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Observed along-wind vibration of a suspension bridge tower

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ABSTRACT

Single-frequency along-wind oscillation under moderate wind velocity was observed on a leeward leg of an H-shaped 132 m suspension bridge steel tower. The oscillation occurred at particular wind velocity range (13–24 m/s) and angle of attack. Two dominant single-frequency oscillations, namely, 0.6 Hz and 0.8 Hz were observed and they had characteristics that resembled the vortex-induced vibration. The single-frequency oscillations 0.6 Hz and 0.8 Hz were related to the tower local in-phase and out-of-phase mode, respectively. Outside the wind velocity range of 13–24 m/s or when wind direction is perpendicular to the tower, the tower responses were mainly characterized by random responses with buffeting trend. The single-frequency tower oscillation influenced girder lateral vibration in that the coupling tower in-plane and girder lateral mode substantially increased the girder lateral vibrations. Wind tunnel experiment on tower model was carried out to investigate the phenomenon under various wind angles of attack and velocities. The results show that under certain angle of attack the bluff body of the windward tower leg created vortex shedding as indicated by the presence of single-frequency oscillation of the wind in front of leeward tower. The vortex shedding generated a periodic force towards the leeward leg that coincides with the tower natural frequency 0.6 Hz and 0.8 Hz in the wind velocity range of 13–17 m/s and 17–24 m/s, respectively, causing in-plane resonance.

1. Introduction

As bridge spans get longer and towers get taller, they become more flexible and prone to vibrate. Steel towers used extensively for cable-supported bridges in Japan are much lighter than concrete towers and consequently are more susceptible to vibrate under wind when the height of the towers exceeds 100 m (Fujino et al., 2012). Tall long-span bridge towers frequently show aerodynamic instability such as vortex-induced oscillations during free standing construction stage (Fujino, 2002; Fujino et al., 2012; Kitagawa, 2004; Larose et al., 1998). They occur mostly in the crosswind direction when the tower local natural frequency coincides with the vortex shedding frequency resulting in resonance oscillation on the tower weak axis. In along-wind direction, there is also report that describes the in-line vortex vibration of a freestanding suspension bridge tower (Larose et al., 1998).

To mitigate the effect of vibration during construction process, temporary vibration control measures such as tuned-mass-damper, tuned-liquid damper and active control system are sometimes required (Fujino et al., 2012; Fujino, 2002; Kitagawa, 2004). Although vortex-induced vibration of tower may not create instability problem, excessive vibration on the tower especially the steel one amid low damping may influence bridge service and eventually result in fatigue damage. To avoid this, aerodynamic countermeasures such as cutting off the corners (Takeuchi, 1990; Shiraishi et al., 1988; Ogawa et al., 1990) or making slits and attaching the aerodynamic appendages, such as deflectors and side-plates are commonly applied (Fujino et al., 2012).

While usually observed during the freestanding construction stage, the occurrence of vortex-induced vibration on the tower of a completed suspension bridge is very rare. In this paper, we present analysis on full-scale measurement of a long-span suspension bridge during strong-wind events, where significant tower in-plane and girder lateral vibrations were observed. The tower in-plane vibration is characterized by single-frequency oscillation in a harmonic-like motion that resembles the vortex-induced vibration. The single-frequency along-wind oscillation is influenced by wind velocity and angle of attack between wind and tower. The paper describes in detail the extent and mechanism of tower and girder lateral vibration using measurement results, finite element model and wind tunnel experiment.

2. Description of the bridge and monitoring system

Hakucho Suspension Bridge is the largest suspension bridge in northeastern Japan. Located in Muroran Gulf, Hokkaido Prefecture, the bridge connects the Muroran Port in the south and the Muroran

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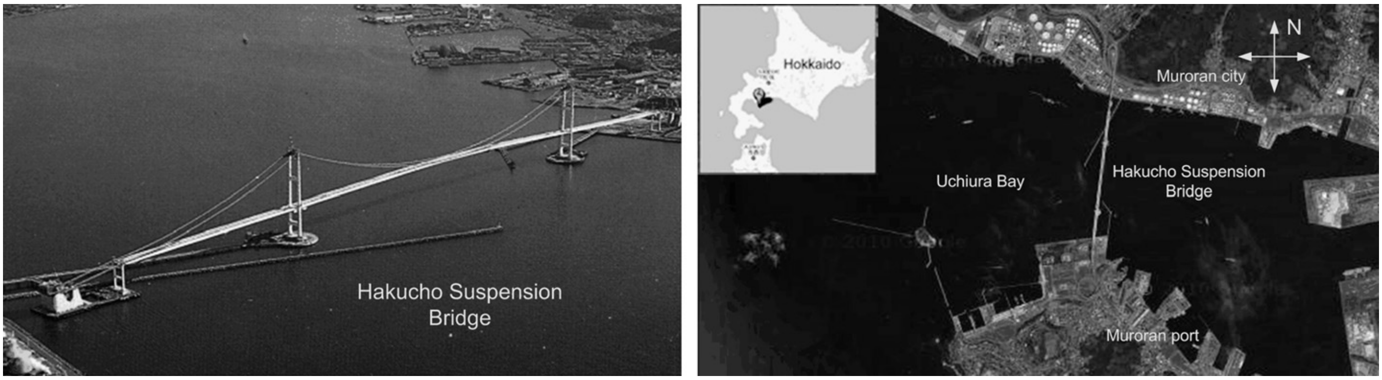

Fig. 1. View and map of Hakucho Suspension Bridge.

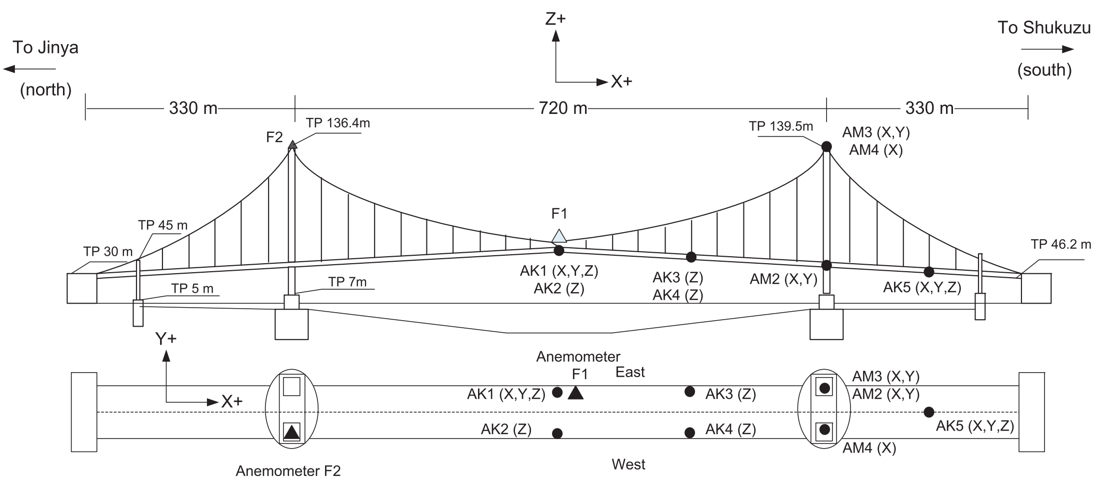

Fig. 2. Hakucho Suspension Bridge monitoring system. *Note*: Accelerometers AK are placed on girder and AM on tower. X, Y, Z denote the measuring directions, F1 and F2 are the anemometers (F1 is on the east side of the center span and F2 is on the west leg of north tower).

City in the north. Total length of the bridge is 1380 m consisting of 720 m center span and two symmetric side spans of 330 m. The bridge was opened to public on June 13, 1998. Bridge towers are 132 m high and 21 m wide giving the suspension cable a sag ratio of 1:10. They are made of steel box and connected by welding. The cross-sectional dimension of tower leg is 5 m × 3.6 m on the base and gradually tapered to 3.2 m × 3.6 m on the top. Bridge girder is a streamlined steel box with the width of 23 m and maximum web height of 2.5 m. The three spans are discontinuous, connected by bearings and extension devices and simply supported at the towers (Fig. 1).

The bridge has permanent wind and seismic monitoring system that consists of 27 channels of vibration sensors placed on fourteen locations. They include twenty-two channels of uniaxial accelerometer, two uniaxial displacement sensors, and a triaxial free-field strong-motion accelerometer (Fig. 2). To monitor velocity and direction of the wind, two ultrasonic anemometers (DA-600 Kaijo-Denki) were installed in the middle of center span and on the top of the north tower, referred to as F1 and F2, respectively hereafter. All sensors measured the response simultaneously and the data were recorded every 10 min with the sampling frequency of 20 Hz.

3. Characteristics of measured winds

3.1. Wind measurements

Since located at the entrance of a bay, the bridge is exposed to relatively strong eastward wind originated from Uchiura Bay on the west side of the bridge. In this paper, we present analysis of vibration records that consist of wind measurement and bridge accelerations obtained from strong-wind events in four different years, namely, March 1999 (March 6 and March 22), December 2005 (December 25, 26, 27 and 28), 2006 (June 29 and July 12) and November 2011 (20, 21 and 22). Fig. 3 shows representative examples of the mean wind velocity and wind direction calculated from 10 min responses recorded by anemometer F1 on the center span at elevation 62 m and by anemometer F2 on top of north tower at elevation 133 m. Note that wind direction equals to 0° when the wind blows from the north and 90° when it blows from the east. The figures clearly show that although the two anemometers are about 360 m away from each other and placed on different elevation, the wind velocity and directions are generally similar.

The average wind directions for most of the strong winds were within 250–320°, indicating the wind originated from the Uchiura Bay on the west side of the bridge. These winds blew eastward forming certain inclination angle to the bridge deck (the bridge's transverse axis is about 277° from the north). Only during few instances in March 22, 1999 did the wind blow westward from Muroran Port with wind direction around 100°.

3.2. Relationship between wind velocity and direction to turbulence intensity

Turbulence intensity ($I_u = \sigma_u/U$) evaluated by comparing the root mean square (RMS) of the fluctuating wind velocity (i.e. σ_u) and the 10 min wind average velocity (U) is shown in Fig. 4 with