C. R. Mecanique 344 (2016) 195–207

Contents lists available at ScienceDirect

Comptes Rendus Mecanique

www.sciencedirect.com

The inertial power and inertial force of robotic and natural bat wing

Dongfu Yin *, Zhisheng Zhang

School of Mechanical Engineering, Southeast University, Nanjing, Jiangsu, 211189, China

A R T I C L E   I N F O

Article history:
Received 12 July 2015
Accepted 9 November 2015
Available online 3 February 2016

Keywords:
Inertial power
Inertial force
Bat wing
Skeleton
Robotic bat
Computational model

A B S T R A C T

Based on the acquired length and angle data of bat skeletons, a four-degree freedom robotic bat wing and an identical computational model with flap, sweep, elbow and wrist motions were presented. By considering the digits motions, a biomimetic bat skeleton model with seven-degree freedom was established as well. The effects of frequency, amplitude and downstroke ratio, as well as the components of inertial power and force on different directions, were studied. The experimental and computational results indicated that the inertial power and force accounted for the largest part on flap direction, the wing fold during upstroke could reduce the inertial power and force.

1. Introduction

Bats have heavy muscular wings with joints that enable higher degrees of dexterity [1]. For different bat species, although the wing mass account for only 11% to 20% of the total bat mass [2], it generates enough lift and thrust to maintain bat flying. The distinctive capacity for powered flight subjects the limb skeletons of bats [3]. The skeletons are important constitutive parts of the wing. They are used to support the wing membrane to generate lift and thrust, to resist primarily bending forces and large torsional forces, to withstand the loads applied to them, and to achieve complex movements by changing the angles between different bones.

The inertial power and force are the power and force needed to make the wings oscillate [4]. Unlike fixed-wing aircrafts, flying organisms cannot continuously generate constant lift and thrust [2]. In each flap cycle, the wing has two accelerations and two decelerations, and the inertial power and force will be changed along with the change of velocities and accelerations. Although the inertial power of native bat wing has already been studied [2,5,6], these results often include the effects of wing membrane, and the effects of the skeleton on the inertial power and force require further investigation.

A flying bat must do work with its flight muscles to move the wings; the rate at which this work is done is the mechanical power [4]. The ratio of inertial power to mechanical power remains controversial [4–9]. Although the inertial power might account for a small percentage of the total power for some native bats [10], this may not be applicable for the robotic bat. By analyzing the recently designed and fabricated robotic bat wings, we found that it is different from the native thinner skeletons; the robotic bat skeletons were often strengthened by increasing the size or selecting high-density materials to keep the rigidity [11–15]. Therefore, for the robotic bat wing, the inertial power and force might be larger than the actual bat skeletons and cannot be neglected.

* Corresponding author. Tel.: +86 15205181132.
E-mail address: ydf678@hotmail.com (D. Yin).

http://dx.doi.org/10.1016/j.crme.2015.11.002

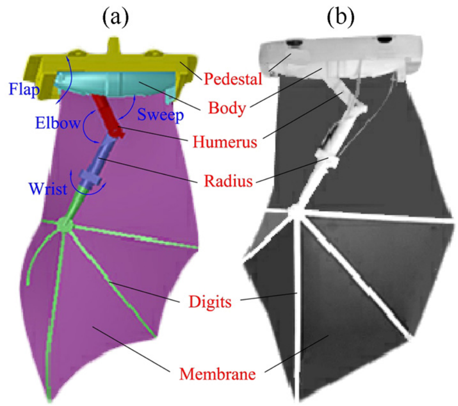

Fig. 1. The motions and structure of the robotic bat wing. (a) Solid works model. (b) Fabricated model.

The inertia force is also an important factor that needs to be considered for the future robotic bat wing design, especially for the large-scaled models. Some simple theoretical formulas of flap motion have been proposed to investigate the factors that affect the inertial power [6,16], but not enough attention has been paid on the effects of inertial force. Meanwhile, some parameters, such as the frequency, amplitude, downstroke ratio, etc., which affect the flight efficiency remarkably might have obvious influence on the robotic bat wing as well. How these factors affect the inertia power and force on bat skeletons still needs to be revealed. As a result, models or equations that can reflect the relationships between the above parameters and inertial power and force need to be established.

For the robotic bat wing, multiple motors were combined to realize complicated manoeuvres of the wing [12–15]. But for a particular motor, it can only change one motion direction. The flap, sweep and elbow motions were three major movements that accounted for the largest proportion of inertial power [13], and these three motions correspond to the inertial power on up–down, forward–backward and expand–contract directions. On the other hand, the robotic wing was installed on the test section and the instantaneous inertial forces quantified with load cells [12–15]. For a full-motion bat wing, it imposes inertial force on the lift direction, the drag direction, and the spanwise direction. The analysis of inertial power and force on different directions can help to choose appropriate motors and load cells for future robotic bat design and application.

In the present study, the influence of bat skeleton movements on inertial power and force were studied. Based on the size and real-time angle data of *Eptesicus fuscus*, a 4DOF (four degrees of freedom) robotic bat wing was designed and fabricated (Fig. 1). Uniformly, a same 4DOF bat skeleton computational model with divided fragments was established to compare the inertial values with the robotic bat wing. Appended with the digit motions, the 4DOF model was then extended to a more accurate 7DOF (seven degrees of freedom) calculation model. Combined with the 4DOF computational model, the sinusoidal flap theoretical equations were detailed to indicate the impact factors to the inertial power and force. The influence of frequency, amplitude, downstroke ratio on the inertial power and inertial force of the 4DOF robotic bat wing, 4DOF and 7DOF computational models were compared together. The inertial power and force components on up–down, stretch–shrink, and fore–aft directions of different fragments were also studied.

2. Materials and methods

2.1. Robotic bat wing

For a bat in level flight, the right wing was used to define the coordinate system. The positive X direction was along the bat tail to head, the positive Y direction was along the wing root to wingtip, the positive Z direction was perpendicular to the XY plane and pointing up. Seven angles were used to describe the complex movements between different skeletons of the bat's wing. These angles reflect the bat wing's flap motion, stretch-shrink motion, rotate motion and motions between digits. For a horizontal flight bat, the flap angle was defined as the angle between the humerus and the horizontal plane. The sweep angle was defined as the angle between the humerus and the vertical plane. The elbow angle was calculated as that between the humerus and the radius. The wrist angle was the angle between two planes, one plane was composed by shoulder joint, elbow joint and wrist joint, another plane consisted of wrist joint, digit3 and digit5 tip markers. Three radius-digit angles were defined as the angle between the radius and the corresponding digit. Nontoxic markers were drawn on the joints and tips of the bat wing, and high-speed cameras (Photron Fastcam-X 1280 PCI camera) were used to track the marker positions during the bat's flight. The real-time angles were calculated based on the obtained marker positions. Fig. 2 shows the real-time angle changing curves of a typical bat.

Based on the measured bat skeleton length and angle data, a 4DOF robotic bat skeleton model was established in Solidworks software and manufactured by a 3D printer (Dimension 1200es, Stratasys). The robotic bat wing was composed by pedestal, body, humerus, radius and digits. To reduce the number of motors and the complexity of the model, the