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STUDY OF A PASSIVE AERODYNAMIC CONTROL SYSTEM FOR BRIDGE DECK FLUTTER SUPPRESSION

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1. INTRODUCTION

The aerodynamic flutter control methods, by means of additional surfaces, can change the flow-structure interaction and suppress flutter. A proposed passive control system (Fig. 1) consists of auxiliary flaps attached directly to the bridge deck. When the deck undergoes pitching motion, control flaps rotation is govern by additional cables spanned between control flaps and an auxiliary transverse beam supported by the main cables. Additional prestressed springs are used to force reverse motion of the flaps. The performance of the system with symmetric connection of additional cables is independent from wind direction. The aim of this paper is to propose a suitable configuration of control system for suppression of wind induced vibration in ultra long-span bridges.

2. EQUATION OF MOTION

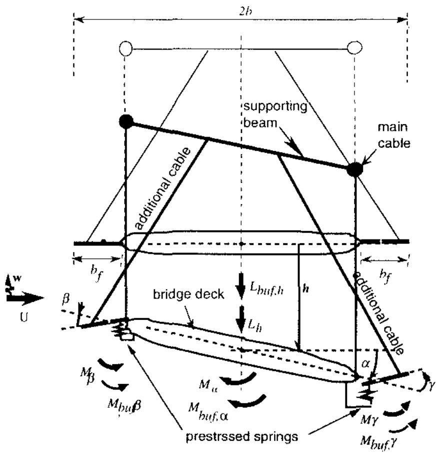

Fig. 1 Cross-section of the bridge deck-flaps passive control system.

The system motion is described by heaving, h, pitching, α, and β, γ denote relative angles of rotation of leading and trailing flap, respectively (Fig. 1).

The governing equation of motion is:

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{F}_{ea}\left(\ddot{\mathbf{x}}, \dot{\mathbf{x}}, \mathbf{x}, s^*\right) + \mathbf{F}_{buf} + \mathbf{F}_{ps} \qquad (1)$$

where $\mathbf{x}'=[h/b\ \alpha\ \beta\ \gamma]$. The matrices **M**, **C** represent system mass and damping, respectively. The stiffness matrix, **K**, attains different values when both cables are in tension, only leading or trailing cable is in tension, or none of the cables is in tension. The equation of motion (1) becomes nonlinear due to variable stiffness of the cables supporting the flaps.

The forces due to prestressing moments, $M_{\beta 0}$ and $M_{\gamma 0}$, are represented by vector $\mathbf{F}_{ps}$. The prestressing moments are expressed in terms of the initial flaps displacements β_0 and γ_0, and stiffness at the deck-flaps connections, k_β and k_γ

$$M_{\beta 0} = k_\beta \beta_0, \quad M_{\gamma 0} = k_\gamma \gamma_0 \qquad (2a, b)$$

$\mathbf{F}'=[L_h\ M_\alpha\ M_\beta\ M_\gamma]$ represents the vector of self-excited aerodynamic forces depending on the complex reduced frequency s^*. Their description is obtained from the Theodorsen solution for wing-aileron-tab combination. The self-excited aerodynamic forces are modeled using rational function approximation[1]. The vector $\mathbf{F}_{buf}$ represents buffeting forces.

3. LINEAR EQUATION OF MOTION

For sufficiently large prestressing moments and initial angles of rotation the supporting cables remain always in tension. In such case, flaps' rotation can be assumed proportional to the rotation of the deck:

$$\beta = t_\beta \alpha, \quad \gamma = t_\gamma \alpha \qquad (3a, b)$$

The linear governing equation of motion becomes:

$$\mathbf{T}'\mathbf{M}\mathbf{T}\ddot{\mathbf{y}} + \mathbf{T}'\mathbf{C}\mathbf{T}\dot{\mathbf{y}} + \mathbf{T}'\mathbf{K}\mathbf{T}\mathbf{y} = \mathbf{T}'\mathbf{F}_{ea}\left(\ddot{\mathbf{x}}, \dot{\mathbf{x}}, \mathbf{x}, s^*\right) + \mathbf{T}'\mathbf{F}_{buf} \qquad (4)$$

where $\mathbf{y}'=[h/b\ \alpha]$ is the displacement vector of the linear system and

$$\mathbf{T}' = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & t_\beta & t_\gamma \end{bmatrix} \qquad (5)$$

4. NUMERICAL SIMULATIONS

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The dynamic parameters of the sectional model of the bridge are ω_h=0.427 rad/s and ω_α=0.917 rad/s for heaving and pitching mode, respectively. Structural damping coefficients are ξ_h=0.0082 and ξ_α=0.0072. The critical flutter wind speed for this bridge without flaps is 50 m/s and divergence wind speed is 70 m/s.

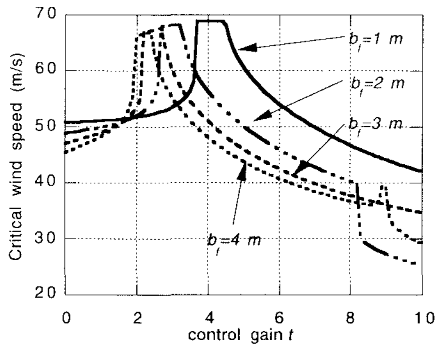

Fig. 2 Critical wind speed vs. control gain

The configuration of the passive deck-flaps control system which brings on maximum improvement in critical wind speed is searched for, using the linearized equation of motion (4). The gains for leading and trailing flap are assumed equal $t_\beta=t_\gamma=t$. The values of the critical wind speed for different flap sizes are shown in Figure 2. 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. The optimal gains are

$$\beta = \gamma = 4.0\alpha \qquad (6)$$

The nonlinear system (1) is studied with the optimal control gains of (5). The stiffness at the deck-flaps connection is assumed as $k_\beta=k_\gamma$=5.3 kNm/m (corresponding to $\omega_\beta=\omega_\gamma=10\ \omega_\alpha$), the axial stiffness of the cables is EA=10 MN/m, and the bending stiffness of the beam is EI=10 MNm^2/m. The simulations are conducted for the wind velocity U=65 m/s. The vertical component of the wind record has a turbulence intensity of 4.2% and the peak vertical wind speed is 9.8 m/s.

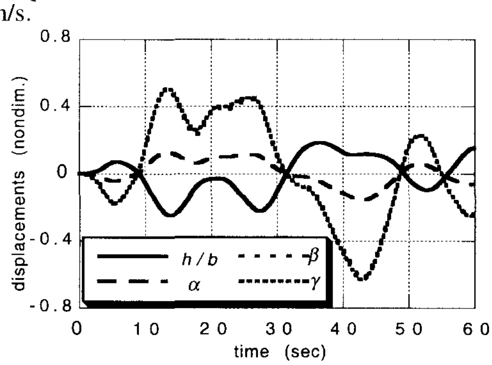

Fig. 3 Time response of the controlled system at U=65 m/s.

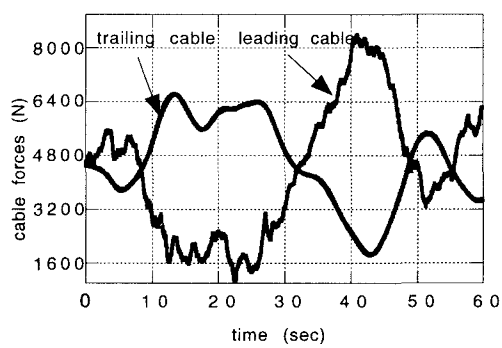

Fig. 4 Time history of forces in the supporting cables.

The simulations revealed that for the additional cables to remain always in tension the required prestressing moments should be at least 8.0 kNm/m and the initial angles of rotation of the flaps are 1.5 rad. The time response of the system is shown in Figure 3. The response of the deck is strongly suppressed and its maximum magnitudes are 0.159 rad for pitching and 4.00 m for heaving motion. The maximum rotational displacements of the control flaps are 0.621 rad and 0.633 rad for leading and trailing flap, respectively. The forces in the supporting cables are shown in Figure 4. The maximum magnitudes are 8.4 kN for the leading flap's cable and 6.9 kN for the trailing flap's one.

5. CONCLUSIONS

In this paper the passive bridge deck-flaps control system consisting of additional control surfaces attached directly to the bridge deck is proposed. Motion of the control surfaces is related to the pitching motion of the deck through additional cables and prestressed springs. Nonlinear equation of motion, taking into account lack of compressive stiffness of the additional cables, is derived. Time domain model of self-exited aerodynamic forces is found through rational function approximation. An optimal configurations of control system is proposed with flaps of 1.0 m. Maximum increase in critical wind speed is 30%. Small size of the flaps implies not only their simple design, but small forces acting on the supporting system as well. Further study is being conducted on a full bridge model to provide detailed information about system performance.

REFERENCE

1) Wilde K., Omenzetter P., Fujino Y.: Modeling of Unsteady Aerodynamics of Bridge Deck-Flaps System and Optimization of Flaps Motion, Proceedings of the 52nd Annual Conference of JSCE, 1997.