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Effect of sway movement and motion axis on flutter and vortex induced vibration in a 3 DOF wind tunnel sectional test

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ABSTRACT

Bridge stability is typically investigated based on 2 DOF wind tunnel measurements and very few wind tunnel facilities are available to simulate 3 DOF flutter of sectional model. In the absence of experimental capacity for extracting the flutter derivatives related to the sway, the quasi-steady approach is generally used for their evaluations. Also, the change of angle of attack is generally achieved by rotating the model relatively to the balance, forcing then the model to move according to the wind's axis as opposed to the section's principal axis. The impact of this experimental limitation needs to be studied. This paper presents a new 3 DOF dynamic force balance and its use to investigate the stability of a typical bridge deck section. The effect of the axis of motion is also studied. An interaction between sway and twist was observed during flutter and, for some angles of attack, the results show that the speed at which the flutter is reached might be influenced by the sway and the direction of motion as compared to principal axis of the section. Further research is needed to properly asses these effects.

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1. Introduction

Bridges are typically designed to withstand severe wind conditions. Long span bridges are lightweight constructions and can be prone to wind-induced oscillations. Well known bridge failures have alerted engineers about the reality of aeroelastic phenomenons. Example of these failures are the Angers Bridge failure in 1850 and the Tacoma Narrow failure in 1940, the later one being the trigger of modern aeroelastic study of bridges; characterizing the aerodynamic stability of these slender structures is now an important design consideration.

According to Farquharson (1947), the first modern aerodynamic testing was done in the design stage of the new Tacoma Narrows. Among the methods used to characterize bridges behavior under wind load is the sectional test where a reduced scale section of the bridge deck is mounted on a dynamic force balance in the wind tunnel. It is typically mounted on a 2 degrees of freedom (DOF) balance representing twist and heave. This sectional test is used to determine aerodynamic force coefficients (Drag, Lift, and Moment) and the onset of instabilities.

As the span of new bridges increases, so does their sway flexibility. This brings new interrogations about the effect of sway on the stability and the limitations of 2 DOF systems in the case of such flexible bridges. A few 3 DOF aerodynamic force balance are described in the literature (Diana et al., 2004; Jones et al., 1995). Jones et al. (1995) used air bearings to mechanically uncouple each DOF. Diana et al. (2004) used a set of four horizontal tight cables to support the model, which allows motion in a single plane. Singh (1997) extracted the 18 flutter derivatives from free motion using a 3 DOF force balance. He concluded that the quasi-steady approximation of the derivatives related to the sway, used when extraction for 3 DOF was not possible, was not always conservative and that experimental extraction should always be conducted. This was also observed by Chen et al. (2000). Numerical studies were performed in order to asses the role of the sway flutter derivative in the aeroelastic behavior of bridges. It was observed that P^* derivatives (related to sway self-excited forces) can affect the global damping of flutter mode (Chen and Kareem , 2008; Falco et al., 1992; Miyata et al., 1994) and, therefore, affect the critical flutter speed of a bridge.

Based on Singh et al. (1996), more research is needed to understand bridge motion in the sway direction. Studies should then be conducted regarding the effect of sway on stability of bridges and the influence of the axis of motion should be assessed. To achieve these goals, a new concept of 3 DOF aerodynamic force balance has been developed. The development of this new balance was also an opportunity to improve on current technology. The objective was to develop a balance where all degrees of freedom are independent and can move freely from one another. Also, magnetic damping was included to provide a constant damping

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throughout the amplitude range of motion of the section. Finally, in order to better represent bridge deck motion trough air, it was decided to develop the balance so that each degree of freedom moves as in the bridge: along body coordinates. The balance is motioned from the outside of the tunnel with a set of electric or hydraulic actuators that can provide desired angle of attack of the section relatively to the wind flow. This is different from typical 2 DOF balance where the change of angle of attack is achieved by rotating the model relatively to the balance. However, the direction of motion of a solid structure in a flow may modify the structure of the flow itself. In the case of a cylinder describing a motion at an angle with the flow axis, the flow structure in the wake as well as the onset of instabilities such as vortex induced vibration (VIV) have been observed to differ from that of a cylinder in cross flow motion (Laneville, 2006).

The first part of this article deals with the new concept force balance and the following parts, with the effects of the sway motion and of the axis of motion.

2. Experimental program and facilities

2.1. Models

For the purpose of this study, a stay cable bridge deck section with a width of 0.405 m and a depth of 0.094 m was used. Fig. 1 shows the section outline and define the terminology and conventions used.

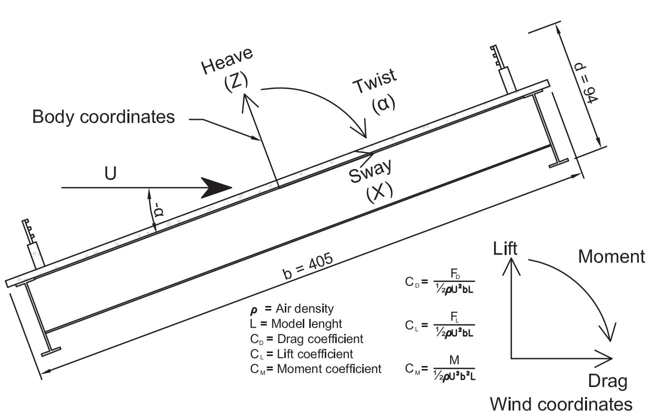

Fig. 1. Bridge section outline, terminology, and conventions.

2.2. Experimental program

All the tests were conducted at the *Université de Sherbrooke* main wind tunnel. The tunnel is a return circuit and closed test section type. The 10 m long test section is 1.83 m wide by 1.83 m high and allows wind velocities ranging from 1.2 to 32 m/s. The models are installed 7 m downstream of the end of the wind tunnel convergent. Velocity profiles of the empty tunnel at this location were measured uniform within 2.5% with an average turbulence intensity of 1.6%.

2.2.1. Stability response investigation

To investigate the stability response of the deck section, the rigidity, mass and damping ratio of the dynamic force balance were adjusted in order to match the dynamic properties to the ones required for similitude. Once the set-up is completed, the wind speed was increased by small increments until the onset of flutter. For each increment, after stabilization of both the flow and the model motion, the displacement signal was recorded over a 90 s period. This procedure was repeated for 3 angles of attack: 0°, +5° and −5°. Table 1 summarizes the dynamic properties of the model.

In order to assess the effect of sway, the horizontal DOF was either set flexible, using springs, or rigid, using chains. To represent the coupling between the rotation and the sway generally observed in dynamic modes of cable-stayed bridges, the horizontal frequency was set as close as practical to the twisting one (see Table 1).

In order to assess the effect of the axis of motion, the angle of attack of the model was changed in two different ways: the first, by the rotation of the entire assembly of the aerodynamic balance and the model (body coordinates), the second, by the rotation of the model only (wind coordinates). Two long slots were machined in each end plate of the cable-stayed bridge's model in order to change the angle of attack for wind coordinates motion (see Fig. 2). The distinction between the two systems is that in body coordinates, the heave and the sway are moving according to the deck's local axis while, in wind coordinates, they are moving according to the wind's axis (lift and drag). The angle between the two sets of axis of motion is the angle of attack.

Table 1
Configuration for stability response investigation.

Sway			Heave			Twist		
f (Hz)	*m* (kg)	*ξ* (%)	*f* (Hz)	*m* (kg)	*ξ* (%)	*f* (Hz)	*mmi* (kg-m^2)	*ξ* (%)
8.20	29.09	0.5	4.66	19.79	0.5	8.41	0.2942	0.5

Fig. 2. End plates with long slots for adjustment in wind coordinates.

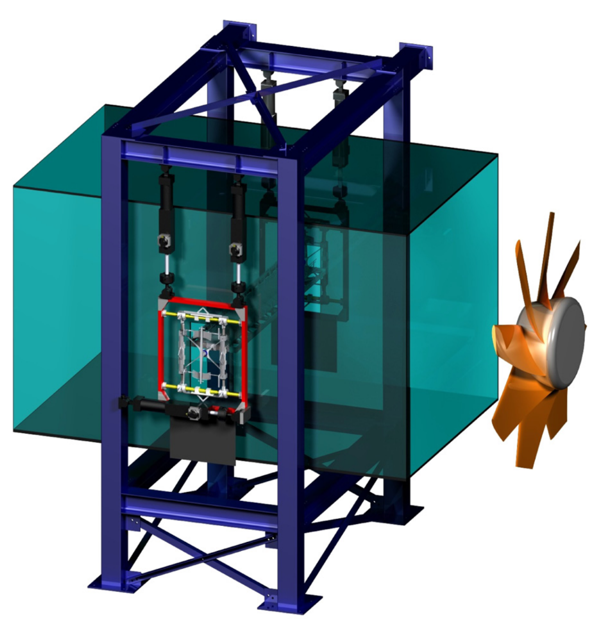

Fig. 3. Rendering of the 3 DOF force balance.

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