Effects of Reduced Frequency on the Behaviors of Burst Point Around a Pitching Double Delta Wing

Jian Liu, Haisheng Sun, Zhitao Liu and Zhixiang Xiao

Abstract The dynamic behavior of burst point (BP) around delta wing (DW) during oscillation has been a hot topic for its close relationship with the stability and control of an aircraft. Delayed detached eddy simulation (DDES) combined with rigid moving mesh techniques was implemented to investigate the dynamic response of the BP around an 80°/65° double delta wing (DDW) during sinusoidal pitching motion at critical angle of attack (AOA). The effects of reduced frequency (RF) on the performance of BP were discussed in detail. The movement of BP is locked in the frequency of pitching motion with a large phase lag. The time-averaged location, oscillation amplitude and phase lag are significantly determined by RF. The time-averaged location reaches its most downstream at RF of 0.2. When the RF is near 0.2, the Root-mean-Square (rms) of displacement of BP is much larger. The phase lag increases linearly with the growth of RF.

Keywords DDES · Double-delta wing · Burst point · Reduced frequency Phase lag

1 Introduction

It is well known that the flow over DW is dominated by a pair of primary stream-wise vortices, which play an extremely significant role in generating considerably additional lift at high AOA. However, when the AOA increases to a certain value, vortex breakdown happens. Especially, when the DW is taking a pitching motion, the flow particularly the BP lags behind the AOA [4]. A few researchers put great enthusiasm into the dynamic behavior of BP [1, 3, 7].

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Nevertheless, most of researches on dynamic response of BP mentioned above are based on experiments. Numerical investigations are much fewer. Consequently, a solver based on finite volume (FV) was developed to investigate the unsteady flows around a pitching DDW. Here, the focus was put on the dynamic behavior of BP during sinusoidal pitching motion and the effects of RF on the response of BP.

2 Numerical Methods and Our Code

The control equations are the integral URANS equations based on rigid moving mesh technique [5]. DDES [2] based on *k*-ω-SST model was applied to simulate the vortex breakdown flows. The detailed formulations and constants of DDES can be found in the literature by Spalart [8]. The inviscid flux is calculated by the S-TVD scheme with adaptive dissipation [9]. The adaptive function, ϕ, is calculated by the ratio of DDES length scale to that of the RANS:

$$\phi = \tanh\left(\frac{C_1}{1 - C_2} \cdot \max(l_{DDES}/l_{RANS} - C_2, 0)\right) \tag{1}$$

Detailed performance analysis can be found in related reference [5].

Our in-house code UNITs (***U***nsteady ***N***av***I***er-s***T***okes ***s***olver) [9] used here is a FV solver based on multi-block structured mesh. The viscid flux is dispersed by the 2nd order central difference scheme. Low-upper symmetric Gauss-Seidel (LU-SGS) method with Newton-like sub-iteration in pseudo time is taken as the time marching method to achieve 2nd order accuracy. Message-passing-interface (MPI) technique is applied to improve computational efficiency.

3 Case Description and Computation Sets

A double-delta wing (DDW) with 80° swept strake and 65° swept main wing during pitching motion was considered. The model and the mesh in the leeward side are shown in Fig. 1. The total number of cells is about 11 M and the grid scale in the leeward side is about 0.015 C, where C is the mean aerodynamic chord.

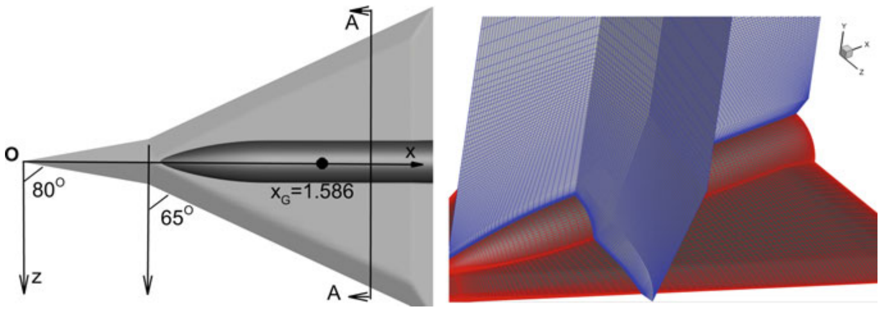

Fig. 1 80°/65° DDW model and distribution of mesh in the leeward side

The angle of attack of pitching motion is determined by $\alpha(t) = \alpha_o + \alpha_m sin(2kt)$, where $\alpha(t)$ is the instantaneous incidence; α_o is the balanced incidence and set to be 36°; α_m is the pitching amplitude and equal to 6°; and $k = \omega C/2U$ is the reduced frequency (RF) and ranges from 0.1 to 0.5. The free-stream velocity U is 40 m/s and the Reynolds number is 1.3×10^6. The normalized time step $\Delta t = \Delta t^* \times U / C = 0.008$. All the computations were run for eight cycles and the last six cycles were used for analyzing.

4 Results and Discussions

4.1 *Dynamic Response of Unsteady Flows in One Pitching Period*

In the computation range, the movements of BP are locked in the frequency of pitching motion, and have a time lag to the instantaneous AOA. Figure 2 presents the spectrum of $\bar{x}_b(t)$ and its stream-wise velocity u_b(t) when the RF is 0.4. The dominant frequency St is equal to 0.127, which is in accordance with the RF of pitching motion ($k_b = \pi St = 0.4$). The corresponding amplitude $x_{b,Am1}$ and root-mean-square $x_{b,rms}$ are about 0.256 C and 0.207 C, respectively. The stream-wise velocity of BP, $u_b = d\bar{x}_b/dt$ is calculated by a 2nd order central difference. The dominant frequency is also 0.127 and the corresponding amplitude is about $0.21U_\infty$.

Figure 3 demonstrates the dynamic response of BP in one pitching period. The BP is determined by the appearance of negative spanwise vorticity (as P1 denotes in Fig. 3c–f).

At t1, the AOA is at 30° and will increase. The BP locates at the equilibrium position and is going to move downstream with maximum speed (Fig. 3c). At t2,

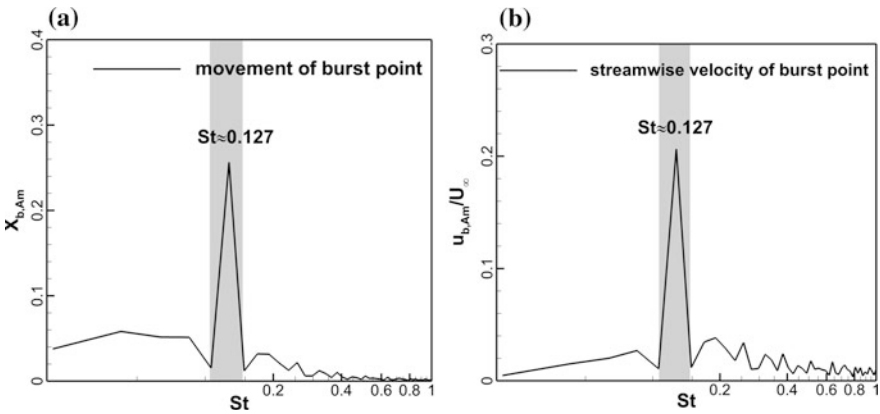

Fig. 2 Spectrum of stream-wise movement and velocity of BP

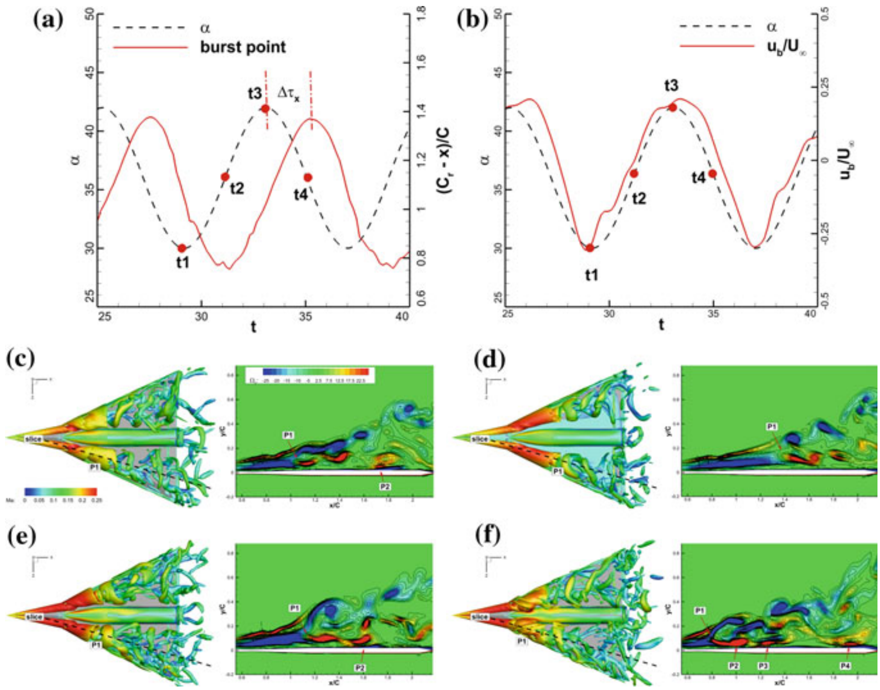

Fig. 3 Evolution of vortex breakdown flows in one period

the AOA arrives at 36°. The BP reaches the most downstream position and its stream-wise velocity almost becomes zero (Fig. 3d). At t3, the AOA increases to 42°. The BP returns to its equilibrium position, but it moves upstream with the maximum velocity (Fig. 3e). At t4, the AOA recovers to 36° and will decrease. The BP moves to the most upstream position. It can be observed that the streamwise movement of BP lags behind the AOA with phase lag of −90°. Thus, the behavior of both $\bar{x}_b(t)$ and u_b(t) can be simplified as sinusoidal functions:

$$\bar{x}_b(t) \approx x_{b,aver} + x_{b,Am1}\sin(2kt + \Delta\phi_x) = x_{b,aver} + x_{b,Am1}\sin(2k(t - \Delta\tau_x U_\infty / C))$$
$$u_b/\mathrm{U}_\infty = \frac{d\bar{x}_b}{dt} \approx x_{b,Am1} \times 2\mathrm{k}\,\cos(2kt + \Delta\phi_x) \approx u_{b,Am1}\sin(2kt + \Delta\phi_u) \tag{2}$$

4.2 *Effects of RF on Dynamic Behavior of BP*

Time-averaged location ($x_{b,\ aver}$), oscillation amplitude ($x_{b,\ Am1}$), RMS of fluctuation ($x_{b,rms}$) and phase lag($\Delta\phi$) at different RF ($0.1 \le k \le 0.5$) are plotted in Fig. 4. All the pitching motions can postpone the vortex breakdown. When RF is smaller than

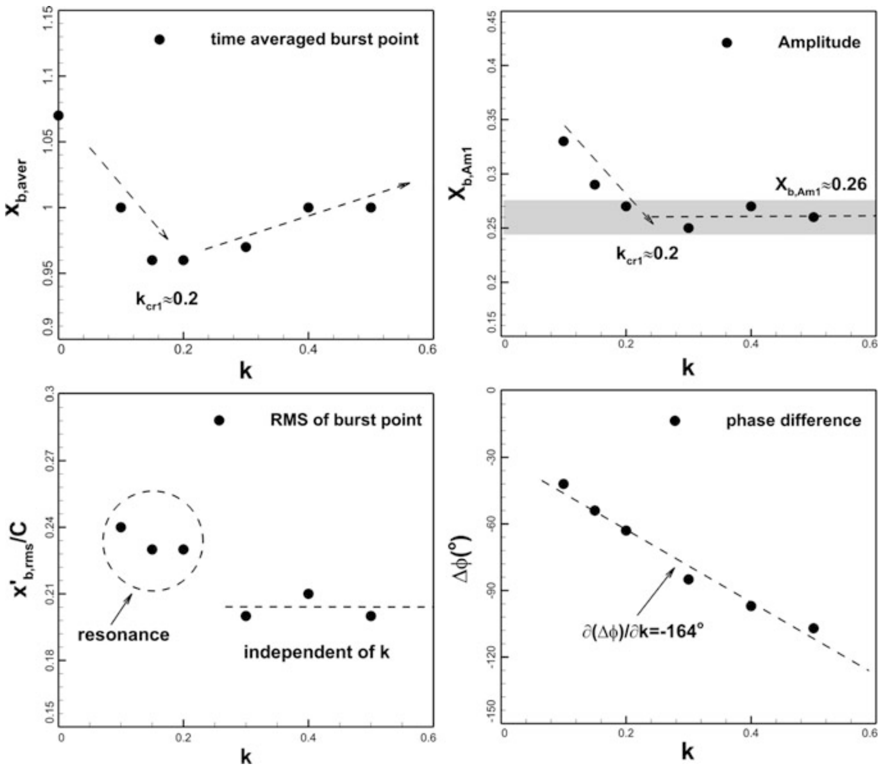

Fig. 4 Performance of dynamic response of burst point varying with RF

$k_{cr1} \approx 0.2$, $x_{b,\ aver}$ moves downstream as it increases. Then the BP reaches the most downstream position at k_{cr1}. When the RF increases continuously, $x_{b,\ aver}$ moves upstream. $x_{b,\ Am1}$ decreases with RF until it reaches k_{cr1}. When RF is larger than k_{cr1}, $x_{b,Am1}$ approaches to 0.26 and is independent of RF. When RF is near the natural frequency of burst point in the stationary case ($k \approx 0.2$, equivalent to $St = k/\pi \approx 0.06$, Liu 2016), resonance effect occurs, and the $x_{b,\ rms}$ reaches the largest value. But for RF larger than 0.3, $x_{b,rms}$ is approximately 0.2 and independent of it. Similar phenomenon was also observed by Menke and Gursul [6].

It has been found that the phase lag of burst point decreases linearly with RF within a certain range.

5 Conclusions

A solver based on the rigid moving mesh and DDES techniques has been implemented to simulate the unsteady flows around a pitching DDW. The focus are put on the dynamic behavior of BP and the effects of RF. It has been found that the temporal evolution of BP is approximately a sinusoidal curve accompanied with a phase lag to the AOA. The phase lag decreases linearly with the growth of RF. When the RF is equal to the natural frequency of BP in the stationary state, the BP reaches the most downstream position and the r.m.s. of displacement is much larger.

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