Aerodynamic Analysis of a Gull-inspired Flapping Wing Glider

Dawei Bie, Shiyu Zuo, Huadong Li, Haoyuan Shao and Daochun Li*
School of Aeronautic Science and Engineering, Beihang University, 100191, Beijing, China

*Corresponding author: lide@buaa.edu.cn

Abstract. This paper provided a gull-inspired flapping wing micro aerial vehicle (FMAV) concept followed with aerodynamic analysis. The FMAV supposed to implement both flapping and gliding mode during the flight to enlarge the endurance. A cambered airfoil is employed for wing cross section different with the traditional flat plate. Aerodynamic analysis is proposed through 3D computational fluid dynamics (CFD) method to get the lift characteristic of two different modes. Result shows that the FMAV is able to generate the lift force up to 5 N with an angle of attack 6 degrees and flight speed 6 m/s without flapping, which proves that the FMAV is able to achieve gliding in specific circumstance. Flapping motion is able to produce a higher lift during the flight. Comparison of the lift performance under a specific condition shows that the average lift generated with flapping is 65.3% higher than gliding mode. Research also found that the effect of airfoil camber on lift generation with flapping is not always positive, further analysis is needed when employs a cambered wing in design of FMAVs.

1. Introduction

Bionic flapping wing micro aerial vehicle (FMAV) has been widely concerned in recent years due to its high aerodynamic efficiency in low Reynolds number flight. Substantial design concepts of FMAV have been published. Researchers in Delft University of technology proposed a series of FMAVs concept named Delfly [1, 2] to process works such as stereo vision and flight control methodologies. Guo et al. [3] provided a design concept of flapping wing rotor MAV. The wing is activated through piezoelectric actuator. Prototype is produced and tested to verify the feasible of the design concept. Structure finite element analysis and aerodynamic simulation based on computational fluid dynamics (CFD) method is then proceeded. Ramezani et al. [4] designed a bat-inspired FMAV named Bat Bot (B2). The wing has a 5-DOFs mechanism to mimic the arm wing of the real bat which able to perform the asynchronously and mediolaterally motions. The employment of multi-DOF mechanism gives B2 ability to process more complex manoeuvre during flight.

To obtain the aerodynamic performance of the design concepts, Tay et al. [2] processed the analysis based on 3D CFD simulation with immersed boundary method, and then made a comparison of the lift and thrust of two types of FMAVs. Detailed vortex structure is revealed to illustrate the principle of lift and thrust generation of the FMAV. Xiang et al. [5] analysed the aerodynamic performance of the gliding mode of locust through 2D CFD simulations. The cross section of the forewing and hindwing is collected from biological data. The effect of wing corrugation is concluded with the simulation results. Mazaheri and Ebrahimi [6] conducted the wind tunnel test to analysis the lift and thrust properties under three design variables including angle of attack, wind speed and flapping frequency, respectively.
Low range and endurance are always the problem which restricted the application of FMAVs. To solve the problem in a view of biomimicry, among the series of birds, gulls are specialized on fast and long-distance migration, and are able to employ different flying strategy respect to different environment conditions during their journey. The gull is able to accomplish a long sea crossing ranges up to 700 km in an average speed 10.7 m/s. [7] The imitation of the wing shape and flight strategy of gulls is a possible way to solve this problem. In this paper, aerodynamic analysis of a gull-inspired flapping wing glider concept is provided. Analysis of flapping mode and gliding mode are proposed based on CFD simulations. Conclusions have been made based on simulation results.

2. Simulation setup

2.1 Model description
The concept of the gull-inspired FMAV employs a traditional layout which consist of wing, tail and fuselage. The CAD model for simulation is shown in Figure 1. Only lift characteristic is discussed in this paper thus the tail structure is ignored within the simulation model. The wing span of the model is 1.6 m and the aspect ratio is 8.

![Figure 1. Simplified simulation model](image1)

The aerodynamic analysis of the flapping mode and gliding mode is provided. Analysis is processed based on 3D CFD simulation. Three dimensional Reynolds-averaged Navier-Stokes (RANS) equation is solved through finite volume method.

2.2 Gliding mode simulation
Structured grid is employed as shown in Figure 2 for the simulation of gliding mode in order to obtain more accurate results. The grid generated is shown in Figure 2. The size of the far field is 100c*25c*50c. The grid thickness of boundary first layer is 10^-4 and the growth rate is 1.1. Symmetry boundary is employed at x=0. The total grid number is 7.3 million.

![Figure 2. Structured grid for simulation of gliding mode](image2)
The simulation is processed based on pressure based steady solver. SST k-ω model is selected as the viscous model. The boundary conditions are velocity inlet, pressure outlet and no-slip wall. SIMPLE scheme is employed for pressure-velocity coupling scheme. Second order upwind scheme is employed for spatial discretization. The initial simulation is processed with five different angles of attack with three free stream velocities including 3 m/s, 6 m/s and 10 m/s. Static lift and thrust at different angle of attack is obtained with the simulations.

2.3 Flapping mode simulation
Unstructured grid is employed for analysis of flapping mode because the unstructured grid is more stable in simulation with dynamic mesh. The generated grid is shown in Figure 3.

Figure 3. Unstructured grid for simulation of flapping mode

The size of the far field is same as gliding mode. The minimum grid size is 0.05c on the fuselage. Density increment is applied to the leading edge of the wing. The minimum grid size is 0.007c for the leading edge and 0.025c for rest of the wing. The total grid number of the model is 2.54 million. Dynamic mesh is implemented to fit the flapping motion of the wing. The wing motion is defined with a sinusoidal function as follows,

$$\theta = \theta_{\text{max}} \cdot \sin (2\pi f \cdot t)$$

where $\theta$ is the flapping angle at each timestep, $\theta_{\text{max}}$ is the flapping amplitude, and $f$ represent the flapping frequency.

The flight speed is selected to be 6 m/s for simulation. The variables selected during the simulation are flapping amplitude, angle of attack and flapping frequency.

3. Result discussion

3.1 Gliding mode results
The lift respect to angle of attack in different flight speed are shown in Figure 4. Result shows that the selected airfoil has a good aerodynamic performance. Results indicate that the designed FMAV has a property of glide in variance of flight speed. The lift slope at 10 m/s is 89% higher than the slope of 3 m/s, which shows the wing has a better lift performance at relatively higher speed.
Figure 4. Lift respect to angle of attack in gliding mode

CFD result shows that the FMAV is able to generate lift force up to 5 N with a flight speed 6 m/s and angle of attack 6 degrees. Pressure distribution with streamline around the wing cross section at half wing span is take for analysis. Data along the flow direction is provided in Figure 5. It can be seen that the air flow around the wing is adhered well at the angle of attack 3 degrees, only a small area of separation at trilling edge. While a large separation appears on the upper surface at the angle of attack 12 degrees, resulted a decrease of the slope of the lift curve.

Figure 5. Streamlines around the wing

3.2 Flapping mode results

3.2.1 Variation of flapping amplitude. The lift characteristic with the flapping amplitude 15 degrees, 30 degrees and 45 degrees are proceeded. Other variables are fixed including angle of attack 3 degrees and flapping frequency 6 Hz. Data of eight points are picked within one flapping cycle for analysis which are described in Figure 6. Lift results in one flapping cycle are shown in Figure 7. Results of average lift with three different flapping amplitude are 3.86 N, 4.90N and 7.29 N, respectively. It is able to obtain from the results that the average lift is growing with the increasing of the flapping amplitude. Serious care must be taken that the average lift with the flapping amplitude 15 degrees is lower than the steady lift without flapping. Pressure distribution with streamline along the flow direction with flapping amplitude 15 degrees are provided in Figure 8. Results show that the leading edge vortex during downstroke is not fully developed, while a strong vortex appears under the lower surface during upstroke, which produced a larger pressure difference compared with the downstroke at the same position.
Figure 6. Schematic drawing of the time points in one flapping period

Figure 7. Effect of flapping amplitude to aerodynamic lift

Figure 8. Pressure distribution with streamlines with flapping amplitude of 15 degrees

Pressure distribution with streamline along the flow direction with flapping amplitude 45 degrees are provided in Figure 9. Results show that the structure and position of the leading edge vortex during downstroke and upstroke has no obvious difference, but the pressure difference at 2/8 T during downstroke is dramatically larger than the result at 6/8 T. The appearance of this circumstance is probably due to the effect of the airfoil camber. Detailed reason may need further analysis in the future.
3.2.2 Variation of flapping frequency and angle of attack. The simulation of lift characteristic respect to different flapping frequency in three angle of attack conditions from 3 to 9 degrees are processed. The flapping amplitude in simulations are fixed to 45 degrees. Results are shown in Figure 10. It can be obtained that the increase of angle of attack and flapping frequency can all resulted a growth of lift at a large flapping amplitude. The high frequency flapping motion is able to increase the lift compared with the steady lift of gliding mode. Take the case with angle of attack 3 degrees as example, the lift increment with 4 Hz and 6 Hz flapping are 8.8% and 65.3% compared with the steady lift in gliding mode. But the lift of the case with flapping frequency 2 Hz resulted a lift decrement of 24%. Results show that a low flapping frequency could also induce a lift reduction as same as the effect of low flapping amplitude.

4. Conclusions
The aerodynamic analysis of a gull-inspired FMAV concept is provided in this paper. The FMAV is designed to flight with two different flying modes, flapping and gliding. 3D CFD simulations has been proceeded for both flapping and gliding modes. Analysis concluded that firstly, the FMAV is able to generate lift in traditional fixed wing mode with no flapping. Secondly, flapping mode is able to support a higher lift compared with the gliding mode at same flight conditions. The implement of flapping motion provides the FMAV a higher manoeuvrability compared with traditional fixed wing glider. Thirdly, the effect of airfoil camber on lift generation with flapping motion is not always positive. Simulation results in this paper show that the lift characteristics performs a decrement with the flapping amplitude 15 degrees. Cases employs a flapping frequency 2 Hz with the flapping amplitude 45 degrees.
has obtained the same effects. Further analysis is needed when employs a cambered wing in future design works of FMAV.

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