Unsteady Flow Features of a Flapping and Pitching Wing at Low Reynolds Number

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The unsteady flow field of a flapping-and-pitching flat plate wing of elliptic planform at a nominal Reynolds number, \( \text{Re}_c = 4100 \) and reduced frequency, \( k = 0.138 \), was studied using flow visualization. Hydrogen bubbles and dye were employed as tracers. The study reveals many vortical flow features. The trailing edge vortex shows very interesting dynamics immediately following pitching at stroke reversal. A leeward surface spanwise flow towards the wing tip immediately following stroke reversal is observed. A vortex trapping model is proposed to explain enhanced lift observed in insects. The study has applications in flow control and micro air vehicle design and development.

I. Introduction

Interest in flapping flight has picked up lately due to the potential for new modes of flight that incorporate features of insect aerodynamics. Better understanding of insect aerodynamics is expected to contribute to improvements in the design and performance of small scale machines such as micro air vehicles. Dickinson’s work\(^1\) on a fruit fly model revealed many interesting features of a flapping and pitching wing. The work of Freymuth\(^2\), Gopalkrishnan et al\(^3\), and Streitlin et al\(^4\) represent other relevant work in this area. This paper is part of an ongoing study on the unsteady flow field of a flapping and pitching wing at low Reynolds numbers. The large body of work available in the literature covering various aspects of insect flight has been reviewed in our previous work\(^5,6\). Previous work by many investigators include experiments on live animals as well as model studies. Our flow simulation\(^5\) and experimental\(^6\) studies have led us to propose some interesting aspects of a flapping and pitching wing at low Reynolds numbers. In addition to Reynolds number scaling, reduced frequency scaling was emphasized as a factor that should be considered in analyzing insect flight. We also suggested a kinematic scheme for leading edge/trailing edge switching to enable using cambered airfoils. Our experimental work appears to support the above suggestions. More work to systematically examine these concepts and cover a large parameter space is necessary to firmly establish the proposed ideas.

II. Experimental Approach

Hydrogen bubble flow visualization is a well-established method that is suitable for imaging large regions of the flow. The bubbles released at the edges of the flapping and pitching wing follow the pathlines in the flow to form streaklines. In an unsteady flow, the streaklines do not coincide with the instantaneous streamlines. Bubble inertia is a factor that may cause a skewed representation of the unsteady flow field. Bubble buoyancy may also contribute to the distorted representation. Flow visualization using dye injection is also commonly employed in fluid dynamics research. Most of the limitations of the hydrogen bubble technique are also present in dye injection. In spite of the above drawbacks, these methods can be successfully used to study unsteady flows by carefully choosing the flow regimes and designing the experiments to minimize the above effects.

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The present experiments were conducted in a water tank. The flapping mechanism is driven by a DC motor and the pitching is done by a servomotor. The overall experimental set up is shown in Fig. 1. Figure 2 shows the motion profile, and the control and data acquisition arrangement. The present experiments do not have the force transducer shown in Fig. 2, and the force data acquisition is inactive. However, the overall dimensions of the set up in the previous study\textsuperscript{6} have been retained to facilitate comparison of the results.

The 75 mm x 150 mm, semi-elliptic planform wing was made from a 2.1 mm thick Lucite sheet. For the hydrogen bubble experiments, the wing was painted flat black to reduce light reflection. A 50 \( \mu \)m diameter platinum wire was mounted along the edges of the wing using epoxy. A 30V DC power supply was used to produce hydrogen bubbles by electrolysis. A graphite rod was used for anode. Naturally occurring minerals in the filtered city water was sufficient for electrolysis. The hydrogen bubbles are estimated to be 25 \( \mu \)m in diameter. For a different set of experiments using dye injection, a separate wing was constructed. Red and green McCormick’s food coloring was injected through hypodermic tubing mounted along the edges, on either side of the wing. The injection port was 60 mm from the wing base. The dye/water/ethyl alcohol mixture was prepared in the ratio 12:120:3 for

Figure 1. Schematic diagram illustrating flapping-and-pitching wing. The wheel is driven by a DC motor. An encoder mounted on the motor shaft sends its Index pulse for synchronizing the flapping and pitching motions. Pitching (rotation about the spanwise axis) is done by the servomotor.
optimum visibility, mixture density, and extended usage before changing the water to keep image quality at an acceptable level. Using dyes of different colors enabled simultaneously imaging the windward and leeward sides of the wing. Dye flow rates were controlled using pressurized bottles. von Ellenrieder et al.\textsuperscript{7} have discussed the importance of adjusting dye flow rate such that no jet or wake structure is formed due to dye injection. The flow was illuminated with a microscope light with two fiber optic light guides. Images in the hydrogen bubble experiment were obtained with a megapixel monochrome digital camera operating at varying rates, up to a maximum of 30 frames/s. The end views were obtained by using a first surface mirror as mounted in Fig. 1. Video clips of the dye experiments were obtained using a digital camcorder.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Left: wing motion profile. Right: Wing motion control and data acquisition flow diagram.}
\end{figure}

### III. Results and Discussion

#### A. Non-Dimensional Parameters

Two important non-dimensional parameters, chord Reynolds number ($Re_c$) and reduced frequency ($k$), can be used to study performance of a flapping wing. The mean translation speed at the wing midspan is given by

$$\bar{U} = 2l_{\alpha} f$$  \hfill (1)

The non-dimensional parameters can be expressed in terms of the root chord length, $c$, the distance from the pivot point to the wing midspan, $l_c$, and the stroke angle, $\psi$, as follows:\textsuperscript{6}

$$Reynolds\ number:\quad Re_c = \frac{\bar{U} c}{\nu} = \frac{2l_{\alpha} f c}{\nu}$$ \hfill (2)

$$Reduced\ frequency:\quad k = \frac{f c}{\bar{U}} = \frac{c}{2l_{\alpha} f}$$ \hfill (3)

Note that the wing beat frequency, $f$, does not appear explicitly in Eq. (3) for the reduced frequency. For a given wing assembly, it varies inversely as the stroke angle, and $Re_c$ is proportional to the product of stroke angle and the beat frequency. The wing was flapped at a frequency, $f = 0.115$ Hz. The corresponding Reynolds number based on root chord and average velocity at midspan, $Re_c = 4100$, and the corresponding reduced frequency, $k = 0.138$. Two values of the angle-of-attack, $30^\circ$ and $45^\circ$, were used in the present set of experiments. In some cases the images were acquired at a rate of 15 frames/s, thus, for those cases, consecutively numbered frames are separated by a 67 ms interval. The interval between frames was increased in some cases to cover a larger segment of the flap cycle.

#### B. Flow Visualization

Figure 3 (a and b) shows 8 frames in end view for $\alpha = 30^\circ$ for different orientations of the wing during pitching at the left end of the stroke. Frame 00, captured just before stroke reversal, shows the leading edge vortex that is stronger towards the wing root. Frame 02 is also before pitching begins at stroke reversal. The features are similar to
those in Frame 00. Frame 04 shows features that have developed during pitching. The two vortices at the two edges created by wing rotation can be clearly seen. In Frame 05, the structure has changed significantly from Frame 04. Vortex A (Fig. 4) has acquired a more three-dimensional structure. Vortex B (Fig. 4) appears to have dissipated almost completely, since it is hardly visible and has moved down. In Frames 06, 08, and 10 Vortex A gradually moves outward and away from the wing. At the same time a leading edge vortex can be seen to form even though the leeward side of the wing is hidden from view.

Figure 3a. $\alpha = 30^\circ$. The above 4 frames and those in Fig. 3b show the wing during pitching. Pitching is in the counter-clockwise direction.
Figure 5 shows one frame from a front view acquisition at the same conditions as in Fig. 3. The lines formed by hydrogen bubbles ejected from both edges during pitching can be seen.

Figure 6 shows frames from the angle view acquisition indicated in Fig. 1. Conditions are the same as in Fig. 3. The chosen frames illustrate a vortex from the windward side ejected from the midspan region during pitching. Also visible is a tip vortex.

A series of 16 frames with the camera in angle view (Fig. 1) when the wing was at the left end of the stroke was acquired and analyzed. The windward side was towards the camera. Two vortices were seen to detach from the two edges of the wing and stayed as line vortices for quite some time after detachment. An interesting
observation is the fate of the trailing edge vortex from the previous stroke. It rolled up as a result of the spanwise flow into a three-dimensional structure. It is worth noting that there was a weak vortex near the wing tip, quite different from the strong tip vortex on a steadily translating wing. As the wing pitched at the stroke extremity, this tip vortex weakened further, diffused and disappeared.

Video clips from the dye injection experiments show several interesting features. Since the Reynolds number is an order of magnitude greater than in von Ellerieder et al.\textsuperscript{7}, the dye diffuses much faster, and long filaments are not formed. Therefore, flow structures only in the vicinity of dye injection are visible. A very interesting part of the cycle is when the wing undergoes pitching, and the leading edge and trailing edge switch roles. In the first set of videos, only red dye is introduced at the edge that becomes leading after pitching. The injection point is on the leeward side of the wing. In most of the videos, it can be seen that initially the dye forms a straight filament nearly aligned with the chord at the injection point, but immediately following this, the leeward side filament near the injection point is stretched towards the wing tip rather quickly (Fig. 7). This is followed by a segment in which the dye diffuses too fast to form a filament. In a second series of experiments, red and green dye were introduced at the edge on either side of the wing. The injection points were very close to each other. No significant stretching of the green filament on the windward side near the injection point was observed. It appears that the stretching of the dye filament on the leeward surface towards the wing tip is caused by the formation and spanwise motion of the leading edge vortex towards the wing tip. It is not clear if the spanwise motion is due to the leading edge having a slight sweep angle because of the elliptic planform shape. Experiments with other planform shapes will be helpful in establishing the cause of this spanwise flow.

C. Vortex Trapping Model

Unsteady flow interacting with a moving surface such as the present can be studied as vortex interaction with a solid surface. Rockwell’s\textsuperscript{8} review covers studies of parallel, streamwise and perpendicular vortices interacting with a surface such as the leading edge of an airfoil. These two-dimensional interactions provide a means to calculate the unsteady forces induced on the surface by the vortex, and the subsequent distortion of the vortex itself. Considering how rapidly the vortices diffuse\textsuperscript{6}, a simple model that includes only one vortex in the interaction might be sufficient to account for most of the effects. The flow physics underlying the two previously proposed concepts\textsuperscript{5,6}, LE/TE switching and frequency tuning, can both be understood in terms of vortex-body interactions considered in our earlier work. The schematic in Fig. 8 would help explain the underlying phenomena. Towards the end of the down stroke, a trailing edge vortex (TEV) forms as shown at left. At stroke reversal, the leading and trailing edges switch roles, and the previously formed TEV having the counter-clockwise sense is now at the leading edge, resulting in an increment in the force, $\Delta F_{TEV}$. Note that the vortex interaction in Fig. 8 is the parallel type\textsuperscript{3}. Gopalkrishnan et al.\textsuperscript{3} and Streitlien et al.\textsuperscript{3} have shown that propulsive efficiency of a foil moving in the wake of a Karman street is dependent on the distance from the body producing the vortex street and the proximity of the foil’s encounter with the vortices in the street, determined by the phase angle of the foil motion. It is not clear if the interaction shown in Fig. 8 is the same type as in the above two studies because of the alternating sense of rotation of their vortices the foil sees in the Karman street. As in the experiments of Gopalkrishnan et al.\textsuperscript{3}, the vortices in the wake decay fast in the present case. LE/TE switching can, therefore, be seen to be helpful in exploiting the TEV from the previous half
stroke (TEV<sub>ds</sub>, Fig. 8) at the optimum instant in its evolution. This description of the vortex-foil interaction suggests methods for flow control. It will be possible to implement passive control by using data from phase-locked flow visualization and digital particle image velocimetry (DPIV). Velocity vector- and vorticity-field data from DPIV images can be used to quantify the forces created during the vortex-surface interaction. It should be noted that the kinematic scheme shown in Fig. 8 is equally applicable for cambered plate airfoils.

IV. Conclusion

Flow visualization results from a flapping-and-pitching wing flow field has been presented and the results discussed. A few interesting features of the vortex dynamics has been observed. The trailing edge vortex was observed to roll up into a three-dimensional structure and eject from the surface at stroke reversal. A leeward surface spanwise flow was present immediately following stroke reversal. Further study is needed to determine if this
spanwise flow towards the wing tip is due to the leading edge sweep of the semi-elliptic planform wing or due to other reasons. Using results from our present and previous work, a vortex trapping model is proposed to explain enhanced force generation in insect flight. At the Reynolds number of the experiments, an overall picture of the flow field could not be constructed, limiting the observations to localized regions such as in the immediate vicinity of the dye injection point. Obtaining a better picture of the overall flow field will be possible by conducting the experiments at lower Reynolds numbers. The experiments are presently being modified to improve the techniques and the results will be reported in future work. DPIV studies are also in progress.

**Figure 7.** Red and green dye streaklines from dye injection at the leading edge on the windward (green) and leeward (red) sides. Images extracted from video recording. Viewing in movie mode gives a much better means of visualizing the evolution of the streaklines.

**Figure 8.** A vortex trapping model for lift augmentation due to the trailing edge vortex (TEV) from the previous half stroke.

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