Journal of Fluids and Structures 73 (2017) 82–99

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

An efficient fluid–structure interaction model for optimizing twistable flapping wings

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A R T I C L E   I N F O

Article history:
Received 15 February 2017
Received in revised form 20 May 2017
Accepted 7 June 2017

Keywords:
Twistable flapping wing
Fluid–structure interaction
Hovering flight
Power efficiency
Optimization

A B S T R A C T

Spanwise twist can dominate the deformation of flapping wings and alters the aerodynamic performance and power efficiency of flapping wings by changing the local angle of attack. Traditional Fluid–Structure Interaction (FSI) models, based on Computational Structural Dynamics (CSD) and Computational Fluid Dynamics (CFD), have been used to investigate the influence of twist on the power efficiency. However, it is impractical to use them for twist optimization due to the high computational cost. On the other hand, it is of great interest to study the optimal twist of flapping wings. In this work, we propose a computationally efficient FSI model based on an analytical twist model and a quasi-steady aerodynamic model which replace the expensive CSD and CFD methods. The twist model uses a polynomial to describe the change of the twist angle along the span. The polynomial order is determined based on a convergence study. A nonlinear plate model is used to evaluate the structural response of the twisted wing. The adopted quasi-steady aerodynamic model analytically calculates the aerodynamic loads by including four loading terms which originate from the wing's translation, rotation, their coupling and the added-mass effect. Based on the proposed FSI model, we optimize the twist of a rectangular wing by minimizing the power consumption during hovering flight. The power efficiency of optimized twistable and rigid wings is studied. Comparisons indicate that the optimized twistable wings exhibit power efficiencies close to the optimized rigid wings, unless the pitching amplitude at the wing root is limited. When the pitching amplitude at the root decreases by increasing the root stiffness, the optimized rigid wings need more power for hovering. However, with the help of wing twist, the power efficiencies of optimized twistable wings with a prescribed root stiffness are comparable with the twistable wings with an optimal root stiffness. This observation provides an explanation for the different levels of twist exhibited by insect wings. The high computational efficiency of the proposed FSI model allows further application to parametric studies and optimization of flapping wings. This will enhance the understanding of insect wing flexibility and help the design of flexible artificial wings for flapping wing micro air vehicles.

1. Introduction

Flapping wings keep receiving attention from biologists and engineers due to the increasing interest in flapping wing micro air vehicles (FWMAVs). Inspired by insect wings, the kinematics and shape for FWMAV wings have been studied more extensively as compared to the wing flexibility.

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http://dx.doi.org/10.1016/j.jfluidstructs.2017.06.006
0889-9746/

The wing thickness is typically one to two orders smaller than the wing span and, consequently, insects wings can be modeled as thin-walled structures. The apparent wing flexibility depends on the morphological characteristics, e.g., the venation layout, cross-sectional profile and the membrane thickness. Due to the inertial and aerodynamic loads, dramatic out-of-plane deformation can be observed for some insect wings. The deformation can be decomposed into three modes (Wootton, 1981): spanwise bending, spanwise twist and chordwise camber. For insect wings, the deformation can be dominated by different modes (Willmott and Ellington, 1997a; Chen et al., 2013; Zheng et al., 2013).

For artificial wings, the deformation can also be described by the three modes. Among them, the twist is of particular interest for realizing power-efficient wing designs because of four reasons. First, to realize the required wing kinematics, the spanwise bending is normally restricted by the wing structural designs, e.g., using longitudinal stiffeners (Bolsman et al., 2009; de Croon et al., 2009; Nan et al., 2017) or chordwise corrugations (Tanaka and Wood, 2010; Tanaka, 2012). Second, the turbulent flow surrounding flapping wings is not as sensitive as a laminar flow to the wing camber (Du and Sun, 2010). Third, cm-scale flapping wings (Bolsman et al., 2009; Deng et al., 2016; Nan et al., 2017) are commonly used for FWMAVs. Such wings can exhibit large twist due to the large difference of the inertial and aerodynamic loads at the wing root and tip. Fourth, the twist can dramatically alter the local angle of attack along the span, which changes the aerodynamic performance and the power efficiency. Therefore, this work exclusively focuses on the modeling and effects of wing twist. In addition, only hovering flight is considered because (1) the wing deformation is most pronounced during hovering flight (Willmott and Ellington, 1997a), and (2) hovering flight is generally more power-consuming as compared to forward flight (Dudley, 2002).

Traditional Fluid–Structure Interaction (FSI) models, based on Computational Structural Dynamics (CSD) and Computational Fluid Dynamics (CFD), have been used to investigate the influence of wing twist on the aerodynamic performance and power efficiency of different flapping wings. For example, Du and Sun (2008) studied the effects of unsteady deformation of flapping wings on the aerodynamic force production and power consumption. They showed that lift is increased by up to 20% and lift-to-drag ratio by around 10% with a deformation of 6% camber and 20° twist when compared with the rigid counterparts. Meanwhile, the power required is reduced by about 16%. Shyy et al. (2010) showed that wing twist can make FWMAVs more susceptible to gusty conditions. Nakata and Liu (2012a) performed a FSI analysis of hawkmoth hovering with flexible wings through an integrated wing-body modeling of the morphology, kinematics and flexibility. Their results demonstrate the importance of inherent flexibility of insect wing in enhancing aerodynamic performance during flapping flight. Dai et al. (2012) conducted three-dimensional FSI simulation of a low aspect-ratio rectangular wing performing a hovering flight. They observed that the twist disappears somewhere between the wing reversal and mid-stroke. More recently, Nguyen and Han (2016) showed that the effects of the FSI are the most significant in hovering flight of an hawkmoth wing and tend to decrease with the forward flight speed. However, limited by the high computational cost, it is impractical to use traditional FSI models for twist optimization. The latter is of great interest for the study of insect wings and the design of artificial wings. There are some analytical models which capture the FSI effect to some levels. For instance, Calogero et al. (2016) modeled the compliant joints as spherical joints with distributed mass and spring–dampers with coupled nonlinear spring and damping coefficients, which greatly reduces computational time as compared to the CSD analysis. However, the realistic aerodynamic loads have not been included in their simulation yet. Moreover, most of the studies on FSI of flexible wings prescribe the pitching motion at the root, while in reality passive pitching is widely used by wings of insects (Ennos, 1989; Bergou et al., 2007) and FWMAVs (de Croon et al., 2009; Bolsman et al., 2009; Dai et al., 2012; Ma et al., 2013). The prescribed pitching motion helps the simulation to converge easier and reduces the computational cost. However, the power consumption of flapping wings with prescribed and passive pitching motion can differ dramatically (Han et al., 2015). In this work, we propose a computationally efficient FSI model to study the (optimal) twist of flapping wings. The proposed FSI model uses an analytical twist model for the structural analysis and a quasi-steady aerodynamic model (Wang et al., 2016) for the aerodynamic analysis.

This paper is structured as follows. The modeling of twistable flapping wings and the FSI is presented in Section 2. In Section 3, the proposed twist model is validated. In Section 4, flapping wing twist and kinematics are optimized by minimizing the power consumption for hovering using the proposed FSI model. Conclusions are presented in Section 5.

2. Modeling of twistable flapping wings

In this work, rectangular flapping wings with uniform thickness are studied. The wings will be modeled as isotropic and homogeneous plates which exhibit twist. Linear elastic material model will be used for structural analysis. In the following subsections, the wing kinematic model and equations of motion will be introduced.

2.1. Kinematics

The wing motion can be described by a combination of three successive rigid-body rotations and an elastic deformation, as illustrated in Fig. 1. The rigid-body rotations consist of the sweeping motion about the z_i axis of the inertial frame $x_iy_iz_i$, the heaving motion about the y_θ axis of the intermediate frame $x_\theta y_\theta z_\theta$, and the pitching motion about the y_η axis of another intermediate frame $x_\eta y_\eta z_\eta$. Thereafter, the frame $x_cy_cz_c$ which co-rotates with the undeformed wing is introduced. The co-rotating frame has its x_c axis directing from the root to the tip of the undeformed wing. Its z_c axis coincides with the