Vortex Formation and Three Dimensional Flows in Flapping Wing Flight

Keywords: Insect Flight, Leading Edge Vortex, Volumetric PIV, Aerodynamics

Background and Goal

Insects exhibit one of the most effective evolutionary means of survival - Flight. Their method of flight, flapping wing flight, is a unique mechanism for generating lift, control, and maneuvering forces. For the associated low Reynolds number regime, the lift producing aerodynamic mechanisms are intrinsically unsteady and vortex-dominated, thus very complex.

Throughout the past few decades progress has been made in understanding flapping flight and a general understanding of the unsteady mechanisms has been identified. Many scientists believe that the leading edge vortex (LEV) is responsible for generating the high lift force found in insects and hummingbirds [1]. However, the current state of the art has been limited to two-dimensional (2D) analysis, which does not capture the whole picture of a highly three-dimensional (3D) flow. This limitation has lead to various contradictory hypotheses that attempt to explain the stability of the LEV. One hypothesis claims that LEV stability is dependent on Reynolds Number, with a stabilizing spanwise flow only visible for high Reynolds numbers [2]. Other studies suggest that LEV stability is not dependent on Reynolds number, but rather on the shape parameter called the Rossby number and the Centripetal and Coriolis acceleration [3]. These contradictory hypotheses suggest that a 3D systematic investigation and accurate extraction of the mechanisms responsible for LEV stability is much needed.

While most research on flapping wing aerodynamics is concentrated in the near field flow and LEV, the far field flow and vorticity patterns involving vortex rings and induced flows remain unexplored. An understanding of the overall flow patterns and unsteady flow is essential to deriving a comprehensive theory of flapping wing flight.

To address the vortex generation of flapping flight and associated forces much work still remains to be done at a fundamental level. My research will focus on furthering the understanding of unsteady vortex formation, evolution, and shedding associated with flapping wings at low Reynolds numbers. The development of a comprehensive theory for flapping wing flight will be used to engineer and develop Micro Aerial Vehicles (MAV) that can be very useful for surveillance indoors and in urban areas for both civilian and military applications.

Research Plan and Preliminary Results

Using Volumetric 3-Component Velocimetry (V3V) from TSI Inc., a state of the art 3D particle image velocimetry system, I plan to complete the following tasks for my PhD research:

- Determine the conditions for vortex formation, evolution, and shedding on flapping wings in 3D flow fields to understand fundamentals of what accounts for LEV stability.
- Understand the aerodynamic and force generation mechanisms of flapping wings under different flight conditions including: hover, takeoff, forward flight, and turning.
- Determine when vortex attachment and shedding is advantageous (or detrimental) in lift and drag force generation as well as calculate the related power efficiency.

Exciting preliminary results have already been obtained during my 2011 Purdue Summer Undergraduate Research Fellowship (SURF). For the first time in flapping wing aerodynamics research the vortex ring and its structure have been identified experimentally as shown in Figure 1. This preliminary study shows great promise and opens a wide range of future research that could potentially revolutionize our understanding of flapping flight. The 3D results can be used to piece together previous 2D studies and eventually lead to a comprehensive theory of flapping wing aerodynamics. It was these results that won me an award for "Top Research Talk" at the 2011 Purdue SURF symposium and evolved into my undergraduate thesis. I will also present this

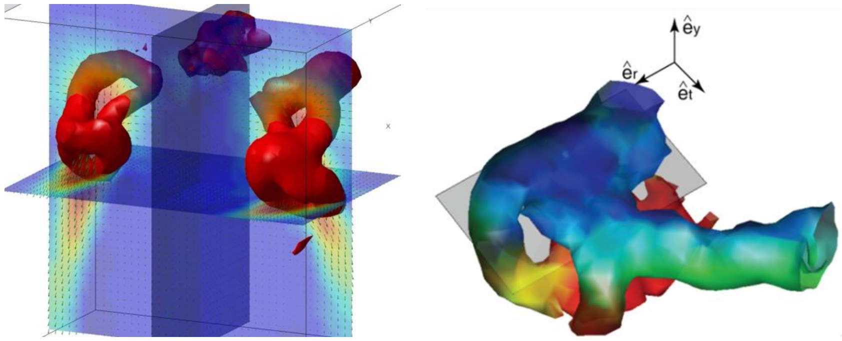
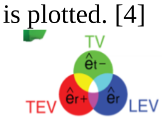


Figure 1. Three dimensional flow on flapping wings: (Left) Far field flow. The vortex ring structure and induced flow beneath a pair of flapping wings. (Right) Near field flow: LEV, trailing edge vortex, and Tip Vortex on flapping wings. Vorticity is plotted. [4]



work at the American Physics Society's Annual Fluid Dynamics Conference [4] this November and a journal paper is under preparation that will further explain vortex tilting and stretching.

For my PhD, I will continue the proposed research plan. Using V3V and experimental fluid dynamic methods, I will study vortex dynamics and the associated force production for all the cases listed. Wing kinematics for various insects and flight conditions have already been extracted from high speed video and some dynamically scaled robots have been constructed for past 2D experiments. Post processing will be done using a Matlab code I helped develop during SURF to obtain results like that of Figure 1. The large amount of 3D flow field information and the associated forces that will be obtained will enable us to perform an in-depth analysis on the correlation of vortex dynamics and force generation for near-field and far-field flows. *Based on our results, we expect that the tilting and stretching of the LEV and trailing edge vortex(TEV) are associated with LEV stability.* I also expect to extract the underlying aerodynamic mechanisms for various flight conditions including the effects of wing-wake interaction during stroke reversal. Additionally, power efficiencies will be studied and rated for the various flight conditions which is important for obtaining power to weight ratios for lightweight MAVs. These results will allow us to make recommendations in the design of next generation flapping MAVs.

Intellectual Merit and Broader Impacts

The proposed study will be the first of its kind in that it systematically investigates 3D flows and associated forces on flapping wings. A comprehensive aerodynamic theory of flapping flight will be developed based on the obtained results. Once the science of bio-inspired motion is understood, it will be possible to design and control flapping wing MAVs.

The broader impact results from the proposed research will have far reaching consequences in biology, fluids, and robotics and disseminated broadly through conferences and journal papers. As previously stated the results could lead to the successful engineering of MAVs. Their ability to fly indoors make them ideal for surveillance in a variety of civil, industrial, and defense applications such as search and rescue, surveillance, and reconnaissance. I will also use this intriguing research to foster creativity in pre-college students at the Annual Purdue Bug Bowl where thousands of people of all ages gather to take part in hands on insect activities. At this event, robotic insect models could be demonstrated to a very broad audience. I certify that this proposal is original and the ideas presented are my own.

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