Unsteady aerodynamics of flapping flight - A fluid-structure interaction study of fore-hind wing phase difference

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Abstract. Flights of dragonflies, various insects and birds have been a subject of active research that may offer insight towards enhanced aerodynamic performance at low Reynolds numbers. To that end, we mimic the flapping biomechanics of a dragonfly by two thin flat airfoils plunging in tandem with each other. In the present study, we aim to investigate the effect of difference in flapping phase between fore and hind wings towards their aerodynamic performances. We computationally simulate incompressible, viscous, laminar flow around two thin flat airfoils that are purely plunging, at a Strouhal number of 0.25 and Reynolds number of 6500, using a flow solver in an Arbitrary Lagrangian-Eulerian framework. Kinematics of both fore and hind wing flapping followed a similar sinusoidal function but with relative phase angle difference to each other, that were varied between $-50^\circ$ to $+50^\circ$ including two cases were phase difference is $0^\circ$ (i.e. in-phase fore-hind wing flapping) and $+90^\circ$ (i.e. fore wing lags hind wing by $90^\circ$). Numerical results indicate that maximum lift and drag forces for each fore and hind wings occur at phase angle of $-40^\circ$ and that power efficiency of tandem wings are better at phase angles when hind wing leads the fore wing, with maximum power efficiency occurring at a fore-hind wing phase difference of $+30^\circ$. The complex fore-hind wing vortex interaction indicate likely benefit on the hind wing as it interacts with the fore wing at different phase angles.

1. Introduction
Dragonflies and many insects flap their wings in tandem during flights. Research in their aerodynamics have attracted much interest in recent decades, as they may offer insight for development of bio-inspired micro air vehicles (MAV) that operate at similar low Reynolds numbers. Previous investigations have shown that dragonflies may benefit from the unsteady wake or vortex interactions between their fore and hind wings [1, 2]. Further experiments in dragonfly flight biomechanics by Thomas et al. [3] suggest that dragonfly may vary their wing angle of attack and flapping kinematics, to control and exploit behaviour of leading edge vortices (LEV), which may consequently enhance or adjust their aerodynamics performance accordingly to type of flights. Under hovering conditions, Usherwood and Lehmann [4] and Rival et al. [5] showed that improved aerodynamic efficiency may be generated under certain fore-hind wing phase difference, which is attributed to the hind wing exploiting energy from fore wing vortices.
While in-phase flapping [6] or flapping within $0 \pm 50^\circ$ phase [7] between tandem wings, were shown to generate high combined thrust that is appropriate for rapid forward flight.

From the literature review, although a number of research has investigated the effect of fore-hind wing phase difference and suggested optimal phase angles where favourable aerodynamic performance may be found, previous studies had focused on certain phase angles or intervals. Numerical investigations by Broering et al. [6] had focused on $0^\circ$, $90^\circ$ and $180^\circ$ phase angles, while wind tunnel experiments by Warkentin and DeLaurier [7] examined phase angles that were varied at intervals of approximately $25^\circ$. Therefore, in the present study, the main objective is to investigate the effect of phase difference between flapping tandem wings towards their aerodynamic performance, but at closer intervals, with a view to better estimate their optimal phase difference. Towards that end, unsteady flow-structure interaction of two purely plunging thin airfoils that are separated by a constant gap equal to their chord length, were modeled at Reynolds number $Re = 6500$. Various phase angle difference between flapping of fore-hind wing, that undergo sinusoidal motion with flapping frequency of 10 Hz, were simulated. Initially, the relationship between unsteady aerodynamic forces, aerodynamic efficiency and power efficiency of tandem wings with their phase difference are presented. Finally, vortex interactions between fore-hind wing are discussed to characterize their aerodynamic performance.

2. Methodology and parameters
Numerical experiments were undertaken using computational fluid dynamics to investigate the present study. Considering a fixed pitch angle of $10^\circ$, the flapping kinematics for both fore-hind wing follows a sinusoidal plunging motion of the form:

$$y(t) = y_0 \cos(2\pi ft + \phi)$$  \hspace{1cm} (1)

where several phase angle or phase difference, $\phi$ were simulated (it is remarked that in equation (1), $\phi$ was fixed to 0 for the fore wing and $\phi$ was varied accordingly for the hind wing). The plunging amplitude, $y_0$ was set to 0.5 of wing chord length and plunging frequency, $f$ was fixed at 10 Hz. In addition to parameters in the following subsections, this gives a Strouhal number $St = \frac{2f y_0}{U}$ of 0.25 that falls within a narrow $St$ range (i.e. $0.2 < St < 0.4$) that was found for several species of insects under cruise flight [8].

2.1. Flow equations for moving mesh
In order to account for movement or deformation of fluid grids that follows the fore-hind wing flapping motions, the present flow-structure interaction problem involves solution of time-dependent Navier-Stokes and continuity equations in the following Arbitrary Lagrangian Eulerian (ALE) form [9]:

$$\frac{\partial u_i}{\partial t} + (u_j - \tilde{u}_j)\frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \frac{\mu}{\rho} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right]$$  \hspace{1cm} (2)

$$\frac{\partial (u_i - \tilde{u}_i)}{\partial x_i} = 0$$  \hspace{1cm} (3)

where $u_i$ are the fluid velocities, $\tilde{u}_j$ are the fluid grid velocities and $p$ is fluid pressure. The flow is considered incompressible and laminar, following previous studies that show minimal force discrepancies for flows below $Re = 50000$ [10, 11]. Therefore, in all the simulation, a constant air density of $\rho = 1.185$ kg/m$^3$ and a constant air dynamic viscosity of $\mu = 1.831 \times 10^{-5}$ Pa s is used. Following previous investigation showing tandem wing vortex interaction to be primarily two-dimensional [5], we begin by considering a two-dimensional model in the present study (and thus $i, j = 1, 2$ that represents the 2-D cartesian directions). Time marching for the
unsteady equation above was implemented using a second order backward euler scheme, while
the convective terms were solved using a high-resolution scheme.

Finally, \( \bar{u}_j \) are computed from grid displacements, based on a diffusion model that is expressed
in a form of Laplacian equation [12]. This Laplacian solution essentially regularizes the grid
displacements (or velocities) from values matching the wing displacements (or velocities) at the
fluid-wing interface, to zero at the fluid domain boundaries that are fixed.

2.2. Computational model and setup

Figure 1 shows the computational domain employed in the present study, where the streamwise
length spans 4 and 20 chord lengths, upstream and downstream of the fore wing respectively.
While in the cross flow direction, the domain spans 4 chord lengths above and below both wings
to the top and bottom walls. Both fore and hind wings are idealized as thin, flat airfoils with
chord length \( C = 50 \) mm and thickness equal to 4% of its chord length (i.e. 2 mm). The fore
and hind wing are separated by a distance equal to their chord length.

Boundary conditions imposed on the present flow problem is also summarized in figure 1,
where uniform velocity \( U \) and atmospheric pressure conditions are prescribed at the inlet and
outlet boundaries respectively. Both fore and hind wing surfaces are defined as no-slip walls,
while both top and bottom walls of the computational domain are imposed with free-slip wall
conditions. In the present study, a uniform inlet velocity \( U = 2 \) m/s is considered, giving a
chord-based Reynolds number of \( Re = 6500 \).

\[\text{Figure 1.} \quad \text{Computational domain and boundary conditions imposed in the present study. C denotes chord length of either fore or hind wing.}\]

Figure 2 shows a close-up of the discretization adopted for the computational domain, where
8-noded hexahedral elements were used. Finer grids were defined in the vicinity and wake regions
of both wings, and finer 8-noded prismatic elements close to wing surfaces were also prescribed,
to better resolve flow separation and consequently, vortex patterns trailing both wings. In total,
yielding 73248 elements and 85284 nodes in the baseline model.

\[\text{Figure 2.} \quad \text{Mesh of flow computational domain, with finer discretization in vicinity and wake regions of tandem wings.}\]

It is remarked that to maintain quality of fluid mesh as they move or deform following the
interfacing tandem wing motion, we considered separate domains for regions enclosing both
wings (indicated by colored regions in figure 2). This may facilitate uniform movements of grids
and thus minimizes grid quality deterioration, especially in regions close to both wing surfaces
where accurate prediction of boundary layers and flow separation is important. Conservation
of flow variables across interfacing domain is achieved using an implicit and conservative grid
interface algorithm [12].
2.3. Case studies
Considering previous work in [7] where maximum thrust and propulsive efficiencies may occur at phase angles $0 \pm 50^\circ$, we focus our attention to cases where $\phi$ was varied between $-50^\circ$ to $+50^\circ$ but at $10^\circ$ intervals, with an additional $\phi = +90^\circ$ case simulated. Positive $\phi$ indicates a phase difference where fore wing lags the hind wing by $\phi$, while a negative $\phi$ indicates that the fore wing leads the hind wing by a phase angle $\phi$. A single wing case (based on similar tandem wing model and configurations, but without hind wing) was also simulated for comparison purposes. In all cases, considering the present flapping frequency, a timestep size of 0.001 s was selected and unsteady simulations were run until completion for 1 s. Therefore, 10 complete downstroke-upstroke cycles were obtained for each case and results presented in the following sections were extracted from the final 10th cycle.

3. Results and discussion

\begin{figure}[!h]
\centering
\includegraphics[width=\textwidth]{draft5.pdf}
\caption{Lift coefficient history of tandem wings for case $\phi = 50^\circ$, at three different grid resolution (T denotes cycle flapping period).}
\end{figure}

\begin{figure}[!h]
\centering
\includegraphics[width=\textwidth]{draft4.pdf}
\caption{Drag coefficient history of tandem wings for case $\phi = 50^\circ$, at three different grid resolution (T denotes cycle flapping period).}
\end{figure}

3.1. Preliminary study
We first report aerodynamic force results for a case where fore-hind wing phase difference $\phi$ was set to $+50^\circ$, between different grid resolutions, as a means to verify the computational model. Three different grid resolution were examined, i.e. a coarse grid with a total of 21344 elements, baseline grid (total 73248 elements) and a finer grid resolution totaling 322072 elements. The coarse grid essentially represented a grid that was approximately double in size to those of the baseline grid, while the finer grid involved further refinement from the baseline grid, especially in domains enclosing both wings and their surrounding regions. Figures 3 and 4 presents the lift and drag coefficient history respectively, over a single flapping cycle for both fore and hind wings. Results indicate good convergence with increasing grid resolution and show acceptable difference between the baseline and finer grids. Thus, in the present study, the baseline grid was used.

To further quantify the error in the grid independence test, we compared the difference in results from both coarse and baseline grids with those from the finer grids. The root mean square (RMS) error based on the difference at every point along a single flapping cycle is tabulated in table 1, showing reduced RMS error for the baseline grid in comparison to the coarse grid. Table 1 also summarizes estimation of representative grid size ($h$) for each grid resolution, showing
that present refinement ratio between grids is greater than the recommended value of 1.3 for an appropriate grid independence study [13].

Table 1. Summary of root mean square error ($e$) in drag on fore and hind wing, between different grid resolution ($y_k$ represents results for grid resolution $k$ where $k = 1, 2, 3$ denotes fine, baseline and coarse grids respectively).

| $h$ (mm) | $e_{21}$ | $e_{31}$ |
|----------|-----------|-----------|
|          | fore wing | hind wing |
|          | fore wing | hind wing |
| fine     | 1.775     | 0.040     | 0.059     | 0.115     |
| baseline |           |           |           |           |
| coarse   | 2.355     | 0.044     | 0.059     | 0.115     |
|          | 3.738     |           |           |           |

3.2. Aerodynamic forces and performance

Table 2 presents time-averaged lift coefficient of the fore wing ($C_{L1}$), lift coefficient of the hind wing ($C_{L2}$), drag coefficient of the fore wing ($C_{D1}$) and drag coefficient of the hind wing ($C_{D2}$) in comparison with the time-averaged lift and drag coefficients of a single wing ($C_{LS}$ and $C_{DS}$ respectively), over a single flapping period.

Table 2. Summary of time-averaged lift coefficient and time-averaged drag coefficient with their corresponding aerodynamic and power efficiencies, for all tandem cases and in comparison with single case.

| $\phi$ | fore wing | hind wing | total tandem | total single |
|--------|-----------|-----------|--------------|--------------|
|        | $C_{L1}$  | $C_{L2}$  | $C_L$        | $C_{Ls}$     | $C_{D1}$  | $C_{D2}$  | $C_D$ | $L/D$ | $\eta_p$ | $C_{Ds$ | $L/D$ | $\eta_p$ |
| 90     | 2.125     | 0.996     | 1.560        | 0.175        | 8.909     | 11.128  | -     | -     | -     |
| 50     | 2.112     | 0.980     | 1.628        | 0.183        | 8.885     | 11.336  | -     | -     | -     |
| 40     | 2.107     | 0.884     | 1.641        | 0.185        | 8.857     | 11.344  | -     | -     | -     |
| 30     | 2.138     | 0.994     | 1.693        | 0.194        | 8.741     | 11.372  | -     | -     | -     |
| 20     | 2.071     | 0.997     | 1.658        | 0.190        | 8.736     | 11.251  | -     | -     | -     |
| 10     | 2.020     | 0.100     | 1.631        | 0.188        | 8.694     | 11.104  | -     | -     | -     |
| 0      | 1.972     | 0.102     | 1.594        | 0.185        | 8.630     | 10.897  | 1.97  | 0.27  | 7.29  |
| -10    | 1.901     | 0.108     | 1.556        | 0.183        | 8.526     | 10.637  | -     | -     | -     |
| -20    | 1.843     | 0.110     | 1.519        | 0.179        | 8.492     | 10.466  | -     | -     | -     |
| -30    | 1.965     | 0.150     | 1.709        | 0.209        | 8.159     | 10.666  | -     | -     | -     |
| -40    | 2.163     | 0.184     | 1.917        | 0.244        | 7.859     | 10.881  | -     | -     | -     |
| -50    | 2.098     | 0.172     | 1.846        | 0.233        | 7.931     | 10.776  | -     | -     | -     |

Although flapping of the fore wing was maintained and was similar in all cases, both its ($C_{L1}$) and ($C_{D1}$) exhibit non-linear variation with different flapping phase of the hind wing, indicating that fore wing aerodynamic performance is affected by fore-hind flapping phase difference. Figures 5 and 6 show that their variation is not symmetrical about $\phi = 0$ (in-phase flapping) and that maximum fore wing lift ($C_{L1}$) occurs at $\phi = -40^\circ$ and $\phi = 30^\circ$, both
of which is higher than the in-phase or $\phi = 90^\circ$ phase difference flapping. In addition, variation of $C_{D1}$ and $\phi$ appears to follow a similar profile with $C_{L1}$. Those phase differences where high fore wing lift occur, are also accompanied by high fore wing drag, suggesting that drag may primarily be lift-induced drag. Both lift and drag of the fore wing are also greater than those of a single wing except at phase difference between $-30^\circ < \phi < 0^\circ$.

![Figure 5. Variation of time-averaged lift coefficient against phase difference ($\phi$) for fore, hind, total tandem and single wing.](image5)

![Figure 6. Variation of time-averaged drag coefficient against phase difference ($\phi$) for fore, hind, total tandem and single wing.](image6)

Figures 5 and 6 also present aerodynamic force relationship with $\phi$ for the hind wing. The hind wing follows similar profile to the fore wing, except that both its $C_{L2}$ and $C_{D2}$ are lower than those of a single wing, for all phase difference. Their maximum lift and drag occurs at $\phi = -40^\circ$, and relatively minimal change in aerodynamic forces occur when phase difference $\phi > -20^\circ$. Higher values of $C_{L2}$ and $C_{D2}$ appears to be skewed towards negative $\phi$, suggesting that aerodynamic forces for hind wing are maximized when fore wing flapping leads the hind wing, for the range of $\phi$ examined in this study.

![Figure 7. Variation of aerodynamic efficiency with phase difference ($\phi$) for tandem and single wing.](image7)

![Figure 8. Variation of power efficiency with phase difference ($\phi$) for tandem and single wing.](image8)

In analyzing the overall tandem wing performance, their equivalent total lift and drag coefficients were determined based on the approach in [14, 15]. Since planform areas of both fore and hind wings are similar, their equivalent total lift coefficient may be given by
\[ C_L = \frac{1}{2}(C_{L1} + C_{L2}) \] and total drag coefficient may be defined as \[ C_D = \frac{1}{2}(C_{D1} + C_{D2}). \] Within the phase difference \( \phi \) in this study, total lift and drag coefficients of tandem wings are actually lower compared to a single wing configuration, as shown in Table 2. However, their aerodynamic efficiency (i.e. lift-to-drag ratio) and power efficiency (i.e. \( \eta_p = \frac{C^3_l}{2C_D} \)) are better compared to a single wing configuration, as shown in Figures 7 and 8. From Table 2, it is noted that the aerodynamic efficiency for \( \phi = 90^\circ \) shows approximately 22% improvement from a single wing case, which agrees well with findings in [4] when the hind wing leads the fore wing by 90°.

Unlike lift and drag, Figures 7 and 8 show that higher values of both aerodynamic and power efficiency tend to occur towards positive \( \phi \), i.e. when the hind wing flapping leads the fore wing. Within \( \phi = \pm 50^\circ \), optimal phase difference for maximum lift-to-drag ratio occurs at \( \phi = 50^\circ \), although this is still slightly lower than lift-to-drag ratio when phase difference is \( \phi = 90^\circ \). In contrast, power efficiency between \( 20^\circ < \phi < 50^\circ \) shows better performance compared to the \( \phi = 90^\circ \) case, with maximum power efficiency predicted at phase difference \( \phi = 30^\circ \). This indicates agreement with experimental findings in [7] and that phase angles where hind wing leads the fore wing shows better power efficiency. Closer examination of aerodynamic force and corresponding power efficiency of the hind wing in Table 2, suggest that the hind wing may benefit from its interaction with the fore wing, by likely experiencing lower drag and enhanced lift, especially when it leads the fore wing.

### 3.3. Fore-hind wing vortex interactions

Figure 9 to Figure 15 presents vorticity contours for a complete flapping cycle, from start of downstroke to end of upstroke, for phase difference cases \( \phi = -30^\circ, 0^\circ, 30^\circ \) and \( 90^\circ \). The contours range from red representing maximum positive (counterclockwise) vorticity to blue representing minimum negative (clockwise) vorticity. Figure 9 compares all four cases at the beginning of their hind wing downstroke. A trailing counterclockwise (CCW) vortex begins to shed from underneath the fore wing trailing edge, with diminishing lengths as phase angle increases from \( \phi = -30^\circ \) to \( \phi = 90^\circ \) (Figures 9(a) to 9(d)). This trailing CCW vortex increases in length as the downstroke cycle progresses in each case, as shown in figures 10 to 12.

![Figure 9](image-url)

**Figure 9.** Contour of vorticity at start of hind wing downstroke (0% of hind wing flapping cycle) for: (a) \( \phi = -30^\circ \) (b) \( \phi = 0^\circ \) (c) \( \phi = 30^\circ \) and (d) \( \phi = 90^\circ \).

Figure 9 also shows presence of both clockwise (CW) and counterclockwise (CCW) vortices shed from the upper surface of the fore wing at the beginning of hind wing downstroke, with their location further upstream as phase angle increases from \( \phi = -30^\circ \) to \( \phi = 90^\circ \). It is noted that the CCW vortex is located between the fore and hind wing for case \( \phi = 90^\circ \) (Figure 9(d)), but for case \( \phi = 30^\circ \) the CCW vortex is almost in contact with the leading edge of the hind wing as presented in Figure 9(c). While for in-phase flapping and \( \phi = -30^\circ \), both these fore wing shed vortices are well beyond the leading edge of the hind wing.

As the downstroke progresses, the size of the CW leading edge vortex (LEV) on the hind wing increases but a noticeable size difference may be observed among all four cases. Figures 10 and 11 shows that the LEV on the hind wing is smaller as the phase difference increases from
Figure 10. Contour of vorticity slightly before middle of hind wing downstroke (20% of hind wing flapping cycle) for: (a) $\phi = -30^\circ$ (b) $\phi = 0^\circ$ (c) $\phi = 30^\circ$ and (d) $\phi = 90^\circ$.

Figure 11. Contour of vorticity slightly after middle of hind wing downstroke (30% of hind wing flapping cycle) for: (a) $\phi = -30^\circ$ (b) $\phi = 0^\circ$ (c) $\phi = 30^\circ$ and (d) $\phi = 90^\circ$.

$\phi = -30^\circ$ to $\phi = 90^\circ$. This is likely due to the timely interaction with the fore wing-shed CCW vortex that inhibits development and size of the hind wing CW LEV. As LEV are low pressure regions, this suggests that the $\phi = 90^\circ$ experience lower lift compared to in-phase flapping or case $\phi = -30^\circ$.

Figure 12. Contour of vorticity at start of hind wing upstroke (50% of hind wing flapping cycle) for: (a) $\phi = -30^\circ$ (b) $\phi = 0^\circ$ (c) $\phi = 30^\circ$ and (d) $\phi = 90^\circ$.

Figure 12 shows the beginning of the hind wing upstroke, with the trailing counterclockwise (CCW) vortex developed during the downstroke from underneath the fore wing, either bisecting or just about to bisect the leading edge of the hind wing in case $\phi = -30^\circ$ and $\phi = 0^\circ$ respectively. This is expected to increase the CCW LEV size on the hind wing and enhance negative lift or downforce during their upstroke. However, the interaction of this CCW hind wing LEV with incoming CW vortex shed from the fore wing (as shown in figures 13(a) and 13(b)), appears to inhibit development of this hind wing LEV and hence downforce generation. In contrast, figures 13 and 14 shows that bisection of the hind wing leading edge by the trailing CCW fore wing vortex for cases $\phi = 30^\circ$ and $\phi = 90^\circ$ occurs without inhibition by incoming fore wing CW vortex, which is located further upstream and interact at later stages of their upstroke. This is evident in figure 15 that shows CCW LEV on the hind wing for case $\phi = 90^\circ$ freely shedding the leading edge at the end of its upstroke, indicating complete development of hind wing LEV without inhibition from fore wing CW vortex, which is just about to leave the fore wing trailing.
edge. This is expected to enhance downforce during hind wing upstroke and in combination with lower lift during downstroke, generates overall lower average lift per flapping cycle, especially for case $\phi = 90^\circ$. This agrees with findings in [6] where $90^\circ$ phase flapping generated lower lift compared to in-phase flapping.

![Figure 13](image1.png)

**Figure 13.** Contour of vorticity slightly before middle of hind wing upstroke (70% of hind wing flapping cycle) for: (a) $\phi = -30^\circ$ (b) $\phi = 0^\circ$ (c) $\phi = 30^\circ$ and (d) $\phi = 90^\circ$.

![Figure 14](image2.png)

**Figure 14.** Contour of vorticity slightly after middle of hind wing upstroke (80% of hind wing flapping cycle) for: (a) $\phi = -30^\circ$ (b) $\phi = 0^\circ$ (c) $\phi = 30^\circ$ and (d) $\phi = 90^\circ$.

![Figure 15](image3.png)

**Figure 15.** Contour of vorticity at end of hind wing upstroke (100% of hind wing flapping cycle) for: (a) $\phi = -30^\circ$ (b) $\phi = 0^\circ$ (c) $\phi = 30^\circ$ and (d) $\phi = 90^\circ$.

Based on the present flow visualization, higher overall lift may be generated at phase angle where the hind wing lags the fore wing by $30^\circ$, compared to phase angle where the hind wing leads the fore wing by $30^\circ$ or $90^\circ$. However, it is hypothesized that higher lift may likely be accompanied by higher lift-induced drag, lending to better lift-to-drag ratio and power efficiency for phase angles $\phi = 30^\circ$ or $\phi = 90^\circ$, as illustrated in figures 7 and 8.

4. **Conclusion**

Effect of fore-hind wing phase difference on aerodynamics of flapping insects, were numerically simulated in the present study. A tandem thin airfoil under uniform flow at $Re = 6500$ and flapping with $St = 0.25$, was employed to replicate biomechanics of this flapping flight. Numerical results suggest that aerodynamic performance of both fore and hind wings are affected
by their phase difference. Within the ±50° phase angle studied, maximum lift and drag occur at phase angle of −40°, while enhanced power efficiency occurs at phase angles where the hind wing leads the fore wing, with a maximum at phase angle $\phi = 30°$. Flow visualization results indicate complex fore-hind wing vortex interactions that are affected by their relative phase cycle, which in turn, influence lift and drag generation on the hind wing. Future studies are recommended to examine effect of phase difference at larger phase angles, different wing spacings and Strouhal numbers, in addition to further experimental investigations.

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