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Flutter suppression and stability analysis for a variable-span wing via morphing technology

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ABSTRACT

A morphing wing can enhance aerodynamic characteristics and control authority as an alternative to using ailerons. To use morphing technology for flutter suppression, the dynamical behavior and stability of a variable-span wing subjected to the supersonic aerodynamic loads are investigated numerically in this paper. An axially moving cantilever plate is employed to model the variable-span wing, in which the governing equations of motion are established via the Kane method and piston theory. A morphing strategy based on axially moving rates is proposed to suppress the flutter that occurs beyond the critical span length, and the flutter stability is verified by Floquet theory. Furthermore, the transient stability during the morphing motion is analyzed and the upper bound of the morphing rate is obtained. The simulation results indicate that the proposed morphing law, which is varying periodically with a proper amplitude, could accomplish the flutter suppression. Further, the upper bound of the morphing speed decreases rapidly once the span length is close to its critical span length.

1. Introduction

A morphing aircraft is capable of changing its shape or geometrical configuration during flight to better accomplish its required mission and provide control authority for maneuvering [1,2]. Various kinds of morphing configurations have been developed in the past two decades. For example, In the Active Aeroelastic Wing (AAW) flight research program of mid-1990s, the aeroelastic flexibility of wing was utilized to produce the required roll moments for control [3,4]. In the NextGen Morphing Aircraft Structures (N-MAS) program, a morphing aircraft termed the ‘batwing’ had been designed which can undergo very large changes in wing sweep, span and area for multiple-mission requirements [5,6]. As part of the N-MAS program, an out-of-plane morphing wing (Z-wing) was developed by Lockheed Martin [7–9]. Besides, a telescopic wing for purpose of a pure roll control was presented and tested, which has the ability to undergo a 230% change in aspect ratio [10,11].

During development of morphing structures, the dynamics of axially moving plate, as an important topic, has drawn attention [12]. For example, Tang and Chen [13,14] investigated the parametric resonance and 3:1 internal resonance of an axially moving viscoelastic plate subjected to in-plane stresses, and analyzed their stability for different resonances. An and Su [15] studied the effects of flexural rigidity ratio, axial speed and aspect ratio on the vibration amplitude of moving plates via generalized integral transform technique. Otsuka and Makihara [16] performed the aeroelastic simulation of a flexible

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deployable wing by means of Absolute Nodal Coordinate Formulation (ANCF). Abundant nonlinear dynamics of axially moving elastic plates under aerodynamic loads were observed, such as the flutter modes and their nonlinear jump phenomena [17–19]. It has been proved that the flutter speed can be improved by increasing morphing speed, which means that the morphing technology can be used for flutter suppression. However, what kind of the morphing strategy can suppress flutter during morphing process is still an open problem. Due to the fact that an increasing morphing rate can improve the critical speed of flutter, while the increasing span length gives rise to the decrease of the structural rigidity [20,21], a feasible approach is that the wing moves axially at a periodically varying value close to the critical length. On the other hand, as a control mechanism, the conventional aileron can implement the flight control and suppress the flutter [22,23], and the control surface replaced by morphing wing could achieve the attitude control [10,24].

This paper concentrates on finding a morphing strategy to suppress the flutter that happens beyond the critical span length. The contributions of this work are as follows: (1) The equations of motion of an axially moving cantilever plate immersed in supersonic fluid are established; (2) A new morphing strategy for the flutter suppression of the morphing wing without control surface is presented; (3) The upper bound of the morphing rate is obtained based on the theory of slowly varying system.

The further discussions are as follows. In Sec.2 the equations of motion of an axially moving plate in supersonic airflow are established via the Kane method and piston theory. In Sec.3 the numerical simulations are given to demonstrate the effects of the proposed morphing strategy for different parameters on dynamic behavior and stability. In Sec.4 the upper bound of morphing speed is presented via the stability analysis of slowly varying system. Finally, Sec.5 concludes this paper.

2. Structural model

2.1. Morphing aircraft model

The variable-span morphing aircraft in this study is modeled as axially moving plates that could extend and contract from the fuselage as depicted in Fig. 1, wherein Δp_{aero} is the local differential aerodynamics pressure of wing surface, V_∞ is the freestream velocity. The thickness of plate is h and the surface density is ρ, the lengths of fixed wing and deployable part are L_0 and ΔL respectively, and $\Delta L < L_0$.

In what follows, it is assumed that the rectangular plate is homogeneous and isotropic one, and that the thickness of plate is small, i.e., $h \ll c$ and $h \ll L$, where c is the width of plate and $L = L_0 + \Delta L$ is the total length of the plate, so that the Kirchhoff hypothesis holds true. In addition, the deploying rate of the plate during morphing process is varying slowly and small relative to the supersonic airflow speed. To describe the motion of plate, a set of fuselage-based Cartesian co-ordinates is established in Fig. 1 such that the X-axis is on the mid-plane of the plate along the wing's leading edge, the Y-axis points the opposite direction of flight, the Z-axis meets the right hand rule.

The mid-planes of the rectangular plate at an arbitrary moment before and after deformation are shown in Fig. 2. The deformation vector of a point P_0 to point P in the mid-plane of the plate is denoted as $\mathbf{u}(u_1,u_2,u_3)$, and s, r are the two in-plane stretch variables [25].

The velocity of point P in inertial frame fixed on the Earth is

$$\mathbf{V}^P = \mathbf{V}^O + \boldsymbol{\omega}^A \times (\mathbf{p} + \mathbf{u}) + {}^A\mathbf{V}^P \tag{1}$$

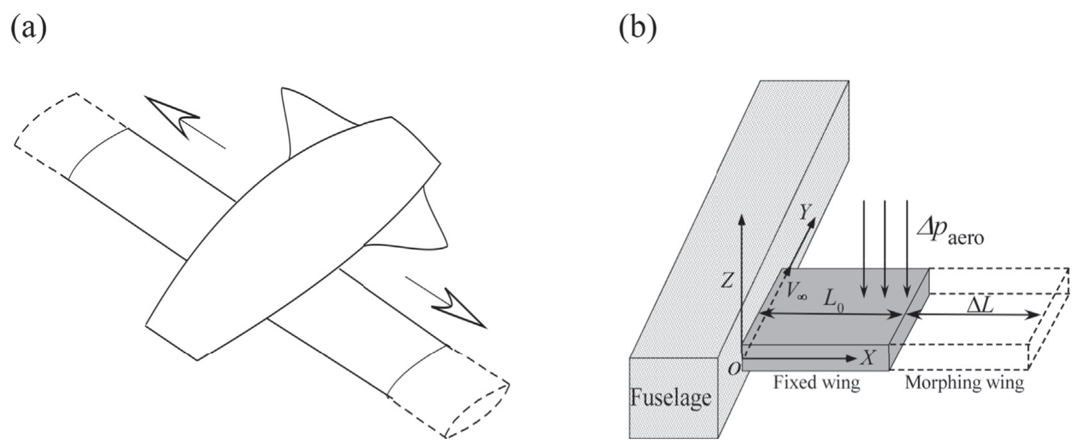

Fig. 1. The schematic diagram of morphing aircraft in supersonic airflow: (a) a morphing aircraft with variable-span wings, (b) the simplified model of axially moving plate.