Method for the Prediction of the Onset of Wing Rock

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Introduction

MANY modern day combat aircraft exhibit lightly damped or constant-amplitude rolling oscillations at moderate to high angles of attack (AOA). These motions are commonly referred to as wing rock. The mechanisms that cause wing rock are not fully understood. It appears that wing rock is triggered by some type of flow asymmetry, causing initial negative roll damping and then sustained by some type of nonlinear aerodynamic roll damping (Ref. 1, p. 921). Therefore, aerodynamically, wing rock may be caused by flow separation at low speeds or shock-induced separations at transonic speeds, oscillatory aerodynamic loads produced by aircraft motion, or vortex flow dynamics over the wing and fuselage.[2] From the stability point of view it is postulated that wing rock is associated with a sign change in $C_{n\beta}$, reduced and nonlinear roll damping, or instability of one or more of the aircraft's longitudinal and/or lateral control modes.

Previous studies have already developed several parameters that provide indications of aircraft behavior at high AOA. Notably are the lateral control divergence parameter (LCDP) and $C_{n\beta,\text{dynamic}}$ or some combination of the two.[3] These parameters provide general estimates of aircraft behavior at high AOA. They are not able to specifically predict aircraft motion at high AOA.

This study takes another step forward and develops a parameter that specifically predicts the onset of wing rock. Utilizing this parameter, a procedure is then developed that allows an aircraft designer, given certain stability derivatives and inertia characteristics, to predict the onset of wing rock in his design without using complicated software and costly computer time.

Analysis Techniques

Three aircraft will be examined to validate the present work: F-15 Eagle, F-4 Phantom, and the T-38 Talon. A description of these aircraft is given in Ref. 8. The nonlinear eight-state, rigid-body equations of motion used in this study are presented in detail in Ref. 8. Only the F-15 was simulated in the bifurcation software. The expansions of the aerodynamic force and moment coefficients were extracted from a McDonnell Aircraft Company F-15 simulator program. The coefficients were obtained from simulator data (combined wind-tunnel and flight test data) tabulated for Mach numbers from 0.3 to 2.5, and from 0 to 80,000 ft. Mach number and altitude dependence had been eliminated by selecting data at 0.6 Mach and 20,000 ft. For a more detailed description of the aerodynamic coefficient development, see Ref. 4, pp. 10–19.

Since wing rock is nonlinear we need an efficient analysis strategy to study its behavior. A number of previous studies have demonstrated that bifurcation analysis can be used to predict and characterize many nonlinear high-angle-of-attack behaviors of fighter aircraft.[2,4–7] This study uses bifurcation theory as the first step to determine aircraft eigenstructure at the onset of wing rock.

Bifurcation Analysis

The bifurcation parameter chosen for the bifurcation study was the F-15 stabilator deflection. AOA was increased in small steps as stabilator deflection was increased (in the negative direction) from the starting point. The point at which wing rock begins will be referred to as the trigger point.

The bifurcation diagram of AOA for the stabilator sweep is shown in Fig. 1. Branch 1, the branch continued from the initial starting point, has zero lateral states (β, p, q, r) along its entire length. Branches 2–5, which all result from a pitchfork bifurcation, have nonzero lateral states, and each represents two branches that are symmetric with respect to the X-Z plane. The periodic branch emanating from the Hopf bifurcation on branch 1 is also shown on Fig. 1. This Hopf bifurcation represents the onset of wing rock, and the trigger point is the Hopf bifurcation point located on branch 1. This point occurs at alpha equals 21 deg. Wing rock begins here, and we will demonstrate later on that this coincides with the complex conjugate pair of dutch-roll eigenvalues migrating into the right-half plane. The 21-deg alpha finding agrees well with previous F-15 flight test results (Ref. 9, p. 50).

Eigenvalue Analysis

Figure 2 depicts a conventional root locus plot for alpha varying from 10 to 30 deg. As can be seen, the dutch-roll mode moves toward the right-half plane as alpha is increased. The motion is neutrally stable at alpha equals 21 deg, and becomes unstable shortly thereafter. The point of neutral stability coincides with the Hopf bifurcation point on branch 1 (Fig. 1). The dutch-roll mode continues further into the right-half plane as alpha is increased. From the lateral root loci it appears that wing rock is an unstable dutch-roll motion as predicted by several authors.[3,10,11] At low AOA, dutch roll is normally approximated by a flat motion that does not contain much roll angle change. As alpha is increased previous research has shown that this motion becomes predominantly a roll oscillation with little yaw change (Ref. 3, p. 14).

Eigenvector Analysis

Figure 3 shows the relationship of the relative magnitudes of each of the components of the dutch-roll eigenvector at AOA = 21 deg for the F-15. When wing rock is triggered at higher alpha, the eigenvector structure of the system reveals that only the primary states of β, ϕ, p need remain. Thus, a lower order approximate system will be based solely on the following linearized β, ϕ, p equations:

$$\Delta\dot{\beta} = \left[\frac{g}{V_0}\sin(\theta_0 + \alpha_0) + \frac{QS}{mV_0}C_{y_\beta}\right]\Delta\beta + \left(\frac{QS}{mV_0}C_{y_p} + \sin\alpha_0\right)\Delta p + \frac{g}{V_0}\cos\theta_0\Delta\phi \tag{1}$$

$$\Delta\dot{p} = AC_{l_\beta}\Delta\beta + AC_{l_p}\Delta p \tag{2}$$

$$\Delta\dot{\phi} = \Delta p \tag{3}$$

where

$$A = (QSb/I_x)$$

In the above equations the I_{xz} terms have been disregarded due to relative size for high-performance aircraft.

Characteristic Equation

In order to study the triggering of wing rock, the characteristic equation of the new approximate state equations must

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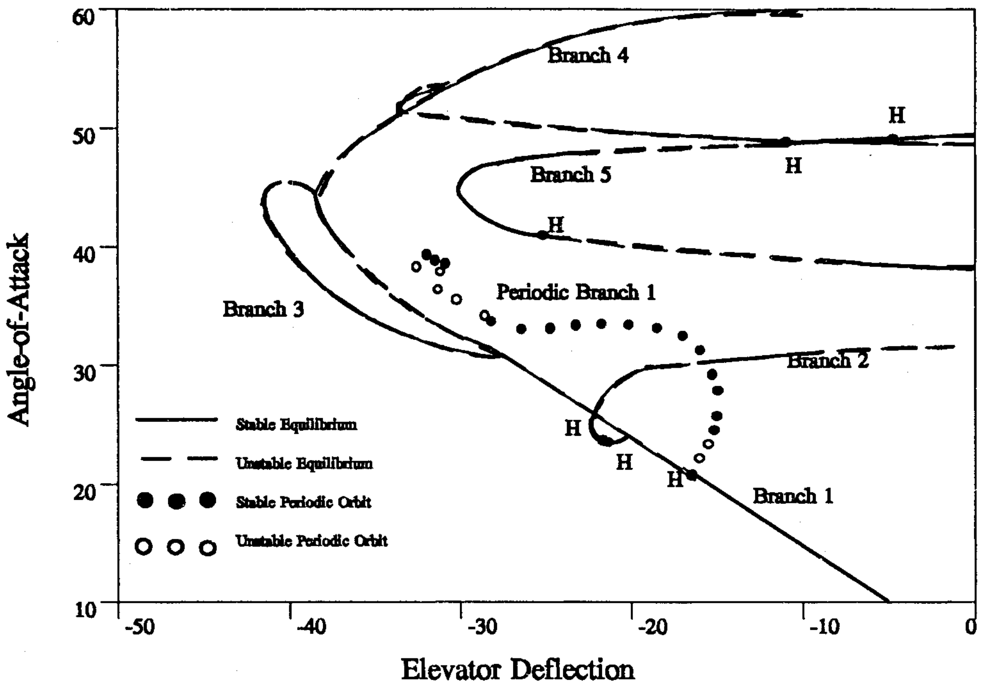

Fig. 1 Alpha bifurcation diagram for F-15.

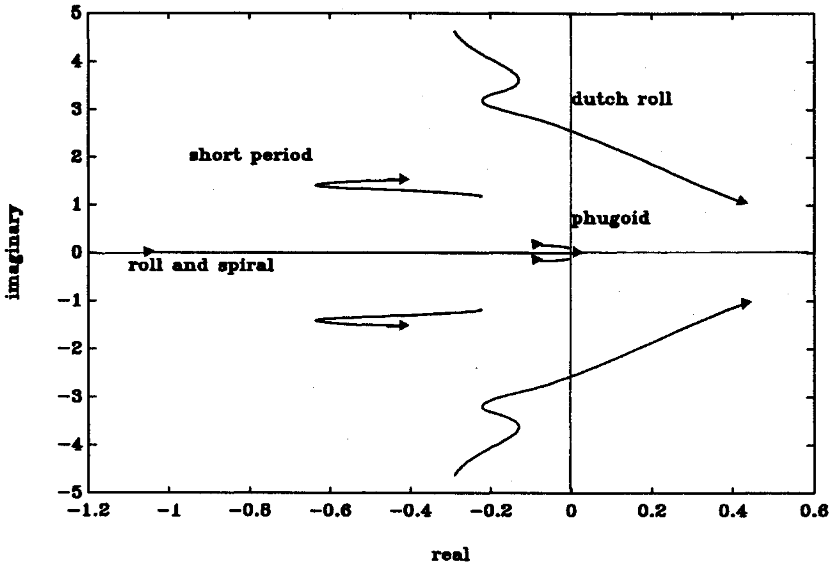

Fig. 2 Root locus of F-15 for varying alpha.

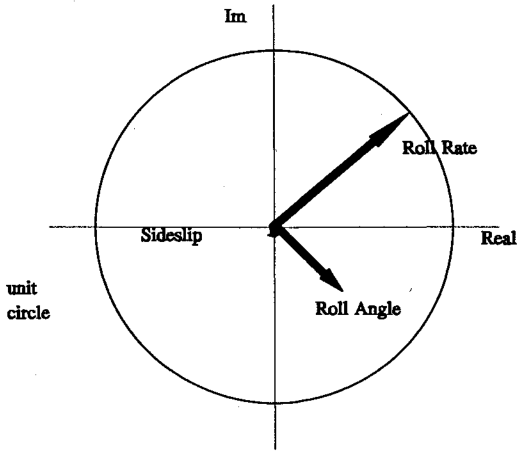

Fig. 3 F-15 dutch-roll eigenvector components at trigger point.

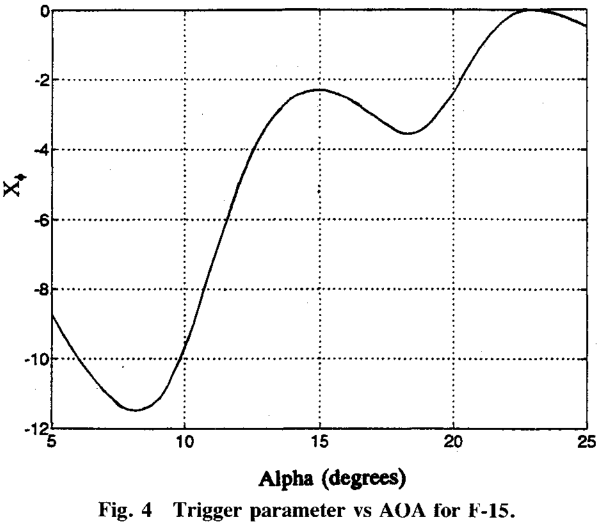

Fig. 4 Trigger parameter vs AOA for F-15.

be determined. The characteristic equation of the above approximate equations is shown below in expanded polynomial form:

$$s^3 - \left[\frac{g}{V_0}\sin(\theta_0 + \alpha_0) + \frac{QS}{mV_0} C_{y_\beta} + AC_{l_p}\right] s^2$$
$$+ \left\{AC_{l_p}\left[\frac{g}{V_0}\sin(\theta_0 + \alpha_0) + \frac{QS}{mV_0} C_{y_\beta}\right]\right.$$
$$\left. - AC_{l_\beta}\left(\frac{QS}{mV_0} C_{y_p} + \sin\alpha_0\right)\right\} s$$
$$- AC_{l_\beta}\frac{g}{V_0}\cos\theta_0 = 0 \tag{4}$$

The dutch-roll mode lies on the imaginary axis at the trigger point. Substituting $s = i\omega$ into the above polynomial expression and equating the real and imaginary parts to zero results in two equalities. Solving yields the following single equality at the onset of wing rock:

$$0 = \left[\frac{g}{V_0}\sin(\theta_0 + \alpha_0) + \frac{QS}{mV_0} C_{y_\beta} + AC_{l_p}\right]$$
$$\times \left\{AC_{l_p}\left[\frac{g}{V_0}\sin(\theta_0 + \alpha_0) + \frac{QS}{mV_0} C_{y_\beta}\right]\right.$$
$$\left. - AC_{l_\beta}\left(\frac{QS}{mV_0} C_{y_p} + \sin\alpha_0\right)\right\} - \left(AC_{l_\beta}\frac{g}{V_0}\cos\theta_0\right) \tag{5}$$

The right side of Eq. (5) will be labeled X_ϕ. Thus, when X_ϕ is zero, wing rock is triggered.

Prediction Procedure

Given the aircraft stability derivatives, inertia data and physical characteristics we should be able to predict the AOA and airspeed at which an aircraft will wing rock using the following iterative procedure. The following is based on an aircraft operating at an equilibrium condition.

1) The first step in this process is to choose an AOA as an initial starting point. This step will provide α_0.

2) At an equilibrium condition the moment coefficient will equal zero. Therefore, with $C_m = 0$ and $C_m(\alpha_0, \delta e_0)$, the elevator deflection can be found.

3) The initial pitch angle can be found (Ref. 12, p. 258) with

$$C_{X_0} = f(\alpha_0, \delta e_0) \tag{6}$$

$$C_{Z_0} = f(\alpha_0, \delta e_0) \tag{7}$$

$$\theta_0 = \tan^{-1}(C_{X_0}/C_{Z_0}) \tag{8}$$

4) With the initial AOA, pitch angle and elevator deflection solve for V_0 with

$$V_0 = (2\ \mathrm{mgsin}\ \theta_0/C_{X_0}\rho S)^{1/2} \tag{9}$$

5) There is now enough information to compute X_ϕ from Eq. (5).

6) Repeat steps 1–5 until the AOA, where X_ϕ equals zero (which corresponds to the onset of wing rock), is reached.

Results

The procedure outlined above was applied to the F-15 data utilized in the earlier bifurcation analysis. The X_ϕ vs AOA curve is shown in Fig. 4. As seen in Fig. 4, the trigger parameter goes to 0 near 22 deg. Thus, the trigger parameter predicts wing rock onset at 22 deg. Hence, for the F-15, the flight test results of Ref. 9, the bifurcation results, and the trigger parameter results all correlate well. Similar accuracies were obtained for the F-4 and T-38 aircraft models and are presented in Ref. 8.

Flight tests flown by the USAF Test Pilot School, and reported in Ref. 8 for the T-38 and F-4, verify that wing rock consists of primarily rolling motion with little or no pitch or yaw motion. For both aircraft the roll-to-sideslip amplitude ratio during the fully developed wing rock limit cycle was greater than 15; thus, verifying the eigenvector plot in Fig. 3, and the validity of retaining only the β, ϕ, p states in the lower-order approximate wing rock model.

Conclusions

The following conclusions are based on a fighter aircraft with a swept wing maneuvering near the 1 g stall:

1) The rolling oscillations that are commonly referred to as wing rock are actually unstable dutch-roll motions developing into a limit cycle. Dutch-roll motion may consist of considerable roll, yaw, and sideslip at low AOA, however, this motion becomes more of a pure rolling motion as alpha is increased.

2) The trigger parameter and the simple procedure developed to predict the onset of wing rock are fairly accurate for a swept-wing fighter design. The developed technique predicted wing rock onset for three different fighter aircraft (F-15, F-4, and T-38) with three distinct planforms. The procedure appears to be accurate to within 1-deg AOA as verified with flight test data.

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