ICAS 2016
30th Congress of the International Council of the Aeronautical Sciences
DCC, Daejeon, Korea ; September 25-30, 2016

THE INFLUENCE OF MORPHING PROCESS ON THE AEROELASTIC CHARACTERISTICS OF A FOLDING WING

Wei Hu*, Zhichun Yang*, Yingsong Gu*
*** School of Aeronautics, Northwestern Polytechnical University**

Keywords: *Folding wing, Aeroelastic, Time variant system*

Abstract

In the present study, a two-segment folding wing model is used to investigate the influence of morphing process on the aeroelastic characteristics. The structure model is formulated by the Lagrange equations, and the aerodynamic model based on the Doublet Lattice method is formulated by the Kriging agent model technique. The aeroelastic response of the two-segment folding wing during the morphing process is simulated, and the results show that the morphing process will change the dynamic aeroelastic stability, and the influences of the folding and unfolding processes are opposite.

1 Introduction

With the development of unmanned aerial vehicle, many new aircraft concepts have been proposed, and some of them, namely the morphing wing aircraft, can change the configuration to have a good multi-mission capability. Compared with the conventional aircraft, the structure the structure model of the morphing wing aircraft changes a lot during the morphing process. Besides, some other unsteady aerodynamics can be induced by the rigid body motion of the morphing wing aircraft.

Many researches on the aeroelastic characteristic of the morphing wing aircraft have been made, especially for the folding wing aircraft. Snyder and Sander [1-3], Dunn [4] used MSC.Nastran to make a parameter analysis of the dynamic aeroelastic stability of the folding wing, and the influences of folding angle and spring stiffness were investigated. Lee and Chen [5] used MSC.Nastran and ZAERO to investigate the nonlinear aeroelastic problem of the folding wing with hinge free-play, and the limit cycle oscillation (LCO) behavior was found. Wang and Dowell [6-8] simplified the folding wing as several uniform plates, and the Lagrange equations was used to couple the beam-theory structure model and the strip-theory unsteady aerodynamics model. The flutter speeds of the folding wing with different folding angles were obtained by the experimental and theoretical methods, and the results agreed well with each other. Tang, Dowell and Attar [9, 10] investigated the folding wing with geometry nonlinearity. The LCO was found in the wind tunnel test, and the theoretical results were also calculated, which agreed well with the experimental results.

The studies mentioned above were all investigated in the quasi-steady condition, and some researches on the aeroelastic problem during the morphing process were also done. Reich, Bowman [11, 12] and Scarlett [13] formulated a morphing aeroelastic system of the folding wing, which was based on the flexible multi-body dynamics method and their in-house vortex lattice code, and the influence of the folding angle on the hinge moments was investigated. Hu and Yang [14] also formulated the aeroelastic system of the folding wing, where the Kriging agent method was used to build the aerodynamics model during the morphing process. The influence of morphing process on the aeroelastic characteristic was researched. Huang and Qiu [15] formulated the aeroelastic system of a variable-span wing, and the similar influence was also found.

In the present study, based on the Lagrange equations and the Kriging agent method, the aeroelastics modeling process of a two-segment folding wing is proposed. The aeroelastic responses of the folding wing during the morphing process are simulated, and the influence of morphing process is investigated.

2 Structure modeling

As shown in Fig. 1, the folding wing consists of two uniform rigid segments: the inboard plate and the outboard plate. The inboard plate can rotate along the x_1 and y_1 axises, and two rotation springs are defined along these two directions. The outboard plate can fold along the x_2 axis.

To formulate the multi-body dynamic equation of the folding wing, two local coordinate systems $x_1y_1z_1$ and $x_2y_2z_2$ are assigned to the inboard and outboard plate, respectively. And a ground coordinate system xyz is also defined. The rotation angle between y axis and y_1 axis is defined as α_1, the rotation angle between y axis and y_2 axis is defined as α_2, and the rotation angle between x axis and x_1 axis is defined as θ_1.

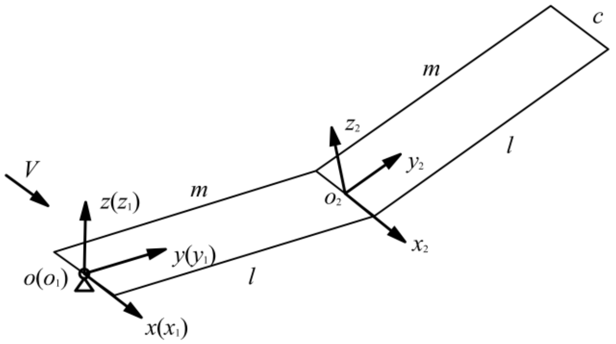

Fig. 1 The sketch of folding wing

The kinetic energy of the folding wing is:

$$T=\frac{1}{2}I_{1x_1}\dot{\alpha}_1^2+\frac{1}{2}m\left(\dot{y}_{c_1}^2+\dot{z}_{c_1}^2\right)+\frac{1}{2}I_{2x_2}\dot{\alpha}_2^2+\frac{1}{2}m\left(\dot{y}_{c_2}^2+\dot{z}_{c_2}^2\right)$$
$$+\frac{1}{2}I_{1y_1}\dot{\theta}_1^2+\frac{1}{2}I_{2y_2}\left(\dot{\theta}_1\cos\left(\alpha_2\right)\right)^2+\frac{1}{2}I_{2z_2}\left(\dot{\theta}_1\sin\left(\alpha_2\right)\right)^2 \tag{1}$$

where subscripts c_1 and c_2 denote the centroids of the inboard and outboard plate, respectively. I_{1x_1} and I_{1y_1} are the inboard plate's moment of inertia about c_1 parallel to x_1 and y_1, respectively. I_{2x_2} and I_{2y_2} are the outboard plate's moment of inertia about c_2 parallel to x_2 and y_2, respectively. I_{2z_2} is the outboard plate's moment of inertia about o_2 parallel to z_2.

The potential energy of the folding wing is:

$$U=\frac{1}{2}k_{\alpha_1}\alpha_1^2+\frac{1}{2}k_{\theta_1}\theta_1^2 \tag{2}$$

The folding angle can be described as Eq. (3):

$$\alpha_{\mathrm{FA}}\left(t\right)=\alpha_2\left(t\right)-\alpha_1\left(t\right)=\alpha_2\left(0\right)-\alpha_1\left(0\right)+\Delta\alpha_{\mathrm{FA}}\left(t\right) \tag{3}$$

According to Eq. (3), the constraint equation is formulated as:

$$\mathbf{C}=\left[\alpha_2\left(t\right)-\alpha_1\left(t\right)\right]-\left[\alpha_2\left(0\right)-\alpha_1\left(0\right)\right]-\Delta\alpha_{\mathrm{FA}}\left(t\right)=\mathbf{0} \tag{4}$$

Let $\mathbf{q}=\{\alpha_1 \quad \alpha_2 \quad \theta_1\}^T$, and substitute Eq. (1) and Eq. (2) into the Lagrange equations. Then combining the constraint equation, the dynamic equation of the folding wing can be formulated as:

$$\begin{array}{l}\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}}+\mathbf{K}\mathbf{q}+\mathbf{C}_{\mathbf{q}}^T\lambda=\mathbf{f}_V\left(\mathbf{q},\dot{\mathbf{q}}\right)+\mathbf{f}_{\mathrm{q}}\\ \mathbf{C}=\mathbf{0}\end{array} \tag{5}$$

where $\mathbf{C}_{\mathbf{q}}$ is the constraint Jacobian matrix. $\mathbf{f}_v$ is called as quadratic velocity vector of the time variant system, which is resulting from the differentiation of the kinetic energy with respect to time and with respect to the generalized coordinate[16]. $\mathbf{f}_{\mathrm{q}}$ is the aerodynamic forces, and will be introduced in the next section.

3 Aeroelastics modeling

Before the aeroelastics modeling, the aerodynamics model is formulated. The AIC matrices at different folding angles are obtained by the Doublet Lattice method, and then the Kriging method is used to build the aerodynamics model of the folding wing during the morphing process. The details about this aerodynamics modeling process can refer to [14], and the aerodynamics can be formulated as:

$$\mathbf{f}_s=\frac{1}{2}\rho V^2\left[\hat{\mathbf{A}}_0\left(\alpha_{\mathrm{FA}}\right)+\frac{b}{V}\hat{\mathbf{A}}_1\left(\alpha_{\mathrm{FA}}\right)s+\frac{b^2}{V^2}\hat{\mathbf{A}}_2\left(\alpha_{\mathrm{FA}}\right)s^2\right]\mathbf{z}_s$$
$$+\frac{1}{2}\rho V^2\hat{\mathbf{D}}\left(\alpha_{\mathrm{FA}}\right)\left[s\mathbf{I}-\frac{V}{b}\hat{\mathbf{R}}\left(\alpha_{\mathrm{FA}}\right)\right]^{-1}\hat{\mathbf{E}}\left(\alpha_{\mathrm{FA}}\right)s\mathbf{z}_s \tag{6}$$

where $\mathbf{f}_s$ and $\mathbf{z}_s$ are the force and displacement vectors for the interpolated structural nodes, respectively. $\hat{\mathbf{A}}_0\left(\alpha_{\mathrm{FA}}\right)$, $\hat{\mathbf{A}}_1\left(\alpha_{\mathrm{FA}}\right)$, $\hat{\mathbf{A}}_2\left(\alpha_{\mathrm{FA}}\right)$, $\hat{\mathbf{D}}\left(\alpha_{\mathrm{FA}}\right)$, $\hat{\mathbf{R}}\left(\alpha_{\mathrm{FA}}\right)$ and $\hat{\mathbf{E}}\left(\alpha_{\mathrm{FA}}\right)$ are the agent models of the coefficient matrices.

To Substitute Eq. (6) into Eq. (5), the transformation matrix $\mathbf{S}$ between $\mathbf{q}$ and $\mathbf{z}_s$ is formulated, and the following equations can be obtained:

$$\begin{aligned} \mathbf{z}_s &= \mathbf{S}\mathbf{q} \\ \mathbf{f}_{\mathrm{q}} &= \mathbf{S}^T\mathbf{f}_s \\ \dot{\mathbf{z}}_s &= \mathbf{S}\dot{\mathbf{q}} + \mathbf{S}_{\mathrm{FA}}\dot{\alpha}_{\mathrm{FA}} \\ \ddot{\mathbf{z}}_s &= \mathbf{S}\ddot{\mathbf{q}} + \mathbf{S}_{\mathrm{FA}}\ddot{\alpha}_{\mathrm{FA}} \end{aligned} \tag{7}$$

Substituting Eq. (6) and Eq. (7) into Eq. (5), yields:

$$\begin{aligned} &\mathbf{M}\ddot{\mathbf{q}} + \mathbf{K}\mathbf{q} + \mathbf{C}_{\mathbf{q}}^T\lambda = \mathbf{f}_V + \tilde{\mathbf{A}}_0\mathbf{q} + \tilde{\mathbf{A}}_1\dot{\mathbf{q}} + \breve{\mathbf{A}}_1\dot{\alpha}_{\mathrm{FA}} \\ &\qquad + \tilde{\mathbf{A}}_2\ddot{\mathbf{q}} + \breve{\mathbf{A}}_2\ddot{\alpha}_{\mathrm{FA}} + \tilde{\mathbf{D}}\mathbf{x}_a \\ &\mathbf{C} = \mathbf{0} \end{aligned} \tag{8}$$

where

$$\tilde{\mathbf{A}}_0 = \frac{1}{2}\rho V^2\mathbf{S}^T\hat{\mathbf{A}}_0\mathbf{S}, \quad \tilde{\mathbf{A}}_1 = \frac{1}{2}b\rho V\mathbf{S}^T\hat{\mathbf{A}}_1\mathbf{S},$$

$$\breve{\mathbf{A}}_1 = \frac{1}{2}b\rho V\mathbf{S}^T\hat{\mathbf{A}}_1\mathbf{S}_{\mathrm{FA}}, \quad \tilde{\mathbf{A}}_2 = \frac{1}{2}b^2\rho\mathbf{S}^T\hat{\mathbf{A}}_2\mathbf{S},$$

$$\breve{\mathbf{A}}_2 = \frac{1}{2}b^2\rho\mathbf{S}^T\hat{\mathbf{A}}_2\mathbf{S}_{\mathrm{FA}}, \quad \tilde{\mathbf{D}} = \frac{1}{2}\rho V^2\mathbf{S}^T\hat{\mathbf{D}}$$

$$\mathbf{x}_a = \left(s\mathbf{I} - \frac{V}{b}\hat{\mathbf{R}}\right)^{-1}\hat{\mathbf{E}}\left(\mathbf{S}\dot{\mathbf{q}} + \mathbf{S}_{\mathrm{FA}}\dot{\alpha}_{\mathrm{FA}}\right)$$

To solve Eq. (8), transform it into Eq. (9)

$$\begin{aligned} &\begin{bmatrix} \mathbf{M} - \tilde{\mathbf{A}}_2 & \mathbf{C}_{\mathbf{q}}^T \\ \mathbf{C}_{\mathbf{q}} & 0 \end{bmatrix} \begin{Bmatrix} \ddot{\mathbf{q}} \\ \lambda \end{Bmatrix} \\ &= \begin{Bmatrix} -\mathbf{K}\mathbf{q} + \mathbf{f}_v + \tilde{\mathbf{A}}_0\mathbf{q} + \tilde{\mathbf{A}}_1\dot{\mathbf{q}} + \breve{\mathbf{A}}_1\dot{\alpha}_{\mathrm{FA}} + \breve{\mathbf{A}}_2\ddot{\alpha}_{\mathrm{FA}} + \tilde{\mathbf{D}}\mathbf{x}_a \\ \gamma \end{Bmatrix} \end{aligned} \tag{9}$$

where $\gamma = -\mathbf{C}_{tt} - 2\mathbf{C}_{\mathbf{q}t}\dot{\mathbf{q}} - \left(\mathbf{C}_{\mathbf{q}}\dot{\mathbf{q}}\right)_{\mathbf{q}}\dot{\mathbf{q}}$.

Besides, according to the defining of $\mathbf{x}_a$, the following equation can be obtained

$$\dot{\mathbf{x}}_a = \frac{V}{b}\hat{\mathbf{R}}\mathbf{x}_a + \hat{\mathbf{E}}\mathbf{S}\dot{\mathbf{q}} + \hat{\mathbf{E}}\mathbf{S}_{\mathrm{FA}}\dot{\alpha}_{\mathrm{FA}} \tag{10}$$

The computational algorithm proceeds of Eq. (9) can refer to [16].

4 Example

The structural and aerodynamic parameters of the two-segment folding wing are: $l = 1\,\mathrm{m}$, $c = 0.5\,\mathrm{m}$, $m = 20\,\mathrm{kg}$, $k_{\alpha_1} = k_{\theta_1} = 1\times10^4\ \mathrm{N\cdot m/Rad}$, $\rho = 1.224\,\mathrm{kg/m^3}$.

To validate the structure model of the present method, the dynamic responses during the morphing process are simulated, and the comparison with the result obtained by MSC.ADAMS is shown in Fig. 2, where the folding angle changes from 60° to 0°, and the unfolding rate is 10°/s.

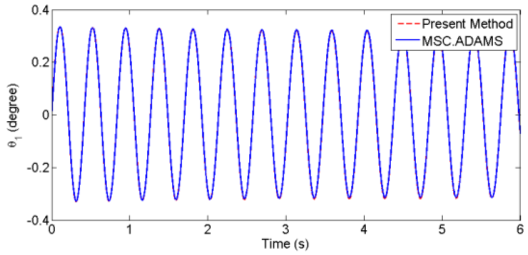

Fig. 2 The comparison of the response during the morphing process

The flutter speed of the folding wing at different folding angles, i.e. flutter speed under quasi-steady condition, obtained by the present method are compared with those obtained by MSC.Nastran, as shown in Fig. 3:

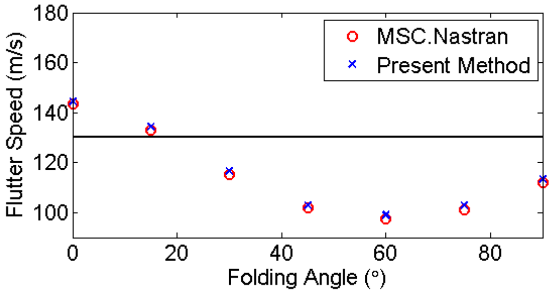

Fig. 3 Comparison of the flutter speed of the folding wing at different folding angles

As discussed in Section 2, $\mathbf{f}_v$ is the additional term in the dynamic equation of a time variant structure induced by the morphing process of the folding wing, so that the aeroelastic response with and without $\mathbf{f}_v$ are simulated to examine the influence of the morphing process on the aeroelastic response. The air speed is set to be 130m/s, marked by the solid line as shown in Fig. 3. It can be seen that during the morphing process, the aeroelastic system is unstable when the folding angle is smaller than 20°, while stable when the folding angle is larger than 20°.

Fig. 4 and Fig. 5 show the θ_1 responses of the folding wing morphing from 60° to 0°, with the unfolding rate of 5°/s and 20°/s, respectively.

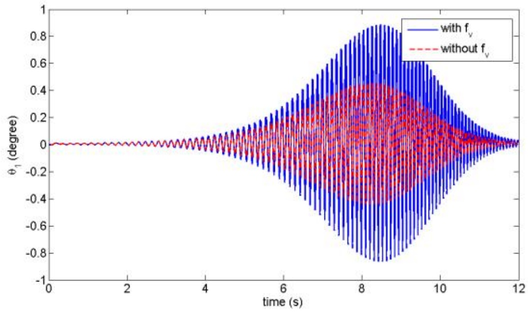

Fig. 4 The θ_1 responses of the folding wing morphing from 60° to 0°, the unfolding rate is 5° /s

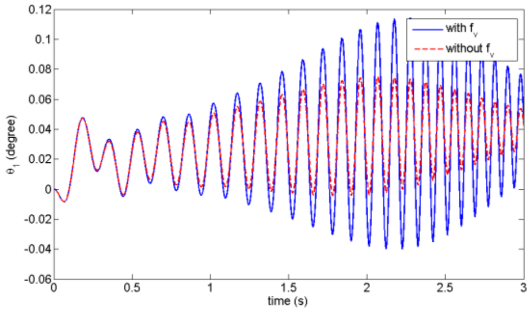

Fig. 5 The θ_1 responses of the folding wing morphing from 60° to 0°, the unfolding rate is 20° /s

Fig. 4 and Fig. 5 indicate that during the unfolding process, the morphing process of the folding wing will induce an additional positive damping effect on the aeroelastic system. And because of this damping effect, the critical folding angle at which the stability of the aeroelastic system changes is decreased, and the damping influence increases with the increasing of unfolding rate.

Fig. 6 shows the θ_1 responses of the folding wing morphing from 0° to 60° and the folding rate is 20° /s. It can be seen that during the folding process, the morphing process of the folding wing will induce an additional negative damping effect on the aeroelastic system. Therefore, the critical folding angle is increased.

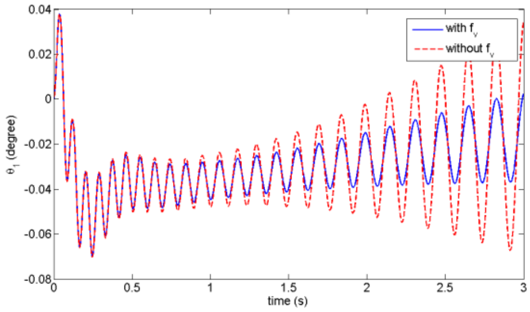

Fig. 6 The θ_1 responses of the folding wing morphing from 0° to 60°, the folding rate is 20° /s

5 Conclusions

In the present study, the aeroelastics model of a two-segment folding wing is formulated, and the influence of morphing process on the aeroelastic characteristics is investigated.

From the simulated aeroelastic responses, it can be concluded that an additional damping effect will be induced on the aeroelastic system during the morphing process. So that when the flutter occurs or exits, the corresponding folding angle will be different from that obtained in the quasi-steady condition, and the difference becomes more significant with the increasing of the morphing rate. Besides, the additional damping effects caused by the folding and unfolding processes are opposite.

6 Reference

[1] Snyder M, Frank G, Sanders B, Aeroelastic Analysis of a Morphing Z-Wing Configuration, *Aerospace Flutter and Dynamics Council Meeting*, May 2004.

[2] Snyder M, Sanders B, Eastep F, Frank G, Sensitivity of Flutter to Fold Orientation and Spring Stiffness of a Simple Folding Wing, *Proceedings of the International Forum on Aeroelasticity and Structural Dynamics 2005*, June-July 2005.

[3] Snyder M, Sanders B, Eastep F, Frank G, Vibration and Flutter Characteristics of a Folding Wing, *Journal of Aircraft*, Vol. 46, No. 3, May-June 2009.

[4] Dunn J, Horta L, Ivanco T, Piatak D, Samareh J, Scott R, Wieseman C, NASA Contributions to DARPA MAS Program, *Aerospace Flutter and Dynamics Council Meeting*, May 2004.

[5] Lee D, Chen P, Nonlinear Aeroelastic Studies on a Folding Wing Configuration with Free-play Hinge Nonlinearity, *AIAA Paper* 2006-1734, May 2006.

[6] Wang I, Dowell E, A Structural Dynamics Model of a Multi-Segmented Folding Wing: Theory and Experiment, *AIAA Paper* 2011-1871, April 2011.

[7] Wang I, Gibbs S, Dowell E, Aeroelastic Model of Multisegmented Folding Wings: Theory and Experiment, *Journal of Aircraft*, Vol. 49, No. 3, May-June 2012.
[8] Wang I, Gibbs S, Dowell E, Aeroelastic Analysis of a Folding Wing: Comparison of Simple and Higher Fidelity Models for a Wide Range of Fold Angles, *AIAA Paper* 2013-1635, April 2013.
[9] Tang D, Dowell E, Theoretical and Experimental Aeroelastic Study for Folding Wing Structures, *Journal of Aircraft*, Vol. 45, No. 4, July-August 2008.
[10] Attar P, Tang D, Dowell E, Nonlinear Aeroelastic Study for Folding Wing Structures, *AIAA Journal*, Vol. 48, No. 10, October 2010.
[11] Reich G, Bowman J, Sanders B, et al., Development of an integrated aeroelastic multibody morphing simulation tool, *AIAA Paper* 2006-1892, May 2006.
[12] Bowman J, Reich G, Sanders B, et al., Simulation tool for analyzing complex shape-changing mechanisms in aircraft, *AIAA Paper* 2006-6727, August 2006.
[13] Scarlett J, Canfield R, Sanders B, Multibody dynamic aeroelastic simulation of a folding wing aircraft, *AIAA Paper* 2006-2135, May 2006.
[14] Hu W, Yang Z, Gu Y, Aeroelastic study for folding wing during the morphing process, *Journal of Sound and Vibration* 365 (2016) 216-229.
[15] Huang R, Qiu Z, Transient aeroelastic responses and flutter analysis of a variable-span wing during the morphing process, *Chinese Journal of Aeronautics*, (2013), 26(5): 1430-1438.
[16] Shabana A, *Dynamics of Multibody System*, Cambridge University Press, New York, 1998.

Copyright Statement

Contact Author Email Address

Hoo_vey@163.com