ACTIVE FLUTTER SUPPRESSION FOR HIGH-DIMENSIONAL AEROELASTIC SYSTEM VIA DELAYED CONTROL

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Summary The paper presents how to design a new optimal control to suppress the flutter of a high-dimensional aeroelastic system with an input time delay in the control loop. Such a time delay usually exhibits a negative effect on the stability of the controlled aeroelastic system. The novelty of the proposed design is to transform the dynamic equation of controlled aeroelastic system with delay terms into a set of delay-free difference equations via a state transformation, instead of any approximations to a short time delay. The paper demonstrates the efficacy of proposed design of active flutter suppression for the wind-tunnel model of a multiple actuated wing with an input time delay of control. The new controller works much better than a conventional LQG controller, which does not take the input time delay into account and may induce unstable oscillations when the input time delay becomes significant.

INTRODUCTION

Active flutter suppression integrated with morphing structures is a promising technique to improve the dynamic performance of aircraft. However, inevitable time delays in digital controls, D/A converters, amplifiers and noise filters may deteriorate the aircraft performance expected in design. Among the studies on active flutter suppression, only a few of them have addressed the effect of time delays on the stability of simple aeroelastic systems [1,2] or designed the delayed feedback for an airfoil [3]. To the best knowledge of authors, previous studies focused only on the two-dimensional aeroelastic system and the proposed methods are not able to deal with any real wings with a low aspect-ratio, which can only be modeled via a set of differential equations of high dimensions. The objective of this paper is to reveal the negative effect of the input time delay in a conventional LQG control on the stability of a high-dimensional aeroelastic system and to design a new effective LQG control with the input time delay taken into account.

DELAYED OPTIMAL CONTROL FOR FLUTTER SUPPRESSION

Discrete dynamic equation of a controlled aeroelastic system with input time delay

As shown in Fig. 1, the aeroelastic system of concern is the wind-tunnel model of a wing with 4 control surfaces, where Leading-Edge Outboard (LEO) and Trailing-Edge Outboard (TEO) control surfaces in Fig. 2 are actuated to suppress the flutter via the feedback control of two channels. The controlled aeroelastic system can be modeled as a set of delayed differential equations

Fig. 1 The wind-tunnel model of a wing equipped with four control surfaces

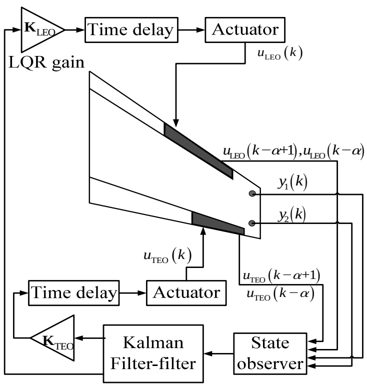

Fig. 2 Diagram of the controlled aeroelastic system with an input time delay

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t-\tau) + \mathbf{w}(t), \quad \mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) + \mathbf{v}(t) \tag{1}$$

where $\mathbf{x}(t) \in \mathrm{R}^{19}$ includes the state variables related to the 4 lower natural modes of wing, 4 aerodynamic lag terms, the actuator model of the 2nd order for each control surface and the turbulence terms of the 3rd orders, $\mathbf{u}(t-\tau)$ is the delayed command vector of LEO and TEO actuators, τ represents the total input time delay of the digital/analog converter, the noise filter and the actuator in a control channel, whereas the other details can be found in Ref. [4].
Given the sampling period Δ, the input time delay can be described as $\tau = \alpha\Delta - \beta$, where α is an integer and β satisfies $0 \le \beta < \Delta$. Now, Eq. (1) is recast into the following discrete-time form

$$\mathbf{x}(k+1) = \mathbf{A}_d\mathbf{x}(k) + \mathbf{B}_{d_1}\mathbf{u}(k-\alpha+1) + \mathbf{B}_{d_2}\mathbf{u}(k-\alpha) + \mathbf{w}_d(k), \quad \mathbf{y}(k) = \mathbf{C}\mathbf{x}(k) + \mathbf{v}_d(k) \tag{2}$$

Delay-free transform and design of a new LQG control

The basic idea of this study is to convert Eq. (2) under the delayed control $\mathbf{B}_{d_1}\mathbf{u}(k-\alpha+1) + \mathbf{B}_{d_2}\mathbf{u}(k-\alpha)$ into a new dynamic equation free of input time delay via the following state transform proposed by Haraguchi and the first author of this paper [5]

$$\begin{cases} \bar{\mathbf{x}}(k) = \mathbf{A}_d\mathbf{x}(k)+\mathbf{B}_{d_2}\mathbf{u}(k-1), \quad 0<\tau\le\Delta; \\ \bar{\mathbf{x}}(k) = \mathbf{A}_d^{\alpha}\mathbf{x}(k)+\mathbf{A}_d\left[\mathbf{I},\mathbf{A}_d,\cdots,\mathbf{A}_d^{\alpha-2}\right]\begin{bmatrix}\mathbf{B}_{d_1}\mathbf{u}(k-1)\\ \mathbf{B}_{d_1}\mathbf{u}(k-2)\\ \vdots \\ \mathbf{B}_{d_1}\mathbf{u}(k-\alpha+1)\end{bmatrix}+\left[\mathbf{I},\mathbf{A}_d,\cdots,\mathbf{A}_d^{\alpha-1}\right]\begin{bmatrix}\mathbf{B}_{d_2}\mathbf{u}(k-1)\\ \mathbf{B}_{d_2}\mathbf{u}(k-2)\\ \vdots \\ \mathbf{B}_{d_2}\mathbf{u}(k-\alpha)\end{bmatrix}, \quad \tau>\Delta. \end{cases} \tag{3}$$

Now, the first equation in Eq.(2) can be recast as a delay-free dynamic equation

$$\begin{cases} \bar{\mathbf{x}}(k+1) = \mathbf{A}_d\bar{\mathbf{x}}(k)+\bar{\mathbf{B}}_d\mathbf{u}(k)+\mathbf{A}_d\mathbf{w}_d(k), \quad 0<\tau\le\Delta; \\ \bar{\mathbf{x}}(k+1) = \mathbf{A}_d\bar{\mathbf{x}}(k)+\bar{\mathbf{B}}_d\mathbf{u}(k)+\mathbf{A}_d^{\alpha}\mathbf{w}_d(k), \quad \tau>\Delta; \qquad \bar{\mathbf{B}}_d=\mathbf{A}_d\mathbf{B}_{d_1}+\mathbf{B}_{d_2} \end{cases} \tag{4}$$

Given the weight matrices $\mathbf{Q}_1$ and $\mathbf{Q}_2$, the LQG controller $\mathbf{u}(k)=[\bar{\mathbf{B}}_d^{\mathrm{T}}\mathbf{S}\bar{\mathbf{B}}_d+\mathbf{B}_{d_1}^{\mathrm{T}}\mathbf{Q}_1\mathbf{B}_{d_1}+\mathbf{Q}_2]^{-1}[\bar{\mathbf{B}}_d^{\mathrm{T}}\mathbf{S}\mathbf{A}_d+(\mathbf{Q}_1\mathbf{B}_{d_1})^{\mathrm{T}}]\mathbf{x}(k)$ for Eq. (4) can be determined by solving the following Riccati equation

$$\mathbf{S}=\mathbf{A}_d^{\mathrm{T}}\mathbf{S}\mathbf{A}_d-[\mathbf{A}_d^{\mathrm{T}}\mathbf{S}\bar{\mathbf{B}}_d+\mathbf{Q}_1\mathbf{B}_{d1}][\bar{\mathbf{B}}_d^{\mathrm{T}}\mathbf{S}\bar{\mathbf{B}}_d+\mathbf{B}_{d_1}^{\mathrm{T}}\mathbf{Q}_1\mathbf{B}_{d_1}+\mathbf{Q}_2]^{-1}[\bar{\mathbf{B}}_d^{\mathrm{T}}\mathbf{S}\mathbf{A}_d+(\mathbf{Q}_1\mathbf{B}_{d1})^{\mathrm{T}}]+\mathbf{Q}_1 \tag{5}$$

The state vector $\bar{\mathbf{x}}(k)$ can not be directly measured, and should be estimated via the following observer

$$\hat{\mathbf{x}}(k\,|\,k)=[\mathbf{I}-\mathbf{K}_f\mathbf{C}]\hat{\mathbf{x}}(k\,|\,k-1)+[\mathbf{0}\quad \mathbf{0}\quad \mathbf{K}_f]\left[\mathbf{u}^{\mathrm{T}}(k-\alpha+1)\quad \mathbf{u}^{\mathrm{T}}(k-\alpha)\quad \mathbf{y}^{\mathrm{T}}(k)\right]^{\mathrm{T}} \tag{6}$$

where $\hat{\mathbf{x}}(k\,|\,k-1)$ is the prediction of $\mathbf{x}(k)$, $\mathbf{K}_0$ is the gain matrix for the observer and $\mathbf{K}_f$ is the Kalman gain matrix, both of which can be determined according to the theory of Kalman filter.

CASE STUDY AND CONCLUSIONS

The computation and wind-tunnel test indicate that the wing model without any control undergoes a torsional flutter when the dynamic pressure reaches 816.7 Pa. To actively suppress the flutter, a conventional LQG control with given $\mathbf{Q}_1=\mathbf{I}$ and $\mathbf{Q}_2=0.001\mathbf{I}$ is designed such that the dynamic pressure of a closed-loop flutter can be increased to 1320 Pa. However, this can not be realized if there exists a short input time delay in control loop. As shown in Fig. 3, for instance, the suppressed flutter becomes unstable when the control loop involves a short input time delay $\tau=0.015$ s. Compared with the conventional LQG method, the new LQG controller exhibits much better stability performance as shown in Fig. 4 when the input time delay arrives at $\tau=0.02$ s or even longer as shown in Fig. 5. Theoretically speaking, it is feasible to design a delayed LQG control for the high-dimensional aeroelastic system provided that the input time delay is given no matter how long it is. Furthermore, it is straightforward to extend the new approach to the case when the input time delay slowly varies with time.

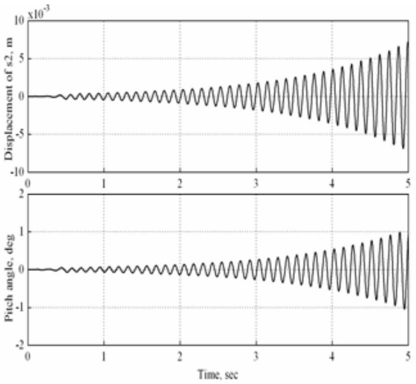

Fig. 3 Tip displacement and pitch angle for a conventional LQG controller at $\tau=0.015$s

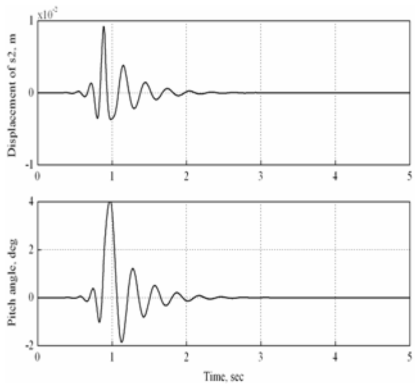

Fig. 4 Tip displacement and pitch angle for a new LQG controller at $\tau=0.02$s

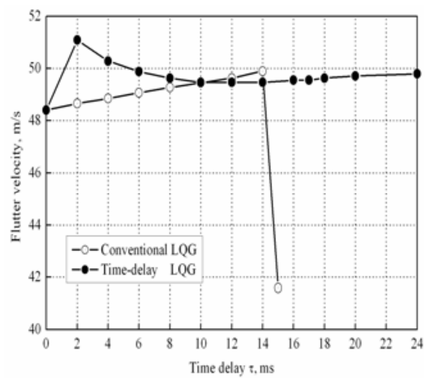

Fig. 5 Comparison of conventional LQG and time-delay LQG with an increase of time delay

In summary, the study enables one to design the active flutter suppression of a high-dimensional aeroelastic system with an input time delay no matter how long it becomes. Numerical simulations show that the conventional LQG controller may fail to work when the aeroelastic system involves a short input time delay induced by D/A conversions and noise filters. However, the new LQG controller designed in the study can successfully suppress the flutter even though the aeroelastic system involves a longer input time delay.

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