

THREE-DIMENSIONAL DYE FLOW VISUALIZATION OF A TWO-DEGREE-OF-FREEDOM FLAPPING WING: COMPETING EFFECTS OF PITCHING AND ROTATION

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Introduction

Hovering phenomena occurs when animals generate collinear lift and thrust forces in a fluid medium to counteract gravity. While previous study has focused on the quantitative forces generated during fixed angle of attack (AoA) rotational motion and continuous flapping maintaining a consistent leading edge (Nagai 2008), little experimental investigation has been pursued on evolution of the 3D flow structures formed during wing supination. It has been shown that force production is maximized when pitching concludes with the start of the subsequent stroke (Dickinson 1999) and minimal rest time between half-strokes (DeVoria 2013), motion constraints that were also used for the present study. However, coupled rate effects of approach and departure from this turn around point remained to be scrutinized. By building the flow piece-by-piece (Figure 3), relative rate parameters can be formed, varied and tested to generate flow structures and observe their behavior with respect to 2-DOF wing motion.

Experimental Setup

Continuous injection 2-camera dye flow visualization was performed in a 13' x 5' x 4' water aquarium on an 8cm x 24cm rounded tip ABS plastic plate set in 2-DOF trapezoidal motions (Figure 4) by two brushed DC motors. White backgrounds illuminated by diffuse LEDs were installed to contrast colored flow structures in video captured by Canon PowerShot SX510HS and Nikon DX DSLR cameras in an orthogonal configuration (Figure 1). The two camera perspective was imperative in illustrating the highly three-dimensional pitching flow evolution. Design of the 3D printed dye-manifold (Figure 2) was motivated by the necessity to deliver new dye marker while mitigating observational data loss from diffusion. Adjustable elevation of the dye reservoirs controlled the delivery rate to any of the 7 internal channels whose exit locations were selected by efficacy of preliminary experiments to mark points of interest.

2 Degree-of-Freedom Motion: Rotation & Pitching

Common vortex structures associated with continuous flapping

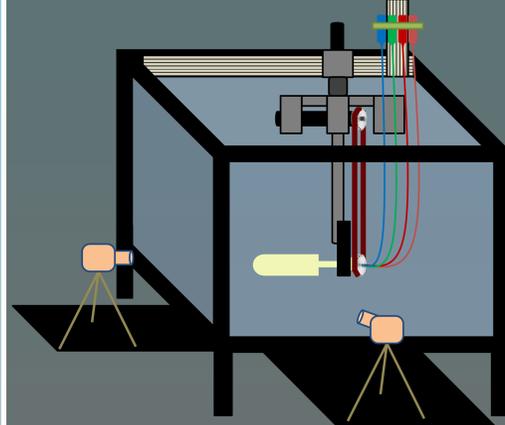


Figure 1: Schematic of facility. Colored dye flows via gravity to 2-DOF flapping wing mechanism video recorded from orthogonal perspectives.

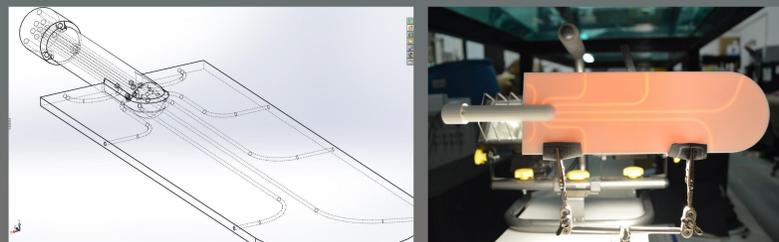


Figure 2: (left) Wireframe view of hidden dye routes. (right) 3D Printed Dye-Manifold backlit to show internal channels.

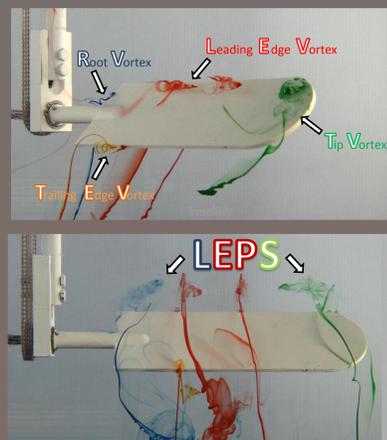


Figure 3: (left) Side view of starting vortex structures formed in quiescent flow for pure rotation at a fixed 45° AoA. (bottom) Orthogonal views of the vortex structures formed during a pure 90° pitching motion.

Figure 4: Dimensionless velocity flapping motion profiles of Figure 5 and Figure 6.

$$k_\alpha = \frac{\text{chord} \cdot \dot{\alpha}_{\max}}{4 \cdot \text{tip} \cdot \dot{\phi}_{\max}}$$

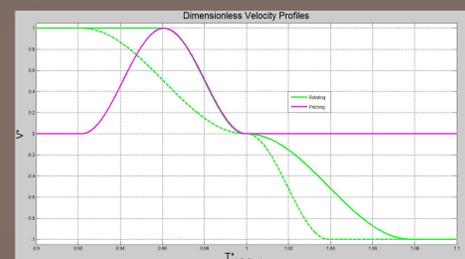
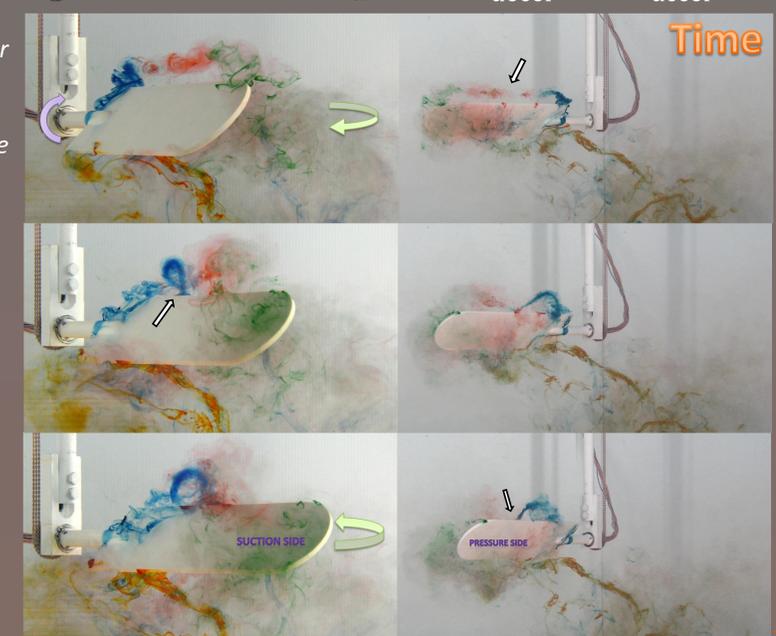


Figure 5: Time series $k_\alpha = 1.2, t_{\text{decel}}^* = 0.5, t_{\text{accel}}^* = 1$.



While larger wake momentum keeps the LEPS closer to the leading edge, the slower acceleration rate provides time for it to move under the leading edge before being pushed to the pressure side of the following stroke.

Figure 6: Time series $k_\alpha = 1.2, t_{\text{decel}}^* = 1, t_{\text{accel}}^* = 0.5$.



With a weaker wake, the LEPS moves far enough away from the quickly accelerating leading edge, sweeping the LEPS to the suction side of the following stroke.

Results

Fluid momenta interacts with the acceleration of the plate in both motions, rotating and pitching. Each of these motions form primary vortex structures along the plate edges while speeding up, and secondary stopping vortices while slowing down. The strength and sign of these vortices align such that two coherent elliptical loop structures are ejected during pitching from both leading and trailing edges of the plate. Since structures around the leading edge are primarily responsible for lift generation, the propagation of the ejected Leading Edge Pitching Structure (LEPS) subject to different rate parameters is of interest. A larger deceleration rate results in a stronger rotational flow from the previous wing stroke, which causes the LEPS to kink in the middle (Figure 5) and move toward the pressure side of the wing, following the stopping vortices. However, when a larger acceleration rate is implemented, the LEPS is pulled to the suction side (Figure 6), causing significant stretching of the ejected loop through the following stroke. These vortical flows are created at the end of every half-stroke and we show that the competing flow effects set by the timing of the wing pitching and deceleration substantially influence the LEPS formation. In turn, this should affect lift generation during this most challenging phase of hovering flight.

Future Work

Quantitative analysis of observed structures during the authors' present work will be conducted using data obtained from Stereo Digital Particle Image Velocimetry. Volumetric reconstruction by stitching span-wise planes of phase-locked flow will illustrate the time varying circulation and force production during turnaround.

References

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