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An enhanced forced vibration rig for wind tunnel testing of bridge deck section models in arbitrary motion

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ABSTRACT

This paper presents a new experimental setup for the aerodynamic section model testing of bridge decks. The rig is designed to move a section model in arbitrary motion in a wind tunnel to imitate the motions of such scaled real bridge motion, step motion or random motion histories to be close to white noise. The proposed setup enables the forces acting on the section model to be measured directly while considering motions that resemble actual bridge motion and still fully utilizing the benefits of the forced vibration testing technique. The excellent performance of the system and testing procedure is proved by performing state-of-the-art forced vibration tests to extract 18 flutter derivatives of the Hardanger Bridge cross-section. The new experimental setup is further used to simulate a three-degree-of-freedom dynamic system driven by white noise to investigate whether the estimates of the aerodynamic derivatives are sensitive to the motion considered. The experimental results demonstrate that the estimates of the aerodynamic derivatives are not sensitive to the motion considered; these results indicate that the principle of superposition is fully applicable for the cross section as long as the motions are within the range considered.

1. Introduction

Wind-induced dynamic response is a critical concern when designing long-span bridges. In particular, instability phenomena, such as galloping and flutter, caused by the self-excited forces have received considerable attention in recent decades. Wagner (Fung, 1955) and Theodorsen (1935) developed analytical expressions for the self-excited forces of thin airfoils as early as 1925 and 1935, respectively. Bridge deck cross-sections are characterized by more complex geometrical shapes and flow patterns, which precludes the formulation of similar mathematical expressions (Kareem and Wu, 2014). Another approach is to use computational fluid dynamics to simulate the flow around a bridge section (e.g. Huang et al., 2009; Sarwar et al., 2008; Zhu et al., 2007); however, it still remains challenging to obtain reliable results, thus making wind tunnel testing necessary. Wind tunnel tests are commonly conducted using full bridge models, taut strip models or section models. Comparative studies of the performance of the approaches have been presented by Scanlan et al. (1997) and Wardlaw (1980). Section models are the most widely used (Diana et al., 2013; Ge and Xiang, 2008; Zasso et al., 2014) because the tests can be performed in reasonably sized wind tunnels and because it is possible to perform the tests at a larger scale (Matsuda et al., 2001; West and Apelt, 1982; Zasso et al., 2014). However, taut strip and full bridge models are commonly used to evaluate the overall performance of new bridge concepts, stretching the present state of the art, because it is possible to include several vibration modes in the modeling.

Despite the considerable progress made in the modeling of self-excited forces using rational or indicial functions (e.g. Cao and Sarkar, 2012; Caracoglia and Jones, 2003; Chowdhury and Sarkar, 2005; Costa, 2007; Costa and Borri, 2006; Salvatori and Borri, 2007; Zhang et al., 2011; Zhang and Chen, 2010; Øiseth et al., 2011, 2012), aerodynamic derivatives, as introduced in bridge engineering by Scanlan and Tomko (1971), remains the most common output from wind tunnel tests of bridges. The aerodynamic derivatives for a bridge cross-section can be determined by either forced or free vibration tests. In a free vibration test, the section model is suspended in springs and moves because of the initial conditions and mutual interactions between the wind flow and model. In contrast, a prescribed motion of the bridge deck independent of the aerodynamic forces is considered in a forced vibration test. The section model is typically forced in either vertical, torsional or horizontal harmonic oscillations or combinations thereof. Thus, free vibration tests are considered to provide more realistic in-wind motion of the bridge deck and are easier to perform and less expensive; however, it is far more challenging to identify the aerodynamic derivatives from free vibration data; see (Bogunović Jakobsen and Hjorth-Hansen, 1995; Brownjohn and Jakobsen, 2001; Chowdhury and Sarkar, 2003; Sarkar et al., 1994; Scanlan, 1978) for an overview of the methodology available. The forced vibration

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technique provides higher data reliability (Diana et al., 2015) and is more suitable for higher velocities, larger motion amplitudes and higher turbulence intensities (Cao and Sarkar, 2012; Sarkar et al., 2009). However, the ability to consider a realistic bridge deck motion might be important for some cross sections. This consideration is reasonable because there are indications that the identification of the aerodynamic derivatives depends on the forced motion. For example, the aerodynamic derivatives have been shown to be influenced by the amplitudes of the motion (Chen et al., 2005; Scanlan, 1997), the frequency ratio between the torsional and vertical frequencies (Qin et al., 2009), and the effects of coupling between different degrees-of-freedom (DOFs) (Matsumoto et al., 1993). These findings indicate the importance of investigating when the current linear model is valid and when more complex nonlinear models should be applied.

This paper presents a new experimental setup that has potential to shed light on the underlying mechanisms of wind-induced forces by forcing the section model in nearly any desired motion. A typically reported weak point of the forced vibration technique is that induced vibrations are somehow different from those that the bridge will encounter in natural wind (Zhu et al., 2007). This enhanced rig overcomes this problem and enables aeroelastic forces to be measured directly when considering motions commonly observed in free vibration experiments. The herein described setup is used to investigate the accuracy of the assumptions frequently introduced to estimate aerodynamic derivatives from free vibration data; for example, the response is very narrow banded (Andersen et al., 2015; Brownjohn and Jakobsen, 2001) rather than being purely harmonic to obtain one reduced velocity. In this paper, the new experimental rig is first used to identify the full set of 18 aerodynamic derivatives for the Hardanger Bridge by performing standard forced vibration tests. Then, a random motion obtained by simulating a dynamic system driven by white noise is considered in the second round of tests. Finally, experimental results considering several frequency ratios are compared to the results obtained using a standard procedure to investigate whether the estimates of the aerodynamic derivatives are sensitive to the motion considered.

2. An enhanced forced vibration rig

Aerodynamic derivatives can be determined by moving a section model of the bridge deck in a prescribed motion while measuring the aerodynamic forces. Significant progress has been made since Ukeguchi et al. (1966) presented the first experimental results for bridge decks in 1966, and an impressive amount of forced vibration rigs used in research can be found in the literature (e.g. Cao and Sarkar, 2012; Chen et al., 2005; Diana et al., 2004, 2010, 2015; Falco et al., 1992; Han et al., 2014; Lee and Kwon, 2009; Li, 1995; Matsumoto et al., 1993; Matsumoto, 1996; Neuhaus et al., 2009; Sarkar et al., 2009). Forced vibration tests considering vertical and pitching motions are now routinely conducted when designing bridges, occasionally allowing for coupling between the two motions (Cao and Sarkar, 2012; Diana et al., 2004; Falco et al., 1992; Han et al., 2014). Several experimental setups capable of forcing the section model in horizontal, vertical and pitching motions have been presented more recently (Diana et al., 2004; Han et al., 2014; Lee and Kwon, 2009; Neuhaus et al., 2009; Sarkar et al., 2004). It is interesting that experimental setup developed at Iowa State University (Cao and Sarkar, 2012, 2010; Sarkar et al., 2007, 2004) is able to perform both free and forced vibration test. It is achieved by a system of springs and pneumatic bushings that glide along polished steel shafts making the friction very low. Forced vibrations tests can the readily be performed by rods that are connected to the driving mechanism placed above the test section. The majority of the setups rely on a fixture of the section model sliding on linear rails that are driven by an eccentric shaft (Chen et al., 2005; Han et al., 2014; Li, 1995; Matsumoto et al., 1993; Neuhaus et al., 2009; Sarkar et al., 2007), whereas some setups are driven by electric or hydraulic actuators (Diana et al., 2004; Lee and Kwon, 2009). The forced vibration setups has advanced impressively regarding both forced frequencies and amplitudes (Neuhaus et al., 2009). Furthermore, the setups can also adapt a fluid medium instead of air to improve the accuracy of the force measurements (Li, 1995), enable the section model to be tested under different angles of attack or yaw angles (Diana et al., 2004) or generate impulsive step motion to be generated to study the step response of the self-excited forces (Caracoglia and Jones, 2003). However, the continuous motion of the section in the forced vibration technique has been restricted to sinusoidal motions, which do not reflect the real bridge behavior. To amend this restriction, a new experimental setup was developed to test bridge deck section models in the forced vibration method. A strict requirement was that the forced vibration setup had to be capable of forcing the section model in an arbitrary motion to enable general-purpose section model tests. An image of the resulting machinery is shown in Fig. 1.

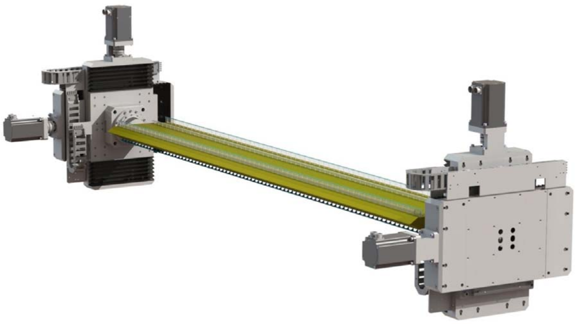

Fig. 1. New experimental forced vibration rig: section model mounted between the two actuators.

The forced vibration device consists of two 3-DOF actuators. These actuators are comprised of two linear motion slides on each side of the wind tunnel driven by ball screws that move the section model in the vertical and horizontal directions. Zero backslash shaft couplings connect the ball screws to servomotors and a servo motor with a planetary gear having a 1:50 gear ratio drives the torsional motion. The horizontal and vertical axes can travel ± 10 cm, and the torsional axes can travel ± 90 degrees. A customized multi-axis modular control system (MC4U from ASC Motion Control) is used to control the servomotors. The controller consists of two four axis servo drives, a 230 V, 8 kW power supply and a SPiiPlus motion controller. The servo processor receives the motion profile from the controller and then executes the real-time control algorithms at 20 kHz. The motion control system generates third-order motion profiles, making the acceleration and velocity linear and quadratic, respectively. This ensures that the motion is smooth, as presented in Fig. 2, where a random motion history is shown. The servo motors have been sized to handle large forces, making it easy to follow the motion profile for typical section models.

Two Gamma load cells supplied by ATI Industrial automation are used to measure three forces and three moments at each end of the section model. The six-axis force/torque transducers are placed between the section model and actuator, as shown in Fig. 3. Each load cell is bolted to the stage while a clamp is designed to attach the section model to the load cell. Similar solutions for force measurements were also used by Cigada et al. (2001), Han et al. (2014) and Körlin and Starossek (2007).

A flow chart of the experimental setup is shown in Fig. 4. As indicated in the Fig. 4, LabVIEW is used to control the experiment. The experiment starts by uploading a motion history to the MC4U controller. The controller communicates with the servo drives and ensures that the stages follow the motion profiles and that the actuators at both sides of the wind tunnel move synchronously. NI 9205 and NI 9239 analog input modules inserted into a NI cDAQ-9178 acquire the