Under the constant shear environment, i.e., when the shear layer is not a concentrated zone but a large region with constant shear around the vortex pair, Brashears et al.[11] showed, using an inviscid method, that there was no influence on the vortex descent behavior. We made a test to allow the vortex pair to pass through a nondeformed shear layer by fixing the shear vortex positions during the simulations. The nondeformed shear layer approximated a constant shear when the vortex pair penetrated the shear layer. That test did not show altitude differences between the two vortices.

Conclusions

It has been shown, from the inviscid vortex method simulations, that the shear-layer deformation causes the vortex descent history difference in the two vortices of the trailing vortex pair. Because of the interactions between the vortices from the shear layer and the vortex pair, the induced velocities on the vortex pair have been changed. Such changes produce different trajectories when the vortex pair is interacting with a concentrated shear layer below or above it. The results show that if a shear layer is put below the vortex pair containing shear vortices with the same sign as the left vortex, the right vortex descends less than the left vortex. While the same shear layer is set above the vortex pair, the right vortex descends more. The descent altitude difference increases with the shear-layer strength. The two vortices of the trailing vortex pair do not show altitude difference when they go through a constant, nondeformed shear layer. These trends are the same as predicted by Proctor et al.[7] in their finite difference numerical simulations using the Navier–Stokes equations. Modifications of this model to include other atmospheric conditions are feasible for real-time wake vortex predictions.

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Model for Development of Backlash in Aircraft Control Circuit Mechanical Links

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Nomenclature

b = semichord length
C = Theodorsen's function
d = inside diameter of the bearing
h = plunging displacement
I_β = mass moment of inertia of the aileron about aileron hinge line
k = specific wear rate coefficient
k_h = bending stiffness of the wing
k_β = torsional stiffness of the aileron
M = restoring moment, Eq. (2)
m = mass of wing–aileron segment (per unit span)
N = frequency of oscillation equal to the frequency of limit cycle oscillation of the aileron
P = nominal pressure
S_β = static mass moment of aileron about aileron hinge line
T_i = geometric functions given in Ref. 5
t = time
U = airspeed
V = rubbing speed
V_f = flutter velocity of the linear system
w = depth of wear
β = control surface rotation
β_0 = amount of freeplay
θ = angle between limits of rotation
ρ = air density

Introduction

THE assumption of structural linearity has usually been made when determining the flutter characteristics of aircraft structures. However, aircraft structures often exhibit nonlinearities that can have a significant effect on the flutter speed and aeroelastic response. For example, it is known that airfoils and wing–aileron systems with structural nonlinearity sometimes demonstrate limit cycle oscillation (LCO) below the flutter boundary of the linear system. It is also known that aging has a significant effect on developing concentrated nonlinearity in mechanical systems. One particular example is worn control surface hinges that lead to a freeplay nonlinearity, called backlash. Nonlinear systems experiencing LCO are likely to require maintenance because of accelerated fatigue and wear.

Woolston et al.[1] studied the effects of several types of structural nonlinearities on wing and control surface flutter. The results for the nonlinear wing and control surface showed the existence of sustained oscillation of limited amplitude below the flutter speed of the linear system for a particular case.

In recent years, the modeling and analysis of aerosurfaces with structural nonlinearities has been the subject of numerous investigations. Yang and Zhao[2] performed experimental and theoretical analysis to investigate oscillations of a two-degree-of-freedom wing model with nonlinear pitching stiffness. They made a comprehensive study of LCO of the two-degree-of-freedom model subjected to incompressible flow using the

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Theodorsen function.[2] Price et al.[3] studied a two-degree-of-freedom airfoil with structural nonlinearity in pitch subjected to incompressible flow. They detected regions of LCO for velocities well below the linear flutter boundary for certain cases. Aeroelastic response of a three-degree-of-freedom wing–aileron system with freeplay nonlinearity was also studied by the present authors.[4]

In this paper, a model is developed to identify the effect of LCOs on wear characteristics of a wing–aileron system in incompressible flow. A simple two-degree-of-freedom system with concentrated nonlinearities was chosen to perform the aeroelastic analysis. LCOs in the wing–aileron system are shown to result in accelerated wear of the control linkage, and the development of further freeplay. A feedback phenomenon develops with forces and wear rates increasing as the freeplay develops.

Two-Degree-of-Freedom System

The simple two-degree-of-freedom (plunge and control surface rotation) wing–aileron system studied in this research is illustrated in Fig. 1a. The general equations of motion of a three-degree-of-freedom wing–aileron section with pitch, plunge, and control surface rotation degrees of freedom can be obtained by using Lagrange's equation of motion, and are given in the literature.[4,5] Scanlan and Rosenbaum[5] give expressions for the aerodynamic loads in terms of the Theodorsen function. In the absence of the pitch degree of freedom, all terms with pitch degree of freedom and its derivatives drop out. The governing equations of the wing–aileron plunge and control surface degree of freedom then become

$$m\ddot{h} + S_\beta\ddot{\beta} + k_h h = -\rho b^2(\pi\ddot{h} - UT_4\dot{\beta} - T_1 b\ddot{\beta}) - 2\pi\rho UbC\left(\dot{h} + \frac{1}{\pi}T_{10}U\beta + \frac{b}{2\pi}T_{11}\dot{\beta}\right) \tag{1}$$

$$S_\beta\ddot{h} + I_\beta\ddot{\beta} + M(\beta) = -\rho b^2\left[\frac{1}{\pi}U^2\beta(T_5 - T_4T_{10}) - \frac{1}{2\pi}Ub\dot{\beta}T_4T_{11} - \frac{1}{\pi}T_3b^2\ddot{\beta} - T_1b\ddot{h}\right] - \rho Ub^2T_{12}C\left(\dot{h} + \frac{1}{\pi}T_{10}U\beta + \frac{b}{2\pi}T_{11}\dot{\beta}\right) \tag{2}$$

$M(\beta)$ in Eq. (2) is the nonlinear restoring moment. In this research, freeplay nonlinearity in control surface stiffness is studied. The freeplay nonlinearity is described by

$$M(\beta) = \begin{cases} k_\beta(\beta - \beta_0) & \beta > \beta_0 \\ 0 & -\beta_0 > \beta > \beta_0 \\ k_\beta(\beta + \beta_0) & \beta < -\beta_0 \end{cases} \tag{3}$$

A fourth-order Runge–Kutta numerical integration routine has been employed to find a time–history response solution of Eqs. (1) and (2). The influence of the magnitude of structural nonlinearity on the response of the system is investigated.

Simulation Results

A two-degree-of-freedom airfoil (pitch and plunge) has been studied by Scanlan and Rosenbaum[5] to illustrate the linear flutter analysis. A control surface has been added to the problem to illustrate the response of the nonlinear wing control surface system. The elastic axis is located at 35% chord, and the control surface hinge line is located at 75% chord. Physical properties of the system are shown in Table 1.

Prior to nonlinear analysis, the flutter velocity of the linear system, V_f, was obtained by removing the freeplay and applying a 0.1 ft (0.0305 m) initial plunge disturbance. The air speed, U, was then increased in specific steps until divergent

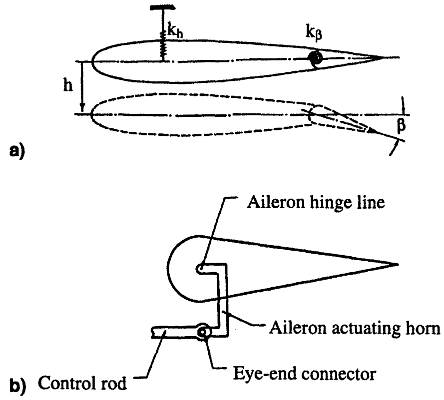

Fig. 1 Two degree-of-freedom wing–aileron system.

oscillation occurred. The nonlinear system with freeplay shows an LCO at U/V_f of ~0.5. To study the sensitivity of the system response to the freeplay band, nonlinear analyses with different β_0 were performed. The calculated time–history responses show that as the freeplay band, β_0, was increased for a fixed initial pitch disturbance, the magnitude of the LCO, and hence, the moment in the restoring spring, increased. Figure 2a shows the amplitude of the LCO vs the freeplay band. Figure 2b shows a typical time–history for ±0.02 rad freeplay in control surface displacement, and an initial plunge disturbance of 0.1 ft (0.0305 m) at U/V_f equal to 0.5.

Wear Model

A sliding wear mechanism in the control surface bearings is considered in this work. A typical component subject to wear of this kind is the eye-end in the control rod in Fig. 1b. The eye-end has a self-aligning ball in a matching socket. The self-aligning ball has a hole through which the connecting pin passes. A suitable wear equation to express the depth of wear of the contacting surfaces is[6]

$$w = k \times P \times V \times t \tag{4}$$

For a control surface experiencing LCO, the motion of the control surface bearing is oscillatory with the angle of rotation determined by the LCO amplitude. The bearing nominal pressure, P, for the given geometry of the bearing and aileron actuating horn (see Fig. 1b), is proportional to the aileron restoring moment. The rubbing speed, the speed at which mating surfaces are rubbing against each other, for an oscillatory rotation is then described by the following equation[6]:

$$V = dN\theta \tag{5}$$

The specific wear rate, k, for the mating surfaces rubbing against each other can be estimated using the standard engineering data sheets.[6] In this work, the required time, t_r, to develop a specific depth of wear, w_s, is then calculated according to

$$t_r = w_s/(kPV) \tag{6}$$

The depth of wear or development of backlash in the control surface bearing vs time is found by the following procedure. The aeroelastic response of the nonlinear wing–aileron system with an initial amount of freeplay is determined from Eqs. (1) and (2). The load applied to the bearing and the sliding velocity corresponding to the aeroelastic response of the control surface are estimated. The required time to develop a specific depth of wear corresponding to the preselected increase in the backlash, $\Delta\beta_0$, is then calculated. The aeroelastic response of the nonlinear system with the new amount of freeplay is then determined, and the new required time to develop the same

Table 1 Physical properties of the wing–aileron system

b, ft (m)	m, slugs (kg)	I_β, slug-ft^2 (kg-m^2)	S_β, slug-ft (kg-m)	k_h, lb/ft (kN-m^{-1})	k_β, lb-ft-rad^{-1} (N-m-rad^{-1})
3.125 (0.95)	0.65 (9.5)	0.1 (0.136)	0.045 (0.2)	1642 (24)	308.4 (418)

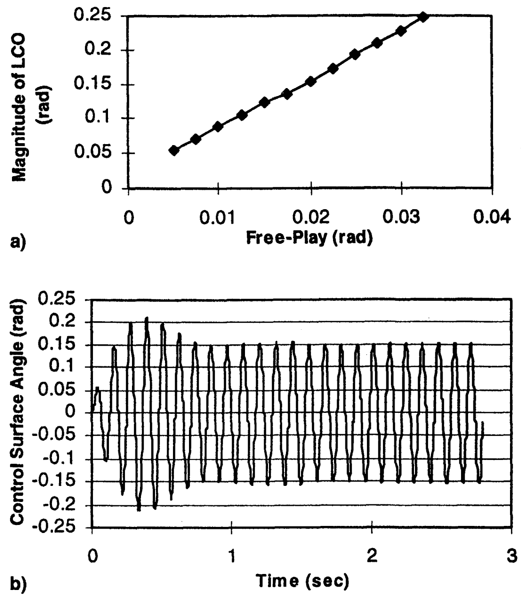

Fig. 2 Effect of freeplay on the aeroelastic response of the control surface: a) effect of freeplay band, β_0, on the LCO amplitude; and b) typical time–history of the nonlinear system.

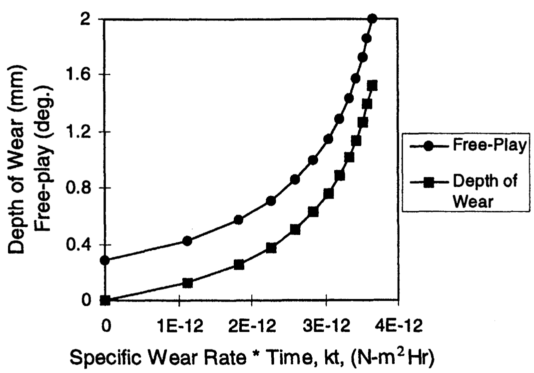

Fig. 3 Development of wear and freeplay in the two-degree-of-freedom nonlinear system.

amount of freeplay corresponding to the new aeroelastic response of the system is calculated. Figure 3 shows the development of backlash in the joint.

Conclusions

In this paper, the wear of a control linkage was considered. The existence of LCOs in a wing–aileron system with freeplay nonlinearity was shown. The wear in the wing–aileron system with freeplay has also been shown to be a coupled problem; i.e., increased wear results in increased amplitude of the LCO and applied load, which in turn, gives rise to increasing wear rate.

Similar feedback phenomena exist in the development of cracks, where crack growth rates increase with crack length. The rate at which the aging process accelerates is the critical issue for maintenance, and accurate prediction depends on the sophistication of the aeroelastic model and the wear model. Here, a two-degree-of-freedom model of an unbalanced aileron, and a wear model that ignores the effect of impact that will occur as the system traverses the freeplay gap, have been implemented.

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Particle Image Velocimetry Study of Wing-Tip Vortices

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Introduction

OCCURRING in a wide variety of flows such as aircraft wakes and helicopter blade-vortex interactions, wing-tip vortices are of great practical significance and have been the subject of extensive research for many decades. Although it is well known that the behavior of wing-tip vortices, particularly in the far field, is strongly influenced by complex atmospheric conditions, the wind tunnel does provide a controlled environment for the detailed study of the vortices in the near field at a relatively low cost (when compared to, say, field studies). Valuable to the understanding of the physics of vortex formation, the data thus obtained can also be used for the validation of near-field simulations, and as the near-field input for far-field predictions.

The wing-tip vortex of an unswept wing at low speeds has been studied[1] in the Institute for Aerospace Research (IAR) 9 m × 9 m Wind Tunnel using the particle image velocimetry (PIV) technique.[2] In particular, measurements of the crossflow

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