STUDY ON THE PASSIVE BRIDGE DECK-FLAPS FLUTTER SUPPRESSION SYSTEM ON FEM MODEL OF THE BRIDGE

Piotr Omenzetter[1], Krzysztof Wilde[2] and Yozo Fujino[3]

1) Department of Civil Engineering, The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
e-mail: piotr@bridge.t.u-tokyo.ac.jp
2) Department of Civil Engineering, Technical University of Gdansk
ul. Narutowicza 11/12, 80-952 Gdansk, Poland
e-mail: wild@pg.gda.pl
formerly, Department of Civil Engineering, The University of Tokyo
3) Department of Civil Engineering, The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
e-mail: fujino@bridge.t.u-tokyo.ac.jp

INTRODUCTION

Structure-wind interaction phenomena, static as well as dynamic, are becoming the most challenging problems as bridge spans become longer. Flutter instability and divergence are most often design governing criteria, since they may lead to the total collapse of a bridge structure.

New solutions for improving aerodynamic stability may be found by aerodynamic means. The aerodynamic control of bridge flutter by additional surfaces attached beneath the deck was proposed by Ostenfeld and Larsen (1992). In their concept the rotational displacement of the control surfaces was actively adjusted by feedback control in order to generate aerodynamic forces stabilizing the deck. High costs of active control systems motivated Wilde et al. (1999) to propose and investigate the concept of passive system utilizing control surfaces. In their study control surface motion was govern by an additional pendulum attached to the center of gravity of the deck.

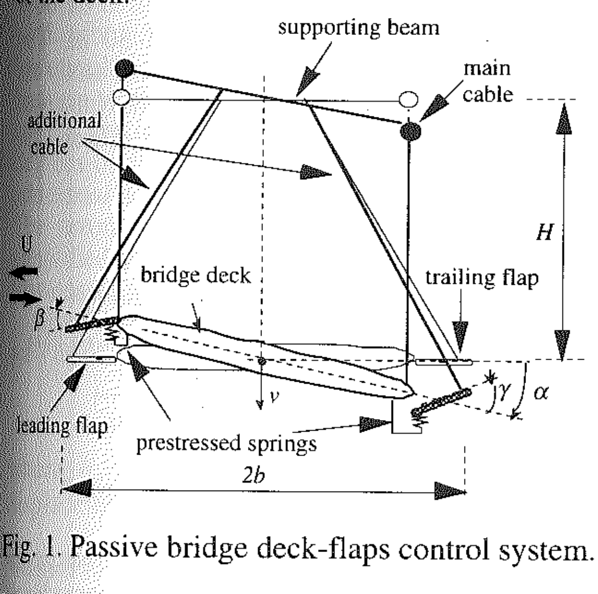

Fig. 1. Passive bridge deck-flaps control system.

Aerodynamic control may be also achieved by additional flaps attached directly to the edges of the bridge deck. In this system the flow pattern around the deck is affected by the motion of the flaps, and thus the stabilizing action comes not only from aerodynamic forces generated on control flaps but also can be achieved through modification of aerodynamic forces exerted on the bridge deck. This control system will be referred to as a bridge deck-flaps control system.

A proposed passive control system (Fig. 1) consists of auxiliary flaps attached directly to the bridge deck. When the deck undergoes torsional motion, control flap rotations are govern by additional cables spanned between control flaps and a supporting beam carried by the main cables of the bridge. Since cables can only pull the flaps but not push them, additional prestressed springs are used to force reverse motion of the control surfaces. The performance of the system with symmetric connection of additional cables is independent of wind direction.

STUDY OF PASSIVE CONTROL SYSTEM ON SECTIONAL MODEL

Equation of motion

The deck of a sectional model of the passive bridge deck-flaps system has two structural degrees of freedom: vertical (heaving), v, and torsional (pitching), α. Horizontal displacements of the deck and main cables are ignored. Relative rotations of the flaps with respect to the deck are denoted as β and γ, respectively. It has been shown by Omenzetter et al. (1999) that for sufficiently large prestressing moments acting on the flaps and stiffness of the supporting beam, relative rotations of the flaps are proportional to the pitching motion of the deck:

$$\beta = t_\beta \alpha, \quad \gamma = t_\gamma \alpha \tag{1, 2}$$

where t_β and t_γ are control gains. The equation of motion in a smooth flow becomes

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{P} \tag{3}$$

where $\mathbf{M}$, $\mathbf{C}$, and $\mathbf{K}$ are structural mass, damping and stiffness matrices, respectively. The vector of nondimentional displacements is

$$\mathbf{x}' = \begin{bmatrix} h/b & \alpha \end{bmatrix} \tag{4}$$

where $2b$ is the width of the deck together with the flaps.

Vector $\mathbf{P}$ denotes self-exited aerodynamic forces. To model the self-exited forces of the deck-flaps system, the solution of Theodorsen and Garrick (1943) for a wing-aileron-tab combination (Fig. 2) is used. This solution describes full aerodynamic interaction between system members under assumptions that the deck is treated as a flat plate, potential flow theory is applicable, oscillations are small, and there is no fluid leak between system members.

The time domain formulation of self-exited forces for the deck-flaps system is obtained through Rational Function Approximation (RFA) of the frequency dependent solution due to Theodorsen and Garrick (Omenzetter et al. 1999). Although this formulation introduces new variables describing the system, referred to as aerodynamic states, and denoted by $\mathbf{x}_a$, it enables writing the equation of motion in the state-space form, which depends only on wind velocity, U:

$$\dot{\mathbf{y}} = \mathbf{A}(U)\mathbf{y} \tag{5}$$

where the augmented vector of states is

$$\mathbf{y}' = \begin{bmatrix} \mathbf{x}' & \dot{\mathbf{x}}' & \mathbf{x}'_a \end{bmatrix} \tag{6}$$

Numerical simulations

The analyzed suspension bridge is shown in Fig. 3. The deck has width of 30 *m*. The frequencies and damping ratios of first few modes are listed in Table 1. For sectional study the first vertical and the second torsional mode are chosen due to their symmetric shapes. Numerical simulations of the sectional model showed that the critical flutter wind speed is 53 *m/s* and the critical divergence wind speed is 70 *m/s*.

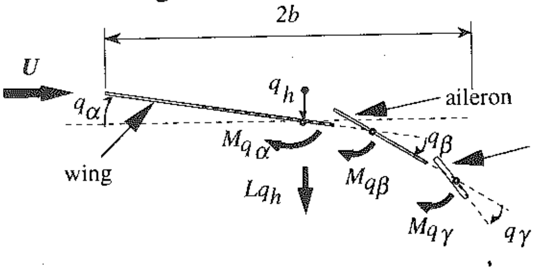

Fig. 2. Wing-aileron-tab combination.

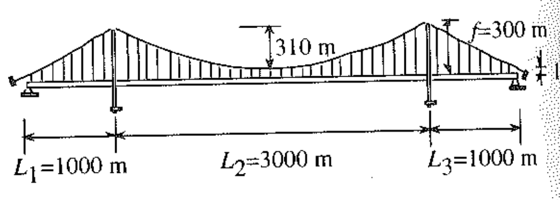

Fig. 3. Geometry of the suspension bridge.

The configuration of the passive deck-flaps control system which brings on maximum improvement in critical wind speed is searched for. Different flap widths, b_f, are considered from 1.0 m up to 4.0 m. To preserve system symmetry, the gains for leading and trailing flap are assumed equal, $t_\beta = t_\gamma = t$, and their values are confined in the interval $0 \le t \le 10$. The values of the critical wind speed for different flap sizes are shown in Fig. 4. The maximum improvement in critical wind speed up to 69 m/s (improvement of 30%) is attained for the system with flaps of width 1.0 *m*. Any increase in flap size causes critical wind speed to deteriorate. For very small flaps of width 1.0 *m* the forces generated on the flaps are small, and hence stabilizing action might be attributed mainly to the changes in flow pattern about the deck introduced by motion of control surfaces. The optimal gains are found to be in the range

$$3.7 \le t \le 4.4 \tag{7}$$

The instability of the controlled bridge for the above range of control gains occurs due to divergence. Since the critical divergence wind speeds for controlled and uncontrolled bridge are nearly the same, it can be deduced that this control system cannot affect and suppress the divergence type of instability.

Table 1. Modal properties of the bridge.

mode	frequency (rad/s)	damping ratio
1st horizontal	0.208	0.010
2nd horizontal	0.389	0.007
3rd horizontal	0.543	0.009
1st vertical	0.412	0.010
2nd vertical	0.413	0.008
3rd vertical	0.611	0.011
1st torsional	0.909	0.008
2nd torsional	1.420	0.011
3rd torsional	2.200	0.014

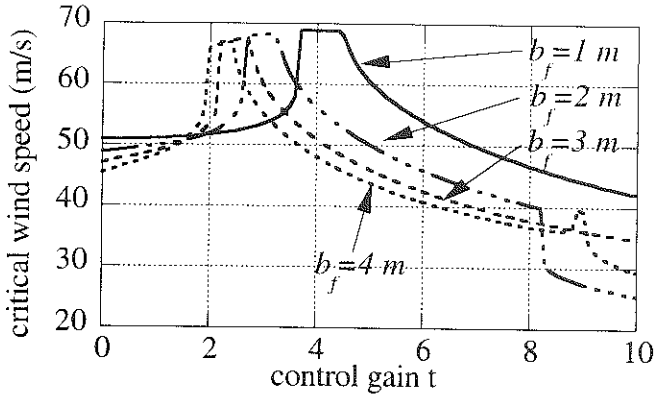

Fig. 4. Critical wind speed for different widths of flaps (sectional study).

STUDY OF PASSIVE CONTROL SYSTEM ON FULL BRIDGE MODEL

FEM model of a bridge

The simplified structural modeling for vertical vibrations of a suspension bridge was proposed by Abdel-Ghaffar (1980). In the present study torsional displacements as well as horizontal motions of the deck and the main cables are included. The basic assumptions are: the dead load is distributed uniformly along the bridge and carried only by the main cables, hangars are inextensible and the forces they apply to the deck are distributed as if the distance between the hangers were very small, longitudinal displacements of the deck as well as dynamics of the towers are ignored. The finite element for the deck-flaps system (Fig. 5) has 18 structural degrees of freedom. The aerodynamic lift and moment are modeled through RFA, and hence additional degrees of freedom corresponding to the aerodynamic states are added at each node. The aerodynamic forces due to lateral motions are modeled by quasi steady theory. The simplified model of a bridge significantly reduces computational burden, but retains all the features of a bridge relevant for flutter analysis.

For 3D model of the passive control system, the motion of the flaps is govern by torsional as well as horizontal motions of the deck:

$$\beta = t_\beta \alpha + \frac{t_\beta}{H}(h_d - h_c), \quad \gamma = t_\gamma \alpha + \frac{t_\gamma}{H}(h_d - h_c) \tag{8, 9}$$

where h_d is the horizontal displacement of the deck, and h_c is the common horizontal displacement of the main cables. *H* is the vertical distance between the main cables and flaps.

Numerical simulations

Numerical simulations of the full bridge model showed that the critical flutter wind speed is 58 *m/s*. It can be noticed that the sectional model underestimated the critical wind speed by approximately 10%. The critical divergence wind speed is found to be 71 *m/s*, and agrees very well with the sectional model results.

The analysis of passive control systems is performed to assess the influence of distribution of the flaps along the bridge on system effectiveness. Four cases are considered with flaps on 30%, 50%, and 100% of the main span, as well as on the whole bridge, respectively. Width of flaps is assumed to be 1.0 *m*. The values of the critical wind speed for different flap distributions are shown in Fig. 6. The maximum improvement in critical wind speed up to 72 m/s (improvement of 24%) is attained for the system with flaps on 30% of the main span. However, for this case large control gains are required. The system with flaps on 50% of the main span offers similar improvement in critical wind speed up to 71 *m/s* (22%), but requires considerably smaller gains confined in the range

$$4.8 \leq t \leq 5.8 \quad (10)$$

Hence, the system with flaps on 50% of the main span is preferable for practical applications.

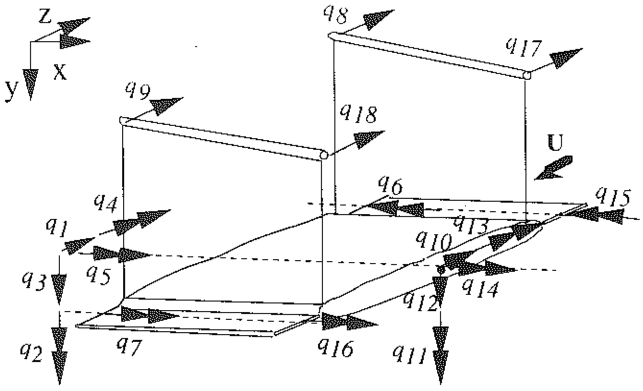

Fig. 5. Finite element for deck-flaps system.

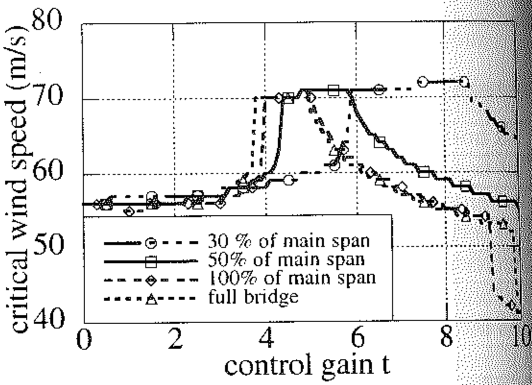

Fig. 6. Critical wind speed for different distributions of flaps.

CONCLUSIONS

In this paper the passive control of flutter in long span bridges by additional flaps attached directly to the deck is presented. The time domain model of unsteady aerodynamic forces is derived through Rational Function Approximation.

Numerical simulations conducted on the sectional model of a bridge show that the system can efficiently use small flaps of 1.0 *m* width. Studies on a full bridge model show that most effective suppression of flutter is achieved by locating the flaps on 50% of the main span. Although the system suppresses flutter it cannot affect divergence, and this type of instability restricts its effectiveness.

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