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New Control Method for Flutter Suppression of Long-Span Bridges

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Summary

In this paper a passive aerodynamic control of flutter of long-span bridge is proposed. The system consists of additional surfaces attached to the bridge deck and an additional pendulum. Rotation of control surfaces is used to generate stabilizing aerodynamic forces. The FEM analysis performed on multimode model of the bridge showed that the flutter critical wind speed can be increased to the required level when the bridge is equipped with the control surfaces of the length of 13% of the total length of the bride deck. It was found that the design of control action of the surfaces must incorporate control of oscillating flutter modes as well as divergent type of instability.

1. Introduction

Remarkable progress has been made over the last twenty years in research on using passive, active and hybrid systems as a means of structural protection against wind, earthquakes and other hazards[1,2]. The first full-scale application of active control to a building[3] was accomplished in 1989. The first application of active control to bridges[4] appeared in 1991. Now 14 bridge towers have employed active systems during erection. The full-scale active control systems that have been installed in bridges, aim mainly at reduction of vortex-induced vibration of towers during erection and are limited only to a relatively small amplitude range. There have been no applications of active control to the wind-induced flutter oscillations of girders of long-span bridges.

Traditionally "passive methods", such as an increase in the structural stiffness of bridge girders, have been used for flutter suppression. A deep truss section with high torsional stiffness was selected for the Akashi suspension bridge (main span of 1990 m) in Japan. Improvement in aerodynamic stability can also be obtained by streamlining the bridge deck. Nevertheless, for suspension bridges with a main span of several kilometers active methods provide new design alternatives. Murata and Ito[5] conducted analytical and experimental study with an active gyro installed on the bridge deck. The motion of the gyroscope was coupled with torsional motion of the deck and the moment of gyration was used for prevention of onset of flutter. The application of the Active Mass Driver (AMD) was studied by Dung et all.[6] The numerical simulations showed good improvement of the flutter wind speed.

The active flutter suppression methods, discussed above, aim at modification of the dynamic properties of the bridge structure itself. Modification of the flow around the bridge deck or generation of stabilizing aerodynamic forces from the flow is another approach to the flutter problem. Active aerodynamic methods can be defined as the prevention of flutter by using aerodynamic control surfaces controlled by signals through an appropriate feedback control law. In this control methods stabilizing forces, generated on the control surfaces, increase proportionally to the wind speed squared, and thus proportionally to the forces acting on the bridge deck. Furthermore, the stabilizing forces are not generated directly by the actuators, but are drawn form the air flow, thus, the energy required for control is much smaller since it is used only for rotation of the control surfaces. The application of such methods for control of bridge vibration was proposed by Ostenfeld and Larsen[7]. Experimental study of the active aerodynamic control method with control surfaces attached to the bridge deck through the pylons was conducted by Kobayashi and Nagaoka[8], and obtained improvement of critical flutter wind speed, when compared to the deck without any devices, was of a factor of 2. However, the control algorithm in the experiment was selected intuitively and further improvement could be obtained by careful design of control law. Wilde and Fujino[9] proposed a variable-gain control law based on the optimal control theory. The analytical study showed that proper design of the amplitude and phase of the control surface motion can provide stability for any wind speed, even for very flexible bridge.

2. Passive aerodynamic control of flutter of bridge section

The active aerodynamic control of flutter of bridge decks gives the designer freedom in shaping the dynamics of a closed loop system. However, the control system requires actuators, sensors, a computer to execute the control law, and an external power supply. Furthermore, this method requires two or three parallel control systems to safeguard reliability, since the failure of the controller would most likely result in a collapse of the bridge. Thus, there is strong interest in developing a passive system which, though it might not be able to solve the flutter problem for any velocity of oncoming wind, could due to its simplicity and reliability, be easily accepted by bridge engineers.

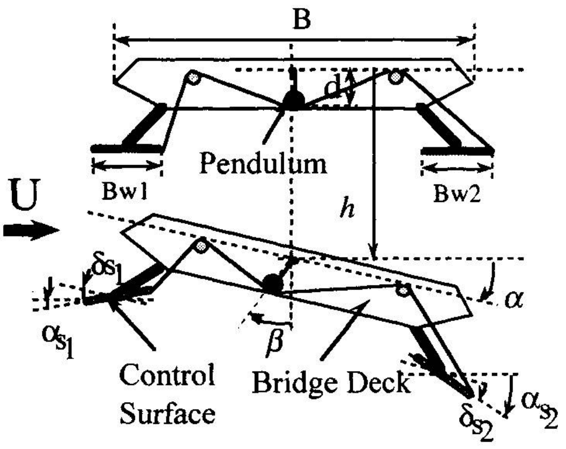

Fig. 1 Cross-section of the deck with passive aerodynamic control system.

A proposed passive system consists of two control surfaces attached to both edges of the deck and a pendulum placed inside the deck (Fig. 1). The pendulum is attached at the center of gravity of the deck. The mass of the pendulum is connected to the control surfaces, such that a torsional displacement of the deck and displacement of the pendulum, result in the appropriate motion of the leading and trailing surface.

2.1 Equation of motion

A mathematical description of the self-exciting aerodynamic forces acting on the bridge deck due to harmonic motion was suggested by Scanlan and Tomko[10]. In his formulation the wind-induced forces are functions of spatial coordinates, their first derivatives and so-called flutter derivatives. The flutter derivatives are the frequency dependent functions, which are determined for each type of bridge deck through specially designed wind tunnel tests. Estimation of the flutter wind speed is performed by an iterative search through the possible flutter frequencies. Wilde et all.[11] suggested the use of rational function approximation, similar to that widely used in aerospace engineering, to represent the unsteady aerodynamics for arbitrary motion. Although, the equation of motion with approximated wind forces, is augmented by additional degrees of freedom, it can be formulated in the form of a set of frequency independent constant coefficient differential equations.

The equation of motion of the section of bridge deck of width B with aerodynamic control with pendulum has three structural degrees of freedom: heaving, h, pitching, α, and displacement of pendulum β. The equation of motion is

$$\mathbf{M}\ddot{\mathbf{q}}(t)+\mathbf{C}\dot{\mathbf{q}}(t)+\mathbf{K}\mathbf{q}(t)=\mathbf{B}_d\mathbf{F}_{ae}^{deck}(t)+\mathbf{B}_{s_1}\mathbf{F}_{ae}^{s_1}(t)+\mathbf{B}_{s_2}\mathbf{F}_{ae}^{s_2}(t), \quad (1)$$

where $\mathbf{M}$, $\mathbf{C}$, $\mathbf{K}$ are mass, damping and stiffness matrices and $\mathbf{q}(t)^T=\left[h/B,\alpha,\beta\right]$. In this equation, $\mathbf{F}_{ae}^{deck}(t)$, $\mathbf{F}_{ae}^{s_1}(t)$ and $\mathbf{F}_{ae}^{s_2}(t)$ are aerodynamic forces acting on the deck and leading and trailing control surface, respectively. The time domain formulation of aerodynamic forces, $\mathbf{F}_{ae}(t)$, is obtained through the rational function approximation[11] as

$$\begin{aligned}\mathbf{F}_{ae}(t)&=\mathbf{V}_f\mathbf{A}_0\mathbf{q}(t)+(B/U)\mathbf{V}_f\mathbf{A}_1\dot{\mathbf{q}}(t)+\mathbf{V}_f\mathbf{D}\mathbf{x}_a(t),\\ \dot{\mathbf{x}}_a(t)&=(U/B)\mathbf{V}_f\mathbf{R}\mathbf{x}_a(t)+(U/B)\mathbf{V}_f\mathbf{E}\mathbf{q}(t),\end{aligned} \quad (2)$$

where $\mathbf{V}_f=diag(-0.5\rho U^2B,0.5\rho U^2B^2)$, U is a mean velocity of oncoming wind and ρ is the air density. The newly introduced variables $\mathbf{x}_a(t)$, called *aerodynamic states,* model the flow structure interaction. The coefficient matrices $\mathbf{A}_0$, $\mathbf{A}_1$, $\mathbf{D}$, $\mathbf{E}$ and $\mathbf{R}$ are computed from the unsteady aerodynamic data obtained from experimentally determined flutter derivatives or theoretically determined flutter derivatives for a flat plate.

Two control patterns of coupling between rotation of control surfaces and torsional displacement of the deck are assumed in this paper. In Pattern 1 the direction of rotation of the leading, δ_{s_1}, and trailing, δ_{s_2}, surfaces are the same. In Pattern 2 the torsional displacement of the leading surface is opposite to the rotation of the deck, α, and the rotation of the trailing surface, is in the same direction as rotation of the deck. For both patterns the rotational ratio, g, of the leading and trailing surfaces are assumed to be the same. The mathematical formulas for both patters are:

Control Pattern 1	Control Pattern 2
$\delta_{s_1}=g(-\alpha+\beta)$,	$\delta_{s_1}=g(-\alpha+\beta)$,
$\delta_{s_2}=g(-\alpha+\beta)$,	$\delta_{s_2}=g(\alpha-\beta)$.

(3)

2.2 Numerical simulations

The bridge deck, used in the simulation, has a flat box section considered for use in the Akashi bridge[12], with a width of 30 m. The undamped natural frequencies of torsional and heaving mode are $T_\alpha=7.48$ s and $T_h=23.27$ s, and the logarithmic decrements of both modes are $\delta_\alpha=0.005$ and $\delta_h=0.005$, respectively. The width of the control surfaces is selected as 10% of the deck width and the surfaces' hinge lines coincide with the edges of the deck.

The root locus of eigenvalues with respect to wind speed of the bridge deck without control system is shown in Fig. 2. The flutter wind speed is found to be 38.8 m/s. Instability occurs due to the negative damping of the torsional dominant mode which is denoted on the graph as mode 2.

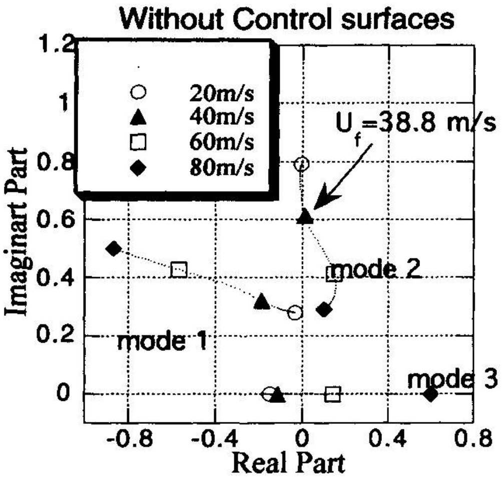

Fig. 2 Root locus of eigenvalues with respect to wind speed of bridge deck without control.

Damping in the heaving dominant mode (mode 1) is significantly increased as the pole moves away form the imaginary axis with increasing wind speed.

The maximum critical wind speeds for controlled system with pattern 1 and 2 with β = 0 are 51.6 m/s and 48.8 m/s, respectively. Increase of rotational ratio, g, above 11 for the system with control pattern 1, and above 6 for control with pattern 2, results in fast decrease of critical wind speed. Fig. 3 shows root locus for bridge controlled by both control patterns for g=6. The antisymmetric motion of the surfaces, pattern 1, adds considerable damping to torsional and heaving modes. However, aerodynamic mode (mode 3) becomes unstable. Instability of this real mode can be interpreted as divergence. The system with control pattern 2 becomes unstable due to negative damping of torsional dominant mode (mode 2). With this control the aerodynamic modes have large damping up to wind speed of 80 m/s.

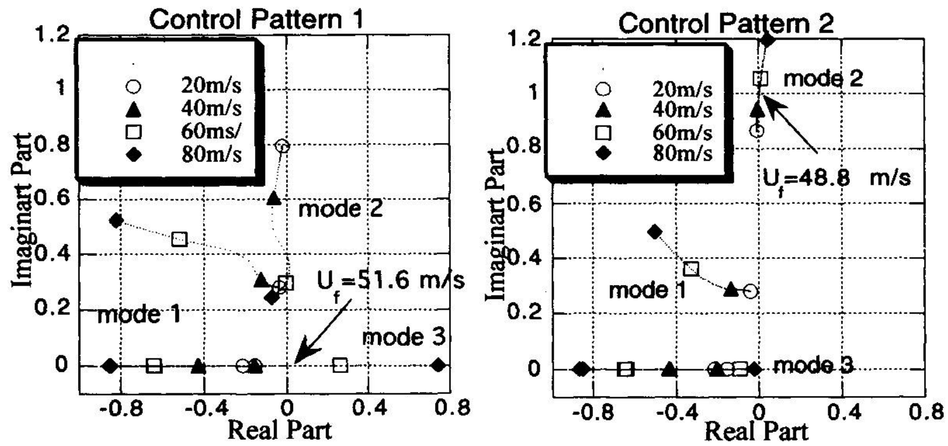

Fig. 3 Root locus of controlled bridge for control pattern 1 and 2.

Numerical simulations which include the motion of the pendulum shows that a long period pendulum is necessary to satisfy the condition of β = 0. For control pattern 1, g=6 and mass ratio of the pendulum of 1% the pendulum period must be larger than 200 s. However, for the mass ratio of 10% the sufficient period of pendulum is 24 s. The control with pattern 2 requires pendulum of period 100 s and 14 s for 1% and 10% mass ratio, respectively.

3. Design of passive aerodynamic control on multimode model of a bridge

A suspension bridge of a main span of 2500 m and side spans of 1000 m is shown in Fig. 4. Since the primary interest in flutter analysis is the coupling of torsional and vertical motion of the deck, the dynamics of the cables and towers are neglected in this study. The bridge is modeled by a three span continues simply supported beam. Standard beam elements are used to derive mass, stiffness and damping element matrices of the system. Each node has two structural degrees of freedom, namely, torsion and vertical displacement, and two degrees of freedom corresponding to aerodynamic states (Eq.2).

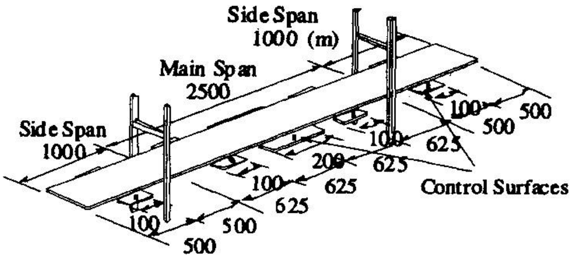

Fig. 4 Model of the bridge with position of control surfaces.

The properties of the bridge are selected such that the frequencies and damping of the first bending and torsional modes are consistent with the frequencies of sectional model of the bridge. The critical wind speed of the uncontrolled bridge is found to be 38 m/s. The instability occurs due to first torsional mode. The divergent type of instability occurs at the wind speed of 49 m/s. The root locus and mode shape of uncontrolled bridge at flutter wind speed are shown in Fig. 5.

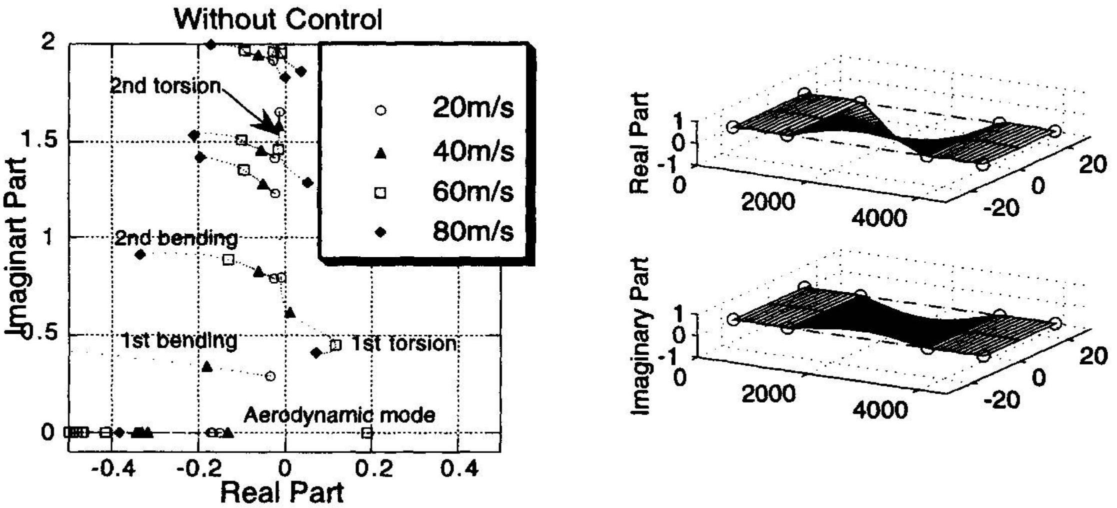

Fig. 5 Root locus of uncontrolled bridge and flutter mode shapes.

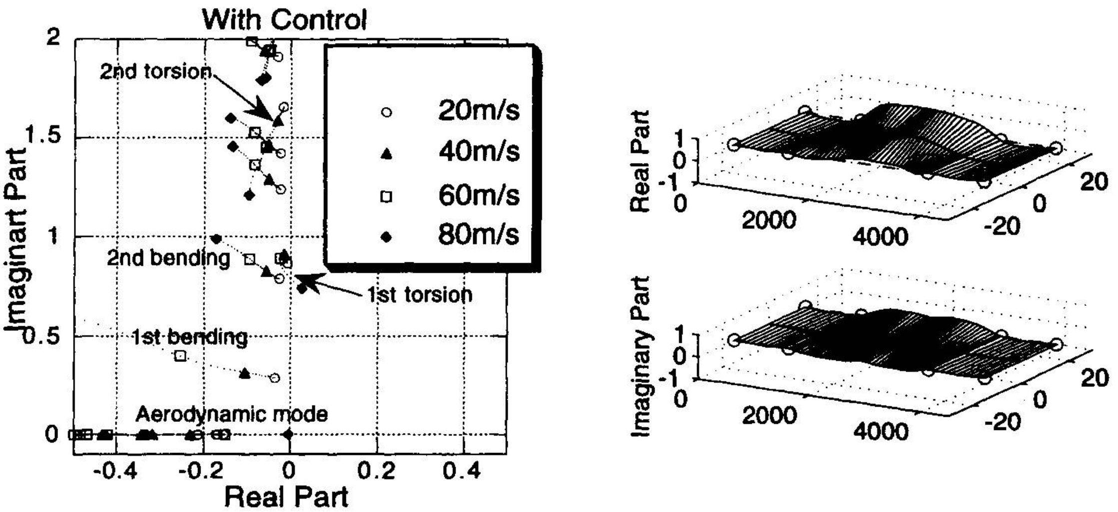

Fig. 6 Root locus of controlled bridge and flutter mode shapes.

Flutter control is performed by 5 additional control units consisting of leading and trailing surfaces. The sizes and positions of control surfaces as well as the rotational ratios and control patterns are optimized such that the critical wind speed of 75 m/s is obtained. The positions and sizes of the surfaces are shown in Fig. 4. The total length of the control surfaces is 13% of the total length of the bridge. The rotational ratio for the control units of side spans are found to be 10, while the rotational ratio for control units located on the main span are 15. The control unit located in the middle of the main span is controlled by control pattern 2. This control is mainly oriented towards the improvement of divergence. All other

10, while the rotational ratio for control units located on the main span are 15. The control unit located in the middle of the main span is controlled by control pattern 2. This control is mainly oriented towards the improvement of divergence . All other control units are controlled by pattern 1 and their main action is directed toward modification of the oscillatory modes of the system. The dynamics of the pendulums of the units is neglected in this study. The root locus of the controlled system is presented in Fig. 6. The instability occurs due to the first torsional mode at wind speed of 75 m/s. The divergent mode is stable up to the wind speed of 79 m/s. The flutter mode of the controlled bridge has large contribution of vertical displacement.

4. Concluding remarks

In this paper the design of passive aerodynamic control of bridge flutter on multimode model of a suspension bridge is presented. The design of the control on multimode model gives larger possibilities of selection of control actions. It was found that the control unit located in the middle of the main span should be concentrated mainly on suppression of divergence while the other units are modifying the flutter oscillatory modes. The flutter wind speed was improved to the required value with the use of the control surfaces which total length was 13 % of the length of the bridge.

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