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Comparison of force-balance and pressure measurements on deck strips on a stationary bridge model

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ABSTRACT

Synchronical measurements of fluctuating lifts and moments on six bridge deck strips in a motionless 1:45 scale model were carried out in the TJ-2 Wind Tunnel at Tongji University by using six miniature force-balances. Furthermore, synchronical measurements of pressures on six same-arranged strips in another identical model were also conducted for comparison. The paper describes how the new balance functioned and measured the fluctuating lift and moments, and compared the results with those from the pressure measurements. The comparisons demonstrate that the shapes of the spectra, and standard deviations of the lift and moment coefficients from the pressure and force-balance measurements show very good agreement, and the span-wise coherences and aerodynamic admittances of lift and moment are also very similar. The innovative miniature force-balance attached to the thin deck strips was proven to work reliably and accurately, and it had many advantages compared to pressure measurements, especially for bridge decks with wind barriers, crash barriers and other ancillaries, on which the wind loads would not be measured in pressure measurement tests. It was found that the ancillaries of bridge have little effect on the span-wise coherence of the buffeting force, but have a strong influence on the aerodynamic admittance.

1. Introduction

Economic growth and modernization has resulted in greater demand for cable-supported bridges that are designed to carry large volumes of vehicle traffic and railways over a long span (Xu, 2013). Buffeting is one of the important sources of wind-induced excitation of long-span bridges which can produce vibration due to bridge flexibility and low fundamental natural frequencies. It has been paid a great attention in both the wind and bridge engineering fields. Up to now, the bridge buffeting analysis in the frequency-domain was initiated by Davenport (1961, 1962) in the early sixties last century. Quasi-static linear theory was employed in Davenport's theory to establish the buffeting forces and aero-elastic damping, and the buffeting response was analyzed mode by mode based on the strip theory of aerodynamics. Buffeting forces are functions of the geometric configuration of bridge sections, the oncoming wind fluctuations, and the reduced frequency. The frequency-dependent aerodynamic characteristics of buffeting force are generally described in terms of span-wise coherences and aerodynamic admittances for the buffeting force (Chen and Kareem, 2002).

The concept of span-wise coherence was introduced to consider the effectiveness of the temporal and span-wise cross-correlation of buffeting loading, which was assumed to be the same as that of the onset wind turbulence and was described using wind structure equations. However, the correlations of fluctuating forces (pressure) are much larger than those of the surrounding wind turbulence (Hjorth-Hansen et al., 1992; Larose, 1992, 1997; Flay and Vickery, 1995; Jakobsen, 1997; Kimura et al., 1997; Matsumoto et al., 2003; Zhu et al., 2009, 2013b; Le et al., 2011; Ito et al., 2014, 2015 and Yan et al., 2016) and should be measured in wind tunnel tests.

Meanwhile, the notion of aerodynamic admittance was adopted to take into account the effects of unsteadiness and spatial variation of wind turbulence surrounding the cross section. The concept of aerodynamic admittance was first introduced by Sears (1941) and followed by Liepmann (1952) when studying the buffeting problem of thin airfoils due to the vertical component of wind turbulence. Because of the bluff body feature of bridge deck and the complicacy of the turbulence in the atmospheric boundary, aerodynamic admittances cannot be simply expressed by the Sears Function, and should be the function of the shape of bridge deck and the oncoming turbulence and

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determined by a wind tunnel test. The aerodynamic admittance was then measured by Davenport (1962); Vickery (1966); Holmes (1975); Irwin (1977); Jancauskas and Melbourne (1986); Sarkar et al. (1994); Larose (1997); Matsuda et al. (1999); Hatanaka and Tanaka (2002); Gu and Qin (2004); Ma et al. (2013) and Zhao and Ge (2015). Recently, Zhu et al. (2016) presented a colligated least square method of auto and cross spectra for identifying the six-component aerodynamic admittances of bluff bridge decks, verified it to some extent by comparing the calculated buffeting responses of a cable-stayed bridge based on the identified aerodynamic admittances with those measured in full bridge aeroelastic model tests.

Although surface pressure measurements on motionless bridge deck section models are accepted worldwide (Vickery, 1966; Hjorth-Hansen et al., 1992; Larose, 1992, 1997; Jakobsen, 1997; Kimura et al., 1997; Matsumoto et al., 2003; Zhu et al., 2009, 2013b; Le et al., 2011; Ma et al., 2013; Ito et al., 2014, 2015 and Yan te al., 2016), they have a few disadvantages as follows: (1) since pressure scanners only record the local point pressures at tap locations around the deck, numerous taps and connecting plastic tubes are needed to grasp the dramatic pressure variations near the edges of decks etc. to ensure that the pressure signals faithfully capture the loading distribution; (2) the measured pressure includes only the normal pressure acting on the deck surface without the frictional shear force acting on the plate surface; (3) the distortion effects of tubes in the pressure measuring system need to be corrected; (4) it is difficult to include the aerodynamic forces on the bridge deck ancillaries, including fixed railings, wind barriers and crash barriers. To overcome these aforementioned drawbacks, the high frequency force balance method (HFFB) has been introduced into the wind tunnel sectional model testing of long-span bridges.

This kind of test is made in a wind tunnel on a sectional model of the deck using a dynamometric system, generally placed outside the motionless model (Jancauskas and Melbourne, 1986; Hjorth-Hansen et al., 1992; Sarkar et al., 1994; Matsuda et al., 1999; Cigada et al., 2001; Hatanaka and Tanaka, 2002; Zhao and Ge, 2015) ; some researchers also use a deck sectional model with an internal balance for its middle part (Cigada et al., 2002; Diana et al., 2002, 2004; Zhu et al., 2013a; Diana et al., 2015 and Gao and Zhu, 2015, 2016). Very few researchers have directly obtained fluctuating forces on several bridge deck strips with different spacings simultaneously ('strip' indicates that each length of bridge deck along the span-wise direction is very small compared to the integral length scale of turbulence, so the coherence of wind-induced forces in the width of deck is much high and the synchronicity of forces can be considered to be the same), and the effects of ancillaries of bridge on buffeting force parameters, especially span-wise coherences, cannot be evaluated.

There are two fundamentally difficult problems in the process of directly measuring aerodynamic forces on narrow bridge deck strips of non-moving sectional models: (1) the aerodynamic force on the strip is very small and the design and manufacture of small capacity balances with high accuracy is a considerable challenge; (2) the air gap between the live and ground sections of the model will affect the air flow movement around the bridge section, and its influence is hard to evaluate and should be considered.

As for the oscillating sectional model in a force measurement test, the biggest problem is the inertia forces coming from the measurement strip itself, so the mass of the strip should be as small as possible. The aerodynamic forces of a moving deck are generally considered to contain two parts: the self-excited force and the buffeting force, and separating them is also worthwhile and challenging. In the later research program, the aerodynamic forces on several thin bridge deck strips of a moving spring-suspended sectional model will be measured and the corresponding outcomes will be published later.

In this study, six new sensitive and stiff five-component force balances were attached to six thin bridge strips on a stationary sectional model. Several different methods were investigated to reduce or eliminate the effect of the 1 mm gap between two adjacent model parts. Fluctuating forces on the six strips in a motionless bridge deck model without railings in grid generated turbulence were measured in separate tests on the pressure and force-balance models. A detailed analysis of the pressure measurements is given in Ref. (Yan et al., 2016). Spectra and standard deviations of the lift and moment coefficients from these two sets of tests are presented and discussed. The two independent span-wise correlations and aerodynamic admittances of the lift and moment coefficient are also compared. Finally, the innovative miniature force balance attached to the thin deck strips was used to get fluctuating forces on the six strips in a motionless bridge deck model with ancillaries in service conditions, including fixed railings, wind barriers and crash barriers.

2. Experimental setup

2.1. A new small high frequency force balance

A new small-sized five-component force balance (Series QSY8309B) was elaborately designed and manufactured by the State Key Laboratory for Disaster Reduction in Civil Engineering at Tongji University in collaboration with the Sichuan Stone Edge Science and Technology CO., LTD at Mianyang City, China. It could measure the five dynamic or quasi-static forces in different directions using piezo-electric measurement technology. The balance met the requirements for high sensitivity and high stiffness, necessary to avoid model vibration and to ensure suitable measurement accuracy. The balance was designed sufficiently small so that it could be placed inside the deck model, and as a result, it became cuboid, with dimensions 50 mm wide, 35 mm high, and 50 mm long, as shown in Fig. 1.

Five groups of strain gauges were glued onto three separate sections of the balance to measure two forces ($F_{\bar{x}}$and $F_{\bar{y}}$) and three moments ($M_{\bar{x}}$, $M_{\bar{y}}$ and $M_{\bar{z}}$) with respect to the center of the balance. The corresponding design maximum capacity was 3.0 N and 12.0 N for two forces $F_{\bar{x}}$ and $F_{\bar{y}}$, respectively, and 0.5 Nm, 1.2 Nm and 0.3 Nm, respectively, for three moments $M_{\bar{z}}$, $M_{\bar{x}}$ and $M_{\bar{y}}$. The balance was "rigid" in its longitudinal direction, and hence not able to measure the bridge span-wise force $F_{\bar{z}}$. As shown in Fig. 1, $\bar{z}$denotes the longitudinal axis of the balance while $\bar{x}$ and $\bar{y}$ denote the other two transverse axes of the orthogonal $\bar{x}$, $\bar{y}$ and $\bar{z}$coordinate system.

The new small-sized five-component force balances were calibrated in a clean and quiet environment with low noise and ground vibration due to their high sensitivity. They were then used for the wind tunnel tests. The balance calibration setup is shown in Fig. 2. The balance could be rigidly held in the device on the bench and loads applied in specified directions using gravity and various low friction pulleys. The electric bridges of the balance (1301025) were powered and connected to five separate complex DC voltage amplifiers (TS5860) which were manufactured by the Taisi Electronic CO., LTD at Yangzhou City,

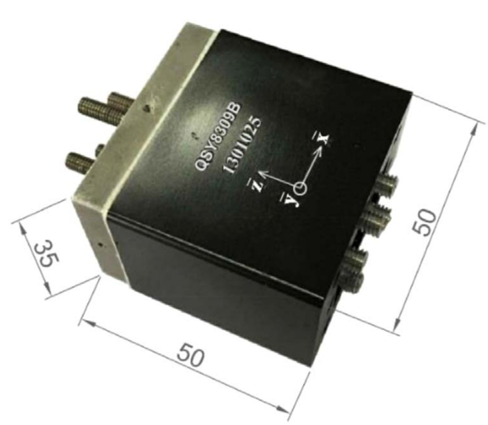

Fig. 1. Five-component force balance (unit in figures: mm).