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On wind–rain induced vibration of cables of cable-stayed bridges based on quasi-steady assumption

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ABSTRACT

Wind–rain induced vibration of cables of cable-stayed bridges is presently a problem of great concern. Similar to the classical galloping theory, this paper adopts quasi-steady assumption to study wind–rain induced vibration of cables. A wind tunnel test was first made to measure wind pressures and thus wind forces acting on a 3-D cable model and the upper artificial rivulet model. A new theoretical model for instability of a 2-D sectional rigid model with a moving artificial rivulet is then established and the instability criterion is proposed. The instability criterion is verified through wind tunnel test on a 2-D rigid sectional cable model with a moving artificial rivulet. Finally, theoretical models of wind–rain induced vibration of 3-D sectional cables and 3-D continuous cables are, respectively, developed based on the measured mean wind forces mentioned above, and the vibration characteristics are investigated as well as an explanation of the mechanism of wind–rain induced vibration of stay cables is made.

1. Introduction

Excessive and unanticipated vibration of cables in cable-stayed bridges under the simultaneous occurrence of wind and rain has been reported widely in the past two decades (Hikami and Shiraishi, 1988; Ohshima and Nanjo, 1987; Matsumoto et al., 2003; Matsumoto, 1998; Pacheco and Fujino, 1993; Main and Jones, 1999; Persoon and Noorlander, 1999; Gu et al., 1998; Shi et al., 2003). The author also observed wind–rain induced cable vibration from cable-stayed bridges built in Shanghai (Gu et al., 1998), and in Nanjing (Shi et al., 2003), which have main span of 602 and 628 m, respectively. Wind–rain induced cable vibration is presently a great concern to bridge engineering and wind engineering communities.

As is well known, wind–rain induced vibration of cables is a complex problem. Field measurements (Hikami and Shiraishi, 1988; Ohshima and Nanjo, 1987; Matsumoto, 1998; Main and Jones, 1999; Persoon and Noorlander, 1999; Shi et al., 2003), wind tunnel simulation tests (Matsumoto et al., 1995; Matsumoto et al., 1992; Flamand, 1995; Bosdogianni and Olivari, 1996; Gu et al., 2002; Gu and Du, 2005b; Cosentino et al., 2003a), and theoretical analyses (Yamaguchi, 1990; Gu and Lu, 2001; Wilde and Witkowski, 2003; Geurts and Staalduinen, 1999; Xu and Wang, 2003; Cao et al., 2003; Cosentino et al., 2003b; Yuscheweyh, 1999; Zhou and Xu, 2007) were conducted to investigate the characteristics and the mechanism of the complex phenomenon. In wind tunnel simulation tests, there are mainly two kinds of approaches for simulating rivulet on cable section model: one is to spray water appropriately onto the surface of cable models to form rivulet (Matsumoto et al., 1995; Cosentino et al., 2003a), mainly for investigating cable's vibration characteristics, and the other is to stick artificial rivulet model on the cable model surface (Gu and Du, 2005a; Yamaguchi, 1990; Gu and Lu, 2001), mainly for vibration characteristics and wind forces. In the theoretical studies on rigid sectional cable, quasi-steady and unsteady aerodynamic force models were both applied to describe the motion of cables. Matsumoto et al. (2005) suggested an unsteady aerodynamic forces, which were expressed by aerodynamic derivatives, $H_i^*(i=1-4)$, to study the aerodynamic damping and the instability of cables. Moreover, Matsumoto et al. (2001) discovered that stay cables might vibrate at high reduced wind speeds, such as 20, 40, 60 and 80, under wind–rain condition or only wind condition, and raised an explanation of axial flow and axial vortexes as another possible mechanism of wind–rain induced vibration. Even so, quasi-steady aerodynamic forces were adopted by most of the researchers to theoretically investigate the vibration characteristics and mechanism of rigid cables (Yamaguchi, 1990; Gu and Lu, 2001; Wilde and Witkowski, 2003; Geurts and Staalduinen, 1999; Xu and Wang, 2003; Cao et al., 2003; Cosentino et al., 2003b; Gu et al., 2009). Through the studies, it is now believed that the water rivulet formed on surface of cables and its motion play important roles in rain–wind induced vibration. But unfortunately, the mechanism of the complex phenomenon has not been clearly recognized up to now. As for

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3-D continuous cables, theoretical studies on wind–rain induced vibration and control were performed based on the above results of 2-D cables (Gu and Huang, 2008; Gu et al., 2009).

In this paper, similar to the classical galloping theory, the quasi-steady assumption is adopted to study wind–rain induced vibration of cables of cable-stayed bridges. A wind tunnel test was first made to measure the wind pressures and then mean wind forces acting on a 3-D sectional cable model and the attached upper artificial rivulet model, which are the base of the new theoretical studies on wind–rain induced vibration of cables in the present paper. A new theoretical model for instability of a 2-D rigid sectional cable model with a moving artificial rivulet is established and the instability criterion is proposed. Finally, theoretical models for wind–rain induced vibration of 3-D sectional cables and 3-D continuous cables are, respectively, developed and the vibration characteristics are investigated and a possible mechanism is suggested.

2. Wind tunnel test for wind pressures and forces acting on cable and rivulet models

To establish the theoretical models of wind–rain induced vibration of 3-D cables, a wind tunnel test on a 3-D sectional cable model with upper and lower artificial rivulet models was performed for obtaining wind forces acting on the models.

2.1. Cable model and test condition

As is known, stay cables in cable stayed bridges usually have diameters from 10 to 18 cm; and, moreover, the width of water rivulet is about 1–2 cm (Gu et al., 1998; Gu and Du, 2005b). This means that if the cable model and the artificial rivulet model for the wind pressure test had the same sizes with the actual ones, the too small artificial rivulet model would make the measurement of wind pressures acting on the rivulet very difficult. Therefore the sizes of cable model and accordingly the artificial rivulet model for the wind tunnel test were both amplified for the test, about two or three times the actual ones. On the other hand, in order to assure the Re number of the model is the same with the actual cable, the test wind speed should be $\frac{1}{2}-\frac{1}{3}$ of the actual wind speed at which the rain–wind induced vibration of real stay cables usually appears. The diameter of the cable was thus 350 mm and the model length was 3.5 m. The testing wind speed ranged from 3 to 10 m/s; the Re number was accordingly from 7.04×10^4 to 2.35×10^5. Two kinds of artificial upper rivulets, which are schematically shown in Fig. 1, were adopted in the test. On the model 176 pressure taps were arranged in four sections. The section B where 63 pressure taps were arranged is shown in Fig. 2. Especially, to understand detailed information of wind pressures on the rivulet, the pressure taps were arranged in three rows on the rivulet model (see Fig. 2b).

The test was carried out in smooth flow in TJ-3 BLWT in Tongji University, which has a working section of 15 m in width and 2 m in height. The cable model could be easily adjusted to the required wind angles and cable's inclined angles on a specially designed experimental set up. Fig. 3 shows the photograph of the test set up and the model. Fig. 4 illustrates the 3-D rigid cable model described by inclined cable angle α and wind angle β. In the test, the cable inclined angle was fixed at 30° and the wind directions were 0°, 25°, 30°, 35°, 40° and 45°. Furthermore, in order to measure the wind pressures under the condition of the rivulet being at different locations, which is denoted by θ_u (see Fig. 2a), the cable model could rotate around its axis to make the rivulet at

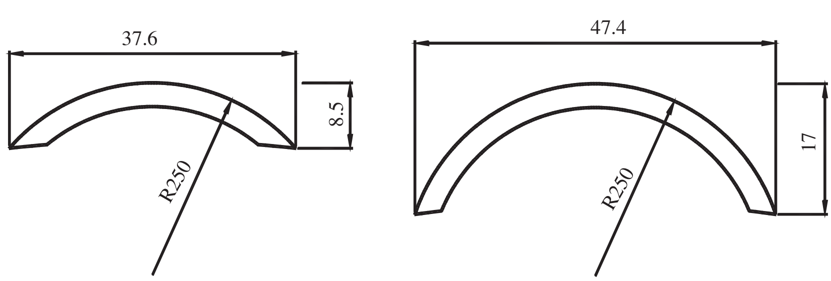

Fig. 1. Sizes of artificial rivulets (unit: mm).

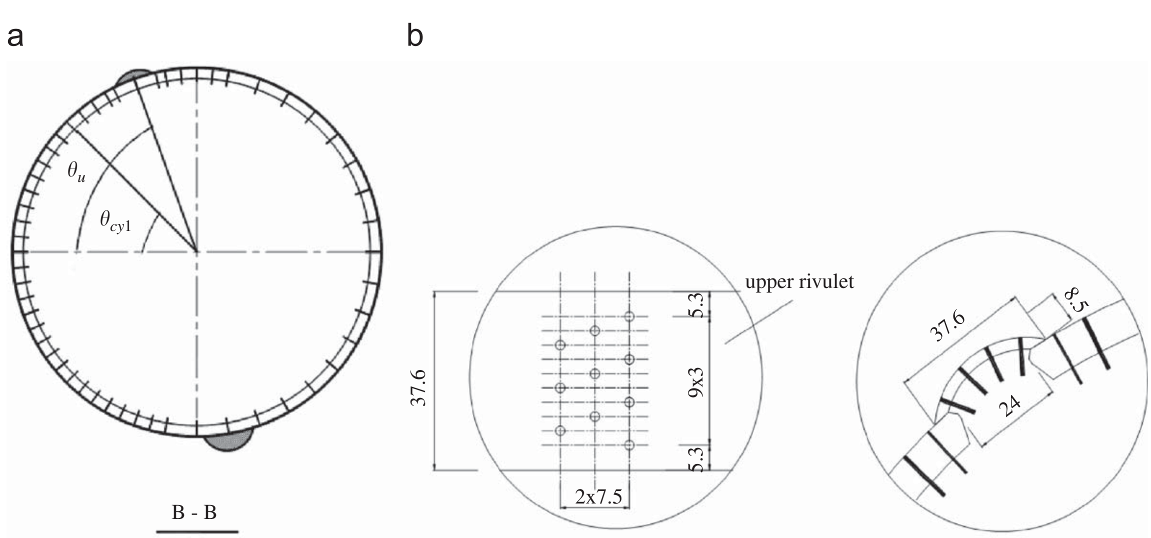

Fig. 2. Arrangement of pressure taps. (a) Arrangement of pressure taps on cable model. (b) Arrangement of pressure taps on upper rivulet.