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ACTIVE AERODYNAMIC CONTROL OF BRIDGE DECK FLUTTER - SYSTEM SENSITIVITY AND PARAMETER IDENTIFICATION

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1. INTRODUCTION: The proposed aerodynamic active control consists of two additional surfaces attached below both edges of the deck. The experimental study conducted by Kobayashi [2] and analytical study on application of optimal variable-output feedback [4] provided promising results concerning effectiveness of this method. The dependence of the aerodynamic active control on reliable estimation of aerodynamic parameters of control wings and bridge deck motivated the sensitivity analysis. To cope with the system uncertainties the on-line parameter identification scheme is proposed.

2. MODELING OF AERODYNAMIC ACTIVE SYSTEM: The streamlined control surfaces are attached below the both edges of the bridge deck (Fig. 2.1) at $e_1 = e_2 = B/2$. The width of control surfaces is assumed to be 10 % of the deck width . The pitch of the control surfaces is actively controlled so as to generate the stabilizing aerodynamic forces $L_{w1}, M_{w1,} L_{w2}, M_{w2}$. The unsteady aerodynamic forces on the control surfaces as well as flutter derivatives of the deck were calculated through Theodorsen's function. The dynamic characteristics of the bridge deck are the same as the cross-section proposed for Akashi Bridge (model scale 1:150) [4]. Both, the deck and wing force data, were approximated by the minimum state Rational Function Approximation formulation with two lag terms. The resulting space-state and output equations of the system (Eqs. 2.1) have the state-space vector of

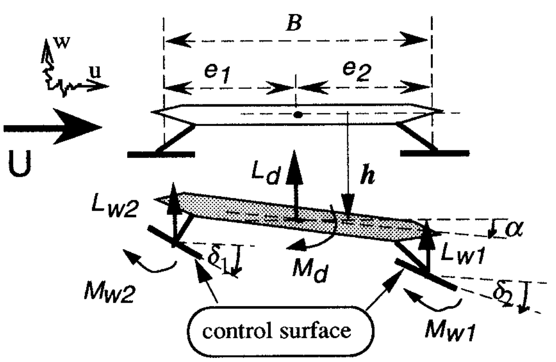

Fig 2.1. Bridge Deck with Control Wings

$\mathbf{x} = \left[\dot{h}/B \;\; \dot{\alpha} \;\; \dot{\delta}_1 \;\; \dot{\delta}_2 \;\; h/B \;\; \alpha \;\; \delta_1 \;\; \delta_2 \;\; x_{a1} \;\; \cdots \;\; x_{a6}\right]^T$ where $x_{a1},\cdots,x_{a6}$ are the new aerodynamic states.

$$\dot{\mathbf{x}}(t) = \mathbf{A}(U)\mathbf{x}(t) + \mathbf{B}_{\text{buf}}\mathbf{F}_{\text{buf}}(t) + \mathbf{B}\mathbf{u}(t) \qquad (2.1a)$$

$$\mathbf{y}(t) = \mathbf{C}\,\mathbf{x}(t) \qquad (2.1b)$$

$\mathbf{F}_{\text{buf}} = \left[L_{buf} \;\; M_{buf}\right]^T$ denotes buffeting forces and the vector $\mathbf{u} = \left[u_1 \;\; u_2\right]^T$ represents torque applied for the control wing movements. Since the newly introduced aerodynamic states are not directly available for measurement, the output vector was selected as $\mathbf{y} = \left[\dot{h}/B \;\; \dot{\alpha} \;\; h/B \;\; \alpha \;\; \delta_1 \;\; \delta_2\right]^T$. For fixed wind velocity U, the equation of the bridge deck describes a linear time-invariant system. The flutter wind speed (no control) was found to be $U_f = 10.7\ m/s$.

The control command $\mathbf{u}$ is generated via output linear feedback with time-invariant gains (Eq. 2.2). The optimal output control [3] is formulated as a mathematical optimization of the averaged performance index (Eq. 2.3) with initial state $\mathbf{x}(0)$ assumed as a random variable. Optimization yields

$$\mathbf{u} = -\mathbf{K}\,\mathbf{y} \qquad (2.2)$$

$$J_l = \frac{1}{2}\int_0^\infty E\left\{ \mathbf{x}^{\mathrm{T}}\mathbf{Q}\,\mathbf{x} + \mathbf{u}^{\mathrm{T}}\mathbf{R}\,\mathbf{u} \right\} dt \qquad (2.3)$$

the gain matrix $\mathbf{K}$ as a solution of three simultaneous equations. Since the system equations depend upon wind velocity, the gain matrix $\mathbf{K}$ is indirectly dependent on U . Thus, the design process requires first to select the design wind velocity and then calculate the associated matrix $\mathbf{K}$.

3. SENSITIVITY OF FLUTTER CONTROL: In the proposed bridge deck active control the dynamic parameters of the system are assumed to be completely known. The parameters, describing the aerodynamic damping and stiffness, are obtained through Rational Function Approximation and are based on the flutter derivatives given by experiment or theoretical solution by Theodorsen's function. In case of experimental flutter derivatives, they may vary from their true values due to differences in turbulence intensity, angle of attack, Reynolds effect, etc. The theoretical derivatives, on the other hand, are derived form purely theoretical assumptions of potential flow theory, valid for airfoil with no flow separation, which are only rough idealization of wind-bridge interaction phenomena. The amount of error in estimating aeroelastic coefficients is, however, crucial for flutter bridge control, since control algorithm design is based on system parameters.

H_∞ norm of system transfer function is considered as a tool to compare the system sensitivity to parameter variations. The larger value of H_∞ norm is, the larger is the system response for the specified excitation.

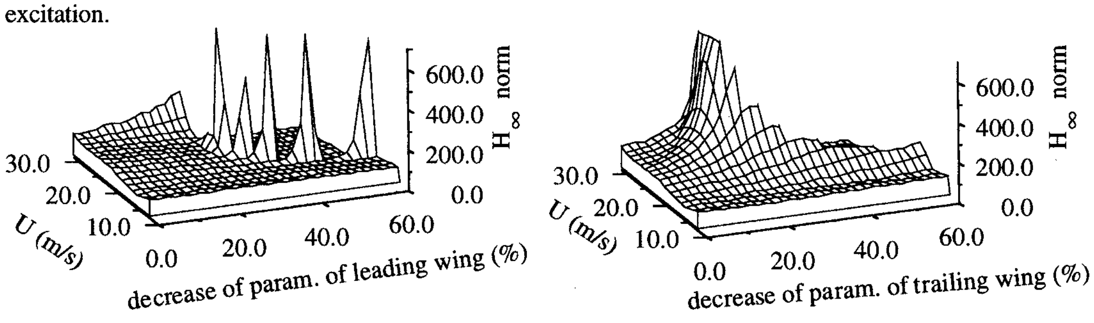

Fig. 3.1 H_∞ Norm for Decreasing Parameters of Leading and Trailing Wings vs. Wind Speed.

The sensitivity analysis was conducted by decreasing the aeroelastic parameters of leading and trailing wing. The perturbations on the parameters of the bridge deck were omitted to clearly determine system behavior due to improper estimation of wing stabilizing forces. The results of H_∞ norm for closed loop system with fixed output gain (design for wind speed U=19 m/s) for decreasing parameters of leading wing and trailing wing versus wind speed are shown in Fig. 3.1.

The system is robust in the low wind range but becomes quicker unstable for uncertainties in the larger wind. The change of the aeroelastic parameters of the wings of about 20% results in undesired system response in the higher wind range ($U > 24$ m/s). Fig. 3.1 shows that the uncertainties of the trailing wing cause quicker system instability than changes in the parameters of the leading wing. The trailing wing is in the wake of the leading wing and bridge deck and therefore, experimental or theoretical precise determination of the parameters is very difficult. Solution of this problem may be found in on-line parameter identification and associated adaptive control.

4. IDENTIFICATION OF SYSTEM PARAMETERS: The basic structure of an adaptive controller combines on-line parameter estimation with the on-line modified control. The on-line estimator scheme produces an updated parameter estimate within the time limit imposed by the sampling period.

The equation of motion (Eq.2.1) was transferred to discrete domain and rewritten in the form of Eq.4.1.

$$\mathbf{x}(k) = \theta_0\, \phi(k-1), \qquad (4.1)$$

$$\hat{\theta}(k) = \hat{\theta}(k-1) + M\, \phi(k-1)e(k), \qquad (4.2)$$

$$M = \frac{P(k-2)}{1+\phi(k-1)^T P(k-2)\phi(k-1)}. \qquad (4.3)$$

Matrix θ_0 consist of all the system coefficients and vector $\phi(k-1)$ is composed of the system states and buffeting forces at time step $k-1$. The applied identification scheme is called Least-Squares and is described by Eqs. 4.2. The term $e(k)$ is the modeling error and M denotes the algorithm gain (Eq. 4.3). The initial parameter matrix $\hat{\theta}(0)$ is given, and initial $P(-1)$ is any positive definite matrix P_0. Matrix P, regarded as a covariance matrix of the process, is updated each time step. Parameter identification simulations were carried out for bridge deck (no control wings) with mean wind speed $U=10$ m/s for given wind fluctuations considered as inputs, and computed bridge deck responses as outputs. The initial parameters of matrix $\hat{\theta}(0)$ were chosen with 20% error comparing to parameters used for response calculation. The history of errors in parameter estimation (Fig. 4.1) shows satisfactory convergence.

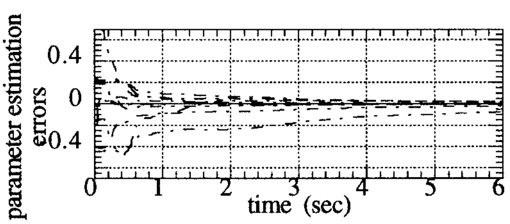

Fig. 4.1 Estimation Errors of Parameters

5. REFERENCES: [1] Goodwin,G., Sang Sin, K., "Adaptive Filtering, Prediction and Control", Prentice-Hall, 1984. [2] Kobayashi, H., Nagaoka, H., (1992), "Active Control of Flutter of a Suspension Bridge", *J. of Wind Eng. and Ind. Aerodyn.*, 41-44. [3] Levine, W., Athans M., (1970), "On the Determination of the Optimal Constant Output Feedback", *IEEE Trans. Auto. Control,* vol. AC-15, no 1. [4] Wilde, K., Fujino, Y., et al., (1994), "Active Control of Flutter of a Suspension Bridge", *1WCSC*, Los Angeles, California, August 1994.