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Aerodynamic Response of Two Parallel Cable-Stayed Bridges

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Abstract

The sectional wind tunnel test of two parallel cable-stayed bridges, namely Rama IX (existing) and new bridge in Bangkok, Thailand, were investigated in this paper. A specific goal of study is the vortex-induced vibrations (VIV) and identify flutter derivative of the bridge deck. The tests were performed with sectional models in a 1:90 scale and divided into 3 configuration cases, namely, 1. the new bridge alone, 2. the new bridge located upstream and the existing bridge located downstream, and 3. the new bridge located downstream and the existing bridge located upstream. The covariance-driven stochastic subspace identification technique (SSI-COV) was presented to identifying aerodynamic characteristics of the two decks. The results found that the two parallel configuration of the bridge result in vortex-induced vibrations (VIV), and significantly lower the flutter speed compared with the new bridge alone.

Introduction

Current issue of traffic is likely to increase and the area is limited. An additional bridge could be added in parallel to an existing bridge to accommodate increasing traffic flow capacity. Since the bridges are located in parallel configuration, their wind induced responses become more complex than the single stand-alone bridge. Therefore, the aerodynamic interferences between the two-bridge decks sections have been investigated by many researchers [1-3]. When new bridge appears parallel to the exist one that affectes to the aerodynamic characteristic of both decks, the main topic that should pay attention is interference effects due to vortex-induced vibrations (VIV) and aero elastic stability (flutter).

In this paper, vortex-induced vibrations (VIV) and aero elastic stability (flutter) of two parallel cable-stayed bridges was studied. The covariance-driven stochastic subspace identification technique (SSI-COV) [4] was presented to extract the flutter derivatives from random responses (buffeting) under the action of smooth wind. The sectional models of two parallel cable stayed bridge with a main span of 450 m, Thailand, were tested in smooth flow. Wind tunnel tests were performed with sectional models in a 1:90 scale and divided into 3 configuration cases, namely, 1. the new bridge alone, 2. the new bridge located upstream and the existing bridge located downstream, and 3. the new bridge located downstream and the existing bridge located upstream. Tests were conducted in TU-AIT Boundary Layer Wind Tunnel in Thammasat University, Thailand.

Theoretical formulation of covariance-driven stochastic subspace identification

The dynamic behaviour of a bridge deck with two degrees-of-freedom (DOF in short), i.e. h (bending) and α (torsion), in turbulent flow can be described by the following differential equations of equilibrium. The self-excited lift and moment are given as follows:

$$L_{se}(t)=\frac{1}{2}\rho U^2 B\begin{bmatrix} K_h H_1^*(K_h)\frac{\dot{h}}{U}+K_\alpha H_2^*(K_\alpha)\frac{B\dot{\alpha}}{U} \\ +K_\alpha^2 H_3^*(K_\alpha)\alpha+K_h^2 H_4^*(K_h)\frac{h}{B}\end{bmatrix} \quad (1)$$

$$M_{se}(t)=\frac{1}{2}\rho U^2 B^2\begin{bmatrix} K_h A_1^*(K_h)\frac{\dot{h}}{U}+K_\alpha A_2^*(K_\alpha)\frac{B\dot{\alpha}}{U} \\ +K_\alpha^2 A_3^*(K_\alpha)\alpha+K_h^2 A_4^*(K_h)\frac{h}{B}\end{bmatrix}$$

where ρ is air mass density; B is the width of the bridge deck; U is the mean wind speed at the bridge deck level; $k_i = \omega_i B/U$ is the reduced frequency (i=h,α); and H_i^* and A_i^* (i=1,2,3,4) are the so-called flutter derivatives, which can be regarded as the implicit functions of the deck's modal parameters. By moving L_{se} and M_{se} to the left side, and merging the congeners into column vectors or matrices, dynamic equation of equilibrium can be rewritten as follows:

$$[M]\{\ddot{y}(t)\}+[C^e]\{\dot{y}(t)\}+[K^e]\{y(t)\}=\{f(t)\} \quad (2)$$

The fluctuations of wind speed u(t) and w(t) in are random functions of time, so the identification of flutter derivatives of bridge decks can be simplified as a typical inverse problem in the theory of random vibration, and thus can be solved by stochastic system identification techniques.

$$\text{Let}\quad [A_c]=\begin{bmatrix} \mathrm{O} & \mathrm{I} \\ -M^{-1}K^e & -M^{-1}C^e \end{bmatrix},\quad [C_c]=[\mathrm{I}\quad \mathrm{O}]$$

$$\text{and}\quad \{x\}=\begin{Bmatrix} y \\ \dot{y} \end{Bmatrix} \quad (3)$$

Then, Eq. (2) is transformed into the following stochastic state equation in discrete form as

$$\{\dot{x}_{k+1}\}=[A]\{x_k\}+\{w_k\}\ \text{and}\ \{y_k\}=[C]\{x_k\}+\{v_k\} \quad (4)$$

Once the modal parameters are identified, the gross damping matrix C^e and the gross stiffness matrix K^e can be readily determined by the pseudo-inverse method. Let: $\overline{C}^e = M^{-1}C^e$,

$\overline{K}^{e} = M^{-1}K^{e}$, $\overline{C} = M^{-1}C^{0}$ and $\overline{K} = M^{-1}K^{0}$ where C^0 and K^0 are the 'inherent' damping and stiffness matrices, respectively. Thus, the flutter derivatives can be extracted from the following equations

$$H_1^*(k_h) = -\frac{2m}{\rho B^2 \varpi_h}(\overline{C_{11}^e} - \overline{C_{11}^0}) \qquad H_2^*(k_\alpha) = -\frac{2m}{\rho B^3 \varpi_\alpha}(\overline{C_{12}^e} - \overline{C_{12}^0})$$

$$H_3^*(k_\alpha) = -\frac{2m}{\rho B^3 \varpi_\alpha^2}(\overline{K_{12}^e} - \overline{K_{12}^0}) \qquad H_4^*(k_h) = -\frac{2m}{\rho B^3 \varpi_h^2}(\overline{K_{11}^e} - \overline{K_{11}^0})$$

$$A_1^*(k_h) = -\frac{2I}{\rho B^3 \varpi_h}(\overline{C_{21}^e} - \overline{C_{21}^0}) \qquad A_2^*(k_\alpha) = -\frac{2I}{\rho B^4 \varpi_h}(\overline{C_{22}^e} - \overline{C_{22}^0}) \quad (5)$$

$$A_3^*(k_\alpha) = -\frac{2I}{\rho B^4 \varpi_h^2}(\overline{K_{22}^e} - \overline{K_{22}^0}) \qquad A_4^*(k_\alpha) = -\frac{2I}{\rho B^4 \varpi_h^2}(\overline{K_{21}^e} - \overline{K_{21}^0})$$

Description of two parallel cable-stayed bridges

Rama IX Bridge is a bridge in Bangkok, Thailand (see Fig. 1.) over the Chao Phraya river. It connects the Yan Nawa district to Rat Burana district as a part of the Dao Khanong – Port Section of Chalerm Maha Nakhon Expressway. It was the first cable-stayed bridge in Thailand and had the second longest cable-stayed span in the world when it opened in 1987. The Main Span of the bridge, which is stretched between two poles has a length of 450 meters and the main span is a trapezoid shape 33 meters wide (see Fig. 2b). Dynamic properties of the existing Rama IX cable-stayed bridges were obtained from the Rama IX Bridge Tenth-Year Inspection [5].

In addition, the main span of new bridge has the same length of existing bridge (450 m.) but the deck width is 42.4 m (see Fig. 2a). The gap distance between two bridges is 7.26 m (see Fig. 3).

Figure 4. Section bridge model for the new bridge located upstream and the existing bridge located downstream for aerodynamic test under smooth wind

Dynamic properties of the new Rama IX cable-stayed bridges were obtained from the Epsilon Co. Ltd. and Weicon Co. Ltd. [6]. The Epsilon Co. Ltd. and Weicon Co. Ltd are the designer of this new bridge.

To study aerodynamic interferences of two parallel decks, the aero elastic test of rigid sectional model (see Fig. 4) were performed in TU-AIT Boundary Layer Wind Tunnel in Thammasat University, Thailand. Test section is 2.5 m wide, 2.5 m. height and 25.5 m. long. The length scale λ_L =1:90, frequency scale λ_f =7.32, velocity scale λ_v =12.28 and modal damping ξ_h= 0.45%, ξ_α=0.31% for Rama IX bridge. The length scale λ_L =1:90, frequency scale λ_f =7.25, velocity scale λ_v =12.40 and modal damping ξ_h= 0.23%, ξ_α=0.14% for new bridge.

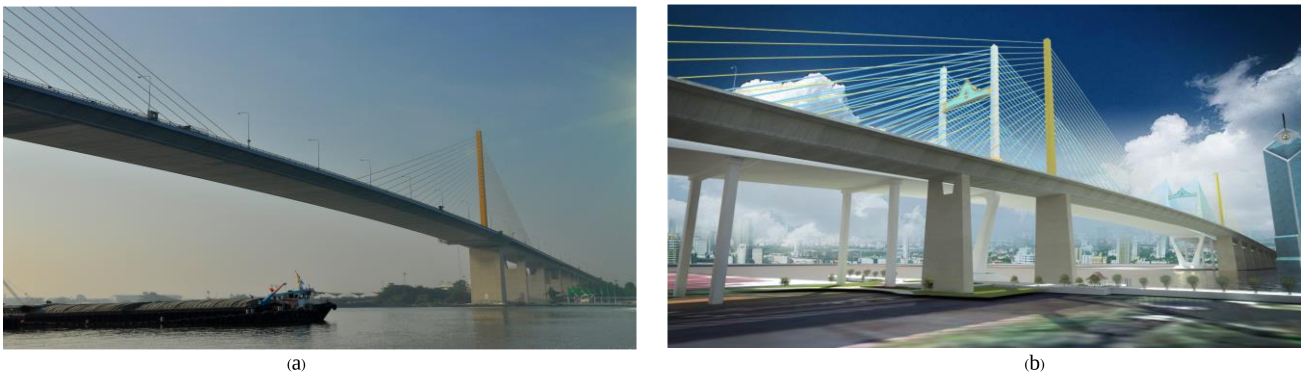

Figure 1 The Rama IX Bridge. (a) The original stand-alone configuration. (b) Image of the new bridge (behind) with the existing bridg (front)

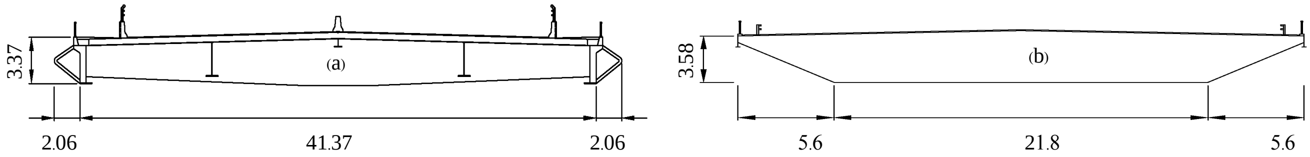

Figure 2 Cross section of prototype (a) new bridge and (b) Rama IX bridge (unit: m.)

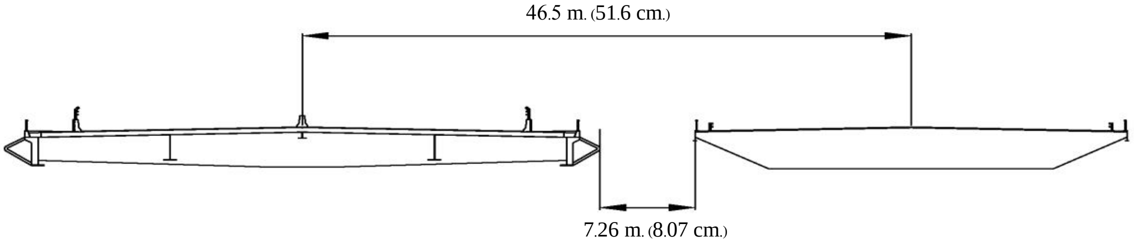

Figure 3 Position of two parallel bridge deck sections (Dimension for the scaled model are shown in parentheses).

Experimental Results

Vortex-induced vibration

From the sectional bridge model test in wind tunnel for 3 cases under smooth winds can be summarized as follows (see Fig. 5).

- For the new bridge alone, the very abrupt transition with increasing velocity from the effectively zero torsional response amplitude to the clear instability occurs in the near neighbourhood of mean wind speed of 81.84 m/s in prototype or equivalent 3 second gust speed of 124.39 m/s. It was found that the instability of the studied bridge model is the torsional flutter type.
- For the new bridge located upstream and the existing bridge located downstream, the very abrupt transition with increasing velocity from the effectively zero torsional response amplitude to the clear instability occurs in the near neighbourhood of mean wind speed of 70.18 m/s in prototype or equivalent 3 second gust speed of 107.7 m/s. It was found that the instability of the studied bridge model is the torsional flutter type. It should be noted that the new bridge located upstream and the existing bridge located downstream result in significantly lower the flutter speed compared with the new bridge alone.
- The new bridge alone and the existing bridge alone exhibit no vortex-shedding responses. However, for the new bridge located upstream and the existing bridge located downstream, the vortex-shedding response of the new bridge under smooth wind moderately occurs at mean wind speed of 25 m/s. This vortex-shedding speed is relatively high. Similarly, for the new bridge located downstream and the existing bridge located upstream, the vortex-shedding response of the existing bridge under smooth wind moderately occurs at mean wind speed of 25 m/s. This vortex-shedding speed is relatively high.

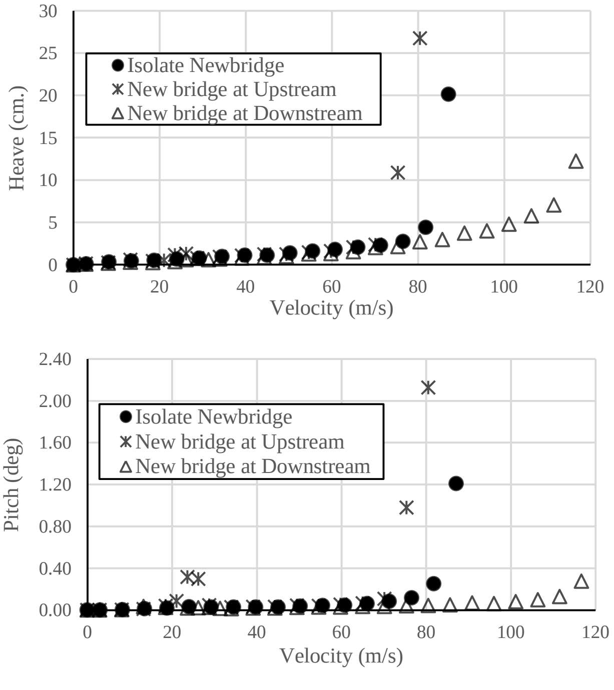

Figure 5. Comparison of aerodynamic response and stability limits of the new Rama IX Bridge in 3 configuration cases.

Aero-elastic stability

Flutter derivative of bridge deck of the new Rama IX bridge under smooth winds from the sectional bridge model test in wind tunnel for 3 cases under smooth winds can be summarized as follows.

- When compared the derivatives A_2^* in the smooth flow between the new bridge located upstream and new bridge alone, the reduced wind speed, which corresponds to the reversed sign of the torsional aerodynamic damping A_2^*, significantly decreases from 5.2 for the new bridge alone to about 4.6 for the new bridge located upstream. Therefore, the new bridge located upstream and the existing bridge located downstream result in significantly lower the flutter speed compared with the new bridge alone.
- The derivatives A_2^* and H_2^* in the smooth flow for the new bridge located downstream show noticeable deviations from those for new bridge alone. The reduced wind speed, which corresponds to the reversed sign of the torsional aerodynamic damping A_2^*, significantly increases from 5.2 for the new bridge alone to about 6.5 for the new bridge located downstream.

Conclusions

The study of aerodynamic interference of two parallel bridge decks section by means of wind tunnel test on sectional models can be summarized as follows.

- The two parallel configurations of the bridge result in vortex-induced vibrations (VIV) and significantly lower the flutter speed compared with the new bridge alone.
- Since the bridges are located in parallel configuration, their wind induced response becomes more complex than the single stand-alone bridge. Therefore, the experimental result from wind tunnel test is necessary to identify and measure aerodynamic problems.

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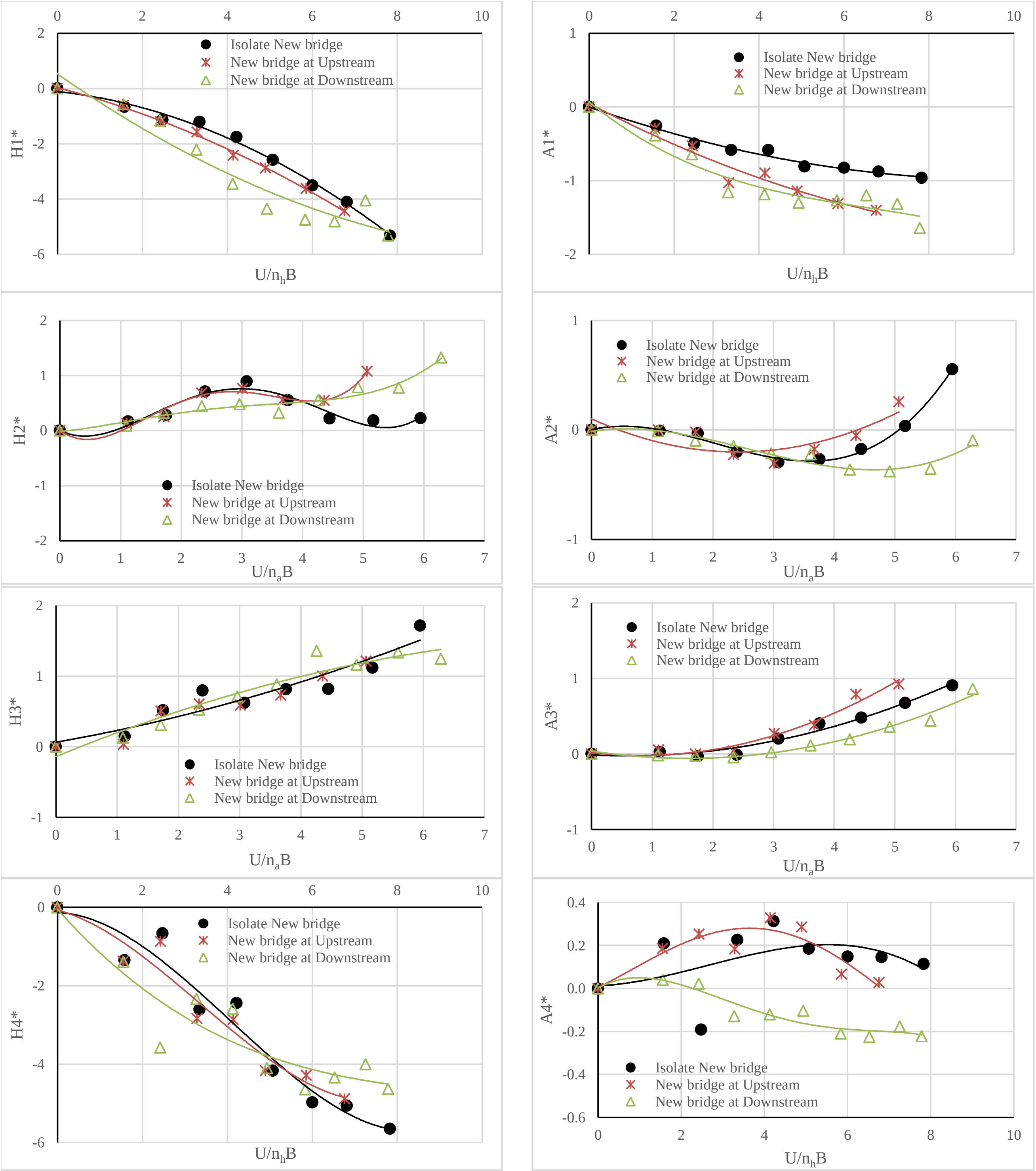

Figure 6. Comparison of flutter derivative of the new Rama IX Bridge in 3 configuration cases.

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