

# Flow visualization and wall shear stress of a flapping model hummingbird wing

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**Abstract** The unsteady low Reynolds number aerodynamics of flapping flight was investigated experimentally through flow visualization by suspended particle image velocimetry and wall shear stress measurement from micro-arrays. Specifically, three major characteristics of the flow are questioned: growth of the developed separation bubble during each half-stroke, location and frequency of the leading edge vortex (LEV) formation, and presence of axial flow. In conjunction, a mechanism was developed to create a flapping motion with three degrees of freedom and adjustable flapping frequency. The flapping kinematics and wing shape were selected for dynamic similarity to a hummingbird during hovering flight. Flow visualization was used to validate the anemometry observations of leading edge vortex (LEV) characteristics and large lift forces in fixed-wing aircraft (Sane 2003). One of the first studies to investigate attached vorticity in flapping flight was by Maxworthy who was attempting to expand on the clap and wing rotation mechanisms that had been observed in various wing speeds. It was observed that a minimum frequency between 2 and 3.5 Hz is required for the formation of a stable LEV. The vortex strength peaked around 30% of the flapping cycle (corresponding to just past the translation midpoint), which agrees with results from previous studies conducted by others. The shear sensors also indicated a mild growth in LEV size during translation and also indicated a mild growth in LEV size during translation. This growth magnitude was underestimated by inviscid models. He also described a helical structure of the LEV where significant axial flow near the leading edge transported vorticity from the LEV core to the wingtips; thereby inhibiting the shedding that would be expected in a two-dimensional analysis.

## 1 Introduction

Although most researchers agree that existence of an attached leading edge vortex (LEV) is a significant contributor to the strong lift forces observed in flapping fliers, *Manduca sexta*, and demonstrated a similar LEV forming at the base of the wing and spiraling outward to join the tip vortices (Fig. 1) (van den Berg and Ellington 1997b). The LEV was helical over the wing with significant axial flow moving from a surface bound focus at the base to the connected tip vortex that swept backward (Fig. 2). This

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Fig. 1 Visualization of a helical leading edge vortex in a hovering hawkmoth. The image also shows an increase in LEV size with distance from the base of the wing. Figure adapted from van den Berg and Ellington (1997b). The view is parallel to the wing chord.

corroborates the observations by Maxworthy, except that Ellington's single wing hovering motion could not simulate interaction with an opposing wing and thus did not recreate Maxworthy's connected root vortices. By observing smoke blobs released from the base of the wing, axial flow velocity at the middle of the wing was calculated as high as the mean velocity of the wing tip. This strong axial flow was proposed as the mechanism for maintaining the stability of LEV by bleeding energy out into the tip vortex. This similar conclusion was reached despite the order of magnitude increase in Reynolds number compared to Maxworthy's model.

While other researchers have similarly observed stable LEV structures attached to flapping wings, some have not noted the same prominent axial flow. For example, Bomphrey has questioned the role of axial flow in LEV stabilization using DPIV and smoke visualizations of a tethered hawkmoth (Bomphrey et al. 2005). The LEV was observed, but not in the helical form noted by Ellington. In fact, the LEV maintained relatively constant diameter across the entire leading edge and was continuous across the thorax (Fig. 2a). Axial flow components were not measured, but it was deduced that if axial velocity was present in the flow, it must have been 15% of the tip velocity. At this maximum value, it would be a significantly smaller percentage than the relative axial velocity found in delta-winged aircraft experiencing dynamic stall. Bomphrey suggests that the Strouhal number of the flight regime is such that vorticity does not build fast enough to be shed before the end of each stroke.

A wide variety of flapping insects have been similarly studied. Flow visualization performed by Srygley and Thomas of free flying red admiral butterflies (*Vanessa atalanta*, did not exhibit helical LEV structures, significant spanwise flow, or the increasing vortex size that is characteristic of a dynamic stall condition (Srygley and Thomas 2002). The LEV did not grow significantly throughout each stroke and was continuous across the thorax (Fig. 2b). This would likely not employ that technique during free hovering flight.

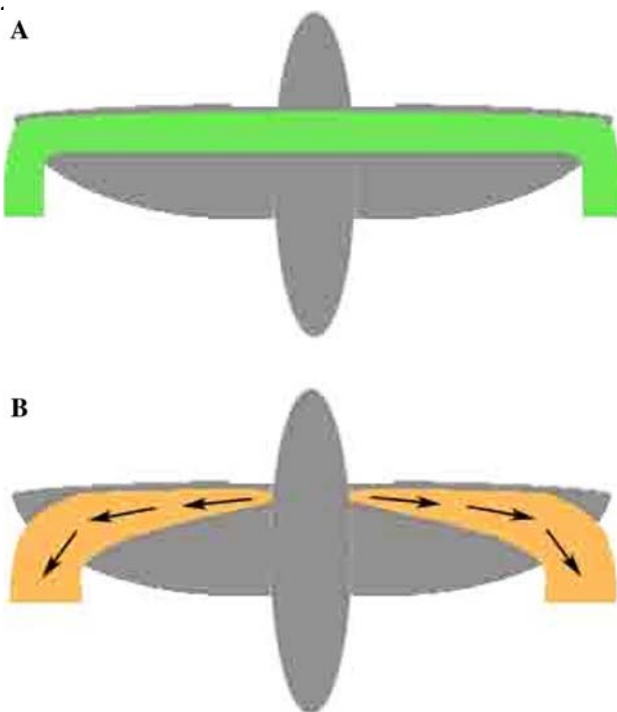


Fig. 2 Two possible LEV vortex structures proposed in literature. A Constant size LEV structure connecting to tip vortices and continuous between the two wings without any axial flow. B Helical LEV structure originating at the wing base with significant axial flow transporting vorticity away from the wing out into the tip vortices. The arrows show the spanwise flow inside the vortex tube

Additionally, lower Reynolds number studies by Birch aerodynamic flow structures during a hovering motion and Dickinson (2001) using a robotic model of the fruit fly along with the measurement of wall shear stress using hot-Drosophila did not indicate any significant axial flow, PIV anemometry will be used in this study. despite the presence of a stabilized LEV during down- Finding an effective tool for characterizing the unsteady strokes. They performed visualization of a flapping mode flow structures over a flapping wing is a vital step toward wing where teardrop-shaped fences were mounted parallel lift control for flapping or fixed-wing MAVs. If hot-PIV to the chord to block axial flow. These tests indicated that anemometry proves an accurate method for measuring bleeding vorticity from the wing tips at very low Reynolds separation bubble size and qualitative vortex strength, then numbers was not required to stabilize the LEV. To account manipulation of LEV characteristics will be within reach. for the vortex stability, they hypothesized that downwash Combined with an understanding of the natural phenomena from the tips vortices induced a decrease in effective angle utilized by flapping fliers to maintain their high lift per- of attack, which slowed the growth of LEV strength during formance and maneuverability, synthetic mechanisms translation. Similar to Bomphrey's later study, Birch and Dickinson could be developed for MAV improvement. For instance, if Dickinson concluded that the translational stroke was too spanwise flow was shown to be the primary stability brief compared to the shedding frequency and that the mechanism for LEV growth, then synthetic jets could be downwash from the tips was enough to prevent a critical used in conjunction with wall shear feedback to control buildup up vortex strength at low Reynolds numbers. these vital parameters of lift generation for flapping MAVs.

However, further study by Birch et al (2004) directly To present the research findings, the materials and investigated the differences between lower and higher methods will first be discussed in Sect. This includes an Reynolds number flapping regimes. Extensive DPIV analysis outline of the flapping mechanism, visualization system, ysis was performed for identical wings and kinematics wing characteristics, flapping kinematics, and the shear operating at Reynolds numbers of 120 and 1,400. The sensors. Results and discussion take place in Sect. study confirmed the lack of axial flow at lower Reynolds beginning with the shear stress variation during one wing numbers, but focused regions of significant axial flow beat cycle and visual confirmation of the hot-PIV ane- appeared at the LEV core for the higher Reynolds number mometry observations. Characteristics of the LEV are then The high Reynolds number visualizations indicated helical discussed including changes with flapping frequency and flow originating near the base of the wing with strong axial variation throughout a single stroke. An analytical model flow at the LEV core moving out toward the tip. The tip for LEV shear stress is also presented relative to the vortex became dominant behind the leading edge, and experimental results. Concluding remarks can be found in significant flow from tip to base was observed. The study Sect. 4.

did not replicate the fences used previously (Birch and Dickinson 2001), and it was not demonstrated whether the axial flow was necessary for LEV stability at the higher Reynolds number. 2 Materials and methods

Although unique in some ways due to their coupled 2.1 BIRDIE mechanism wing interactions, the unsteady flight mechanisms of dragonflies have also been studied extensively. Numerous response to the need to study the low Reynolds number, studies by Saharon and Luttges (1988), Thomas et al. unsteady, aeroelastic aerodynamics of flapping flight, a (2004) provide characterization of wing kinematics, LEV mechanism was developed called BIRDIE (Biologically structure, and potential stabilization methods for both free inspired low Reynolds Number Dynamic Imagery Experi- flying dragonflies and mechanical models of the dual wing ment) capable of producing a variety of flapping kinematics system. for investigation. The mechanism employs three indepen-

Overall, most research is in agreement that attached servomotors that can actuate a wing through 180 leading edge vorticity appears during maximum lift per-lateral motion, 90 of vertical motion, and 360 of rotation formance of flapping flight. The mechanism of LEV sta- about the wingspan axis. Existing models for the study of bilization is still a point of contention, but most likely some unsteady lift production include spinning wings that do not combination of axial flow, effective angle of attack, and capture the actual flapping (Altshuler et al 2004 Usher- shedding frequency allows the LEV to remain stable wood and Ellington 2002), systems that are constrained to throughout each downstroke. In order to study these specific frequencies (Saffman and Shephard 1977), or per- unsteady aerodynamic phenomena and their possible form in alternative fluids to reduce operation frequency applications to micro aerial vehicle (MAV) flight, a ver- (Birch and Dickinson 2001; Dickinson and Gtz 1993 satellite test bed has been built capable of mimicking hov- Maxworthy 1979). The BIRDIE mechanism can model ering flight of various natural fliers. Visualization of the nearly any complex flapping motion via three servomotors

providing three degrees of freedom. Flapping kinematics can also be changed without modifying parts of the mechanical system. Figure 3 shows the setup of the entire BIRDIE mechanism.

The BIRDIE setup consists of the visualization system, the test structure encased in polycarbonate to isolate the aerodynamics, the power delivery system for the motors and the actual flapping mechanism (Fig. 3). The polycarbonate box measures 1.0 m × 0.8 m × 0.8 m. The right image in Fig. 3 shows a close-up of the wing mechanism and the positioning of the servomotors on the support structure.

The wing mechanism (Fig. 4a) consists of three interconnected mechanisms (rotational, vertical, and horizontal), which can be independently operated. The horizontal gimbal is the largest part of the moving mechanism and rotates back and forth to create the horizontal motion (Fig. 4b). The vertical mechanism is mounted in the horizontal gimbal and can independently rotate the wing up and down (Fig. 4c). Finally, the rotational mechanism turns inside of the vertical gimbal to create rotation along the wingspan axis (Fig. 4d).

The horizontal gimbal provides lateral motion and structural support for the entire wing mechanism (Fig. 4). It has a direct connection to the horizontal motor using two spur gears (Fig. 5). The shaft supporting the mechanism stays in place using a collar and lock nut, and the two rotary bearings allow horizontal rotation while also securing the mechanism in the stationary support structure.

The vertical gimbal is supported by the horizontal mechanism and held in place by rotary bearings to provide smooth vertical rotation (Fig. 5). A control arm connects the vertical gimbal to the gear interface mounted above on the horizontal gimbal with a linear bearing. The vertical stays aligned when the mechanism is rotating horizontally. The motor drives the linear bearing up and down using a rack and pinion arrangement. This motion is transferred to the vertical gimbal through the control arm. Guides were placed on either side of the rack to ensure that the pinion

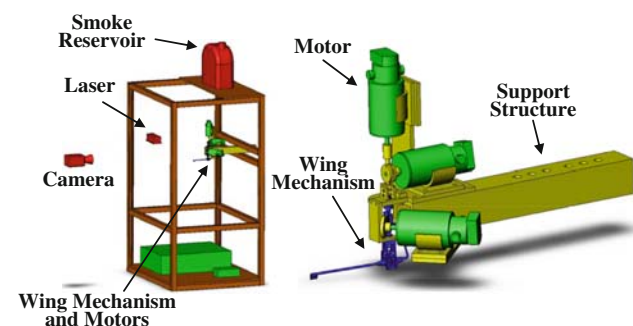


Fig. 3 CAD model of BIRDIE mechanism (left). Close-up of the wing mechanism (blue), support structure (yellow), and the motors (green) on the right

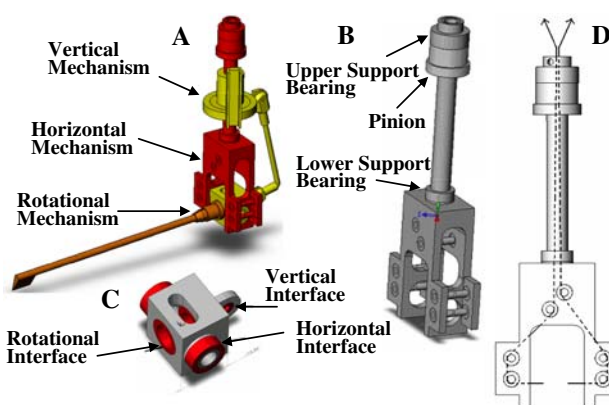


Fig. 4 The wing mechanism broken into the rotational (orange), vertical (yellow), and horizontal (red) mechanisms

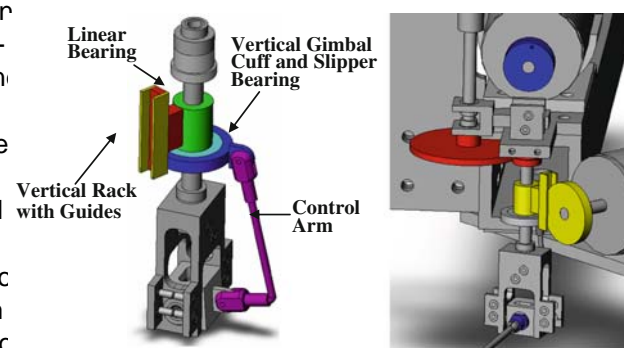


Fig. 5 Left Vertical and horizontal uncoupling mechanism with the control arm (purple), vertical gimbal cuff (dark blue), vertical rack (red) with guides (yellow), linear bearing (green), and slipper bearing (light blue). Right Wing mechanism and motor interfaces, the horizontal interface is shown in red, the vertical in yellow, and the rotational in blue

The slipper bearing provides horizontal freedom to the rack and pinion while the horizontal gimbal is in motion.

The rotary arm uses a Dremel collet and chuck system to allow quick interchange of wings. Cables pass through the horizontal and vertical gimbal and wrap around the rotary arm to produce motion by pulling the strings in either direction (Fig. 4d). The cable is guided through the horizontal gimbal by grooved rollers, and the ends are attached to the rotation motion motor for actuation. Cable was chosen to control wing rotation because it offers independent control with minimum complexity and weight.

This mechanism can independently rotate the wing while simultaneously moving the wing horizontally and vertically. The motor interfaces are highlighted in Fig. 5 (right). The rotational motion interface is shown in blue, with a cable connecting the pulley on the motor to the rotary arm. The yellow indicates the vertical motor interface driven by a rack and pinion. Finally, the horizontal motion is driven by two spur gears shown in red.

## 2.2 Visualization

To determine the geometry and stability of the LEV, suspended particle imagery (SPI) was employed using particulate oil smoke and high-speed videography. Smoke was delivered from a diffuser above the wing, creating a laminar stream of particulates across the test section.

As the wing passed through the smoke, a thin section of the wing was illuminated by a laser beam split with a beveled line-generating lens. For adequate power, an Aixiz Service and International AIX-532-1000 laser was used operating at a 532 nm wavelength and 1,000 mW. The lens chosen to reduce the complexities of the model and focus was an Edmond Optics line generator with a divergence of 15 to minimize variation of the laser sheet with distance. The hot-plate geometry sensor is mounted near the base of the wing. For the PS31ST Oil Based Smoke Generator provided very fine particles (0.2–0.3 micron diameter), high reflectivity and no residue on the wing. See Fig. 6 for an image of the test setup.

Images of the visualization were gathered using a Vision Research Phantom v4.3 color high-speed camera operating between 500 and 1,200 fps depending on the flapping frequency.

## 2.3 Model wing and kinematics

Although insects are the most common animals capable of hovering flight, hummingbirds may provide an improved basis for investigation into MAV design due to their size, maneuverability, and lift capabilities. However, to achieve a reproducible mechanism that loosely mimics hummingbird flight, some simplifications were used to create the model wing and its associated movement. The model wing is a simple rectangular shape shown in Fig. 7 with a span

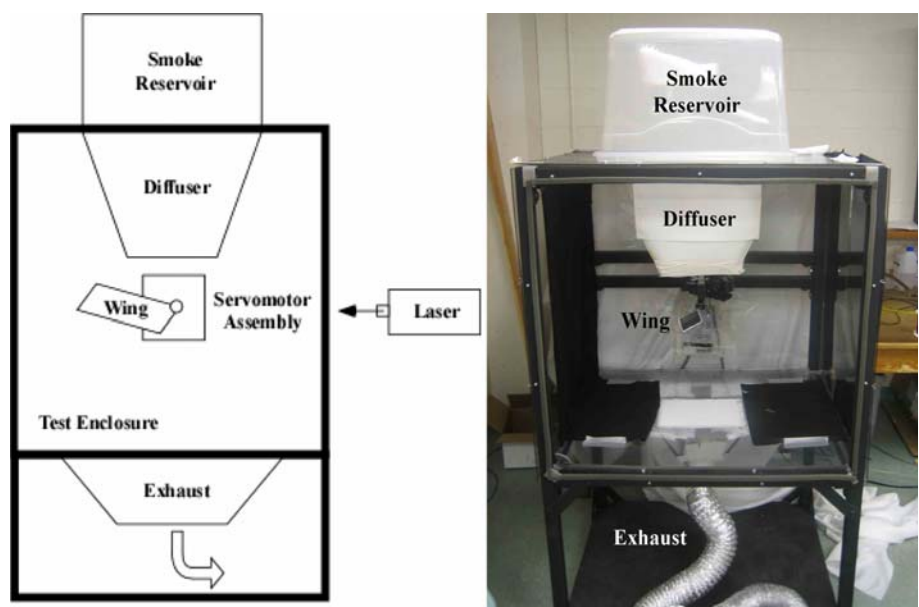
of 15 cm and a chord length of 4 cm. The aspect ratio was chosen according to the average wing dimensions of the suspended particle imagery (SPI) was employed using particulate oil smoke and high-speed videography. Smoke was delivered from a diffuser above the wing, creating a laminar stream of particulates across the test section.

made of a carbon fiber spar wrapped in bidirectional carbon fiber weave to produce a stiff yet light wing platform. The high stiffness was intended to reduce the possible effects of a wing tip deflection. Although wing twisting and tip deflection are utilized by free flying hummingbirds, especially during pitch and roll maneuvers, a stiff wing was used on LEV stability (Warrick et al. 2005). The hot-plate geometry sensor is mounted near the base of the wing. For the PS31ST Oil Based Smoke Generator provided very fine particles (0.2–0.3 micron diameter), high reflectivity and no residue on the wing. See Fig. 6 for an image of the test setup.

For simplicity, the mechanism was programmed so that the leading edge traced a basic figure eight shape if viewed in a plane perpendicular to the span axis. While not strictly a reproduction of hummingbird wing kinematics, the motion resembles the general hovering stroke parameters of most natural fliers.

The periodic figure eight motion was modeled using three sinusoidal functions where the vertical motion was twice the frequency of the horizontal and rotational motion (Fig. 8). The actual parameters of motion for the model were chosen based on a study of the wing kinematics of a hummingbird during hovering flight (Tobalske et al. 2007). The motion amplitudes used during testing were 10° horizontally, 20° vertically, and 70° rotationally about the wing axis. This provided a 20° geometric angle of attack during mid-downstroke, a stroke amplitude of 14° and a

Fig. 6 Visualization test setup. The reservoir above feeds smoke through the diffuser to the test section where the wing is located. Below the test section is a second diffuser with a low suction exhaust. The image is viewed from the same position as the high-speed camera, with the laser positioned on the right and aimed into the structure



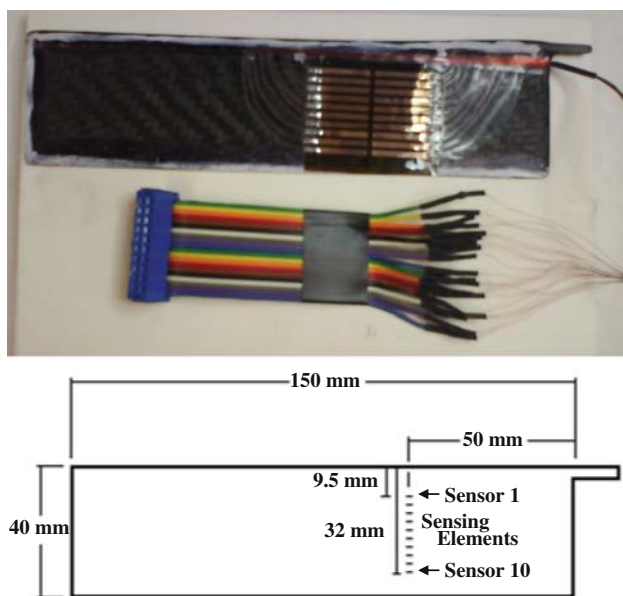


Fig. 7 *Top* Model wing with hot-film anemometer mounted at section of interested *Bottom* Diagram of wing with and location of primary chord section of interest. The section of interest is where all cross-sectional visualizations were located, as shown in the Sect.

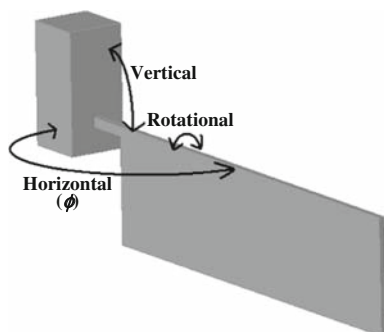


Fig. 8 Figure defining the rotations characterizing the motion

maximum stroke deviation of 20(Sane and Dickinson 2001). For analysis of the accuracy of the mechanism producing the proposed motion, see the work by Vanier (2008).

For hovering flight in three dimensions, using the wing tip as the reference and accounting for both the span and the cord, the Reynolds number is defined as (Shyy et al. 2008):

$$Re_3 = \frac{\phi f R^2}{\nu} \left( \frac{4}{AR} \right), \quad (1)$$

where  $\phi$  is the amplitude of the horizontal wing motion in radians (see Fig. 8),  $f$  is the frequency,  $R$  is the wing length,  $\nu$  is the kinematic viscosity,  $AR$  is the aspect ratio, where  $AR = (2R)^2/S$ , and  $S$  is the total surface area of the wings, Fig. 9.

and the subscript 3 represents the Reynolds number for a 3D flapping wing in hovering flight. For this study, Reynolds numbers ranged from ~1,000 to 5,100, or very nearly 1,000 times the experimental flapping frequency.

## 2.4 Wall shear sensors

To provide feedback that can assist in the control of flapping flight, a sensor was selected capable of characterizing the aerodynamic flow structures over the wing. Hot-film anemometry provides a light but sensitive means of determining the size of the leading edge separation bubble through estimation of flow reattachment along the wing chord. Monitoring the evolution of the separation bubble and wall shear provides insight into lift production and therefore could enable flight control.

### 2.4.1 Hot-film calibration

The preliminary focus of the hot-film sensors is to detect LEV existence and any variation in the flow reattachment point; therefore, an absolute calibration is not necessary. A relative calibration of the sensors is adequate because the voltage signal from the circuit directly relates to the flow conditions. The calibration was performed by subjecting the sensors to a reference flow and then normalizing the subsequent voltage responses. All sensors are normalized relative to one reference sensor, in our case hot-film sensor number 1. This ensures a similar response of each sensor, accounting for the differences in each element and the components in each constant temperature circuit. These voltages can then be used to determine the wall shear stress at any location relative to the reference hot-film sensor.

In order to generate consistent flow conditions for a normalization of the elements, a small tube provided a steady flow velocity. With the wing and sensor array secured on a platform, slides were placed to allow smooth platform movement along a fixed path. The tube was then positioned with an adjustable vice so that its exit aimed along the sensor array with a shallow angle, just a few millimeters off the wing surface.

The activated sensor array was guided under the tube at a constant velocity, the data were logged, and the procedure repeated while alternating between the front and rear sensors entering the calibration flow first. A sample result of the sensor output voltage during the calibration process is shown in Fig. 9.

Once the output spikes are captured, the baseline voltage response (with no applied airflow) is subtracted from the signal to obtain the pure response. The values are then plotted against the 10th sensor response to determine a relative scaling factor using a linear regression shown in Fig. 9.

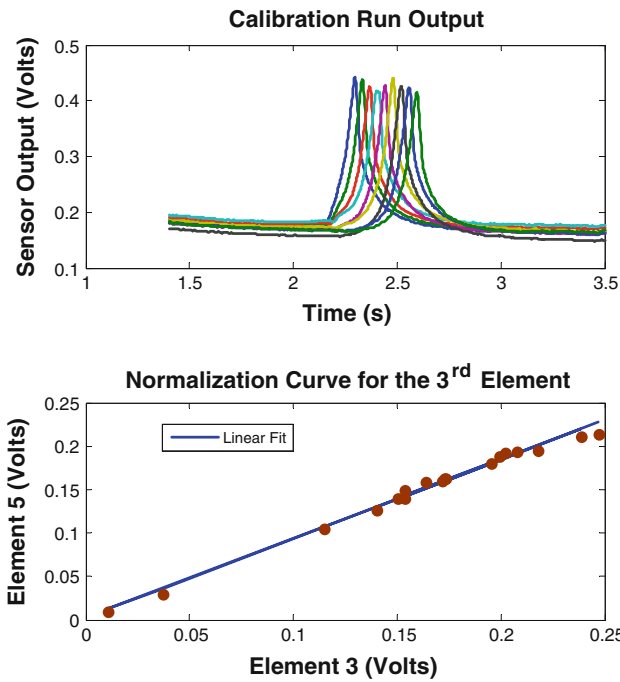


Fig. 9 *Top* Calibration run, each signal spikes as it passes under the tube, which are then used to normalize their response. The first spike corresponds to the first element, with the last element at the end. *Bottom* Normalization curve for the third element to the fifth element

The linear fit of each element was used to normalize each signal relative to the fifth element. The normalization takes the form:

$$V_{5,i} = \alpha_i + \beta_i V_i, \tag{2}$$

where  $i$  represents the element that it is being normalized (ranging from one to ten), the five indicates the element that it is being normalized to,  $\alpha$  is the offset, and  $\beta$  is the slope of the normalization. For the first element and normalizes it to the fifth element, which ensures that all elements are behaving similarly. The modified King's law is typically used to calibrate the voltage response of a constant temperature anemometer circuit to the wall shear stress (Tavoula [2005](#)).

$$\frac{V^2}{T_w - T_f} = A + B\tau_w^{1/3}, \tag{3}$$

where  $V$  is the voltage output of the circuit,  $T_w$  is the temperature of the sensor,  $T_f$  is the temperature of the fluid, and  $A$  and  $B$  are coefficients established during the calibration. The offset voltage that is removed for acquisition purposes is added back into the voltages so that the modified King's law can be used properly. The modified King's law is rearranged, and the normalized voltage can be substituted in to give the normalized shear stress as:

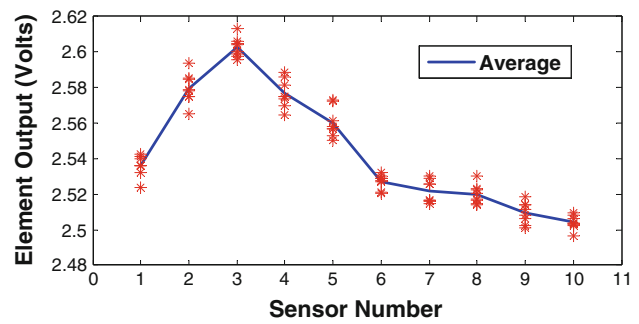


Fig. 10 A graph of the sensor voltage measurements during seven different stroke periods at 25% of the cycle. The x-axis indicates the sensor position, and the solid line shows the average voltage output over the cycles

$$\tau_{5,i}^{1/3} = \gamma_5 + \delta_5 V_{5,i}^2, \tag{4}$$

where  $\gamma$  and  $\delta$  are unknown coefficients that are specific for each sensor. By factoring out  $\tau_0$  and using the voltage signal with no flow the ratio of  $\delta$  and  $\gamma$  can be found as:

$$\frac{\gamma_5}{\delta_5} = -V_0^2 \tag{5}$$

Equation 4 is then referenced to values for the shear stress and voltage of the fifth sensor. The final equation is shown below.

$$\tau_{5,i} = \left( \frac{V_{5,i}^2 - V_0^2}{E_0^2 - V_0^2} \right)^3 \tag{6}$$

$E_0$  and  $\tau_0$  are the reference voltage and shear stress. For the full derivation see the work by Vanier [2008](#).

#### 2.4.2 Post processing

The data gathered during experimentation are passed through a 125 Hz low pass filter to eliminate high frequency noise. To remove other signal variations, the voltage outputs from seven full periods are averaged together. This produces a mean signal representing the general response for a particular wing beat frequency. Figure 10 shows a curve of the averaged response for a 4 Hz motion midway through the downstroke. The data points indicate the individual voltages measured during each period. The averaged signal is then converted to a relative shear stress profile using the calibration results.

### 3 Results and discussion

#### 3.1 Shear sensor signal evolution

A quick comparison of wall shear stress on the top and bottom wing surfaces indicates that some transient

phenomenon occurs over the top of the wing through each begins to decrease as the wing decelerates and the vortex downstroke (Fig.11). During the half-cycle with the sensor begins to separate with wing rotation. As the wing moves on top of the wing, a large increase in shear stress is observed, which disappears as the wing decelerates at the end of the stroke. This is likely due to formation of the wall shear stress on the bottom of the wing increases with LEV, since trapped vorticity above the wing would locally augment the shear stress. Figure 11 shows the signal evolution of the six sensors closest to the leading edge (numbers 1-6) during one full cycle at a frequency of 4 Hz. The last four sensors did not diverge significantly from the behavior of sensor 6, so they were removed for clarity.

The stroke cycle starts at point A, which is labeled on the lower figure at its position and on the upper figure at its corresponding time. The start of the top stroke occurs when the wing moves from point A to point B. The top stroke is defined as the stroke with the sensor array on the top face of the wing. Once the wing accelerates through the top stroke, a large change in shear stress is observed as the wing moves rapidly across the top of the wing. Sensors 2, 3, and 4 report especially sharp increases in shear stress as leading edge vorticity builds and accelerates the fluid above the wing, and the sensors near the leading edge observe up to five times the stress of the rear sensors. This localized effect indicates the growth in circulation of the LEV, and as a result, increased lift production would be expected during this section of the stroke. This enhanced lift is confirmed by results from Dickinson et al. (1999). The shear stress holds through point C, where the wing starts to rotate in expectation of the bottom stroke, and then stress

3.2 Verification of LEV detection  
Using visualization of the flow during wing translation, the relative shear stress results and conclusions can be validated. Figure 12 shows sensor output and corresponding visualizations for the top stroke in the middle of the translational section. The visualizations have the corresponding signal overlaid at the appropriate position above the wing. There is a large signal spike located around the vortex followed by a rapid decrease past the reattachment point. The small dips following the large spikes could indicate a proximity to the reattachment point, where the shear stress is zero. See Sect. 6 for a representation of the expected wall shear stress over the wing.

### 3.3 LEV changes with frequency

To determine the behavior of the flow structures at various stroke velocities, the location of the LEV was monitored at a fixed cycle position while increasing the wingbeat frequency. This information was intended to shed light on the stability of the vortex, critical flapping frequencies, and optimal Reynolds number regimes.

Using the baseline kinematics described earlier, visualizations were collected at frequencies starting at 1 Hz and increasing to 5.5 Hz at intervals of 0.5 Hz. This corresponds to Reynolds numbers of about 1,000-5,100. The section in question was along the chord at 1/3 the half-span from the base (Fig.7). Figure 13 shows the flow structures at half way through the downstroke for increasing frequencies. This is the position of greatest vertical and horizontal velocities with a maximum effective angle of attack.

The first two images of 1 and 2 Hz indicate that the LEV does not stabilize at low frequencies. When LEV stability is not attained, the vortices caused by leading edge separation are shed back along the chord. The periodic

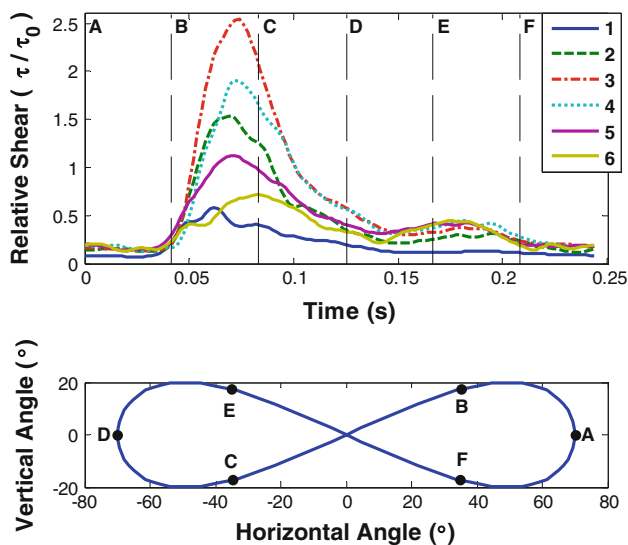
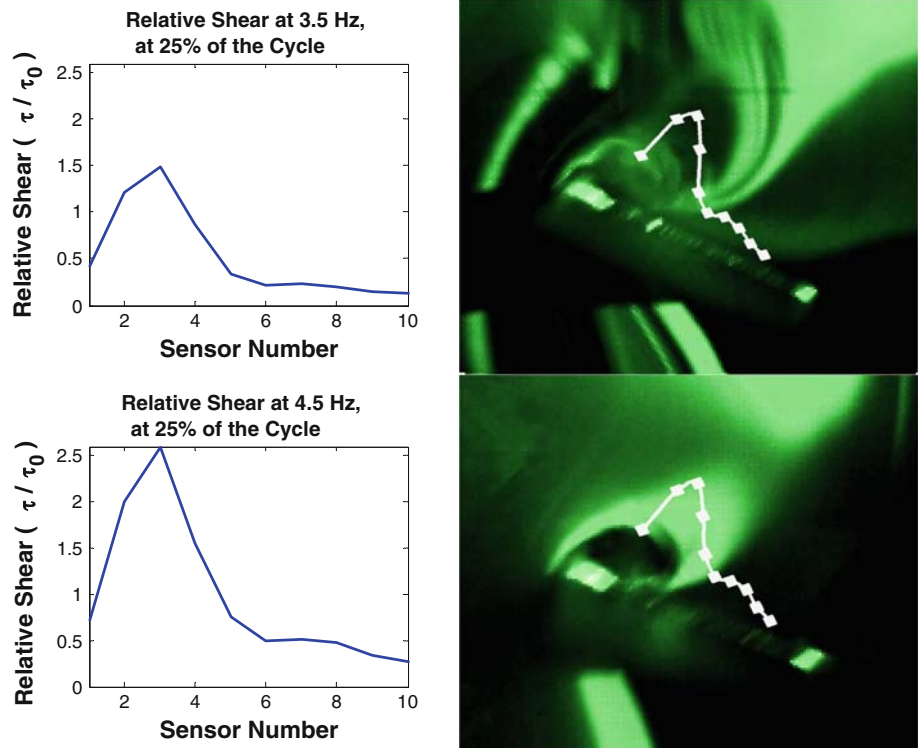


Fig. 11 Top Relative shear stress for hot-Ptm sensors 1-6 vs. time over a full flapping cycle at a flapping frequency of 4 Hz. Bottom Shows marked points during the flapping cycle. Points A and D represent the beginning and ending of the top stroke, respectively



Fig. 12 Sensor output and smoke visualization with signal overlay at the middle of the top stroke at 3.5 Hz (top) and at 4.5 Hz (bottom)



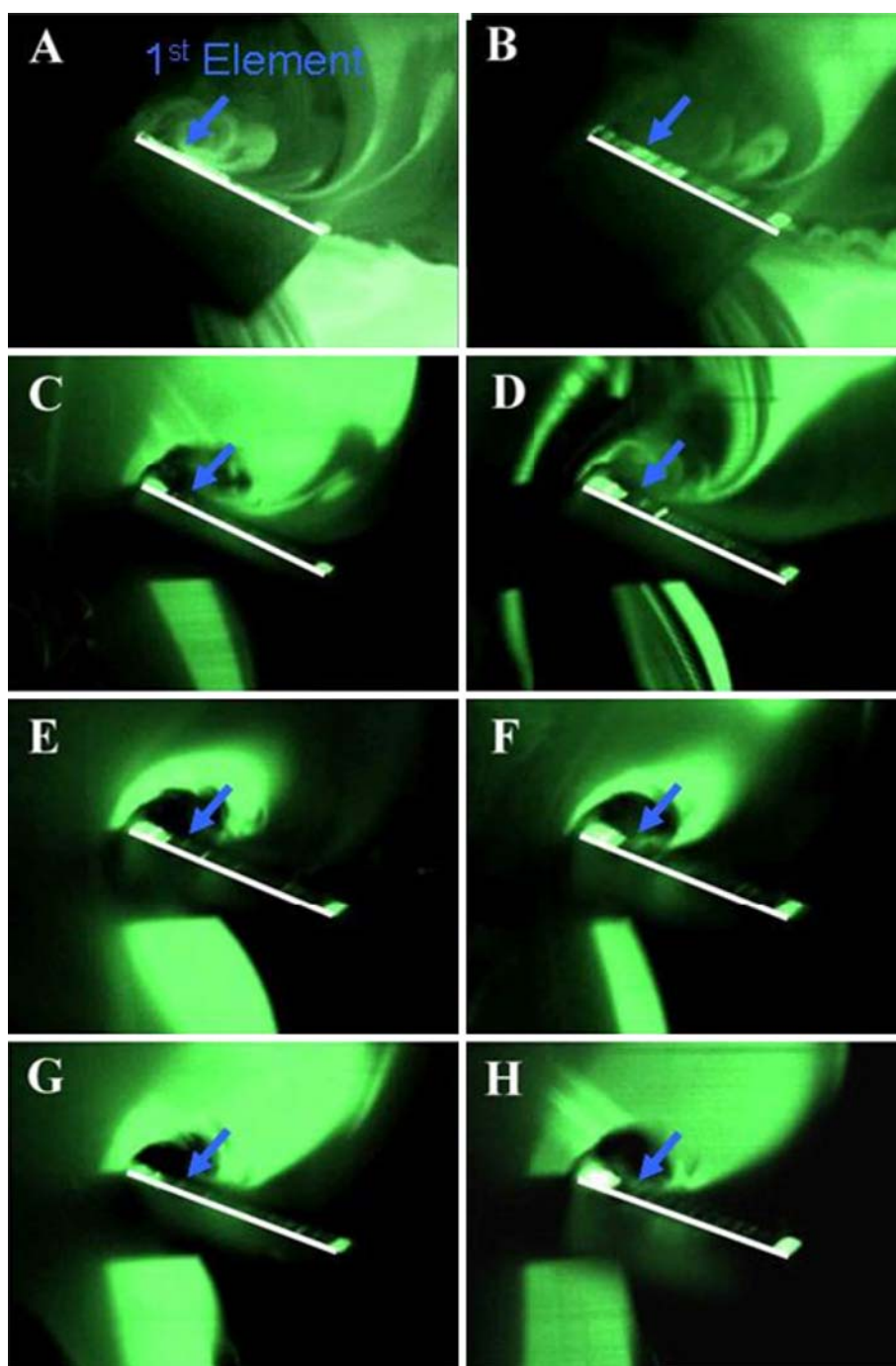
shedding of the leading edge vorticity results in an averaged chaotic region above the entire wing. At 3 Hz, vortex shedding begins to stabilize at the leading edge, but the structure appears disrupted along the outside of the vortex core. This instability indicates that the LEV is not completely stable and still likely to shed or be disrupted later in the stroke period. However, at 3.5 Hz, a clear LEV structure is present with far less instability around the vortex core. As frequency increases, this instability is diminished and a consistent leading edge structure appears and remains stable on the leading edge.

Figure 14 shows resulting sensor signals at 25% of the cycle for each frequency. As the frequency of the motion increases, the peaks in the shear stress increase in magnitude but remain near the same relative position. The increase in signal strength suggests that the vortex strength increases with higher flapping frequency, which is to be expected. The peaks of the signals are constant within the spatial resolution of the sensors, so the vortex location stays within  $\pm 0.063$  chord lengths for these frequencies.

Interestingly, the maximum normalized shear increases with frequency until it peaks at 4.5 Hz, at which point the trend collapses with decreased normalized shear for 5 and 6 Hz. It is difficult to confidently characterize this behavior of the LEV without higher resolution shear measurements or more complex flow visualization. However, this trend should be investigated further and may provide insight into the interaction and effectiveness of flapping flight parameters.

Interestingly, while there is an evolution of LEV stability with increasing frequency, the size of the LEV does not appear to change noticeably between the frequencies tested. Since the wing path is unchanged, a two-dimensional analysis would hypothesize increasing vorticity and augmented LEV size at higher wing speeds. However, the uniform size seems to support the existence of a mechanically stable and still likely to shed or be disrupted later in a dynamic stall condition and maintaining the LEV size.

Fig. 13 Visualization of the LEV at the middle of the downstroke (position D on Fig. 16) with increasing frequencies: 1 Hz,  $Re \sim 920$  (a), 2 Hz,  $Re \sim 1,850$  (b), 3 Hz,  $Re \sim 2,770$  (c), 3.5 Hz,  $Re \sim 3,230$  (d), 4 Hz,  $Re \sim 3,690$  (e), 4.5 Hz,  $Re \sim 4,150$  (f), 5 Hz,  $Re \sim 4,610$  (g), 5.5 Hz,  $Re \sim 5,070$  (h). The wing has been highlighted with a white line for easy recognition. LEV structure begins to stabilize at about 3 Hz, and then there is no significant change in vortex size through 5.5 Hz. The blue arrow shows the location of the first hot-Plm element



### 3.4 LEV growth during translation

To characterize the transient nature of the LEV, the evolution of the shear stress over the wing was observed throughout the top stroke for a 4 Hz flapping motion. Specifically, the intent was to monitor any growth and indicate some disturbances in the LEV during formation of the reattachment point during the translation. A two-dimensional analysis predicted that vorticity to build during the entire downstroke, leading to growth of the separation bubble until it sheds off the backwing of the wing. Figure 16 shows the specific positions of the stroke cycle that were monitored for the 4 Hz frequency. Visualization of the motion at designated positions is shown in Fig. 16. The first two images are near the beginning of the translational section (position B and C). Specifically, the intent was to monitor any growth and indicate some disturbances in the LEV during formation of the reattachment point during the translation. This may be due to wake interactions with vorticity shed during the transition from supination to translation. A two-dimensional analysis predicted that vorticity to build during the entire downstroke, leading to growth of the separation bubble until it sheds off the backwing experiments (van den Berg and Ellington 1997a, b).

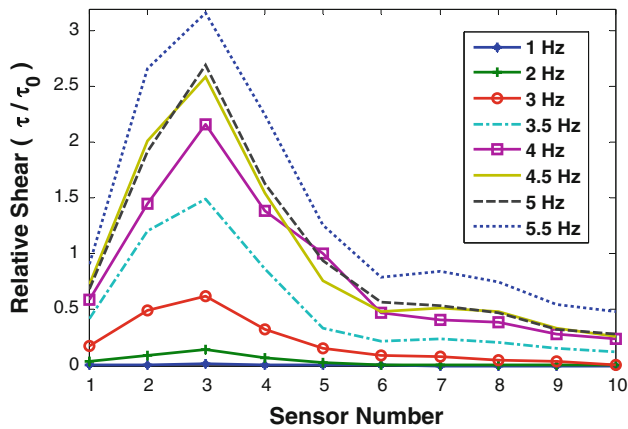


Fig. 14 Relative shear stress along the chord for various frequencies at 25% of the cycle

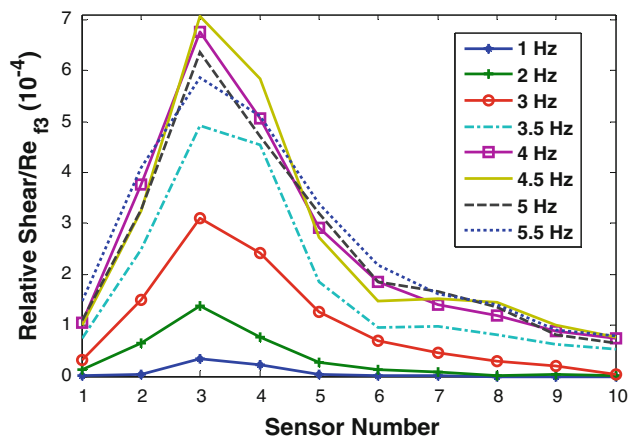


Fig. 15 Relative shear stress at different frequencies divided by the corresponding Reynolds number at 30% of the cycle

Once the LEV stabilizes, it appears to grow slightly during the translation downward. This is most clearly seen by movement of the reattachment point along the chord. The first images show reattachment at about one-third of the chord, while this reattachment has moved nearly past the half-chord position by the end of translation. While experimental error results in some discrepancies, all visualizations indicate a gradual yet perceptible increase in vortex size throughout each downstroke. This corresponds to a slight growth in trapped vorticity between the start and end of the wing translation associated with a dynamic stall condition.

Figure 17 shows the relative shear stress measured through the stroke at the positions indicated in Fig. 1. Location A shows the beginning of the down stroke. The wall shear stress on the wing does not show significant variation along the wing, indicating that the flow is still attached to the wing. At location B, however, the shear stress along the chord becomes disrupted, likely indicating that the flow has begun to separate from the leading edge. The

indication of LEV formation appears near location C where the wall shear stress shows a spike at the leading edge of the wing. This would be caused by trapped vorticity speeding up the flow and locally augmenting the shear. Strength of the LEV is proportional to the magnitude of wall shear stress, and the size of the LEV can be assessed by the number of sensors registering a significant disturbance. Therefore, the plots in Fig. 17 indicate an increase in strength and slight growth of the LEV between points C and F. In Fig. 1, the max strength of the LEV occurs at 30% of the cycle, and F is positioned at 31% of the cycle. Wang et al. (2004) measured the forces created by a generic hovering motion using an airfoil. Lift production of a symmetric motion was calculated from experimental and computational studies, indicating that maximum lift was near 30% of the cycle. This closely agrees with our estimated location of maximum LEV strength, which is expected since trapped vorticity greatly augments lift generation (Shyy et al. 2008). From point F toward the end of the down stroke the wing's velocity and angle of attack decreases. This corresponds to a decrease in the LEV strength. The final shedding of the LEV is associated with the drop in the magnitude of the detected wall shear stress near point K. The regularity of the signal pattern along with the corresponding visualization indicates successful detection of an attached LEV through the majority of the top stroke.

### 3.5 LEV wall shear stress model

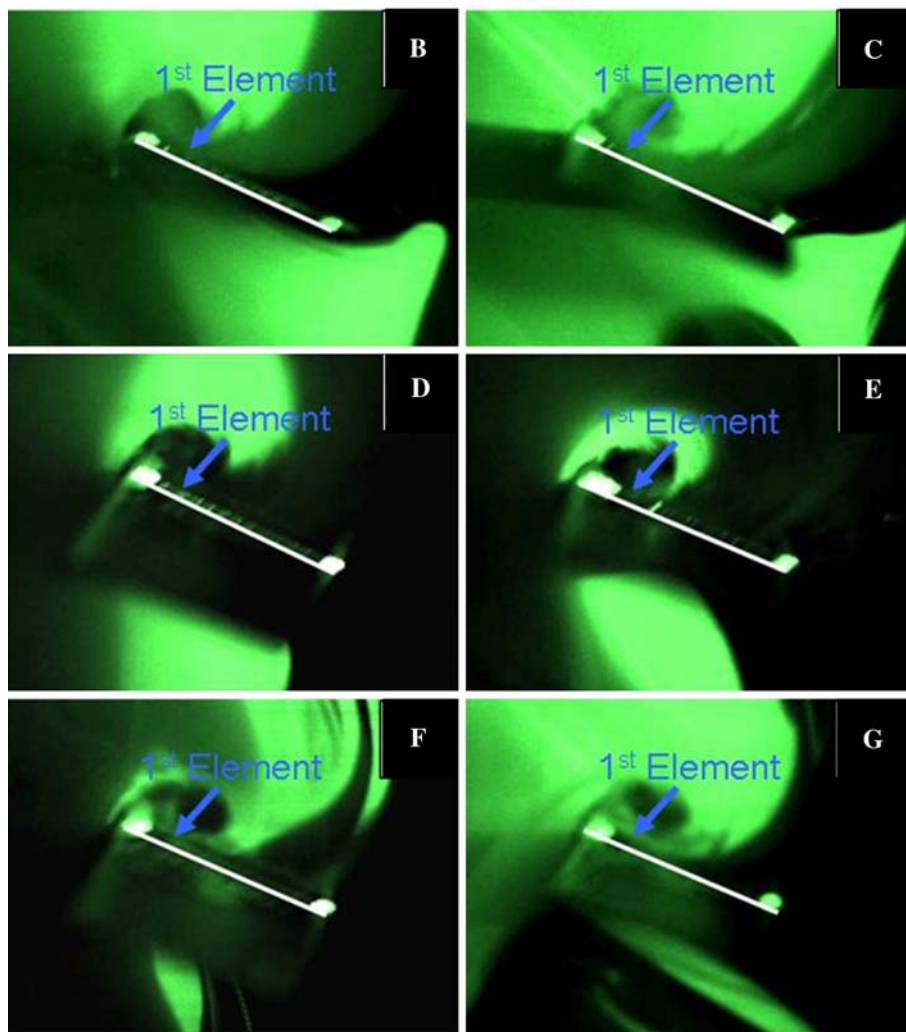
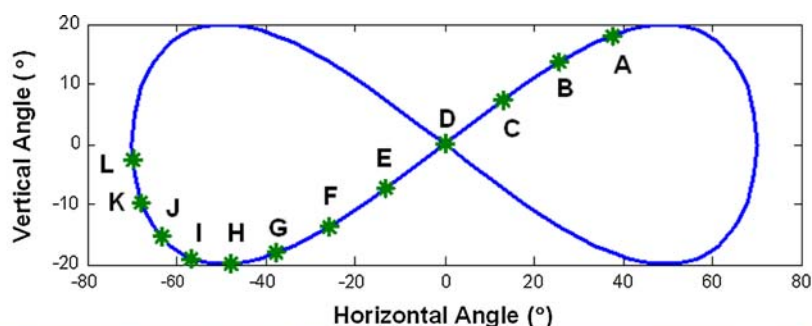
The reattachment point of the LEV can be a very useful piece of information when trying to control the trapped vorticity. Because there is a forced separation point at the leading edge of the wing, the reattachment point establishes the size and position of the separation bubble. This information can be coupled with the magnitude of the wall shear stresses to provide insight into the size, strength, and stability of the LEV. To develop a model for estimating the reattachment point using hot-film sensors, the instantaneous wall shear stress was observed from direct numerical simulation of a typical flow around a low Reynolds number airfoil (Sahin et al. 2008). Figure 18 shows an instantaneous vorticity field for flow over an Eppler 387 airfoil (Sahin et al. 2008). The box at the top represents the vortex that is being considered in the bottom of the figure.

The bottom of Fig. 18 is a plot of the instantaneous coefficient of friction over the wing, where the coefficient of friction is simply the non-dimensional wall shear stress and their relationship is seen as:

$$\tau = \frac{C_f}{1/2\rho U_\infty^2}$$

where  $C_f$  is the coefficient of friction and  $\rho$  is the density of the fluid.

Fig. 16 *Top* Positions for sequenced shear stress plots over time, these points correspond to 16.49% of the cycle in 3% increments. *Bottom* Flow visualization at 4 Hz ( $Re \sim 4,000$ ) starting at the top of the translational section and moving downward. Letters correspond roughly to the positions indicated in the top figure. The bottom of the wing has been highlighted in white for easy visibility



There are two attachment points of the vortex, both of stress distribution, and the absolute value of the wall shear which occur where the coefficient of friction is zero. In stress. This last graph should mimic the data gathered from between the two attachment points, there is a large negative value of the hot-film sensors because they do not register flow value as the vortex causes the flow at the wall to move in the opposite direction of the external flow velocity. Following Inside of the separation bubble, the flow near the wing the last attachment point, the friction value is positive as the flow will be traveling in the opposite direction of the external flow over the wing is traveling in the same direction as the flow, resulting in a negative shear stress value. Toward the external flow. This behavior was used to create a model for edges of the separation bubble the shear stress decreases, the reattachment point over the flapping wing. until it reaches zero. Outside of the separation bubble, the flow is traveling in the same direction as the external flow, and the shear stress is positive. The reattachment point is

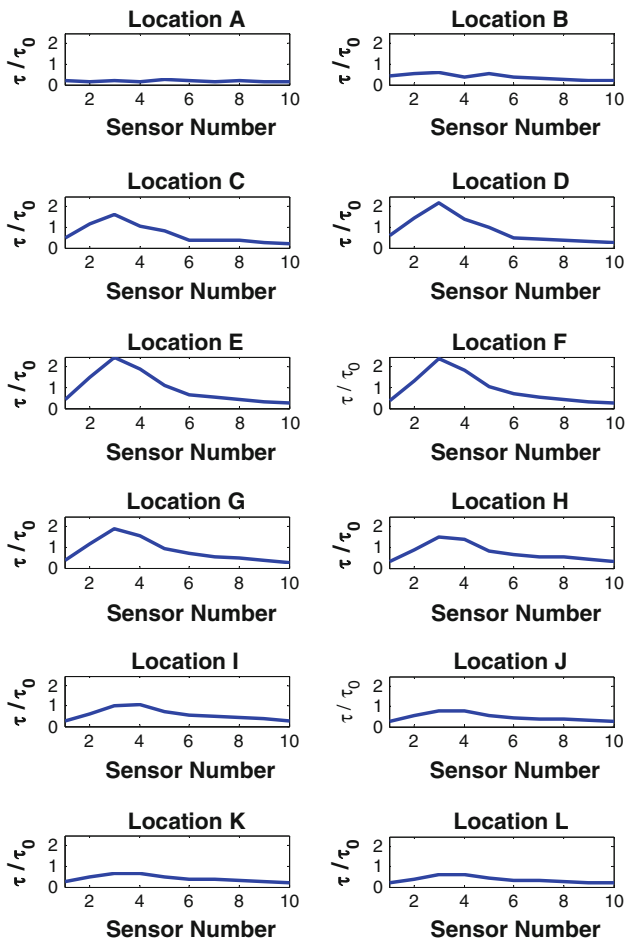


Fig. 17 Relative shear stress distribution for 4 Hz at specific sensor positions

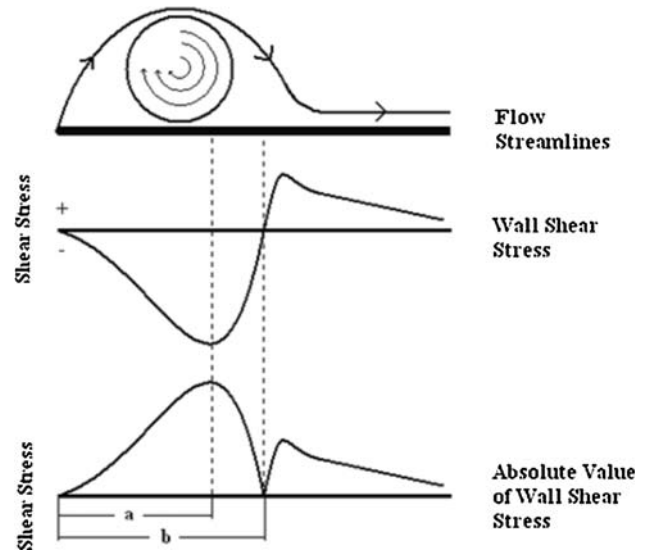
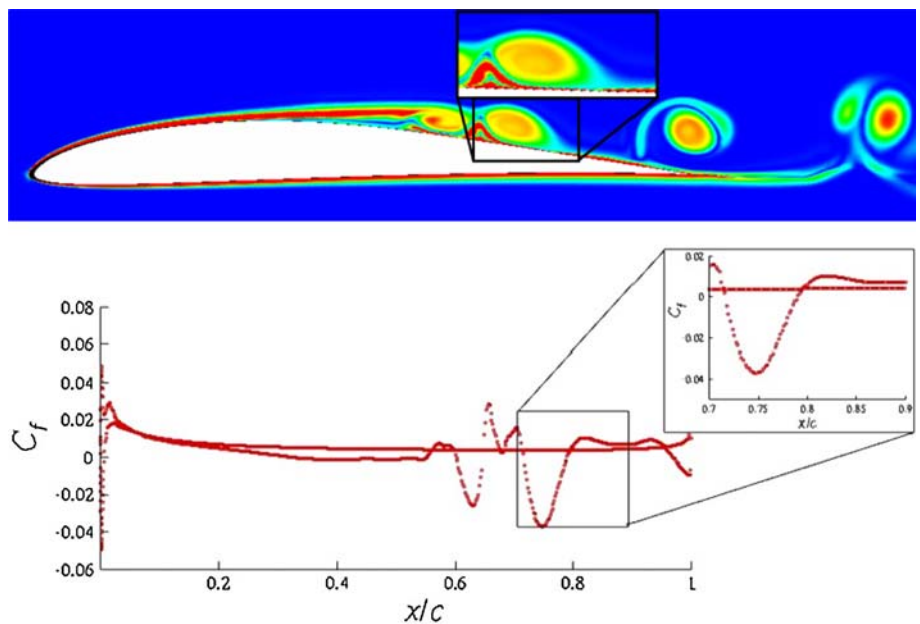


Fig. 19 Schematics of the LEV and wall shear stress. *Top*: typical streamlines. *Middle*: wall shear stress distribution. *Bottom*: absolute value of wall shear stress

located where the shear stress changes from a negative to a positive value. The maximum shear is located slightly aft of the center of the vortex. Because the sensors cannot differentiate the direction of the flow, both a positive and negative shear stress would look the same, as in the last image. The large peak at position a, is quite noticeable in the signal during the top stroke; however, the reattachment point at b is much harder to detect. This is due to the low spatial resolution of hot-film sensors relative to the short chord length of the wing. The simple model used here in

Fig. 18 *Top* Instantaneous vorticity field for a separated flow over an EPPLER 387 airfoil at a Reynolds number of  $\sim 60,000$  at an angle of attack of  $6^\circ$ . Figure compliments of Sahin et al. (2008). *Bottom* Instantaneous friction coefficient over airfoil depicted in Fig. 22. Figure adapted from Sahin et al. (2008)



order to determine the reattachment point assumes that the ratio of  $a$  and  $b$  is constant regardless of the vortex size.

This ratio was determined experimentally by analyzing flow visualizations with a visible reattachment point and comparing them with the measured shear distribution. The peak point in the signal was determined and then compared with the adjacent sensor reading. The maximum value of the parabolic curve is then taken as  $a$ . Comparing with the reattachment position in the visualization, the ratio  $b/a$  was calculated to be 1.22. Because this type of analysis is particularly sensitive to the signal and noise level, a linear regression was plotted to each signal to show the trend of reattachment behavior. The calculated reattachment points are plotted in Fig. 20. Despite increasing stroke frequency and wing velocity against non-dimensional time, which is time divided by the flapping frequency of the associated data. The graph indicates removing vorticity and inhibiting shedding of the LEV. It indicates slightly increasing trends in vortex size through the translational stroke for all frequencies. Although precise qualitative observations of these growth rates may require more refined measurement of the reattachment point, the evolving shear distribution consistently demonstrates an increasing trend in LEV size for all testing frequencies during translation. The growth of the LEV supports the hypothesis that a dynamic stall condition exists with flapping motion. The max strength of the vortex is attached vorticity is building during translation but never reaches the critical strength to shed from the trailing edge with the location of the maximum lift at 29% found by Wang et al. (2004) when looking at a generic hovering and is associated with significant increase in lift production for a brief time (Shyy et al. 2008). Dynamic stall conditions are known to appear when wings travel at high angles of attack but vorticity is still bound to the top of the wing (Shyy et al. 2008). While this gives insight into the behavior of the trapped vorticity, the source of the LEV stability is still in question.

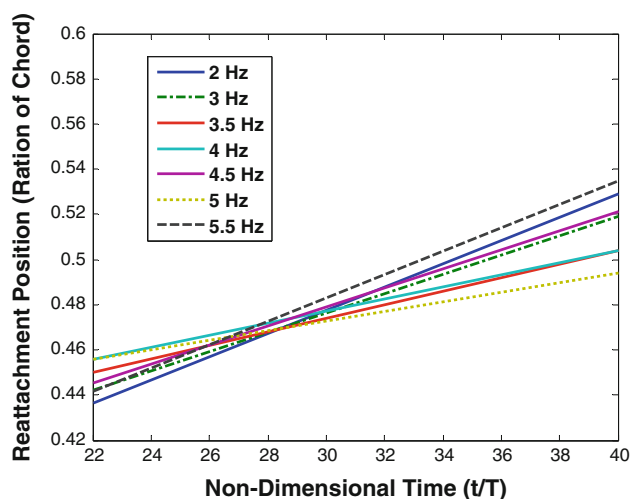


Fig. 20 Modest growth trends in LEV size during each downstroke. The location of the reattachment point during the translational part of the top stroke for frequencies 2, 3, 3.5, 4, 4.5, and 5 Hz

By validating the ability to predict separation bubble size and maximum vortex strength, hot-P1m anemometry proves to be a potential tool for LEV control and lift optimization of flapping MAVs. The translational section of the stroke cycle is thought to produce the majority of lift for MAV-sized animals (Warrick et al. 2005), so aerodynamic feedback during this section would be extremely useful for flight control. Coupled with an improved understanding of wing rotation characteristics, control of this complicated flight regime may be possible.

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