Lateral Stability and Control of a Flying Wing Configuration Aircraft

Yankui Wang*, Xiangxi Tang and Tao Li

Ministry-of-Education Key Laboratory of Fluid Mechanics, Beihang University.
Beijing 100191, P.R. China

*Email:wangyankui@buaa.edu.cn

Abstract. A numerical investigation was conducted on an Unmanned Combat Air Vehicle (UCAV) model which is a moderately swept, tailless and flying wing configuration. A wind tunnel test was performed to validate the numerical results. Model forces and moments were measured using a six-component strain-gauged force balance. The computations were performed using a commercial Reynolds-Averaged Navier-Stokes (RANS) flow solver. The numerical results show that the lateral unstable of the model is caused by asymmetrical breakdown of the body vortex, and the flaps installed can induce earlier breakdown and intensity loss of the leeward vortex resulting in the enhancement of lateral stability.

1. Introduction

Flying wing configuration is an advanced design of future aircraft because it has superior aerodynamic performance than the conventional wing-and-tube configuration. The 1303 unmanned combat air vehicle (UCAV) concept configuration originated with Boeing Phantom Works is an example of the tailless configuration. As a combat fighter, 1303 UCAV may need to improve its maneuver-ability through flight at high angles of incidence. However, this tailless configuration can easily lose lateral stability at high angles of attack, and experience the lateral self-excited oscillation known as “wing-rock” which is detrimental to flight security.

The low-speed flow over the 1303 UCAV has been studied extensively [1-7], these studies focus on the longitudinal stability characteristics and the effect of leading edge shapes, Reynolds number and Mach number. These investigations suggest that the onset and development of the flow separation over the outer portion of the wing result in the forward shift of centroid of the lift, causing the absence of longitudinal stability, or pitch-up. It is found that leading edge shape can affect the onset of the pitch-up, and the sharp leading edge configuration is less sensitive to Mach number and Reynolds number than the rounded leading edge configuration. These papers have explained the flow structure over the 1303 UCAV at zero sideslip, while few papers have mentioned the lateral stability and flow structure with sideslips.

In this paper, low speed wind tunnel experiments have been conducted to investigate the lateral stability of a flying wing configuration UCAV at pitching angle θ=26°. In order to further explore the flow structure related to the lateral stability, numerical simulations have been performed as well. The accuracy of the numerical methods will be verified by the experiments. In addition, four flaps have been installed near the trailing edge of the wing to enhance the lateral stability.
2. Experiment Setup and Numerical Methods
The low speed wind tunnel experiments and numerical simulations are carried out on a scaled model of the UCAV, the key dimensions of the model are listed in table 1. As is illustrated in figure 1, the span of the UCAV baseline model is 0.6m, the length of the model is 0.356m. To improve the lateral stability of the UCAV, as is shown in figure 2, four flaps are installed near the trailing edge of the controlled model. In addition, the baseline model is divided into three main parts, body, inner-wing and outer-wing, and the controlled model has another part called flaps. The flaps have the height of 20mm and the thickness of 2mm, which are perpendicular to the surface of the wing, and three flaps deflect upward and one flap deflects downward.

| Parameter              | Value       |
|------------------------|-------------|
| Span                   | 0.6m        |
| Reference length       | 0.6m        |
| Reference area         | 0.96336 m²  |
| Leading edge sweep     | 47°         |

Table 1. Key model dimensions of baseline model.

![Figure 1](image1.png)

Figure 1. Sketch of Baseline model, top view.

![Figure 2](image2.png)

Figure 2. (a) Top view and (b) bottom view of the model with flaps.
Experiments were conducted in the D4 low-speed open-return wind tunnel at Beihang University. The test section is 1.5m wide by 1.5 high by 2.5m long. As is listed in table 2, the tests were carried out at free stream velocity $V_\infty = 30\text{m/s}$, which corresponds to a Reynolds number based on the span $Re_b = 1.2\times10^6$. Rolling moment was measured using an internal six-component strain-gauged force balance with a measurement uncertainty of 0.3%.

| Parameter      | Value         |
|----------------|---------------|
| Velocity       | 30 m/s        |
| $Re_b$         | $1.2\times10^6$ |
| Static pressure| 101325 Pa      |
| Density        | 1.225 kg/m$^3$|

Table 2. Free stream conditions for computational studies.

Numerical simulations were achieved using a commercial software based on an unstructured finite volume code. The computations were implemented using menter’s $k-\omega$ SST turbulent model based on steady incompressible RANS (Reynolds-averaged Navier–Stokes) equations. SIMPLEC (Semi-Implicit Method for Pressure-Linked Equations Consistent) algorithm was used to deal with the pressure-velocity coupling, second order upwind scheme was applied to the convective terms to discretize the equations, freestream boundary conditions were applied on the inlet and sides of the domain and fixed pressure condition ($p=p_\infty$) on the outlet. As is illustrated in figure 3, hybrid unstructured polyhedral meshes were generated for both baseline model and the controlled model, $y^+<5$ is achieved by limiting the first element height below 0.02mm, and the total number of elements is about 3 million.

![Figure 3](image)

Figure 3. Surface mesh distribution of (a) baseline model and (b) controlled model.

3. Results and Discussions
The variation of total rolling moment with rolling moment is shown in figure 4 for experiments and computations. The introduction of rolling angle can induce the following effective angles of attack and sideslip, $\alpha_{eff}=\arctan(\tan\theta \cos\phi)$, $\beta_{eff}=\arctan(\tan\theta \sin\phi)$[8]. When pitching angle $\theta=26^\circ$, both experimental results and numerical results show that $\partial C_l/\partial\phi>0$ or $\partial C_l/\partial\beta>0$ near $\phi=0^\circ$, namely the baseline model has lost its lateral stability. In addition, the numerical results are identical to the experimental results, the numerical results are reliable.
Figure 4. Validation of the numerical results, baseline model, $\theta=26^\circ$.

Figure 5 shows the variation of the rolling moment with rolling angle obtained by computations for baseline model and controlled model, the results suggest that the lateral stability near $\phi=0^\circ$ is improved with the implementation of the flaps, the controlled model is lateral stable near $\phi=0^\circ$. To further investigate the reason that the flaps have such lateral-stabilizing effect, the rolling moment of each part of the model is extracted, figure 6(a) and (b) show the variation of rolling moment of each part with rolling angle for baseline model and controlled model, respectively. For baseline model, the inner-wing is the main lateral unstable part, while for the controlled model, the lateral-unstable rolling moment of the inner-wing is largely reduced, and the outer-wing can provide a significant lateral-stable rolling moment, the flaps can produce a small rolling moment. As is shown in figure 6 and figure 7, the implementation of the flaps induces the decrease of the lateral-unstable rolling moment of the inner-wing and the increase of the lateral-stable rolling moment of the outer-wing.

Figure 5. Variation of total rolling moment with rolling angle, $\theta=26^\circ$.

Figure 6. Variation of rolling moment of each part with rolling angle at $\theta=26^\circ$, (a) baseline model and (b) controlled model.
Figure 7. Flap effect on the variation of rolling moment of with rolling angle, $\theta=26^\circ$.

In order to further understand the fluid mechanism of the flap effect, the vortex structures over the upper surface of the models are extracted, figure 8 shows vortex structures captured by Q criterion [9]. As is illustrated in figure 8(a) and (b), the body vortices break down asymmetrically, the windward body vortex breaks down earlier than the leeward body vortex, and therefore suction induced by the leeward vortex is larger than the suction induced by windward vortex resulting in an unstable rolling moment. As is shown in figure 8(a) and (c), when $\phi=20^\circ$, for the baseline model, the leeward body vortex breaks down at the inner-wing, the leeward vortex can induce a wide range of suction on the surface, while for the controlled model, as shown in figure 8(b) and (d), the adverse pressure gradient increases with the inner-flaps installed, resulting in the earlier leeward vortex breakdown at the body leading edge. Thus, the intensity of the leeward vortex is reduced and the region influenced by the leeward vortex is largely reduced, and therefore the unstable rolling moment of the inner-wing is largely reduced as is shown in figure 7. In addition, the outer-wing is under the fully breakdown wake flow, as a consequence, the out-wing is lateral-stable as is shown in figure 7.

Figure 8. Iso-surface of $Q=1\times 10^5\text{s}^{-2}$ at $\theta=26^\circ$, colored by axis velocity (a: baseline model, $\phi=20^\circ$; b: baseline model, $\phi=-20^\circ$; c: controlled model, $\phi=20^\circ$; d: controlled model, $\phi=-20^\circ$).
Vorticity field and spanwise pressure distribution at section $x/l = 0.429$ are shown in figure 9 and figure 10, respectively. As is shown in figure 9, at section $x/l = 0.429$, the leeward body vortex is over the inner-wing, and the leeward body vortex of the baseline model is stronger than that of the controlled model, which induces larger suction peaks at the leeward inner-wing in figure 10, thus the inner-wing of the controlled model has smaller unstable rolling moment.

![Figure 9](image1.png)

Figure 9. Streamlines and dimensionless vorticity at $x/l = 0.429$ (a: baseline model, $\phi = 20^\circ$; b: baseline model, $\phi = -20^\circ$; c: controlled model, $\phi = 20^\circ$; d: controlled model, $\phi = -20^\circ$).

![Figure 10](image2.png)

Figure 10. Spanwise pressure distribution at $x/l = 0.429$ (a: $\phi = 20^\circ$; b: $\phi = -20^\circ$).

Vorticity field and spanwise pressure distribution at section $x/l = 0.714$ are shown in figure 11 and figure 12, respectively. As is shown in figure 11(a) and (b), the leeward body vortex over the baseline model is still strong at section $x/l = 0.714$, thus can induce observable suction peaks at the leeward outer-wing of the baseline model in figure 12. As is shown in figure 11(c) and (d), the leeward body vortex over the baseline model is weak and has moved inboard at section $x/l = 0.714$, the flow over the outer-wing is the breakdown wake flow of the leading edge, thus there is no observable suction peaks at the leeward outer-wing of the controlled model in figure 12.
Figure 11. Streamlines and dimensionless vorticity at $x/l = 0.714$ (a: baseline model, $\phi = 20^\circ$; b: baseline model, $\phi = -20^\circ$; c: controlled model, $\phi = 20^\circ$; d: controlled model, $\phi = -20^\circ$).

Figure 12. Spanwise pressure distribution at $x/l = 0.714$ (a: $\phi = 20^\circ$; b: $\phi = -20^\circ$).

4. Conclusion
A wind tunnel experiment and a series of numerical investigation have been conducted to explore the lateral stability of the 1303 UCAV model. The computed results have been compared with the experimental data. The results presented demonstrate that reasonable predictions for the lateral-unstable phenomenon at high angles of attack can be obtained using the $k$-$\omega$ SST turbulence model. The numerical results show that the baseline model is lateral unstable because the asymmetrical breakdown of the body vortex, the leeward body vortex can induce large suction over the inner-wing and the inner-wing provides the majority of the lateral unstable rolling moment. In addition, four flaps installed near the trailing edge of the wings can increase the adverse pressure gradient, resulting in the earlier breakdown and the density loss of the leeward body vortex, and therefore the unstable rolling moment of the inner-wing is largely reduced and the outer-wing becomes lateral stable.

Acknowledgement
The research work was supported by the National Natural Science Foundation of China (Nos. 11472028 and 11721202).
References

[1] McParlin, S., Bruce, R., Hepworth, A., & Rae, A. (2006, June). Low speed wind tunnel tests on the 1303 UCAV concept. In 24th AIAA Applied Aerodynamics Conference, P2985.

[2] Sherer, S., Gordnier, R., & Visbal, M. (2009, June). Computational study of Reynolds number and angle-of-attack effects on a 1303 UCAV configuration with a high-order overset-grid algorithm. In 47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition, P 751.

[3] Wong, M., McKenzie, G., Ol, M., Petterson, K., & Zhang, S. (2006, June). Joint TTCP CFD studies into the 1303 UCAV performance: First year results. In 24th AIAA Applied Aerodynamics Conference, P2984.

[4] Arthur, M., & Petterson, K. (2007). A computational study of the low-speed flow over the 1303 UCAV configuration. In 25th AIAA Applied Aerodynamics Conference, P4568.

[5] Chung, J., & Ghee, T. (2006, June). Numerical investigation of UCAV 1303 configuration with and without simple deployable vortex flaps. In 24th AIAA Applied Aerodynamics Conference, P2989.

[6] Atkinson, M., & Ferguson, F. (2006). A computational fluid dynamics investigation of the 1303 UCAV configuration with deployable rao vortex flaps. Networking IEEE/ACM Transactions on, 16(4), p 749-762.

[7] Milne, M., & Arthur, M. (2006, June). Evaluation of bespoke and commercial CFD methods for a UCAV configuration. In 24th AIAA Applied Aerodynamics Conference, P2988.

[8] Ericsson, L. E. (1984). The fluid mechanics of slender wing rock. Journal of Aircraft, 21(5), p322-328.

[9] Jeong, J., & Hussain, F. (1995). On the identification of a vortex. Journal of fluid mechanics, 285, p69-94.