Forebody Flow During the Wing Rock Over Low Swept Wing/Body Configuration in High Rate Pitching-up

S. W. Xu,*, X. Y. Deng, Y. K. Wang, W. Tian

*Ministry-of-Education Key Laboratory of Fluid Mechanics, BeiHang University, Beijing 100191, China

Abstract

Over the configuration of a pointed ogive-cylindrical body with 30° swept wing, wind tunnel experiments are conducted to investigate the wing rock motion in pitching-up as well as the flow structure responsible for it. Results show that wing rock would present as a sinusoid like motion during angle of attack 20°~85° in high rate pitching-up. And the evolution of forebody vortices with angle of attack should be responsible for the sinusoid like motion. Firstly, the wing rock is triggered by forebody asymmetric vortices at moderate angle of attack (about 30°). Secondly, the variation of forebody asymmetric vortices with angle of attack sustains the wing rock during angle of attack 30°~60°. At last, the wing rock after angle of attack 60° is a convergent process of rolling due to the breakdown of forebody asymmetric vortices.

Keywords: wing rock; pitching-up; forebody asymmetric vortices

Nomenclature

\[ C_p \] Surface pressure coefficient, \((P-P_0)/q_0\)
\[ C_y \] Sectional side force coefficient, \(\frac{1}{2} \int_{0}^{2\pi} C_p \sin \theta d\theta\)
\[ C_l \] Sectional rolling moment coefficient, \(C_l = \frac{\int_{D/2}^{l_{local}} C_p \cdot y \,dy}{\Delta L \cdot l_{local}}\)
\[ D \] Cylinder body diameter (mm)
\[ L \] Wind span (mm)
\[ l_{local} \] Local wind span (mm)

* Corresponding author. Tel: (+86) 010-82317524.
E-mail address: mist1987@163.com
1. Introduction

The wing rock (roll oscillation about the longitudinal axis) phenomenon induced by the vortical flow separating from forebody, is liable to occur on aircrafts flying through large angle of attack. The modern aircrafts with the slender body, such as F-18 HARV, X-31, have been found to present wing rock motion resulting from forebody vortices [1]. Therefore, after Brandon and Nguyen’s first investigation [2] about the wing rock induced by forebody asymmetric vortices over the model of a pointed ogive-tangent cylinder body with very low swept wing (\( \Lambda = 26^\circ \)), some researchers such as Ericsson [3][4], Deng [5] have also made efforts on the wing rock induced by forebody asymmetric vortices with the similar configuration. According to their researches, a limit cycle oscillation which is built up rapidly is the typical wing rock pattern induced by forebody asymmetric vortices at the fixed angle of attack. And the switching of forebody vortices asymmetry is thought to be indispensable for driving the wing rock [2]–[4], [6].

However, the wing rock in high rate pitching-up which is more approach to the real instance is actually less mentioned for some reasons. The flow characteristic of it is still unknown. Therefore, over the configuration of a pointed ogive-cylindrical body with 30° swept wing, the paper makes the preliminary investigation on the variation of forebody flow during the wing rock induced by forebody asymmetric vortices in high rate pitching-up.

2. Experimental setup and techniques

2.1. Wind Tunnel and Experimental Model

The experiments are conducted in the open test section of D4 wind tunnel of Beihang University. The D4 wind tunnel is a low-speed and return-flow wind tunnel with turbulence level of 0.08%. The size of test section is 1.5m×1.5m and 2.5m long. In the experiments, the wind velocity is fixed at 25 m/s. The Re number is 1.6×10^5 based on the diameter of the cylindrical segment of the model. The Re number is much smaller than it is in the real conditions (the ReD number is around 8×10^6 when Su-27 is pitched-up in Cobra maneuver according to the reference[7]). However, as the fundamental research, effect of Re number may be studied in future but very sorry not in present paper. On the other hand, the paper focused on the effect of non-dimensional pitch rate which may be more important than Re number effect in pitching-up related researches. The maximum non-dimensional pitching rate (\( \gamma = 5.6 \times 10^{-3} \)) in paper is about one fourth of it is in cobra maneuver[7].
The test model is shown in Fig. 1, all dimensions are in millimeters. The body of model is a pointed ogive-tangent cylinder, and the 30° swept flat wings are employed as the downstream surfaces needed for generation of the rolling moment. The wing is double-beveled with the thickness of 4 mm. Pressure measurement is made at \( x/D = -2.5 \), 24 equally spaced pressure taps are arranged around the body. The azimuth angle (\( \theta \)) of pressure tap which locates at the windward stagnation of the local section is defined as 0° (or 360°), as shown by A-A view of Fig. 1. There are also 6 equally spaced pressure taps located at \( x/D = -4.85 \) for each wing. The locations of the pressure tap are also shown in Fig. 1. The model is made of aluminum, and the moment of inertia is about 0.007 kg\( \cdot \)m². The tip of the model is rotatable and is driven by the motor installed in the forebody. In order to make the forebody asymmetric vortices as well as the wing rock induced by it be determined\([5, 7–9]\), a spherical particle with the diameter of 0.2 mm which is attached onto the rotatable tip of the model is employed as the artificial perturbation, as shown in Fig. 2. The perturbation’s axis location and the definition of circumferential angle (\( \gamma \)) can also be drawn from Fig. 2.

2.2. Technique of Synchronous Measurements during the Wing Rock

The model is sting-mounted, and driven by the apparatus shown in Fig. 3. The free to roll motion is obtained with free to roll bracket. In order to reveal the flow structure responsible for free to roll motion. Measurements of pressure and PIV are synchronous conducted when representing the wing rock motion. The synchronous measuring system can be described as following:

- The servo motor employed in dynamic pitching system (Fig. 3) is used to drive the pitching-up motion. Another servo motor mounted in forced-to-roll bracket (substituted it for free-to-roll bracket in Fig. 3) is employed to represent the wing rock motion. 12 Bits coder connected with motor is used to record the displacement of attack angle or roll angle. With help of gear reducer, the precision for attack angle is 0.0088° while it’s 0.0176° for roll angle. Therefore, wing rock motion in high-rate pitching-up can be represented with help of the two motors.
- The DTC Initium system is employed for pressure measurements. The module has a range of \( \pm 1 \) psi (7 kpa) and the precision of module is 0.1%FS. PIV experiments are conducted with Dantec PIV system. The special bracket is employed to actualize the PIV measurements. In the tests, the bracket was first move to the wanted angle of attack.
- The signal is sent out by the computer to trigger measurements of pressure and PIV when the model moves to the wanted roll angle or the wanted angle of attack. The sampling frequency is 512 Hz with help of a calculagraph.
3. Results and Discussion

3.1. Wing Rock Motion in High-rate Pitching-up

Free to roll tests show that the pitch rate has great effect on the wing rock pattern. Fig. 4 presents the time histories of wing rock for different pitch rates during angle of attack $20^\circ$~$85^\circ$. Results show that the model would turn around before non-dimensional pitch rate $\psi=2.0 \times 10^{-3}$, as shown in Fig. 4a) (time histories after turn around are not presented). But the sinusoid like motion would be obtained after pitch rate $\psi=2.6 \times 10^{-3}$, as shown in Fig. 4b). Therefore, the paper defines the two ranges of pitch rate as low pitch rate range and high pitch rate range respectively. And the paper would mainly focus on the wing rock in high rate pitching-up.

![Fig. 3 Model installed in the wind tunnel](image)

As for the variation of forebody flow during the wing rock, pressure experiments during the limit cycle oscillation at fixed angle of attack show that the forebody asymmetric vortices will switch between left vortex pattern and right vortex pattern, as shown in Fig. 5a. However, take the non-dimensional pitch rate $\psi=3.2 \times 10^{-3}$ for example, pressure tests during the wing rock in high rate pitching-up shows that the switching of forebody asymmetric vortices doesn’t happen, as shown in Fig. 5b. This means that forebody flow structure during the wing rock in high rate pitching up has great difference with the forebody flow during limit cycle oscillation at fixed angle of attack.

![Fig. 4 Time histories of oscillations in pitching-up(α=20°~85°, Re=1.6×10^5, γ=45°) for (a) $\psi \leq 2.0 \times 10^{-3}$ and (b) $\psi \geq 2.6 \times 10^{-3}$](image)
3.2. Rolling Moment Analysis during Oscillating

For the wing rock motion in pitching-up, the angle of attack instead of roll angle might have more important effect on the flow responsible for the wing rock. Therefore, paper tries to depict the wing rock motion as follow (the black curve in Fig.6): the variation of roll angle with angle of attack. The synchronous pressure measurements are first conducted when representing the wing rock motion. By comparing with the curve of rolling acceleration (the blue curve in Fig.6), sectional rolling moment (the red curve in Fig.6) at $x/D=-4.85$ (named by Sec4.85Cl) is validated to be appropriate for representing the rolling moment of model. As indicated by the variation of sectional rolling moment, the model starts to accelerate and moves to minus side during $30^\circ$~$40^\circ$. After angle of attack $40^\circ$, the sign of rolling moment is different with the sign of roll angle for most angles of attack, which means that the model always try to back to the equilibrium position.
The sectional rolling moment contains two parts: sectional rolling moment over the leeward and sectional rolling moment over the windward. The variation of leeward rolling moment and windward rolling moment with angle of attack are shown in Fig.7. As indicated by the figure, the windward rolling moment (the blue curve in Fig.7) always try to make the model move to 0° roll angle. As for leeward rolling moment (the pink curve in Fig.7), the following items could be summarized easily.

• During angle of attack 30°~40°, leeward rolling moment is primary resource of total rolling moment. It’s leeward rolling moment that triggers the wing rock.

• During angle of attack 40°~60°, due to the small leeward rolling moment around angle of attack 45°, the windward rolling moment becomes the major resource of total rolling moment, therefore the model starts to decelerate and moves to 0° roll angle.

• During angle of attack 60°~85°, the value of leeward rolling moment is very small, therefore the model becomes to convergent under the effect of windward rolling moment.

Fig.7. The variation of wing rock motion and sectional integrated rolling moment (multiplied by 45) with angle of attack during wing rock in pitching-up ($\nu=3.2\times10^{-3}$, $\alpha=20°~85°$, $Re=1.6\times10^5$, $\gamma=45°$)

3.3. Variation of Forebody Flow during Oscillating

Above results about rolling moment show that the variation of leeward rolling moment with attack angle is key point for understanding wing rock in high rate pitching-up. Fig.8 shows that the leeward rolling moment comes forth after the generation of sectional side force after angle of attack 30° (named by Sec2.5Cy) and varies with the sectional side force. The figure indicates that the leeward rolling moment is induced by forebody asymmetric vortices. Therefore, the evolvement of forebody flow responsible for the variation of leeward rolling moment may reveal the mechanism of wing rock in high-rate pitching up.
Fig. 8. The variation of sectional side force and sectional integrated rolling moment of leeward with angle of attack during wing rock in pitching-up ($\nu=3.2\times10^{-3}$, $\alpha=20^\circ$~$85^\circ$, $Re=1.6\times10^5$, $\theta=45^\circ$).

Fig. 9 shows the variation of pressure distribution at $x/D=-2.5$ with angle of attack during the wing rock in pitching-up. And the following items could be drawn from the figure.

- As shown in Fig. 9a, the forebody vortices become asymmetric after angle of attack $30^\circ$, therefore the model starts to move due to the rolling moment resulting from the forebody asymmetric vortices.

- As shown in Fig. 9b, the asymmetry of forebody vortices becomes more apparent during $45^\circ$~$60^\circ$. According to the previous studies at the fixed angles of attack [11][12], the increased number of forebody asymmetric vortices should take responsible for the variation of pressure distribution. The variation of rolling moment during the range of attack angle should be dominated by the forebody multi-asymmetric vortices. However, the relationship between the rolling moment and the forebody asymmetric vortices is still unknown yet.

- As shown in Fig. 9c, the asymmetric of pressure distribution is inconspicuous after angle of attack $65^\circ$, the reason should be the breakdown of multi-asymmetric vortices and the random wake shedding. Therefore, the leeward rolling moment during the range of attack angles is very small.
Fig. 9. Pressure distributions at $x/D=-2.5$ for different angles of attack during wing rock in pitching-up ($\gamma=3.2\times10^3$, $Re=1.6\times10^5$, $\theta=45^\circ$)

The synchronous PIV experiments are also conducted at $x/D=-3.35$ when representing the wing rock in pitching-up. Vorticity fields for three angles of attack including 47.5° (the attack angle with minimum roll angle about -31°), 61.6° (the attack angle when model moves to 0° roll angle) and 70.5° (the attack angle with maximum roll angle about 25°) are shown separately as Fig. 10a, b, c. Every PIV figure is the average of 80 measurements. Fig. 10a shows that forebody asymmetric vortices are still twin-asymmetric vortices at $x/D=-3.35$. At angle of attack 61.6° (Fig. 10b), PIV figure clearly shows the structure of triple-asymmetric vortices. However, the small value of dispersive vorticity indicates that the vortex breakdown may happen. When angle of attack reaches to 70.5°, the forebody asymmetric vortices have broken down and only the shear lay can be found, as shown in Fig. 10c.
4. Conclusion

Over the configuration of a pointed ogive-cylindrical body with 30° swept regular wing, the forebody flow responsible for the wing rock in high rate pitching-up ($\gamma = 3.2 \times 10^{-3}$) was studied in the wind tunnel with the technique of synchronous pressure/PIV measurements when representing the wing rock motion. The following conclusions could be drawn.

• The wing rock induced by forebody asymmetric vortices in high rate pitching-up presents as a sinusoid like motion.
• The evolvement of forebody vortices with angle of attack, rather than switching of forebody asymmetric vortices, is proven to be main flow mechanism for wing rock in pitching-up.
• Although forebody asymmetric vortices trigger and sustain the wing rock during angle of attack 30°~60°, the wing rock after angle of attack 60° is in fact a convergent process under the influence of the windward flow because of the breakdown of forebody asymmetric vortices.

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References