SPANWISE STRETCHING AND COLLAPSE MOTIONS STABILIZE LEADING-EDGE VORTEX IN SLOW-FLYING BATS

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Summary A stable leading-edge vortex (LEV) could generate high lift which could not be predicted by the conventional aerodynamics theories. The mechanisms to keep the LEV stable is still not clear. In this study, we numerically simulate the slowing-flying bats using immersed boundary method. The morphology and kinematics of bat are taken from experimental measurements. It is observed from our simulation that the stretching and collapse motions of wing determine the flow structures around the bat. The observation is further investigated by using a simple model: the flows around a spanwise oscillating plate, where the spanwise motion enhances the LEV and make it more stable. This result implies a link of bat kinematics with its unusual aerodynamic performances.

INTRODUCTION

Animal flights exhibit the intricate kinematics and complex time-varying geometries in wings, which generate a high aerodynamic performance. One typical example is that bats manipulate their wings to achieve high lifts. It is experimentally observed that bats exploit both flapping and spanwise stretching-collapse motions, while insects and birds operate their flapping motions alone. The central problem is how to link wing motions with high aerodynamic performance.

A high aerodynamic performance achieved by flapping motions cannot be predicted by the conventional aerodynamic theory. It predicts a stall which results in lift loss. The mechanism of high lift has been experimentally found to be the formation of a stable intensive leading-edge vortex (LEV) on the top surface of wing. If LEV is detached from leading-edge, the lift may lose. Therefore, a stable LEV attached to leading edge is critical to lift generation. The stable LEV is unique to link the flapping motions and high lifts and play an important role in unsteady aerodynamic theory.

The mechanisms to keep the LEV stable during flapping is still controversial. It may attribute to the axial flow driven by the dynamic pressure gradient, the rotational acceleration, or the induced velocity of tip-vortex[1].In the present study, we find that the spanwise stretching and collapse motions can enhance the LEV and contribute to its stability.

NUMERICAL MODEL AND METHOD

Numerical model

The numerical bat model used in the present work is constructed based on a slow flying Pallasąŕ long-tongued bat (*Glossophaga soricina*). The morphology of the model wing is scaled based on work of Watts et al[2], where the outline of a most extended wing of a grey-headed flying fox (*Pteropus poliocephalus*) is provided. The morphology of the wing is assumed to be geometrically similar among species in the present model. The flapping motion is described using 3 keypoints (wrist, wingtip and the fifth digit) on each wing.The kinematics of the three key-points are recovered from the work of Wolf et al[3]. For a given point on the surface of the wing, the position at each time step is constructed from the key-points using a piecewise interpolation.

Numerical method and settings

The 3D incompressible Navier-Stokes equations are solved using an IB method in the framework of discrete streamfunction formulation, which provides an efficient implicit approach to get the forcing term representing the effects of solid body. The details of the numerical method and the validations of the present code can be found in the work of Wang and Zhang [4].

The computational domain of the present work is $22c \times 12.4c \times 12.4c$, with a local refined domain of $(-1.5c, 1.2c) \times (-2.7c, 2.7c) \times (-0.9c, 1.5c)$ (c is the mean chord length). The minimum grid size is $0.015c$. The surface of the bat is represented by $50,000$ Lagrangian markers. A uniform velocity is prescribed at the inlet, free convection boundary condition at the outlet, and non-slip boundary condition on the surface of bat. The Strouhal number $St = fA_z/U = 1.36$ is kept being the same with the experiment, while the Reynolds number is set to be 1000 in the present simulation(Re=2380 in experiment), assuming that the flow is dominant by the Strouhal number.

RESULTS

A stable LEV exists on the top surface of each wing during flapping flight of a slow-flying bat. The instantaneous flow structures is shown in Fig.1. The LEV on each wing connects to a small root vortex at the wing-base, and connects to the tip vortex at the wing-tip. The vortex system is similar to that around a hovering hawkmoth in the work of Ellington et al [1]. But unlike the LEV of a hovering hawkmoth, there is not a unidirectional axial flow in the core of the LEV of a slow-flying bat. The axial flow in the LEV changes directions during the flapping in the present results. Indeed, the spanwise flow profiles on the top surface of the wing show the characteristics of an oscillating boundary layer. It means

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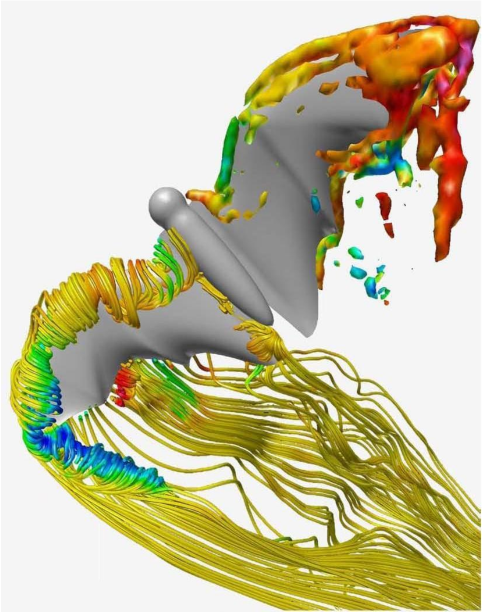
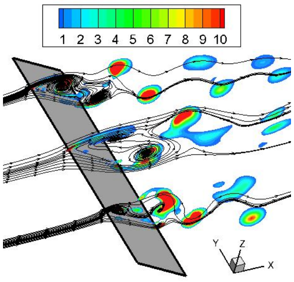


Figure 1. The leading edge vortex (LEV) and streamlines around the bat at the mid-downstroke (top view). The wings are most extended at this time. The vortex structures on the right wing are identified using the Q-criterion (Q=200). The color on the vortex structures and streamlines indicates the strength of the streamwise vorticity. Each wing generates a separated LEV. The LEV is connected to a small root vortex at the wing-base, and connected to the tip vortex at the wing-tip.



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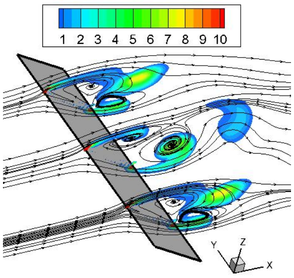

b)

Figure 2. The spanwise oscillation stabilized and enhanced LEV. The instantaneous flow when the lift reaches the maximum value are shown. (a) flow around a spanwise oscillating plate, the plate passing the equilibrium position and moving with the maximum velocity in -Y direction; (b) flow around a static plate. The flow at 3 different slice are shown. The three slices sit at 20%, 50% and 80% of the span respectively. The contours of Q and streamlines in the slice are shown. The stable LEV exists in the slices positing at 20% and 80% spanwise positons for the oscillating case. The LEV sheds into the wake for the static case.

that the spanwise stretching and collapse of the wing plays an important role in determining the flow structures. The observation is further investigated by using a more simpler model: the flows around a spanwise oscillating plate. The flow around a spanwise oscillating plate, with aspect ratio AR=4 at angle of attack AoA=30°, is shown in Fig.2(a). The flow around a static plate with the same AR=4 at AoA=30° is presented in Fig2.(b) as a reference. At the instantaneous when lift reaches the maximum value for each case, a LEV is observable for the spanwise oscillating plate case. There is not stable LEV on the top surface of the static plate case. At the meanwhile both the maximum and mean lift for the spanwise oscillating plate case is larger than these for the static plate case. The results indicate that the spanwise motion could enhance the LEV and make it more stable.

CONCLUSIONS

The 3D flow around a slow-flying bat is investigated in the present work. LEVs exist on the top surface of the wing during flapping. The spanwise stretching and collapse of the wing dominant the flow structures around the bat, enhance the LEV and contribute to its stability. This may implies a link of bat kinematics with its unusual aerodynamic performances.

Acknowledgements
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