行政院國家科學委員會專題研究計畫 成果報告

應用強制振動技術之橋梁顫振導數識別研究(II)
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行政院國家科學委員會補助專題研究計畫 **v 成果報告**
□期中進度報告

應用強制振動技術之橋梁顫振導數識別研究

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計畫參與人員：（研究生）顏上為，王軍瀚

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中 華 民 國 98 年 12 月 28 日

中文摘要及關鍵詞:

我國近年來經濟高度成長，加快公共建設如高速公路或快速道路等的興建步伐。其中，橋樑常扮演交通運輸上的樞紐，橋樑結構之安全與否，直接間接地對附近地區經濟造成衝擊。橫跨河川的交通運輸橋樑，因聯接距離較長，在力學以及造型美觀的雙重考量下，工程上常採用纜索支撐橋樑設計，加上現今高強度且輕質建材之相繼發明，跨度愈來愈長的橋樑逐漸出現。我國近年來亦逐漸出現跨度較長的纜索支撐橋樑，隨著橋樑跨度的增長，增加了橋樑柔軟度，將使得這些纜索支撐橋樑受風力影響的振動行為愈來愈顯著，在可能發生較大變形之情況下，可能因發散型態之顫振現象出現，在某一臨界風速下，會形成橋樑動態不穩定而崩塌，對於橋樑結構之安全構成相當威脅，1940 年美國之 Tacoma 吊橋在風速二十米左右即發生顫振崩塌之例證可為殷鑑，所以工程上必須對顫振現象有深入的了解。

顫振臨界風速值來自顫振導數(Flutter Derivative)之計算，當風速增加至某一特定值時，自身擾動風力與原結構結合開始出現不穩定，此時之風速即為顫振臨界風速，因此，顫振導數值決定顫振行為。土木橋樑斷面有別於機翼之流線型特性，其形狀多半為鈍體，因此顫振導數無適合之理論式可使用，必須藉由風洞試驗予以識別。傳統自由振動識別法常伴隨兩個主要缺點，其一，由於自由振動之歷時短，試驗者操作之細膩度及風洞周遭天候環境常嚴重影響識別結果；其二，識別出顫振導數之對應頻率為自由振動頻率，並非對應至理論上之外來振動頻率，因此所識別結果與真實值會有差異。

本計畫之研究目標為提出一套全新的氣彈實驗設計與流程，克服傳統自由振動識別法之缺點，提高識別結果之準確度。利用間接強制振動方式驅動斷面模型之振動，藉由反應量測以逆向方式有系統地進行氣彈互制力之識別，可歸類為逆向問題(Inverse Problem)之範疇。工作時程共三年，第二年(2008/8~2009/7)之主要工作內容為提出識別耦合項顫振導數之方法與流程，並以流線型平板斷面模型進行實驗驗證。

關鍵詞：橋面版，氣彈互制效應，顫振，顫振導數，強制振動

英文摘要及關鍵詞：

Among many infrastructures, bridge structures are specifically crucial in terms of the development of a country since they in general are responsible for connecting cities culturally and economically. Most of the cross-river bridges, due to their longer span, are considered to be cable-supported style to meet both the esthetical and mechanical needs. In addition, the trend toward using newly developed stronger and lighter material in construction further makes the design of cable-supported bridges with longer span plausible. However, the increased flexibility by the longer span will aggravate the wind effect on bridge structures. The induced vibration becomes large enough to initiate the occurrence of flutter – the most prominent aeroelasticity that can even cause the structural instability under a critical wind speed (flutter speed). A typical example is the collapse of Tacoma Narrows suspension bridge in 1940.

Basically, the flutter speed is obtained from the calculation of the so-called flutter derivatives, which are the essential quantities in the self-excited forces. Because of the bluff body nature of bridge decks in civil infrastructures, the flutter derivatives are best configured by directly performing wind tunnel tests on bridge section models. The methodology of the conventional free vibration approach has been well developed and widely used in many actual practices to date. However, the typical shortcomings out of it include (1) the lack of consistency because of high sensitivity of free vibration responses to test condition and environment, and (2) the discrepancy inherently inherited by treating the free vibration frequency as the excitation frequency.

To overcome these, this project proposes a new approach to identify flutter derivatives using white-noise forced actuation technique, which can be categorized to the scope of inverse problem. A two-axes actuating device, which is composed of two independent electric servo-motors, was used to indirectly drive the motion of the bridge section model through the serial connection of springs. This project is scheduled to be completed in three years. The main task of the 2nd year (2008/8-2009/7), the main objective is to develop the identification scheme and technique for determining the coupled flutter derivatives, and also perform verification tests for a chamfered plate section model that simulates thin plate.

Keywords: Bridge Deck, Aero-elasticity, Flutter, Flutter Derivative, Forced Actuation

1. INTRODUCTION

In wind engineering, the importance of bridge aero-elasticity is well recognized because it could potentially cause devastation. It has drawn much attention on researches in the last few decades, among which the most important initiative of modeling such behavior was proposed by [Scanlan *et al.* (1971)] by introducing the idea of flutter derivatives. Because of the bluff body nature on civil bridge sections, the flutter derivatives are usually determined by performing wind tunnel tests on section models. The typical shortcomings by the conventional approach that basically uses free vibration technique include (1) the lack of consistency because of high sensitivity of free vibration responses to test condition/environment, and (2) the discrepancy inherently inherited by treating the free vibration frequency as the excitation frequency. To overcome these, this paper presents a new approach for identifying flutter derivatives, with emphasis on the coupled ones, by using white-noise forced actuation technique.

2. EXPERIMENTAL SETUP AND PERTINENT FORMULATION

2.1 Equation of Bridge Motion Subjected to Smooth Wind Flow and Forced Actuation

Consider a schematic diagram of the experimental setup shown in Fig. 1. Under smooth wind flow and forced actuation, the equations of motion can be expressed respectively as

$$J\,\ddot{\theta} + c_\theta\,\dot{\theta} + k_\theta\,\theta = 2\,c_l\,r^2\,\dot{\theta}_0 + 2\,k_l\,r^2\,\theta_0 + L_s\,M(t)\,; \tag{1}$$

$$m\,\ddot{h} + c_h\,\dot{h} + k_h\,h = 2\,c_l\,\dot{h}_0 + 2\,k_l\,h_0 + L_s\,L(t) \tag{2}$$

in which m and J are mass and mass moment of inertia; h and θ are heaving and pitching displacement; $c_\theta = (2c_1 + 2c_2)\,r^2$, $k_\theta = (2k_u + 2k_l)\,r^2$; $c_h = 2c_u + 2c_l$; $k_h = (2k_u + 2k_l)$; k_u, k_l and c_u, c_l are spring stiffnesses and internal damping coefficients, r is spring location to the elastic center of the deck; L_s is length of bridge section, $L(t)$ and $M(t)$ are motion-induced lift and moment per unit length; h_0 and θ_0 are heaving displacement and pitching angle generated by the actuating device. For identifying the bridge model dynamics, the responses were measured due solely to the forced excitation by assigning a white noise to θ_0 and h_0 independently. The uncoupled damping ratios (ξ_h, ξ_θ) and natural frequencies (ω_θ, ω_h) can be determined by curve-fitting the frequency response functions. In addition, the mass m and mass moment of inertia J can be identified by traditional calibration. With the aid of knowing the values of J (or m), the values of c_θ, k_θ, c_h, k_h as well as c_l, k_l can thus be obtained.

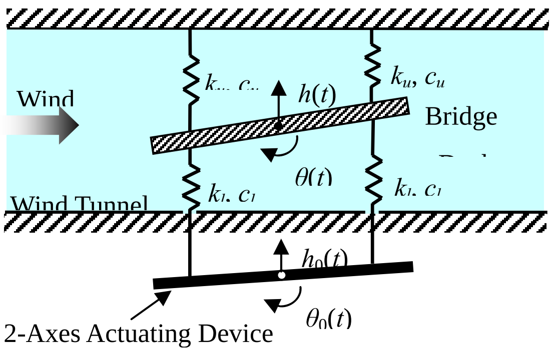

Fig. 1: Configuration of Experimental Setup

2.2 Identification of Coupled Flutter Derivatives

2.2.1 *Aero-elasticity Formulation*

The motion-induced $M(t)$ and $L(t)$ per unit length under smooth wind flow can be expressed as [Scanlan *et al.* (1971)]

$$L(t) = \rho U^2 B\,[K\,H_1^*\,\dot{h}(t)/U + K\,H_2^*\,B\,\dot{\theta}(t)/U + K^2 H_3^*\,\theta(t) + K^2 H_4^*\,h(t)/B\,] \tag{3}$$

$$M(t)=\rho U^2B^2\,[K\,A_1^*\,\dot h(t)/U+K\,A_2^*B\,\dot\theta(t)/U+K^2A_3^*\,\theta(t)+K^2A_4^*\,h(t)/B\,] \quad (4)$$

in which ρ is air density; U is mean wind velocity; B is bridge section width, K is non-dimensional frequency defined as $K=B\omega/U$; ω is excitation frequency in radian/sec; (A_2^*, A_3^*, H_1^* and H_4^*) and (A_1^*, A_4^*, H_2^* and H_3^*) are called uncoupled and coupled flutter derivatives. By taking Fourier transform on Eqs. (3) and (4), their expressions in frequency domain lead to

$$\overline{L}(iK)=H_{L/h}(iK)\cdot\overline{h}+H_{L/\theta}(iK)\cdot\overline{\theta}\;;\;H_{L/h}(iK)=\rho U^2\,[i\,H_1^*+H_4^*]\,K^2\,;\,H_{L/\theta}(iK)=\rho U^2\;B\,[i\,H_2^*+H_3^*]\,K^2 \quad (5)$$

$$\overline{M}(iK)=H_{M/h}(iK)\cdot\overline{h}+H_{M/\theta}(iK)\cdot\overline{\theta}\;;\;H_{M/h}(iK)=\rho U^2B\,[i\,A_1^*+A_4^*]\,K^2\,;\,H_{M/\theta}(iK)=\rho U^2B^2\,[i\,A_2^*+A_3^*]\,K^2 \quad (6)$$

Since $H_{L/\theta}(iK)$ represents the frequency response function of L induced by θ, it is conceivable to assume that $H_{L/\theta}(iK)$ can be realized by an equivalent linear system that has a form of frequency response function

$$\begin{aligned}H_{L/\theta}(iK)&=\rho U^2[\overline{b}_{3L\theta}(iK)^3+\overline{b}_{2L\theta}(iK)^2+\overline{b}_{1L\theta}(iK)^1+\overline{b}_{0L\theta}\,]/[(iK)^2+\overline{a}_1(iK)^1+\overline{a}_0\,]\\&=Q_{L\theta}\,(i\omega)+D_{L\theta}+[c_{1L\theta}(i\omega)^1+c_{0L\theta}\,]/[(i\omega)^2+a_1(i\omega)^1+a_0\,]\end{aligned} \quad (7)$$

$$Q_{L\theta}=\rho U^2B(B/U)\,\overline{b}_{3L\theta}\;;\;D_{L\theta}=\rho U^2B\,(\overline{b}_{2L\theta}-\overline{a}_1\overline{b}_{3L\theta})\;;\;c_{1L\theta}=\rho U^2B\,(B/U)^{-1}\left[\overline{b}_{1L\theta}-\overline{b}_{3L\theta}\,\overline{a}_0-\overline{a}_1\,(\overline{b}_{2L\theta}-\overline{a}_1\,\overline{b}_{3L\theta})\right];$$
$$c_{0L\theta}=\rho U^2B\,(B/U)^{-2}\left[\overline{b}_{0L\theta}-\overline{a}_0\,(\overline{b}_{2L\theta}-\overline{a}_1\,\overline{b}_{3L\theta})\right];\,a_1=\overline{a}_1\,(B/U)^{-1}\;;\;\;a_0=\overline{a}_0\,(B/U)^{-2} \quad (8)$$

In Eq. (7), $\overline{a}_i$, $\overline{b}_{iL\theta}$ are dimensionless constant coefficients to be determined. The same realization can be applied to $H_{L/h}(iK)$, $H_{M/h}(iK)$ and $H_{M/\theta}(iK)$ and thus the corresponding coefficients with subscripts Lh, Mh and $M\theta$ will appear in the formation that is omitted herein. In fact, the identification scheme for determining coefficients for uncoupled frequency response functions $H_{L/h}(iK)$ and $H_{M/\theta}(iK)$ (and thus the uncoupled flutter derivatives) has been proposed in [Wu *et al*. (2006)], and the results of $\overline{a}_1$, $\overline{a}_0$, $\overline{b}_{3Lh}$, $\overline{b}_{2Lh}$, $\overline{b}_{1Lh}$, $\overline{b}_{0Lh}$, $\overline{b}_{3M\theta}$, $\overline{b}_{2M\theta}$, $\overline{b}_{1M\theta}$ and $\overline{b}_{0M\theta}$ will be used in this paper as the given parameters for identifying coupled flutter derivatives.

According to linear system theory, the motion-induced lift L and moment M in Eqs. (5) and (6) can be converted into state space equation in time domain as

$$\dot{\boldsymbol\eta}=\mathbf{A}_{\boldsymbol\eta}\boldsymbol\eta+\mathbf{B}_{\boldsymbol\eta}\,\mathbf{x}\,;\quad\mathbf{F}=\mathbf{C}_{\boldsymbol\eta}\boldsymbol\eta+\mathbf{D}_{\boldsymbol\eta}\mathbf{x}+\mathbf{Q}_{\boldsymbol\eta}\,\dot{\mathbf{x}} \quad (9)$$

$$\boldsymbol\eta=\begin{bmatrix}\mathbf{Z}_1\\\mathbf{Z}_2\end{bmatrix};\mathbf{x}=\begin{bmatrix}h\\\theta\end{bmatrix};\mathbf{F}=\begin{bmatrix}L\\M\end{bmatrix};\mathbf{A}_{\boldsymbol\eta}=\begin{bmatrix}\mathbf{A}&\mathbf{0}\\\mathbf{0}&\mathbf{A}\end{bmatrix};\mathbf{A}=\begin{bmatrix}-a_1&-a_0\\1&0\end{bmatrix};\mathbf{B}_{\boldsymbol\eta}=\begin{bmatrix}\mathbf{B}&0\\0&\mathbf{B}\end{bmatrix};\mathbf{B}=\begin{bmatrix}1\\0\end{bmatrix};\;\mathbf{C}_{\boldsymbol\eta}=\begin{bmatrix}\mathbf{C}_{Lh}&\mathbf{C}_{L\theta}\\\mathbf{C}_{Mh}&\mathbf{C}_{M\theta}\end{bmatrix};$$
$$\mathbf{C}_{Lh}=[c_{1Lh}\quad c_{0Lh}];\mathbf{C}_{L\theta}=[c_{1L\theta}\quad c_{0L\theta}];\mathbf{C}_{Mh}=[c_{1Mh}\quad c_{0Mh}];\mathbf{C}_{M\theta}=[c_{1M\theta}\quad c_{0M\theta}];$$
$$\mathbf{D}_{\boldsymbol\eta}=\begin{bmatrix}D_{Lh}&D_{L\theta}\\D_{Mh}&D_{M\theta}\end{bmatrix};\mathbf{Q}_{\boldsymbol\eta}=\begin{bmatrix}Q_{Lh}&Q_{L\theta}\\Q_{Mh}&Q_{M\theta}\end{bmatrix} \quad (10)$$

When the section model is subjected to the actuation of h_0 and wind flow, the incorporation of aero-elasticity expressed in Eqs. (9) and (10) into the equations of motion, Eqs. (1) and (2), yields an overall state equation in time domain with the output h given by

$$\begin{aligned}\dot{\mathbf{q}}&=\mathbf{A}_{\mathbf{q}}\,\mathbf{q}+\mathbf{B}_{\mathbf{q}}\,h_0\\h&=\mathbf{C}_{\mathbf{q}}\,\mathbf{q}\end{aligned} \quad (11)$$

$$\mathbf{q}=\begin{bmatrix}\mathbf{X}\\\dot{\mathbf{X}}\\\boldsymbol\eta\end{bmatrix};\;\mathbf{A}_{\mathbf{q}}=\begin{bmatrix}\mathbf{0}_{2\text{x}2}&\mathbf{I}_{2\text{x}2}&\mathbf{0}_{2\text{x}4}\\-\mathbf{M}_{\mathbf{a}}^{-1}\,\mathbf{K}_{\mathbf{a}}&-\mathbf{M}_{\mathbf{a}}^{-1}\,\mathbf{C}_{\mathbf{a}}&\mathbf{M}_{\mathbf{a}}^{-1}\,\mathbf{C}_{\boldsymbol\eta}\,L_s\\\mathbf{B}_{\boldsymbol\eta}&\mathbf{0}_{2\text{x}2}&\mathbf{A}_{\boldsymbol\eta}\end{bmatrix};\;\mathbf{B}_{\mathbf{q}}=\begin{bmatrix}\mathbf{0}_{2\text{x}1}\\\mathbf{M}_{\mathbf{a}}^{-1}\mathbf{H}\\\mathbf{0}_{4\text{x}1}\end{bmatrix};\;\mathbf{C}_{\mathbf{q}}=\begin{bmatrix}2\,k_l&0&2\,c_l&0&\mathbf{0}_{1\text{x}4}\end{bmatrix}$$

$$\mathbf{C}_{\mathbf{a}}=\begin{bmatrix}c_h&0\\0&c_\theta\end{bmatrix}-L_s\cdot\begin{bmatrix}Q_{Lh}&Q_{L\theta}\\Q_{Mh}&Q_{M\theta}\end{bmatrix};\mathbf{K}_{\mathbf{a}}=\begin{bmatrix}k_h&0\\0&k_\theta\end{bmatrix}-L_s\cdot\begin{bmatrix}D_{Lh}&D_{L\theta}\\D_{Mh}&D_{M\theta}\end{bmatrix};\mathbf{H}=\begin{bmatrix}1\\0\end{bmatrix} \quad (12)$$

Therefore, with the aero-elasticity incorporated, the frequency response function of h induced by h_0 can be given by

$$H_{h/h_0}(i\omega) = \mathbf{C_q}\left((i\omega)\mathbf{I} - \mathbf{A_q}\right)^{-1}\mathbf{B_q} \tag{13}$$

In the same manner, if the section model is subjected to the actuation of θ_0 and wind flow, the frequency response function of θ due to $\theta_0, H_{\theta/\theta_0}(i\omega)$, can be obtained by following the same equations shown in Eqs. (11)-(13) except that h_0 and h should be replaced by θ_0 and θ; and $\mathbf{H}$ and $\mathbf{C_q}$ should be rewritten as $\mathbf{C_q} = \begin{bmatrix} 0 & 2k_l r^2 & 0 & 2c_l r^2 & \mathbf{0}_{1\text{x}4} \end{bmatrix}$ and $\mathbf{H} = \begin{bmatrix} 0 & 1 \end{bmatrix}^T$, respectively.

2.2.2 Identification Scheme

Under wind flow, by measuring the frequency response function H_{h/h_0} induced by actuation of h_0, and H_{θ/θ_0} induced by actuation of θ_0, the coefficients $\bar{b}_{iL\theta}$'s and $\bar{b}_{iMh}$'s (totally 8 parameters) can be determined properly by minimizing a performance index

$$PI = \sum_{U=U_1}^{U_n}\left(\sum_{k=1}^{N} w_{hk}^U \,|\, H_{h/h_0}^U(i\omega_k) - f_{hk}^U \,|^{\,2} + \sum_{k=1}^{N} w_{\theta k}^U \,|\, H_{\theta/\theta_0}^U(i\omega_k) - f_{\theta k}^U \,|^{\,2}\right) \tag{14}$$

in which $H_{h/h_0}^U(i\omega_k)$, $H_{\theta\theta_0}^U(i\omega_k)$ and f_{hk}^U, $f_{\theta k}^U$ represent the theoretical and experimental frequency response function at the k-th frequency under mean wind velocity U; and w_{hk}^U and $w_{\theta k}^U$ are weightings. In addition, the minimization problem should be constrained by the conditions that $\mathbf{A}$ and $\mathbf{A_q}$ are all stable. To ensure global minimization in the optimal search, the genetic algorithm (GA) [Man, Tang and Kwong (1999)] and gradient method are used in cooperation. Once $\bar{b}_{iL\theta}$ and $\bar{b}_{iMh}$ are determined, the flutter derivatives (H_2^*, H_3^*) and (A_1^*, A_4^*) can be computed by considering the imaginary and real parts accordingly, as shown in Eqs. (5) and (6).

3. EXPERIMENTAL RESULTS

Fig. 2: Bridge Deck Section

For demonstration, the bridge deck of a chamfered plate with a width/depth ratio of 27, as shown in Fig. 2, was placed in a wind tunnel to conduct the identification. Wind tunnel tests at 4 different wind velocities under white-noise actuation were performed. Following the approach presented, the identified flutter derivatives H_2^*, H_3^* and A_1^*, A_4^* versus the reduced wind speed $\hat{U}$ ($\hat{U} = U/fB$; f is the excitation frequency) are shown in Fig. 3 (a)-(d), respectively, in which the flutter derivatives from Theodorsen functions are also plotted for comparison. Time history analysis was also simulated for verifying the identification results and the comparison with the experimental data shows excellent correlation.

4. CONCLUSION

This paper presents a new approach to identify the coupled flutter derivatives of bridge decks by using white-noise forced actuation. A bridge deck composed of a chamfered plate with a width/depth ratio of 27 has been used to successfully demonstrate the applicability of this approach. This approach also provides a direct link between flutter derivatives and state space equations, which can facilitate the time domain analysis for buffeting responses of bridges. For instance, when the bridge is subjected to buffeting lift force, Eqs. (11) and (12) can be used to simulate the heaving response by replacing h_0 by the external buffeting lift force and rewriting $\mathbf{C_q}$ by

$$\mathbf{C_q} = \begin{bmatrix} 1 & 0 & 0 & 0 & \mathbf{0}_{1x4} \end{bmatrix}.$$

5. REFERENCES

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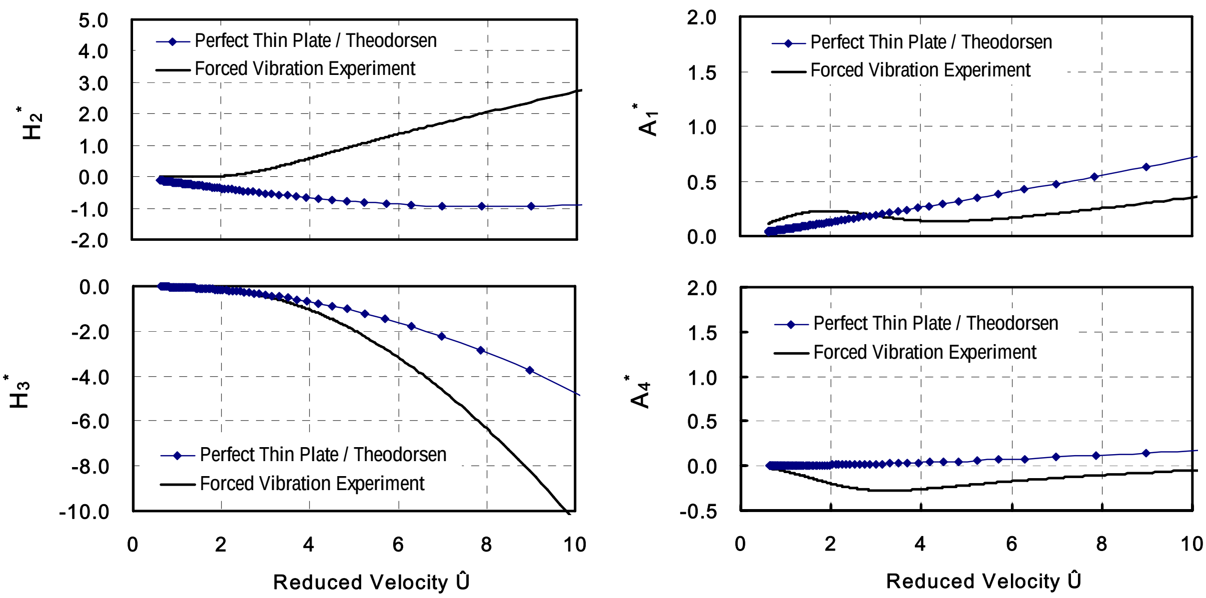

Fig. 3: Comparisons of Identified Coupled Flutter Derivatives with Those from Theodorsen Functions