referred to as "heavy truck," while the vibrations measured during normal operations are classified as "ordinary vehicle."

The stationary excitation data shown in Fig. 2 has no extreme peaks due to passing vehicles, and the kurtosis value was identified as 4.17, which indicates a stationary status. The power spectral density (PSD) shows that the main structural modes—the first (0.415 Hz) and third vertical modes (0.842 Hz)—were dominant.

In contrast, as shown in Fig. 3, the structural modes around 2 Hz were amplified when a heavy truck passed over the bridge. As a truck entered the main span, the amplitude increased gradually, and invoked a nonstationary response. The kurtosis value was 12.47, which exceeded the criterion for a stationary mode.

Ordinary vehicles also amplified a higher mode of structures compared with a stationary mode, as shown in Fig. 4. The structural modes of 4–5 Hz were excited by lighter vehicles that excited relatively higher frequencies. The kurtosis value was 49.69, which exceeded the stationary criterion of 10, and indicated a nonstationary mode.

Fig. 5 represents the time-frequency distribution calculated using a short-time Fourier transform. A Hamming window was used to calculate a spectrogram with segment lengths of 2^{13} and a 50% overlap. Fig. 5 clearly shows that the higher structural modes of 2–5 Hz were particularly excited when a vehicle crossed the bridge.

3. Signal stationarization using amplitude-modulating function

3.1. Amplitude-modulating function

Chiang and Lin [18] proposed a method for the identification of modal parameters from response data gathered from a structure

Table 2
Statistics of TIV and corresponding wind velocity.

	Vibration categorized as stationary	Vibration induced by heavy truck	Vibration induced by ordinary vehicle
Root-mean-square (Gal)[a]	0.49	2.61	1.74
Peak (Gal)	2.98	21.82	26.08
Kurtosis	4.17	12.47	49.69
10 min averaged wind velocity ($m \cdot s^{-1}$)	8.81	6.91	2.43

[a] 1 Gal = 1×10^{-2} $m \cdot s^{-2}$.

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