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Automated Kinematics Measurement and Aerodynamics of a Bioinspired Flapping Rotary Wing

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Abstract

A physical model for a micro air vehicle with Flapping Rotary Wings (FRW) is investigated by measuring the wing kinematics in trim conditions and computing the corresponding aerodynamic force using computational fluid dynamics. In order to capture the motion image and reconstruct the positions and orientations of the wing, the photogrammetric method is adopted and a method for automated recognition of the marked points is developed. The characteristics of the realistic wing kinematics are presented. The results show that the non-dimensional rotating speed is a linear function of non-dimensional flapping frequency regardless of the initial angles of attack. Moreover, the effects of wing kinematics on aerodynamic force production and the underlying mechanism are analyzed. The results show that the wing passive pitching caused by elastic deformation can significantly enhance lift production. The Strouhal number of the FRW is much higher than that of general flapping wings, indicating the stronger unsteadiness of flows in FRW.

Keywords: bioinspired flapping rotary wing, aerodynamics, wing kinematics measurement, computational fluid dynamics, micro air vehicle

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1 Introduction

Over the past two decades, Micro Air Vehicles (MAVs) have attracted widespread interest because of their considerable potentials in civil and military applications[1–6]. MAVs have numerous advantages, such as lightweight, flight in confined spaces, good maneuverability, and low cost[7]. Apart from fixed wing, flapping and rotating wing configuration, a novel MAV design, called Flapping Rotary Wing (FRW), was recently proposed[8,9]. The design has a pair of wings flapping vertically and rotating passively around its vertical shaft (Fig. 1). The FRW combines the motions of the flapping and rotating wings, therefore, whether aerodynamic performance can benefit from both configurations attracts the interest of engineers. Although the aerodynamic characteristics of rotating wing and flapping wing at scale of MAV have been studied extensively[10–18], investigation into FRW still needs to be conducted further because its flow is more complex than either of the aforementioned aerodynamic configurations. Moreover, how the aerodynamic forces are generated and what underlying mechanisms are used remain unclear.

Some preliminary works were conducted to investigate the feasibility and aerodynamic performance of FRW[9,19–21]. The experiment and analysis of a piezo-driven model and a motor-driven model showed that FRW can generate sufficient lift to fly and may be an alternative to MAV design. Thus, examining the characteristics of its aerodynamics in detail is significant. The wing rotation around the vertical axis is a passive motion, and both the rotating velocity and the flapping velocity determine the effective Angle of Attack (AoA) of the wing. Thus, the lift depends heavily on flapping kinematics and wing deformations. Wu *et al*. used Computational Fluid Dynamics (CFD) to study the flow features of a FRW model and the critical non-dimensional parameters affecting its aerodynamic characteristics. They assumed that the flapping and pitching motions of wings are simple sinusoid functions, and the rotating speed around the vertical axis is pre-specified. Actually, wings are usually lightweight and flexible, and their rotating speed depends strongly on flapping frequency, wing deformations, and friction

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of the mechanisms. Therefore, the realistic wing kinematics, including wing deformations under trim wing rotating conditions, should be further considered in FRW studies.

In this study, we design a physical FRW model and measure the realistic kinematics of wings. Then, CFD method is used to obtain flows around wings and the aerodynamic forces and moments according to the measured wing kinematics. Through this method, we can explore the underlying fluid mechanisms and the effects of passive rotation and deformation of wings on aerodynamics in a FRW MAV.

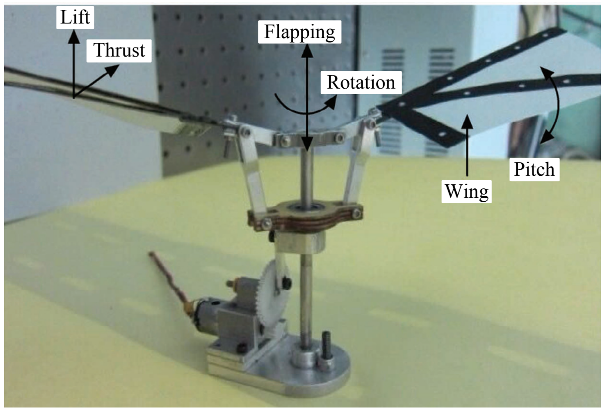

Fig. 1 Illustration of an implementation of a FRW design.

2 Model and methods

2.1 Experimental model and setup

The mechanical structure of the FRW model is shown in Fig. 1. The model consists of three components: an electric motor, a transmission system, and a pair of wings. The circular motion of the motor is transferred to an up-and-down motion of a slider that drives the wings to flap vertically. After several flaps, the aerodynamic forces propel the wings to rotate horizontally around the vertical shaft in a steady rotational motion.

The wings are made of three beams (carbon fiber strips) that support a thin skin. The planform of the wing and its size and the relative position of the three beams are shown in Fig. 2a. Ten white circular marks are placed along the beams to allow their motion image captured to automatically reconstruct the wing motion.

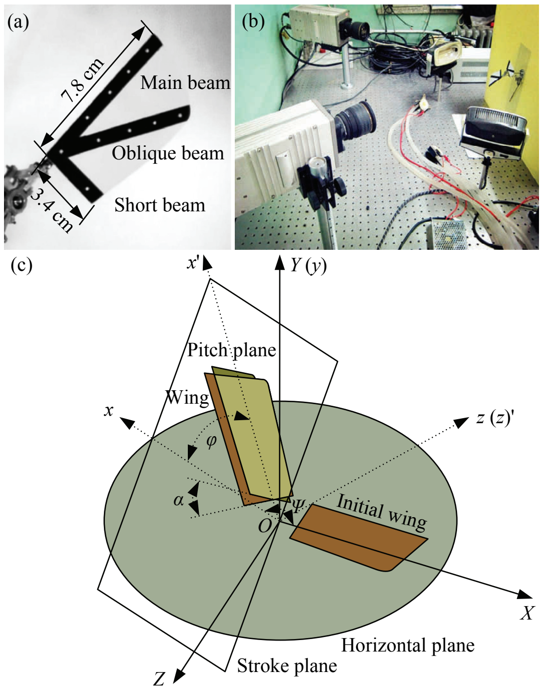

Fig. 2 (a) A FRW model; (b) experiment setup; (c) definition of a coordinate system and the Euler angles.

The motion and deformation of the wings are captured using a binocular filming system composed of two synchronized high-speed cameras mounted on an optical table (Fig. 2b). The synchronized cameras are triggered manually to capture the wing motion when the wings rotate constantly. The 2D images of wing motion are captured from different views, thus the 3D position information of the marked points on beams can be obtained after calibrating the two cameras, and then the wing motion can be reconstructed from the positions of the marked points.

2.2 3D reconstruction method

A program is developed to capture and process the 2D images automatically in two-stages. The critical part of this process involves detecting the marked points and matching them with one another from the two cameras. First, the marked points in each single image frame are detected and extracted. Second, the marked points are grouped into three classes and matched to identify the spatial coordinates of the three beams of the wing.

The raw Red, Green and Blue (RGB) images are pre-processed to binary images by converting to grayscale and setting a threshold. Then, opening and closing operations were applied, enabling us to extract clear edges. The results of each step are shown in Fig. 3.

After edge detection, we can label foreground pixels to several objects based on the neighborhood connection relationship. These objects include parts of beam line, marked point edges, models, shadow of light, and image noises. We then extract the marked point edges