FLUTTER SUPRESSION VIA DELAYED FEEDBACK CONTROL

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Summary This paper investigates the delay effect on the stability of the controlled two-dimensional airfoil with delayed feedbacks, arising from the problem of flutter suppression of aircraft wings, where the feedback gain is allowed to be both negative and positive. Based on the stability analysis of the controlled system, it shows that a delayed position feedback with positive gain is superior to that with negative feedback, the delayed acceleration feedback with negative gain is superior to that with positive gain, and the delayed acceleration feedback with negative gain is superior to the delayed position feedback with positive gain.

INTRODUCATION

Flutter is an aeroelastic self-excited oscillation of aircraft wing with high frequency and large amplitude resulted from the interactions of aerodynamic, elastic structure and servo effects. The high-frequency and large-amplitude motion can cause a loss of structural integrity in wings. Thus flutter suppression is an important topic in the study of aeroelastic dynamics. Now active control has become a major method for flutter suppression of aircraft wings. On one hand, the feedback signals of the active control for flutter suppression can be simply plunging position, plunging velocity, pitching position, pitching velocity, or their combination, and it is found that the feedback signal derived from the measurement of pitching variables is more effective [1]. Though acceleration sensor is widely used in vibration control, studies that use acceleration feedback directly to suppress flutter are actually rare. On the other hand, one issue resulted from active control is the inevitable time delay in the control path. Because the time delay is usually very small, it is neglected for simplicity in modelling and analysis. A recent study reveals that, however, a very short delay may reduce the flutter velocity significantly [1], a case that is very dangerous from the viewpoint of flight safety. The introducing of time delay in the control path can also make the delayed feedback control unique. As shown in [3], a delayed position feedback with positive gain can not only stabilize an unstable free vibration, but also be superior to the corresponding feedback with negative gain. Such a case cannot occur if the delay disappears. In addition, a delayed acceleration feedback with small gain and short delay can be used as a resonator to absorb the vibration totally of a forced vibration [4]. Therefore, the delay effect must be taken into consideration in the control design and system analysis of aircraft wings. In this paper, the delay effect on the stability of a controlled two-dimensional airfoil system with delayed feedback with respect to the pitching signals is investigated, where the feedback gains can be both negative and positive. The delayed position feedback and delayed acceleration feedback are addressed.

THE PITCHING-PLUNGING EQUATIONS OF THE CONTROLLED SYSTEM

Consider the following 2-dof system shown in Figure 1, where h is the plunging deflection (positive downward direction), α is the pitching angle (positive nose up). The closed-loop aeroelastic equations of the airfoil can be described by [1]

$$\begin{cases} m\ddot{h} + mx_\alpha\ddot{\alpha} + c_h\dot{h} + k_h h = -L_{qs}(t) \\ mx_\alpha\ddot{h} + mr_a^2\ddot{\alpha} + c_\alpha\dot{\alpha} + k_\alpha\alpha = T_{qs}(t) + u \end{cases} \tag{1}$$

where L_{qs}, T_{qs} are the quasi-steady aerodynamic lift and moment respectively, and u is the control. In [1], the control $u = g_v\dot{x}(t-\tau)$, where $\tau > 0$ is the time delay. With $X = [h, \alpha, \dot{h}, \dot{\alpha}]^{\mathrm{T}}$, Eq.(1) can be rewritten in the form

$$\dot{X} = A_0X + A_dX(t-\tau) \tag{2}$$

When $u = g_p x(t-\tau)$ or $u = g_a\ddot{x}(t-\tau)$ as addressed below, a similar state equation can be obtained accordingly.

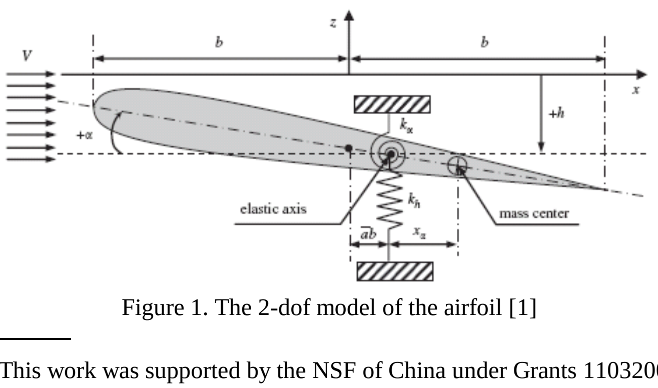

Figure 1. The 2-dof model of the airfoil [1]

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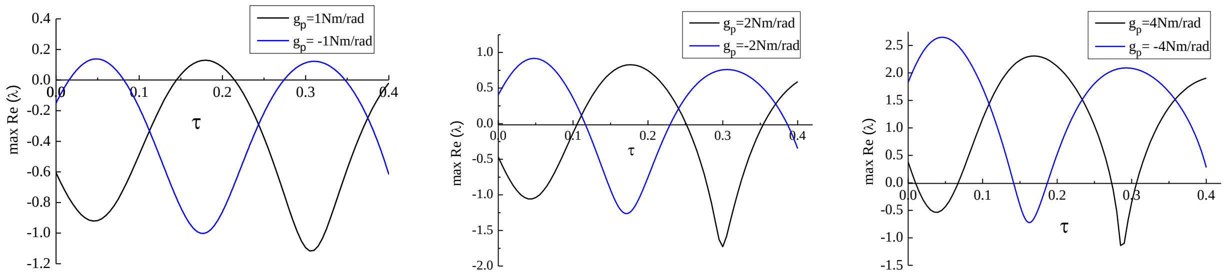
STABILITY ANALYSIS OF THE CONTROLLED SYSTEM

When the delay effect on the stability of the controlled system is addressed, it is preferable to find out firstly the critical values of delay for which the corresponding characteristic equation described by

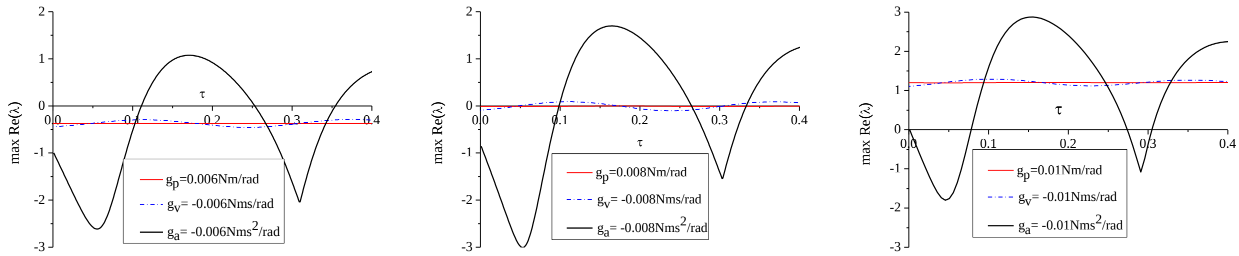
$$\det(\lambda I - A_0 - A_d \mathrm{e}^{-\lambda\tau}) = 0 \tag{3}$$

has a pair of conjugate pure imaginary roots, and then to determine the crossing direction of this pair of branches of characteristic roots as the delay increases. For each delay interval where Eq.(3) has roots with negative real parts only, the closed-loop is asymptotically stable, and in each delay interval where Eq.(3) has at least one root with positive real parts, the closed-loop is unstable so that flutter occurs. We use the plots of the real parts of the rightmost characteristic roots with respect to (w.r.t.) the delay to show this phenomenon, where the parameter take the same values given in [1].



(a) $V = 23.0\ m/s$ (b) $V = 23.45\ m/s$ (c) $V = 25.0\ m/s$

Figure 2. The real part of the rightmost characteristic roots w.r.t. the delay, for the delayed position feedback.



(a) $V = 23.0\ m/s$ (b) $V = 23.45\ m/s$ (c) $V = 25.0\ m/s$

Figure 3. Comparison of the real part of the rightmost characteristic roots w.r.t. the delay for different kinds of delayed feedback.

In real applications, a larger delay in the control path usually means a more complicated controller, thus a smaller delay is usually preferable. As seen in Figure 2 for all the three cases with the flow speed less than the flutter speed, equal to the flutter speed, and greater than the flutter speed respectively, a delayed position feedback with *negative* gain deteriorates the stability of the controlled system, while a delayed position feedback with *positive* gain enhances the stability of the controlled system, if the admissible delay is assumed small. The revised case occurs for the delayed velocity feedback or delayed acceleration feedback. The delayed position feedback with positive gain is superior to that with negative feedback. Figure 3 presents a comparison among three delayed feedbacks, the delayed position feedback with *positive* gain, the delayed velocity feedback with *negative* gain and the delayed acceleration feedback with *negative* gain, and it shows that within a wide range of delay, a delayed acceleration feedback with a very small negative gain can draw the pitching-plunging motion rapidly to the steady state, while the corresponding delayed position feedback or delayed velocity feedback either makes the closed-loop unstable or makes the stability very poor. Thus, the delayed acceleration feedback with *negative* gain is preferable in suppressing flutter of the two-dimensional airfoil.

CONCLUSIONS

In active flutter suppression of aircraft wings, the time delay in the control path must be taken into account. In addition, using delayed acceleration feedback directly is a promising control strategy for suppressing flutter because accelerometers have small volume, light weight, accurate measurement and wide frequency band, and feedback gain can be very small.

References

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