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Interpretation of field observations of wind- and rain-wind-induced stay cable vibrations

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A B S T R A C T

Wind- and rain-wind-induced vibrations have been a long-standing and frequent problem for the stays of cable-stayed bridges. This paper summarizes characteristics of wind- and rain-wind-induced vibrations observed during two long-term full-scale measurement efforts. Based on these characteristics, and their relationship to the ambient meteorological environment (wind and rainfall), several distinct types of vibration are identified. The potential connection between the prevalent, large-amplitude, rain-wind-induced vibration and a type of large-amplitude dry cable vibration is explored. The characteristics of these large-amplitude vibrations are also compared to those of the classical Kármán-vortex-induced vibration, which provides considerable insight into the mechanisms of wind- and rain-wind-induced stay cable vibrations.

1. Introduction

Under certain wind conditions, stay cables of cable-stayed bridges have frequently exhibited large-amplitude vibrations. A prevalent type is associated with the simultaneous occurrence of wind and rain, and has been consequently referred to as rain-wind-induced vibration. This type of vibration, as well as other vibrations occurring without rainfall, has been a concern for researchers and engineers because it can potentially induce undue stresses that lead to fatigue in the stays themselves as well as in the anchorages, and consequently threatens the safety and serviceability of the bridge.

Because observed large-amplitude stay cable vibrations were often associated with rainfall, previous studies have been primarily focused on the problem of rain-wind-induced vibration. These investigations first considered full-scale measurements on several bridges around the world (e.g., Hikami and Shiraishi, 1988; Wianecki, 1979), from which some characteristics of the vibrations, such as the range of amplitude and frequency, as well as the perceived onset conditions have been reported. However, observations from these full-scale measurements were not comprehensive and did not necessarily reveal a complete picture of wind- and rain-wind-induced stay cable vibrations. In fact, many observations previously reported in the literature have been contradictory. While early reports suggested that only stays declining in the direction of wind were susceptible to rain-wind excitation (Hikami and Shiraishi, 1988), subsequent observations indicated that stays with opposite inclination can be excited simultaneously (Matsumoto et al., 1990). Early reports also indicated that the occurrence of rain-wind-induced vibration was restricted to a wind speed range of 6–17 m/s, which was in the subcritical range of the corresponding Reynolds number (Matsumoto et al., 1995). Later observations, however, have reported vibrations occurring at wind speeds as high as 40 m/s (Matsumoto et al., 1998). Further, the role of rainfall in the excitation mechanism has also been debated. While most observations suggested that large-amplitude vibrations occurred only with rainfall and that it was the water rivulets forming on the cable surface that rendered the cable cross-section aerodynamically unstable (e.g., Hikami and Shiraishi, 1988), other observations (e.g., Matsumoto et al., 1998) have reported stay cables vibrating at large amplitude without precipitation. It is therefore unclear whether the vibrations occurring with and without rainfall are related and, in particular, whether rainfall is an absolutely necessary condition for the onset of the so-called "rain-wind-induced vibration".

To study the problem in a controlled manner, wind tunnel tests have been conducted in an attempt to replicate the vibrations observed in the field. Many tests were designed expressly to study the perceived important role of rainfall. Very different observations and, consequently, different hypotheses on the mechanism of the vibrations have resulted from these tests, depending on the

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manner in which rainfall was simulated. In the tests that used shower heads to spray water onto cable models (e.g., Cosentino et al., 2003; Hikami and Shiraishi, 1988; Ruscheweyh, 1999), water rivulets were observed to form and to oscillate at the same frequency as that of the cable vibration. It was later suggested that the large-amplitude cable vibrations are the result of a two-degree-of-freedom aerodynamic instability formed by the coupled oscillations of the stay cable and the water rivulet. The tests that used solid bars to simulate water rivulets (e.g., Bosdogianni and Olivari, 1996; Matsumoto et al., 1992) indicated, however, that the actual motion of the water rivulets plays a negligible role in the excitation mechanism, and that it is the average position of the water rivulet that is important in changing the cross-section of the cable and in rendering it susceptible to wind excitation.

In addition to the wind tunnel tests designed to study rain-wind-induced vibration, a number of tests were also performed without the simulation of rainfall to investigate the inherent aerodynamic instability of dry stay cables. Observation of vortex-shedding from dry cable models at a frequency that is much lower than the nominal frequency of classical Kármán vortex shedding was reported (Matsumoto et al., 1992, 2001), and it was suggested that under specific wind conditions, the interaction between the Kármán vortices and axial vortices traveling along the axis of the cable can result in dry cable vibrations. In a recent wind tunnel test, a type of "limit-amplitude" dry-cable vibration and a galloping-like divergent vibration at high wind speed were also observed (Cheng et al., 2003b). It was suggested that dry stay cables are inherently susceptible to galloping excitation when wind speed is in the critical Reynolds number range (Cheng et al., 2003a).

Because the understanding from field observations is still limited, however, it is unclear whether the large-amplitude vibrations of the sectional models observed in the wind tunnel tests are faithful replications of the prototype stay cable vibrations, and therefore unclear whether the interpretation of the observations is appropriate or adequate in explaining the mechanisms of wind- and rain-wind-induced vibrations.

Due to these considerations, it was necessary to comprehensively investigate the characteristics of prototype wind- and rain-wind-induced stay cable vibrations, and to effectively categorize the vibrations based on these characteristics and their relationship to wind and rain. This paper attempts to address these issues by interpreting stay cable vibrations observed using two long-term, systematic, full-scale measurement systems.

2. Full-scale measurement systems

The investigation described herein is primarily based on data recorded through a long-term full-scale measurement system on the Fred Hartman Bridge in Houston, Texas, USA. In certain cases, data collected through a similar instrumentation system on the Veterans Memorial Bridge in Port Arthur, Texas, USA will also be presented and discussed.

The Fred Hartman Bridge is a twin-deck cable-stayed bridge with a main span of 381 m. Each of the decks, which consist of precast concrete slabs on steel girders and floor beams, is 24 m wide and 2.87 m high (from the bottom of the bottom flange to the top of the concrete barrier.) The decks are supported by a total of 192 stays, arranged in four inclined planes (designated A, B, C and D, respectively) originated at each of the two double-diamond shaped towers. The stays range from 59 to 198 m in length, with varying diameters. Fig. 1 shows an elevation and plan view of the bridge (Main and Jones, 1999). The scheme used to label and identify the individual stays is also shown in the figure.

The instrumentation system on the Fred Hartman Bridge was installed and began collecting data in October 1997. Major measurements by the system included the acceleration response of selected stays, the acceleration response of the decks at a number of locations, and the ambient meteorological conditions. The acceleration of the stays was monitored by tri-axial accelerometers (Crossbow Technology, model CXL04LP3) installed at cable locations with an elevation of 6 m above the deck surface. The accelerometers had a range of ± 4 g and a threshold noise level of 10 mg. They were oriented so that two of their axes record the components of the vibrations in the in- and out-of-plane (referred to as "lateral" hereafter) directions simultaneously. The wind speed and direction at the bridge site were monitored by three anemometers. At deck level, two three-component UVW anemometers (Young Instruments model 27005) were installed on steel poles that extended 4.6 m from the edge of the east deck at mid-span and at the anchorage of stay AS18, respectively. The propellers of the UVW anemometers had a threshold of 0.4 m/s, a resolution of 0.1 m/s, and could measure wind speeds up to 35 m/s. At the top of the southeast tower, the wind speed and direction were measured by a propeller-vane anemometer (Young Instruments model 05305) installed on a steel pole that extended 3 m above the tower top. This propeller-vane anemometer had a threshold of 0.4 m/s and could measure wind speeds up to 50 m/s. The resolution of this anemometer was 0.2 m/s for speed measurement, and 3° for direction measurement.

A problem with the wind measurement at the deck level was that when wind approached from the west side of the bridge, the anemometers were in the wake of the bridge decks and could not provide a faithful measurement of the free-stream wind. When wind approached from the east side of the bridge, however, the measurements by the two sets of UVW anemometers were statistically consistent (as expected.) Statistical analysis of the measurement data also reveals that the wind directions measured

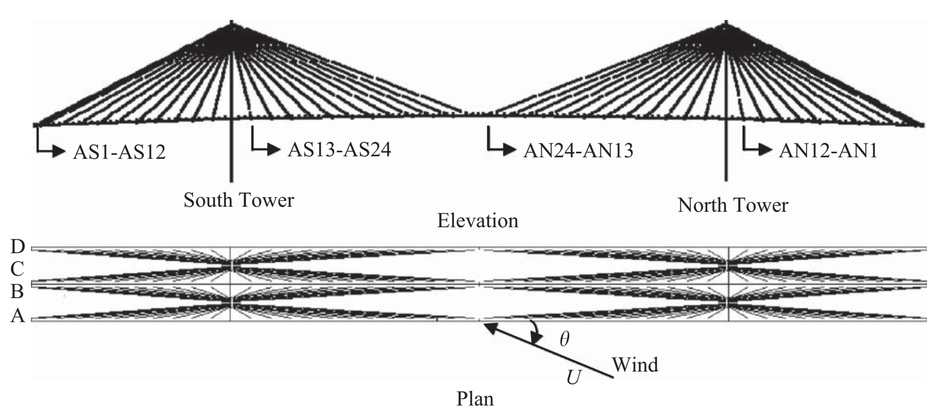

Fig. 1. Elevation and plan view of the Fred Hartman Bridge showing stay lines A–D.