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Aeroelastic study for folding wing during the morphing process

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ABSTRACT

This paper focuses on the aeroelastic characteristics of a folding wing during the morphing process. The folding wing structure is modeled by using the flexible multi-body dynamics approach, and an efficient method is proposed to calculate the aerodynamic force of the folding wing during the morphing process. The aerodynamic influence coefficient (AIC) matrices at different folding angles are obtained by the Doublet Lattice based aerodynamics theory, and then the orders of these AIC matrices are reduced by the spline interpolation technique. Through the minimum state approximation, the reduced AIC matrices are described as rational functions in the Laplace domain. Then the Kriging agent model technique is used to interpolate the coefficient matrices of the rational functions obtained from several different folding angles and to build the aerodynamics model in the time domain. At some different folding angles, the element values of the coefficient matrices before and after the interpolation are compared to verify the accuracy of the aerodynamics model, and then the aeroelastic responses of the folding wing during its morphing processes are simulated. The results demonstrate that the folding and unfolding processes have opposite influences on the dynamic aeroelastic stability of the folding wing, and the influences become much more significant with the increasing of the folding and unfolding rates. When the folding wing is morphing with a very slow rate, the dynamic aeroelastic stability will be similar to that obtained by the quasi-steady aeroelastic analysis.

1. Introduction

Since the beginning of the Morphing Aircraft Structures (MAS) Program, some novel morphing aircraft concepts have been proposed. Morphing aircraft holds several advantages over conventional aircraft designs including multi-mission capability, stemming from its ability of varying wing geometries during the flight. One of the famous morphing aircraft concepts is the folding wing aircraft, proposed by Lockheed Martin Corporation [1].

In recent years, many studies have been conducted on the aeroelastic characteristics of the folding wing aircraft. Several investigations [2–4] were performed to study the influences of structural parameters, such as the folding angle and the hinge spring stiffness, on the aeroelastic characteristics. Weisshaar and Lee [5] built a high fidelity aeroelastics model of the folding wing, and the results showed that the flutter dynamic pressure increases with the increasing of the inboard wing folding angle. For the extended wing configuration, the flutter dynamic pressure is much more sensitive to the changes in

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the inboard hinge stiffness, while for the folded wing configuration, the flutter dynamic pressure is much more sensitive to the changes in the outboard hinge stiffness. Zhao and Hu [6] proposed a parameterized aeroelastic modeling procedure, and the flutter characteristics of a folding wing with different configurations were investigated. Some studies on the nonlinear aeroelastic characteristics of the folding wing were also carried out. Lee and Chen [7] investigated the nonlinear aeroelastic characteristics of a folding wing with free-play hinge nonlinearity. In their study, even with a small free-play nonlinearity, the limit cycle oscillation (LCO) was observed when the folding angle is 0–30°. And the LCO phenomenon would disappear when the folding angle is larger than 30°. Tang, Dowell and Attar [8,9] investigated the influence of geometric nonlinearity on aeroelastic behaviors of a folding wing through experimental and computational methods, and the responses obtained by these two methods agreed well with each other. The result showed that the LCO appeared at air speed beyond the linear flutter speed of the folding wing, and the LCO phenomenon was changed at different folding angles.

It is noted that all of these studies mentioned above were analyzed in the quasi-steady condition with fixed folding angles, so the results were only suitable for the folding wing during very slow morphing process. Few studies have explored whether these results are suitable for the folding wing with a rather rapid morphing rate in normal morphing process.

Zhao and Hu [10] have developed the flexible multi-body dynamics formulation by combining the Craig–Bampton synthesis technique with the flexible multi-body dynamics approach, and the accuracy of this method was verified by simulating the morphing process according to a certain morphing schedule. Reich, Bowman [11,12] and Scarlett [13] built a time-varying aeroelastic simulating system of the folding wing using the flexible multi-body dynamics method and their in-house vortex lattice code, and the details about the development of this system were shown in [11,12]. The flight performances during the morphing process of a folding wing aircraft were investigated in [13], and the results indicated the influence of the folding angle on the structural load paths and the fold hinge moments.

In this paper, the study is focused on the aeroelastic behavior of a folding wing during the morphing process, and the aerodynamics model is built based on the Doublet Lattice based aerodynamics theory, which is more accurate than the vortex lattice based aerodynamics. The structure model is built by incorporating the Craig–Bampton mode with the flexible multi-body dynamics approach, and the aerodynamics model is built by the Kriging agent model technique with the interpolation of the reduced AIC matrices in the time domain at several different folding angles. The aeroelastic responses of the folding wing during the morphing process are simulated, and then the influences of some morphing parameters, such as the morphing mode (folding or unfolding) and the morphing rate, on the dynamic aeroelastic stability of the folding wing are examined.

2. Structure model

2.1. Substructure mode orthonormalization

The folding wing structure can be treated as a flexible multi-body structure, and each flexible body is a substructure, i.e. the central wing (I), the inboard wing (II) and the outboard wing (III) as shown in Fig. 1. The folding angle is defined as the angle between the inboard wing and the x–y plane, and to guarantee the lift performance of the folding wing, the outboard wing remains parallel to the x–y plane at all time.

In order to build the dynamic model for the flexible multi-body structure, the Craig–Bampton synthesis technique [14] is employed. For each substructure, the equation of motion is written as follows:

$$\begin{bmatrix} \mathbf{m}_{ii}^{l} & \mathbf{m}_{ij}^{l} \\ \mathbf{m}_{ji}^{l} & \mathbf{m}_{jj}^{l} \end{bmatrix} \begin{Bmatrix} \ddot{\mathbf{u}}_{i}^{l} \\ \ddot{\mathbf{u}}_{j}^{l} \end{Bmatrix} + \begin{bmatrix} \mathbf{k}_{ii}^{l} & \mathbf{k}_{ij}^{l} \\ \mathbf{k}_{ji}^{l} & \mathbf{k}_{jj}^{l} \end{bmatrix} \begin{Bmatrix} \mathbf{u}_{i}^{l} \\ \mathbf{u}_{j}^{l} \end{Bmatrix} = \begin{Bmatrix} \mathbf{0} \\ \mathbf{f}_{j}^{l} \end{Bmatrix} \tag{1}$$

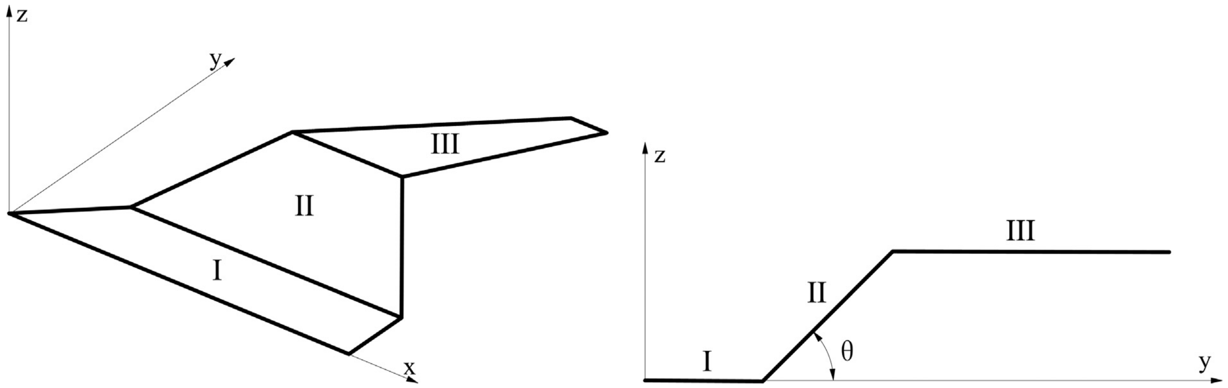

Fig. 1. Sketch of a folding wing.