Available online at www.sciencedirect.com

ScienceDirect

Journal of Bionic Engineering 13 (2016) 478–490

Wing Kinematics, Aerodynamic Forces and Vortex-wake Structures in Fruit-flies in Forward Flight

Xueguang Meng, Mao Sun

Institute of Fluid Mechanics, *Beijing University of Aeronautics and Astronautics*, *Beijing* 100191, *China*

Abstract

Wing kinematics in forward-flying fruit-flies was measured using high-speed cameras and flows of the flapping wing were calculated numerically. The large lift and thrust coefficients produced by the wing were explained. The wing flaps along a forward-tilting stroke plane. In the starting portion of a half-stroke (an upstroke or downstroke), the wing pitches down to a small pitch angle; during the mid portion (the wing has built up its speed), it first fast pitches up to a large pitch angle and then maintains the pitch angle; in the ending portion, the wing pitches up further. A large aerodynamic force (normal to the wing surface) is produced during the mid portion of a half-stroke. The large force is produced by the fast-pitching-up rotation and delayed-stall mechanisms. As a result of the orientation of wing, the thrust that propels the insect is produced by the upstroke and the major part of the vertical force that supports the weight is produced by the downstroke. In producing the thrust the upstroke leaves a "vortex ring" that is almost vertical, and in producing the vertical force the downstroke leaves a "vortex ring" that is almost horizontal.

Keywords: fruit-fly, wing kinematics, forward flight, Navier-Stokes simulation, vortex

doi: 10.1016/S1672-6529(16)60321-9

---

1 Introduction

Due to the small size and relative velocity of the flapping wing of an insect, the lift coefficient of its wing is relatively high[1–4], while the Reynolds number (*Re*) is small [*Re*, based on the mean chord length of wing and the mean flapping velocity at the radius of gyration of the wing, ranges from about 10 (*Encarsia formosa*[5]) to 3500 (Hawkmoths[2,6])]. In this low-*Re* range, conventional steady-state aerodynamic theory is insufficient to explain the required high aerodynamic-force coefficients and unsteady aerodynamic mechanisms must be operating[3].

Based on flow visualization studies using tethered insects and experimental and computational studies using wing models, several unsteady high-lift mechanisms have been identified[7–9], including delayed stall[10,11], rapid-acceleration or added-mass at the beginning of an up- or downstroke and fast pitching-up rotation near the end of an up- or downstroke[7,12,13]. The wingbeat cycle of an insect is typically divided into four parts[2]: two translations (azimuthal rotation): the upstroke translation and downstroke translation, and two rotations: pitch rotations at stroke reversal (when half the pitch rotation of wing is conducted near the end of an up- or downstroke and the other half in the beginning of the next down- or upstroke, the rotation is called symmetrical rotation; when the major part of rotation is conducted before the stroke reversal, it is called advanced rotation). The delayed stall mechanism operates during the translational phases[11,14]; and the added-mass and fast pitching-up rotation mechanisms operate during the stroke reversal[7,12,13]. The added-mass mechanism and the fast pitching-up rotation mechanism are significant only when the translational acceleration at the beginning of an up- or downstroke is very large (e.g. when the translational velocity varying according to a trapezoidal function of time with large accelerations at stroke reversal) and the pitch rotation of wing at stroke reversal is advanced[12,13]. In recent years, detailed, free-flight wing kinematics have been measured for several insects, including hawkmoths[15], fruit-flies[16], and droneflies[17,18]. It was found that the wing-tip velocity varies with time approximately according to the

---

Corresponding author: Xueguang Meng
E-mail: mengxg@buaa.edu.cn

simple harmonic function and hence the acceleration at the beginning and deceleration near the end of an up- or downstroke are not large, and furthermore the wing rotation is symmetrical. Therefore, the delayed stall mechanism is the major unsteady aerodynamic mechanism responsible for the high-lift coefficient in these, and possibly in many other insects. Recently, our group conducted a study on freely-hovering fruit-flies[19]. We found that in the early portion of the translational phase of an up- or downstroke, the wing had a fast pitching-up motion. Flow analysis showed the insect used two unsteady mechanisms, the fast-pitching-up mechanism and the delayed stall mechanism, to produce the high-lift coefficient. This is different from insects mentioned above (hawkmoth, droneflies), which mainly use the delayed stall mechanism to produce the high-lift coefficient[16,17,20,21].

The above studies are within the context of hovering flight. In contrast to the case of hovering flight, there are only very limited works on forward flight. Sun and Wu[22] conducted a numerical investigation into the aerodynamic force and flows in a fruit-fly in forward flight with various advance ratios (J, defined as the ratio of the flight speed of an insect to its mean flapping velocity at wing-tip) and stroke plane angles. Because no free-flight data were available, simplified wing motions were used in their study. Dickson and Dickinson[23] measured the aerodynamic forces on a revolving model fruit fly-wing with a uniform free-stream velocity that acted in the "stroke plane" (the plane of the wing's rotation). Bross *et al.*[24] conducted a particle image velocimetry experiment on a revolving wing with a uniform free-stream velocity that was normal to the stroke plane, simulating a vertical flight. Harbig *et al.*[25] studied the effect of advance ratio and aspect ratio on the characteristics and stability of the LEV for flapping wings at insect Reynolds numbers.

In the above studies on forward flight[22,23,25] and vertical flight[24], wing kinematics used is either an idealization on the basis of flapping motion of tethered fruit-flies: the translational (azimuthally rotational) velocity varying according to a trapezoidal function of time with large accelerations at stroke reversal and the angle of attack being constant during the translational phases and changing only during the stroke reversal[22,25]; or a further simplification: constant translational (azimuthally rotational) velocity and angle of attack[23,24]. Furthermore, in most of these studies[23–25], the stroke plane was assumed to be horizontal. For insects in free forward-flight, the stroke plane is inclined[2,15,26], and the stroke kinematics could be very different from that in tethered ones[16,19]. How the aerodynamic forces (lift and thrust) are produced and what the vortical wake is like for insects in free forward-flight are still unknown. In the present study, we first measured the free-flight wing kinematics of forward-flying fruit flies using high-speed cameras, and numerically computed the flows and forces produced by the measured wing motion. We then used the wing-motion data and the computed flows to explain how the large lift and thrust coefficients are produced.

2 Experimental and computational methods

Fruit-flies (*Drosophila virilis*) were obtained from the Laboratory of Genetics of the School of Life Sciences of Peking University, which were descendents of wild-caught fruit-flies. To obtain forward flight of the insect, a "long" flight chamber with the size of 12×12×40 cm^3 was employed (Fig. 1). The chamber was built from plexiglass. In the experiment, the flight chamber was in room light. The part of the chamber at the left end was made darker by shading and the part at the right end was made brighter by an additional light (Light A in Fig. 1). When the fly was introduced into the chamber at the left end where it was dark, it had a tendency to fly towards the right end of the chamber where it was bright. We thus obtained the forward flight of the fly. The experiment was conducted at room temperature 22 ˚C – 25 ˚C.

The flight was filmed using three high-speed cameras. Description of the cameras and their set-up can be found in Mou *et al.*[27]. The method used to extract the three-dimensional body and wing kinematics from the filmed data was the same as that used in several

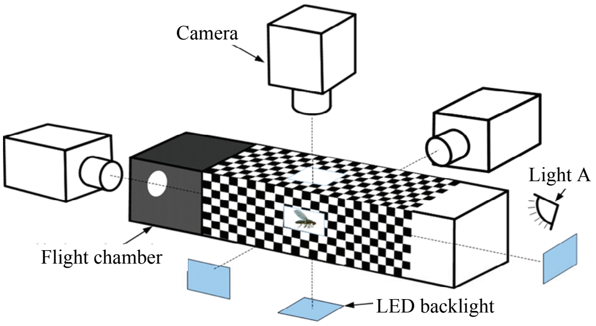

Fig. 1 A sketch showing the experimental system.