ICAS 2016
30th Congress of the International Council of the Aeronautical Sciences
DCC, Daejeon, Korea ; September 25-30, 2016

# STRATEGIES FOR ACHIEVING BACKWARD FLIGHT BY A DRAGONFLY

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**Keywords**: *backward flight, aerodynamics, wing-wing interaction, kinematics, CFD simulation*

## Abstract

*Highly maneuverable insects such as dragonflies have a vast array of flight capabilities including forward flight, hovering, sideways flight, upside down flight and even backward takeoff flight. In this disquisition, we studied the kinematics and aerodynamics of backward takeoff in dragonflies and compared them to those of forward takeoff. High speed videography and accurate 3D surface reconstruction techniques were employed to extract details of the wing and body motions. While the body velocities of both forward and backward flights were similar, the body orientation as well as the wing kinematics largely differed. Our results indicate that tilting the stroke plane angle of the wings and changing the orientation of the body relative to the flight path are the major means to achieve backward flight. In addition, our detailed analysis of the flow in these flights shows that interaction of the wakes from the fore and hind pair of wings enhances performance of backward flight.*

## 1. Introduction

Insects, one of three groups of organisms to evolve flight, are known for their aerial prowess due to their ability to perform complex flight motions in the blink of an eye. One of such flamboyant displays of their aerial repertoire is the ability to fly backward. Although to pedal organisms such as humans the concept of backward or retro locomotion may seem unnatural and uneasy, flying insects and hummingbirds[1, 2], insectivorous birds [3-5], aquatic organisms such as eels and other anguilliform swimmers [6], electric fish [7], and terrestrial organisms such as hexapods have evolved to perform this type of motion with ease. Here, we study a dragonfly in backward flight.

Flying backward appears to be essential to locomotion because it does not involve turning around before manipulating flight in a desired direction as is required in forward flight. Consequently, backward flight provides an alternative in excursing from one point to another. This way, backward flight may be beneficial especially during hunting in that a prey may not fully anticipate and respond to a backward attack. Fully equipped with a panoramic visual system and advanced flying strategy, flying backward without having to turn around becomes plausible. In the context of designing a micro-aerial vehicle (MAV), the possibilities of taking off backwards increases the robustness of the vehicle and its ability to initiate from unconventional surfaces such as vertical walls and also respond to imminent threat.

Till date, however, there exists a handful of kinematics data and even sparser aerodynamic data present in literature on insect backward flight. The primary takeaway from existing studies are mostly behavioral indicating that insects may appropriate backward locomotion to predator evasion, prey capture, transient flight, takeoff or flight initiation, station keeping and load lifting [1, 3, 8, 9]. Titling of the stroke plane was found to be a primary means by which different flying species change the direction of flight in general. While a few insect species such as damselflies are capable of substantially changing the direction of the stroke plane relative to the body, most bird and insect species are biomechanically constrained in this regard [3, 10]. To reorient the force relative to the flight path, several insect species slightly tilt their stroke plane forward-up during backward flight [3]. The major reorientation of the force, however, occurs due to modulation of the body posture. In addition, large angles of attack are postulated to be employed as auxiliary mechanisms [3]. A detailed study on the backward flight of hummingbird enumerates other wing kinematics patterns employed in backward flight such as higher wingbeat frequency, higher upstroke to downstroke duration ratio, higher ratio of maximum to minimum positional angle and smaller advance ratio relative to forward flight [1].

While backward flight has not gained much attention over the years, forward flight and hovering have been extensively studied in literature. During forward flight, counter stroking with phase difference, wherein the hindwing leads the forewing is the normal flight mode preferred by dragonflies [3, 11, 12]. During hover flight, the wings beat out of phase at about 180 degrees [12, 13] and the dragonfly employs an asymmetric rowing motion on an inclined stroke plane wherein the majority of the force is generated in downstroke [14]. With regard to force generation, during forward flight, dragonflies generate the majority of the lift forces to balance their weight during the downstroke while the upstroke is primarily for thrust production [3, 15]. Body motion also differs during forward flight, hovering and backward flight. During hovering, the dragonfly body is horizontal [16] while in forward flight the body angle depends on the flight speed. It has been shown that as flight speed increases, an insect chooses a more horizontal posture[17].This may reduce drag. On the contrary, an upright body posture was reported for a dragonfly flying backwards [3] and in other insects [18].

Finally, when dealing with a four winged flier such as a dragonfly, wing-wing interaction (WWI) is inevitable. WWI is evident in the presence of tandem wings in that the dragonfly forewing will experience inwash due to the hindwing and the hindwing will be influenced by downwash from the forewing. Some scholars have opined that hindwing may extract energy from the forewings wake if the phase relationship between the fore and hindwings are chosen appropriately albeit for hovering flight [19, 20].

A lack of available data of backward flight of insects, therefore, serves as a catalyst in this study is to improve the understanding of the kinematics and the aerodynamic mechanisms that make backward flight in dragonflies possible. We are interested in understanding how the motions of the wings and body is coordinated and how the flight forces are generated. A high speed photogrammetry setup coupled with 3D surface reconstruction techniques [21] and a high fidelity Computational Fluid Dynamics (CFD) flow solver [22] are used to elucidate both the kinematics and aerodynamic features, respectively.

We hope that this work will both uncover new science and serve as a catalyst for better designs of tomorrow's micro-aerial vehicles (MAV).

## 2. Materials and Methods

### 2.1 Dragonfly, High Speed Photography and 3D Motion Reconstruction

Dragonflies *(Erythimus simplicicollis)* were captured from the wild in Dayton, Ohio in the summer of 2012. Prior to the experiments, their wings were dotted. The dragonflies were then placed inside a flight chamber where they initiated flight autonomously. Their flight triggered a camera system comprising of three orthogonal camera which recorded their motion at 1000 frames per second (see Fig.1). After recording the flight, the wings were removed and the mass and length of the wings and the body were measured. A backward flight sequence was chosen for analysis and reconstructed frame by frame by manually tracking the dotted wings. The accuracy of the reconstruction technique is discussed elsewhere in [21]. The same method has been used in the study of other insects such as damselflies and cicadas [24-26].

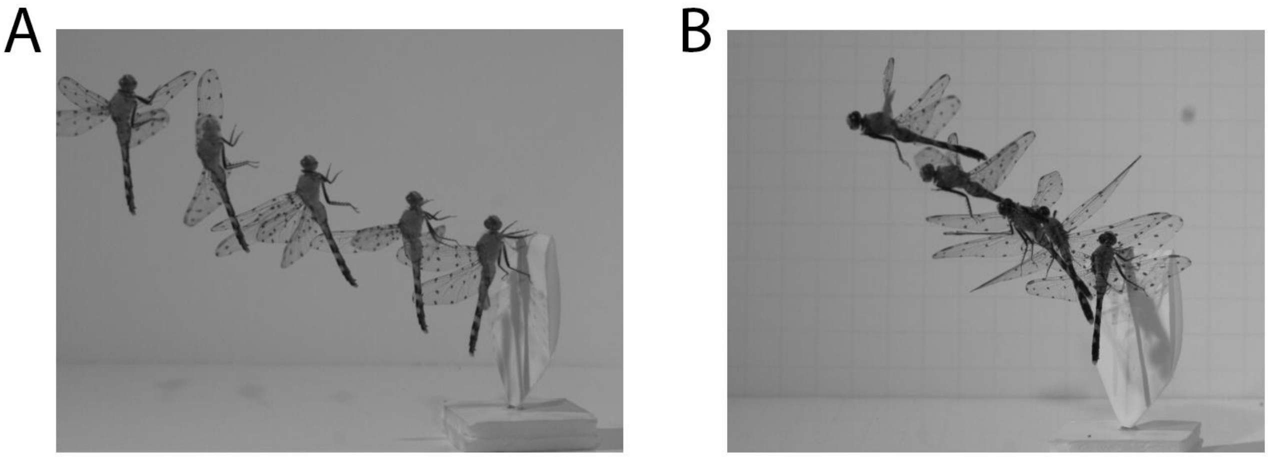


**Fig 1**. **High Speed Photography of a dragonfly in A) Backward Flight B) Forward Flight.** A selected sequence of images of a dragonfly in free flight is shown. The duration of flight is about 15ms for both flights.

## 2.2 Computational Fluid Dynamics (CFD) Simulation

A high fidelity CFD solver based on the immersed boundary method was used to simulate the flows generated by the dragonfly wing. We solve the incompressible Navier-Stokes Equation (Eqn. (1)) using a finite difference method with 2nd order accuracy in space and a 2nd order fractional step methods for progressing in time. More details of this method and its application in other insect flight studies on dragonflies, damselflies and cicadas can be found in [24, 27]. For further validation see [28] .

$$\nabla \cdot \mathbf{u} = 0; \quad \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho}\nabla p + \upsilon \nabla^2 \mathbf{u} \qquad (1)$$

Where $\mathbf{u}$ is the velocity vector in the Cartesian coordinate system, $t$ is time, $p$ is the pressure, $\rho$ is density and $\upsilon$ is the kinematic viscosity. The vortex structures are visualized by the Q-criterion [29].

$$Q = \frac{1}{2}\left[ |\mathbf{\Omega}|^2 - |\mathbf{S}|^2 \right] > 0 \qquad (2)$$

Where $\mathbf{\Omega} = \frac{1}{2}\left[ \nabla \mathbf{u} - (\nabla \mathbf{u})^T \right]$ and $\mathbf{S} = \frac{1}{2}\left[ \nabla \mathbf{u} + (\nabla \mathbf{u})^T \right]$ are the vorticity and strain rate tensors respectively.

The forces on the wing surface are calculated by the integrating the surface pressure and viscous shear stress.

# 3. Results and Discussion

## 3.1 Comparison of Forward and Backward Flight

### 3.1.1 Body Kinematics

Here we compare the flight of two dragonflies of the same species, in the same initial orientation, one in forward and the other in backward flight (see Fig.1). The length of both flights is approximately 15ms. For kinematic analysis, we only consider the last two wing beats during the forward flight wherein the heading changes are minimal. First, we study the body motions and show the stroke-averaged kinematic parameters for comparison in Table 1. Fig. 2A and B show the average orientation of backward and forward flight respectively. Surveying the figure, the first distinction between forward and backward flight is the body angle. On average, the body angle during forward flight was more horizontal.

Although the forward flight is initiated in a vertical posture, there is a tendency to settle in a more horizontal posture at later stage of flight (see Fig. 1B). On the contrary, the dragonfly during backward flight maintained its vertical posture (about 90 degs) throughout the flight (Fig. 1A). Since there was no need to initiate a turn before traversing from its initial to final position during backward flight, the dragonfly also travelled faster within the same flight time.

**Table 1: Kinematic Parameters.** Table shows the relevant kinematic parameters for the comparison of backward and forward flight. SP-stroke plane, DS-downstroke, US-Upstroke.

| Parameter | Forward Flight | Backward Flight |
|---|---|---|
| Avg. body velocity (m/s) | 0.7 | 0.8 |
| Avg. body pitch angle (°) | 17 | 90 |
| SP angle w.r.t. body (°) | 60 | 41 |
| SP angle w.r.t horizon (°) | -41 | 47 |
| Avg. wing pitch angle in DS (°) | 45 | 43 |
| Avg. wing pitch angle in US (°) | 44 | 42 |

### 3.1.2 Wing Kinematics

The wing kinematics is measured by defining a rigid plane made by a reference span line, connecting the wing root and the tip, and a reference chord line. This rigid plane defines the wing orientation with respect to the body. Assuming the deformations are small, the orientation of the wing can be described by Euler angles; flap, deviation and pitch (Fig 2C). The motions of the wing during a stroke are shown by the wing tip trajectories. We observe a “figure 8” tip trajectory for backward flight. The dashed lines superimposed on the wing tip trajectories indicate the stroke plane orientation (see Fig. 2A and B). For clarity, we show only the tip trajectories of the forewings. The hindwings, however, have a similar stroke plane inclination as the forewings. We then quantify the stroke plane angles both with respect to the longitudinal axis of the body and the horizon for forward and backward flight (Table 1 and Fig. 2A, B). We notice that the angle between the stroke plane and the horizontal is drastically different in both flights due to the body orientation. In essence, backward flight is forward flight rotated to a vertical posture. On the contrary, the stroke plane angle relative to the body is only slightly different by about 20 deg.

The stroke-average motion of the wing within the stroke plane is also documented in Table 1. It appears that the wings flap with similar pitch angles both in the upstroke (US) and downstroke (DS) although body motions as well as wing kinematics with respect to body are different in forward and backward flight. Therefore, to achieve backward flight, a dragonfly combines two strategies; tilting of the stroke plane slightly up and pitching the body in an upright orientation to change the global orientation of the force.

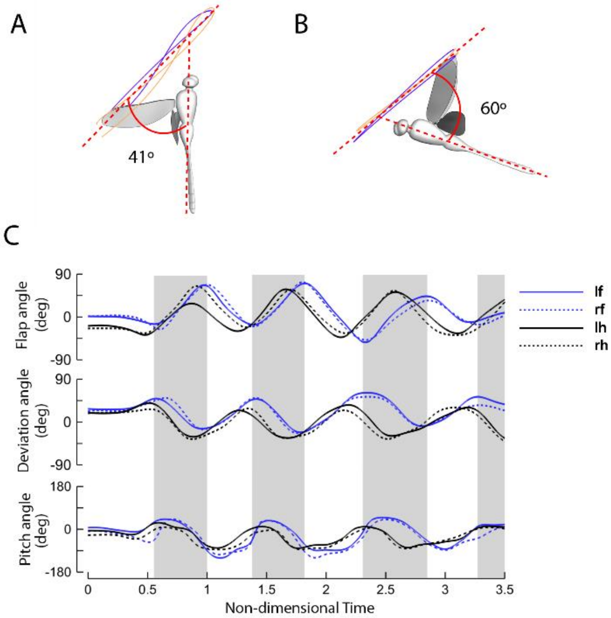


**Fig 2**. **Kinematics.** 2A) Body orientation and Wing Motions in for Backward flight. 2B) Body orientation and Wing Motions in for Backward flight. 2C) Wing Euler angles for Backward Flight**.** lf - left forewing, lh - left hindwing, rf - right forewings, rh - right hindwing.

Fig. 2C shows the Euler angles of a backward flying dragonfly. For more details about dragonfly forward flight kinematics see [10]. Flapping motion is defined as the back and forth motion of the wing. The up and down rotation of the wing is expressed by the deviation angle. The wing pitch angle is characterized by the rotation of the wing about its pitching axis close to the leading edge. The kinematics of left wings and right wings are shown with solid and dashed lines, respectively. All four wings did not show significant variation in the kinematics throughout the flight. Rather wing motions between the left and right side are symmetric although forewings flap with a higher amplitude than the hindwings. In addition, a phase difference is evident between the fore and hind wings pairs and increases throughout the flight which may be essential for maintaining body posture

## 3.2 Backward Flight

### 3.2.1 Force Generation

Having reported the wing and body motions, we investigate their coordination and how the aerodynamic force is generated. As aforementioned, the flapping motion of the wings is reported in Fig. 2C. We observe that the left and right wings flap symmetrically to generate the forces to induce straight flight. Fig. 4A (purple line) shows the force generation throughout the flight. The dragonfly generates large forces both in the upstroke and downstroke. The downstroke generates thrust and the upstroke generates lift meaning that in backward flight their roles are reversed. The reorientation of the body in the global frame reverses the actions of the down and upstrokes.

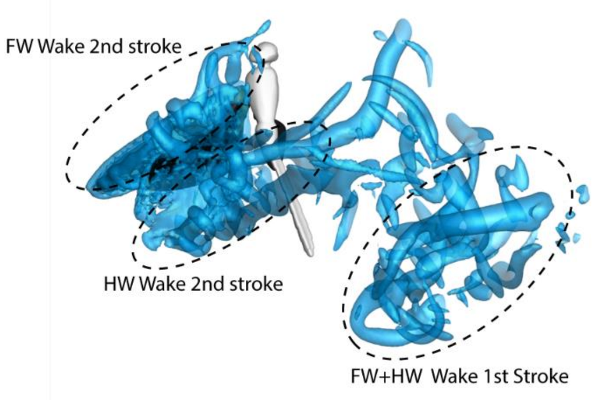


**Fig 3**. **3D Flow Phenomena.** Figure shows the flow phenomena at the end of the 2$^{nd}$ stroke of the forewings. The dashed lines are for emphasis of regions of interest

### 3.2.2 3D Flow Phenomena

To understand how the forces are generated by the wings, we study the flow structures in the near and far field. Vortical structures around the wing surface point to the existence on an LEV and consequently tip vortices. This is important for lift production in particular. We also see the interaction of the fore and hindwing vortices together. The vortex structures shed from each pairs of wings moves in a direction opposite to that of the body motion.

Fig. 3 shows a snapshot of the flow field at the end of the second flapping stroke of the forewings. The distinct vortex rings from the fore and hindwings from the 2nd stroke are obvious and circled in broken lines. However, the wake from the first stroke is tangled up into one bundle (see FW+HW Wake 1$^{st}$ Stroke in Fig 3). This indicates that the vortex shed by the forewing in the first stroke moved faster than that of the hindwing and caught up.

### 3.2.3 Wing-Wing Interaction (WWI)

To further probe this phenomenon and understand how all four wings work together to make this flight possible, we ran two numerical simulations. In one, we simulated the forewings only and in the other, the hindwings only. In Fig. 4B, a snapshot of the flow at the end of the second stroke of the forewings with isosurfaces of the two numerical simulations superimposed on each other. The green color represents the wake shed by the forewings and the gold indicates the wake shed by the hindwings. Each pair of wings generates a vortex ring during each stroke which sheds and travels away. Two separate vortex rings are also clearly visible for each wing (denoted as FW wake and HW wake); one close to the wing surface and the other far downstream. It appears that as the vortex travels further from the dragonfly, it slightly tilts to a more horizontal posture.

Now superimposing the flow field from the simulation with all four wing on top of the forewings only and hindwings only in Fig. 4C, we see that in the near field, the forewings are not affected by WWI. However, small changes in the vorticity transport is visible in the near field of the hindwings. In the far field, coexistence of the vertical structures of the fore and hindwings significantly alters the overall flow. It is obvious that the first vortex ring shed by the forewings has travelled faster and merged with the hindwing vortex (Fig.3 and 4C). The blue wake has travelled further than the green wake in the same time interval. The induced flow field by the hindwing vortex sucks the forewing vortex in. This is analogous to the leapfrogging of vortex rings. As a result of this suction effect, there is larger force generation due to increased momentum (Fig.4A).

The other noticeable flow feature is the orientation of the wake. WWI causes the vortex rings to tilt upward (blue wake) in an anticlockwise orientation thus generating a larger horizontal flow velocity in the direction of travel which should increase thrust. This is shown by two dashed lines and the arrow indicating tilting in Fig. 4C. To see if this observation is realistic, we plotted the lift and thrust coefficients generated by all the wings and compared that to the sum of the forces generated by forewings only and hindwings only in Fig. 4A. The total magnitude of the force generated by the wings was increased due to WWI with the thrust being more enhanced than the lift. The major benefit of WWI was experienced in the 2nd stroke where the thrust forces were boosted by about 15%. At this instance the dragonfly also experienced its largest acceleration.

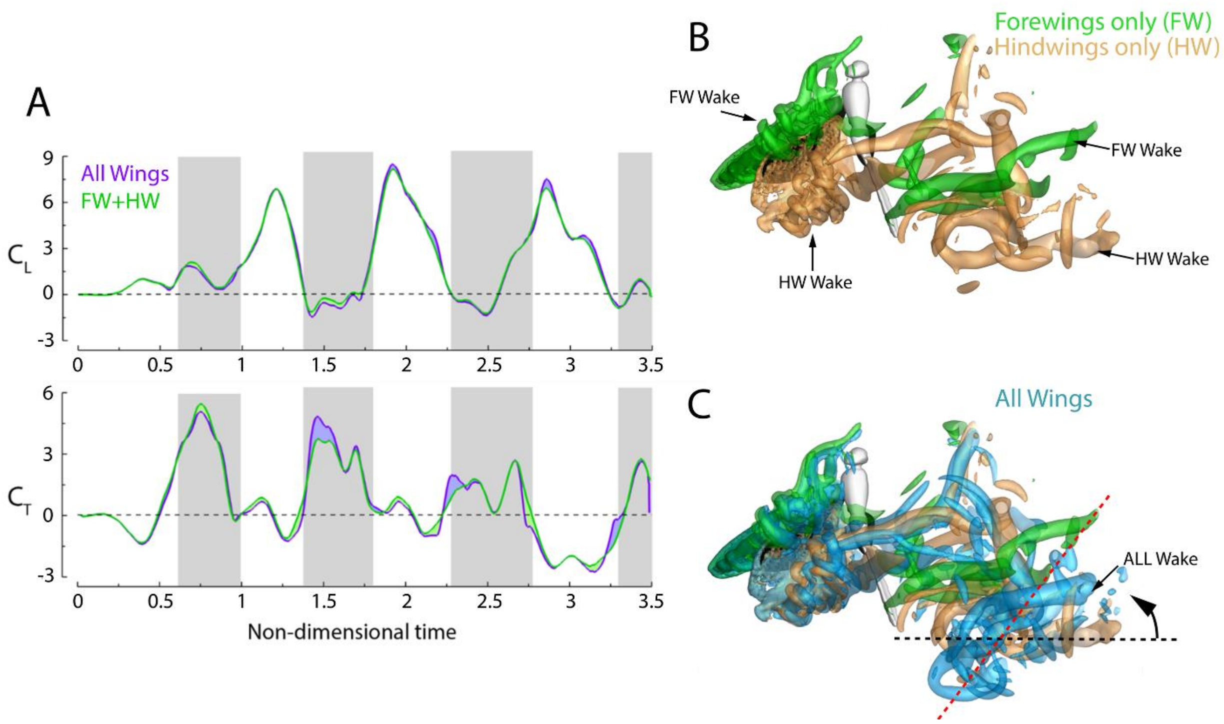


**Fig 4**. **Effect of Wing-Wing Interaction (WWI).** Fig 4A shows the force generation of a dragonfly in backward flight. The purple lines indicate the forces generated when the fore and hindwings interact. The green line shows the force when there is no interaction. The gray shading represents the downstroke of the forewing. Fig 4B and 4C show the 3D flow features at the end of the 2nd stroke of the forewings. Fig 4B shows the isosurfaces of the wings superimposed on each other when there is no interaction. The red and green colors indicate the wakes shed by the fore and hindwings respectively. Fig 4C shows the isosurface from Fig 4B superimposed on the flow structures from Fig 3 where there is wing-wing interaction.

## 4. Conclusion

Here we studied the motion of a dragonfly in backward flight. We report new data on the kinematics and aerodynamics thus giving glimpses into how backward flight is achieved.
We found that both the orientation of the stroke plane with respect to the longitudinal axis of the body as well as the wing motions through the stroke plane are alike in forward and backward flight. However, the orientation of the stroke plane with respect to the horizon is drastically different due to the upright posture adopted by the dragonfly in backward flight. This helps in reorienting the force. The downstroke which is usually the lift generating stroke become the thrust generating. Likewise, the upstroke generates lift instead of thrust. We also showed that having two pairs of wings is beneficial to the flight. The interaction of the wake between the fore and hind wing as well as the wake from the previous stroke improved force production.

## 5. Acknowledgment

This research is supported by AFOSR Grant No. FA9550-12-1-0071, NSF Grant No. CBET-1313217.

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