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Vortex interaction of tandem pitching and plunging plates: a two-dimensional model of hovering dragonfly-like flight

David Rival\textsuperscript{1,2}, Dirk Schönweitz and Cameron Tropea

Institute of Fluid Mechanics and Aerodynamics, Technische Universität Darmstadt, Darmstadt, Germany

E-mail: derival@ucalgary.ca

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Abstract

The force evolution and associated vortex dynamics on a nominal two-dimensional tandem pitching and plunging configuration inspired by hovering dragonfly-like flight have been investigated experimentally using time-resolved particle image velocimetry. The aerodynamic forces acting on the flat plates have been determined using a classic control-volume approach, i.e. a momentum balance. It was found that only the tandem phasing of $\psi = 90^\circ$ was capable of generating similar levels of thrust when compared to the single-plate reference case. For this tandem configuration, however, a much more constant thrust generation was developed over the cycle. Further examination showed that the force and vortex development on the fore-plate was unaffected by the tandem configuration and that nearly all variations in performance could be attributed to the vortex interaction on the hind-plate. By calculating the trajectory and strength of the hind-plate’s trailing-edge vortex, the chain-like vortex interaction mechanism responsible for improved performance at $\psi = 90^\circ$ could be identified. The underlying result from this study suggests that the dominant vortex interaction in dragonfly flight is two dimensional and that the spanwise flow generated by root-flapping kinematics is not entirely necessary for efficient propulsion but potentially due to evolutionary restrictions in nature.

(Some figures in this article are in colour only in the electronic version)

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>$A$</td>
<td>area enclosing a vortex</td>
</tr>
<tr>
<td>$c$</td>
<td>profile chord length</td>
</tr>
<tr>
<td>$C_n$</td>
<td>non-dimensional normal force</td>
</tr>
<tr>
<td>$C_t$</td>
<td>non-dimensional thrust force</td>
</tr>
<tr>
<td>$f$</td>
<td>frequency of pitch/plunge motion</td>
</tr>
<tr>
<td>$F$</td>
<td>force vector acting on a profile</td>
</tr>
<tr>
<td>$\vec{g}$</td>
<td>gravity vector</td>
</tr>
<tr>
<td>$h$</td>
<td>plunge position</td>
</tr>
<tr>
<td>$h_0$</td>
<td>plunge amplitude</td>
</tr>
<tr>
<td>$h_{\text{max}}$</td>
<td>peak plunging velocity</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>pitch angle</td>
</tr>
<tr>
<td>$\alpha_0$</td>
<td>mean pitch angle</td>
</tr>
<tr>
<td>$\vec{n}$</td>
<td>normal vector to control surface S</td>
</tr>
<tr>
<td>$p$</td>
<td>pressure</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>$S$</td>
<td>control surface bounding control volume V</td>
</tr>
<tr>
<td>$t$</td>
<td>time</td>
</tr>
<tr>
<td>$T$</td>
<td>period</td>
</tr>
<tr>
<td>TEV</td>
<td>trailing-edge vortex</td>
</tr>
<tr>
<td>TR-PIV</td>
<td>time-resolved particle image velocimetry</td>
</tr>
<tr>
<td>$\vec{u}$</td>
<td>velocity vector</td>
</tr>
<tr>
<td>$u$</td>
<td>velocity in horizontal direction</td>
</tr>
<tr>
<td>$v$</td>
<td>velocity in vertical direction</td>
</tr>
<tr>
<td>$V$</td>
<td>control volume for force estimation</td>
</tr>
<tr>
<td>$x$</td>
<td>horizontal coordinate</td>
</tr>
<tr>
<td>$y$</td>
<td>vertical coordinate</td>
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\textsuperscript{1} Author to whom any correspondence should be addressed.
\textsuperscript{2} Present address: Department of Mechanical and Manufacturing Engineering, University of Calgary, 2500 University Dr NW, Calgary, AB, T2N 1N4, Canada.
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Introduction

By studying the kinematics of live dragonflies, Alexander (1984) observed that the wing phasing (ψ), the offset between fore-wing and hind-wing flapping motions, was of great importance to their effective flight performance. It was found that in-phase flapping was used for high-lift maneuvers such as take-off, whereas out-of-phase flapping was common for steady-state flight conditions where energetics were a consideration. In fact Azuma and Watanabe (1988), among many others, recognized that dragonflies modulated not their flapping frequency but their fore-wing/hind-wing phasing depending on their flight speed, i.e. transition from hover to cruise conditions. This phasing was found to vary from $60^\circ \leq \psi \leq 90^\circ$, with lower phasing angles observed in hover and higher phasing angles found for cruise flight. Similar to rotorcraft, Azuma and Watanabe (1988) examined the relationship between the tilting of the body axis (body attitude) and the fore- and hind-wing stroke planes ($r_f$ and $r_h$) such that the latter approach vertical and horizontal configurations in cruise and hover conditions, respectively. In figure 1, a schematic demonstrating this varying geometry between stroke planes, body axis and the flight path angle is shown.

A range of investigations into unsteady, tandem-wing aerodynamics, almost exclusively for hover conditions, have been performed with the hope of better understanding the complex aerodynamic interaction associated with dragonfly flight. Among these investigations, Bosch (1978), Lan and Sun (2001), Sun and Lan (2004), and Wang and Sun (2005) considered the problem from a two-dimensional standpoint with either the assumption of inviscid or laminar flow. Although insightful, these studies did not go as far as identifying the specific vortex interactions associated with dragonfly-like flight. Isogai et al. (2004), Maybury and Lehmann (2004), Yamamoto and Isogai (2005), Usherwood and Lehmann (2008), and Lehmann (2008, 2009) investigated the interaction in three dimensions (root-flapping flight), primarily using force measurements and to a lesser extent particle image velocimetry (PIV). Again, these studies did not offer quantitative information regarding the vortex interactions. One particular study stands out where Maybury and Lehmann (2004) used a mechanical system inside an oil-reservoir to mimic the three-dimensional dragonfly kinematics in hover, see figure 2. Although they were able to identify the phase angles for which maximum beneficial interaction occurred, quantitative measurements regarding the vortex interaction were not provided.

Parameter space

The pitching ($\alpha$) and plunging ($h$) movement of the fore-(F) and hind-plates (H), can be described through equations (1–4), where the hind-plate leads the fore-plate with a
For the determination of the full, time-resolved velocity fields around the two profiles. In turn a complete control-volume analysis could be performed in order to obtain normal ($C_n$) and thrust forces ($C_t$) fixed in the vertical and horizontal directions, respectively. The orientation of these forces relative to the experimental setup is shown in figure 3(a), while the equivalent orientation for a hovering dragonfly combating gravity ($g$) is shown in figure 3(b). These forces have been non-dimensionalized using the maximum plunge velocity ($\dot{h}_{max}$) such that

$$C_n = \frac{2N}{\rho h_{max}^2 c}$$  \hspace{1cm} (5)$$

$$C_t = \frac{2T}{\rho h_{max}^2 c}.$$  \hspace{1cm} (6)

where $N$ and $T$ are the normal and thrust forces, respectively. For both profiles, pitching leads plunging by a phase angle of $\phi = 90^\circ$.

The dimensionless plunge amplitude, based on the quarter-chord position ($c/4$), was maintained at $h = \pm 0.5 c$ throughout this study. The rotation points for both fore- and hind-foils were fixed at the quarter-chord position and the plate spacing was fixed at $\Delta x = 2 c$ between plate quarter-chord positions. This is a relatively large spacing when compared to live dragonflies. Nevertheless, Maybury and Lehmann (2004) showed that the salient interactions remain the same at these higher spacings and that the optimal phase angle reduces with a reduction in wing spacing, i.e. there is a linear correlation between the two parameters. It has also been shown that in-phase flapping generates a single LEV shared over both wings. This could not be recreated in this study due to the larger plate spacing. Rather the focus has been placed on the vortical interactions at non-zero phase angles.

Both profiles were oscillated symmetrically about $\alpha_0 = 0^\circ$ such that the stroke planes were normal to the gravity vector, as shown in figure 3. The pitch amplitude on the other hand was set to $\alpha_1 = 30^\circ$. Lehmann (2008) used $\alpha_1 = 45^\circ$ in his study; however, the vortex formation was found to be very similar despite the difference in pitch amplitude since full separation was maintained throughout the cycle. Finally, the dynamic motions were set to a frequency of $f = 1$ Hz, corresponding to a maximum plunge velocity of $\dot{h}_{max} = 0.38$ m s$^{-1}$. The Reynolds number based on this plunge velocity was approximately $Re = 3000$. The plate phasing ($\psi$) was varied in increments of $45^\circ$, i.e. from $\psi = 0^\circ$ through to $\psi = 315^\circ$. For each phasing, an experimental run with seven cycles was performed approximately 15–20 times, with the exception of $225^\circ$, $270^\circ$ and $315^\circ$, where only three experimental runs were performed for each phasing.

Since plexiglass plates were used in this study, shadows and reflections around the profiles were minimal. This allowed for the determination of the full, time-resolved velocity fields around the two profiles. In turn a complete control-volume analysis could be performed in order to obtain normal ($C_n$) and thrust forces ($C_t$) fixed in the vertical and horizontal directions, respectively. The orientation of these forces relative to the experimental setup is shown in figure 3(a), while the equivalent orientation for a hovering dragonfly combating gravity ($g$) is shown in figure 3(b). These forces have been non-dimensionalized using the maximum plunge velocity ($\dot{h}_{max}$) such that

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$$C_t = \frac{2T}{\rho h_{max}^2 c}.$$  \hspace{1cm} (6)

where $N$ and $T$ are the normal and thrust forces, respectively. For both profiles, pitching leads plunging by a phase angle of $\phi = 90^\circ$. Using these time-resolved forces, tandem cases with similar performance to the single-plate have been examined. Particular focus is placed on specific vortex interactions where good hovering performance is observed.

### 3. Experimental set-up and methods

#### 3.1. Hover chamber

As shown in figure 4, a 120 cm long plexiglass box with a cross-section of $45 \text{ cm} \times 45 \text{ cm}$ was used for these hover-type experiments; note that the back wall was 44 cm ($x/c = 3.6$) from the hind-foil trailing edge. The tip spacing between the plates and the sidewall was less than 2 mm on either side, thus approximating an infinite span. PIV seeding particles were injected 30 s prior to the experimental run in order to allow for quiescent initial conditions. In figure 5, the experimental rig with hover chamber is shown with the laserhead located on the left and the high-speed camera on the right.

#### 3.2. Flat-plate profile

For the hover experiments, the flow was to remain fully separated and therefore the sensitivity to the profile shape was expected to be negligible. For this reason, simple plexiglass flat plates with $0.067c$ thickness and rounded leading and trailing edges were used. Since maximum pitch/plunge frequencies of only $f = 1$ Hz were used for these experiments, the plates remained effectively rigid throughout all tests. A great advantage of using plexiglass for these measurements was the full optical access around the profile, as shown in figure 6. The thin shadow regions at the leading and trailing edges were eliminated using a moving-average filter during post-processing, as reported in section 3.4.

#### 3.3. Experimental rig

The experimental rig consisted of a base structure, four linear motors and two flat-plate profiles. The linear motors used to drive the motion were of type LinMot PS01-48x240F-C. A displacement accuracy of $\leq 0.5$ mm was achieved during all experimental runs. The linear motors were controlled with
a custom LabView 8.2 program developed at the Institute of Fluid Mechanics and Aerodynamics (TU Darmstadt). Additional external position sensors were mounted on the motor units for higher positional accuracy, allowing for a dynamic angle-of-attack accuracy of less than 0.5°. More details about the drive can be found in (Rival et al 2010).

3.4. Time-resolved PIV system

A commercial time-resolved PIV system (Dantec Dynamics A/S) incorporating a Nd:YLF (λ = 527 nm) Litron dual-cavity laser with a maximum repetition rate of 10 kHz per cavity was used for the investigation. In this set of experiments only one cavity was fired at 500 Hz at its maximum output energy of 22 mJ per pulse. Such high-energy levels were necessary for the large imaging area of 0.15 m². A Phantom V12 high-speed camera with 1280 × 800 pix resolution was fitted with a 60 mm f/2.8 Nikkor lens and was triggered in a single-frame mode. 3500 images were taken per run, equivalent
to seven full cycles at $f = 1$ Hz. The imaging field was $x/c \cong 4$ and $y/c \cong 2.5$ in size, with a resolution of 317 pix/c (2.65 pix mm$^{-1}$).

Parallax effects were strongest at the top of the stroke. At this position, parallax was responsible for hiding a region 0.16$c$ normal to the plate surface, while at the bottom of the stroke the parallax effects hid a region 0.06$c$ normal to the plate surface. The vector fields were calculated using an adaptive correlation analysis. This method is described at length in Dabiri (2005).

Further to identifying vortical structures in the flow, the velocity data allows for the non-intrusive measurement of the vorticity and circulation with PIV. Vorticity was calculated by taking the curl of the velocity field using a central-differencing discretization:

$$\omega_z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}. \tag{7}$$

The circulation of the vortices was then calculated from the local vorticity field using Stoke’s theorem via numerical integration:

$$\Gamma = \int_A \omega_z \, dA, \tag{8}$$

where $A$ is the window encompassing the vortex in question. The vortex trajectories were determined by tracking the approximate center of highest vorticity within the core. The spacial resolution of this tracking method was approximately $\Delta x/c = \Delta y/c = \pm 0.02$. The integration window for circulation, based on a threshold value of zero, subsequently tracked these trajectories maintaining a constant window around the vortex in question.

3.5. Vorticity and circulation

The accuracy of the vector fields was estimated to lie well below 3% of the maximum plate displacement speed for all cases assuming a maximum sub-pixel interpolation accuracy of 0.2 pix, see Raffel et al (2007). Due to the coarse measurement resolution and the low vector overlap (50%), neighboring vectors were assumed to be weakly correlated.

This weak correlation of the neighboring vector fields allowed for the estimation of the vorticity and circulation with uncertainties of $\Delta \omega/cU_{\infty} = \pm 0.5$ and $\Delta \Gamma/U_{\infty}c = \pm 0.05$, respectively. For more details regarding these estimates, the reader is referred to (Raffel et al 2007).

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3.6. Force estimation

PIV allows for the non-intrusive measurement of the instantaneous velocity field in a flow. Further to identifying and tracking vortical structures in the flow, the velocity data can be used to estimate the forces on the moving body using a momentum balance, which is referred to as control-volume analysis. This method is described at length in Dabiri (2005). One such implementation of this technique is found in van Oudheusden et al (2007) where this method was used to predict forces on a static airfoil. Further to this, Unal et al (1997) used this method to examine the forces on an oscillating cylinder, while Jardin et al (2009) used this technique to estimate forces on a foil with asymmetric pitching and plunging motion. In (Noca et al 1997) and (Noca et al 1999), a similar formulation is used, albeit a term containing velocity and vorticity is derived to replace both the shear–stress tensor and the pressure terms in the Navier–Stokes equations. In this particular formulation, the momentum equation is only dependent on the velocity and its temporal and spatial derivatives.

The time-resolved forces on an arbitrary moving body in an incompressible flow can be obtained from the following integral form of the Navier–Stokes equations:

$$\tau(t) = -\rho \iint_V \left[ \frac{\partial \vec{u}}{\partial t} - \rho \vec{u} \cdot \nabla \vec{u} \right] \, dV - \iiint_S \left( \nabla \cdot \vec{p} \right) \, dS + \iiint_S \left( \nabla \cdot \vec{f} \right) \, dS, \tag{9}$$

where $\vec{p}$ is the pressure normal to the control surface $S$ bounding the control volume $V$ (see figure 7) and $\rho, \vec{u}, \vec{p}$ represent the density, velocity, pressure and viscous stress in the fluid, respectively. It is important to note here that for a moving body, i.e. a flat plate shown in figure 7, the velocity component at the body surface is non-zero and must be taken into account.

While examining equation (9) it becomes clear that all terms except for pressure can be obtained directly using TR-PIV. The pressure gradient, however, can be indirectly estimated through the integration of the Navier–Stokes equations across the appropriate control surfaces:

$$\iint_S \nabla \vec{p} \, dS = \iiint_S \left[ \mu \frac{\partial \vec{u}}{\partial t} - \rho \left( \frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} \right) \right] \, dS, \tag{10}$$

where the integration constant cancels out when one integrates around both sides of the control volume, i.e. from A–B–C and A–D–C in figure 7. Note that in this study the pressure was evaluated by assuming a perfectly two-dimensional flow field, which is a reasonable assumption since the bulk of the vortical energy at low Reynolds numbers lies in the plane of
interest. This assumption is supported by a recent study by Kat et al. (2009), which showed a marginal improvement in the pressure evaluation of only 3% when considering the full three dimensionality of the flow behind the shedding of square cylinder at Re = 9500.

In order to test the robustness of the control-volume method, six control volumes of varying size were used to evaluate the fixed-axis normal ($C_n$) and thrust ($C_t$) forces on a single pitching and plunging plate, see figure 8. CV1 corresponds to the smallest control volume, as shown in figure 7. The control volumes were then increased stepwise by $\Delta x/c = \Delta y/c = 0.1$, where CV6 was the largest tested. One can observe that the extracted forces are nearly independent of the control-volume placement. Nevertheless, for all subsequent force estimations, two control volumes with equivalent size to CV1 were used around both fore- and hind-profiles.

4. Results and discussion

4.1. Mean forces

In this section the cycle-averaged aerodynamic forces are extracted for combined as well as for individual plates and
are compared with the performance of a single-plate reference case. The resulting curves, plotted as a function of the phase angle $\psi$, are obtained by spline-fitting together the data points. Due to start-up effects, all results are based on ensembles of the fourth cycle averaging between 15 and 20 separate runs.

4.1.1. Combined. In figure 9, the dependence of the combined (fore- and hind-plate) mean normal and thrust coefficients versus the phase angle ($\psi$) is presented. The normal force of the reference case shows a small positive value. This can be explained by the asymmetry of the initial condition (the plate was always started at one end of the stroke). When examining the combined normal forces, the dependence on the phase angle is found to be weak. For $\psi = 0^\circ$, $\psi = 45^\circ$, and $\psi = 180^\circ$ the normal force is negligibly small. Only at $\psi = 135^\circ$ is the absolute value of the normal force at the same level as the reference case. In this sense the tandem cases show better performance than the reference case since normal forces in hover are minimized.

The combined thrust varies sinusoidally with the phase angle. The maximum thrust is observed at $\psi = 90^\circ$. The lowest thrust values are measured at $\psi = 225^\circ$ and...
Figure 12. Ensemble-averaged thrust force for fore-plate (a) and hind-plate (b) during representative cycle; note that the plot of $\psi = 90^\circ$ for the hind-plate is shifted in time such that the top dead center is at $t/T = 0$ to coincide with the single-plate and fore-plate curves.

Figure 13. Trajectories and non-dimensional circulation of downstroke TEV from the single-plate and hind-plate at $\psi = 90^\circ$; note that the curves for $\psi = 90^\circ$ are shifted in time such that the top dead center is at $t/T = 0$ to coincide with the single-plate and fore-plate curves.

$\psi = 270^\circ$, which agree with the measurements made by Maybury and Lehmann (2004). Of interest here is that the standard deviations for $\psi = 135^\circ$, $\psi = 180^\circ$ and $\psi = 225^\circ$ are significantly higher than for the other phases. This is due to an unstable behavior of the vortex trajectories, which vary to some extent in size and distribution from one cycle to the next.

4.1.2. Fore-plate. Examining the fore-plate’s normal and thrust forces over different phase angles in figure 10, one finds similar values to those obtained for the single-plate case. In particular, the normal forces with low phase angles ($0^\circ \leq \psi \leq 135^\circ$) match the reference case almost perfectly. The only phase to show a large deviation in normal force is $\psi = 315^\circ$. The thrust forces for small phase angles ($0^\circ \leq \psi \leq 90^\circ$) also match the reference case very closely. The higher phase angles, again with the exception of $\psi = 315^\circ$, produce even larger values of thrust. As with the normal forces, the thrust of the fore-plate shows little variation with the different phase angles, except for the case of $\psi = 225^\circ$ where
vortex formation was found to be sensitive to the hind-plate position.

4.1.3. Hind-plate. While the fore-plate’s normal and thrust forces share similar values with those obtained for the reference case, the hind-plate’s forces vary drastically due to the strong vortical inflow and hence demonstrate a strong variation with phase angle, as presented in figure 11. The normal force is found to vary significantly as the phase angle is varied. The thrust force, on the other hand, exhibits a
Figure 15. Tandem configuration with $\psi = 90^\circ$ (left) and single-plate (right) around the bottom dead center; note time referenced to the hind-plate position for the tandem case.

sinusoidal dependence on the phase angle. While the fore-plate produces thrust at all phase angles, the hind-plate does so only for $45^\circ \leq \psi \leq 135^\circ$. For other phase angles the force is negative, i.e. drag is produced. Thus, it is clear that the difference between the reference case and the combined forces depends predominantly on the hind-plate’s capacity to produce thrust in the fore-plate’s oncoming wake. Conversely, one can observe that the vortex production and therefore...
variation of force on the fore-plate, as shown in figure 10, is virtually unaffected by the presence of the hind-plate in its wake.

In stark contrast to the fore-plate, it can be observed that the cycle-to-cycle variation in both normal and thrust forces is higher for many of the phase angles. This can be attributed
to the unstable trajectories of the vortices emanating from the fore-plate.

4.2. Vortex interaction

Since the $\psi = 90^\circ$ case is the only phasing with significant levels of thrust, its flow field was examined in detail. The comparison between the fore-plate and the reference case flow fields shows strong similarities, i.e. their time-resolved thrust variation over the cycle is nearly identical, as presented in figure 12(a). However, the hind-plate force development, particularly for the thrust component, shows distinct differences compared to the reference case, as depicted in figure 12(b). These differences in the hind-plate thrust variation can be better understood by examining the associated velocity and vortical fields in figures 14–16. For sake of clarity, note that only every fifth velocity vector is plotted in the $x$ direction and that shed vortices are marked with letters and numbers for the fore- and hind-foils, respectively.

4.2.1. Effects on TEV and thrust production. Examining the thrust-producing mechanisms of the single-plate, one finds flow structures which can be associated with the two larger peaks ($t/T = 0.25$ and $t/T = 0.75$) shown in figure 12(b). The vortical structures relating to these peaks in thrust are pairs of opposite-sign vortices establishing a reverse von Kármán street behind the hind-plate, i.e. a jet is developed creating thrust. The first peak in the force diagram at $t/T = 0.25$ (for flow field see figure 14) arises just before the downstream TEV (vortex 3) begins to break off the hind-plate surface. Examining the subsequent time steps, one finds that the vertical position and circulation of this TEV remains fairly constant from $t/T = 0.375$ until $t/T = 0.625$, as identified in figures 13(a) and (b), respectively. This results in a constant thrust force over this time period acting in the horizontal plane.

Simultaneously the upstream TEV (vortex 4) grows rapidly because of the strong influence of the downstream TEV on the developing shear layer, see figures 15 and 16, time steps $t/T = 0.625$ to $t/T = 0.875$. With the creation of the upstream TEV, the second pair of counter-rotating vortices is formed during the upstream establishing again a reverse von Kármán street and therefore a strong jet behind the plate, which results in the second, more substantial thrust peak as seen at $t/T = 0.75$ in figure 12(b). Due to its mutual induction, the vortex pair convects away from the trailing edge and therefore thrust decreases rapidly.

When comparing the flow-field and thrust-force development between the single-plate and the tandem configuration, several distinct differences are revealed. For one, the fore-plate TEV (vortex A) strengthens the shear layer at the hind-plate leading edge as it passes by. This interaction encourages an earlier formation of the hind-plate LEV (vortex 2), which can be clearly seen at $t/T = 0.25$ in figure 14. This mechanism has been previously identified by Maybury and Lehmann (2004). This earlier formation of the LEV in turn shifts the hind-plate TEV (vortex 3) further downstream, as seen at $t/T = 0.5$. Finally, at $t/T = 0.625$, the thrust force on the hind-plate remains fairly constant, in contrast to the single-plate case where the more compact spacing of the TEV is found to be responsible for generating the stronger jet and therefore the higher thrust peak, see TEV positioning in figure 13(a). When comparing with the single-plate case, the tandem configuration allows for a more constant production of thrust over the cycle, which might be of importance during predation, as discussed by Alexander (1984).

In the meantime, the upstroke TEV over the hind-plate (vortex 5) is again developed earlier due to the interaction of the shed TEV from the fore-plate (vortex B), see the time step $t/T = 0.625$ in figure 15. This faster development of the LEV again influences the relative positioning of the upstroke TEV (vortex 4) through induction, pulling the developing TEV further forward when comparing with the single-plate; see $t/T = 0.75$, figure 16. This strong interaction between the hind-plate LEV and TEV (vortices 5 and 4, respectively) is responsible for the quick elimination of the LEV by the time step $t/T = 1$. In summary, the difference in the thrust force during the second half of the cycle is due to the lower circulation and less compact spacing of the downstroke and upstroke TEVs as compared to the single-plate reference case.

5. Conclusions

This investigation concerns the unsteady aerodynamics associated with a simplified model of dragonfly-like hovering. This study has expanded on previous investigations by providing a detailed understanding of the vortex interaction at various phase angles, of which $\psi = 90^\circ$ was found to be most synergistic. At this optimal phasing, the shed fore-plate TEV is found to influence the development of the hind-plate LEV. This LEV in turn acts to reposition the hind-plate TEV, which for these optimal phasings is primarily responsible for thrust generation. For this phasing similar levels of net thrust are produced when compared to a single plate. However, for the tandem arrangement, thrust production is found to be more constant throughout the cycle. The chain-like vortex interaction mechanism identified here for the simplified model of two-dimensional dragonfly-like hovering agrees with the observations of wing phasing by Azuma and Watanabe (1988) for live dragonflies as well as with the force measurements of three-dimensional flapping wings by Maybury and Lehmann (2004) and Lehmann (2008). This general agreement between this simplified model and more complex three-dimensional studies suggests that the dominant aerodynamic mechanism for hovering in tandem-wing configurations is predominantly two-dimensional in nature. This finding supports the argument provided by Thomas et al (2004) that a spanwise flow is not necessarily required for efficient vortex control and propulsion. Ultimately this result might be of use for the development of future aerodynamic applications where strong spanwise flows are not present.

Acknowledgments

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References

Alexander D E 1984 Unusual phase relationships between the forewings and hindwings in flying dragonflies J. Exp. Biol. 109 379–83
Bosch H 1978 Interfering airfoils in two-dimensional unsteady incompressible flow AGARD CP-227 Paper No 7
Ellington C P 2006 Insects versus birds: the great divide 44th AIAA Aerospace Sciences Meeting and Exhibit, AIAA-2006-35 (Reno, USA)
Jardin T, David L and Farcy A 2009 Characterization of vortical structures and loads based on time-resolved PIV for asymmetric hovering flapping flight Exp. Fluids 46 847–57
Lehmann F-O 2008 When wings touch wakes: understanding locomotor force control by wake-wing interference in insect wings J. Exp. Biol. 211 224–33
Lehmann F-O 2009 Wing-wake interaction reduces power consumption in insect tandem wings Exp. Fluids 46 765–75
Maybury W J and Lehmann F-O 2004 The fluid dynamics of flight control by kinematic phase lag variation between two robotic insect wings J. Exp. Biol. 207 4707–26
Noca F, Shiels D and Jeon D 1997 Measuring instantaneous fluid dynamic forces on bodies, using only velocity fields and their derivatives J. Fluids Struct. 11 345–50
Noca F, Shiels D and Jeon D 1999 A comparison of methods for evaluating time-dependent fluid dynamic forces on bodies, using only velocity fields and their derivatives J. Fluids Struct. 13 551–78
Sun M and Lan S L 2004 A computational study of the aerodynamic forces and power requirements of dragonfly (Aeshna juncea) hovering J. Exp. Biol. 207 1887–901
Usherwood J R and Lehmann F-O 2008 Phasing of dragonfly wings can improve aerodynamic efficiency by removing swirl J. R. Soc. Interface 5 1303–7