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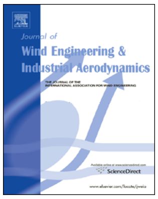

A model for vortex-induced vibration analysis of long-span bridges

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ABSTRACT

Long-span structures are susceptible to wind-induced vibrations due to their low oscillation frequency and low mechanical damping. Although many efforts have been made in the past to model vortex-induced vibration of circular cylinders, limited studies can be found for non-circular cross sections representative of long-span bridge decks. A model for vortex-induced vibration analysis of long-span bridge is presented in this paper. The aeroelastic equation of motion of the model, a procedure to extract aeroelastic coefficients from wind tunnel experiments, analysis of full-scale structures incorporating loss of spanwise correlation of aeroelastic forces, and comparison between simulated and full-scale measured responses on a twin deck bridge (Fred Hartman bridge, Baytown, Texas) are discussed. Six bluff sections – Deer Isle bridge, Tsurumi bridge, Fred Hartman bridge, generic rectangular, H shaped, and circular models – were considered in this research program.

1. Introduction

The study of flow-induced vibration of long-span civil engineering structures has emerged as an important field after the collapse of the Tacoma Narrows bridge in 1940 (Billah and Scanlan, 1991). Since then significant progress has been made in the understanding of aerodynamic and aeroelastic phenomena specially flutter, buffeting, and galloping vibration of long-span civil structures and various analytical tools for analyzing structural responses have been developed, which are now routinely implemented in design. However, despite some efforts made in the past, vortex-induced vibration of non-circular long-span structures still challenges structural and wind engineers. When flow is separated by a bluff body, a regular pattern of vortices develops in the downstream region that exerts periodic pressure on the body. The frequency (f_s) of vortex shedding may approach one of the natural frequencies (f_n) of a flexible structure at some critical wind speeds. If the ratio f_s/f_n becomes close to unity, the structure and the wake begin to oscillate at a common frequency close to the natural frequency of the structure over a certain band of wind speeds. The oscillation frequency of the structure takes control of the shedding frequency over the bandwidth; as a result, shedding frequency violates the linear Strouhal relationship. The overall phenomenon described above is sometimes called "locked-in" vibration and the region within which it occurs is often called the "lock-in" region. This type of vibration can generate moderately large amplitude response on a structure.

Locked-in vibration was first carefully investigated by Bishop and Hassan (1964) by subjecting a circular cylinder to forced oscillation in water and then by Feng (1968) on a spring-mounted rigid circular and D-shape sections in air. Motivated by the interesting findings of these pioneering experimental investigations, Hartlen and Currie (1970) first proposed a mathematical model similar to the Van der Pol equation, which was originally developed to idealize a spontaneously oscillating but self-limiting valve circuit (Van der Pol, 1926). Thereafter, a number of researchers had developed different models for predicting locked-in vibration of circular cylinders (Skop and Griffin, 1975; Iwan and Blevins, 1974; Landl, 1975; Sarpkaya, 1978; Dowell, 1981; Vickery and Basu, 1983; Staubli, 1983; Billah, 1989; Goswami et al., 1993). As the models for circular cylinders cannot be used directly for the analysis of non-circular sections due to considerable differences between the characteristics of locked-in vibrations of circular and non-circular sections, a few researchers proposed mathematical models suitable for long-span bridges (Scanlan, 1981; Simiu and Scanlan, 1986; Ehsan and Scanlan, 1990). One of the major limitations of the existing models for full-scale bridges is that these models are not rigorously developed like those for flutter and buffeting. Although Ehsan (1989) simulated the responses of several long-span bridges using the Scanlan–Simiu model, the results were not validated with full-scale measurements. Additionally, the Scanlan–Simiu model employs a Van der Pol type equation, as was done in the Hartlen–Currie and other models, without much physical justification. A few recent events of vortex-induced vibration on prototype bridges and a general consensus found in technical articles and reports (Fujino and Yoshida, 2002; Larsen, 1993; Irwin, 1998;

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Larsen et al., 2000) on the lack of good analytical models have led to the conclusion that a model capable of reliably predicting the response of a full-scale bridge is much needed. Additionally, research on locked-in vibration of twin-deck bridge sections is limited.

A systematic approach was considered towards developing the model. Wind tunnel experiments were first performed on several spring-mounted rigid models, including a twin-deck bridge model, to advance the understanding of the mechanism of vortex-induced vibration of non-circular sections and collect necessary data. Based on the experimental observations, a practical mathematical model was developed and associated experimental procedure was established. A modal analysis technique was developed for predicting the locked-in response of prototype structures, which was used to predict the response of the Fred Hartman bridge. Simulated locked-in response of the bridge was validated by long-term, full-scale data measured on the bridge.

2. Summary of experiments

Experiments were performed in an open-return, low-speed, low-turbulence wind tunnel in the Subsonic Aerodynamics Laboratory at the University of Illinois, Urbana-Champaign. The working cross section of the tunnel is 0.9 m × 1.3 m and maximum attainable speed is 71 m/sec. A force-balance consisting of two identical suspension systems were installed on each side of the tunnel to support vertically the two ends of a test section in the center of the tunnel's working section. The vertical and the torsional degrees-of-freedom were unrestrained. Each component of the force balance consisted of four vertical springs connected to flexure elements, which sensed the vertical motion. Strain gages mounted on the flexure elements were formed into Wheatstone bridges that measured the resistance due to change in strain. Downstream and upstream displacements were recorded separately by two channels. Each model was attached to the force balance at the two ends and end-plates were used to promote a two-dimensional flow around the model. A pitot tube was placed in the downstream region at a suitable distance from the centerline of a model to record the velocity fluctuations in the wake.

Section profiles of the six bluff sections considered in this study are shown in Fig. 1 and pertinent model properties are listed in Table 1. The twin-deck Fred Hartman bridge model was tested with 45.7 mm (representative of the gap/D ratio of the full-scale bridge) and 30.5 mm gap. A single deck model of the bridge was also considered. The aeroelastic coefficients of the windward and the leeward sections of the Fred Hartman bridge were obtained under two different configurations. In one configuration, the leeward model was restrained while the response of the unrestrained windward model was recorded. In another configuration, the windward deck was restrained while the leeward deck was free to oscillate.

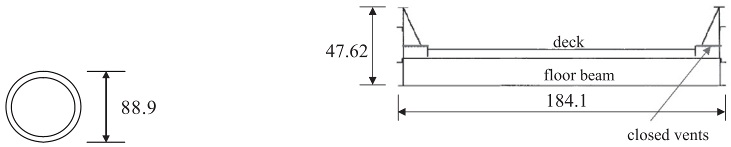
For each section model steady responses were obtained at a number of wind speeds before, inside, and beyond a lock-in region. Experiments were performed in both increasing and decreasing wind speeds. Two types of transient response behaviors were recorded – high initial displacement (higher than the steady response) to steady response and small initial displacement (smaller than the steady response) to steady response. In order to determine the Strouhal number of a model, the vertical and the rotational degrees of freedom of the model were restrained and velocity fluctuations in the wake were recorded using a pitot tube at several wind speeds. The natural frequency and the damping ratio of a model were obtained from its free-decay responses. More information on the experimental procedure and results can be found in Mashnad (2006).

Following important observations were made in the wind tunnel experiments:

- When a section model with two degrees-of-freedom experienced locked-in vibration, it was found to oscillate in a single mode only. When motion occurred in the vertical mode, the effect of the twisting motion on the aeroelastic forces acting on a section became negligibly small.

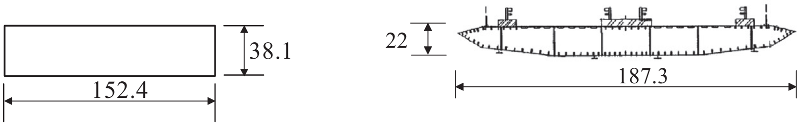
Table 1
Section model geometry and dynamic properties.

Properties	O	R	DIB	H	TB	FHB
Length (L), m	0.914	0.914	0.914	0.914	0.914	0.914
Depth (D), m	0.089	0.038	0.0476	0.0476	0.022	0.0287
Width (B), m	0.089	0.152	0.184	0.184	0.187	0.250
System mass (M), kg	2.4	2.3	1.9	1.9	2.7	1.9
Mass/unit length (m)	2.65	2.46	2.05	2.05	2.95	2.07
Width-to-Depth ratio (B/D)	–	4.00	3.87	3.87	8.5	8.7
Vertical frequency (f_n), Hz	3.33	3.45	3.72	3.7	3.15	5.0
Torsional frequency (f_t), Hz	–	6.32	5.50	5.5	6.19	6.26
Vertical damping ratio (ζ_n), %	0.19	0.26	0.24	0.24	0.24	0.17



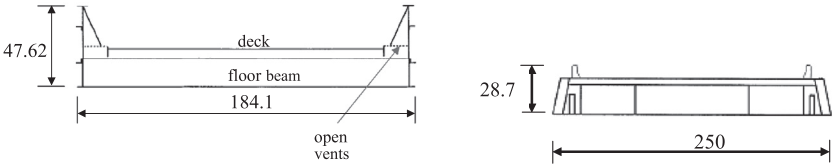
Circular Model (O)

H-section (H)
(Deer Isle Bridge with vents closed)



Rectangular Model (R)

Tsurumi Bridge Model (TB)



Deer Isle Bridge Model (DIB)

Fred Hartman Bridge Model (FHB)

Fig. 1. Cross sections of six experimental models (all dimensions are in mm).