EXPERIMENTAL STUDY OF GROUND EFFECT ON THREE-DIMENSIONAL INSECT-LIKE FLAPPING MOTION*

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This paper focuses on an experimental investigation aimed at evaluating the aerodynamics force characteristics of three-dimensional (3D) insect-like flapping motion in the vicinity of ground. The purpose is to establish whether flapping wing insects can derive aerodynamic benefit from ground effect similar to that experienced by a fixed wing aircraft. To evaluate this, force measurements were conducted in a large water tank using a 3D flapping mechanism capable of executing various insect flapping motions. Here, we focus on three types of flapping motions, namely simple harmonic flapping motion, hawkmoth-like hovering motion and fruitfly-like hovering motion, and two types of wing planforms (i.e. hawkmoth-like wing and fruitfly-like wing). Results show that hawkmoth-like wing executing simple harmonic flapping motion produces average lift to drag ratio ($\overline{CL}/\overline{CD}$) similar to that of fruitfly wing executing the same motion. In both cases, they are relatively independent of the wing distance from the ground. On the other hand, a hawkmoth wing executing hawkmoth flapping motion produces $\overline{CL}/\overline{CD}$ characteristic different from that of fruitfly wing executing fruitfly motion. While the $\overline{CL}/\overline{CD}$ value of the former is a function of the wing distance from the ground, the latter is minimally affected by ground effect. Unlike fixed wing aerodynamics, all the flapping wing cases considered here do not show a monotonic increase in $\overline{CL}/\overline{CD}$ with decreasing wing distance from the ground.

Keywords: Flapping wing; hovering flight; ground effects; unsteady aerodynamics; force measurement.

1. Introduction

It is well known that flight performance of insects far exceeds those of conventional flyers in terms of the ability to hover, engage in abrupt changes of direction while in

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flight as well as to transit from translational to hovering mode and vice versa. The excellent flying capability of insects mainly originates from the complex wing flapping motion. This mode of unsteady locomotion is different from that of a conventional aircraft wing where smooth and steady or quasi-steady flow is essential. These unique characteristics have attracted much interest from both academia and industry in flapping wing aerodynamics for the development of micro aerial vehicles (MAVs)¹⁻⁵. These vehicles can be used for research and reconnaissance purposes. The latter ability is significant especially if potentially unknown dangers exist at the site of interest. Unfortunately, there are still many problems associated with the flapping wing flight, for example, flow separation in the low Re regime, strong tip vortices that reduce the angle of attack and susceptibility to gusts resulting in instability⁶. The most important issue surrounding the difficulties is that the unsteady mechanisms underlying flapping wing flight are not fully understood as they do not adhere to the principles of conventional aerodynamics theory.

Past studies have shown that leading edge vortex (LEV) and its prolonged attachment on the wing plays a crucial role in enhancing lift generation in insect flapping wings⁷⁻¹². Various explanations have been provided to explain the prolonged attachment of LEV; some attributed it to the draining of energy from the vortex core by spanwise (or axial) flow analogous to the attached vortex on a leading edge of a delta wing^{7,8} while others credited it to a reduction in the effective angle of attack due to the downwash induced by wing-tip vortices¹². A more recent numerical and experimental study attributed it to vortex stretching caused by positive axial velocity gradient along the core of LEV¹³. This hypothesis suggests that it is possible for a small axial flow, like the one encountered in fruitfly insect, to prolong the attachment of LEV, as long as sufficient vortex stretching is present.

It is well established that when a fixed wing aircraft flies in close vicinity to ground (usually one wing span or less above the ground), lift increases and drag decreases, leading to the increase in lift to drag ratio, thus making it more efficient to fly. This so called ground effect has led to the development of various ground effect crafts to take advantage of this aerodynamics effect. This interesting aerodynamic phenomenon raises a question as to whether insects, which have a different mode of generating lift by flapping their wings, also benefit from ground effect when they are flying or hovering in the vicinity of the ground. The desire to answer this question motivates the present experiment. Here, our attention is focused on three-dimensional flapping wings, with attention focused on three specific flapping motions, namely, simple harmonic motion, hawkmoth-like hovering motion and fruitfly-like hovering motion. These motions are executed using two different types of wing planforms, namely hawkmoth-like and fruitfly-like wings. As far as we aware, the ground effect on the lift generation and efficiency of three-dimensional flapping wings has not been studied previously. The only experimental study on ground effect of three-dimensional flapping foil is that of Quinn and Smits¹⁴, but their investigation was focused on the thrust generation and efficiency that were more related to the fish swimming than insect flight. Recently, Guo and Lu¹⁵

conducted a numerical study on the ground effect on the lift generation and efficiency that are more related to insect flight, but their calculations were restricted to a two-dimensional flapping foil only.

2. Experimental Apparatus and Procedure

The present experiments were performed using the same apparatus as that described in Lua et al.¹⁶ but with a horizontal floor installed beneath the flapping wing. Since the experimental apparatus has been discussed in some details by Lua et al., only the essential aspects are presented here. The apparatus consists of a large water tank with the base measuring 1.5 m $\times$ 1.5 m, and 2.0 m high (see Fig. 1). Mounted on the top of the tank is the drive system of a three-dimensional flapping mechanism, and connected to the mechanism are two set of drive transmission shafts, one for each wing, that extend to the middle of the tank. Each wing was driven by three stepper motors, through three stainless steel coaxial transmission shafts and a gear box. All the stepper motors were controlled by a Pentium 4 PC and configured to run at micro-step angle of 0.036°. The PC calculated TTL pulses required for the predetermined motion, and the pulses were sent to the motors through a digital I/O card to generate predetermined flapping motion physically.

Fig. 1. The 3-D flapping wing facility.

One wing model was attached to the actuating gearbox via a force transducer, and the other wing was similarly attached via a “dummy” transducer. During the experiments, the gearbox, the force transducer and the wings were fully immersed in the large tank filled with water up to a height of 1.7 m.

Three sets of flapping motions were considered, namely a simple harmonic flapping motion, hawkmoth-like hovering motion and fruitfly-like hovering motion. Combined with these flapping motions are two types of wing planform, namely hawkmoth-like wing and fruitfly-like wing. A total of four combined motions were investigated, they are hawkmoth wing and fruitfly wing flapping with simple harmonic motion; hawkmoth wing flapping with hawkmoth motion and fruitfly wing flapping with fruitfly motion. In all cases, the wing distance from the floor can be varied to study the ground effect.

The planform of the hawkmoth wing used here was extracted from Liu et al.¹⁷ (see Fig. 2(a)). The wing has a span (R_{tip}) of 0.25 m, mean chord ($\bar{c}$) of 0.0784 m and surface area (S) of 0.01963 m². The dimensionless second moment of wing area ($\hat{r}_2$) about the centre of the sweeping motion was 0.628. The radial distance between the wing tip and the flapping axis (R) is 0.365 m. The wings were fabricated from 1.5 mm thick aluminum sheet, which can be considered as rigid in the present experiment. The temperature of water during the experiment was 22 °C, giving the corresponding kinematic viscosity, $\nu = 9.570 \times 10^{-7}$ m²/s and density, $\rho = 997.86$ kg/m³.

Fig. 2. Planform of (a) hawkmoth wing and (b) fruitfly wing.

The planform of the fruitfly wing was extracted from Fry et al.¹⁸ (see Fig. 2(b)). The wings were also fabricated from 1.5 mm thick aluminium sheet. Since the wing span (R_{tip}) is also maintained at 0.25 m (similar to that of the hawkmoth wing), the radial distance between the wing tip and the flapping axis (R) remains the same (i.e. 0.365 m). Since the geometry of the fruitfly wing differs from that of hawkmoth, the mean chord ($\bar{c}$) and surface area (S) become 0.0929 m and 0.02296 m², respectively. Likewise, the dimensionless second moment of wing area ($\hat{r}_2$) about the centre of the sweeping motion becomes 0.664. Table 1 shows the detailed parameters of the two wing geometries.

Table 1. Wing parameters used in this study

Wing Type	$R[m]$	$S[m^2]$	$\hat{r}_2(S)[-]$	$\bar{c}[m]$
Hawkmoth	0.3678	0.01968	0.6222	0.07843
Fruitfly	0.3605	0.02296	0.6674	0.09186

The three axes of wing motion are defined as sweeping motion, elevation motion and rotational motion (see Fig. 3). The sweeping motion refers to the wing motion in a horizontal plane, and the sweep angle (ϕ) is defined as the angle between the projection of the rotational axis on the horizontal plane and the line joining the centers of the two coaxial shafts. The wing elevation motion refers its deviation from the horizontal plane, and the elevation angle (θ) is defined as the angle between the rotational axis and the horizontal plane. Finally, the rotational motion is the wing pitching (up and down) motion about the rotational axis, and the angle of attack (α) is defined as the angle from the horizontal plane to the wing chord. The kinematics (or flapping motion) of simple harmonic motion, the hawkmoth hovering motion and the fruitfly hovering motion are shown schematically in Fig. 4.

Fig. 3. Schematic drawing of the flapping wing.

The simple harmonic flapping motion is governed by the following equations:

$$\text{Sweeping angle: } \phi(t) = \Phi \cos(2\pi n_\phi t) \quad (1)$$

$$\text{Elevation angle: } \theta(t) = 0 \quad (2)$$

$$\text{Angle of attack: } \alpha(t) = 90^\circ - \beta \sin(2\pi n_\alpha t) \quad (3)$$

where Φ and β are the amplitude of the sweeping motion and rotational motion, respectively.

Fig. 4. Different wing kinematics. (a) Simple harmonic motion, (b) hawkmoth motion, (c) fruitfly motion.

Reynolds number is defined as $Re = \bar{c}\bar{U}/\nu$, where ν is the kinematic viscosity of water and $\bar{U}$ is the average velocity given by $\bar{U} = n_\phi l$. The l is the path traced out by the wing at the location of the second moment of area over one complete flapping cycle; the location of second moment of area is indicated in Fig. 3. In this study, the Reynolds number is fixed at 10,000, which is of the same order as the hawkmoth insect, but significantly higher than that of fruitfly insect which is of the order of 150. Unfortunately, the considerable cost to acquire a large quantity of glycerine in order to increase the viscosity of working fluid and reduce the Reynolds number to 150 has prevented us from doing so. Nevertheless the data for the fruitfly motion is still valuable to compare with that of the hawkmoth motion at the same Reynolds number, thus giving us clue as to the effect of different flapping motions.

Lift and drag coefficients are given by

$$C_L = \frac{2F_L}{\rho \bar{U}^2 S} \quad (4)$$

$$C_D = \frac{2F_D}{\rho U^2 S} \quad (5)$$

The force balance was calibrated using exactly the same procedure as that outlined in Lua et al.¹⁵, and will not be repeated here. Each set of the force measurements consisted of ten flapping cycles and twenty repeated runs. The measurements were then ensemble-averaged to obtain the final results. Between each flapping motion, a waiting time of four minutes was allowed for the background turbulence from the earlier runs to subside. Preliminary test showed that three minutes after the end of each run is more than sufficient for the residue velocity to diminish and have negligible influence on the force measurement. Also, a series of tests conducted with a false wall located at various distances from the flapping wing show that the side walls of the tank have no noticeable effect on the force measurements, and the tank is sufficiently large to give a good approximation of an infinite volume.

3. Results and Discussion

Prior to the discussion of the results, it is important to stress that although the wing planforms and flapping motions of hawkmoth and fruitfly are employed in the present experiment, we are not mimicking the real insect motion as their wing flexibility is rather complex and is not easy to modeled. The wing shape and motion are used merely to provide a more realistic investigation of the issue at hand.

Fig. 5. Ground effect of hawkmoth and fruitfly wing executing simple harmonic motion. (a) average lift coefficient $\overline{CL}$, (b) average drag coefficient $\overline{CD}$, (c) $\overline{CL}/\overline{CD}$.

Fig. 5 shows the ground effect on the average lift and drag coefficients of hawkmoth-like and fruitfly-like wings executing simple harmonic motion. The average lift and drag coefficients are obtained by averaging the transient lift and drag coefficients of 6th cycle of flapping. It can be observed that both the wings display similar force characteristics, although the $\overline{CL}$ and $\overline{CD}$ of hawkmoth-like wing are consistently higher than those of fruitfly; in fact by approximately 8.7% and 7.6%, respectively. As each wing approaches the ground from a large distance, there is an initial reduction in both $\overline{CL}$ and $\overline{CD}$ until they reach their respective minima before reversing direction to increase with decreasing distance from the ground. Unlike fixed wing aerodynamics where $\overline{CL}$ increases and $\overline{CD}$ decreases with decreasing ground distance, here both $\overline{CL}$ and $\overline{CD}$ exhibit similar trend and this has resulted in lift to drag ratio ($\overline{CL}/\overline{CD}$) which is relatively independent of the ground distance for both the insect-like wings (see Fig. 5(c)). This finding suggests that there is little aerodynamic advantage to be gained from ground effect when wings are performing simple harmonic motion, at least for the flow conditions investigated here. For the purpose of comparison, the transient force coefficients at locations 1.53c, 2.5c and 5.0c from the floor are presented in Fig. 6 for the hawkmoth-like wing and in Fig. 7 for the fruitfly-like wing. It is of interest to note that when the wings are in close proximity to the ground (i.e. 1.53c), most of the gains in CL and CD occur during the first half of each stroke (both downstroke and upstroke). Likewise, the reduction in CL and CD at location 2.5c also occur during that part of the flapping cycle. This suggests that some kind of interaction is taking place between shed LEV and TEV (trailing edge vortex) with the wings at the beginning of each stroke to produce the observed beneficial and detrimental effects. In an attempt to better understand how this comes about, dye visualization was conducted in an attempt to observe the development and interaction of these vortices in the presence of the ground. Unfortunately, this turns out to be more complex than we first anticipated because the wing flapping motion creates a “stirring” action which causes the dye to mix and diffuse very quickly, especially at the vicinity of the ground, thus making the dye pattern difficult to interpret. DPIV measurements was not conducted as our previous attempts to measure the flow field of a three-dimensional flapping motion did not produce meaningful results due to the complex nature of the wing motion. Interestingly, it is found that Gao and Lu¹⁵ had recently conducted numerical study to examine the ground effect on a two-dimensional elliptic foil executing simple harmonic motion, and they obtained mean CL and CD values which are similar in characteristics to the 3D flapping wings illustrated in Fig. 5. Gao and Lu¹⁵ divided the force characteristics into three distinct regimes, which they termed “force enhancement”, “force reduction” and “force recovery”. The “force enhancement” is the regime closest to the ground. In this region, the aerodynamic force is higher than the mean force coefficient (obtained without the floor, henceforth referred to as floor-free) and each force increases with decreasing wing-ground distance. As the wing moves away from the ground, the force decreases gradually and eventually reaches the “force reduction” regime, where aerodynamics force falls below the mean floor-free value. Receding further from the ground leads to the “force recovery” regime, where each

force gradually returns to the mean floor-free value. Based on their results, they postulated that the force enhancement is due to the augmentation of the leading edge vortex (LEV) of the current stroke as the result of the interaction between the existing vortex (i.e. LEV formed in previous stroke) and the flapping foil. In the force reduction regime, they noted that the existing vortex and TEV form a vortex pair which, as a result of ground effect, moves away in the horizontal-upward direction. In the force recovery regime, they postulated that the vortex pair produces a jet-like mean velocity profile in the wake, similar to the situation where the ground effect is absent. Whether similar vortex interaction occurs in the 3D flapping wing is unclear (due to the difficulties we faced in attempting to visualize the vortex structures) but the fact that the 2D wing possesses similar force characteristics as the 3D wing suggests that there may be some degree of similarity in their salient flow structures. Obviously, one would expect the flow topology during 3D flapping to be significantly more complex and convoluted than 2D wing. Our difficulty in performing flow visualization study to resolve this important issue opens the possibility of conducting CFD calculation on 3D wing to elucidate the physics of flow, similar to what Gao and Lu¹⁵ had done for 2D wing.

Fig. 6. Transients force coefficients for hawkmoth wing with SHM during the 6th cycle.

(a) lift coefficient (CL), (b) lift coefficient (CD).

Fig. 7. Transients force coefficients for fruitfly wing with SHM during the 6th cycle.

(a) lift coefficient (CL), (b) lift coefficient (CD).

Fig. 8 shows the results for the hawkmoth-like wing flapping with hawkmoth-like motion and the fruitfly-like wing flapping with fruitfly-like motion. For ease of reference, they are simply referred to as hawkmoth motion and fruitfly motion, respectively in the subsequent discussion. In contrast to simple harmonic motion, fruitfly motion possesses higher $\overline{CL}$ and lower $\overline{CD}$ than the hawkmoth motion. Although the $\overline{CL}$ and $\overline{CD}$ of both the motions also display three regimes of forces similar to that encountered in the simple harmonic motion, they are not as well-defined. When plotted in terms of $\overline{CL}/\overline{CD}$, that of the fruitfly motion is almost independence of the wing distant from the floor and is significantly higher than that of the hawkmoth motion. This suggests that ground effect has very little influence on the efficiency of fruitfly motion, at least for the conditions investigated here. However, this is not the case with the hawkmoth motion whose $\overline{CL}/\overline{CD}$ or efficiency shows strong dependent on wing-ground distance. The fact that $\overline{CL}/\overline{CD}$ of hawkmoth motion increases with decreasing wing distance from the ground suggests that hawkmoth motion operates more efficiently as it gets closer to the ground, although it is still less efficient than the fruitfly motion, which has significantly higher $\overline{CL}/\overline{CD}$ (see Fig. 8(c)). Figs. 9 and 10 show the transient force results at different wing-ground distance ($1.5c$, $2.5c$ and $5.5c$) for both the hawkmoth motion and fruitfly motion. Unlike simple harmonic motion, ground effects on these two motions seem to influence only the force generation around the middle of each stroke. The reason for the difference is unclear as we were unable to properly visualize the vortex structures and their interaction.

Fig. 8. Ground effect of hawkmoth and fruitfly wing executing their respective motions.

(a) average lift coefficient $\overline{CL}$, (b) average drag coefficient $\overline{CD}$, (c) $\overline{CL}/\overline{CD}$.

Fig. 9. Transients force coefficients for hawkmoth wing with hawkmoth motion during the 6th cycle.

(a) lift coefficient (CL), (b) lift coefficient (CD).

Fig. 10. Transients force coefficients for fruitfly wing with fruitfly motion during the 6th cycle.

(a) lift coefficient (CL), (b) lift coefficient (CD).

4. Conclusions

Ground effect on three-dimensional flapping wings has been investigated experimentally using force measurements technique. Four combinations of wing shape and flapping motion were studied, namely hawkmoth wing with hawkmoth motion; fruitfly wing with fruitfly motion, and hawkmoth wing and fruitfly wing with simple harmonic flapping motion. Results show that ground effect experienced by flapping wings is distinctly different from that experienced by fixed wings. While the $\overline{CL}/\overline{CD}$ of a fixed wing increases monotonically with decreasing wing distance from the ground, that of a flapping wing may or may not increase by the ground effect depending on the type of flapping motion. For example, the $\overline{CL}/\overline{CD}$ of hawkmoth wing and fruitfly wing subjected to simple harmonic motion are relatively independent of the wing distance from the ground. This is partly due to $\overline{CL}$ and $\overline{CD}$ possessing similar force characteristics, with each displaying three distinct regimes of force generation, namely force enhancement, force reduction and force recovery. These three regimes are also found in a 2D foil undergoing simple harmonic motion

close to the ground, which suggests that there may be some similarity in the salient vortical structures of 2D and 3D wing subjected to similar flapping motion. A further investigation is needed to establish the degree of similarity as the technical constraints of the present apparatus prevented us from doing so. Nevertheless, the present results would provide useful database, from which future numerical calculations can be carried out to elucidate the physics of the flow. As for the other flapping motions, the results show that hawkmoth wing flapping with hawkmoth motion makes some aerodynamic gains from ground effect, whereas fruitfly wing flapping with fruitfly motion makes insignificant gain. Whether the latter finding is due to the mismatch in the Reynolds number between the present study of $Re=10,000$ and the actual situation ($Re = 150$), which fruitfly wing is designed to operate in nature requires further investigation.

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