

Detailed Analysis of Variables Affecting Wing Kinematics of Bat Flight

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ABSTRACT

Body motions of flying animals can be very complex, especially when the body parts are greatly flexible and they interact with the surrounding fluid. The wing kinematics of an animal flight is governed by a large number of variables and thus the measurement of complete flapping flight is not so simple, making it very complex to understand the contribution of each parameter to the performance and hence, to decide the important parameters for constructing the kinematic model of a bat is nearly impossible. In this paper, the influence of each parameter is uncovered and the variables that a specified reconstruction of bat flight should include in order to maximally reconstruct actual dimensional complexity, have been presented in detail. The effects of the different kinematic parameters on the lift coefficient are being resulted. The computation analysis of the lift coefficient for different camber thicknesses and various wing areas is done by unsteady thin airfoil theory and vortex lattice method, respectively.

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INTRODUCTION

Since the dawn of the era, humans have always been fascinated and inspired by the movement of animals through the air. The animal flight has not only aroused passion but also served the most utilitarian function of inspiring design innovations. Nonetheless, the early attempts to develop a flapping wing MAV were bound to fail due to insufficient knowledge of the flapping motion and lack of tools required for the analyses and design of the unsteady flight, and consequently, research concerning flapping flight has been overshadowed by the study of fixed and rotary wing aircrafts for almost 100 years [1]. Interests in bio-inspired flight and rigorous desire to develop highly efficient and maneuverable flapping wing MAVs have resurfaced among the biologists and engineers in the last two decades. The greatly improved capabilities of modern equipments to image animal motion and visualize complex fluid flows have brought the attention back to animal flight research.

Although the tools for the analysis and design of vehicles optimized for steady flight are well developed, the mechanics of highly unsteady flight remains uncertain due to the gap

present in our understanding of the basic mechanics of the highly unsteady, three-dimensional and complex character of animal flight. This is an issue of growing interest, driven by the desire to build vehicles that can perform extremely unsteady aerodynamic maneuvers.

Flapping flight is the single most evolutionarily successful mode of animal locomotion: there are today over 1200 species of bats, more than 10 000 living species of flying birds, and somewhere between millions and tens of millions of species of flying insects [2]. Birds, insects and bats apply a variety of flapping patterns in hovering and forward flight to generate lift and thrust but among these, bats are proven to be the most superior and efficient flyers due to their highly articulated motion. Birds and insects can fold and rotate their wings but more than two dozen independently controlled joints overlaid in the flexible wing membrane [2, 3, 4] and highly deformable bones [5,6] enable the bat to fly at either positive or negative angle of attack, dynamically change wing camber and create complex 3D wing topology to achieve extraordinary flight performance. The difference in the wing kinematics of the bats with respect to birds and insects is irrespective of the flight speed and other flight conditions.

Bat wing kinematics is a very complex phenomenon (especially at slow flight speeds) with the wing changing its shape continuously as it flaps [7]. It cannot be simply viewed as a flapping plate, or even as a flapping plate with one or two simple hinges [1]. Many of the joints of the handwing are extended during the downstroke until the lower reversal point, where they begin to flex, and the wingtip moves closer to the body in horizontal direction. At the same time, early in the upstroke, the wingtip moves simultaneously upwards and outwards and the wing adapts an extended posture at the end of the upstroke. Moreover, the motion of the wingtip is not primarily vertical with respect to either gravity or the animal's body, and a strong wing tip vortex is shed from the wing tip during the downstroke and either from the wing tip or a more proximal joint during the upstroke. The wings sweep forward during downstroke, increasing the relative forward velocity, and sweep backward during upstroke along with decreasing the angle of attack. Moreover, adding to the complexity of the bat flight, the flight speed and elevation are not constant, but oscillate in synchrony with both the horizontal and vertical movements of the wing.

A bat's wing motion is not governed by one or two variables; instead the wing kinematics is a function of numerous variables, having a significant role in the wing kinematics. The kinematic measurements of such complex motions are very difficult due to the large number of variables involved and thus the contribution of each parameter to performance is not clearly apparent. In this study, the influence of all variables on wing kinematics has been uncovered in detail and priority variables (having the most significant influence on performance) are decided to be focused on for developing a kinematic model of the bat.

The flight of bats, much like that of birds has often been modeled to first approximation as quasi-steady, with wings treated as rigid plates [8, 9, 10]. The assumption of steady flight was largely necessitated by the lack of analytical and experimental tools to analyze the complex flows, but this situation has changed considerably in the past few years. Recently, numerous experiments on bats have been done by many scientists and engineers to study the importance of various parameters of the bat wing kinematics. In 2006, Tian [2] experimented and analyzed the bat flight kinematics and observed that bats possess unique flight characteristics at relatively low flight speeds, including a flexion of the wing during upstroke. Riskin [7], in 2008, used proper orthogonal decomposition method (POD) for assigning importance to kinematic variables, using dimensional complexity metric, concluding that it does not change with flight speeds. While in 2010, Riskin [11], Hubel [12] and Leigh [13] performed different studies on bats to analyze the variation in their wing posture and kinematics on account of varying body mass, flight speed and power output required, respectively. Leigh [13] found out that variation of kinematics alone can increase sufficient aerodynamic power to accommodate even a 21% increase in body weight. In 2012, Riskin [14] analyzed kinematics of the folding and unfolding of the bat wing

during upstroke motion for inertial cost of flight, while Rhea [15] studied the three-dimensional wingbeat kinematics of a bat to determine how factors affecting the lift production vary across flight speed and within wingbeat.

This paper explains the influence and importance of different variables on the wing shape and kinematics of a bat flight. The focus has been given on parameters which are critically important for the construction of the kinematic model of bat flight in order to maximally reconstruct actual dimensional complexity.

EFFECT OF PARAMETERS ON WING KINEMATICS

Bat wings have a high potential to adjust wing morphology according to the aerodynamic demands due to their highly flexible wings with flexible wing bones and a compliant wing membrane, enabling them to carefully control their wing shape and motion. The morphology and kinematics of a bat wing determines the resulting aerodynamic lift through the regulation of the flight speed, wing area and lift coefficient. Thrust and weight support of the bat is generated by the aerodynamic lift (L) of the wing, which is determined by the density of the medium (ρ), the speed of the wing relative to the air (U_{eff}), the wing area (S) and the lift coefficient (C_l) given by equation (1) [16]:

$$L = \frac{1}{2} \rho S U_{eff}^2 C_l \quad (1)$$

Each of these factors, except density, is controlled by different parameters of the wing morphology and kinematics. The speed of the wing is determined by the combination of flight speed and flapping speed, with the latter being determined by the amplitude and frequency of the wing beat. Wing area can be controlled by retracting or extending the wing. Finally, the lift coefficient depends on the shape of the wing profile (e.g. camber and thickness) and the angle of attack, the angle between the chord line and the direction of the airflow.

To have a more clear understanding of the correlation between the wing kinematics and aerodynamic variables, a detailed explanation has been presented for the effect of these variables on the wing morphology and the performance of the bat.

Wing Speed

Due to the strong dependency of generated aerodynamic lift on speed of the wing, bats are expected to alter their kinematics and wing morphology across flight speeds to generate sufficient weight support and thrust.

The stroke plane angle (β), increases from less than 30° at low to about 75° at high flight speed [15], indicating a change from a horizontal to a more vertical stroke plane (as depicted in fig.1) while the downstroke ratio and span ratio, both increases when going from low to medium flight speed and then decreases slightly when flight speed is increased further.

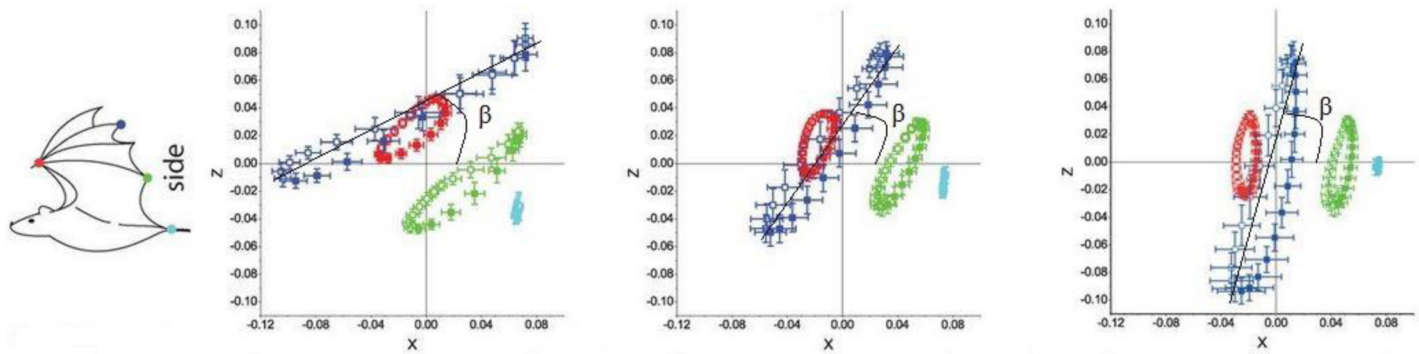


Fig.1. The trace of the wrist (red), the wingtip (blue), the tip of the 5th finger (green) and the foot (sky blue) for one wing beat with the shoulder as the origin for three different speeds (0 m/s, 3 m/s, 7 m/s respectively). Filled symbols represent the downstroke, open symbols the upstroke. The variation of stroke plane angle is clearly visible varying from around 30° at low speeds to 75° at the high speeds. All distances are shown in meter [15].

while the body angle is relatively constant throughout the stroke across speeds, with higher body angle at low speeds.

The wing area varies sinusoidally over the wing beat cycle with the largest area found at the time of mid-downstroke while the lowest is present in the middle of the upstroke. On increasing the flight speed both the minimum and maximum areas tend to decrease slightly and increase on decreasing the flight speed. The innermost part of the wing is aerodynamically relatively inactive at the lowest flight speed range due to the low speed of the flow across the wing, but potentially more important at intermediate flight speeds when the upstroke is more or less inactive [17].

A higher angle of attack produces higher lift, but also higher drag, and therefore the bats are expected to reduce the angle of attack with increasing flight speed when the demand of a high lift coefficient is reduced (as shown in fig.2).

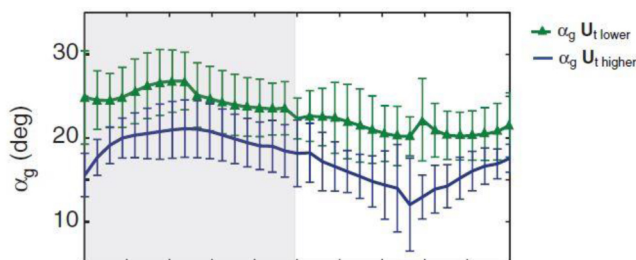


Fig.2. Geometric angle of attack, vertical wrist and wingtip excursion at lower and higher wind speeds averaged over four bats. Grey shading indicates downstroke [12].

The leading edge flap angle has a very large variation with the flight speed, varying from around 5° at high speeds to around 25° at low speeds, with an increase in the lift force during the downstroke, and a decrease during the upstroke. At high speeds, the entire upstroke shows negative values.

The mean angular velocity directly affects the performance of the flyer. It shows a minimum at the speed of

maximum lift to drag ratio, suggesting a simple way to determine the optimal speed from kinematics alone.

The wing velocity (V) is a function of forward velocity (U_∞) and flapping velocity (V_f) as given by equation (2) [18]:

$$V = \sqrt{U_\infty^2 + V_f^2} \quad (2)$$

Forward velocity

Several changes in the kinematics of bats are being observed with changes in the flight velocity. The horizontal velocities of bats are much greater than vertical velocities, so flight paths are more close to horizontal [2]. When flight speed is reduced, sustaining weight support becomes more demanding and bats need to compensate for the lower velocity over the wings by increasing the wing area, flapping speed or lift coefficient. This is particularly important during hovering and slow flight.

Flapping velocity

The flapping velocity of the wing is determined by the stroke amplitude (ϕ_0) and the flapping frequency of the wing beat (f) given by the equation (3) [18]:

$$V_f = 4f\phi_0 R \quad (3)$$

where R is the half of the total wingspan of the wing.

Amplitude

The vertical amplitude of the wing beat increases with increasing the speed while the horizontal amplitude decreases (as shown in fig.3). The angular amplitude in the stroke plane follows a U-shaped pattern with high values at low flight speed, with decreasing and then increasing values with increasing speed. It is highest at low speeds at around 90°, drops to 65° at 3 m/s and rises back to about 80° at high speeds [15]. Stroke plane and wing stroke amplitude at the