Dynamic characteristics analysis and flight control design for oblique wing aircraft

Wang Lixin, Xu Zijian, Yue Ting *

School of Aeronautics Science and Engineering, Beihang University, Beijing 100083, China

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Abstract The movement characteristics and control response of oblique wing aircraft (OWA) are highly coupled between the longitudinal and lateral-directional axes and present obvious nonlinearity. Only with the implementation of flight control systems can flying qualities be satisfied. This article investigates the dynamic modeling of an OWA and analyzes its dynamic characteristics. Furthermore, a flight control law based on model-reference dynamic inversion is designed and verified. Calculations and simulations show that OWA can be trimmed by rolling a bank angle and deflecting the triaxial control surfaces in a coordinated way. The oblique wing greatly affects longitudinal motion. The short-period mode is highly coupled between longitudinal and lateral motion, and the bank angle also occurs in phugoid mode. However, the effects of an oblique wing on lateral mode shape are relatively small. For inherent control characteristics, symmetric deflection of the horizontal tail will generate not only longitudinal motion but also a large rolling rate. Rolling moment and pitching moment caused by aileron deflection will reinforce motion coupling, but rudder deflection has relatively little effect on longitudinal motion. Closed-loop simulations demonstrate that the flight control law can achieve decoupling control for OWA and guarantee a satisfactory dynamic performance.

1. Introduction

Oblique wing aircraft (OWA) can vary wing sweep for optimal configuration at various flight speeds and extension of their flight envelope.1,2 Compared to conventional fixed-wing aircraft, an OWA maintains excellent low-speed, takeoff and landing performance at no sweep while being capable of large lift to drag ratio via high skew angle in supersonic flight. Cruise and maneuvering performance can also be enhanced when the wings are at a moderate oblique angle. As a result, OWA have the ability to adapt to multi-mission flight and possess higher operational efficiency than traditional fixed-wing designs.3

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supersonic flight. The lift dependent wave drag and the volume dependent wave drag of OWA are 1/4 and 1/16 less than those of variable sweep aircraft, respectively.\(^4\) Furthermore, oblique wing designs are simple and reliable in structure, thus reducing the complexity of fuselage structure and related aerodynamic drag.\(^5\) However, the asymmetry of OWA introduces special flight dynamics problems and challenges for flight control.\(^6\)–\(^8\) The asymmetric configuration will produce side force, rolling moment and yawing moment in level flight, which do not exist in conventional aircraft, leading to severe coupling and nonlinearity of the aircraft. Moreover, aileron deflection induces not only rolling moment but also pitching moment, and rolling effectiveness is insufficient at high skew angle. Only with flight control systems can the longitudinal and lateral motions of OWA be decoupled to meet operational requirements of pilots and achieve good flight quality.

Currently, the flight controllers for OWA are mostly designed by linear control methods based on linear equations.\(^9\)–\(^15\) For example, Alag et al.\(^13\) and Pahle\(^14\) used linear quadratic optimal control theory based on model-following technology to design control laws. Clark and Letron\(^15\) proposed a command and stability augmentation system where eigenstructure assignment techniques are combined with an optimization procedure to determine the feedback matrix for approximating the desired eigenstructure. Evaluation of these controllers on nonlinear equations of motion seems to be less desirable with certain time delays and great oscillations.\(^16\) With regard to the research on applying modern control technologies, such as intelligent control theory, to OWA with high cross-coupling and nonlinearity, Pang\(^16\) designed an attitude controller with a sliding mode control method for near-space vehicles with an oblique wing. However, the overshoot of this closed-loop system was relatively high, and no reports are available about OWA in the conventional flight envelope.

This paper investigates the nonlinear dynamic model of OWA, and dynamic response is numerically simulated and analyzed. According to the highly cross-coupled and nonlinear properties of OWA, model-reference dynamic inversion is used for flight control law design. Differential horizontal tail and ailerons are allocated for roll control. This approach can successfully maintain multivariate decoupling control for OWA.

### 2. Layout and aerodynamic characteristics

The OWA investigated in this paper is presented in Fig. 1. The oblique wing is designed to pivot from 0° to 60° with the right wing forward.

The asymmetry of an OWA significantly affects its aerodynamic characteristics. The pressure distribution along the chord direction changes due to the spanwise flow of air. The aerodynamic load of the right forward-swept wing is concentrated on the wing root; thus, the leading-edge suction of the right wing tip and the lift coefficient decrease. The left back-swept wing is the opposite: aerodynamic load is concentrated on the wing tip, and the leading-edge suction and lift coefficient increase, which can be seen in Fig. 2(a). Since leading-edge suction makes a greater contribution to lift, the left wing has a lift increment. As seen in Fig. 2(b), the lift increment of left wing \(\Delta L_L\) is greater than the lift increment of right wing \(\Delta L_R\), which produces nose-down pitching moment \(\Delta M\) and rolling moment \(\Delta L\) that make the right wing move downward.
Moreover, the aileron moment arm caused by aileron deflection, the additional pitching moment produces pitching moment. So, apart from the rolling moment that the asymmetric drag produces a yawing moment, the cross freedom nonlinear equations and cannot be divided into longitudinal and cross products of inertia in body axes. Therefore, necessary to use horizontal tail to help roll control when the wings are oblique (see Fig. 3); thus, the rolling effectiveness of ailerons will decrease with the increase of skew angle. This will lead to insufficient rolling effectiveness of the ailerons. It is therefore necessary to use horizontal tail to help roll control when the wings are highly skewed.

3. Modeling and dynamic characteristics analyses

3.1. Flight dynamic modeling

The aerodynamic forces and moments of OWA become highly nonlinear and cross-coupled as the skew angle becomes larger. In addition, the inertia is also cross-coupled between an aircraft’s longitudinal and lateral-directional axes. So the flight motion of OWA should be modeled by six-degree-of-freedom nonlinear equations and cannot be divided into longitudinal and lateral equations. Compared with conventional fixed-wing aircraft, OWA’s asymmetry leads to great changes in moments of inertia and cross products of inertia; the cross products of inertia \( I_{xz} \) and \( I_{xy} \) are no longer zero. Therefore, the moment equations cannot be simplified like with conventional fixed-wing aircraft, and they are expressed in Eq. (1).\(^5\)

\[
\begin{align*}
L &= I_\phi \ddot{\psi} - I_{xy}(\dot{\theta}^2 - \dot{\phi}^2) - I_{x\phi}(\dot{\phi} + \dot{\psi}) \\
&\quad - I_{xy}(\dot{\phi} + \dot{\psi}) - (I_\phi - I_\psi)\dot{\psi}r \\
M &= I_\psi \ddot{\theta} - I_{xz}(\dot{\phi}^2 - \dot{\psi}^2) - I_{xz}(\dot{\phi} + \dot{\psi}) \\
&\quad - I_{xz}(\dot{\phi} + \dot{\psi}) - (I_\psi - I_\phi)\dot{\phi}r \\
N &= I_x \ddot{\psi} - I_{xy}(\dot{\phi}^2 - \dot{\psi}^2) - I_{xz}(\dot{\phi} + \dot{\psi}) \\
&\quad - I_{xz}(\dot{\phi} + \dot{\psi}) - (I_x - I_y)\dot{\psi}q
\end{align*}
\]

where \( L, M, \) and \( N \) are total moment components in body axes; \( p, q \), and \( r \) are roll, pitch and yaw angular rate in body axes respectively; \( I_x, I_y, I_z, I_{xy}, I_{xz}, \) and \( I_{yz} \) are moments of inertia and cross products of inertia in body axes.

Due to its asymmetry, OWA wing rotation, lift, drag and pitching moment vary greatly, and asymmetrical side force, rolling moment and yawing moment are generated. The non-linear aerodynamic forces and moments can be expressed as follows:

\[
\begin{align*}
X &= X_0(u, \alpha, \beta, A) + X_p\beta + X_q\alpha + X_r
\quad + X_{\alpha \beta}\alpha + X_{\alpha \alpha}\alpha \\
Y &= Y_0(u, \alpha, \beta, A) + Y_p\beta + Y_q\alpha + Y_r\alpha
\quad + Z_{\alpha \beta}\alpha + Z_{\alpha \alpha}\alpha \\
Z &= Z_0(u, \alpha, \beta, A) + Z_\beta \dot{\beta} + Z_\alpha \dot{\alpha} + Z_\alpha \dot{\beta} + Z_{\alpha \beta}\alpha \beta \\
&\quad + Z_{\alpha \alpha}\alpha \alpha + Z_{\beta \beta}\beta \beta + Z_{\beta \alpha}\beta \alpha
\end{align*}
\]

(2)

Fig. 3 Decrease in aileron moment arm caused by oblique wing.

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where \( \mathbf{x} = [p, q, r, \alpha, \beta, \mu, \gamma, H]^T \) are state variables related to control allocation, with \( \gamma \) and \( H \) are flight path angle and flight altitude; \( \mathbf{u} = [\delta_{\alpha L}, \delta_{\alpha R}, \delta_{\beta L}, \delta_{\beta R}, \delta_{\gamma L}, \delta_{\gamma R}]^T \); \( \mathbf{f}(\mathbf{x}) \) is a nonlinear three-element vector function varied with state variables, and \( \mathbf{g}(\mathbf{x}) \) is a nonlinear \( 3 \times 5 \) matrix function representing the control matrix.

To avoid a situation where deflection of the differential horizontal tail approaches full but deflection of ailerons is still small, \( \mathbf{A} = \text{diag}(\delta_{\alpha L_{\max}}, \delta_{\alpha R_{\max}}, \delta_{\beta L_{\max}}, \delta_{\beta R_{\max}}, \delta_{\gamma L_{\max}}, \delta_{\gamma R_{\max}}) \) is introduced for weighting. Therefore, Eq. (3) can be rewritten as follows:

\[
\begin{bmatrix}
\dot{\mathbf{p}} \\
\dot{\mathbf{q}} \\
\dot{\mathbf{r}}
\end{bmatrix} = \mathbf{f}(\mathbf{x}) + \mathbf{g}(\mathbf{x}) \mathbf{u} = \begin{bmatrix}
f_{p}(\mathbf{x}) \\
f_{q}(\mathbf{x}) \\
f_{r}(\mathbf{x})
\end{bmatrix} + \begin{bmatrix}
g_{p_{\alpha L}} & g_{p_{\alpha R}} & g_{p_{\beta L}} & g_{p_{\beta R}} & g_{p_{\gamma L}} & g_{p_{\gamma R}} \\
g_{q_{\alpha L}} & g_{q_{\alpha R}} & g_{q_{\beta L}} & g_{q_{\beta R}} & g_{q_{\gamma L}} & g_{q_{\gamma R}} \\
g_{r_{\alpha L}} & g_{r_{\alpha R}} & g_{r_{\beta L}} & g_{r_{\beta R}} & g_{r_{\gamma L}} & g_{r_{\gamma R}}
\end{bmatrix} \cdot \begin{bmatrix}
\delta_{\alpha L} & \delta_{\alpha R} & \delta_{\beta L} & \delta_{\beta R} & \delta_{\gamma L} & \delta_{\gamma R}
\end{bmatrix}^T \tag{3}
\]

where the superscript “\(^{-1}\)” symbolizes pseudo-inverse.

3.2. Dynamic characteristics

1. Trimming in different skew angles

OWA can vary skew angle at different speeds for a multi-mission flight. The following three typical conditions are chosen for trimming and the trimming parameters are presented in Table 1, where \( \phi \) is the bank angle.

The results in Table 1 show that:

(a) To trim the asymmetric aerodynamic moments caused by an oblique wing, the triaxial control surfaces should deflect in a coordinated way. At the same time, OWA make use gravity to balance the side force by rolling an angle.

(b) As the angle of attack for trimming decreases with the increase in flight speed, the resulting nose-down pitching moment decreases. Thus the horizontal tail takes up less to trim the pitching moment.

(c) The bank angle and the deflection of lateral control surfaces become larger, since the asymmetric aerodynamic forces and moments increase with the increase in flight speed and skew angle.

(d) Because of the allocation by pseudo-controls, the left and right ailerons hold different deflection areas based on different control effectiveness. The differential horizontal tail takes part in roll control; thus, it decreases the deflection of ailerons and facilitates their efficient use.

2. Natural modes

The linear equations of motion can be derived from the six-degree-of-freedom nonlinear equations by utilizing the small-disturbance theory. Based on these linear equations, five modes corresponding to the modes of conventional airplanes can be obtained. Taking Condition 2 as an example, the eigenvalues of modes are presented in Table 2.

Five modes of OWA are similar but not identical to those of conventional airplanes. The short-period mode of straight wings is seen to be a motion in which longitudinal parameters \( x \) and \( q \) are present with significant magnitude. But the short-period mode of OWA is highly longitudinal/lateral coupled, and all rotation parameters change significantly, as shown in Fig. 4(a). This phenomenon is mostly caused by the cross static derivatives \( L_\gamma \) and \( N_x \). In Fig. 4(a), \( \Delta x, \Delta \beta, \Delta \alpha \) and \( \Delta \phi \) are variations of angle of attack, sideslip angle, angle of pitch and bank angle. In the phugoid mode, bank angle also changes, as seen in Fig. 4(b). This is because the side force varies with flight speed; thus, the bank angle for balancing side force also changes. In Fig. 4(b), \( \Delta V \) is variation of airplane speed. Nevertheless, the changes in lateral mode shape are generally small. The motion responses are similar to those of the straight wing, and longitudinal parameters have no significant variations in lateral modes.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Eigenvalues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short period</td>
<td>(-1.51 \pm 6.70i)</td>
</tr>
<tr>
<td>Phugoid</td>
<td>(-0.0018 \pm 0.058i)</td>
</tr>
<tr>
<td>Rolling convergence</td>
<td>(-39.68)</td>
</tr>
<tr>
<td>Dutch roll</td>
<td>(-0.52 \pm 6.70i)</td>
</tr>
<tr>
<td>Spiral mode</td>
<td>(-0.0074)</td>
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</tbody>
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<table>
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<th>Trimming parameters at typical conditions.</th>
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</thead>
<tbody>
<tr>
<td>Condition</td>
<td>Parameter</td>
</tr>
<tr>
<td></td>
<td>Sweep (°)</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
</tr>
</tbody>
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4. Flight control design based on model-reference dynamic inversion

Nonlinear dynamic inversion (NDI) is a kind of modern control method aimed directly at nonlinear motion models. Because unsteady aerodynamic forces of OWA are obvious and triaxial motion is highly cross-coupled and nonlinear, it is difficult to build an accurate motion model for OWA. Without an accurate model, the control effectiveness of pure NDI is unsatisfying. Hence, ideal models established according to the requirements for handling qualities are introduced based on NDI. OWA can track these models by NDI, thereby ensuring the controlled aircraft enjoys satisfactory flight qualities in quite a large flight envelope.18–20

4.1. Flight control structure

As shown in Fig. 6, the flight control system based on model-reference dynamic inversion includes four parts: ideal reference models, compensators, NDI inner loop and NDI outer loop. Each part is introduced as follows:

(1) Ideal models form the ideal control response $\dot{\beta}_{RM}$, $q_{RM}$ and $\beta_{RM}$ under the control command $[k_c, q_c, \beta_c]^T$, where $\dot{\beta}$ is the velocity bank angle. According to the low-order equivalent system method for assessing flying qualities, the low-order equivalent models are chosen as ideal models, and their parameters are determined by requirements for handling qualities. The ideal models are expressed in Eq. (6).

$$\begin{align*}
\dot{\beta}_{RM} &= \frac{1}{s + \omega_p} \\
q_{RM} &= \frac{\omega_p}{s + \frac{1}{T_{\beta_2}}} \\
\beta_{RM} &= \frac{\omega_p}{s + \omega_q}
\end{align*}$$

where the reciprocal of rolling time constant $\omega_p$ is 4 rad/s; $\omega_p$ and $\omega_q$ are the frequency and damping of short-period mode, respectively, taken as $\omega_p = 5$ rad/s, $\omega_q = 1/2$; time constant $T_{\beta_2}$ can be solved by control anticipation parameters (CAP), and the value of CAP is 1; the desired response for sideslip angle is taken as the first order inertia link, and $\omega_q = 3$ rad/s.

(2) PI compensators are used to generate the control commands for the NDI loop and timely track the response of ideal models. It compensates for errors of loop and the external disturbance, $\dot{\beta}_{RM}$, $\dot{\beta}_{RM}$ and the corresponding feedback signals pass through the compensator to generate $\beta_{cmd}$ and $l_{cmd}$ as the control command of outer loop while $q_{RM}$ is directly taken as the pitching control command of inner loop $q_c$.

(3) The NDI outer loop is used to generate control commands of the inner loop. $[\beta_{cmd}, l_{cmd}]^T$ is resolved to $[p_c, c]_T$, which combines with the pitching control command of inner loop $q_c$ to generate the commands of inner loop. According to Ref. 21, the control forces resulting from control surfaces are much smaller than...
aerodynamic forces; thus, the effect of these small perturbations on dynamics is negligible and can be canceled in steady state by incorporating integrators into the control law. So the control forces can be neglected when designing the outer loop, and the differential equation of $[\alpha, \beta, \lambda]^T$ can be expressed as

$$
\begin{bmatrix}
\dot{\alpha} \\
\dot{\beta} \\
\dot{\lambda}
\end{bmatrix} = f_m(x) + g_m(x) 
\begin{bmatrix}
p \\
q \\
r
\end{bmatrix}
\begin{bmatrix}
\cos \zeta / \cos \beta & 0 & \sin \zeta / \cos \beta \\
- \cos \zeta \tan \beta & 1 & - \sin \zeta \tan \beta \\
\sin \zeta & 0 & - \cos \zeta
\end{bmatrix}
\begin{bmatrix}
p \\
q \\
r
\end{bmatrix}$$

where $f_m(x)$ is a nonlinear three-element vector function varied with state variables; and $g_m(x)$ is a nonlinear $3 \times 3$ matrix function varied with $\alpha$ and $\beta$; $f_p, f_q$ and $f_r$ are continuous functions related to state variables.

According to the time-scale separation method, the dynamic responses of fast variables are considered to have arrived at steady state when designing the outer loop. Ref. demonstrates that this approximation justifies slow-state control law. So the control commands of the inner loop can be solved by pseudo-inverse:

$$
\begin{bmatrix}
p_c \\
q_c \\
r_c
\end{bmatrix} = g_m^{-1}(p) = \left( \begin{bmatrix}
\dot{p} \\
\dot{q} \\
\dot{r}
\end{bmatrix} - \begin{bmatrix}
f_p \\
f_q \\
f_r
\end{bmatrix} \right)
$$

In Eq. (7), the equations of $\dot{\beta}$ and $\dot{\mu}$ do not contain $q$, which means that the command of $\dot{\beta}$ and $\dot{\mu}$ can be realized just by controlling $p$ and $r$, and the pitching control command of inner loop $q_c$ is free from the influence of $\beta_c$ and $\mu_c$. By making pitching control command $\chi_c = 0^\circ$, $q_{RM}$ can replace the pitching command generated by the outer loop, which is intended to be the pitching control command of inner loop.

(4) The NDI inner loop calculates the required control surfaces to track the command $[p_c, q_c, r_c]^T$ and achieve the desired control. Based on the principles of NDI, a control law of the inner loop can be obtained that allocates ailerons and differential horizontal tail by pseudo-controls. The expression is presented in Eq. (4).

According to the characteristic response of the first order inertia link to the step signal, the output $[p, q, r]$ is designed to track the command $[p_c, q_c, r_c]^T$ asymptotically by making $[\dot{p}, \dot{q}, \dot{r}]_{x_c} = -\omega_v [p - p_c, q - q_c, r - r_c]^T$. $\omega_v = \text{diag}(\omega_{p_v}, \omega_{q_v}, \omega_{r_v}) = \text{diag}(15, 10, 10)$ rad/s is taken to achieve good tracking results.
Fig. 6  Flight control system scheme based on model-reference dynamic inversion.

Fig. 7  Structure of inner loop considering control saturation.

Fig. 8  Closed-loop response to triaxial input.
where \( \omega_1 \) and \( \omega_2 \) are reciprocals of time constant of first order inertia link. The structure of inner loop is shown in Fig. 7.

### 4.2. Closed-loop flight simulation and analysis

To validate the control law based on model-reference dynamic inversion, the pitching, side slipping and rolling maneuvers are simulated. Condition 2 is taken as an example, and the dynamic response curves are presented in Fig. 8.

In Fig. 8(a), the velocity bank angle \( \beta \) does not appear to oscillate; it tracks the commands quickly and almost matches with the response of the ideal model. Meanwhile, \( \beta \) and \( p \) change little and recover to zero quickly, as seen in Fig. 8(b). This demonstrates that the flight control system successfully maintains decoupling control between the longitudinal and lateral axes. In side slipping maneuvers, the response of side-slip angle has a little delay compared to the ideal model, but they are still pretty close, as seen in Fig. 8(c). Therefore, the flight control system enables the OWA to track commands quickly and maintain decoupling control.

The actual responses are close to those of the ideal model, so good handling qualities can be achieved by these designs. According to the response of the control surfaces in Fig. 8, it can be found that the differential horizontal tail takes part in roll control for the allocation by pseudo-controls. Thus it decreases the deflection of ailerons and facilitates their efficient use.

### 5. Conclusions

1. Oblique wings change the lift, drag and pitching moment greatly, and generate side force, rolling moment and yawing moment that symmetric wings do not have. To trim the asymmetric aerodynamic moments, triaxial control surfaces should deflect in a coordinated way that balances the asymmetric moments. Meanwhile, OWA should roll on an angle to balance the side force.

2. OWA have significant aerodynamic and inertial cross-coupling between the longitudinal and lateral-directional axes. The short-period mode of an OWA is highly coupled, and all rotation parameters take on a substantial amount of variation. In the phugoid mode, the bank angle also changes. Nevertheless, the changes in lateral mode shape are generally small. The motion responses are similar to those of straight wings, and longitudinal parameters have no significant variations in lateral modes.

3. The control characteristics of OWA are quite distinct from those of conventional aircraft. Although symmetric deflection of the horizontal tail only generates pitching moment, the response has a fairly large rolling rate \( p \). Ailerons generate both rolling moment and pitching moment; thus, coupling between longitudinal and lateral axis becomes more obvious. The deflection of rudder introduces both sideslip and rolling angles, which have little effect on longitudinal motion parameters.

4. The aileron moment arm shortens in OWA, which leads to insufficient rolling effectiveness. So they need a differential horizontal tail to assist roll control at high skew angles. Ailerons and the differential horizontal tail are allocated by pseudo-controls to facilitate efficient use and combine control power. This decreases the deflection of ailerons and has satisfactory control effect.

5. The control law based on model-reference dynamic inversion maintains decoupling control for OWA. The actual response is close to that of the ideal model, and good handling qualities can be realized from ideal model designs.

### References


Wang Lixin is a professor and Ph.D. supervisor at Beihang University. His main research interests lie in aircraft design, flight dynamics, and flight control.

Xu Zijian received his B.S. from Beihang University and is now Ph.D. student. His main research interests are flight dynamics, flight simulation and flight control.

Yue Ting is an assistant professor at Beihang University. He received his B.S., M.S. and Ph.D. in aircraft design from Beihang University in 2004, 2006 and 2010 respectively. His main research interests are aircraft flight dynamics and control.