Fluid-Structure Interaction Analysis on Camber Effects of Flapping Micro Air Vehicles

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ABSTRACT

This study investigates the unsteady aerodynamic characteristics of the cambered wings of a flapping-wing micro air vehicle (FW-MAV) in hover. A three-dimensional fluid–structure interaction solver is developed for a realistic modeling of large-deformation in wing structure and geometry. Cross validation is conducted against the experimental results obtained also in the present study to establish a more accurate analysis of cambered wings. An investigation is carried out on the unsteady vortex structures around the wings caused by the passive twisting motion. A parametric study is then conducted to evaluate the aerodynamic performance with respect to the camber angle at normal operating flight conditions. The camber angles producing the largest thrust and propulsive efficiency are estimated, and their effects on aerodynamic performance are analyzed in terms of the stroke phase. The timing and magnitude of the passive twisting motion, which are influenced by the camber angle greatly affects the unsteady vortex structure. As a result, it is observed that the camber angle is an important parameter that is capable of improving the aerodynamic performance of FW-MAVs.

INTRODUCTION

Flapping-wing micro air vehicles (FW-MAVs) are small flyers mimicking flight characteristics of biological flyers. The aerodynamic characteristics are generated by various wing trajectories derived from muscles and flexible wing structures. In order to implement these flapping motions in FW-MAV, it can be achieved by using a complex driving mechanism and a plurality of motors, but it is inefficient. Thus, a simple mechanism utilizing flexible wing structure is mainly adopted. In fact, a twisted wing with camber has been applied to maximize the rotation effect of FW-MAVs’ flexible wings. Studies have been performed to determine the ideal camber angle using either experimental methods or simple aerodynamic theory. Since the effect caused by a cambered wing is essentially a kind of aeroelastic phenomenon, detailed computational investigation with accurate fluid-structure interaction analysis (FSI) solver needs to be carried out to understand the unsteady aerodynamic mechanism.

In this study, as a way to analyze the effect of a camber angle on the aerodynamic performance of FW-MAVs flexible wing, an FSI solver is developed that can simulate realistic wing geometry with detailed structural components. The solver is firstly validated using the anisotropic Zimmerman wing. Additionally, an experiment is performed to validate
the FSI analysis of the flexible wings of FW-MAV consisting of complex geometry and structures. Using the present solver, an investigation of the unsteady vortex structures around the wings is carried out. In addition, to analyze the effects of the camber angle, a parametric study is conducted.

FLUID-STRUCTURE INTERACTION FRAMEWORK

To couple the flow and structural solver, an implicit coupling strategy is applied. The unsteady three-dimensional Navier-Stokes equations are employed as the governing equations for the fluids. The arbitrary Lagrangian-Eulerian (ALE) description is used to consider arbitrarily moving and deforming control volume. In structural analysis module, the CR beam is employed for the veins and the CR shell elements for the wing membrane. To have interconnection among the finite elements, globalized Lagrange multipliers are employed. In particular, a twisted camber wing shape using the pre-structure solver that decides the shape in the gravitational field. Along the nonmatching interface, a radial basis function is chosen in consideration of efficiency and accuracy. Body movement and/or shape deformation occurs from the structural solver, which causes the geometric deformation of the flow grid system. For efficient transformation in the structured grid, a transfinite interpolation method is used.

EXPERIMENTAL SETUP AND NUMERICAL MODELING

Figure 1-a shows the conceptual design of the flapping mechanism used in this experimental study. Here, the brushed motor is used to drive the Scotch-yoke linkage and rack–pinion gear in a flapping mechanism. This mechanism rotates in an alternating fashion and can generate a cosine motion trajectory. The maximum amplitude of the flapping angle is about 82°. To measure the trajectory of wing, two high-speed cameras are used to track the markers on the wing using the DLTdv digitizing tool. And, the thrust and the power are collected ten times for 3 seconds and averaged.

![Figure 1. Experimental system & cambered wing of FW-MAV](image)

Flapping angle is $\phi_{amp}=82^\circ$ and the flapping frequency is $f=24$Hz, which is in normal operating condition. The cambered wing (Fig. 1-b) utilized in FW-MAVs are modeled realistically with complex shapes and material characteristics. In order to implement the shape of the cambered wing as shown in Fig. 1-c, the initial geometry is derived using a preprocessor module, in which the camber axis is moved in a gravity field (Fig. 2-a). As shown in Fig. 2-b, beam elements are utilized in order for carbon/epoxy rod (leading edge), and shell elements are employed for Mylar (wing membrane) and carbon composite plate on the wing membrane. In addition, physical boundary conditions are assigned to each material.
Comparison of aeroelastic behavior between the experiments and FSI results shows that the cambered wing can be simulated accurately, and the thrust is derived with the accuracy within 3%. Using these results, the aeroelastic effect of cambered wings is analyzed. Thus, it is found that the passive twisting motion (pronation/supination) has a significant effect on cambered wing aerodynamic performance and identified the advantageous features of cambered wing. In cambered wings, the camber angle significantly affects the formation and attachment of the vortex by changing the timing of these movements and by limiting the maximum twist angle.

To analyze the effects of the camber angle, a parametric study is conducted to derive the camber angle at which the largest thrust and efficiency occurs. Analysis cases are selected from 5° to a maximum of 25°. It shows that the 12.5° cambered wing with the largest thrust resulted in a 9% thrust improvement, while 15° cambered wing with the largest efficiency results in a 14% efficiency improvement, when compared to the flat wing (Fig. 3-a).
CONCLUSION

In this study, an FSI solver that can reliably simulate the FW-MAV’s cambered wing is developed. By expanding the previous research performed on wings with simple geometry, cambered wings are simulated at more complicated conditions and cross-validation is performed by experiments to ensure the analytical reliability. This enables practical research for the actual development of FW-MAVs.

With this advantage, the aeroelastic effect of cambered wings is analyzed. It is found that the passive twisting motion (pronation/supination) has a significant effect on cambered wings’ aerodynamic performance and identified the advantageous features of cambered wing. In cambered wings, the camber angle significantly affects the formation and attachment of the vortex by changing the timing of these movements and by limiting the maximum twist angle. To analyze the effects of the camber angle, a parametric study on the camber angle at normal operating flight condition. It shows that the 12.5° cambered wing with the largest thrust results in a 9% thrust improvement, while 15° cambered wing with the largest efficiency resulting in a 14% efficiency improvement, when compared to the flat wing.

In the past, camber angle was only applied using experimental methods or simple theories. However, through this study, we drive the proper camber angle through the analysis of physical phenomena. Therefore, the moderate camber angle considering the operating frequency is an important parameter that can greatly improve the aerodynamic performance of the FW-MAV by changing the passive twist motion. However, it is also possible to alter the pattern by changing the shape, material, or driving speed. In addition, when both wings are fitted, the clap-and-fling effect can affect the start of the twist motion. An analysis of such additional parameters and understanding of trends can improve the performance of FW-MAVs that utilize flexible wings.

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