SUPPRESSION OF WING FLUTTER VIA DIAGONAL PIEZOELECTRIC ROD CONTROLLER

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Introduction

The capability of Piezoelectric (PZT) self-sensing actuators to suppress the transonic wing-box flutter is studied. The unsteady general frequency modified Transonic Small Disturbance (TSD) equation is used to model the flow about the wing. The wing-box structure and the piezoelectric actuators are modeled using the equivalent plate method, which is based on the First-order Shear Deformation Plate Theory (FSDPT). The piezoelectric actuators are used as segments of piezoelectric diagonal-rod. Three main different control strategies; Linear Quadratic Gaussian (LQG), Optimal Static Output Feedback (SOF), and Simple Feedback Controller (SFC); are studied and compared. The optimum actuators and sensors locations are determined using the Norm of Feedback Control Gains (NFCG) and Norm of Kalman Fillter Estimator Gains (NKFEG) respectively. A Genetic Algorithm (GA) optimization technique is used to calculate the controller and estimator parameters to achieve a target response.

Structural Model

The wing box structures and the PZT patches are modeled using the equivalent plate model based on the First-order Shear Deformation Plate Theory (FSDPT). Equivalent plate modeling bridges the gap between models based on beam theory and detailed finite element models. This makes it possible to obtain structural information at the aerodynamic grid points used in the aerodynamic force computation. The displacement field is assumed as [1]:

$$u(x,y,z,t) = u_o(x,y,t) - z\left(\frac{\partial w(x,y,t)}{\partial x} - \alpha_x(x,y,t)\right)$$

$$v(x,y,z,t) = v_o(x,y,t) - z\left(\frac{\partial w(x,y,t)}{\partial y} - \alpha_y(x,y,t)\right)$$

$$w(x,y,z,t) = w_o(x,y,t)$$

The kinetic and potential energies are derived for win-box members then added together. The general equations for kinetic and potential energies are:

$$U_M = \frac{1}{2}\int_{\forall}\{\varepsilon\}^T[Q]\{\varepsilon\}d\forall\,,\quad T_M = \frac{1}{2}\int_{\forall}\rho[\dot{u}\quad \dot{v}\quad \dot{w}][\dot{u}\quad \dot{v}\quad \dot{w}]^T d\forall$$

Unsteady Transonic Flow Model

The model used is the Approximate Factorization (AF) developed by [2] for the time accurate solution of the unsteady Transonic Small Disturbance (TSD) equation. This involves a Newton linearization procedure coupled with an internal iteration technique. The flow is assumed to be governed by the general-frequency modified Transonic Small Disturbance (TSD) potential equation:

$$\frac{\partial f_0}{\partial \bar{t}} + \frac{\partial f_1}{\partial \bar{x}} + \frac{\partial f_2}{\partial \bar{y}} + \frac{\partial f_3}{\partial \bar{z}} = 0$$

where f_0, f_1, f_2, and f_3 are functions dependent on the flow field assumptions. Nonreflecting far-field boundary conditions consistent with the complete TSD equation are used. These absorb most of the error-waves that are inclined on the boundaries.

Piezoelectric Actuators and Sensors

The mechanical and electrical response of piezoelectric ceramics can be described by the stress field and Maxwell's equations respectively. The linear constitutive relations expressing coupling between the elastic and electric fields are given by

$$\{\sigma\} = [Q](\{\varepsilon\} - [d]^T\{E_E\}) \qquad \{D_E\} = [d]\{\sigma\} + [\alpha^\sigma]\{E_E\}$$

Control Methods

Three main categories of controllers are used; the first one is the Linear Quadratic Gaussian (LQG) which combines the full-state feedback Linear Quadratic Regulator (LQR) with the full-state Kalman Filter Estimator (KFE). The second one is optimal Static Output Feedback (SOF) controller based on direct feedback from the sensors output. The third one is a Simple Feedback Controller (SFC). Simply; the output charge of each strain-rate self-sensing actuator is measured and multiplied by a gain; and then feedback to the same actuator.

Genetic Algorithm

The Genetic Algorithm (GA) optimization technique is used to calculate the controller tuning-parameters to achieve a target dynamic response which set by the designer. This is equivalent to the pole placement control design method.

Case Study and Results

The selected wing box model is similar to the wing used in [3]. The airfoil is a cubic arc in a transonic flow with Mach number=0.85. All PZT patches are self-sensing and electric field-driven actuators and made of G-1278. For each bay, a diagonal PZT rod is bonded to the upper and lower surfaces. The PZT rod has an area equals to $3.2258\times10^{-4}\,m^2$, and is divided to four equal actuators.

Critical Dynamic Pressure: The flutter dynamic pressure is calculated to be 21.17 KPa which is in agreement with [3] results.

LQR Results: Fig. 1 shows the results of applying the LQR to suppress the smart-wing flutter. The LQR suppressed the wing flutter effectively without saturation of any actuators. At the last two cycles; wing damped-frequency is very close to actuators natural-frequency. So resonance occurred and is noted by high amplitude waves in control signals. These waves affected the wing as a plant noise but the LQG is robust to plant and sensor noises.

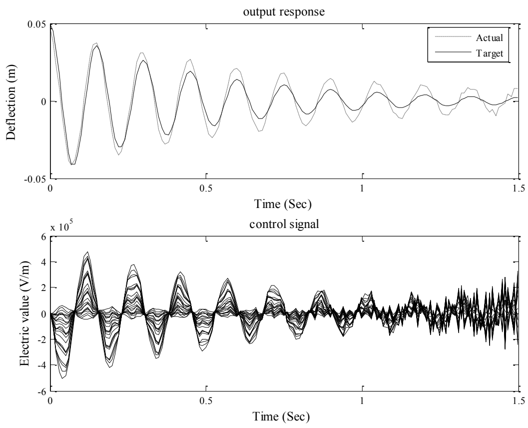

Fig. 1 Results of Linear Quadratic Regulator (LQR)

Kalman Filter Estimator Results: Fig. 2 shows the results of applying the KFE to estimate the wing states and deflection. The KFE succeeded in estimating the wing states and tip-deflection exactly after 1.5 cycles.

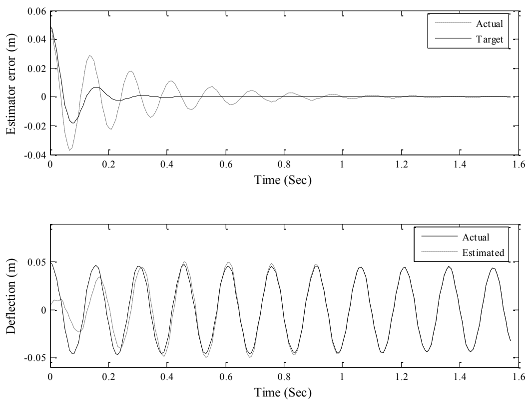

Fig. 2 Results of Kalman Filter Estimator (KFE)

Optimal Static Output Feedback (SOF): This controller introduces less damping to the system and fail to suppress the wing box flutter. Because SOF controller performance is a strong function of the choice of sensors and their locations; while using charge or charge-rate sensors is a bad selection as the regions of high strain (near root); preferable actuators locations; nearly don't contribute to the system output, i.e not observable.

Simple Feedback Controller (SFC): Fig. 3 shows the results of the SFC which succeeded in suppressing the wing flutter with control signals larger than the LQG controller. The wing damped frequency increased the target one after two cycles (the actual response leads the target one). This prevents resonance between the wing and actuator frequencies. The SFC does not introduce coupling between actuators and by increasing GA iterations; more actuators are saturated and increase the wing stiffness.

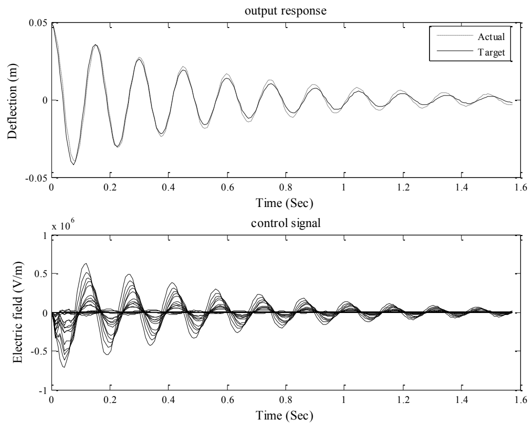

Fig. 3 Results of the Classic Feedback Controller (SFC)

Optimum Locations for Actuators and Sensors: Fig. 4 shows the PZT sensors and actuators optimum locations. The most effective PZT actuators are found to be located near the wing root.

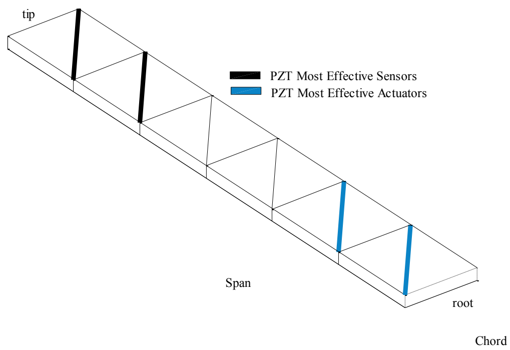

Fig. 4 Optimum locations for PZT actuators and sensors

Conclusion

In general, LQG performance is better than SFC because the coupling between actuators in LQG (via state equations). But because of resonance between the wing and actuator frequencies in LQG case, the SFC is more preferable. To avoid resonance, the dimensions (area or length) of PZT actuator must be changed

Reference

1. Giles, G. L. Equivalent plate modeling of conceptual design of aircraft wing structures. *AIAA J* ***95**-3945*.
2. Batina, J. T. Efficient algorithm of the unsteady transonic small-disturbance equation. *Journal of Aircraft* **25** (1988) 598-605.
3. Forster, E. E. and Yang, H. T. Flutter control of wing boxes using piezoelectric actuators. *Journal of Aircraft* **35** (1998) 949-957.