Journal of Theoretical Biology 266 (2010) 485–495

Contents lists available at ScienceDirect

Journal of Theoretical Biology

journal homepage: www.elsevier.com/locate/yjtbi

Numerical investigation of the aerodynamic characteristics of a hovering Coleopteran insect

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ARTICLE INFO

Article history:
Received 6 April 2010
Received in revised form
14 July 2010
Accepted 15 July 2010
Available online 27 July 2010

Keywords:
Insect hovering flight
Flapping kinematics
Elytron
Wing interaction

ABSTRACT

The aerodynamic characteristics of the Coleopteran beetle species *Epilachna quadricollis*, a species with flexible hind wings and stiff elytra (fore wings), are investigated in terms of hovering flight. The flapping wing kinematics of the Coleopteran insect are modeled through experimental observations with a digital high-speed camera and curve fitting from an ideal harmonic kinematics model. This model numerically simulates flight by estimating a cross section of the wing as a two-dimensional elliptical plane. There is currently no detailed study on the role of the elytron or how the elytron–hind wing interaction affects aerodynamic performance. In the case of hovering flight, the relatively small vertical or horizontal forces generated by the elytron suggest that the elytron makes no significant contribution to aerodynamic force.

1. Introduction

Understanding how flapping mechanisms generate outstanding aerodynamic performance has been a major focus of insect flight research in recent years (Ellington et al., 1996; Wang, 2000b). The research includes accurate quantification of complex kinematics of flapping insect wings, measurement of forces produced by flapping wings, and visualization of flows developed around wings. Visualization tools such as the smoke wire technique (Thomas et al., 2004) and the digital particle image velocimetry technique (Bomphrey et al., 2005) have enabled researchers to formulate the basic flapping mechanism of insects. These techniques have revealed that the flow characteristics of flapping flight differ from those of non-flapping flight.

The application of smoke visualization techniques inside a wind tunnel enables the vortices generated by an insect's wings to be observed (Grodnttsky and Morozov, 1992; Willmott et al., 1997). However, it is extremely difficult to obtain repeatable airflow data from live insects because of their small size and handling difficulty. Researchers have used two strategies to overcome these limitations. The first approach is to construct a scale-up robotic insect for direct measurement of aerodynamic forces and visualization of the flow characteristics. Such robotic insect is much easier to manipulate and duplicate its motion than that of a living insect (Berg and Ellington, 1997; Dickinson et al., 1993, 1999). The second approach utilizes computational fluid dynamics to simulate flapping wings (Sun and Lan, 2004; Wang, 2000a, 2004; Zuo et al., 2007; Ishihara et al., 2009).

During flight, an insect wing produces a leading-edge vortex. This vortex has a helical shape, and it is stably attached on a wing during the wing's downstroke (Berg and Ellington, 1997; Birch and Dickinson, 2001; Ellington et al., 1996; Lu and Shen, 2008; Lentink and Dickinson, 2009). Three mechanisms, namely the delayed stall, rotational circulation, and wake capture mechanisms, were proposed to explain the flapping wing flight of insects (Birch et al., 2004; Dickinson et al., 1999; Fry et al., 2003). They attempted to prove their theory by constructing and using dynamically scaled-up robotic wings to acquire quantitative velocity data via a digital particle image velocimetry technique. Various kinds of vortex were found through recent 3D vortex structure analysis (Bomphrey et al., 2005; Sun and Lan, 2004). When a wing movement is accompanied with flapping, lagging and rotating, vortices such as leading-edge vortex, trailing-edge vortex, wing-base vortex, upper surface vortex, and lower surface vortex and axial flow are observed (Zuo et al., 2007). During the early downstroke and upstroke, a horseshoe-shaped primary vortex is observed to wrap around each wing, doughnut-shaped vortex rings break up into two circular vortex rings as they propagate downstream in the wake in a hovering hawkmoth study (Aono et al., 2009).

Researchers have been using the computational fluid dynamics to simulate the insect flapping wings as a means of investigating

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0022-5193/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jtbi.2010.07.013

the details of the insect flight mechanism (Liu and Kawachi, 1998; Sun and Lan, 2004; Wang and Russell, 2007; Kim et al., 2009). Wang (2000a) developed a computational fluid dynamic code to simulate a 2-D flapping wing. Her numerical results revealed that a downward dipole jet is formed from the leading-edge and trailing-edge vortices. A comparison of a 2-D numerical simulation and 3-D experiments of scaled-up robotic fly wings was recently published (Wang et al., 2004). From this comparison, the main difference between a 3-D revolving wing and a 2-D translating wing is the absence of vortex shedding in a 3-D wide domain by a revolving wing, though this absence of vortex shedding has a negligible effect in the case of a small translational distance. Other main phenomena, namely leading-edge vortex shedding and a delayed stall, were also observed in the 3-D simulations just as they were in the 2-D simulations; these phenomena explain the high lift mechanism (Ramamurti and Sandberg, 2002; Zuo et al., 2007). 2D simulation was performed to compute the aerodynamic force and power of dragonfly as a function of the phase. The out-of-phase motion used in steady hovering spends nearly minimal power to generate the required force to balance the weight, and the in-phase motion seen in takeoffs provides an additional force to accelerate the body (Wang and Russell, 2007). The vortex in the corrugation valleys near the leading-edge forms smooth streamline around the wing like an airfoil, and relatively reduces the drag coefficient in steady simulation (Kim et al., 2009).

The study of insect flight is motivated by the need to understand the flapping mechanism and by the practical purpose of producing an unmanned air vehicle based on the flapping wing mechanism instead of a conventional fixed wing. Flapping-type unmanned air vehicles can operate in extreme environmental conditions, as in the case of a Mars exploration mission (Ellington, 1999; Ho et al., 2002). Insect species such as the dragonfly, fruit fly, butterfly, and hawkmoth have been used as typical models for insect flapping flight (Buckholz, 1981; Srygley and Thomas, 2002). Several methods were proposed to measure 3D body and wing kinematics of free-flying insects (Ristroph et al., 2009, Zhang et al., 2008). However, few investigators have studied the flight mechanism of the Coleopteran insect. The wing system of the Coleopteran insect is uniquely composed of highly flexible hind wings that are folded and covered by a stiff elytron (fore wing). This mechanism differs from that of a dragonfly, cicada, and butterfly, which all have a front and rear wing configuration. Recently, microstructures and mechanical properties of the elytron have been investigated (Dai and Yang, 2009).

In this paper, we present the aerodynamic performance of the hind wing and elytron of a Coleopteran insect in hovering flight. We created a flapping kinematics model on the basis of experimental observation and then used the model in a 2-D numerical simulation. We systematically studied the kinematics of the Coleopteran insect flapping wing to gain a better understanding of the interaction between the elytron and the hind wing in hovering flight condition.

2. Materials and methods

2.1. Experimental method

A digital high-speed camera (Photron Inc., APX) was used to observe the wing kinematics of a Coleopteran insect in hovering flight. The Coleopteran insect *Epilachna quadricollis* was released into an enclosed cubic chamber made of transparent acrylic. The dimensions of the chamber were 50 cm × 50 cm × 50 cm. The insect had a body length of around 1.0 cm, a wing span of 1.2 cm, and a maximum wing chord of 0.6 cm. The high-speed camera was orthogonally aligned and located outside the acrylic chamber, and a halogen lamp was used as a light source. Images of the Coleopteran insect wing motion were taken with the high-speed camera at 2000 fps in a shutter time of 1 μs and a screen resolution of 1024 × 1024 pixels. Fig. 1 shows the setup of the experimental apparatus for this observation.

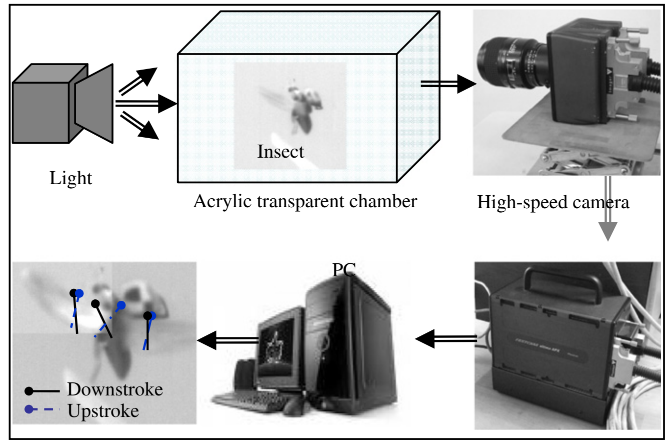

Fig. 1. Schematic of the experimental apparatus setup.

2.2. Numerical method

To investigate the aerodynamic characteristics, we performed a 2-D numerical simulation by using the commercial software program ADINA (2008). Here we considered hovering flight of Coleopteran insect. After obtaining the wing kinematics from the experiment, we implemented the hovering flight condition into the numerical simulation. Hence the advance ratio is definitely zero, where the advance ratio is defined as the ratio of forward velocity and wing tip velocity (Dickson and Dickinson, 2004). The wing geometry was modeled as a simple 2-D elliptic model. The hind wing is composed of a thin membrane and veins, which form the bumpy (cambered and corrugated pattern) structure of the cross section. For simplification, we therefore assume that the wing shape is elliptic.

The governing equations of the flow are described by the 2-D unsteady incompressible Navier–Stokes equation as follows:

$$\nabla V = 0, \tag{1}$$

$$\rho \frac{\partial V}{\partial t} + \nabla(\rho VV - \tau) = f^B, \tag{2}$$

where t is the time, ρ is the density of air, V is the velocity vector, f^B is the body force vector of the fluid medium, and τ is the stress tensor. The τ equation is $\tau = -pI + 2\mu e$, p is the pressure; I is the identity matrix; μ is the dynamic coefficient of fluid viscosity; and e is the velocity strain tensor, which is expressed as $e = 1/2(\nabla V + \nabla V^T)$.

The Reynolds number is defined as

$$Re = \rho \frac{V_{max}}{\mu} c, \tag{3}$$

where c is the chord length and V_{max} is the maximum translation velocity of a hind wing during flapping. The value of V_{max} is obtained in the body-coordinate frame. While the flaps up and down, the flapping speed reaches a maximum value at the middle of the downstroke or at the middle of the upstroke. Another non-dimensional parameter, the Strouhal number, is usually considered for insect flight or for plunge and oscillation motions where the flow should have a forward velocity. Because this study