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SCIENCE DIRECT
Aerospace Science and Technology 10 (2006) 27–35
Aerospace Science and Technology
www.elsevier.com/locate/aescte

Variable phase control of wing rock

Zeng Lian Liu *, Chun-Yi Su, Jaroslav Svoboda ✠

Department of Mechanical Engineering, Concordia University, 1455, de Maisonneuve Blvd. W., Montreal, Quebec, Canada, H3G IMS

Received 12 February 2004; accepted 24 November 2004

Available online 9 June 2005

Abstract

This paper addresses a variable phase control issue for suppressing wing rock with hysteresis. In free-to-roll tests, as the angle of attack (AOA) is increased, the roll angle versus the rolling moment indicates hysteresis and provides clues about where wing rock motion is being driven and where the motion is being damped. We present the analysis method of wing rock energy to explain the mechanism of wing rock and the formation of hysteresis, and then develop a variable phase control (VPC) scheme to compensate the phase and magnitude distortions. The effectiveness and robustness of the proposed scheme are demonstrated by suppressing wing rock phenomenon at various AOA and any initial conditions.

Keywords: Hysteresis; Nonlinear system; Variable phase control; Wing rock

1. Introduction

Many modern combat aircraft often operate at subsonic speeds and high angles of attack. At a sufficiently high angle of attack (AOA), these aircraft become unstable and enter into a limit-cycle oscillation (LCO), mainly rolling motion known as wing rock [3,5,7,13]. In practice, high-speed civil transport and combat aircraft can fly in conditions where this self-induced oscillatory rolling motion is observed; moreover, wing rock phenomenon can be highly annoying to the pilot and may pose serious limitations to the combat effectiveness of the aircraft. Therefore, the control of wing rock phenomenon is of significant importance.

Considerable research has been conducted on the motion of 80° swept delta wing to help understand the fundamental mechanisms causing wing rock [1,3–5,7–9,12]. Free-to-roll tests are usually used to determine build-up and limit-cycle characteristics of wing rock. These results reveal the magnitude of limit cycles of wing rock varying with the AOA. In addition, the tracking tests [1,3,4,8,9,12] of the primary vortex positions in the cross-flow plane provide the data to understand the driving mechanism of wing rock phenomenon. That hysteresis exists between the roll angle and the rolling moment provides clues for explaining wing rock phenomenon. This hysteresis shows three loops during one cycle. The researchers [1,3,7,9] have *observed* that the work done by the rolling motion is driving the oscillation during the central loop since the aerodynamic motion acts in the direction of wing rolling motion whereas during the two reverse outer loops the oscillation is being damped. In this paper, we will theoretically analyze this hysteresis mechanism instead of physical insight.

In this work, inspired by the hysteresis mechanism of driving wing-rock motion, we will directly apply hysteresis compensation or reduction methods to suppress wing rock. The conception of the *phaser* proposed by Cruz and Hernandez [2] is adopted to design variable phase control (VPC) schemes.

The main objective of this paper is to study the VPC to suppress wing rock with hysteresis. The rate of energy change of wing rock is derived to analyze the hysteresis mechanism of driving wing rock. The hysteresis loops, based on a defined critical angle, are divided into two parts: a center loop and two reverse outer loops. We develop a VPC scheme to compensate the hysteresis effects of wing rock

* Corresponding author.
E-mail address: liu_22001@yahoo.com (Z.L. Liu).
✠ Deceased.

1270-9638/$ – see front matter
doi:10.1016/j.ast.2004.11.002

for each part. To verify the effectiveness and robustness of the proposed method, we will demonstrate the several cases of wing rock suppression. Simulation results show that the proposed control scheme can quickly suppress wing rock at various AOAs and any initial conditions.

2. Wing rock model

The phase plane representation of wing rock shows that wing rock phenomenon is dominated by nonlinear damping and a relationship can be established with one-degree-of-freedom analytical models [3].

The differential equation of describing wing rock is given by [6,11,14]

$$\ddot{\phi} = (\rho U_\infty^2 Sb/2I_{xx})C_l + u \tag{1}$$

where $\phi(t)$ is the roll angle, ρ is the density of air, U_∞ is the freestream velocity, S is the wing reference area, b is the chord, I_{xx} is the mass moment of inertia, $u(f)$ is the control input, and C_l is the rolling moment coefficients written as

$$C_l = b_0 + b_1\phi + b_2\dot{\phi} + b_3|\dot{\phi}|\dot{\phi} + b_4\phi^3 + b_5\phi^2\dot{\phi}. \tag{2}$$

The aerodynamic parameters b_i $(i = 0, 1, 2, 3, 4)$ are the time-varying functions of AOA.

Substituting (2) into (1), we have [10]

$$\ddot{\phi} + a_0\phi + a_1\dot{\phi} + a_2|\dot{\phi}|\dot{\phi} + a_3\phi^3 + a_4\phi^2\dot{\phi} = u \tag{3}$$

where a_i $(i = 0, 1, 2, 3, 4)$ are the parameters relative to free-to-roll experiment conditions [3,4]. A typical set of coefficients a_i (at Reynolds number = 636 000) is depicted in Fig. 1.

To illustrate the behaviors of wing rock, the uncontrolled wing-rock motion at AOA = 32.5° with the initial condition $\phi(0) = 0.1°$ and $\dot{\phi}(0) = 0$ is demonstrated in Fig. 2, which shows a small initial disturbance is enough to cause wing rock.

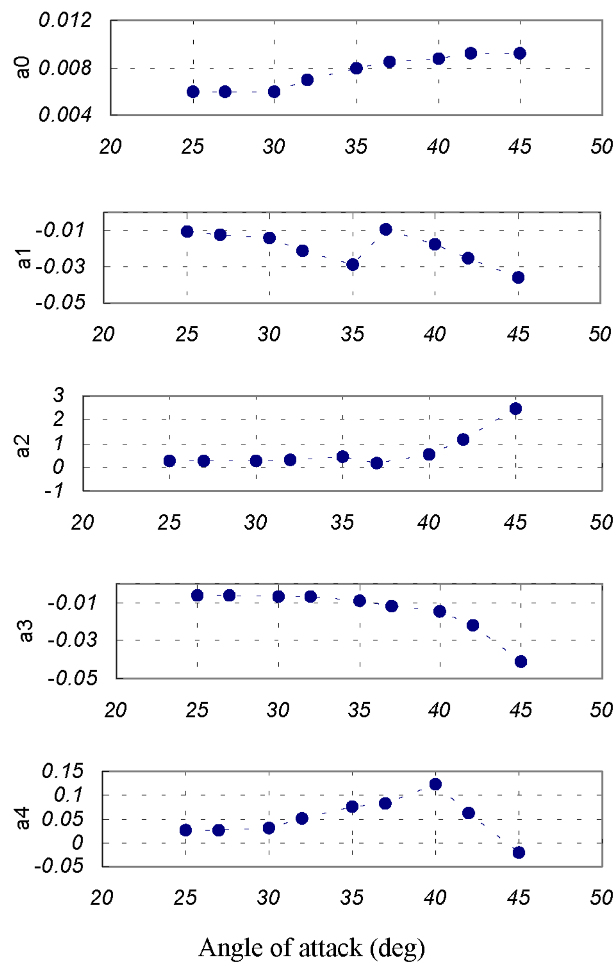

Fig. 1. Coefficients a_i in Eq. (3).

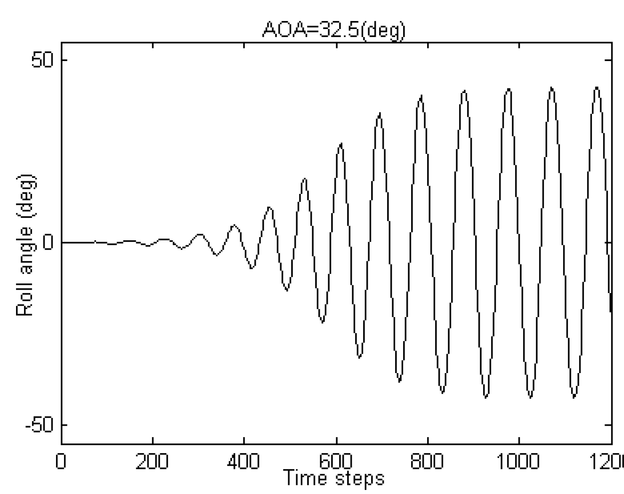

Fig. 2. Time history of wing rock at $\phi(0) = 0.1°$ and $\dot{\phi}(0) = 0$.

3. Hysteresis analysis of wing rock

The uncontrolled wing-rock model in (3) can be written in the following form:

$$\ddot{\phi} + \left(a_1 + a_2|\dot{\phi}| + a_4\phi^2\right)\dot{\phi} + \left(a_0\phi + a_3\phi^3\right) = 0. \tag{4}$$

Let $x_1 = \phi$ and $x_2 = \dot{\phi}$; Eq. (4) is then expressed in a state-variable form:

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = -(a_1 + a_2|x_2| + a_4x_1^2)x_2 - (a_0x_1 + a_3x_1^3). \end{cases} \tag{5}$$

Eq. (5) is further expressed in the phase-trajectory equation:

$$\frac{\mathrm{d}x_2}{\mathrm{d}x_1} = \frac{-(a_1 + a_2|x_2| + a_4x_1^2)x_2 - (a_0x_1 + a_3x_1^3)}{x_2}. \tag{6}$$

By integrating Eq. (6) and substituting $x_2 = \dot{x}_1$ we have

$$\frac{1}{2}x_2^2 + U(x_1) = C - \int_0^t \left(a_1 + a_2|x_2| + a_4x_1^2\right)x_2^2\,\mathrm{d}t \tag{7}$$

where $U(x_1) = \int (a_0x_1 + a_3x_1^3)\,\mathrm{d}x_1$ is the potential energy and C is an integral constant. Define E as the total mechanical energy of the system given by [15]

$$E = \frac{1}{2}x_2^2 + U(x_1). \tag{8}$$