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Modeling and vibration control of the flapping-wing robotic aircraft with output constraint

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ABSTRACT

In this paper, we propose the boundary control for undesired vibrations suppression with output constraint of the flapping-wing robotic aircraft (FWRA). We also present the dynamics of the flexible wing of FWRA with governing equations and boundary conditions, which are partial differential equations (PDEs) and ordinary differential equations (ODEs), respectively. An energy-based barrier Lyapunov function is introduced to analyze the system stability and prevent violation of output constraint. With the effect of the proposed boundary controller, distributed states of the system remain in the constrained spaces. Then the IBLF-based boundary controls are proposed to assess the stability of the FWRA in the presence of output constraint.

1. Introduction

The flapping-wing robotic aircraft (FWRA) is one of the unmanned aerial vehicles inspired by birds, bats and flying insects [1,2,37]. The flapping-wing movement is a common way that natural flying creatures used to produce lift and thrust. This flapping mechanism offers significant improvement in flight performance in comparison with traditional fixed-wing or even rotary-wing aerial vehicles [3]. Fixed-wing aerial vehicles lack hovering ability, thus they cannot be applied to complex urban and indoor environments. Although rotary-wing aerial vehicles can hover, they are susceptible to adverse disturbances. With the development of Micro-Electro-Mechanical system (MEMS), many designers and researchers pay more attention to the research of FWRA. Because of the unmatched maneuverability, lower costs, and lighter weight, FWRV has application markets in military and civilian fields. (see Fig. 1)

We recognize that the open-loop flapping wing system is unstable, so the control method must be designed for better flight performance. Existing studies have focused on attitude and position control of FWRA based on a six-degrees of freedom nonlinear model [4]. They mainly researched insect-like micro aerial vehicles that can be regarded as a kind of rigid body model. Then the dynamics is analyzed through the coordinate transformation among the inertial frame, the body frame, and the wing frames; details can be found in Refs. [5,6,38]. A composite control method for the rigid-flexible coupling of the air-breathing hypersonic vehicles is shown in Ref. [7]. The control method can accomplish the proper pitch rate as well as the desired trajectory tracking. In this paper, since we study a bird-like FWRA with 1–2 m wingspan, the wing flexibility is believed to play a key role in flight performance. However, considering infinite dimensional states, the flexible-wing FWRA is harder to model and control than the conventional rigid wing aircraft does. Moreover, the flexibility of the wing may cause undesired vibrations [8], making it more complicated to analyze the stability of the FWRA system. Vibrations of flexible wings may lead to aerodynamic changes

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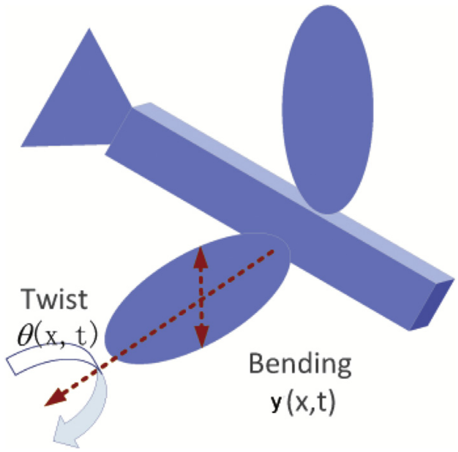

Fig. 1. Diagrammatic figure of the FWRA.

of the FWRA as well as potential undesired aircraft responses. Thus, it is necessary to design a control strategy for vibration suppression of flexible wings.

There are plenty of research studies on the vibration suppression for flexible structures [9,10,39], such as flexible cranes [11], flexible Euler-Bernoulli beams [12–14], flexible Timoshenko beams, flexible marine risers, flexible strings [15] and so on. In this paper, we consider that the flexible wing has bending and torsion degrees of freedom [16–18]. The dynamics of the flexible wing is a distributed parameter system (DPS) obtained by using Hamilton's principle. It contains a second-order hyperbolic partial differential equation (PDE) for torsion movement, a fourth-order Euler-Bernoulli beam PDE for bending movement, and a set of ordinary differential equations (ODEs) for boundary conditions of the flexible wing aircraft system. Hence many control methods that aim at the conventional lumped parameter system (LPS) cannot be used for the DPS directly.

Because of the limitations of actuators and sensors, the boundary control method [19–23] is regarded as a utility way to deal with the DPS of the flexible structure compared to the distributed control method. There are two ways to deal with PDEs with the boundary control method. The first way approximates the PDEs with a finite number of ODEs [24], or a sliding mode control algorithm for chattering attenuation under Euler's discretization [25]. The primary problem of this reduced-order model for control design is the possible spill-over instability because of the neglected higher-order modes. Another way is to propose controller based on the original PDEs, without discretization or simplification of the dynamics. Consequently, torsion and bending control schemes are developed according to the no omission PDEs to suppress severe vibrations of the flexible wing in this paper.

The Lyapunov's direct method is the most popular theory applied for analysis of the controlled closed-loop system stability [26], which also offers a technique for control design [27]. As for flexible FWRA, He et al. proposed a boundary control strategy in Ref. [28] to address the vibration problem. However, they simplified the boundary conditions of system dynamics by considering the Kelvin-Voigt damping coefficient to be zero. Meanwhile, they did not concern the output constraint addressing the durability of the FWRA. A neural dynamical approach was proposed to solve constrained variation inequality problems in Ref. [29], but they only concerned the linear system. The barrier Lyapunov function is a relatively novel concept that can be used to realize the output constraint problem [30,31] and to avoid performance degradation or hazards for the physical system. Different from many of papers mentioned above, the barrier Lyapunov function has its unique expression, which allows the barrier limit to vary with the desired trajectory in time [32]. There have been some research studies applying the barrier Lyapunov function to linear or nonlinear ODE systems. However, we adopt this method of barrier Lyapunov to handle the constraint on the PDE system. In our recent work [33], boundary control with output constraint has been developed for the vibration suppression of flexible wings, whereas the proposed control algorithms contain high-order derivatives of the deformation states and lead to a time-consuming computation. Thus, there needs a more practical control strategy for the PDE system with output constraints.

This paper presents the derivation of the flexible wing PDE model under unknown distributed disturbance. Then the boundary controller is put forward to suppress bending and torsion deformations effectively. Next we use the original integral barrier Lyapunov function to analyze the PDE system stability and guarantee outputs in constraints. Two lemmas, an assumption and the dynamic model of the FWRA system for control development are given in Section 2 and Section 3. Based on the dynamic model, we propose boundary control strategies to regulate the bending and torsion vibrations of the flexible wings in Section 4 where the uniform boundedness of distributed states is proved by utilizing the Lyapunov's direct method. In Section 5, the performance of the BLF-based control is illustrated with a numerical example.

2. Preliminaries

Remark 1. *To simplify formulae, we use notations* $(*)' = \partial(*)/\partial x$ *and* $(\dot{*}) = \partial(*)/\partial t$ *throughout the full paper.*

Lemma 1. [34] *Let* $\phi_1(x,t), \phi_2(x,t) \in \mathbb{R}$ *with* $x \in [0, L]$, *there is the inequalities:*

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