EXPERIMENTAL STUDY OF THE DEFORMATION AND FLEXIBILITY OF INSECT WINGS

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INTRODUCTION

An insect wing is a key determinant of flight performance. In the past few decades, insect flight mechanisms have been extensively studied theoretically, computationally and experimentally. The seminal work of Weis-Fogh (Weis-Fogh, 1956 and 1973) uncovered the "clap-and-fling" mechanism that is known to be used by a number of insects and birds. Ellington (Ellington et al., 1996) drew attention to the importance of the leading-edge stall vortex as a key factor in lift generation by insects. More recently, Dickinson and coworkers (Dickinson and Gotz, 1996; Dickinson et al., 1999) identified delayed stall, rotational circulation and wake-capture as three distinct mechanisms that appear in experiments conducted with a dynamically scaled fruitfly wing. Wing-wing interaction in functionally four-winged insects such as dragonflies has also been studied by Mittal et al. (Mittal et al., 2006 and 2008) and Wang et al. (Wang et al., 2005). All of the studies mentioned above have assumed insect wings perfectly rigid. This however, is far from reality since wing flexibility and the associated deformation is widely accepted to play a significant role in insect flight (especially large insects such as moths, butterflies and dragonflies as shown in Figure 1) (Wootton, 1981 and 1993). The potential that wing deformation leads to the generation of aerodynamic mechanism of lift/thrust production that are not possible with rigid wings has been hinted by a number of researchers (Combes et al., 2001; Lehmann, 2008; Sane, 2003; Wootton, 1993) but experiments or computational studies to date have found it hard to investigate this issue. Insects are difficult to visualize and model with a high level of detail as they are small, fast moving and flap their wings at high frequencies. Despite some recent quantitative visualization of insect in free flight (Sunada et al., 2002), the current literature lacks the necessary 3-D detail of body and wing kinematics needed for input into CFD analyses. As a result, no computational models of flapping flight have been validated with experimental data from freely flying insects. The effect of insect wing deformation and flexibility on the aerodynamics and flight performance has been even more difficult to quantify (Dudley, 2000). Not a single study to date has managed to extract the kinematics of an insect wing that is undergoing significant deformation.

In recent years, direct linear transformation (DLT) (Abdel-Aziz et al., 1971; Chen et al., 1994) has been employed quite extensively in high-speed videogrammetry systems by Lauder et al. (Lauder et al., 2006; Standen et al., 2005) and
Hedrick et al. (Hedrick et al., 2004 and 2007) for reconstructing fish swimming and avian flight kinematics respectively. However, it has not been applied to the study of the insect flight kinematics. In this work, we will experimentally measure 3-D kinematics (position, velocity and acceleration) for a grid of points on the surface of both the wings and body of free flying butterflies and different maneuvers (climbs, turns and hovers) with high-speed videogrammetry and DLT algorithm. This data is to be used in the CFD-FSI tool which is based on an existing Navier-Stokes immersed-boundary solver (Mittal et al., 2005 and 2006) developed to simulate the hydrodynamics of flexible fish pectoral fins (Lauder et al., 2006; Mittal et al., 2006). In future, the solver will be modified to simulate the aerodynamics of insect flight and quantify the role of wing deformation and flexibility on the flight performance.

Figure 1. Various insect in flight showing wing flexibility. (a) Moth in climbing flight (b) Butterfly in flight hover (c) Dragonfly in flight (Thomas et al., 2004).

METHODS AND PROCEDURES

The insects studied in this work are Painted Lady butterflies (*Vanessa Cardui*) and Monarch butterflies (*Danaus plexippus*) and are shown in Figure 2. The insect flight videogrammetry setup is shown in Figure 3. Butterflies are kept in a holding facility and transferred into glass chambers (chamber size varies according to the butterfly size) before the experiments. These butterflies fly inside the chambers which are illuminated by halogen photo optic lamps (OSRAM, 54428) with heat shields. Note that past studies have found that butterflies flying in enclosure maintain the allometry of their natural (unconstrained) flight (Dudley et al., 1994). Three synchronized Photron FASTCAM 1024 PCI high-speed cameras with 1024×1024 pixel resolution, operated at 1000 Hz with at least 1/3000 sec. shutter speed are applied to capture the butterfly free flight videos. Given that the butterflies flap at about 20Hz, this provides us excellent temporal and spatial resolution of the butterflies in flight. The cameras are calibrated in three-dimensions using a portable calibration rig (shown in Figure 3) which is recorded at the end of each set of videogrammetry trial. The calibration rig was rapid prototyped with a precision of 0.25mm that allows accurate reconstruction of the positions of the body and wings during flight.

![Painted Lady butterfly and Monarch butterfly](image)

Figure 2. Painted Lady butterfly and Monarch butterfly.

Various flight modes are elicited using fresh flowers, sugar water and other stimuli. The recorded sequences from the three cameras are downloaded continuously to a desktop computer for subsequent analysis. The video sequences are then examined and useable segments (segments where we get good quality visualization of 4-5 wing beats in level, climbing, hover or turning flight modes) identified for detailed DLT analysis. The objective of the DLT videogrammetry analysis is to determine with accuracy in time and space, the geometric conformation of the wings and body during flight. The individual
body parts (wings, head, thorax, and abdomen) of the butterflies are weighed with a 0.01 mg accuracy balance (Ohaus, Analytica Plus). The wings are cut into about 25 pieces and each piece weighed individually to determine the center-of-mass and moment of inertia of the wings (note that total weight of a butterfly is about 150 mg).

**Figure 3.** High-speed insect flight videogrammetry setup.

Natural markers on the butterfly wings and body are identified in image pairs and DLT is used to extract the 3D coordinates of these points at roughly 15 time-instants during each wing beat. An accurate representation of this butterfly in flight is constructed from the DLT analysis at each time instant.

**RESULTS**

Preliminary tests have been performed reconstructing the 3-D geometry and measuring the 3-D trajectory, velocity and acceleration of Painted Lady butterflies performing level and climbing flights.

**Figure 4.** Preliminary reconstruction of wing kinematics and flight trajectory using high-speed videogrammetry. (a-d) Frames from high-speed videos and reconstructed wing and body coordinates using DLT. (e) Flight trajectory of the butterfly tracked using location of head.

Figure 4 shows reconstruction of wing kinematics and flight trajectory of a butterfly performing level flight using high-speed videogrammetry. The four images (a-d) on the left are extracted from the same flapping cycle showing apparent wing deformation. The 3-D reconstructed body and wing coordinates are shown on the right. The trajectory of the butterfly is also obtained by tracking the position of the head via DLT and is shown in Figure 4e. A critical component of these 3-D kinematic studies is the analysis of body acceleration. Determination of the
mass distribution of insect body and wings and total body mass allows direct
determination of net flight forces if whole
body accelerations is measured accurately and
inertial components of motion are accounted
for. Determination of body acceleration
together with a knowledge of the mass
distribution of the butterfly body allows a
quantitative comparison of different
maneuvers and provides data for the
validation of forces calculated from the CFD
models. Figure 5 shows experimental
estimates of the acceleration of this butterfly
by tracking the position of the head. The high
values of the instantaneous acceleration (up to
3g) are experienced by the butterfly, and
similar high values have been reported in
other studies (Sunada et al, 1993).
Furthermore, the acceleration clearly allows
us to determine the flapping frequency of the
butterfly and is about 16Hz. The same
procedure is used to obtain the 3-D
kinematics of different points in the body and
wings.

**Figure 5.** Body acceleration of Painted Lady
butterfly in level flight extracted via
videogrammetry.

Similarly, Figure 6 shows reconstruction
of wing kinematics and flight trajectory of a
Painted Lady butterfly performing climbing
flight. The four images (a-d) on the left are
extracted from the same flapping cycle
showing apparent wing deformation. The
reconstructed body and wing coordinates are
shown on the right. The trajectory of the
butterfly is also obtained by tracking the head.
location via DLT study and shown in e. The acceleration of the butterfly is shown in Figure 7 which indicates the flapping frequency of the butterfly to be about 20Hz.

**Figure 7.** Body acceleration of Painted Lady butterfly in climbing flight extracted via videogrammetry.

**DISCUSSION AND SUMMARY**

In this work, the high-speed videogrammetry setup and the DLT algorithm are employed for reconstructing butterflies flight kinematics. It turns out that various flight modes of the butterflies are elicited using fresh flowers, sugar water and other stimuli. To date, the level and climbing flight of Painted Lady butterflies have been reconstructed, and the 3-D geometry, trajectory, velocity and acceleration have been measured. The acceleration profiles are quite periodic, and the maximum acceleration value is comparable with the value reported in literature. In addition, the flapping frequency obtained from the acceleration profiles is 16-20Hz, which agrees with the frequency observed from the flapping videos.

Our particular interest is to study the role of wing deformation and flexibility on aerodynamics and force production for the free flight of insects with our high-speed insect flight videogrammetry setup, DLT algorithm, and CFD-FSI tool. Study of different maneuvers (turns and hovers) of butterflies are anticipated prior to the conference. These measurements will aid in quantifying the kinetics of a grid of points in the butterfly body and wings and serve as input for our CFD-FSI tool modeling to simulate insect free flight for better understanding the fundamental role of wing deformation and flexibility on the flight performance of the insects.

**REFERENCES**


Lauder, GV et al. (2006). *Bioinspiration & Biomimetics*, 1: s25-s34.
