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Operational field monitoring of interactive vortex-induced vibrations between two parallel cable-stayed bridges ☆

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ABSTRACT

An in-depth study was conducted on interference VIV between two parallel cable-stayed bridges with respect to the mutual motion of both decks downstream as well as upstream. The mechanical damping ratios of both bridges were estimated by the Natural Excitation Technique (NExT) combined with the Eigen Realization Algorithm (ERA) method. The test setup in a wind tunnel takes two wind directions as well as the identified damping ratios of both decks into consideration. The findings, based on parametric wind tunnel tests, suggest that interference VIV is possible, even in the downstream area of the bridge although this has not been reported before. However, the higher lock-in velocity as well as the higher damping ratio of the downstream bridge would be expected to decrease the possibility of VIV. The interactive behavior was further examined using field monitoring data and the results were in good agreement with the findings obtained in wind tunnel tests, in terms of the threshold wind velocity, the frequency components of the motion and the amplitude ratio between the two bridges. Unfortunately, however, a strong wind was not observed opposite to the main wind direction and it was not possible to confirm the interactive behavior for this situation.

1. Introduction

As the volume of traffic increases, the necessity of building new bridges in the form of a parallel bridge has become a necessity. The Tacoma Narrow Bridge, the Puente Juan Pablo Duarte (Larsen et al., 2000) and the Haihe Bridge (Meng et al., 2011) are examples of recently constructed parallel cable-supported bridges. The Jindo Bridge (Fig. 1) is one of the parallel bridges adopting cable-stayed structural systems. The First Jindo Bridge was built in 1984 and the Second Jindo Bridge was opened to traffic in 2005. For convenience, the First Jindo Bridge is hereafter referred to as Bridge 1 and the Second Jindo Bridge as Bridge 2. Vortex-induced vibrations (VIVs) have been reported a few times in the case of Bridge 2, since it has opened to traffic.

Interference effects between two parallel cable-stayed bridges was investigated by Kimura et al. (2008), who reported governing factors through wind tunnel tests. Meng et al. (2011) proposed a mitigating measure of the interference effect for two adjacent cable-stayed bridges. It was concluded that gap distance as well as deck shape were dominant parameters that affect the interference effect in both studies. However, the more intensive studies were also recommended, in order to expand our general insights related to this complicated interactive behavior.

On April 19, 2011, a significant VIV with a duration of one hour was detected in Bridge 2, as shown in Fig. 2. The single amplitude of acceleration exceeded the recommended value of 0.5 m/s^2 (Korean Society of Civil Engineers (KSCE), 2006) and double amplitude of displacement reached 0.4 m at the center of the main span in Bridge 2 located upstream. Since the noticeable vibration in the upstream deck was an interesting phenomenon, a series of wind tunnel tests were performed in an attempt to identify the main sources of VIV (Seo et al., 2013). The study pointed out that the amplitude of the VIV in Bridge 2 was sensitive to the mechanical damping of the bridge. The estimated damping ratio of Bridge 2 was lower than the design value and this was proposed to constitute one of the sources of the VIV. It was also

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Fig. 1. The parallel twin Jindo Bridge.

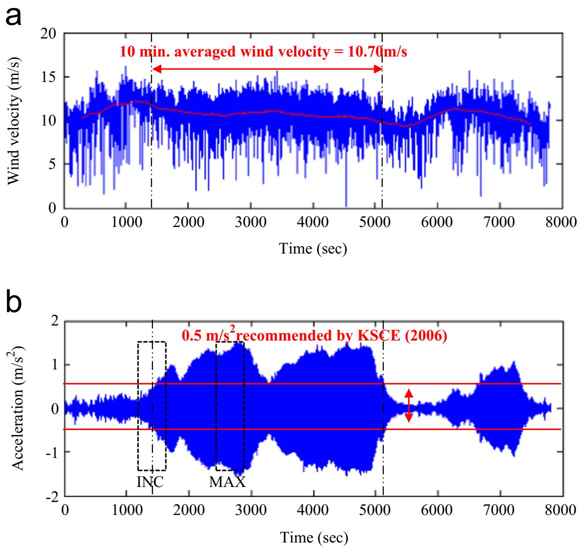

Fig. 2. Observed wind velocity and interference VIV at the center of the main span in Bridge 2: (a) wind velocity and (b) acceleration.

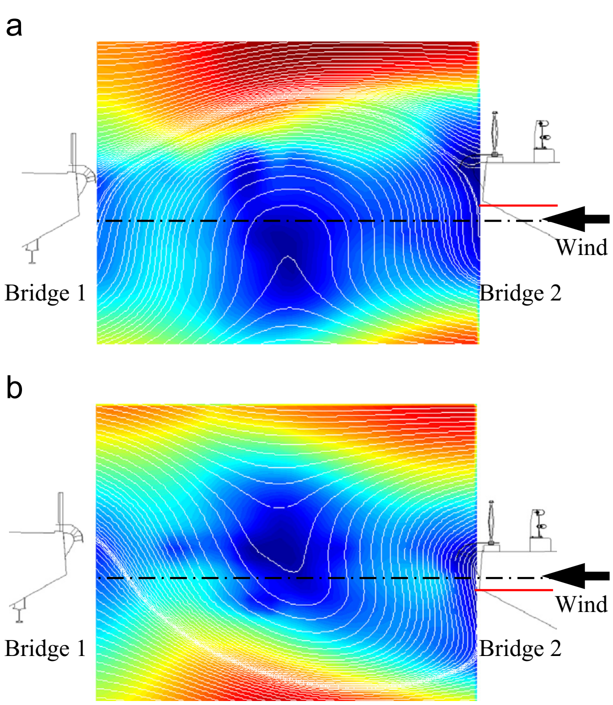

Fig. 3. Alternating "Ω" and "℧" shaped large vortexes between two decks during the significant VIV in the Bridge 2 at the moment the deck reaches: (a) top position and (b) bottom position.

found that large vortexes were developed between two decks with alternating "Ω" and "℧" shaped streamlines, as shown in Fig. 3. Seo et al. (2013) traced the pattern of the streamlines and flow speeds between the two decks and successfully demonstrated an interference effect on the upstream deck. However, the study mainly focused on the motion of the upstream deck which was subjected to a huge VIV.

Fig. 3 shows that the large vortex streams developed behind Bridge 2 upstream and pass through Bridge 1 downstream. Consequently, it is possible that the vortex streams could affect the motion of, not only Bridge 2, but Bridge 1 as well even though Bridge 1 unaffected by the huge VIV in 2011. At this moment, several questions can be raised. Is the interference VIV only observable in Bridge 2? Otherwise, what are the conditions required for the interference VIV for Bridge 1 to be observed and why have VIVs not been reported yet for Bridge 1? In addition, VIVs in Bridge 2 have been reported only a few times in spring seasons after the opening of the bridge. What conditions need to be satisfied for observing a significant VIV in Bridge 2?

According to Seo et al. (2013), several factors may be involved in answering these questions, including the main wind direction and the differences between the inherent damping ratios and the triggering wind velocities for the two bridges. Accordingly, more in-depth analyses should be conducted to clarify the interactive behaviors between bridges by taking these potential parameters into consideration.

Based on these research backgrounds, parametric wind tunnel tests were carried out for the two scaled parallel decks mounted on spring supports. The order of disposition of the two decks can be changed, as a function of the wind direction. The mechanical damping ratios were set to the values identified from an operational modal analysis. The interactive behaviors were also investigated with field data obtained from the built-in monitoring system of two bridges. The monitoring data covers a wide range of excitations in both bridges including a typhoon as well as daily winds. The overall field observations were in good agreement with the result of wind tunnel tests and demonstrated the interesting interactive behaviors between two bridges.

2. Identification of damping ratios from an operational modal analysis

2.1. Built-in sensors and three-day monitoring of vibration

Since the amplitude of the interference VIV in the upstream bridge was found to be sensitive to the mechanical damping ratio (Seo et al., 2013), the identification of the actual structural damping ratio of two bridges would be a starting point of investigation on interactive behavior. Acceleration data accumulated for three days between 2012/10/15 10:00 and 2012/10/17 24:00 were utilized for the operational modal analysis. During the period, the bridges were subjected to ambient vibrations cause by the movement of traffic as well as ambient, daily winds.

The vertical accelerations of bridge deck were monitored at the center of the main spans in both bridges. The vertical responses of the decks were obtained by averaging two vertical accelerations at both sides of the cross-section. Unfortunately, one of the accelerometers in Bridge 1 was not functioning at the time of measurement, and the vertical acceleration at the other side of the cross section is only utilized by ignoring the contribution of the torsional motion of the deck.

Fig. 4 shows the built-in sensors utilized in this study. Acceleration was measured in gal (cm/s^2) with a sampling frequency of 100 Hz. Wind direction and wind velocity were also recorded by ultrasonic anemometers that were installed on Bridge 2 and Bridge 1 at a height of 3 m from the top of decks, respectively. Even though both anemometers were connected to the same data