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THE PROPULSIVE EFFICIENCY OF FLEXIBLE FLAPPING-WING

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Abstract

Bionic flapping wing MAV has excellent aerodynamic performance and a wide application potential, which is usually equipped with a pair of flexible wings. Flexible flapping wing will deform in the flight for the pressure of aerodynamic and inertial forces generated in flapping movements. The propulsive efficiency of flexible flapping-wing is different with its rigid situation. At the meantime, the different flight conditions or parameters also affect the propulsive efficiency. This problem is investigated by numerical simulation method in this paper. The effects of flight velocity and flapping frequency are simulated. The results are given both in flexible and rigid flapping wings for comparison. The results show that the deformation can change the propulsive efficiency notably. The propulsive efficiency of flexible flapping wing is far larger than that of rigid wing. There will be a best parameters combination to make a highest propulsive efficiency for the flexible wings. The flapping wing air vehicles fly in this state will have long endurance or range.

1 Introduction

Flapping-wing MAV (FMAV) is a kind of bionic air vehicle, which uses flapping wings to generate lift and thrust simultaneously to balance the gravity and drag to sustain the vehicle in the air, whose flight manner is just as that of natural birds or insects. The FMAV has attracted a lot of interests because of its excellent aerodynamic properties and its unique bionic concealment.

The FMAV always use flexible wings, which will deform in the pressure of aerodynamics and the inertial force generated during the flapping motion. The flexible flapping wing deforms periodically in the flapping cycle, which is determined by structure stiffness, aerodynamic and inertial forces. There are some researches about the fluid structure interaction method [1-3].

When the wing deformation happens, the aerodynamic performance of flapping wing is different with its rigid situation, especially the thrust, which also makes a very different character in the propulsive efficiency. Lee et al [4] have studied the propulsion velocity of a flapping wing. Ashraf et al [5] studied some parameters effects on flapping airfoil propulsion. However, the propulsive efficiency are barely be noticed.

For a certain kind of flexible wing structure, the deformation increase with the increasing flapping frequency, flapping amplitude or flapping velocity. Moreover, larger deformation always brings on higher thrust. At the same time, the total power consumed changes. However, we do not know whether the corresponding propulsive efficiency increase or not.

The research domain of this paper is around the medium size bird scale as pigeon or pied magpie, which has a Re number range about 10^4-10^5. From the bird flight with medium size, we observed that the flapping motion can mainly generate enough thrust to push bird fly forwardly, and a notable part of the lift is generated by dynamic pressure in advanced speed. That is a mixture of unsteady and steady aerodynamic mechanism, which is different from the totally unsteady flight of small insect or hummingbird, who generates vector forces by flapping wings in high frequency, whose flight mechanism is more likely as helicopters. That is to say, the thrust has more significance for the bird scale FMAV than the insect scale FAMV, the later one mainly generate vector force.

In this paper, we concentrated the propulsive efficiency of flexible flapping-wing in different flight conditions by numerical simulation method. Firstly, the wind speed (the flight speed) effects on propulsive efficiency are analyzed. Secondly, the flapping frequency effects are analyzed.

3 Flexible Flapping-wing

The wing investigated has a topology of simplifying of bird wing, which composes of carbon fiber skeleton and polyester membrane, has a light mass, good strength and modulus, shown in Fig.1. The chord length is 10cm, and the span length is 26cm.

Fig.1. Flexible flapping wing.

The wing has a comparatively stiffer leading edge and relatively flexible rib. When the wing deforms in flapping motion, its trailing edge will deform larger than leading edge. This deformation manner makes the aerodynamic force deflect backward, which increase the thrust notably. At the same time, the stiffer leading edge can maintain the wing motion and basal shape.

The flapping wing motion is defined as a single-degree of freedom (DOF) motion. The motion is described as a basic state,

$$\psi(t) = \psi_1 \cos(\omega t) \qquad (1)$$

where, ψ is the flapping angle in the t time step, ψ_1 is the flapping amplitude, ω is the frequency.

The propulsive efficiency η is defined as,

$$\eta = Cp_{out} / Cp_{in} \qquad (2)$$

where, Cp_{in} is input power coefficient, which is the total energy consumed by flapping movements; Cp_{out} is output power coefficient, which is the energy consumed by thrust; so the η is the propulsive efficiency.

A larger η indicates a higher flight efficiency, also can be explained as easier flight. That is the focus of this paper.

2 Computational Fluid-Structural Dynamics

This proposed problem is investigated by numerical simulation method, which is developed in our previous research and is validated through comparisons with experimental results [6].

The unsteady aerodynamics of the flapping wing is derived by solving three-dimensional unsteady compressible Navier-Stokes equations , which can be written as,

$$\frac{D}{Dt}\iiint_{\Omega} W dV + \iint_{\partial\Omega} \overline{\overline{H^{'}}} \bullet n dS = \iint_{\partial\Omega} \overline{\overline{H_v}} \bullet n dS \qquad (3)$$

where, W is the state vector of conservative variables, Ω is the control volume, S, n denote the boundary of control volume and its unit-normal outer vector, $H^{'}$, H_v denote the inviscous and viscous fluxes, respectively.

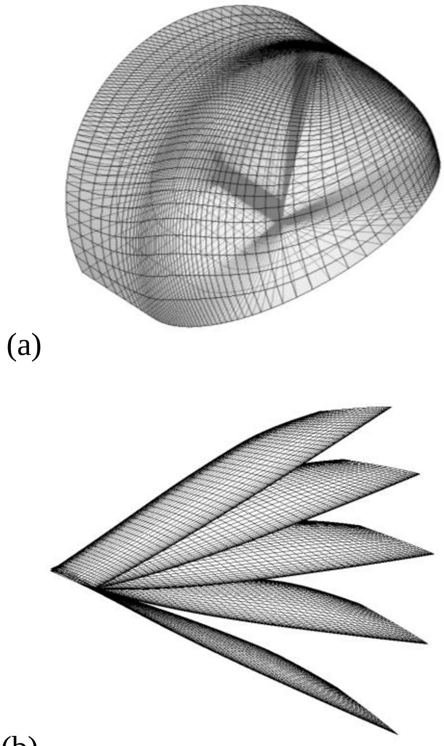
The governing equations are solved by means of a cell-centered finite volume approach using a LU-SGS time-stepping method with multi-grid acceleration, and the $k-\omega$ SST turbulence model is applied.

A CO type body-fitted grid is used for the aerodynamic simulations. Grid size is 176, 56, and 60 in the tangential, radial and spanwise directions respectively. Fig.2 shows the grid system of the flapping wing generated by our grid generation program.

By use of the Hamilton principle [7], the structural equation of wing motion can be expressed as follows,

$$\int_{t_1}^{t_2} (\delta U - \delta V - \delta T) dt = 0 \qquad (4)$$

where, $\delta U, \delta T, \delta V$ are the items of strain energy, kinetic energy and work done by external force respectively.


(a)

(b)

Fig.2. (a) The topology of the grid distribution of the wing; (b) the view of wing surface grid.

A beam elements based on Timoshenko beam theory is applied to simulate the carbon fiber; Shell elements with ability of both bending and membrane simulation is applied to simulate the membrane of flapping wing.

Fluid-structure interaction requires an interface between the flow system and the structural system. An interpolation method -- Radial Basis Functions (RBF) [8,9], is applied for the information interaction between fluid and structure solvers.

A coupling method in entire flapping cycle is developed to solve the problem. The periodic aerodynamic force is calculated by fluid solver firstly, then the periodic structural displacement and velocity as well as acceleration are calculated by structure solver, and then the periodic aerodynamic force is calculated again until both the structural deformation and the aerodynamic forces are convergent. Fig.3 shows the flowchart of this coupling method.

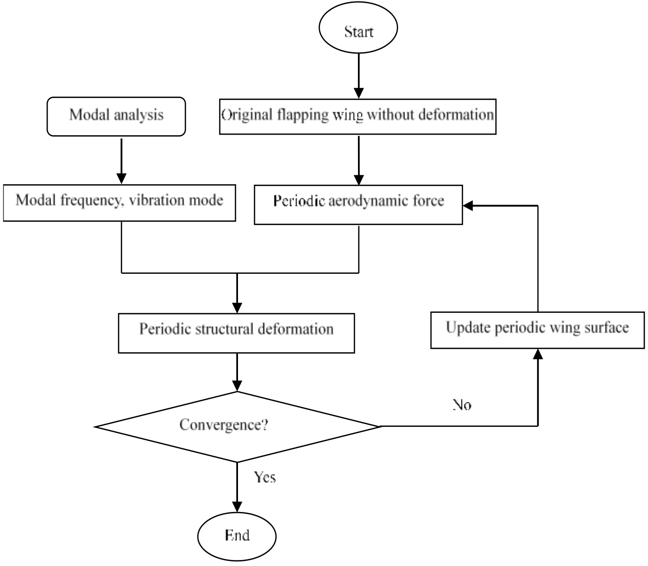


Fig.3. The flowchart of the coupling approach.

4 Results and Discussions

The effects of wind speed and flapping frequency are simulated. Firstly, the effect of wind speed is researched. The rigid wing situation is also be simulated for comparison. When the wind speed changes from 5m/s to 10m/s and the flapping frequency remain 6Hz, simulated results is shown in Table 1. Secondly, the effect of flapping frequency is researched. When the flapping frequency changes from 3Hz to 8Hz and the wind speed remain 6m/s, simulated results is shown in Table 2.

The results in Table 1 and Table 2 show that the deformation can change the propulsive efficiency notably. We can find that the propulsive efficiency shows different properties. In both tables, the input power of rigid flapping wing is larger than that of flexible wing, but the output power of rigid flapping wing is far less than that of flexible wing, which makes the propulsive efficiency of flexible flapping wing far larger than that of rigid one.

The propulsive efficiency of rigid flapping wing increases a little with the increase of wind speed, but the propulsive efficiency of flexible flapping wing will increase to the top when the wind speed is around 9m/s, which means there will be a best flight velocity for a flexible flapping wing MAV with best propulsive efficiency.

The propulsive efficiency of rigid flapping wing decrease with the increase of flapping frequency, but the propulsive efficiency of flexible flapping wing does not change significantly with the flapping frequency, which might be caused by the adaptive deformation of flexible wings, the increment of output power is similar with that of input power.

Analyze above results comprehensively, there will be a best parameters combination to make the highest propulsive efficiency. The air vehicles flying in this state will have long endurance or range.

Table.1 Wind speed effects on the propulsive efficiency

Wind speed (m/s)	Rigid flapping wing			Flexible flapping wing		
	Input power coefficient Cp_{in}	Output power coefficient Cp_{out}	Propulsive efficiency η	Input power coefficient Cp_{in}	Output power coefficient Cp_{out}	Propulsive efficiency η
5	11.113	0.067	0.60%	6.781	2.966	43.74%
6	8.843	0.056	0.63%	4.436	2.241	50.52%
7	7.564	0.049	0.65%	3.276	1.771	54.07%
8	6.592	0.044	0.68%	2.240	1.314	58.67%
9	5.967	0.048	0.80%	1.462	0.886	60.59%
10	5.275	0.045	0.84%	0.901	0.537	59.58%

Table.2 Flapping frequency effects on the propulsive efficiency

Flapping frequency (Hz)	Rigid flapping wing			Flexible flapping wing		
	Input power coefficient Cp_{in}	Output power coefficient Cp_{out}	Propulsive efficiency η	Input power coefficient Cp_{in}	Output power coefficient Cp_{out}	Propulsive efficiency η
3	4.533	0.050	1.09%	2.249	1.095	48.69%
4	5.950	0.047	0.78%	3.159	1.521	48.14%
5	7.474	0.051	0.68%	3.408	1.759	51.63%
6	8.843	0.056	0.63%	4.436	2.241	50.52%
7	10.745	0.066	0.61%	5.288	2.690	50.87%
8	12.600	0.073	0.58%	5.542	2.866	51.71%

5 Conclusions

This paper concentrated the propulsive efficiency of flexible flapping wing in different flight conditions by numerical method.

The flexible wing of this study is at the scale of medium birds, with a 10cm chord length and 26cm span length of single wing.

The effects of the wing speed and the flapping frequency are simulated. The results are compared between the flexible and rigid wings.

From the results, we known that the propulsive efficiency of the flexible flapping wing is far larger than that of the rigid one. That is a proof of why most FMAV use flexible flapping wings but not rigid wings.

In the situation of this paper, wind speed of 9m/s has a best propulsive efficiency, and propulsive efficiency is not sensitive with flapping frequency, might since the adaptive deformation.

The high propulsive efficiency can lead to a long endurance or range. That also means an easier flight.

This study aims at investigating the propulsive efficiency of flexible flapping wing. This paper has significance to understand and advance the mechanism of micro flexible flapping wing.

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