Aerospace Science and Technology ••• (••••) •••–•••

Contents lists available at ScienceDirect

Aerospace Science and Technology

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Analysis and experiment of a bio-inspired flyable micro flapping wing rotor

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A R T I C L E I N F O

Article history:
Received 24 July 2017
Received in revised form 4 June 2018
Accepted 4 June 2018
Available online xxxx

Keywords:
Bioinspired flapping wing
Flyable micro FWR
Aeroelastic effect
Flight simulation

A B S T R A C T

Inspired by insect flapping wings, a novel flapping wing rotor (FWR) has been developed for micro aerial vehicle (MAV) application. The FWR combines flapping with rotary kinematics of motions to achieve high agility and efficiency of flight. To demonstrate the feasibility of FWR flight and its potential MAV application, an extensive and comprehensive study has been performed. The study includes design, analysis, manufacture, experimental and flight test of a flyable micro FWR model of only 2.6 gm weight. By experiment, the FWR kinematic motion and aerodynamic lift were measured using high speed camera and load cells. Within a range of input power, the difference between the measured aerodynamic force and the analytical results by a quasi-steady model was found to be within 3.1%–15.7%. It is noted that the FWR aeroelastic effect plays a significant role to obtain an ideal large angle of attack especially in up-stroke and enhance the FWR performance. Further analysis of the unsteady aerodynamic characteristics has been carried out based on the detailed airflow field of the FWR in a flapping cycle by CFD method. A successful vertical take-off and short hovering flight of the micro FWR model has been achieved for the first time in the research field. The flight test demonstrates the FWR feasibility and its unique feature of flight dynamics and stability for the first time. These characteristics have also been simulated by using ADAMS software interfaced with the aerodynamic model.

1. Introduction

Micro air vehicles (MAV) of high performance including the capability of vertical take-off and landing (VTOL) and hovering capability can be operated in complex and risky environments including inside buildings. Two decade ago, the U.S. Defence Advanced Research Projects Agency (DARPA) launched a three-year MAV programme with the goal of creating a micro flyer for military surveillance and reconnaissance [1]. US Air Force Research Laboratory has the goal to develop a bird-sized MAV by 2015 and an insect-sized MAV by 2030. Motivated by the potential and growth demand of employing high performance micro air vehicles, various MAVs have been developed including fixed wing and rotorcraft configurations being used to carry out special missions. Inspired by the high agility of flying animals, research attention has also been attracted to studying bird-like and insect-like flapping wings [2–4].

In previous research, most of the attention was paid to the aerodynamic study of insect wing flapping in horizontal plane at very low Reynolds number ($Re \sim 10^3$) [5]. The subsequent study has revealed that the stall delay associated with attached leading edge vortex (LEV) plays a key role for high aerodynamic lift of insect flapping wings [6]. The LEV is stabilized by the spanwise flow which transports vorticity towards wingtip similar to a conventional delta wing, which produces majority of the high mean lift force (about 80%) in a flapping cycle [7], while the rotational circulation and added mass effects contribute to the instantaneous lifting peaks at stroke reversals [8]. Experimental and numerical results also indicate that the vortex stretching could significantly delay the detachment of the LEV, even when the spanwise flow was weak [9]. Subsequent studies on rotary wing of small aspect ratio showed that the LEV could be stabilized by the centripetal and Coriolis accelerations at low Rossby number ($Ro = \frac{R_2}{\bar{c}}$, where R_2 is the radius of the second area moment, and $\bar{c}$ is the mean chord length) as the results of previous numerical and experimental studies [10–12]. In the same period, there were more investigations on the aerodynamic simulation of insect flapping wings [13–15].

Because of the LEV attachment aerodynamic characteristics, the insect flapping wings are capable of operating at large angle of attack (AoA) to meet the requirement for high average lift coef-

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https://doi.org/10.1016/j.ast.2018.06.009
1270-9638/

ficient. For the same reason however, the associated drag is also large in the same magnitude as the lift. As opposed to flapping wings, the conventional rotorcraft blade keeps operating at small AoA to prevent stall, but at high rotational speed to gain the required lifting force. Experimental studies have shown that at low *Re* (100–14000), the rotary wing have higher aerodynamic efficiency in terms of lift production than flapping wing [10]. It was therefore suggested that the rotary wing may be superior for insect-sized MAV design in terms of energy efficiency [16]. However, the above findings are limited to the conventional rotary wing and the prescribed insect-like flapping wing kinematics.

In order to improve the aerodynamic efficiency of flapping wings, a bioinspired novel flapping wing rotor (FWR) was proposed earlier [17]. The FWR combines two types of motion, i.e. the insect-like flapping motion and man-made rotary motion. Driven by a vertical oscillating force to generate a prescribed primary flapping motion, the FWR produces lift and thrust forces simultaneously. The thrust propels the FWR to rotate in its horizontal plane. Since the FWR rotation is in a self-propelled passive mode, it keeps in a balanced equilibrium status of thrust against drag. For the same reason, there is no actuating torque and hence there is no need for counter rotation torque input, as opposed to the conventional rotorcraft. This feature leads to a power saving and system simplicity. In addition, the horizontal air velocity of the rotating FWR enhances the aerodynamic lift. Furthermore, it also leads to a significant reduction of necessary pitch angle in the upstroke comparing with the dragonfly wing, which makes the FWR kinematics of motion feasible and practical. The FWR adds new specie in the bioinspired flapping-wing field as an alternative option for MAV application. Since then, increasing efforts have been contributed to the study of FWR aerodynamic behaviours. Guo and Zhou et al. studied the aerodynamic performance of FWR by experimental and numerical methods [18,19]. By effectively changing the pitch angle in the up-stroke and down-stroke, the FWR will achieve different status for lift and efficiency. Wu et al. [20] performed further detailed study of the forces produced by FWR at $Re = 350–9000$ using CFD method. Their results showed that the LEV formed on the wing of FWR stays attached throughout the flapping cycle, which provides lift enhancement similar to insect wings.

In a recent work by the authors [21,22], the optimal kinematics of motion for FWR was identified and the aerodynamic lift and efficiency were calculated and compared with the conventional rotary and insect-like flapping wings. The results showed that the FWR can produce significantly greater aerodynamic lift coefficient and power efficiency than the insect-like flapping wings. The rotary wing has greater power efficiency, but smaller lift coefficient than the FWR and flapping wings. The FWR offers a significantly broader range of combination of aerodynamic lift and power efficiency. The FWR kinematics thus takes advantages of both the insect-like flapping wing and the rotorcraft and offers an alternative design for MAV.

Based on extensive studies of the FWR by the first author and his research teams in the last 10 years, investigation has been continued into the design, analysis, manufacture and experiment of a flyable micro FWR MAV test model. Driven by a micro electric motor and using carbon/epoxy composite to build most of the components, the total weight of the FWR test model is achieved to be only 2.6 gm. In the experiment, the wing kinematics and aerodynamic lift of the FWR model were measured using high speed camera and load cell. A desirable FWR wing structure was realised after a series of design and experiment to achieve the desired large pitch angle in the up-stroke for the FWR test model. The aerodynamic analysis was carried out using CFD method together with a quasi-steady aerodynamic method which employs empirical coefficients that accounts for unsteady aerodynamic effects [23,24]. The comparison of the analytical and experimental results shows excellent agreement. Subsequently a vertical take-off and short flight test of the FWR model was successfully carried out. This is, to our knowledge, the first flight test of the FWR vehicle. To further reveal the free-body dynamics and stability of the FWR model, flight simulation was performed using ADAMS combined with the quasi-steady aerodynamic method.

2. FWR model and analysis method

2.1. FWR coordinate and kinematics

The coordinate system for the FWR model including the inertial frame (x, y, z) and the wing-fixed frame (x_w, y_w, z_w) is defined and illustrated in Fig. 1. The FWR device is essentially mounted with two wings in axial symmetry although only the right wing is shown in Fig. 1. The pair of wing root o is attached to a lever mechanism at the top of the FWR body. The rotation, flapping, and pitch angles of the wing are denoted by ψ, ϕ, and α, respectively.

Based on the above definition, the angular velocity of the wing in the inertial frame can be obtained by the time derivatives of the three Euler angles as:

$$\vec{\omega}_i = \begin{bmatrix} 0 \\ \dot{\psi} \\ 0 \end{bmatrix} + R(\psi)\begin{bmatrix} \dot{\phi} \\ 0 \\ 0 \end{bmatrix} + R(\psi)R(\phi)\begin{bmatrix} 0 \\ 0 \\ \dot{\alpha} \end{bmatrix} \tag{1}$$

where $R(\psi)$ and $R(\phi)$are the rotation matrixes of the corresponding Euler angles. The angular acceleration in the inertial frame $\dot{\vec{\omega}}$ can be derived directly by differentiating the above equation. The angular velocity and acceleration of the wing in the wing-fixed frame are obtained by applying the following frame transformation:

$$R_{i\to w} = R^T(\alpha)R^T(\phi)R^T(\psi) \tag{2}$$

The velocity and acceleration vector of a 2D wing chord at span-wise location r in the wing-fixed frame are given by:

$$\vec{U}(r) = \vec{\omega} \times \vec{r} = [u_x \quad u_y \quad 0]^T \tag{3a}$$

$$\dot{\vec{U}}(r) = \dot{\vec{\omega}} \times \vec{r} + \vec{\omega} \times (\vec{\omega} \times \vec{r}) = [\dot{u}_x \quad \dot{u}_y \quad \dot{u}_z]^T \tag{3b}$$

where $\vec{\omega}$ denotes the rotation rate of the wing (in the wing-fixed frame); $\vec{U}(r)$ and $\dot{\vec{U}}(r)$ refers to the velocity and acceleration vector; u_x, u_y and $\dot{u}_x$, $\dot{u}_y$, $\dot{u}_z$ are used to indicate the corresponding velocity and acceleration components. Based on the kinematic parameters, the effective angle of attack (AoA) of the wing at any instantaneous time can be determined by inversing the trigonometric function of the velocity ratio:

$$\alpha_e = \arctan\left(\frac{u_y}{u_x}\right) \tag{4}$$

The kinematics of the wing is defined by three elementary motions: rotation, flapping and pitch, each corresponds to an Euler angle described above. The rotation of the wing is passively induced by aerodynamic force and the rotation speed at equilibrium is a constant number ψ_0. The wing flaps up and down passes through the level plane while pitches at the same time. The flapping angle and frequency are denoted by Φ and f. The pitch angles of the wing at mid-upstroke and mid-downstroke are denoted as α_u and α_d, respectively. Fig. 2 illustrates a typical FWR kinematics (simple harmonic motion) with a flapping amplitude d and asymmetric AoA in up-stroke and down-stroke.

The above kinematic parameters in a series of flapping cycles for the experimental cases are obtained using discrete image processing method. The resulting wing motions are presented in section 3.