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Experimental study of wake-induced instability of coupled parallel hanger ropes for suspension bridges

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ABSTRACT

Hangers in suspension bridges are usually composed of closely-spaced multiple cables, and they may suffer from server wind-induced vibrations due to the wake interference effect. The primary objective of this research was to examine the wake-induced instability of the coupled twin or quadruple cylinders that are tied together to have the same motion, instead of separate cylinders vibrating independently. The elastically mounted twin cylinders free to oscillate in streamwise and transverse directions were tested at various cylinder spacings. The Scruton (Sc) number, $Sc = 2m\delta/\rho D^2$ (D is cylinder diameter, δ is logarithmic decrement, m is cylinder mass per unit length, and ρ is fluid density), was varied from about 65–420 by changing the damping, and the critical damping necessary to suppress the wake-induced instability was established. The wake-induced instability occurred with an elliptical orbit at cylinder spacing of 3.2D and wind incidence angle of 10°, while no instability was found at other spacings. The results of force measurements were presented and used to discuss the excitation mechanism based on the 1-DoF and 2-DoFs quasi-steady model. Despite some differences between theoretical analysis and measurements, the 2-DoFs model outperforms greatly the 1-DoF model in predicting the critical wind speed. For the coupled quadruple cylinders arranged in rectangular configuration, no large amplitude vibrations were found at all wind incidence angles due to complicated flow interference. Finally, the wake-induced instability of hanger subspans divided by spacers was investigated with a new aeroelastic model, and it was found that four spacers placed at equal intervals along hanger length are sufficient to suppress the wind-induced instability within the subspan for hangers in the Xihoumen Bridge.

1. Introduction

Wind-induced vibrations of hangers in suspension bridges have become a serious problem with increase of bridge span [13]. Large amplitude violent vibrations have been observed in long hangers of several major suspension bridges, including the Akashi Kaikyo Bridge in Japan [30], the Great Belt East Bridge in Denmark [20], and the Xihoumen Bridge in China [16]. Excessive wind-induced vibrations raise concerns about the fatigue life at both ends of the hangers and other structural members and can also cause visual discomfort for drivers.

Hangers are usually made of the conventional twisted wire strand ropes or the relatively new parallel wire strands (PWS) coated with PolyEthylene sheath [42]. In order to avoid using large-size cables, each hanger unit is usually deployed in pairs or groups, and therefore exists in form of multi-cylinder, parallel configuration. Due to the interference effects, flow around a cylinder can be dramatically altered by its proximity cylinders. Therefore the aerodynamic behavior of multiple cylinders becomes very complex and considerably differs from that of the isolated ones. A considerable amount of fundamental work has been published relating to complex flow around multiple circular cylinders and the ensuing flow-induced vibrations when they are free to oscillate [35,39,40,41,4,36,2,26]. Multiple cylinders in cross flow may be subjected to turbulence-induced buffeting, vortex-induced vibrations (VIV) and wake-induced instability. The wake-induced instability, which is the primary subject of this paper, is a rapid build-up of very large oscillation amplitude once the flow speed exceeds certain threshold far beyond the typical resonance speed of VIV. The critical wind speed is influenced by a large number of variables such as the Scruton (Sc) number, the center-to-center (CC) cylinder spacings, and the Reynolds number. The cylinder spacings play decisive roles on gap flow dynamics around cylinders [1,14]. According to the ratio of inter-cylinder spacings W with respect to cylinder diameter D, wake-induced instability can be roughly classified as the proximity interference for small spacings, the wake-induced galloping/flutter for relatively large spacings,

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and a combination of these for moderate spacings [39,10,7]. However the boundary of cylinder spacings to distinguish above three phenomena is still rather crude. If only two cylinders are concerned, the interference effect may occur for cylinder spacings up to about 8*D* when they are positioned one behind the other relative to the approaching wind direction; when they are positioned side-by-side, interference effect remain for cylinder spacings up to about 4*D*; the interference may extend for cylinder spacings as far as 20*D* when the two cylinders are arranged in slightly staggered configuration. Assi et al. [1] verified that the cylinders with spacings of about 3–4*D* has extreme variation of lift and drag coefficients and may lead to most severe oscillations.

The excitation mechanisms responsible for the wake-induced instability have been investigated theoretically which include the displacement mechanism and the velocity mechanism [28,6,27]. The displacement mechanism is related to the fluid coupling of neighboring cylinders' vibration and since it is dependent on the relative displacement between cylinders, it is called the "stiffness mechanism". The damping mechanism is related to the fluid forces in phase with cylinder velocity in which the phase lag between cylinder displacement and the induced forces must exist, and is therefore called the "damping mechanism". Price [29] reviewed the available theoretical models that employed the analytical or experimental aerodynamic coefficients to predict the critical flow velocity of wake-induced instability. Despite considerable differences in various theoretical models, Price concluded that these models gave better agreement with experiments when the phase lag between the cylinder displacement and the fluid force is considered, as also recently pointed out by Assi et al. [1]. Several time delay models for modeling the phase lag have been recently proposed [17,18,11,22].

Suspension bridge hangers or stay cables are also prone to wake-induced vibrations, as their cable spacings often fall in the interference regions. Compared to above fundamental research focusing on cylinder conditions with very low Sc number, the Sc number for stay cables or hangers is relatively high. The aerodynamic responses of multiple parallel cables at relatively large Sc number have been experimentally studied by using section models [25,31,21] and aeroelastic models [5,32,23]. The suppression of wake-induced instability through using rigid spacers and optimizing cylinder spacings has been studied by Cigada et al. [7], Maeda et al. [24], and Nago et al. [25]. The work by Maeda et al. [24] showed the critical wind velocity can be greatly improved by placing two cylinders very close to each other. The theoretical investigation for predicting the critical wind velocity for wake-induced instability of bridge cables/hangers seems rather limited. Yagi et al. [37] carried out the force and vibration measurement based on section model tests in wind tunnel and they analyzed the critical wind velocity from the measured unsteady forces.

The extension of bridge span and therefore the increased hanger flexibility reduce the critical velocity of wake-induced instability to a lower value of practical concern. Large amplitude vibrations have been observed on the long hangers of the Akashi Kaikyo Bridge, the Great Belt Bridge, and the Xihoumen Bridge. Saito et al. [30] reported that violent vibrations with amplitudes up to 8*D* of downstream cylinder were observed on the 100–200 m long hangers with spacings of about 9*D* in the Akashi Kaikyo Bridge. They successfully reproduced the wake-induced instability of downstream cylinder in the wake of a stationary one. For the Great Belt Bridge, the spacing of a hanger pair is about 5.5–7.5*D* and large amplitude vibrations occurs more frequently on the hangers over 100 m long and at relatively low wind velocity range of 6–15 m/s [20,3]. The vibration mechanism seems to be not well explained up to now, it was recently shown that section and spanwise irregularities may play important roles on aerodynamic excitation [8,9].

In August 2012, during passage of the typhoon Haikui (1211), large amplitude vibrations were observed on a few long hangers of the Xihoumen suspension Bridge with a main span of 1650 m. While it is common to use rigid spacers to strap multiple cables in a hanger unit at regular intervals, studies on aerodynamic behaviors of coupled multiple cables that are joined to have synchronous motions are rather limited [24,25,14]. Instead, most research has been focused either on two separate cylinders vibrating independently or on one cylinder freely oscillating in the wake of a stationary one. In this study, wind tunnel tests were performed to investigate the wake-induced vibrations of coupled twin or quadruple parallel cables by employing section models and aeroelastic model. In section model test, wake-induced vibration of the coupled twin or quadruple cylinders was studied for various cylinder spacings. The Scruton number, $\mathrm{Sc} = 2m\delta/\rho D^2$, was varied by changing the damping ratio, where m is cylinder mass per unit length, δ is logarithmic decrement and ρ is fluid density. A new aeroelastic model of quadruple parallel cylinders was constructed and employed to investigate the hanger motion within the subspan and to establish the minimum number of rigid spacers for inhibiting the excitation of large amplitude oscillations in the Xihoumen Bridge. Force measurement on coupled twin cylinders was presented and vibration excitation mechanism was discussed.

2. Hanger vibrations in Xihoumen bridge

2.1. Description of hanger ropes

The Xihoumen Bridge is a two-span suspension bridge with a main span of 1650 m and a suspended side span of 578 m, as shown in Fig. 1 [34]. It carries six-lane roadway by twin steel box girders. As the bridge is located at coastal areas of Eastern China, the twin steel box girders are adopted to enhance the aerodynamic performance against flutter [33]. The sag-to-span ratio of the bridge is 1/10. The bridge was open to traffic in 2010.

The bridge has 238 hanger units on each side of bridge deck, ranging 2.5–169 m in length. Each hanger unit is formed by a pair of twisted bare wire strand ropes that passes over the cable bands on the main cables and is then attached to the bridge deck by steel sockets. There are thus four strand ropes for each hanger unit, which are transversely connected by the flexible damper-type spacers. The damper-type spacer is actually a kind of viscoelastic dampers which supply additional damping only for out-of-phase vibration modes. The three units of hanger ropes closest to the pylon have a nominal diameter 88 mm, those for the remaining hangers 60 mm. The center-to-center spacing of the hanger ropes is 300 mm and 600 mm in the longitudinal and transverse directions of the bridge, respectively. Fig. 2 shows the layout of the arrangement of ropes per hanger unit.

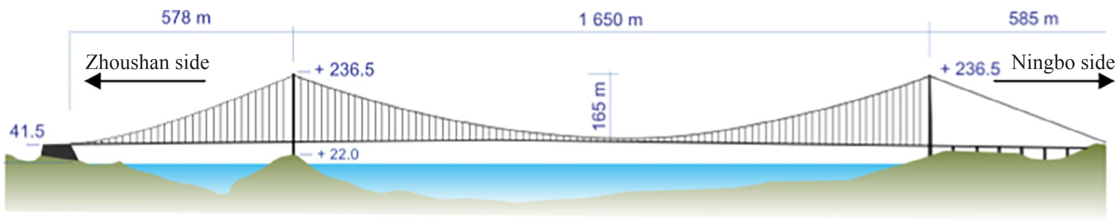

Fig. 1. Layout of Xihoumen suspension Bridge (unit: m).