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Letter

Cicada (*Tibicen linnei*) steers by force vectoring

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HIGHLIGHTS

- Several free flights of cicada (*Tibicen linnei*) are studied (total of 42 wingbeats).
- Coordination between the aerodynamic force generation and change in flight path is investigated.
- Measurements and calculations show that the aerodynamic force is fixed to the body frame.
- Findings reveal that a simple force vectoring technique is used for steering all these flights.
- A similar strategy can be applied to the design of Micro Air Vehicles.

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ABSTRACT

To change flight direction, flying animals modulate aerodynamic force either relative to their bodies to generate torque about the center of mass, or relative to the flight path to produce centripetal force that curves the trajectory. In employing the latter, the direction of aerodynamic force remains fixed in the body frame and rotations of the body redirect the force. While both aforementioned techniques are essential for flight, it is critical to investigate how an animal balances the two to achieve aerial locomotion. Here, we measured wing and body kinematics of cicada (*Tibicen linnei*) in free flight, including flight periods of both little and substantial body reorientations. It is found that cicadas employ a common force vectoring technique to execute all these flights. We show that the direction of the half-stroke averaged aerodynamic force relative to the body is independent of the body orientation, varying in a range of merely 20 deg. Despite directional limitation of the aerodynamic force, pitch and roll torque are generated by altering wing angle of attack and its mean position relative to the center of mass. This results in body rotations which redirect the wing force in the global frame and consequently change the flight trajectory.

The capacity to change the flight trajectory is essential for aerial locomotion and survival of flying animals. To adjust the flight course, flying animals modulate the magnitude and orientation of aerodynamic force by altering their wing kinematics. Highly maneuverable insects such as dragonflies [1,2], damselflies [3] and fruit flies [4] are capable of adjusting the wing stroke plane angle as well as the orientation of the wing in this plane to achieve exceptional control over the aerodynamic force. The ability to change the force direction relative to the body allows these insects to generate aerodynamic torque about the center of mass for body reorientation. While this enhances the maneuverability of a flying animal, it imposes complexity to the wing biomechanics as well as the control system of the flight [5]. Alternatively, measurements have shown that during banked turns flying insects and birds change the flight trajectory while maintaining the direction of aerodynamic force relative to their bodies. In these maneuvers, animals rely on whole-body rotations to redirect the force in the global frame. This strategy is referred to as force vectoring [5] and was observed in banked turns of insects [6], bats [7] and birds [5,8]. It was argued that force vectoring allows minimal modulations of the wing motion relative to the body [5]. While this is beneficial for simplifying the wing biomechanics, some degree of control over the aerodynamic force direction relative to the body is essential for stability and maneuverability [9].

Understanding the coordination between the aerodynamic force production and the flight reorientation is fundamental to comprehending the aerial locomotion of the insects and birds. Previous measurements and investigations mostly focused on a single flight mode and therefore their conclusions cannot be generalized to other flights without further investigations. Here we asked to what extend a flying animal alters the force orientation relative to its body in order to steer. To pursue this goal, we studied a variety of flights of cicada (*Tibicen linnei*), including periods of little as well as substantial body reorientations, to examine the

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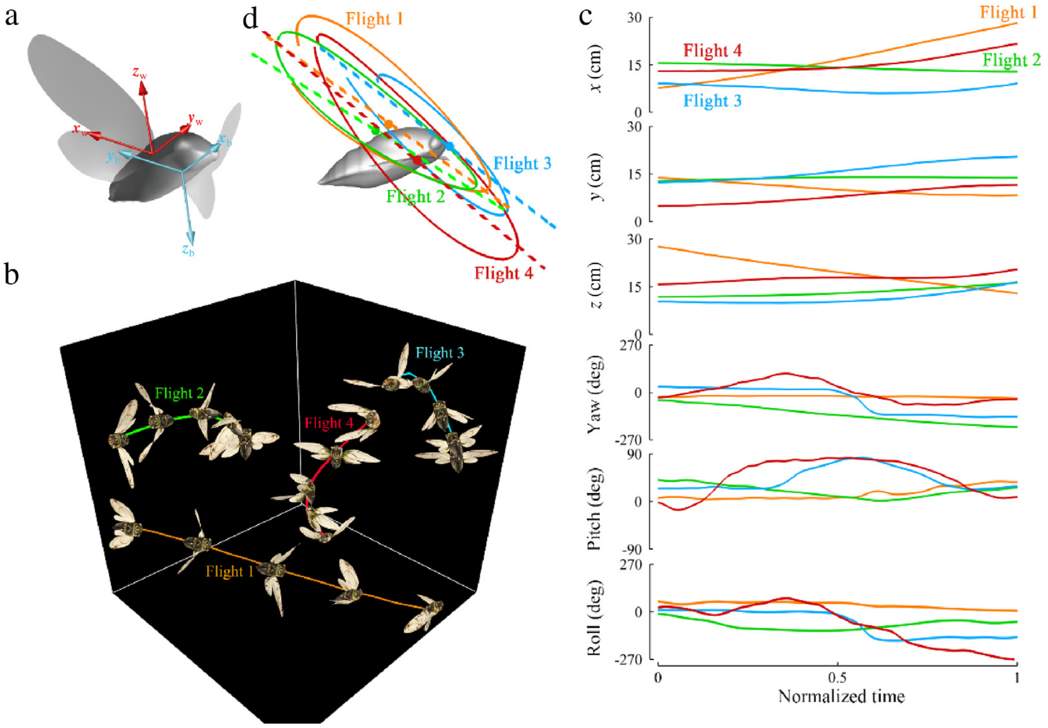

Fig. 1. (a) Wing and body coordinate systems of cicada. (b) A selected sequence of images from the reconstructed wing and body motion of different flights. (c) Body kinematics of the cicada in different flights. (d) A sample wing tip trajectory of each flight. The dashed straight line shows the average stroke plane.

extent to which the aerodynamic force is modulated for achieving this range of flights.

Several cicadas (*Tibicen linnei*) were captured in Dayton, Ohio. A network of marker points were drawn on the wings which were later used to track the motion of the wings. Natural features of the body such the eyes were used to track the body motion. The recording area is equipped with three orthogonally placed Photron Fastcam SA3 60k high speed cameras synchronized to record at 1000 frames per second. After recording several flights of each individual, the wing and body length ((35 ± 2) mm and (30 ± 1) mm for wing and body, respectively) as well as the body mass ((1050 ± 100) mg) were measured. All statistical results are presented as (mean ± standard deviation (SD)). A manual 3D surface reconstruction technique was applied to the output from the cameras [10]. The motion of the wings and the body were tracked at each frame (every millisecond) using all three orthogonal images. The reconstructed 3D surfaces of the wings and the body were then meshed using triangular grids [11]. The location of mesh nodes were used to define the wing and the body kinematics. Kinematics of the body can be easily extracted by identifying the location of three points on the body that define a surface (not along a single line). We used the tail, head and the top-thorax points. To obtain rigid wing kinematics, the root mean squared plane of the wing was defined based on the position of the marker points on the wing at each frame. Since the fore and hind wing move together during flight, they were treated as one wing platform. The orientation of the rigid wing relative to the body was then expressed by three Euler angles; flapping, deviation and pitch. The flapping angle represents the forward–backward motion of the wing. Deviation is up and downs motion of the wing with respect to its joint and pitch is the wing rotation about its hinge axis to the body (Fig. 1a).

Over 50 free flights of cicada were recorded during summers of 2011 and 2012. Different flight modes including forward flight, vertical takeoff, banked turn and Immelmann turns were captured among these flights. While the majority of these flights involve significant change in flight heading, we never observed a yaw turn as was reported in other insects and birds such as fruit flies [12], dragonflies [1], damselflies [3] and hummingbird [13]. The flight heading change was executed via banked turns or Immelmann turns. To advance with our investigation on understanding the aerodynamics and flight mechanics of cicada free flight, we selected four representative flights composing total of 42 full wingbeats. A selected sequence of images of all these flights are shown in Fig. 1b with the quantitative measurements of the body displacement and orientation being presented in Fig. 1c. Flight 1, consists of two phases of moving on a straight line with a small body pitch angle and an average forward velocity of 1.88 $\text{m} \cdot \text{s}^{-1}$ followed by a pitch up and deceleration of the forward velocity. Flight 2 is a banked-turn during which the flight heading changed by 150 deg. The body rolled to the left within the first two flapping stokes, reaching a 90 deg bank angle. The bank angle is very extreme compared to what was observed in turn flights of other insects such as fruit flies [4] and blowflies [14]. The maximum body roll velocity approached 4000 $\text{deg} \cdot \text{s}^{-1}$ in this phase. The turn is followed by a slow roll back and flying forward while maintaining the body orientation. Flight 3 resembles an Immelmann (or roll-off-the-top) turn which consists of an ascending half-loop followed by a fast roll. After takeoff and a short phase of forward flight, the cicada pitched up in a vertical loop, with mean radius of 0.9 body length, until it attained an upside down orientation with respect to the ground. The maximum pitch velocity exceeded 3000 $\text{deg} \cdot \text{s}^{-1}$ and was reached at the early stages of pitching up phase. Subsequently, the cicada rolled to reposition the body in straight flight orientation. In flight 4, the cicada body pitched up from 0 to 90 deg within two wingbeats and continued to ascend while maintaining its orientation (body axis normal to the ground) for the next five wingbeats. The vertical velocity of the center of mass was 0.36 $\text{m} \cdot \text{s}^{-1}$ during this phase. The initial phase was followed by a fast spinning which altered the body's bank angle more than 180 deg. Rotations faster than 700 $\text{deg} \cdot \text{s}^{-1}$ occurred about an axis which lies in the body's frontal plane with the angle between rotation axis and the body normal being (92 ± 22) deg.