Effects of pitching rotation on aerodynamics of tandem flapping wing sections of a hovering dragonfly

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ABSTRACT
This paper studies hovering capability of flapping two-dimensional tandem wing sections inspired by a real dragonfly wing configuration and kinematics. Based on unsteady numerical simulations, the dragonfly corrugated wings have been benchmarked against a flat wing in terms of the aerodynamic forces and flow structures generated during a flapping cycle. The timing of rotation at each stroke is studied by pitch rotation at three different rates, i.e., 80%, 60% and 40% of a flapping period. The results suggest that the longer time pitch rotation with the period of 80% of the overall flapping period is closer to the force calculations obtained of a balanced flight, that is, the mean vertical force $C_V = 1.076$ supports the dragonfly weight of 0.754 g with a small difference of 0.92% and the mean horizontal force $C_H = 0.051$ indicates negligible thrust. However, the corrugated wing performs aerodynamically differently from the flat plate with differences in $C_H$ by ±4.32% and in $C_V$ by ±2.06% for the corrugated shape. The vorticity flow field for both wings have been recorded at some instants of flapping motions which give more explanation of such dissimilarity.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$A_x$</td>
<td>flapping amplitude motion in $x$ direction (m)</td>
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<tr>
<td>$A_y$</td>
<td>flapping amplitude motion in $y$ direction (m)</td>
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<tr>
<td>$c$</td>
<td>chord (m)</td>
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<tr>
<td>$c_{fw}$</td>
<td>fore-wing chord (m)</td>
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<tr>
<td>$c_{hw}$</td>
<td>hind-wing chord (m)</td>
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<tr>
<td>$C_H$</td>
<td>mean horizontal force coefficient</td>
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<tr>
<td>$C_V$</td>
<td>mean vertical force coefficient</td>
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<tr>
<td>$f$</td>
<td>wing beat frequency (Hz)</td>
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<tr>
<td>$F_H$</td>
<td>horizontal force (N/m)</td>
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<tr>
<td>$F_V$</td>
<td>vertical force (N/m)</td>
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<tr>
<td>FWMAVs</td>
<td>flapping wing micro aerial vehicles</td>
</tr>
<tr>
<td>$k_{ij}$</td>
<td>stiffness constant between the centre node and its neighbours</td>
</tr>
<tr>
<td>$II$</td>
<td>matrix given by Equation (11)</td>
</tr>
<tr>
<td>LE</td>
<td>leading edge</td>
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<tr>
<td>LEV</td>
<td>leading-edge vortex</td>
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<tr>
<td>LEVS</td>
<td>leading-edge vortex shedding</td>
</tr>
<tr>
<td>LS</td>
<td>lower surface</td>
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<tr>
<td>$m$</td>
<td>arbitrary instant of grid deformation</td>
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<td>MAVs</td>
<td>micro air vehicles</td>
</tr>
<tr>
<td>$n$</td>
<td>number of iterations</td>
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<tr>
<td>$N$</td>
<td>number of time steps</td>
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<td>$n_i$</td>
<td>number of the surrounding nodes in interconnection with the node $i$</td>
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<td>PIV</td>
<td>particle image velocimetry</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>$S$</td>
<td>wing surface area (m$^2$)</td>
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1.0 INTRODUCTION

The advantages offered by micro air vehicles (MAVs) over ground-based remotely operated machines have motivated a lot of research activities to find the best promising designs of ‘hand-held’ MAVs. Such a vehicle has to fly in the range of Reynolds number similar to insects or small birds $O(10^5-10^6)$. However, it is expected to be a highly efficient craft in terms of manoeuvrability to perform miscellaneous tasks, e.g. to reconnoitre in confined spaces, which are difficult for most of the current generation of unmanned aerial vehicles (UAVs). In addition, the contemporary UAV does not have the capability to accomplish some extreme tasks of reconnoitre buildings, civil search, rescue operations in hazardous places and power-line inspection.

Since MAVs have become a highly demanding platform for many applications as aforementioned, different sources of propulsion have also been implemented and examined in efforts of enhancing MAV flight and manoeuvre at a low Reynolds number (Re) regime. For such small planes, the reliance on a fixed-wing integrates typical propulsive sources may not be appropriate especially for indoor purposes. Accordingly, new methods have been applied to fly MAVs more efficiently where researchers have introduced flapping wings as an alternative approach to fixed and rotary wings for very low flight speeds.

Flapping wings are demonstrated well by nature as being seen from countless genera of insects and birds or the fins of fish. The flying techniques of numerous natural fliers such as birds and/or insects have been investigated and imitated in many studies to create state-of-the-art MAV designs. However, biologists, aerodynamicists, control engineers and the general public have been attracted more by flight of insects than other natural fliers. They are so often wondering ‘how easily these flying creatures stay aloft, propel themselves and perform autonomous navigation’. Many researchers have drawn upon nature to serve as an inspiration for novel designs to enhance or supplant traditional sources of lift and propulsion — nature has a lot more to offer in solving engineering design problems.

Among different kinds of manoeuvres, hovering flying is widely considered as an extreme mode of manoeuvre. However, numerous insects perform it with high efficiency. A range of studies have been conducted on modelling flapping wings mechanism as observed from real insects, such as those reported in Refs 2, 3, 5 and 8. The most fascinating flying creatures are the hummingbird among birds and the dragonfly amongst insects due to their capability of hovering flight.

Because of the highly unsteady flow associated with flapping wings, researchers have so far been unable to rigorously quantify the complex flapping wings phenomena and to measure accurately the forces generated by their wings. Nevertheless, ongoing studies on flapping wings are highly encouraging in the hope that they may provide greater propulsive efficiencies than fixed and rotary wings for the applications of MAVs.

The development of insect-size aircraft is widely predicted in the near future with relevance across military sector which is one of the main driving factors. Flapping wing micro aerial vehicles (FWMAVs) is one of the greatest challenges. According to the US Defence Advanced Research Projects Agency (DARPA), MAVs are defined as flying vehicles with no overall dimension larger than 15cm, a mass of less than 100 grams and a flight speed does not go beyond 25ms$^{-1}$, potentially reducible down to large-insect size, and may be used for a variety of tasks as aforementioned.

This paper studies the hovering capability of flapping tandem wings as inspired by the dragonfly which is adopted due to two interesting points: firstly, it has two winged pairs (fore- and hind-wing), and secondly, its cross-sectional wings are unique and not commonly seen in aeronautic applications. However, a small size of this insect makes it preferred in comparison with hummingbirds in terms of meeting the requirements of MAV conceptual designs. A review of flapping wings literature shows that modelling of the corrugated wing of dragonfly is mostly performed by simplifying it as a flat plate. Many researchers have drawn upon nature to serve as an inspiration for novel designs to enhance or supplant traditional sources of lift and propulsion. Many researchers have drawn upon nature to serve as an inspiration for novel designs to enhance or supplant traditional sources of lift and propulsion. Many researchers have drawn upon nature to serve as an inspiration for novel designs to enhance or supplant traditional sources of lift and propulsion. Many researchers have drawn upon nature to serve as an inspiration for novel designs to enhance or supplant traditional sources of lift and propulsion. Many researchers have drawn upon nature to serve as an inspiration for novel designs to enhance or supplant traditional sources of lift and propulsion. Many researchers have drawn upon nature to serve as an inspiration for novel designs to enhance or supplant traditional sources of lift and propulsion. Many researchers have drawn upon nature to serve as an inspiration for novel designs to enhance or supplant traditional sources of lift and propulsion. Many researchers have drawn upon nature to serve as an inspiration for novel designs to enhance or supplant traditional sources of lift and propulsion.
2.0 MODEL

This work as aforementioned employed a 2D corrugated cross section of a fore- and hind-wing mid-span as adopted from the dragonfly *Anax julius* (14). Figure 1 (a), (b) and (c) represent the insect and its forewing and hind-wing mid-span cross section, respectively.

Tandem flapping wing trajectory was modelled in a comparable replica as demonstrated by a real dragonfly see Fig. 2 where kinematics associated with this trajectory is tabulated in Table 1. An incoming flow velocity was set to zero to model hover case. This study was also deliberated on three cases of pitching periods: short 40%, medium 60% and long 80% of the whole period of flapping as can be seen in Table 1.

As can be seen in Fig. 2, a fore-wing moves out of phase with respect to a hind-wing, i.e., phasing between front and aft-wing about 180º which is inherently used by dragonflies to perform hovering(15). This pattern is named as counter-stroking manoeuvre. The wings move in a rowing motion, pushing down with a board side and slicing through the air in the upstroke which was verified by the inspection of dragonflies in hovering with advanced flow visualisation techniques such as particle image velocimetry PIV(15). Therefore, during the down-stroke either the fore- or the hind-wing moves horizontally with $\alpha_d = 60^\circ$ while they moves parallel to stroke plane in the upstroke with $\alpha_u = 0^\circ$. This explains that the motion of the fore- and the hind-wing is alternating during flapping cycle. The wings reverse to perform the up-stroke by doing supination and to accomplish the down-stroke by doing pronation. A further illustration of how this trajectory was modelled is given in the next section. The wing pitches at supination time so that the leading edge always leads the trailing edge during the up-stroke phase. However, the wing pitches at pronation time so that the leading edge was always on the left of the trailing edge during the down-stroke phase.

| Table 1 Hovering flapping wing kinematics based on dragonfly |
|---------------------------------|------------------|
| Flapping kinematic terminologies and their symbols | Value |
| Up-stroke angle of attack ($\alpha_u$) | 0º |
| Down-stroke angle of attack ($\alpha_d$) | 60º |
| Stroke plane angle ($\beta$) | 60º |
| Flapping amplitude (A) | $\approx 2.5c$ |
| Up-stroke pitch time ($t_u$) | 20%, 30% and 40% $T$ |
| Down-stroke pitch time ($t_d$) | 20%, 30% and 40% $T$ |
| Incoming flow velocity ($U_\infty$) | 0 |

As there is not much work on modelling MAV flapping tandem wings, particularly, based on dragonfly corrugated wing, the focal point of this paper is to conduct two-dimensional (2D) unsteady simulations of the flow around tandem flapping wings and to compare the corrugated shape of dragonfly wing(14) versus a flat plate cross section. Moreover, another aim was to investigate the effect of the timing of stroke reverse on the aerodynamic force production. Three cases of a pitching period were being considered: short 40%, medium 60% and long 80% of the whole period of flapping as can be seen in Table 1.
3.0 FLAPPING TRAJECTORY SIMPLIFICATIONS

The chord-based Strouhal number $St_c$ and the Reynolds number $Re$ were regarded as the most important parameters that affect such a flapping wing modelling. Especially, the former has a considerable influence in the case of unsteady vortical flow simulations. They are defined as

$$St_c = \frac{fc}{V} \quad \ldots (1)$$

$$Re = \frac{\rho V c}{\mu} \quad \ldots (2)$$

Here $c$ is the forewing mid-span chord of 0.1054m and $V$ is the mean flapping velocity of 0.1471ms$^{-1}$. On the basis of dragonfly’s averaged $Re = 1,350$ and $St = 0.117$, this simulation was conducted where morphological data was taken as the fore-wing chord ($c_w = 0.1054$m), hind-wing chord ($c_h = 0.127$m) for a MAV wing design and the distance separates the wings was about 1/5$c_w$ in similar proportion to the corresponding dragonfly wing’s chords. Hence, the model flapping frequency ($f = 0.226$ cycle/sec) is the equivalent figure to the dragonfly flapping wings frequency of 36 cycle/sec to match the Strouhal number of a dragonfly.

Therefore, the flapping period ($T$) was lasted almost 4.44 sec based on $f = 0.226$ cycle/sec according to.

$$T = \frac{1}{f} \quad \ldots (3)$$

PIV photos have allowed biologists to identify that the motion of wing tip approximately draws a sinusoidal shape in hovering mode. The assumption of modelling hovering flapping wings based on a pure sinusoidal variation has been deployed in many studies. Therefore, the plunging motion was computed with respect to the inertia co-ordinate ($x$ and $y$) shown in Fig. 2 based on sinusoidal harmonic assumption as

$$x = A_x \sin(\omega t + \gamma) \quad \ldots (4a)$$

and

$$y = A_y \sin(\omega t + \gamma) \quad \ldots (4b)$$

where $\gamma$ is the phase difference during hovering which is 180°, and $A_x, A_y$ represent the flapping amplitude of motion in $x$ and $y$ directions, respectively. $\omega$ is the angular velocity of the flapping motion

$$\omega = 2\pi f \quad \ldots (5)$$

The convention of positive directions is shown in Fig. 2. According to Bergou et al. $A_x$ and $A_y$ were assumed as 1.2 and 2.1 chord length, respectively. This approximately gives a stroke plane angle of 60 degrees as performed by a real dragonfly as well as flapping amplitude of approximately 2.5 fore-wing chord based calculations. However, similar formulae were applied to the hind-wing plunging except that the distance separates the wings added to the hind-wing horizontal plunging $x$ and $\gamma_h = 0^\circ$ was used to obtain out-of-phase flapping. Similarly, the pitching rotation phase about an axis which moves with the flapping wings is defined as

$$\theta = \pm A_r \left(1 - \cos 2\pi \frac{t - t_r}{T_r} \right) \quad \ldots (6)$$

where $A_r$ refers to the pitching amplitude which should be chosen so that the wing rotates 120° to reverse stroke from 60° to 0° at supination, and vice versa at pronation (minus and plus signs signify that, respectively). Here $t_r$ is the commencement of each stroke reverse and $T_r$ is the period of pitching mode which was considered for three cases: 40%, 60% and 80% of the whole flapping period ($T$).

Figure 3 represents harmonic motions assumed for a hovering mode. The normalised flapping period defined as the time interval ($t$) at each instant of flapping motion over $T$ is given as

$$\tau = \frac{t}{T} \quad \ldots (7)$$

As can be seen from Fig. 3 (a) and (b), three scenarios represent the pitching phase plotted after scaling $\theta$ to obtain a more compact comparative plot. Clearly, it is also depicted that longer pitch timing has smaller amplitude of rotation.

4.0 METHOD

4.1 Computational grid

The computational domain was discretised by using Gambit 2.2.30 grid generator where a hybrid mesh was constructed as depicted in Fig. 4. As can be noted from Fig. 4, this consists of an inner structured grid with viscous boundary layer clustering that moves with the wing as a rigid body and an outer unstructured grid to fill the remaining regions of computational domain. The reason of creating the structured mesh around geometry (meshing of ~ 2c x 1c lengths) was to maintain the quality of grid and to secure the integrity of the
where \( \tau \) is the stress tensor, \( \vec{u}_g \) is the grid velocity of moving mesh, \( \vec{u}_f \) is the flow velocity vector (\( \vec{u}_f = \vec{u}_i + \vec{v}_j \)). The general scalar \( \phi \) can be written in a vector form as

\[
\phi = \begin{bmatrix} u \\ v \end{bmatrix}
\]

(10)

The matrix \( \mathbf{II} \) is defined as

\[
\mathbf{II} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}
\]

(11)

Second-order discretisations were used for the spatial part, and the pressure-velocity coupling was via the fully-implicit scheme for the pressure-linked equations (the SIMPLE algorithm). The time derivative was discretised using backward differences in first order formulation. A dynamic mesh approach was utilised to solve the unsteady flow coupled with flapping wings based on the advanced time scheme (ATS) provided in the pressure based solver in Fluent 6.3.2 as charted in Fig. 5. The momentum equations were solved and the resulting flow field was corrected by pressure to fulfill the continuity constraints as shown by the inner loop as depicted in Fig. 5. Then, the solution was advanced to the next time step and so on until periodic solution is obtained or a maximum time step reached.

The convergence history of the flow solver is plotted in Fig. 6, where 100 pseudo iterations were carried out at each time step. The residuals were reduced by five orders of magnitude at each time step for the two components of velocity and four orders magnitude for the continuity as signified by Fig. 6. As shown in this figure, a reasonable convergence was obtained from the second flapping wing cycle where 2,000 iterations (baseline case) was taken at each cycle and 100 pseudo iterations were proceeded at each time step.

4.2 Flow solver

With a very low Re regime, incompressible and laminar states were assumed in the solution of the Navier-Stokes equations NSEs to model flapping wing unsteady flow. NSEs can be written for moving boundary based on geometry conservation law GCL in integral Cartesian arrangement for an arbitrary control volume \( V \) with differential surface area \( dA \) containing surface boundary \( \delta A \) as:

\[
\frac{d}{dt} \iint_V \rho \vec{u} dV + \iint_{\delta A} \rho \vec{u} (\vec{u}_f - \vec{u}_i) d\delta A = -\iint_{\delta A} \rho \vec{V} \sigma d\delta A + \iint_{\delta A} \sigma \vec{V} d\delta A
\]

(9)

where \( \vec{F} \) is the stress tensor, \( \vec{u}_g \) is the grid velocity of moving mesh, \( \vec{u}_f \) is the flow velocity vector (\( \vec{u}_f = \vec{u}_i + \vec{v}_j \)). The general scalar \( \phi \) can be written in a vector form as

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Three different density grids were generated and studied their influences on the results obtained in this work, the reader is referred to Section 6.1. Figure 4 portrays the medium grid of 15,330 cells which has the overall quadrilateral cells of 5,152 (78 × 32 for the forewing and 83 × 32 for the hind-wing) and 10,178 triangular cells. The first cell in the boundary layer out of 20 points perpendicular to the wing surface was created with \( \frac{1}{15} \) to adequately resolve the flow passage where there was expected a steep velocity gradient at the wall when the wing pitching. The resolution of the laminar boundary layer (i.e., mesh adjacent to spacing near wall) was chosen to obey the following relation to accurately compute wall shear stress:

\[
y_p \frac{\rho u}{\nu x} \leq 1
\]

(8)

where \( y_p \) is the distance between the wall surface and the adjacent cell centroid, \( u_\infty \) is the free stream velocity taken as the mean flapping wing velocity for hovering (\( V = 0.1471 \text{m/s} \)), \( \mu \) is the fluid viscosity (1.7849×10^-5 kg/(m·sec)) and \( \rho \) is the fluid density (1.223 kg/m^3) and \( x \) is the distance along the wall from the leading edge.

4.2 Flow solver

With a very low Re regime, incompressible and laminar states were assumed in the solution of the Navier-Stokes equations NSEs to model flapping wing unsteady flow. NSEs can be written for moving boundary based on geometry conservation law GCL in integral Cartesian arrangement for an arbitrary control volume \( V \) with differential surface area \( dA \) containing surface boundary \( \delta A \) as:

\[
\frac{d}{dt} \iint_V \rho \vec{u} dV + \iint_{\delta A} \rho \vec{u} (\vec{u}_f - \vec{u}_i) d\delta A = -\iint_{\delta A} \rho \vec{V} \sigma d\delta A + \iint_{\delta A} \sigma \vec{V} d\delta A
\]

(9)
where
\[ \Delta x_i \] displacement of node \( i \)
\[ \Delta x_j \] displacement of surrounding nodes
\( n_i \) number of the surrounding nodes in interconnection with the node \( i \) by assumed springs
\( k_{ij} \) stiffness constant between the centre node and its neighbours taken as 0.7 after different values were tested.

Equation (12) is reformulated at equilibrium in an iterative form at the instant \( m \) as
\[ \Delta x_i = \frac{\sum_{j=1}^{n_i} k_{ij} \Delta x_j}{\sum_{j=1}^{n_i} k_{ij}} \] ... (13)

Therefore, the following updating formula was used to compute the new locations
\[ x_i^{n+1} = x_i^n + \Delta x_i^m \] ... (14)

where \( n+1 \) and \( n \) are the new and current location of a mesh node, respectively.

4.3 Dynamic mesh method

To facilitate flapping wings simulation to be conducted properly, two techniques of dynamic mesh were included, namely, remeshing and spring tension analogy. The former (remeshing) allows to rescue the integrity of cells and control the deforming regions subjected to flapping wings motion (preventing potential grid cross over). A user defined function (UDF) script was written to define a prescribed motion based on the position (sliding ‘\( x \’ \) and plunging ‘\( y \’ \) motions) and orientation (pitching phase ‘\( \theta \’ \) motions) of the centre of gravity of a moving object, refer to Section 3.

4.3.1 Spring-based smoothing

With this method, the grid will deform as a network of springs interconnecting mesh nodes as exposed in Fig. 7. The motion is governed by the force exerted on a mesh node as
\[ \bar{F}_i = \sum_{j=1}^{n_i} k_{ij} (\Delta x_j - \Delta x_i) \] ... (12)

Figure 8. Snapshot of vorticity contours at a down-stroke phase of hovering flapping wing (a) Water tunnel experiment(13) (b) CFD simulation(10).

Figure 6. The convergence history for the second flapping wing cycle (cycle = 2,000 iterations) with 100 iterations at each time step.

Figure 7. A schematic depiction of spring-based smoothing method.

Figure 8. Snapshot of vorticity contours at a down-stroke phase of hovering flapping wing (a) Water tunnel experiment(13) (b) CFD simulation(10).

4.3.2 Local-based remeshing concept

Mainly, the reliance upon the spring analogy method alone was not sufficient to avoid some deteriorated cells particularly born close to the moving object. To circumvent this, therefore, these cells were locally re-meshed to satisfy some skewness and size limit criteria in order to improve the accuracy performance of the dynamic meshing technique. The solution was interpolated from the old cells, and, the new cells were not updated if they had not been met these specified criteria, e.g., maximum skewness should be less 0.6.

5.0 MODEL VALIDATION

In order to validate the CFD results for flapping wings modelling, in an earlier work in 2008 by Ezzeddin and Qin(10), flow visualisations comparison was performed between CFD simulation and a water-tunnel experiment(13) at different instants of flapping cycle, where a flat plate was deployed(10). For a fair assessment, dimensionless quantities, i.e. Re and St, were matched with those applied in the water-tunnel experiment(13). Figure 8 pictures the flapping wing flow structure comparison between the computer simulation and the water-tunnel test at the down-stroke phase, from
observed. An asymptotic behaviour was obtained from forming flapping wing simulation after three cycles. Figure 9 illustrates that the overall pattern of the force calculations over three flapping wing cycles was not very sensitive to mesh density refinement. The medium grid was employed in the following because the CPU requirements and the sensitivity study. The mean force coefficients of medium grid are plotted for reference in Fig. 9.

6.2 Investigation of time step size independence

The flapping wing force coefficients were investigated for three different time steps as shown in Table 3 and the medium time step on the medium grid was deemed adequate considering computational costs.

Again asymptotic behaviour was obtained from forming flapping wing simulation for three cycles. Figure 10 demonstrates that the overall pattern of the force calculations was studied over three flapping wing cycles with three time steps. The mean in Fig. 10 was plotted for 0.00222 sec time step.

Ref. 10. Overall, a reasonable correspondence was found between the CFD results and the water tunnel experiment in terms of the sizes and positions of the various vortices generated during varied stages of flapping motion in hover. However, this should not be considered as a full validation because, the strengths of vortices and/or other quantitative data were not given for the water tunnel experiment.

6.0 SENSITIVITY ANALYSIS

To verify the numerical results and exclude numerical artefacts from the solution obtained here this section focuses on the effects of grid resolution and time step size on solutions. Time-averaged (mean) horizontal and vertical force coefficients \( C_{VH} \) and \( C_{V} \) measured in the inertial co-ordinates \( x \) and \( y \), respectively, were used to assess the independence of numerical solution with respect to grid and time step refinements. The force coefficients are defined as:

\[
C_{VH} = \frac{2}{\rho V^2 S T} \int_{T}^{T} F_{HV} \, dt
\]

\[
C_{V} = \frac{2}{\rho V^2 S T} \int_{T}^{T} F_{V} \, dt
\]

The integration of the forces was conducted by averaging over one converged flapping cycle where \( F_{HV} \) and \( F_{V} \) are the total force components which were computed by summing the pressure and viscous forces. Here, \( T \) is the flapping period (4.44sec), \( V \) is the mean flapping wing velocity (0.1471 m/sec), \( S \) is wing surface area which was assumed as the wing chord because the forces produced for a 2D model is in Newton per unit span. The fore- and the hind-wing chords were used in the same proportion to the dragonfly wings chord ratio as 0.1054m and 0.1270m, respectively.

6.1 Investigation of grid resolution independence

Table 2 highlights three sizes of grid which were studied by roughly doubling the overall number of structured cells. Two parameters were examined in this connection, i.e. the mean vertical and horizontal force coefficients \( C_{V} \) and \( C_{VH} \), respectively.

Note that the difference in the force coefficients were not significant but slight increase in \( C_{V} \) and slight decrease in \( C_{VH} \) can be observed. An asymptotic behaviour was obtained from forming flapping wing simulation after three cycles. Figure 9 illustrates that the overall pattern of the force calculations over three flapping wing cycles was not very sensitive to mesh density refinement. The medium grid was employed in the following because the CPU requirements and the sensitivity study. The mean force coefficients of medium grid are plotted for reference in Fig. 9.

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7.0 RESULTS AND DISCUSSIONS

This part of the paper is devoted, firstly, to check the timing of rotation effects on the force calculations of the tandem flapping dragonfly corrugated wings, and secondly, to compare the performance of the corrugated wings against a flat plate wing in tandem arrangement.

7.1 Corrugated wing analysis

In order to examine the timing of rotation effect for stroke reversal on the force balance, three scenarios were studied by allowing a quick, medium and slow rotation performed within a period of 40%, 60% and 80% of the whole flapping period, respectively. Figure 11 gives the tandem wings time histories of $C_V$ and $C_H$ in one cycle for these three cases. The mean force was plotted by considering the 80% $T$ rotation timing such that more accurate force balance was obtained to support the typical dragonfly weight of 0.754g (18) and negligible body thrust during hovering.

To find the contribution of each wing to the overall vertical force, each wing was considered independently here. Figure 12 presents the fore- and hind-wing time variation of $C_V$ in one cycle for the timing of rotation with a rotation period of 80% $T$. This was found as the most appropriate setting for force generation of a balanced flight, see Fig. 11.

As can be observed from Fig. 12, the fore-wing produces just above half of the vertical force and the hind-wing produces just under half of the vertical force where the $C_{V}$ of fore- and hind-wing were found as 0.581 and 0.52, respectively. Therefore, it can be concluded that the fore-wing contributes a little more by roughly 8% than the hind-wing to the vertical force required to support the weight.

7.2 Flat plate wing versus corrugation wing

This section includes the comparison of tandem flapping wings between the flat plate and the dragonfly wing-corrugated shape. First, the vertical and horizontal force coefficients of those geometries due to flapping motion were calculated for three cycles as shown in Fig. 13. As can be observed from Fig. 13, small difference was found between the flat plate and the corrugated shape in the force production by flapping motion. It is found that the flat plate was defeated by the corrugated wing when the mean vertical force coefficient was calculated. The difference in mean vertical force coefficients...
wing returns to perform upstroke transition, it travels in the wake of the past down-stroke, and vice versa for the hind-wing. In this event, the flow no longer satisfies the Kutta-Joukowski condition which means that the rate of change of the bound circulation was negative. Moreover, the leading edge vortex was attached in the hind-wing down-stroke phase started to shed as the wing pitches about the leading edge. However, this vortex now pushes the lower surface of the hind-wing in comparison to the hind-wing pronation phase. This may be aerodynamically in favour of a wing where the lift was enhanced due to this, see Figs. 12 and 13 (a). However, the contribution of this phenomenon has been observed in many previous studies. The flow suction can be observed on the LE lower surface of the fore-wing which was detrimental to the aerodynamic force. Figure 17 shows the vorticity contour at $\tau = 0.8$ during down-stroke of the fore-wing and up-stroke of the hind-wing. Once again, the vortices generated by the corrugated wing were much stronger than the flat plate. There was a considerable difference between the flat plate and the dragonfly wing at this phase of a flapping motion in comparison with the pervious stages. A strong shedding vortices interaction appeared between the fore- and hind-wing of the corrugated shape compared to the flat plate. The reason behind this may be due to the natural performance of a corrugated wing coefficient of 2.06% was for the corrugated wing. Subsequently, a comparison between the performance of the flat plate and the corrugated wing in terms of flow structure was drawn for certain phases of flapping wings motion.

Figure 14 shows the vorticity contour at the normalised flapping period $\tau = 0.14$ during fore-wing supination (stroke reversal, i.e., pitching to perform up-stroke) and hind-wing pronation (stroke reversal, i.e., pitching to perform down-stroke). In correspondence with the first peak produced by the fore-wing in Fig. 12, obviously, the leading edge vortex LEV shedding from fore-wing pushes the fore-wing to perform supination, which refers in flapping wings literature as a rotational lift phenomenon as observed in many previous studies. However, the flow pattern interacts more smoothly with a flat plate than corrugated wing as seen by comparing the fore-wing, which explains the difference in Fig. 13. This may be a significant indication that the corrugated wing works as 'turbulators' (protruding corners). LEV was created for hind-wing and the hind-wing was pushed by the trailing-edge vortex TEV shedding to perform pronation, which causes the drop in the hind-wing force contribution. The LEV was attached to the hind-wing in the pronation phase started to shed as the wing pitches around the leading edge.

Figure 15 shows the vorticity contour at $\tau = 0.34$ during up-stroke of the fore-wing and down-stroke of the hind-wing. The flow suction was observed on both the LE and TE of the fore-wing. Moreover, it is clear that an important role was played by the valleys of a corrugated wing to trap the flow, preventing the separation, by comparing the fore-wing in Fig. 15 (a) and (b). A second separation appears at the mid-span upper surface of flat plate which has less strength on the corrugated wing. This verifies that the corrugated shape was acted more efficiently than the flat plate to prevent the flow separation. The vortices of the corrugated wing seem to be more concentrated than the flat plate ones. The flow for fore- and hind-wing satisfies the Kutta-Joukowski condition as it smoothly leaves the trailing edge. Moreover, unstable vortex generation causes a train of the unsteady vortices shed behind the wings created a similar pattern to a Kármán vortex street. This may not be aerodynamically favourable due to the drop observed in the vertical force as shown in Figs (a) and (12).

Figure 16 shows the vorticity contour at $\tau = 0.54$ during fore-wing pronation and hind-wing supination phases. The wings interact with the shedding vortices of the previous phases. The so-called wake capture (wake interaction or wake re-entry as differently named) is another physical phenomenon of a flapping wing illustrated in detail in Ref. 7, which was expected to exist here. Basically, when the fore-wing returns to perform upstroke transition, it travels in the wake of the past down-stroke, and vice versa for the hind-wing. In this event, the flow no longer satisfies the Kutta-Joukowski condition which means that the rate of change of the bound circulation was negative. Moreover, the leading edge vortex was attached in the hind-wing down-stroke phase started to shed as the wing pitches about the leading edge. However, this vortex now pushes the lower surface of the hind-wing in comparison to the hind-wing pronation phase. This may be aerodynamically in favour of a wing where the lift was enhanced due to this, see Figs. 12 and 13 (a). However, the contribution of this phenomenon has been observed in many previous studies. The flow suction can be observed on the LE lower surface of the fore-wing which was detrimental to the aerodynamic force. Figure 17 shows the vorticity contour at $\tau = 0.8$ during down-stroke of the fore-wing and up-stroke of the hind-wing phases. Once again, the vortices generated by the corrugated wing were much stronger than the flat plate. There was a considerable difference between the flat plate and the dragonfly wing at this phase of a flapping motion in comparison with the pervious stages. A strong shedding vortices interaction appeared between the fore- and hind-wing of the corrugated shape compared to the flat plate. The reason behind this may be due to the natural performance of a corrugated wing.
Figure 14. Vorticity contours snapshot of hovering flapping tandem wings during pronation of hind-wing and supination of fore-wing at particular instant $\tau = 0.14$.

Figure 15. Vorticity contours snapshot of hovering flapping tandem wings during up-stroke phase of fore-wing and down-stroke phase of hind-wing at particular instant $\tau = 0.34$. 
9.0 FUTURE WORK

There is a plan to conduct an optimisation on flapping wing kinematics such as the setting angles, frequencies and amplitudes using surrogated models method (19). Finally, 3D effects such as spanwise flows and wing tip vortices will be included in future study for full 3D modelling.

REFERENCES


wing which has a well-known capability to work as a turbulator. However, no significant contributions to lift were found at this phase of the flapping wing even though a small improvement was observed for the fore-wing as shown in Fig. 12. Once more, the wings enter the wake of the previous stroke when the fore-wing moves in the past up-stroke shedding vortices, and vice versa for the hind-wing.

8.0 CONCLUSIONS

Based on a two-dimensional study of hovering flapping wings in tandem arrangement, three scenarios of the pitch timing of rotation have been considered to examine their effects on force balance constraints. Comparison has been conducted between the dragonfly corrugated and the flat plate wings. Mesh size and time step sensitivities were both investigated during the study. A slow pitching performed during the flapping cycle is probably closer to dragonfly hovering flight as the force balance is satisfied. In other words, a long stroke reversal time period of 80% of the overall flapping period \( T \) has fulfilled the hovering flight criteria where \( C_f = 1.076 \) supports approximately the dragonfly weight of 0.754 g and \( C_l = 0.051 \) indicates the thrust is insignificant. No significant difference is found in the major flow pictures between the flat plate and the real dragonfly wing despite of the difference in \( C_f \) by ±4.32 % and in \( C_l \) by ±2.06% for the corrugated shape. However, detailed analysis of the flow field indicates differences in the vortical flow structures, which result in the differences in the force generation.