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Effect of pitch down motion on the vortex reformation over fighter aircraft

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ABSTRACT

The aerodynamic characteristics of a realistic aircraft undergoing high amplitude pitching motions ranging from angle of attack 0° to 80° are studied using a combination of delayed detached eddy simulation (DDES) method and experimental approach with reduced oscillation rates $\kappa = 0.036$, 0.054 and 0.072. According to the DDES-based results and experimental data, it is confirmed that asymmetric vortex structure reformation process can be induced by pitch down motion when sideslip angle $\beta = 0°$, thereby leading to abrupt and substantial increases in both dynamic normal and side forces. In addition, the effect of pitching frequency on the asymmetric vortex redevelopment is also studied, it will be suppressed with the increase of the oscillation rate, and the bubble and spiral modes are observed to dominate the left and right vortex breakdown process respectively on the left and right upper surface.

1. Introduction

The aerodynamic characteristics of combat air vehicle undergoing large amplitude pitching motions are largely dependent on the vortex breakdown process, as such has received considerable attention. It is well known that vortex breakdown can be delayed as the aircraft pitches up, inducing a larger lift coefficient, and pitch-down motion will lag the reformation of the vortex along the surface of aircraft [1,2]. The bulk of the existing work on the experimental observations of flow structure adjacent to the aircraft featured by pitching motions at high angles of attack has mainly focused on the flow field response induced. With the use of the high speed motion picture photography, LeMay Batill and Nelson [3] studied the vortex breakdown process over a 70 deg swept delta wing, it was found that the onset of vortex breakdown could be delayed during pitching up motion. Also, the increase of reduced frequency κ was seen to lead to significant acceleration of the hysteresis effect over a wide range of κ ($0.05 \le \kappa \le 0.3$). The investigation of the influence of initial flow field on the vortex breakdown position over a pitching 52° delta wing experimentally studied by Ericsson [4], revealed that the vortex breakdown position would move upstream during the initial pitch-up process in comparison with the static characteristics. It was also showed that the vortex breakdown process can be delayed by the pitch-up motion, and an opposite conclusion can be obtained when undergoing pitch-down movement. Experiments on the unsteady aerodynamic effects on a pitching 65 deg delta wing carried out by Myatt [5] showed that a significant unsteady phenomenon can be induced by a constant time lag associated with the flow filed response. Menke and Gursu [6] experimentally investigated the vortex breakdown process over a 75 deg swept delta wing undergoing small amplitude pitching in a water channel. They reported that the vortex breakdown positions were in phase and locked to the pitching rate at moderate mean angle of attack, and low-frequency antisymmetric mode were dominant. The low-frequency mode would be significantly enhanced at large mean angle of attack, implying that the flow filed response to the pitch-motion may be dependent on the mean angle of attack. Ericsson [7] have conducted the experiments on the flow process over a pitching 76/40 deg double-delta wing at large frequency and high angle of attack. They found that aerodynamics characteristics of the swept wing were dominated by the interaction between the strake and wing vortices, thereby leading to the rolling moment characteristics, which is sensitive to the pitching rate. Furthermore, Liu et al. [8] found the lift enhancement based on the interaction between the canard and the wing in pitching maneuver on an X31A-like model, they also observed that the vortex breakdown can be delayed by the large-amplitude oscillations in both pith-up and pitch-down motion as the favorably interaction between the canard and the wing vortex. Yavuz [9] experimentally studied the influences of pitching rate and Reynolds number on the development of vortex structures on a delta wing, it was found that the leading-edge vortex moved forward and toward the upper wing surface as increasing the pitch-up frequency. Elkhoury [10,11] investigated the influence of the pitching-up rate

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on the transient flow structure over X-45-like air vehicle, the vortical field was found to develop slowly at low pitching rates in comparison with that in the high pitching rate case.

Recent years, due to the risk and costs of experiments in wind tunnel and flight tests, significant efforts have also been conducted on numerical approach to accurately predict and understand the nonlinear aerodynamic behavior over fighters. Especially, the massively separated flows over static realistic fighter at high angles of attack were calculated using DES and DDES [12–16], and a wide range of turbulent scales as well as the vortex breakdown process had been proved to be captured correctly by the part of LES in DES approach. Further, the force coefficients obtained from DES agree with the flight-test data much better than that from RANS. Xu et al. [17] using DDES studied the effect of angle of attack on the flow structure over the general aircraft, they found that the dominate frequency associated with the vortex shedding process reduced with the increase the angle of attack. The rolling-movement behavior of a simplified fighter was studied by Jeans et al. [18] using DDES with the maneuvering frequency ranging from 1.43 Hz to 17.1 Hz. A significant hysteresis was observed in comparison with the static state, and it was suppressed with the increase of the maneuvering frequency. The massively flow separation over the F16-C undergoing sinusoidal pitching motion was simulated by Dean et al. [19] using DES with the initial angle of attack of 30 deg and the oscillation amplitude of 15 deg. A good agreement can be observed between the numerical results and those from the multivariate polynomial model predictions.

As is mentioned above, for the flow over platforms such as delta wings [1–4], the flow-filed asymmetry can be excited by the asymmetry vortex breakdown process at high angles of attack, and considerable efforts had been devoted to understanding the transient flow structures on combat air vehicles undergoing pitch-up motion. Interesting, asymmetric vortex structure reformation can also be induced due to pitch-down motion. Brandon [20] experimentally studied the influence of pitch-down motion on the lateral characteristic of the F-18 configuration at sideslip angle $\beta = 10°$ in low speed wind tunnel. They observed significant changes of the rolling moment when the aircraft pitched from angle of attack 75 deg to 5 deg in comparison with static conditions, it was suggested that the leeward vortex system was relatively long delayed. However, few details on the flow structure and mechanisms have been discussed. Thus, the aim of the present work is to shed light on the nature of asymmetric vortex structure redevelopment subjected to pitch-down motion over fighter aircraft, and to investigate the influence of pitching rate are also investigated with the maneuvering frequency $f^* = 0.4$ Hz, 0.6 Hz and 0.8 Hz.

2. Experimental approach and flow solver

The realistic aircraft configuration shown in Fig. 1 is considered in the present study. Experiments were performed in a large-scale low speed wind tunnel of low speed aerodynamics institute of China Aerodynamic Research and Development Center (CARDC). The main test section is open column form, the diameter is about 3.5 m, and the length is 5.5 m. The model is supported with a tail strut to avoid any interference with vortices in the wind tunnel. The freestream Mach number is maintained about 0.088, and the corresponding Reynolds number Re_c based on the mean aerodynamic chord c^* of the aircraft is about 8.93E5.

Our well validated in-house code is also used to solve the flow governed by the unsteady, compressible Navier–Stokes equations [17]. It is built on the cell-centered finite-volume frame able to deal with the block structured grid, and the free stream quantities and the mean aerodynamic chord are used to scale. A standard second-order Roe upwind scheme is used to treat the convective fluxes, while the diffusive fluxes are discretized using a second

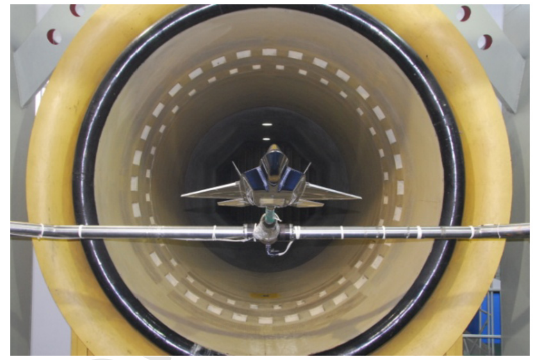

Fig. 1. The wind tunnel and aircraft configuration.

order centered scheme [21]. Furthermore, the solution of time integration is based on the dual times stepping scheme LU-SGS implicit method [22] coupling with the low-Mach-number preconditioning [23]. The means of DDES, as an improved version of DES first proposed by Spalart et al. [24] and extensively used tool in CFD to assess massively separated flows in engineering, is used to investigate the complex flow structures over the realistic aircraft. The version of DES based on the SST model [25] was firstly proposed by Strelets [26], and the governing equations of SST-DES can be written as:

$$\left.\begin{aligned}
&\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho U_j k)}{\partial x_j} = P_k - D_k + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\tilde{\sigma}_\kappa}\right)\frac{\partial k}{\partial x_j}\right] \\
&\frac{\partial(\rho\omega)}{\partial t} + \frac{\partial(\rho U_j \omega)}{\partial x_j} \\
&\quad = P_\omega - \beta\rho\omega^2 + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\tilde{\sigma}_\omega}\right)\frac{\partial \omega}{\partial x_j}\right] \\
&\qquad + (1 - F_1)\frac{2\rho\tilde{\sigma}_{\omega,2}}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}
\end{aligned}\right\} \tag{1}$$

where

$$D_k = \rho\frac{k^{3/2}}{L_{DES}}, \quad L_{DES} = \min(L_t, C_{DES} \cdot \Delta);$$
$$C_{DES} = F_1 \times C_{DES,k-\omega} + (1 - F_1) \times C_{DES,k-\varepsilon}$$
$$F_1 = \tanh\left(\Gamma^4\right); \quad \Gamma = \min\left(\max(\Gamma_1, \Gamma_3), \Gamma_2\right)$$
$$\Gamma_1 = \frac{500\mu}{\rho d^2\omega}; \quad \Gamma_2 = \frac{4\rho\tilde{\sigma}_{\omega,2}k}{d^2(CD_{k-\omega})}; \quad \Gamma_3 = \frac{\sqrt{k}}{0.09\omega d}$$

F_1 is the blending function, d is the wall distance. Moreover, L_t denotes the turbulent length scale:

$$L_t = \frac{\sqrt{k}}{\beta^*\omega}$$

and $\Delta = \max(\Delta x, \Delta y, \Delta z)$ represents the grid scale. However, early separation would be created by DES. For instance, the separated point on an airfoil trailing edge predicted by the SST-DES will move upstream than that by SST-RANS [27]. To improve the SST-DDES approach, a modification was proposed by Menter et al. [28] using the SST-F_2 function as a shield function to delay the LES simulation in boundary layer region, then the new revision of SST-DDES method can be given as:

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