Analysis of Asymmetric Control Efficiency for Folding Wing Morphing Aircraft

Xiao-wu XU\textsuperscript{1,2}, Wei ZHANG\textsuperscript{1,2,*} and Hao ZHAN\textsuperscript{1}

\textsuperscript{1}College of Aeronautics, Northwestern Polytechnical University, Xi’an 710072, China
\textsuperscript{2}Experimental Aircraft Design and Flight Testing Lab of Shaanxi. Xi’an 710072, China
*Corresponding author

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Abstract. The purpose of this paper is studying the asymmetric morphing control efficiency of a folding wing morphing aircraft. Firstly, the nonlinear dynamic equations and aerodynamic model that can depict the full morphing process are derived. Then, an asymmetric morphing control model is proposed based on the asymmetric morphing control method. Finally, by comparing with the efficiency of conventional control and the dynamic response of simulation, we find the maximum effective interval of the asymmetric morphing control. The results show that the efficiency of asymmetric morphing control is higher at lower flight speeds, and the asymmetric morphing control can provide the highest roll handling efficiency near the reference folding angle of 90°.

Introduction

Morphing aircraft can initiatively change the aerodynamic configuration to expand the flight envelope and according to the different flight missions. The investigation shows that the asymmetric sweep is beneficial to maintaining sensor pointing the target despite crosswinds and be able to complete the mission planning more effectively.\textsuperscript{[1]} Morphing wing aircraft can be more propitious to enhance the maneuverability and the agility than conventional aircraft through asymmetric morphing. In recent years, some investigations have been carried out on asymmetric morphing of various variant aircraft. Beaverstock C S et al investigated the influence on flight dynamics when the aircraft in the process of symmetric and asymmetric span morphing.\textsuperscript{[2]} Yang G T studied the mechanism of asymmetric morphing to achieve roll control for low roll efficiency problem in lateral control of morphing aircraft with variable sweep and variable span.\textsuperscript{[3]} Tong L studied the multi-body dynamic modeling and flight control of asymmetric variable sweep aircrafts.\textsuperscript{[4]}

Folding wing morphing aircraft have larger variants. Thus it is essential to carry out the investigation of the feasibility of improving the maneuverability and the agility by asymmetric morphing. Most investigations in recent years on dynamic modeling and control methods of this type variant aircraft are based on the symmetric morphing process.\textsuperscript{[5, 6]} Obradovic B et al studied the aerodynamic load distribution in the asymmetric morphing process.\textsuperscript{[7]} This paper studies asymmetric morphing control scheme and efficiency of asymmetric morphing control, defines and simplifies the asymmetric morphing control. By comparing asymmetric morphing control with conventional control surface and numerical simulation, the maximum effective range of asymmetric control is obtained.

State Representations

Geometry Configurations

Taking a micro folding wing morphing aircraft as an example, two separate actuators allow the inner wings to rotate related to the axes which are parallel to the fuselage axis, modifying the dihedral angles up to 120° while the outer wings keep level (see Fig 1).
Dynamic Equations

Given certain assumptions regarding the aerodynamic behavior, the equations of motion for a morphing aircraft can be expressed as the general form \[8\]

\[
\dot{x} = f(x, u) + \delta f(x, u) \tag{1}
\]

Where \(x\) is the state vector, \(u\) is the control input, and \(\delta f\) is a function variation that allows for model uncertainty.

And the control input as

\[
u = [\delta^T \ T^T \ u_k^T]^T \tag{2}
\]

Where \(\delta\) is the aerodynamic control effectors, \(T\) is the thrust, and \(u_k\) is the morphing input command.

When morphing is used as a control input, the morphing process needs to respond quickly and has a small morphing range. Therefore, the time-varying characteristics of the center of gravity and the inertia caused by the morphing are no longer considered. According to the method of dynamic modeling in the reference \[9\], the nonlinear dynamics equations can be simplified to the following form

\[
\begin{bmatrix}
\dot{u} \\
\dot{v} \\
\dot{w}
\end{bmatrix} = \frac{1}{m} \begin{bmatrix}
F_{G,x} & F_T & F_{A,x} + \begin{bmatrix}
F_{G,y} \\
0 \\
0
\end{bmatrix}

\begin{bmatrix}
F_{G,z} \\
F_{A,y} \\
F_{A,z}
\end{bmatrix} - \begin{bmatrix}
qw - rv \\
rw - pu \\
qv - qu
\end{bmatrix}
\end{bmatrix}
\tag{3}
\]

Where \(m\) is the mass of the aircraft, \(F_T\) is the thrust, \((u,v,w)\) are the aircraft velocity components in body axes, \((p,q,r)\) are the aircraft rotation rates in body axes, \((F_{G,x}, F_{G,y}, F_{G,z})\) are the component of gravity in body axes, and \((F_{A,x}, F_{A,y}, F_{A,z})\) are the aerodynamic force in body axes.

\[
\begin{bmatrix}
\dot{p} \\
\dot{q} \\
\dot{r}
\end{bmatrix} = I^{-1} \begin{bmatrix}
L_A & L_G \\
M_A & M_G \\
N_A & N_G
\end{bmatrix} \begin{bmatrix}
p \\
q \\
r
\end{bmatrix} - \begin{bmatrix}
p \\
q \\
r
\end{bmatrix} \times \begin{bmatrix}
p \\
q \\
r
\end{bmatrix} \tag{4}
\]

Where \(I\) is the inertia tensor in body axes, \((L_A, M_A, N_A)\) are the aerodynamic moment in body axes, and \((L_G, M_G, N_G)\) are the gravity moment under the asymmetric state in body axes.
Aerodynamic Modeling

Ignoring the unsteady aerodynamic effect, the aerodynamic force of the morphing aircraft under certain configuration in morphing process nearly equals to that of corresponding static configuration. Then the forces and moments in body axes of the morphing aircraft in morphing process can be expressed as

\begin{align*}
F_{A,x} &= QS_w (C_L \sin \alpha - C_D \cos \alpha) \\
F_{A,y} &= QS_w C_Y \\
F_{A,z} &= QS_w (-C_D \sin \alpha - C_L \cos \alpha) \\
L_A &= QS_w b_w (C_I \cos \alpha - C_n \sin \alpha) \\
M_A &= QS_w c_A C_m \\
N_A &= QS_w b_w (C_n \cos \alpha + C_I \sin \alpha)
\end{align*}

Where, \( Q = \frac{1}{2} \rho V^2 \) is the dynamic pressure, \( \rho \) is the air density, \( V \) is the airspeed, \( \alpha \) is the angle of attack, \( S_w \) is the wing reference area, \( c_A \) is the mean aerodynamic chord, \( b_w \) is the wing reference span.

Note \( F_{u,y}, \ L_u \) and \( N_u \) as the additional side-force, additional rolling moment and additional yawing moment caused by the asymmetric morphing, which depends on \( \mu = [\mu_1 \ \mu_2]^T \) (where \( \mu_1 \) and \( \mu_2 \) are folding angles of the wings on both sides, respectively). Here we introduce three aerodynamic parameters caused by asymmetric morphing, which are defined as

\begin{align*}
C_{Yur} &= F_{u,y} / (QS_w) \\
C_{lur} &= L_u / (QS_w b_w) \\
C_{mur} &= N_u / (QS_w b_w)
\end{align*}

Where \( C_{Yur}, \ C_{lur} \) and \( C_{mur} \), i.e. additional side-force coefficient, additional rolling moment coefficient and additional yawing moment coefficient.

The aerodynamic coefficient model in the morphing process can be expressed as

\begin{align*}
C_L &= C_{L0} + C_{La} \cdot \alpha + C_{L\delta} \cdot \delta_e \\
C_D &= C_{D0} + C_{Di} \cdot \alpha^2 \\
C_Y &= C_{Y\beta} \cdot \beta + C_{Y\delta_e} \cdot \delta_e + C_{Yur} \\
C_I &= C_{I\beta} \cdot \beta + C_{I\delta_e} \cdot \delta_e + C_{I\delta_r} \cdot \delta_r + C_{I\alpha} \cdot \alpha + C_{I\theta} \cdot \theta + C_{I\phi} \cdot \phi + C_{Iur} + C_{Iur} \cdot \delta_e + C_{Iur} \cdot \delta_r + C_{Iur} \cdot \alpha \cdot \alpha + C_{Iur} \cdot \theta \cdot \theta + C_{Iur} \cdot \phi \cdot \phi \\
C_m &= C_{m\alpha} + C_{ma} \cdot \alpha + C_{mo\delta_e} \cdot \delta_e + C_{mo\delta_r} \cdot \delta_r + C_{m\theta} \cdot \theta + C_{m\phi} \cdot \phi + C_{m\alpha} \cdot \alpha + C_{m\alpha} \cdot \theta \cdot \theta + C_{m\phi} \cdot \phi \cdot \phi \\
C_n &= C_{n\beta} \cdot \beta + C_{n\delta_e} \cdot \delta_e + C_{n\delta_r} \cdot \delta_r + C_{n\phi} \cdot \phi \cdot \phi + C_{n\theta} \cdot \theta \cdot \theta + C_{n\alpha} \cdot \alpha \cdot \alpha + C_{n\alpha} \cdot \theta \cdot \theta + C_{n\phi} \cdot \phi \cdot \phi + C_{nur} + C_{nur} \cdot \delta_e + C_{nur} \cdot \delta_r + C_{nur} \cdot \alpha \cdot \alpha + C_{nur} \cdot \theta \cdot \theta + C_{nur} \cdot \phi \cdot \phi
\end{align*}

Where \( \beta \) is sideslip angle, \( \delta_a \) is the aileron deflection angle, \( \delta_e \) is the elevator deflection angle and \( \delta_r \) is the rudder deflection angle.

Control Approaches

Flight control of a morphing aircraft mainly includes two aspects: the first one is morphing control that changes the shape of the aircraft, and the other is flight control that controls the attitude and trajectory of the aircraft. There are two common control methods. The first method is the morphing control and the flight control independently. Morphing aircraft change the shape through the morphing command, and the flight states does not feedback the morphing control. The function of the control law is to ensure that the morphing aircraft in any variant state maintain the stability and performance. The second method is combining morphing with flight control. The variant of the
morphing aircraft is also used as an additional control input to take direct part in the flight control using the aerodynamic changes caused by morphing.

Asymmetric aerodynamic parameters caused by morphing as described in Equation (6). When the aircraft begin to asymmetrically morphing, the variant can be treated as an additional input command. According to the method of the definition of aileron deflection, asymmetric morphing of the morphing control input is note as morphing deflection, which defined as

$$\delta_\mu = \frac{1}{2}(\mu_2 - \mu_1)$$  \hspace{1cm} (8)

The baseline state of morphing aircraft is defined as

$$\mu_0 = \frac{1}{2}(\mu_1 + \mu_2)$$  \hspace{1cm} (9)

Therefore, the aerodynamic parameters due to asymmetric morphing can be can be simplified to the following form

$$C_{Yur} = C_{Y\delta_\mu} \cdot \delta_\mu,$$
$$C_{lur} = C_{l\delta_\mu} \cdot \delta_\mu,$$
$$C_{nur} = C_{n\delta_\mu} \cdot \delta_\mu$$  \hspace{1cm} (10)

Where $C_{Y\delta_\mu}$, $C_{l\delta_\mu}$ and $C_{n\delta_\mu}$, i.e. additional side-force coefficient, additional rolling moment coefficient and additional yawing moment coefficient due to morphing deflection, respectively.

Taking into account the rate of morphing and the response speed, the actual morphing control should not be too large. In order to verify the applicable interval of Equation (10), the error analysis of simplified aerodynamic parameters in the morphing interval is shown in Table 1. The results show that the relative errors are less than 0.05 when the morphing deflection is less than 30°, which can meet the accuracy requirements.

<table>
<thead>
<tr>
<th>Morphing Deflection</th>
<th>10°</th>
<th>20°</th>
<th>30°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Error</td>
<td>0.005</td>
<td>0.021</td>
<td>0.047</td>
</tr>
</tbody>
</table>

### Analysis of Asymmetric Control Efficiency

#### Control Efficiency

In order to describe the asymmetric morphing control efficiency intuitively, Note the control efficiency parameters as $\eta_y$, $\eta_l$, and $\eta_n$, i.e. side-force efficiency, rolling moment efficiency and yawing moment efficiency, defined as follow

$$\eta_y = \frac{C_{Y\delta_\mu}}{C_{Y\delta}}$$
$$\eta_l = \frac{C_{l\delta_\mu}}{C_{l\delta}}$$
$$\eta_n = \frac{C_{n\delta_\mu}}{C_{n\delta}}$$  \hspace{1cm} (11)

Figs 2 shows the control efficiency at different flight speed when the morphing aircraft at the reference state from fully expanding to fully folding. As seen in Figs 2, the yawing moment efficiency is very low and can be neglected. The asymmetric control efficiency increase as the flight speed down. The asymmetric morphing control can provide the highest roll handling efficiency near the reference folding angle of 90°.
Numerical Simulation

When the morphing aircraft in a steady longitudinal condition with flight speed at $V = 25m/s$ and the morphing deflection at $\delta_\mu = -15^\circ$, the dynamic response of difference reference states are simulated respectively (see Figs 3 and 4). The equilibrium states are shown in Table 2.

Table 2. Equilibrium States.

<table>
<thead>
<tr>
<th>Reference States</th>
<th>30°</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle of Attack</td>
<td>1.75°</td>
<td>3.0°</td>
</tr>
<tr>
<td>Elevator Deflection</td>
<td>-0.73°</td>
<td>-1.47°</td>
</tr>
<tr>
<td>Throttle Command</td>
<td>0.264</td>
<td>0.215</td>
</tr>
</tbody>
</table>

From the response curve, it can be seen that side-slip angle, roll rate and yaw rate have relatively large oscillations due to the inertial coupling and damping derivatives. The side-slip angle does not significantly increase with the increase of the reference angle, which was due to the decrease of the side-force efficiency offsetting the roll-induced side. When the folding angle is very small, the initial yaw rate is negative due to the low roll efficiency but the high yaw efficiency. Therefore, asymmetric control efficiency have the maximum near the reference folding angle of 90°, in which only considering the rolling effect.

Conclusions

This paper presents a method of simplified modeling of asymmetric morphing control. By comparing asymmetric morphing control with conventional control surface and numerical simulation, the maximum effective range of asymmetric control is obtained. The results of the
numerical simulations show that the asymmetric control efficiency increase as the flight speed decrease. Asymmetric morphing has little effect on yawing moment and can be neglected. Since the lateral maneuvers of the aircraft are mainly accomplished by rolling, so it is priority to utilize the rolling efficiency due to Asymmetric morphing deflection input at the maximum efficiency near the reference folding angle of 90°.

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References