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Feedback tracking control for dynamic morphing of piezocomposite actuated flexible wings

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ABSTRACT

Aerodynamic properties of flexible wings can be improved via shape morphing using piezocomposite materials. Dynamic shape control of flexible wings is investigated in this study by considering the interactions between structural dynamics, unsteady aerodynamics and piezo-actuations. A novel antisymmetric angle-ply bimorph configuration of piezocomposite actuators is presented to realize coupled bending-torsional shape control. The active aeroelastic model is derived using finite element method and Theodorsen unsteady aerodynamic loads. A time-varying linear quadratic Gaussian (LQG) tracking control system is designed to enhance aerodynamic lift with pre-defined trajectories. Proof-of-concept simulations of static and dynamic shape control are presented for a scaled high-aspect-ratio wing model. Vibrations of the wing and fluctuations in aerodynamic forces are caused by using the static voltages directly in dynamic shape control. The lift response has tracked the trajectories well with favorable dynamic morphing performance via feedback tracking control.

1. Introduction

New generations of highly maneuverable aircrafts, high altitude long endurance (HALE) unmanned aerial vehicles (UAV) and micro air vehicles (MAV), are likely to feature very flexible wings. The aerodynamic properties and aeroelastic responses of the flexible wings can be improved via active shape control using smart piezoelectric actuators [1,2]. These type of wings, which can adjust their shape or profile to enhance the performance and control characteristic of aircrafts, can be called “morphing wings” or “smart wings” [3]. Compared to the traditional discrete trailing-edge control surfaces, piezoelectric actuator has the advantage of fast response, wide actuation bandwidth and reducing weight and complexity of wings [4]. Continuous camber or surface changes of the morphing wings can be realized so that the aerodynamic efficiency can be improved without moving any mechanical part [5]. Moreover, the morphing wing concept has the capability to outperform conventional servo-actuation in terms of required flight control energy consumption [6,7].

Piezoelectric fiber composite materials have been emerged as the new class of piezoelectric materials which are composed of piezoelectric fiber reinforcements and epoxy matrix so they can provide wide range of effective material properties, good conformability and strength integrity [8]. Piezocomposite materials can utilize the d_{33} piezoelectric effect to the direction of

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piezoceramic fibers which is larger than the d_{31} piezoelectric effect of the typical piezoelectric actuator [9]. Piezocomposite actuators have been widely used for structural control. Active shape control of flexible wings, including rotary-wings and fixed-wings, is an important application of piezocomposite actuators in aviation field [10]. With the actuation of piezocomposite materials, the wing's shape or profile can be adjusted actively to obtain favorable aerodynamic properties such as lower drag and enhanced lift. Flight performance and control characteristics of aircrafts can also be improved, for example roll performance can be increased using morphing wings compared to conventional wings [11,12]. MFC (macro-fiber-composite), which was developed by NASA Langley Research Center, is an advanced piezocomposite actuators that employs rectangular cross-section and unidirectional piezoceramic fibers [13,14]. Its lightweight, robust construction and increased actuation strain energy density have made it a popular choice for shape control of flexible morphing wings [15–17]. Bilgen [18,19] presented the wind tunnel tests and flight tests for a MAV with morphing wings actuated by MFCs. The tests indicated that the continuous surface of the morphing wing produced lower drag and wider actuation bandwidth. Ohanian [7] compared the flight performance of MFC-actuated morphing wing MAV and traditional servo-actuated MAV in flight tests. The morphing actuation demonstrated lower drag and more efficient production of control forces and moments.

Realization of accurate shape control is of fundamental importance for the piezo-actuated wings to obtain desired control effectiveness. Static and dynamic shape control of piezo-actuated structures has also received extensive attentions [20]. The process of static shape control estimates the final voltage values for the piezocomposite actuators to reach a command shape or profile. However, the voltage profiles, i.e. variation of voltage with respect to time, for each actuator may not be obtained because the static shape control process provides only the initial and final static voltage values [21]. Nevertheless, the arbitrary selection of any admissible control voltage profile such as step and ramp signals may excite the low structural modes because of the flexibility necessary to achieve shape control, especially for short time interval. Vibrations of the wing and fluctuations in aerodynamic forces reduce morphing effectiveness and flight performance [18]. Therefore, the dynamic shape control of flexible wings should be carefully studied to achieve continues, smooth morphing motion with gentle aeroelastic responses. Different from static shape control, dynamic shape control concerns the time-varying effects, disturbances and dynamic behaviors of the morphing process. Kalaycioglu [21] investigated the dynamic shape performances of flexible structures with different voltage profiles and presented the optimum voltage profiles to minimize the vibration of the structure during shape control. Kugi [22] and Schröck [23] investigated the dynamic shape control of piezo-actuated flexible structures based on flatness-based design methodology. Hubbard [10] studied the dynamic shape control of a MFC-actuated morphing airfoil with minimal energy. Compared with many flexible structures, the important coupling effect between structural dynamics and aerodynamics loads must be concerned in the modeling, analysis and control of flexible wings [24]. The inherent fluid-structure interaction will lead to complex aeroelasticity problem. Dynamic shape control of flexible wings requires knowledge of aeroservoelasticity interactions (interactions between structural dynamics, unsteady aerodynamics and controls) [25]. Furthermore, the command wing shape may be required to vary in flight, thus good dynamic tracking performance is needed to follow the pre-defined morphing trajectories. Moreover, multiple actuators may be used to enhance control authority and characteristic. Then an MIMO (multi-input multi-output) control system might be constituted and makes the problem more complex and challenging [26]. In conclusion, the effective dynamic shape tracking control system should be investigated for the piezo-actuated flexible wings.

In this paper, a feedback tracking control approach is investigated for dynamic morphing of the piezocomposite actuated flexible wing to obtain desired aerodynamic properties. The objective of shape control is to achieve lift enhancement which has received extensive attentions for morphing wings [24,27]. To this end, mathematical model of the piezocomposite actuated flexible wing is established including structural finite element equations and time-domain Theodorsen unsteady aerodynamic loads. The state space representation is given to facilitate controller design. The tracking control problem for dynamic morphing of flexible wings is described and a time-varying LQG tracking controller is designed. Such controllers with time-varying feedback gains can bring preferable control effect than constant-gains controllers [28]. A proof-of-concept simulation, which demonstrates the efficacy of the proposed tracking control technique for dynamic morphing, is presented to a scaled high-aspect-ratio wing model.

The paper is organized as follows. Section 2 introduces the mathematical modeling of the piezo-actuated wing. The formulation and solution of the tracking control approach are presented in Section 3. Section 4 presents the numerical simulation results and discussions. Conclusions are drawn in Section 5.

2. Mathematical modeling

The flexible wing in the present study is characterized by means of a cantilever plate with two piezocomposite actuators which are bonded to the upper and lower surfaces of the wing substrate, as depicted in Fig. 1.

The piezocomposite actuators are implemented in bimorph configuration. In addition, the piezoelectric fiber orientations (i.e. the angle from x-axis to 1-axis) of the upper and lower side actuators are opposite: the fiber orientation angle of the upper actuator is -45°, while the lower one is 45°. The main purpose of this antisymmetric angle-ply bimorph configuration of piezocomposite actuators is to achieve both bending and torsional shape control. With this specific actuation concept, torsional deformation of the host wing structure can be produced by applying same voltages for the actuators, as shown in Fig. 2(a). Twisting motion can change the angle of attack of the wing so that the favorable aerodynamic properties can be obtained with morphing lifting surfaces [29]. On the other hand, bending deformation can also be produced by applying