Ground Effect in Fruit Fly Hovering:  
A Three-Dimensional Computational Study*

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Abstract
In very few studies it is shown that an increase in vertical force can be achieved when a flapping-wing hovers in ground effect (IGE). The body, however, has usually been neglected and its influence on three-dimensional vortex structures and consequent aerodynamic forces is still unclear. In this study we carried out a computational fluid dynamic study of a fruit fly (Drosophila melanogaster) hovering for two cases: “in ground effect” and “out of ground effect” (OGE), where the heights from the ground are less than one and more than five times the wing length, respectively. The wings in the IGE computation generated merely 0.7% larger wingbeat cycle-averaged vertical force than in the OGE condition. The body, in contrast, exhibited a significant increase in the vertical force: when out of ground effect, the average vertical force of the body was almost zero (-0.0025 μN); whereas in ground effect, the force increased to 0.78 μN, which is the major contributor to the 8.5% increase in the total vertical force (from 9.9 μN at OGE to 10.8 μN at IGE). Meanwhile, the aerodynamic power of the wings decreased by 1.6%, resulting in a 10% improvement in the overall vertical force-to-aerodynamic power ratio. The flow-field visualization revealed that the downwashes generated by the wings create a high pressure “air cushion” underneath the body, which should be responsible for the enhancement of the body vertical force production. Our results point to the importance of the presence of body in predicting the vertical forces in flapping flights in ground effect.

Key words: Ground Effect, Flapping Flight, Insect Flight, Fruit Fly, Computational Fluid Dynamics

1. Introduction
Hovering is a miracle of insects that is observed for all sizes of flying insects. Insects fly by flapping their wings to create lift force and thrust force simultaneously. Flapping-wing aerodynamics associated with insect flight prominently features unsteady motions at an intermediate Reynolds number, which is normally characterized by large-scale vortex structures, complicated flapping-wing kinematics, and flexible wing structures1). One of the challenging problems in uncovering aerodynamic mechanisms in insect flight is to answer a central question of how the complicated wake topology is generated and how it correlates with the aerodynamic force generation.

Studies on unsteady flapping-wing aerodynamics of a single or a paired wing model in hovering and/or forward flight have been the main subject until recently, which have been done either experimentally with robotic insect wing models or real insect or bird wings, or computationally with numerical wing models1). However, there has been little focus on the
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aerodynamic characteristics when an animal is flying close to the ground, i.e., takeoff, landing, or hovering just above the ground or leaves e.g. for feeding nectar. In the previous studies of flapping wing in ground effect, Gao colleagues used two-dimensional numerical simulation for low Reynolds number regime (Re = 100)²,³ and Van Truong et al. used a robotic flapper for beetle’s wing⁴,⁵. Both of the studies reported increase in vertical force. However, both are the single-wing studies and the bodies of the insects were neglected.

In a rotorcraft in ground effect, there is a high-pressure region on the lower side of fuselage which somewhat compensates the vertical drag or so-called download⁶,⁷. We therefore hypothesized that in hovering flights in ground effect by flapping wings, bodies may play some role in the vertical force production. To investigate the body effect, we have carried out a three-dimensional computational fluid dynamic study on the hovering of a model fruit fly (Drosophila melanogaster) in ground effect (IGE) and out of ground effect (OGE) where the model insect is composed of a body and two wings. Comparison between IGE and OGE results revealed that a specific positive pressure region observed on the lower side of the body is responsible for a pronounced increase in the vertical force in the IGE hovering.

2. Methods

2.1. Numerical model and computational conditions

The computational fluid dynamic method used in this study is a finite volume method-based Navier-Stokes solver specified for a multi-blocked, overset-grid system, which has been validated by showing various applications to insect flapping flights⁸,⁹ as well as to a flapping wing micro air vehicle¹⁰. The governing equations are the three-dimensional, incompressible, unsteady Navier-Stokes equations written in strong conservation form for mass and momentum, with artificial compressibility method applied. The governing equation in dimensionless form is:

\[ \int_{V(t)} \frac{\partial q}{\partial t} \, dV + \int_{S(t)} Q \, dS + \oint_{S(t)} (f - Qu_g) \cdot n \, dS = 0 \]

where

\[ q = \begin{bmatrix} u \\ v \\ w \\ \rho \end{bmatrix}, \quad Q = \begin{bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial w}{\partial z} \\ \frac{\partial \rho}{\partial \tau} \end{bmatrix}, \quad f = \begin{bmatrix} F + F_v \\ G + G_v \end{bmatrix}, \quad F = \begin{bmatrix} u^2 + p \\ uv \\ uw \\ \lambda u \end{bmatrix}, \quad G = \begin{bmatrix} vu \\ v^2 + p \\ vw \\ \lambda v \end{bmatrix}, \quad H = \begin{bmatrix} wu \\ wv \\ w^2 + p \\ \lambda w \end{bmatrix}, \]

\[ F_v = -\frac{1}{Re} \begin{bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial w}{\partial z} \\ 0 \end{bmatrix}, \quad G_v = -\frac{1}{Re} \begin{bmatrix} \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \\ \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \\ \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \end{bmatrix}, \quad H_v = -\frac{1}{Re} \begin{bmatrix} \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \\ 2 \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \end{bmatrix} \]

Here, \( V(t) \) is an arbitrary deformable control volume; \( S(t) \) is the surface of the control volume; \( \tau \) is physical time; \( \tau \) is pseudo time; \( \mathbf{n} \) is the unit outward normal vector; \( \mathbf{u} \) is the local velocity of the moving cell surface; \( u, v, \) and \( w \) are velocity components in the Cartesian coordinate system \( x, y \) and \( z \); \( p \) is pressure; \( \lambda \) is the pseudo-compressibility coefficient; and \( Re \) is Reynolds number. Aerodynamic force and aerodynamic power (time rate of work done to the surrounding air by the flyer) for each wing and body are defined as¹¹:

\[ F_{\text{aero}} = \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = -\sum_i^N (\text{Flux}_{\text{invis}} + \text{Flux}_{\text{vis}}), \quad P = -\sum_i^N (F_{\text{aero},i} \cdot \mathbf{v}_{\text{surf},i}) \]
where \( N \) denotes number of the cells on the surface of the wing or the body; \( \text{ Flux}_{\text{inv}} \) and \( \text{ Flux}_{\text{vis}} \) are the inviscid and viscous fluxes, respectively; and \( \mathbf{v}_{\text{surf}} \) is the velocity of the cell face on the surfaces. Note that, in this study \( \mathbf{P}_{\text{body}} = 0 \) because body is tethered and \( \mathbf{v}_{\text{surf/body}} = 0 \). Note that the force and power in this paper are given in dimensional forms. Details of the flow solver can be found elsewhere\(^{11}\). To evaluate how efficiently the flyer generates forces, the vertical force divided by aerodynamic power (both are averaged over one wingbeat cycle) is defined as force-to-power ratio \( \frac{F_{z,\text{ave}}}{P_{\text{ave}}} \), as used by Zheng et al.\(^{12} \) in a numerical simulation of butterfly forward flight.

The computational conditions are taken almost the same as those by Aono et al.\(^{13} \) but with some modifications to consider the effect of the ground. Instead of an O-O type spherical grid\(^{13} \), in this study we employed a Cartesian grid as the background grid, in which a body grid and two wing grids are immersed in, as depicted in Fig. 1. Note that the outer boundary of the wing grid blocks are taken closer to the wing surfaces compared to the grid in Fig. 1B by Aono et al.\(^{13} \) to ensure more accurate wing-wing interaction particularly when the wings are getting close to each other in pronation or supination (Fig. 1C). The outer boundary of the body grid block is also taken closer to the body surface than before, so as to avoid contacting or penetrating from the ground surface. In the global grid block, the grids are clustered to the flyer blocks (Fig. 1A and B). For the IGE computation, the grids close to the bottom boundary are further clustered to the ground surface to better resolve the boundary layer (Fig. 1B).

Two computations were performed: in ground effect (IGE) and out of ground effect (OGE). The model parameters are summarized in Table 1. The height \( h \) of the model fly measured at wingbase from the bottom boundary is normalized by the wing length \( R \) as \( h/R \), which is set to 5.2 for OGE and 0.8 for IGE. For the bottom boundary in the OGE computation, zero gradient conditions are taken for velocities and pressure to avoid any

![Figure 1](image-url). Grid systems. Global grid blocks for (A) OGE and (B) IGE computations, where \( h \) is the height from bottom outer boundary to the wing root of a fruit fly model. Grids of a fruit fly body and wings (C), where some portions of the outer boundaries for the body and left wing as well as a cross section for the right wing are colored in blue.

**Table 1.** Model parameters for both OGE and IGE computations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wingbeat frequency, ( f ) (Hz)(^{13} )</td>
<td>218</td>
</tr>
<tr>
<td>Wingbeat amplitude, ( \Phi ) (rad)(^{13} )</td>
<td>2.44</td>
</tr>
<tr>
<td>Mean chord length, ( c_m ) (mm)(^{14} )</td>
<td>0.8</td>
</tr>
<tr>
<td>Wing length, ( R ) (mm)(^{13} )</td>
<td>2.39</td>
</tr>
<tr>
<td>Body angle, ( \beta ) (deg)(^{13} )</td>
<td>45</td>
</tr>
<tr>
<td>Stroke plane angle, ( \chi ) (deg)(^{13} )</td>
<td>0</td>
</tr>
<tr>
<td>Density of air, ( \rho ) (kg/m(^3 ))</td>
<td>1.225</td>
</tr>
<tr>
<td>Kinematic viscosity of air, ( \nu ) (m(^2 )/s)(^{13} )</td>
<td>1.5 \times 10^{-5}</td>
</tr>
<tr>
<td>Reference velocity, ( U_{\text{ref}} ) (m/s)</td>
<td>2.55 (( U_{\text{ref}} = 2\Phi R f ))</td>
</tr>
<tr>
<td>Reduced frequency, ( k )</td>
<td>0.215 (( k = 2\pi f c_m / 2U_{\text{ref}} ))</td>
</tr>
<tr>
<td>Reynolds number, ( \text{Re} )</td>
<td>136 (( \text{Re} = U_{\text{ref}} c_m / \nu ))</td>
</tr>
</tbody>
</table>
possible influence from the bottom boundary. For IGE, the bottom boundary is treated as a solid wall with zero pressure gradient condition. For all the other outer boundaries of the global grid, pressures are set to be initial (ambient) value and the zero velocity gradient conditions are taken. At the interfaces of the local and global grid blocks, velocities and pressures are interpolated and transferred each other\(^{11}\). The body angle, the stroke plane angle (Table 1) and the wing kinematics\(^{13}\) were set to be the same in the two cases. Note that the height \(h/R = 0.8\) chosen for the IGE computation is the lower limit for ensuring the sufficient clearance between the body grid outer boundary and the ground. Any further reduction in height would require a manipulation in body angle or body shape.

The pressures \(p\) shown in the following sections are all the dimensionless gauge pressures. A gauge pressure is the deviation from ambient pressure and this pressure is further normalized with \(\rho_{\text{air}}U_{\text{ref}}^2\) (= 7.94 Pa). For example, \(p = 0\) in the pressure contour is the same value as the ambient pressure, and \(p = -1.0\) is the 7.94 Pa lower than the ambient.

2.2. Validation

The grid size and the number of grid points were carefully selected after a test to ensure sufficiently qualified grids as well as a reasonable computational time. The global grid block is a cube with a side 10 times the wing length (10\(R\)). The number of grid points in \(i\times j\times k\) directions are: global grid, 89×97×93; body grid, 45×45×9; and right and left wing grids, 49×49×11 each.

The influence of the grid resolution on the computational results were investigated by further introducing a fine grid system with a global grid of 161×141×127, a body grid of 61×61×9, and wing grids of 65×65×11 each. The computations with the fine grids for both OGE and IGE conditions were carried out for five wingbeat cycles. While the fine grids (Fig. 2A, open symbols) show slightly greater values in vertical forces compared to the coarse grids (Fig. 2A, filled symbols), it seems that the values in the two grid resolutions are converging for both OGE and IGE. Also the vertical force ratios between IGE and OGE defined as \((F_{z,\text{ave},\text{IGE}}/F_{z,\text{ave},\text{OGE}})\) is almost the same in coarse (Fig. 2B, red filled triangles) and fine (Fig. 2B, green open triangles). From the results of the coarse grids, it is seen that achieving the minimum stroke-to-stroke variation in vertical force takes a long time (ten to twenty wingbeat cycles, see the next section). Since the finer grids are computationally more expensive, the coarse grid systems were therefore chosen for the following investigations of the forces, powers, and flow visualizations.

3. Results and discussion

3.1. Mean aerodynamic forces and power

Wingbeat cycle-averaged vertical forces are plotted in Fig. 2. Blue filled squares and black filled circles represent IGE and OGE, respectively. It is seen that the vertical force in the IGE case shows larger magnitude than the OGE case in any wingbeat cycles. Also, in both cases it is observed that the vertical force has a strong peak in the first wingbeat cycle due to the unsteady effect. It is also seen that the time-averaged vertical force reached a plateau by around 10 wingbeat cycles in the case of OGE. In contrast, it took approximately twice the time in the case of IGE. Note that the vertical forces in both OGE and IGE cases are always greater than the body weight of the model fruit fly (= 9.41 \(\mu\text{N}\)\(^{13}\)).

As shown in Table 2, for the 20th wingbeat cycle, the IGE case shows an 8.5% increase in the vertical force \(F_{z,\text{ave}}\) but a slight (1.6%) decrease in the aerodynamic power \(P_{\text{ave}}\) compared to the OGE case, which results in an approximately 10% improvement in the vertical force-to-power ratio \((F_{z,\text{ave}}/P_{\text{ave}})\). On the other hand, the horizontal forces are more than three orders magnitude smaller than the vertical forces in both OGE and IGE. It may be presumed that the real fruit fly likely takes the advantage of this bonus in the
Figure 2. History of wingbeat-cycle averaged vertical forces including the comparison between fine and coarse grids. In A, open symbols are for fine grids and filled symbols are coarse grids; black circles and blue squares are for OGE and IGE, respectively. In B, the relative vertical force ratios between IGE and OGE are illustrated for coarse grids (red filled triangles) and fine grids (green open triangles).

$F_{z,\text{ave}}/P_{\text{ave}}$ in ground effect for e.g. a reduction in metabolic rate during hovering by adjusting the wing kinematics, or an augmentation of the force during the early phases of takeoff.

It is seen that the vertical force generated by wings in the IGE condition was merely $6.78 \times 10^{-8}$ N larger than in the OGE (Table 3), which is less than one percent improvement from OGE. This indicates that the wings are essentially out of ground effect. In fact, in the flapping wing experiment (single wing, without body) by Truong et al.\textsuperscript{4}, the vertical force exhibited a prominent increase when the wing is at $h/R = 0.5$ or 0.6 but no significant increase at $h/R = 0.72$ or above. Even though the wing shape, the wing kinematics and the Reynolds number are different from our current study, this is consistent with our results at $h/R = 0.8$.

In the OGE case, obviously the body shows negligible influence on the overall vertical force (Table 4). In the IGE case, however, the body generates $7.79 \times 10^{-7}$ N more vertical force compared to the OGE case (Table 4), one order of magnitude greater than the increase found in the wings. Thus, it is obvious that the pronounced increase in the overall vertical force is mainly due to the body rather than the wings.

Similarly to the total horizontal forces, the horizontal forces on the body or on the wings do not show substantial differences between OGE and IGE. Although the drag variation on each wing when in ground effect is of some interest, it is beyond the scope of the present study. Instead, in the following sections we will pay our attention mainly to the issues associated with the vertical forces on the body.

Table 2. Comparison of aerodynamic force components and power between OGE and IGE, each averaged for the 20th wingbeat cycle ($19.0 < t/T < 20.0$). The ratio of vertical force to power is also compared.

<table>
<thead>
<tr>
<th></th>
<th>$F_{x,\text{ave}}$ (N)</th>
<th>$F_{y,\text{ave}}$ (N)</th>
<th>$F_{z,\text{ave}}$ (N)</th>
<th>$P_{\text{ave}}$ (W)</th>
<th>$F_{z,\text{ave}}/P_{\text{ave}}$ (N/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OGE</td>
<td>$9.53 \times 10^{-9}$</td>
<td>$-9.70 \times 10^{-12}$</td>
<td>$9.91 \times 10^{-9}$</td>
<td>$2.39 \times 10^{-5}$</td>
<td>0.415</td>
</tr>
<tr>
<td>IGE</td>
<td>$9.50 \times 10^{-8}$</td>
<td>$2.27 \times 10^{-10}$</td>
<td>$1.08 \times 10^{-5}$ (8.5%)</td>
<td>$2.35 \times 10^{-5}$ (-1.6%)</td>
<td>0.458 (+10%)</td>
</tr>
</tbody>
</table>

The values in the parentheses are the relative increases in the IGE compared to the results in the OGE.
Table 3. Comparison of force components generated by wings between OGE and IGE, each averaged for the 20th wingbeat cycle. The increases in the IGE from OGE are also shown.

<table>
<thead>
<tr>
<th></th>
<th>( F_{x,\text{ave,wings}} ) (N)</th>
<th>( F_{y,\text{ave,wings}} ) (N)</th>
<th>( F_{z,\text{ave,wings}} ) (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OGE</td>
<td>(-4.29 \times 10^{-8})</td>
<td>(-5.08 \times 10^{-11})</td>
<td>(9.91 \times 10^{-6})</td>
</tr>
<tr>
<td>IGE</td>
<td>(-7.88 \times 10^{-8})</td>
<td>(-5.00 \times 10^{-10})</td>
<td>(9.98 \times 10^{-6})</td>
</tr>
<tr>
<td>IGE-OGE</td>
<td>(-3.59 \times 10^{-8})</td>
<td>(5.51 \times 10^{-10})</td>
<td>(6.78 \times 10^{-8})</td>
</tr>
</tbody>
</table>

Table 4. Comparison of force components generated by body between OGE and IGE, each averaged for the 20th wingbeat cycle. The increases in the IGE from OGE are also shown.

<table>
<thead>
<tr>
<th></th>
<th>( F_{x,\text{ave,body}} ) (N)</th>
<th>( F_{y,\text{ave,body}} ) (N)</th>
<th>( F_{z,\text{ave,body}} ) (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OGE</td>
<td>(3.33 \times 10^{-8})</td>
<td>(4.11 \times 10^{-11})</td>
<td>(-2.46 \times 10^{-9})</td>
</tr>
<tr>
<td>IGE</td>
<td>(1.74 \times 10^{-7})</td>
<td>(-2.72 \times 10^{-10})</td>
<td>(7.77 \times 10^{-7})</td>
</tr>
<tr>
<td>IGE-OGE</td>
<td>(1.40 \times 10^{-7})</td>
<td>(-3.14 \times 10^{-10})</td>
<td>(7.79 \times 10^{-7})</td>
</tr>
</tbody>
</table>

3.2. Instantaneous aerodynamic forces and power

As depicted in Fig. 3C, compared to hovering out of ground effect, the fly in ground effect produces slightly greater vertical force in the several time instances within the wingbeat while almost no change is observed in horizontal forces (Fig. 3A, B) or in the aerodynamic power of the wings (Fig. 3D). Furthermore, when separating the force histories into the body and wings (Fig. 4), we find that the body in ground effect keeps producing positive (upward) vertical force throughout the wingbeat period whereas the body out of ground effect apparently exhibits slight positive vertical force at downstroke but negative (downward) vertical force at late upstroke (Fig. 4C). On the other hand, the vertical forces due to the wings show marginal discrepancy between IGE and OGE except for the slight increase at the early downstroke (Fig. 4F).

Figure 3. Time courses of total aerodynamic forces (A-C: \(F_x, F_y, F_z\)) and powers (D) during the 20th wingbeat cycle for IGE (blue solid lines) and OGE (black dashed lines), respectively. The shaded region of downstroke corresponds to \(0 < \nu/T < 19.54\).
Figure 4. Time courses of aerodynamic forces in IGE (blue solid lines) and OGE (black dashed lines) for body (A-C: $F_x, F_y, F_z$) and wings (D-F: $F_x, F_y, F_z$) during the 20th wingbeat cycle.

Figure 5. (A) Comparison of difference in vertical force between IGE and OGE during the 20th wingbeat cycle. Red solid line, body; blue dotted line, wings; and black dashed line, total vertical force. (B) Decomposition of the vertical forces into inviscid components (Solid lines), viscous components (dashed lines); body (red lines), and wings (blue lines).

We further quantified the differences in vertical force between IGE and OGE for body and wings separately, which are plotted in Fig. 5A-B. The increase in the instantaneous vertical force due to wings in ground effect (Fig. 5A, blue dotted line) does have a feature of time-variation but shows a very small cycle-averaged value as shown in Table 3. The difference in the vertical forces in the body, however, keeps a large positive value.
throughout the wingbeat period, which obviously is responsible for the most of the difference in vertical forces between IGE and OGE.

Furthermore, with considering the low Reynolds number effect we evaluated the influence of inviscid and viscous force components contributing to the vertical forces on the body and on the wings (Fig. 5B). For wings, obviously most of the vertical force is coming from the inviscid (pressure) component. For body, apparently both inviscid and viscous force components maintain the positive value, although the inviscid force component is always larger. This can be further illustrated by means of the pressure distributions on the body surface as discussed in the following section.

3.3. Flow visualization and correlations with aerodynamic force augmentation

Fig. 6 illustrates the wingbeat cycle-averaged pressure contours on the body of IGE and OGE as well as the difference ($p_{\text{IGE}} - p_{\text{OGE}}$) for the 20th wingbeat cycle. It is seen that a pronounced difference lies on the ventral surface of the body as well as the tip of the abdomen, where high pressure regions are observed; the head in IGE shows slightly lower pressures than OGE, which may also contribute to the vertical force. Here the high pressures on the ventral side can explain the increase in $F_{x,\text{ave, body}}$, i.e. increase in the backward force component (Tables 2, 4 and Fig. 4A). This unbalance in the horizontal forces may be coped with by altering (decreasing) its body angle in the real-life situation, even though there would be a limitation to the change of body angle because the backside of the body may interfere with the trailing edges of the wings. In fact, the margin is about 30 degrees if the wing kinematics is unchanged.

In Fig. 7 the body pressure contours are plotted at ten instances for OGE and IGE. It is seen that the pressures on a certain region are not stable in strength but time-varying. Nevertheless, compared to OGE the abdominal tip in IGE always shows a high-pressure region. This is corresponding to the time-averaged pressures shown in Fig. 6. Similarly, at the joints between head and thorax as well as thorax and abdomen, relatively high-pressure regions are also observed, again showing similar tendency as in Fig. 6A.

To further provide an overall image of correlations between flow fields and vertical force production in terms of velocities and pressures we plotted pressure contours and velocity vectors around the hovering model fruit fly in Fig. 8. A high-pressure region can be found close to the ground throughout the wing strokes (Fig. 8, transparent red surfaces and the pressure contours on the ground). At a glance, the body seems to be effectively lifted up on this high pressure “air cushion”. The contacting portions with the air cushion appear to have high pressures.

How is this high-pressure region created? Specifically, why this region is observed mainly under the wings and the body but not beneath the wing roots (see e.g. Fig. 8F or

![Figure 6](image-url)  
**Figure 6.** Comparison of wingbeat cycle-averaged pressures on body surface between IGE (left) and OGE (middle). The pressures are averaged during the 20th wingbeat cycle (over 50 time frames). Note that the difference between IGE and OGE is also shown (right). Ventral (A) and dorsal (B) sides are shown.
We believe the downwash is the answer. The downwashes induce by the flapping wings during down- or up-stroke (Fig. 8C, 8H, and 8I, white arrows) are forced to stagnate and change their directions to horizontal while they are approaching the ground.

This results in a significant reduction in the downward flow speed and pressure rise near the ground surface by converting the dynamic pressure into the static pressure. It is further seen that some of the deflected downward flows originally generated from right wing and left wing head to the center of the body from both sides, subsequently collide each other right under the body, thereby providing another pressure recovery. These are likely the

Figure 7. Comparison of pressure contours between IGE and OGE during the 20th wingbeat cycle. The ribbons on sides present approximately stroke phases.
Figure 8. Front view of visualized flows fields around a hovering model fruit fly in the IGE computation during the 20th wingbeat cycle. Pressure contours, iso-pressure surfaces (transparent blue, at -0.1, and transparent red, at +0.05), and velocity vectors at the yz-plane cutting through the wing bases (white arrows).

main sources of the high pressure on the lower abdominal section, considering that this portion always exhibits higher pressure than the other part of the body (Fig. 8A, 8E, and 8J, also see Fig. 5A, red line). Moreover, portions of the flows at the center further form an upward flow, resulting in a fountain of the airflow, which eventually impinges against the lower side of the body and probably becoming an aid to the further pressure recovery. This whole process is sometimes termed as “fountain effect” in the rotary wing community\(^9\) and is essentially how a hovercraft lift itself, but it has not been reported for the flapping wing
flight before. Unlike hovercrafts, however, as clear from the pressure “footprints” on the
ground in Fig. 8, in flapping wings the horizontal locations of the downwashes fluctuate
back and forth in accordance with the wing motions. Nevertheless, the directions and the
intensities of velocity vectors under the ventral side of the body seem to remain rather stable
(Fig. 8). Therefore, the above-mentioned mechanism is probably responsible for creating
the time-averaged high pressure region on the ventral side of the body (Fig. 6A).

It should be also noted that there found several other features in the body surface
pressure contours, although they are not directly correlated to the vertical force increase in
the IGE because these features are common in the two cases. The low pressure on the back
of the body at the early-downstroke (Fig. 7B), high pressure on the head at supination (Fig.
7F), low pressure on the head just after the supination (Fig. 7G), and high pressure on the
back of the body at late-upstroke (Fig. 7J and 7I), all seem to be due mainly to the direct
influence from the high or low pressure regions on the wings (see Fig. 8B, 8F, 8G, and 8J &
8I, respectively). They possibly explain the within-wingbeat variation in $F_{x,\text{body}}$ and $F_{z,\text{body}}$
(Fig. 4A, 4C). In addition, the low pressure regions on the lateral sides of the body (Fig.
7C-7E, 7G-7I) appear presumably due to the wingroot vortices which are probably only
found in the specific wing planforms (i.e. narrow near the wingroot). The point is that these
pressure regions are available in both IGE and OGE computations and should not contribute
to the overall force difference, although the intensities of which slightly differs. This can be
confirmed by the time-averaged contour difference (Fig. 6A and 6B, right models).

4. Concluding remarks

Ground effect in a hovering fruit fly in terms of aerodynamic force and power was
explored by numerical simulation. It has been confirmed that a fly in ground effect (IGE)
experiences greater vertical force compared to out of ground effect (OGE), provided that
both the wing kinematics and body attitude are unchanged from the stable hovering at OGE.
It was also found that the major contribution is from the presence of the body. Visualization
of velocities and pressures unveiled that in the IGE computation, the wing-induced
downwashes are vectored to horizontal direction due to the ground, and portions of which
merge together under the body, together forming a high pressure region on the lower ventral
side of the body. We believe that this mechanism usually termed as “fountain effect” in
helicopter aerodynamics$^{9}$ is the main source of the vertical force enhancement in fruit fly
hovering in ground effect. This mechanism may be applied to the development of flapping
micro air vehicles (fMAVs) with a tailored fuselage shape to effectively and efficiently
capture the high pressure air and deflected downwash during low altitude hovering, takeoff
or landing.

We showed the wings are essentially out of ground effect at $h/R = 0.8$, but when a real
fly is flying at $h/R < 0.8$, the wings may be benefited from the ground effect. However, in
such a case the wing kinematics as well as the body attitude is fairly likely different from
the OGE hovering$^{15}$. To provide concrete answers to these questions, we need to measure
the real insects’ flights near the ground with sufficient precision not only for wing
kinematics but also body shapes and postures, and carry out an extended study to clarify the
influence of these parameters on the ground effect.

Also, we did not consider the force balance or moments in the present study. These
cannot be ignored in the real situation but the treatment would not be easy because of the
nonlinear coupling. The slightest changes in vertical position or body attitude would result
in the increase or decrease of the intensity of the ground effect, which would provoke the
alteration of aerodynamic force or moment again. Further investigations on this issue would
provide insights into the passive stability or active control in the flapping flight near the
ground.
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References


