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Active Flutter Suppression by Feedback Compensation of Transport Lags

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I. Introduction

AIRCRAFT wings are deigned to be flexible, and as a consequence of this feature they are known to be continuously oscillating under the action of wind loads leading to the well-known phenomenon of "flutter." Flutter in wings was conventionally inhibited by passive design techniques based on altering the mass and stiffness distributions of the wing. However, the recent trend in building highly flexible aircraft has demonstrated the inadequacy of passive techniques for inhibiting the occurrence of flutter.

To overcome the inadequacy of passive techniques in inhibiting the occurrence of flutter within the design envelope of the aircraft, a new technique, based on feedback control, was developed in the early 1970s, called "active flutter suppression." Two distinct approaches emerged for the design of the control law for active flutter suppression, the first based on optimal control, and the second approach [1], emerging from the concept of passivity, considers the energy flowing in and out of the "system." There are several applications of this method to real aircraft, and [2] is archetypal of these examples. References [3,4] are typical examples in which the techniques based on the modeling methods were applied to the synthesis of optimal and near-optimal control laws for active flutter suppression.

In this paper we propose a third approach towards controlling flutter. By careful consideration of the unsteady aerodynamic loading, those components that contribute to the delay in the growth of the loading in response to changes in the wing motion are isolated. These delays or transport lags are then eliminated by an appropriate control law that ensures the constancy of circulatory component of the unsteady lift. With secondary compensation one could increase the flutter speed, which is the primary objective of active flutter suppression. Furthermore, the constancy of the circulatory component implies that the flow is less likely to separate and the circulation is more likely to remain steady. To evaluate the method we consider the archetypal problem of the typical section and implement such a control law.

The motivation for this work arose from the need to develop smart, flexibly actuated morphing control surfaces for future aircraft wings in low-speed flight. The method described in this paper can be routinely implemented with control surfaces. Morphing control surfaces can be deflected in a multitude of modes and the method itself is based on observations of bird flight.

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II. Typical Section Unsteady Aerodynamics

We shall assume that a variable camber airfoil may be modeled as an articulated flat plate airfoil with trailing- and leading-edge flaps attached to the main surface. The equations of motion, derived by the energy method with the generalized forces obtained by the application of unsteady thin airfoil theory, are

$$\mathbf{M}_{\mathbf{s}}\begin{bmatrix}\ddot{h}/b\\ \ddot{\alpha}\\ \ddot{\beta}\\ \ddot{\gamma}\end{bmatrix}+\mathbf{K}_{\mathbf{s}}\begin{bmatrix}h/b\\ \alpha\\ \beta\\ \gamma\end{bmatrix}+2\pi b^2\left(\frac{1}{2}\rho U^2\right)\left(\tilde{\mathbf{M}}_{4a}\begin{bmatrix}\ddot{h}/b\\ \ddot{\alpha}\\ \ddot{\beta}\\ \ddot{\gamma}\end{bmatrix}+\tilde{\mathbf{C}}_{4a}\begin{bmatrix}\dot{h}/b\\ \dot{\alpha}\\ \dot{\beta}\\ \dot{\gamma}\end{bmatrix}+\tilde{\mathbf{K}}_{4a}\begin{bmatrix}h/b\\ \alpha\\ \beta\\ \gamma\end{bmatrix}\right)=\begin{bmatrix}0\\0\\0\\0\end{bmatrix} \tag{1}$$

where $\tilde{\mathbf{M}}_{4a}$ is the symmetric, aerodynamic virtual inertia matrix.

The aerodynamic virtual inertia force is independent of the freestream velocity. They are functions of the freestream velocity U, the airfoil semichord b, the nondimensional distances of the trailing-edge flap hinge line c, or of the leading-edge flap hinge line c', as defined by Theodorsen [5], in terms of his T functions.

The airfoil velocity dependent loading is expressed as the sum of the noncirculatory and the circulatory components, where the latter is further split into terms with no transport lag and terms including transport lag effects. Hence,

$$\tilde{\mathbf{C}}_{4a}=\tilde{\mathbf{C}}_{4\mathrm{anc}}+\frac{b}{U}\left(\begin{bmatrix}0\\1\\-T_4/\pi\\1+T_4'/\pi\end{bmatrix}+C(k)\begin{bmatrix}2\\-(1+2a)\\T_{12}/\pi\\-T_{12}'/\pi-(1+2c')\end{bmatrix}\right)\boldsymbol{W}_{\mathrm{tl}} \tag{2}$$

$$\boldsymbol{W}_{\mathrm{tl}}=\left[1\left(\frac{1}{2}-a\right)\frac{T_{11}}{2\pi}\left(\frac{T_4'}{2\pi}+\frac{T_{10}'}{2\pi}(1-c')+c'-\frac{1}{2}\right)\right] \tag{2a}$$

where $\tilde{\mathbf{C}}_{4\mathrm{anc}}$, the noncirculatory component, is entirely gyroscopic, being antisymmetric with zeros on the diagonal. The circulatory components of velocity dependent loading are linear functions of Theodorsen's lift deficiency function, $C(k)$ and of the row vector, $\boldsymbol{W}_{\mathrm{tl}}$.

The term directly proportional to $C(k)$ represents the influence of the wake on the circulation. However, both the circulatory components are functions only of the rate-dependent terms in a downwash component which, in the absence of the flaps, is the downwash at the rear quarter chord point, as the wake is totally independent of the leading edge. Furthermore, when this, the "circulatory" component of the downwash, that is, the downwash contributing to the circulatory components of the generalized forces, is held fixed, the corresponding components of the generalized forces are steady and the delays due to the transport lags are absent. We refer to this concept as transport lag compensation. The airfoil displacement dependent loading terms can likewise be split into noncirculatory and circulatory terms. Hence,

$$\tilde{\mathbf{K}}_{4a}=\tilde{\mathbf{K}}_{4\mathrm{anc}}+\left(\begin{bmatrix}0\\1\\-T_4/\pi\\T_4'/\pi+1\end{bmatrix}+2C(k)\begin{bmatrix}1\\-(a+1/2)\\T_{12}/2\pi\\-T_{12}'/\pi-(c'+1/2)\end{bmatrix}\right)\times\begin{bmatrix}0 & 1 & \dfrac{T_{10}}{\pi} & \left(\dfrac{T_{10}'}{\pi}-1\right)\end{bmatrix} \tag{3}$$

The form of the equations of motion (1) clearly indicates that if the total circulatory downwash were naturally constant, the unsteady dynamics of the airfoil would be completely conservative and no dynamic instabilities, such as flutter, can be expected in an ideal situation. However, if a feedback control system is employed to regulate the circulatory component of the downwash, the closed loop would no longer be conservative unless the controller is passive. When an active controller is employed, it implies that the closed-loop system would still be prone to dynamic instability, although this could be chosen to occur at a higher freestream velocity than in the uncontrolled case, by design. Finally, we add that the properties discussed are generic and could be applied to other multielement airfoils such as a wing-flap-tab system.

III. Feedback Compensation of Aerodynamic Transport Lag Effects

There have been very few studies of the active control of separation on a wing with controlled camber and related methods [6]. Camber control can be employed for the elimination of transport lags in the growth of lift as well as in the inhibition of the formation of the separation bubble by flying at a preset angle of attack. To consider the problem of compensating the effects of the transport lags, we adopt the simplified model for a variable camber airfoil and assume that the leading-edge flap motion is prescribed. The governing equations of motion representing the coupled dynamics of plunging, pitching, and the flap modes may be expressed in the same form as Eq. (1). For transport lag compensation we assume that the circulatory downwash, as defined in an earlier section, is a constant and determined entirely from the desired angle of attack α_d, and the desired trailing-edge flap deflection β_d. Hence we obtain the control law,

$$\frac{b}{U}\boldsymbol{W}_{\mathrm{tl}}\begin{bmatrix}\dot{h}/b\\\dot{\alpha}\\\dot{\beta}\\\dot{\gamma}\end{bmatrix}+\begin{bmatrix}0 & 1 & \dfrac{T_{10}}{\pi} & \left(\dfrac{T_{10}'}{\pi}\right)\end{bmatrix}\begin{bmatrix}h/b\\\alpha-\alpha_d\\\beta-\beta_d\\\gamma\end{bmatrix}=0 \tag{4}$$

and the generalized aerodynamic restoring moments may be accordingly simplified.

On the basis of the desired control law, the leading-edge flap angle γ satisfies the equation

$$\frac{b}{U}\tau\dot{\gamma}+p\gamma=-\frac{b}{U}\frac{\dot{h}}{b}-\frac{b}{U}\begin{bmatrix}\left(\dfrac{1}{2}-a\right) & \dfrac{T_{11}}{2\pi}\end{bmatrix}\begin{bmatrix}\dot{\alpha}\\\dot{\beta}\end{bmatrix}-\begin{bmatrix}1 & \dfrac{T_{10}}{\pi}\end{bmatrix}\begin{bmatrix}\alpha-\alpha_d\\\beta-\beta_d\end{bmatrix} \tag{5}$$

with

$$\tau=\left(\frac{T_4'}{2\pi}+\frac{T_{10}'}{2\pi}(1-c')+c'-\frac{1}{2}\right)\quad\text{and}\quad p=\left(\frac{T_{10}'}{\pi}-1\right) \tag{5a}$$

which could, in principle, be modified to include the effects of minitabs that provide for the on–off control of a fraction of the angle of attack as well as the effects of other devices such as canards and strakes that influence the circulatory component of the downwash. Thus the leading-edge flap's angular velocity satisfies a linear dynamic equation. Substituting it in the governing equations of motion, the closed-loop dynamics to the form

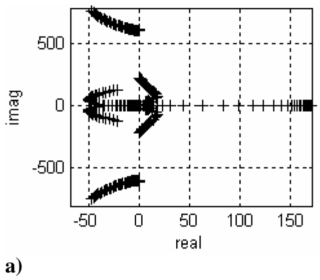
$$\mathbf{M}'_{\mathbf{s}}\begin{bmatrix}\ddot{h}/b\\\ddot{\alpha}\\\ddot{\beta}\end{bmatrix}+\mathbf{K}'_{\mathbf{s}}\begin{bmatrix}h/b\\\alpha\\\beta\end{bmatrix}+\mathbf{K}'_{\mathbf{s}}\begin{bmatrix}0\\\alpha\\\beta\end{bmatrix}+\tilde{\tilde{\mathbf{K}}}'_{\mathbf{s}}\gamma+\begin{bmatrix}Lb\\-M\\-M_\beta\end{bmatrix}=\begin{bmatrix}0\\0\\M_t\end{bmatrix} \tag{6}$$

$$\dot{\gamma}=-\frac{1}{(b/U)\tau}\left(p\gamma+\frac{b}{U}\begin{bmatrix}1 & \left(\dfrac{1}{2}-a\right) & \dfrac{T_{11}}{2\pi}\end{bmatrix}\begin{bmatrix}\dot{h}/b\\\dot{\alpha}\\\dot{\beta}\end{bmatrix}+\begin{bmatrix}0 & 1 & \dfrac{T_{10}}{\pi}\end{bmatrix}\begin{bmatrix}h/b\\\alpha-\alpha_d\\\beta-\beta_d\end{bmatrix}\right) \tag{7}$$

The modified structural mass and stiffness matrices are defined in terms of the original mass and stiffness matrices and the aerodynamic parameters. The point is that the closed-loop dynamics is no longer a function of Theodorsen's lift deficiency function, $C(k)$, and therefore all the transport lags have been eliminated, by forcing the circulatory component of the downwash to be independent of time. Of course there is no guarantee that the closed loop is sufficiently stable. In fact, computations indicate the need for further compensation as the transport lag compensation of the circulatory component of the downwash drives the angle of attack mode to instability, unless a full order controller is used. Further compensation is provided by feeding back to a second control surface at the trailing edge all combinations of states that do not contribute to the circulatory component of the downwash. Yet it is fair to say the complexity of the controller synthesis problem is greatly reduced, because the elimination of the transport lags also eliminates the additional states arising from the approximation of Theodorsen's function that are physically absent. Although the methodology cannot be directly applied to compressible flows, the spirit of the technique can be implemented numerically by employing singular value decomposition of the frequency-dependent aerodynamic loads and the effects of transport lags substantially minimized but not completely eliminated. When the steady angle of attack is large, the methodology could be extended to an airfoil with controlled camber assuming the camber line to be a circular arc and employing a control law that maintains the circulatory downwash component as a constant. In practice it is important to employ multiple control surfaces and to include the second-order thickness effects, to meet the transport lag constraint without degrading the closed-loop stability. Although it is not possible to include the second-order effects within the framework of unsteady thin airfoil theory, which is essentially linear, it is in fact possible to consider fully flexible morphing control surfaces.

IV. Open- and Closed-Loop Stability

We now present some representative results concerning the open- and closed-loop stability. The methodology was applied to a typical wing section with leading- and trailing-edge flaps with a width of 20% of the chord. The root locus plots were obtained based on the symmetric root locus concept and on high gain feedback for loop transfer recovery of stability margins associated with observer-based control. These control laws can be shown to have the maximum gain and phase margins in practice and are most suitable for



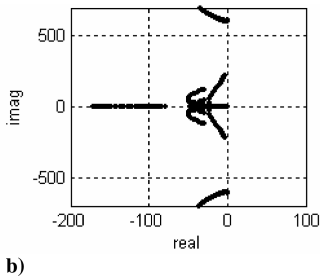


Fig. 1 a) Root locus plot, with transport lag compensation; b) closed-loop root locus plot, with a trailing-edge and leading-edge flap.

implementation. The open-loop root loci reveal a flutterlike instability in the plunging mode. As a check of system controllability with flap full state gain scheduled feedback laws were synthesized. The closed-loop root locus with a full state feedback optimal controller with minimal weighting on the states were entirely in the left half of the complex s plane and the locus indicates stability over the entire range of U/b values.

At this stage, transport lag compensating control, forcing the circulatory component of the lift to remain stationary, was introduced to the leading-edge flap. Figure 1a is a root locus plot, with lag compensation to the leading-edge flap for U/b ranging from 5 to 200, zooming in near the origin to reveal the root locus detail, particularly the instability in an angle-of-attack mode. The effect was substantially destabilizing as can be observed in Fig. 1a.

Further compensation was then provided to the trailing-edge flap in terms of a reduced-order optimal control law. The reduced-order model employed for the purpose of the synthesis of the control law here is based on aerodynamic considerations as presented in the preceding section. Figure 1b illustrates the closed-loop root locus plot, with a trailing-edge and leading-edge flap, transport lag compensation to the leading-edge flap, and reduced-order optimal feedback to the trailing-edge flap with minimal state bounds, for U/b ranging from 5 to 200. The control gains are synthesized for a range of freestream velocities and the gain scheduled control law had no difficulty in stabilizing the closed-loop system as is seen in Fig. 1b.

V. Conclusions

In this paper a new approach to the synthesis of control laws for active flutter suppression is presented. It is based on forcing the component of the downwash at the airfoil surface that contributes directly to the circulatory component of the lift, to remain a constant, thus inhibiting all transport delays in the growth of lift. The main strength of the method is that there is no need to augment the states of the system by including spurious states to account for the circulation lag effects. The feasibility of designing suitable control laws is demonstrated, although there are several practical issues that must be addressed. It must be added, that although only the reduced-order case was presented, it is also possible to design a full order controller without the need to provide additional compensation to a secondary control surface.

The method is proving to be particularly useful in synthesizing control laws for controlling low-speed aircraft with flexibly actuated smart flaps. In the case of these aircraft, the flaps may be deflected in one or more of several modes and the method presented here is feasible. In such situations the aircraft wings are capable of morphing and resemble bird wings in several respects.

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