JOURNAL OF AIRCRAFT
Vol. 45, No. 6, November–December 2008

Engineering Notes

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Effects of Unsteady Freestream on Aerodynamic Characteristics of Pitching Delta Wing

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DOI: 10.2514/1.38925

I. Introduction

AS COMBAT aircraft become more and more maneuverable, the need to understand the unsteady, nonlinear characteristics of aircraft in dynamic flow fields becomes more important [1]. A good understanding of the unsteady aerodynamics is beneficial to the design of supermaneuverable aircraft, flight control systems, and the prediction of aerodynamic loads for wing structure design.

Delta wings have been widely used in aircraft design. It is well known that delta wings at a fixed angle of attack generate lift by separating a shear layer of air at the leading edge, and this shear layer forms two strong counter-rotating vortices on either side of the wing. These leading-edge vortices are critical to the generation of lift, as they produce a large suction peak on the surface [2,3]. However, with an increasing angle of attack, a brutal disorganization of the vortical structure occurs, known as vortex breakdown [4]. For slender delta wings, vortex breakdown plays an important role in the induced flow fields, which causes the loss of aerodynamic lift forces and leads to stalling of the lifting surfaces. Vortex breakdown has an impact on aircraft stability and control and wing buffeting. Deeply understanding the unsteady vortex flows due to vortex breakdown is very helpful in designing successful, highly maneuverable aircraft [5].

Research on pitching delta wings have been performed for many years. Unsteady aerodynamic loading, unsteady flow structure, and vortex breakdown phenomenon of pitching delta wing were researched [6–9]. The hysteresis phenomenon of vortex breakdown was observed, and it was found that the magnitude of hysteresis depends on pitch range and rate. However, all of these only consider the effect of the angle of attack changing, and the velocity variations have been ignored. Actually, very large velocity variations exist while the aircraft is undergoing the high angle-of-attack maneuvers, such as the cobra maneuver. The effects of an unsteady freestream on the aerodynamics of static wings are researched in [10–13]. Gursul and Ho [10] found that the phase-averaged lift coefficient of NACA0012 airfoil in an unsteady steam is larger than 10. Shih and Ho [11] have demonstrated that the variation of aerodynamic properties can be understood through the basic vorticity balance concept and the time scales of the flow field. Gursul et al. [12,13] also researched the response of static delta wings in an unsteady freestream. It was found that if the leading-edge vortices attached, the lift produced by a delta wing is independent of freestream velocity. Once the leading-edge vortices detached, lift force would increase. This is mainly due to the variation of the vortex breakdown position over delta wings in an unsteady freestream. The effects of the combined dynamic pitching and unsteady freestream have not been published (to the author's knowledge). Therefore, the research of a dynamic pitching delta wing in an unsteady freestream is necessary.

To study the unsteady behavior of a pitching-motion delta wing in an unsteady freestream, an experimental apparatus is setup for a pitching motion in the unsteady wind tunnel in Nanjing University of Aeronautics and Astronautics, which can provide highly controlled large-amplitude velocity variation profiles. The unsteady aerodynamic behavior of a pitching-alone delta wing and the pitching delta wing coupled with an unsteady freestream are investigated by measuring unsteady loads and unsteady pressure distribution.

II. Experimental Facility and Techniques

Experiments were conducted in a low-speed unsteady wind tunnel with a cross-sectional area of 1.0×1.5 m. The unique feature of this wind tunnel is that a bypass has been developed in the traditional wind tunnel, and there is an unsteady setup between the bypass and diffuser, which consists of many rotating gates. The instantaneous freestream speed can be determined by adjusting the area of those gates. The variation in freestream speed is measured by the hot-wire anemometer. For a periodic freestream, the velocity can be expressed as

$$\frac{U(t)}{U_\infty} = 1 + R\cos 2\pi f t \tag{1}$$

where U_∞ is the time-averaged velocity, R is the dimensionless amplitude, and f is the frequency.

To simulate the pitching motion of a delta wing, an oscillating motion apparatus driven by a hydraulic actuator has been developed in the unsteady wind tunnel. The experimental equipment consists of the model support, the drive setup of oscillation, the control setup, and the data acquisition and processing system. The swing cylinder drives the swing support to rotate around the longitudinal axis and carries out the pitching motion of the model. The oscillation rule of pitching for the model can be described by

$$\alpha = \alpha_m - \alpha_a \cos 2\pi f t \tag{2}$$

where α_m is the mean angle of attack and α_a is the amplitude of oscillating angle of attack.

A six-component balance is used to measure the lift force and pitching moment on the delta wing. The uncertainty in the lift measurement is 0.2% and the uncertainty in the pitching-moment measurement is 0.15%. The lift coefficient and the pitching-moment coefficient are defined by

$$C_L(t) = \frac{L(t)}{\frac{1}{2}\rho U(t)^2 S} \qquad C_M(t) = \frac{M(t)}{\frac{1}{2}\rho U(t)^2 S b_A} \tag{3}$$

Received 3 June 2008; accepted for publication 2 September 2008.

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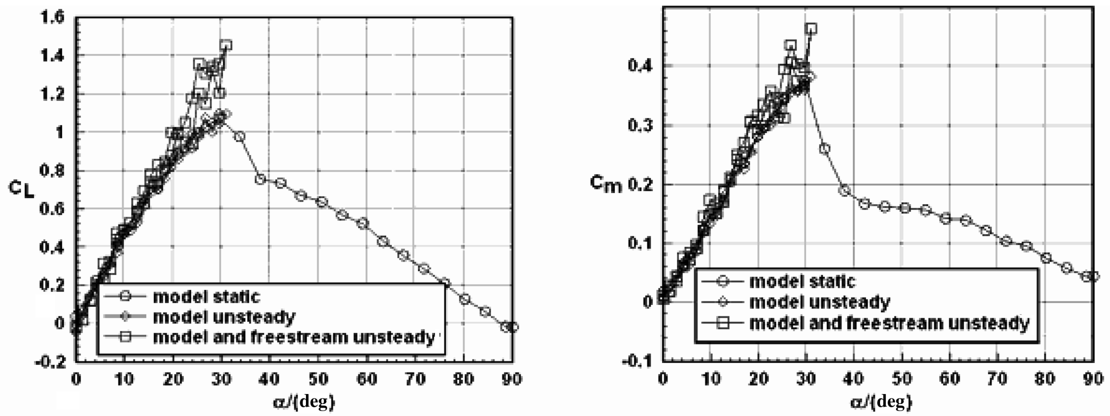
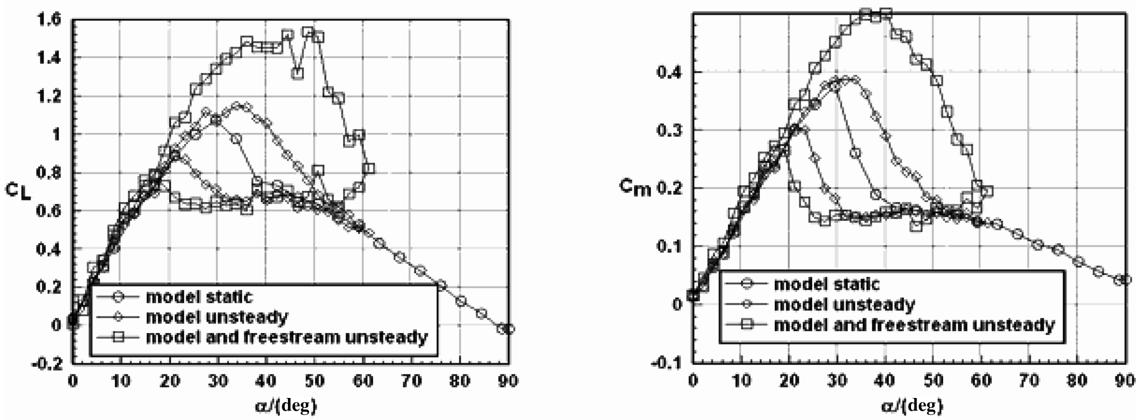
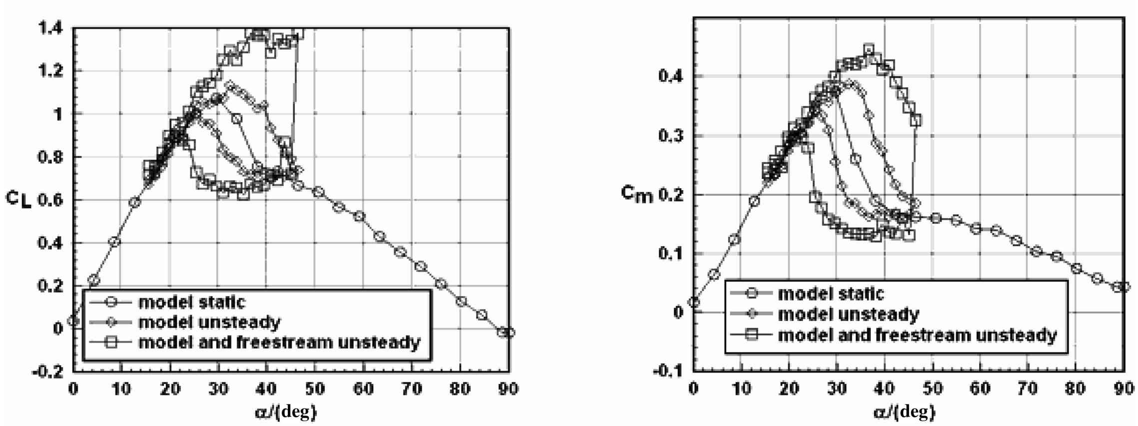


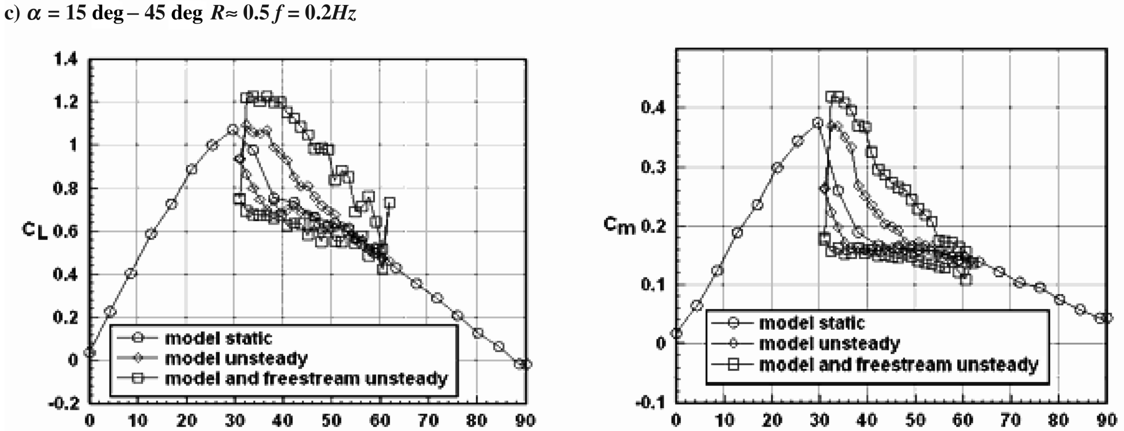
a) α = 0 deg – 30 deg $R \approx 0.5$ $f = 0.2Hz$



b) α = 0 deg – 60 deg $R \approx 0.5$ $f = 0.2Hz$



c) α = 15 deg – 45 deg $R \approx 0.5$ $f = 0.2Hz$



d) α = 30 deg – 60 deg $R \approx 0.5$ $f = 0.2Hz$

Fig. 1 Unsteady aerodynamic behaviors of a pitching delta wing in an unsteady freestream.

where ρ is the air density, S is the area of the delta wing, and b_A is the mean aerodynamic chord. The test results shown in this paper are the phase-averaged coefficient of 10 cycles. Unsteady pressure measurements are performed using pressure tubes and pressure transducers. The length of the tubes is 300 mm and the inside diameter is 1.5 mm. Through the calibration, the effect of the tubes on the amplitude and phase of pressure signals can be ignored. The detailed information on the unsteady pressure measurements can be found in [14].

The test model is a 60 deg delta wing, in which the span is 0.4157 m, the wing area is 0.075 m^2, and the mean aerodynamic chord is 0.24 m. The model could be used in the unsteady aerodynamic forces measurements and the unsteady pressure distributions measurements. The Reynolds number based on the mean aerodynamic chord of the delta wing is in the range of 0.8×10^5 to 2.4×10^5.

III. Results and Discussion

A. Unsteady Aerodynamic Forces

It is known that the airspeed of aircraft is decelerating while the aircraft is undergoing the cobra maneuver. To simulate this maneuver in a wind tunnel, two motions are controlled mutually. The freestream decelerates with the delta wing pitching up, whereas the freestream accelerates with the delta wing pitching down. For both the pitching model and the oscillating freestream, the frequency is set to $f = 0.2$ Hz. The time-averaged velocity is $U_\infty = 12$ m/s. The range of the oscillating angle of attack is set to 0–30 deg, 0–60 deg, 15–45 deg, and 30–60 deg. The dimensionless amplitude of the freestream variation is $R \approx 0.5$.

Figure 1a presents the unsteady aerodynamic forces and moments of delta wing pitching at 0–30 deg in an unsteady freestream. The results show that there are not hysteresis loops, not only in the pitching-alone test but also in the combined motion test. It can be

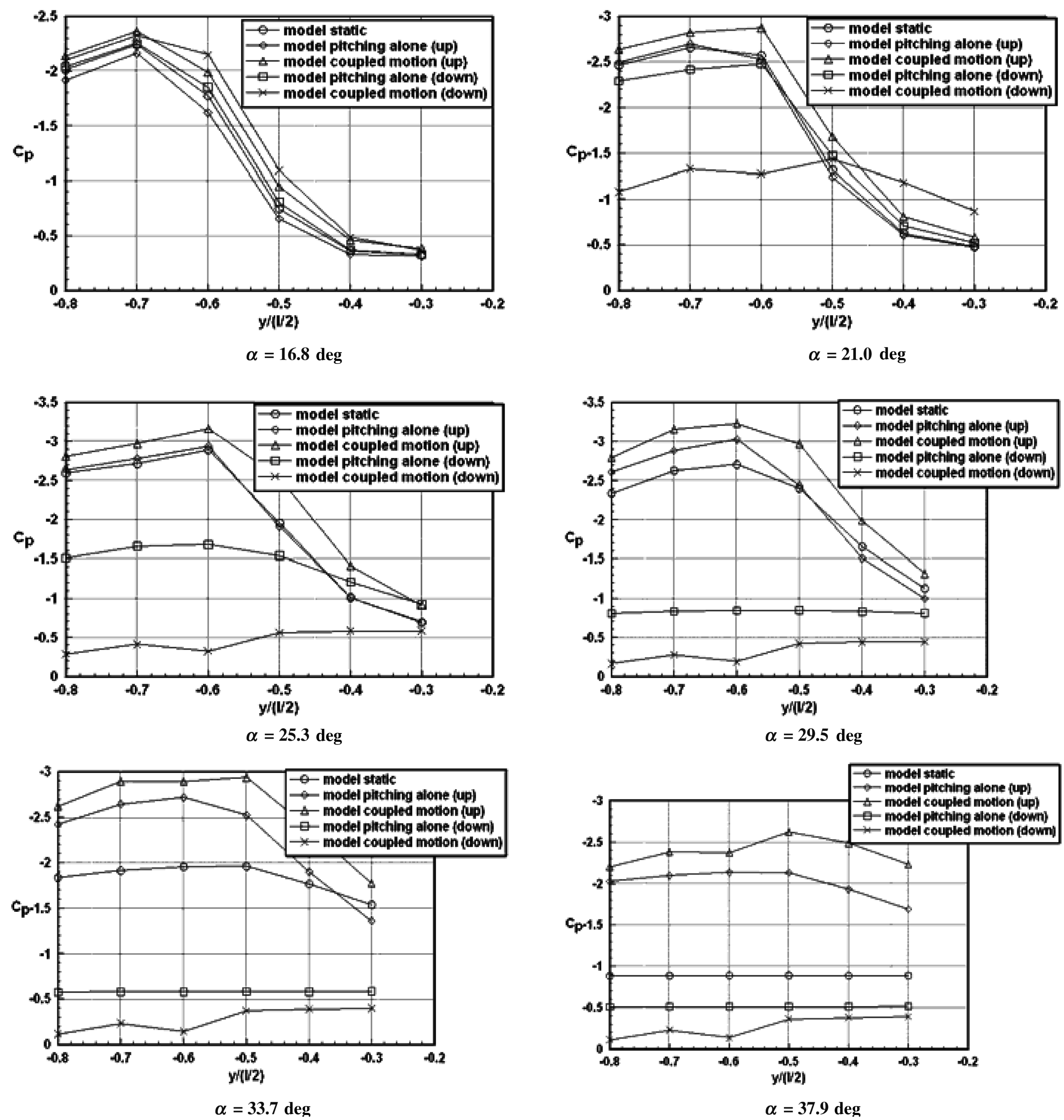


Fig. 2 Pressure distributions of a pitching delta wing in an unsteady freestream ($x/c = 0.25$).

seen that the lift coefficient of the static delta wing, pitching-alone delta wing, and coupled-motion delta wing are accordant approximately when the angle of attack is smaller than 20 deg. The difference only can be observed at nearly 30 deg. This implies that at the low angle of attack the vortical structures of the leading-edge vortex are not changed by the pitching motion or the unsteady freestream. The effect of the unsteady freestream is observed only when the leeward of the delta wing is controlled by the breakdown vortical flow.

Figure 1b presents the unsteady aerodynamic forces and moments of delta wing pitching at 0–60 deg in an unsteady freestream. In the pitching-alone test, C_L is slightly higher during pitching up and slightly lower during pitching down, compared with the steady state cases. In the dynamic pitching motion combined with an unsteady freestream, it is shown that the oscillating freestream velocity affects the dynamic characteristic of the pitching delta wing further. When the delta wing pitches up, the decelerating freestream makes the $C_{L\max}$ increase and the stalling angle of attack is delayed. The angle at which the lift coefficient recovers to a steady state value is delayed by the accelerating freestream, when the delta wing pitches down. In the coupled motion, the hysteresis loops-of-lift-force coefficient and pitching-moment coefficient are enlarged.

Figure 1c gives the unsteady aerodynamic forces and moments of delta wing pitching at 15–45 deg in an unsteady freestream. It is shown that the effects of external disturbance are significant near the static stall angle of attack. The reason might be that the flow field over the delta wing is controlled by the breakdown vortical flow.

Figure 1d presents the unsteady aerodynamic forces and moments of delta wing pitching at 30–60 deg in an unsteady freestream. When the delta wing pitches up, the decelerating freestream makes the C_L increase compared with that of the pitching-alone delta wing. But when the delta wing pitches down, the lift coefficient of combined motion is identical to the pitching-alone delta wing. Because in this case the flow field of the delta wing is controlled by the full separated flow, the unsteady freestream does not have any effect on the flow structure. The aerodynamic forces also do not change.

B. Pressure Distribution

The measurements of pressure distribution of a pitching delta wing in an unsteady freestream are conducted at the positions of $x/c = 0.25$, $x/c = 0.45$, $x/c = 0.65$, and $x/c = 0.85$. The frequencies of the model pitching and oscillating freestream are set to $f = 0.2$ Hz. The time-averaged velocity is $U_\infty = 12$ m/s. The range of angle-of-attack oscillating is set to 0–60 deg. The dimensionless amplitude of the freestream variation is $R \approx 0.5$.

The unsteady pressure distribution of the pitching delta wing in an unsteady freestream is presented in Fig. 2. It can be seen that the pressure distributions of the static delta wing, pitching-alone delta wing and coupled-motion delta wing are accordant approximately when the angle of attack is smaller than 16.8 deg. This implies that the structures of the leading-edge vortex at the low angle of attack are not changed. With the angle of attack increasing, the difference of the pressure distribution is presented primarily at the coupled-motion delta wing. When the delta wing pitches down in the unsteady freestream, the pressure distribution becomes a horizontal line, which indicates that the accelerating freestream makes the flow field become the full separated flow completely. With the angle of attack increasing continuously, the values of the pressure coefficient in the coupled motion are higher than that of the pitching-alone delta wing during the time that it pitches up. This can be explained by the change of flow structure [15]. This also proves that the decelerating freestream makes the breakdown move downstream further while the delta wing is pitching up. The fact that the hysteresis loops-of-lift-force coefficient and pitching-moment coefficient are enlarged in the coupled motion can be explained by the pressure distribution and flow structure variation.

IV. Conclusions

The unsteady freestream has important effects on the aerodynamic characteristics of the pitching-motion delta wing. When the delta wing pitches up, the decelerating freestream makes the $C_{L\max}$ increase and the dynamic stall angles of attack are delayed. The angle at which the lift coefficient recovers to a steady state value is delayed by the accelerating freestream, when the delta wing pitches down. In the coupled motion, the hysteresis loops-of-lift-force coefficient and pitching-moment coefficient are enlarged. The pressure distribution proves that the changes of the leading-edge vortices structure of the delta wing are the main reason. These studies also conclude that a good understanding of the unsteady aerodynamics is vitally important in the design of supermaneuverable aircraft.

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