# AERODYNAMICS OF HOVERING FLIGHT IN BAT

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*Summary* In this paper, we study numerically the aerodynamics in the hovering of a small-sized bat *Glossophaga soricina*. We developed a three-dimensional Navier-Stokes solver which can handle large deformation of the bat's membraneous wing in flapping motion. The kinematics of the wing is constructed using the data measured in experiment. Our prediction shows that the lift generated is almost sufficient to support the weight of the bat. We also provide the first evidence from simulation that the upstroke in bat's hovering is inactive in lift generation. The near-filed vortex structures is also discussed.

## INTRODUCTION

Hovering is a common habit of insects, hummingbirds and small-sized bats. Comparing to forward flying, hovering is a power-demanding type of flight which requires much higher frequency of wing beat. The thorough understanding of the high-lift mechanism in animal hovering can aid the design of the micro air vehicle (MAV) which mimics the nature flyers. All previous studies indicated that the quasi-steady-state aerodynamic theory can not explain the hovering flight, since not enough lift can be generated for the animal to remain aloft. Therefore, various unsteady aerodynamic mechanisms to enhance lift production have been proposed, including leading-edge vortex (LEV), rotational circulation, clap-and-fling, wake capture, and added mass [1]-[3]. Although the mechanisms of high lift generation in hovering insects and hummingbirds have been extensively explored, the number of studies of the aerodynamics in the flight (including hovering) of bat are relatively fewer [4][5]. Large progresses have been achieved recently in the understanding of bat's flight. However, there are some open questions, for example, the lift generation mechanism and the topology of vortical structure. In this work, we use numerical simulations to study the aerodynamics in hovering bats.

## NUMERICAL MODEL AND METHOD

The flow field around the hovering bat is governed by the 3D incompressible Navier-Stokes equations:

$$\begin{aligned} &\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{u}) = -\nabla p + \frac{1}{\mathrm{Re}_f}\nabla^2 \mathbf{u} + \mathbf{f}_b \\ &\nabla \cdot \mathbf{u} = 0, \end{aligned} \tag{1}$$

where $\mathbf{u}$ is the fluid velocity, $p$ the pressure. Eq. 1 is written in a non-dimensional form and $\mathrm{Re}_f$ is the Reynolds number which characterizes the relative importance of inertial and viscous force. $\mathbf{f}_b$ is a body force which represents the effect of the solid body on the fluid. The 3D Navier-Stokes equations (Eq.1) is solved by using a newly developed immersed boundary method [6].

In the simulation, the bat is located at the center of a rectangular computational domain (box) with the dimensions of $12c \times 16c \times 16c$, where $c$ is the averaged chord length of the bat's wing. The non-slip condition is prescribed on the surface of bat's body and six walls of the box. The initial condition is that both the body surface of the bat and the ambient fluid are stationary. The kinematics of the bat's body and wing in hovering flight are constructed using the measurement performed in the wind tunnel at Brown University. The parameters for the morphological characteristics of the bat and the wing-beat cycle are listed in Table 1.

## RESULTS AND DISCUSSIONS

First we study the aerodynamic forces generated by the wing-beat in hovering bat. The time history of force coefficients in one period of flapping is shown in Figure 1 for the Reynolds number of 100. The predicted mean lift coefficient is 31.59. Further study indicates that the force coefficients only differ slightly if the Reynolds number is increased to 1776. Thus we assume that the force coefficient are not sensitive to the Reynolds number (in the range of the order of $10^2$ to $10^3$). Then the estimated averaged lift production at the Reynolds number of the experiment is $8.5 \times 10^{-2}N$, which is approximately 85% of the body weight of the bat. From Figure 1, it is also seen that almost all the lift is produced during downstroke. It is well known that the downstrokes in hovering insects and humming birds contribute significantly to lift generation. More specifically, it amounts to 50% of the lift generation in hovering flight for hawkmoth [1] and 25% for hummingbird [7]. But for bat's flight, the function of upstroke is still a controversial issue. It is claimed in [8] that lift is not generated in upstroke of slowly flying bat, while a contradictory conclusion was drown in [5]. Our observation provides the first evidence from numerical simulation that in bat's hovering upstroke is inactive in lift generation.

The predicted mean drag coefficient is 11.06 within one period of flapping, with a contribution of 26.01 (drag) from downstroke and -15.0 (thrust) from upstroke. The resultant drag force at the Reynolds number of the experiment is estimated to be $2.79 \times 10^{-2}N$, which is roughly 1/3 of the bat's weight. Clearly, a positive value of horizontal force is

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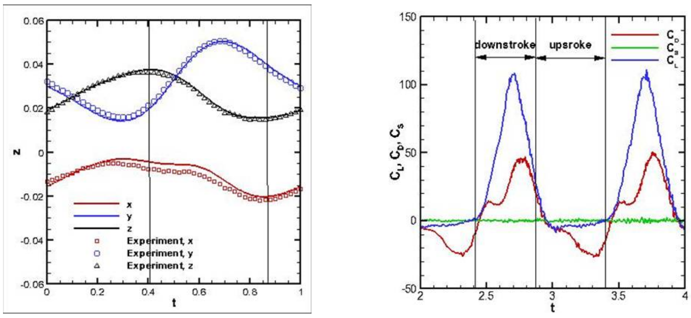
**Table 1.** The parameters for the morphological characteristics of the bat and wing-beat in hovering flight.

| Parameter | Value |
|---|---|
| Mean chord length $c$ | $0.036m$ |
| Wing area $2S$ | $0.0086m^2$ |
| Wing span $2L$ | $6.47c$ |
| Wingtip amplitude $A_w$ | $1.74c$ |
| Flapping frequency $f$ | 6.67 Hz |
| Body AoA | 0.49 rad |
| $\mathrm{Re}_f = fc^2/\nu$ | 100; 1176 |




a) b)

**Figure 1.** The kinematics of wrist and time history of force coefficients within one period of wing flapping.

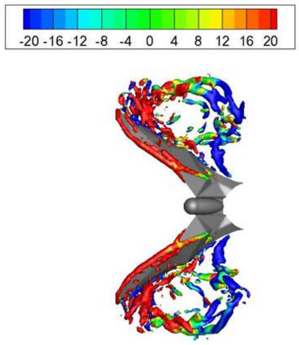



**Figure 2.** The vortex structure around the wing at the end of downstroke for $Re_f = 100$. The vortex structures are identified using the Q-criterion while the colors are based on the values of spanwise vorticity.

indicative of unstable hovering with possible draw-backs from the target point. We believe that more ideal kinematic data for stable hovering can correct this problem. The predicted side-force coefficients from the simulations are sufficiently small.

Next, we investigate the vortex structure around the bat in hovering. In the previous studies, a stable leading edge vortice (LEV) has been found to greatly enhance lift in slowly-flying bats [4]. Our finding is consistent with their experimental observations. The existence of a stable LEV has confirmed by our simulations (both $Re_f = 100$ and $Re_f = 1176$). For good visualization effect, the data from the simulation of $Re_f = 100$ (Figure 2) is used to identify the global topology of the vortical structure in the near field. It is seen that each wing generated its own vortex loop. Our simulation is basically in support of the wake model proposed in [4].

## CONCLUSIONS

We study the hovering of a small-size bat using numerical simulations by solving 3D Navier-Stokes equations. The kinematics data for wing flapping are from the experiment on the Pallas' long tongued bat. The predicted lift force generated is almost sufficient to support the weight of the bat. The existence of a stable LEV is found to be the main mechanism for high lift generation. The function of upstroke in lift generation is found to be inactive. The observed global topology of vortex structure in the simulation is basically in support of the model proposed in [4].

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