Force Measurements on a Flapping and Pitching Wing at Low Reynolds Numbers

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Force measurements from experiments conducted in water on a flapping-and-pitching thin flat plate wing of semi-elliptic planform at low Reynolds numbers are reported. Time varying force data, measured using a force transducer, provide a means to understand the mechanisms that lead to enhanced performance observed in insect flight compared to fixed wing aerodynamics. Experimental uncertainties associated with low level (~1N) fluid dynamic force measurements on flapping-and-pitching wings are addressed. A previously proposed pitching mode in which the leading edge and trailing edge switch roles to allow using cambered airfoils has been shown to be viable, and may have advantages over the non-switching mode. The present data are part of a larger database planned to experimentally investigate various aspects of insect flight including another previously proposed idea that performance may be improved by flying at optimum reduced flapping frequency. The study has applications in micro air vehicle development.

I. Introduction

Investigation of low Reynolds number flapping wings has picked up momentum lately because of the potential applications in micro air vehicles. The authors and their co-investigators studied two such candidate vehicles for planetary exploration and terrestrial applications, and the results have been reported [1,2]. These studies emphasized the vehicle as a system from the point of view of its payload, aerodynamics, materials, propulsion, control, navigation, and communication. The studies concluded that flapping wing aerodynamics have many desirable features such as providing thrust and lift forces from the same source, and the ability to integrate all the subsystems into a solid state aircraft. These studies also concluded that vehicle development will require further research on the subsystems. The present work is a continuation of the above efforts to better understand insect flight mechanisms and incorporate their desirable features into micro air vehicle development.

Insects generate thrust and lift by controlling wing kinematics that include flapping and pitching during the stroke cycle. Other mechanisms such as camber control, wing flexure, fore-wing-hind-wing coordination, and variation of stroke plane inclination have also been observed. Insect aerodynamics have been investigated largely by two groups, biologists and aerodynamicists. Reviews by Weis-Fogh and Jenson [3], Maxworthy [4], Ellington [5], Spedding [6], Dickinson [7], Mueller and DeLaurier [8], and Wang [9] cover flapping flight aerodynamics from various angles. Nachtigall [10] has discussed the various aspects of insect flight based on his work on live insects using high speed photography. Childress [11] approaches bio fluid dynamics from a mathematical perspective. Azuma [12] has compiled the work of various investigators and provided rudimentary analytical tools for adapting insect flight features into engineering design. There exists a large body of experimental work on insect aerodynamics; though they provide good qualitative descriptions, because of the difficulties associated with doing experiments on small live animals, the reported quantitative results are often incomplete, and have large experimental error bands.

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Some insects execute the “clap-and-fling” mechanism (Weis-Fogh mechanism) during the wing beat cycle. Insects that execute this mechanism start the stroke cycle with the wing surfaces in contact with each other. The beat cycle starts with the wing leading edges moving apart as if the wings were hinged at the trailing edges. After reaching the maximum angular displacement, the two wings separate at the trailing edges, change the sense of rotation and linear motion, and come together with the leading edges coming in contact first. A motion, in reverse to the fling motion is executed with the leading edges forming the hinge. The wings then rotate about the leading edge hinge in a clapping motion to complete the cycle. Weis-Fogh [13] and Lighthill [14] modeled the corresponding aerodynamics in terms of bound vortices using inviscid theory. Lighthill also applied a correction factor for viscous effects. Even though their model satisfied the Kelvin-Helmholtz theorem, according to which the circulation should remain zero, Weis-Fogh pointed out that the effect is not the common Magnus effect since the lift produced during the fling is in the opposite sense to that would be created by the Magnus effect. Other unsteady mechanisms are suggested for the creation of circulation of the right sense. At the Reynolds numbers of interest (Re ~ 1000), inviscid theories have limitations. Later, Maxworthy [15] performed experiments to explain the Weis-Fogh mechanism in terms of the interaction of the leading edge vortices as the wings fling apart.

Not all insects execute the clap-and-fling motion described above. Dickinson and Gotz [16], Dickinson [17,18], Dickinson et al. [19], Sane and Dickinson [20] and Birch and Dickinson [21] examined various aspects of wing kinematics and proposed the “delayed-stall-rotational-lift-wake-capture” mechanism to explain lift generation during all phases of the wing beat cycle. They investigated the effects of wing rotation on unsteady aerodynamic performance using a flat plate airfoil geometrically scaled in wing planform, and dynamically scaled to the Reynolds number of fruit flies (Drosophila). Sane and Dickinson [20] estimated wing inertia effects by replacing the wing with a brass knob and assuming that negligible fluid dynamic forces will be exerted on the brass knob. Wang et al. [21] compared flapping and pitching wing experiments to two-dimensional plunging and pitching airfoil simulations and made qualitative comparisons.

Vest and Katz [23] investigated wing motion in pitch and heave using unsteady, three-dimensional potential flow model. Comparisons to limited experimental data showed agreement within the error bounds of the experiments. Guglielmo and Selig [24] and Gopalarathnam and Selig [25] investigated profile drag and inverse design methods for low Reynolds number airfoils. To provide basic steady state aerodynamic characteristics, experimental investigation of low-Reynolds number, low-aspect ratio flat-plate wings have been recently conducted by Torres and Mueller [26]. Four Planform shapes were considered. Lift, drag and pitching moment characteristics were compared. In another similar study, Sunada, et al. [27] compared low-Reynolds number data from 20 wings of different airfoil shapes. Effects of camber, leading edge profile and surface corrugation are reported. Laitone [28] has reported that the lift coefficient at low Reynolds numbers can be increased by using sharp leading edges. Vortical signatures of heaving and pitching airfoils were investigated by Freymuth [29] who observed a reverse Karman vortex street that resulted in thrust production. Experiments were done using a plunging and pitching NACA 0015 airfoil in a wind tunnel. Results are given for Re_c = 5,200 and 12,000 and reduced frequency, k = 2.7 and 2.9, respectively. The authors noted that the vortex street was not entirely laminar. Tuncer and Platzer [30], and Lai and Platzer [31] studied a plunging airfoil in a free stream (Re_c = 500-50,000) flow. Reduced frequencies for thrust-producing conditions were identified. Sunada et al. [32] reported on experiments on a plunging and pitching wing at Reynolds number, Re_c = 1000 and reduced frequency, k = 0.35, which correspond to the hovering flight of a dragonfly. A nearly rectangular wing with an aspect ratio of 5 and thickness ratio, t/c = 0.05 was used.

Spedding et al. [33] investigated the vortex wakes generated by birds in level flight and deduced the generated forces from the wake structure. Warrick et al. [34] recently reported on hovering hummingbird flow field data using digital particle image velocimetry (DPIV). Milano and Gharib [35] recently reported on plunging-and-pitching wing force and DPIV data. A rectangular flat plate wing with an aspect ratio of 6 was used. Force balance and DPIV were used for lift and flow field measurements, respectively. Trajectories that maximized average lift over 4

Figure 1. Coordinate systems used to describe wing motion. The pitch axis, y, sweeps in the XY plane of the inertial XYZ system, while the wing pitches about the y-axis of the wing-fixed xyz system.
cycles were searched for using Genetic Algorithm (GA).

Most of the flapping wing experimental studies with models and numerical simulations assume a rigid wing. However, wing flexure is another important parameter that must be considered in analyzing wing characteristics. Combes and Daniel [36] investigated the relative importance of inertial-elastic forces and aerodynamic forces in hawkmoth wing deformation, and suggested that inertial-elastic forces may exert a greater influence compared to aerodynamic forces. Real hawkmoth wings were tested in air and helium.

Several computational fluid dynamics (CFD) studies of insect flight have recently appeared. Wang [37] presented computation simulation results of a plunging airfoil in an incoming uniform flow. Most of the three-dimensional simulations dealt with rigid body motion of the wing in pitch (about the y-axis, Fig. 1) and sweep (about the Z-axis), mimicking the two important motions of an insect wing. To avoid grid generation complexities, flat-plate wings were used. Ramamurti and Sandberg [38] conducted numerical simulation of insect flight and compared their results with experiments of Dickinson et al. [19]. They used the Euler equations, while Emblemsvag et al. [39] and Sun and Tang [40] utilized the laminar Navier-Stokes equations. Almost all of them used structured grid, with some using Cartesian grid to simplify dynamic gridding necessary to accommodate rigid body motion. All used a flat plate airfoil with the planform shape resembling the fruit fly wing. Emblemsvag et al. [39] used a fruit fly model wing about 3.7 times thicker than the one used in the experiments, which had a thickness to chord ratio of approximately 2.5%. The computations revealed that wing thickness plays an important role in the magnitude of the lift force and the force peaks. Sun and Tang [40] used a 12% thick wing with an elliptic airfoil section due to limitations of the numerical scheme to handle sharper edges and thinner airfoils. Both Sun and Tang [40] and Emblemsvag et al. [39] reported lift coefficients significantly lower than from experiments [19]. One reason for the lower predicted $C_L$ values [39, 40] may be due to not using the same thickness as in the experiments.

Triantafyllou et al. [41] have shown that optimal thrust producing conditions occur at non-dimensional frequencies that favor maximum spatial growth of vortices in the wake. Anderson et al. [42] conducted a systematic investigation of thrust producing mechanisms of harmonically oscillating foils in a steady free stream flow by flow visualization at $Re = 1100$, and by force measurements at $Re = 40,000$. Angle-of-attack, plunging amplitude, frequency and phase angle between plunging and pitching were varied. Koochesfahani’s [43] work on NACA 0012 airfoil also examined the vortical pattern in the wake, and thrust generation, when oscillations by pitching the airfoil about the quarter chord point were imposed. Visbal and Shang [44] did numerical computations of a pitching NACA 0015 airfoil. The basic vortical structure of their studies agreed with experimental flow visualization for chord-based Reynolds number, $Re_c = 45,000$. Maxworthy [15], Willmott et al. [45], Van den Berg and Ellington [46, 47] and Liu et al. [48] have proposed that the leading edge vortex (LEV) on three-dimensional wings might be stabilized by spanwise flow and cause the LEV to spiral out towards the wing tip.

### II. Two-Dimensional Simulation Results

In our previous work [49], time-accurate, unsteady simulation results were analyzed and the phase relations of the leading edge and trailing edge vortex (LEV/TEV) dynamics to cyclical lift variation were established. The results show the fixed wing undergoing a high-lift phase during each lift cycle. At moderately high $\alpha$, the LEV dominates, and at higher $\alpha$ the LEV and TEV are equally dominant. The Strouhal number for all the cases considered was close to that of the Karman vortex shedding. It is interesting to note that the lift curve from our work is very similar to that of Claupeau et al. [50]. These observations led us to propose that, by matching the reduced beat frequency of biomimetic wing that incorporate wing kinematics to the Strouhal number of Karman vortex shedding, the wing can avoid operating in the low lift phase, explaining, at least in part, the high lift associated with insect flight. Analysis of flight data of a large number of insects [51, 52] showed that their reduced beat frequencies indeed lie in a narrow band close to the Strouhal number of Karman vortex shedding.

In order to establish the phase relationship between the $C_L$ variation and the dynamics of the LEV/TEV, results from one case are presented in Figs. 2 and 3. The corresponding chord-Reynolds number, $Re_c = 2040$ and the angle-of-attack, $\alpha = 29.4^\circ$. The $C_L$ curve spans slightly more than one cycle with a period, $\tau \approx 0.3$ s. A Strouhal number calculated using the frequency, $f (\equiv 1/\tau)$, the chord length, $c$ and the free stream velocity, $U_\infty$, is given by the expression, $St = fc/U_\infty$. 

\[ St = \frac{fc}{U_\infty} \]
Several important flow features can be discerned from these results. At this high angle-of-attack, the wing generates large amount of lift, indicating that extrapolation of high Re results would be erroneous, especially the catastrophic stall pattern of conventional high Re airfoils is not observed in the present cases. The other feature is the large amplitude of the \( c_l \) oscillations with time. The frequency and amplitude of the lift and drag variations depend on the angle-of-attack and Re.

Figure 2. Lift coefficient (left) and vorticity contours (right). Simulation results for a cambered plate airfoil.

Figure 3. The numbers on the \( c_l \) curve, Fig. 2, correspond to the eight pressure contour frames, captured sequentially at eight instants during the lift cycle. Frames 2 and 10 have been omitted to conserve space.

Lift and drag coefficient variations for two values of \( \alpha \) (44.2° and 29.4°) and five values of free stream velocity ranging from 1.4 m/s (Re = 510) to 14 m/s (Re = 5100) were plotted and analyzed [49]. This set of \( c_l \) and \( c_d \) plots reveals several interesting characteristics of low-Re, high angle-of-attack aerodynamics. The plots (not reproduced here) show that there are distinct frequencies associated with each case, and both the lift and drag variations have fairly large amplitudes. The salient features have been summarized in Table 1. The Strouhal number has been calculated in two ways, one based on the chord

<table>
<thead>
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<th>Table 1. Strouhal Number from Simulations</th>
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<tr>
<td>Reynolds number</td>
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<tr>
<td>Angle-of-attack (deg)</td>
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<tr>
<td>Strouhal number ([SI]), A</td>
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<td>Strouhal number ([SI]), B</td>
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length (A) and the other based on the projected length normal to the free stream (B). These results indicate that, for all these cases, the flow is dominated by the formation and shedding of the leading edge and trailing edge vortices (LEV/TEV). The LEV forms at the leading edge, stays attached to the top surface and grows as it convects downstream. During this phase, the airfoil has a high $c_l$ value, and then it drops as the vortex detaches from the surface, leading to the low $c_l$ phase of the cycle. The low $c_l$ phase continues during the formation, growth and detachment of the TEV. The $c_d$ variation has a phase difference of approximately 180° from the $c_l$ variation. From the summary results, several useful design guidelines can be drawn. Over the Reynolds number range considered, the Strouhal number based on the chord length (2nd row from the bottom, Table 1) stays close to 0.22, the established value for Karman vortex shedding in bluff body flows at low Reynolds numbers [53]. Another important observation is that the cases in the above Reynolds number range do not yield a steady state solution, indicating that such a solution will violate the flow physics. A similar observation has also been made by Kunz and Kroo [54], and several others. Note that, for the Reynolds number range of this study, the flow cannot be approximated as being dominated by viscous forces, a valid assumption for $Re_c < 1$, nor can it be approximated as being dominated by inertia forces, a common assumption for $Re_c > 1$. For this reason, analytical results are not available in the literature for this flow regime [55].

If the wing stroke reduced frequency were to match the Strouhal number, the low $c_l$ phase can be avoided, and the airfoil can always stay in the high $c_l$ phase. In a practical design, this would require establishing the relationship between the flow velocity and the frequency of the LEV/TEV dynamics, so that, by choosing appropriate stroke cycle frequency, the wing would operate in the high $c_l$ mode during the entire cycle. The present results suggest that the ability to have variable beat frequency depending on flight conditions to improve performance should be a design goal. Formulating control laws that take into account the above effects should, therefore, be part of designs based on this concept.

### III. Experiments

![Figure 4. Left: Schematic diagram illustrating flapping and plunging wings. 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, and for acquiring data from the force transducer. Pitching (rotation about the spanwise axis) is done by mounting a servo motor below the fixed pivot shown at left. The servomotor-force transducer-attachment rod assembly is the same for the flapping wing on the left and the plunging wing on the right.](image-url)
Schematic diagrams of the present flapping mechanism, and the plunging mechanism to be used in future experiments are shown in Fig. 4. Figure 5 shows the down stroke and up stroke motion profiles and a flow diagram for servo motion control and data acquisition. Figure 6 shows the DC motor-encoder-wheel arrangement and the timing diagram for servo control. The timing of the servo actuation and the force transducer signal acquisition are controlled by National Instruments LabView software. The data acquisition (DAQ) board and a timer board are installed in the same computer. The cranking mechanism is adjusted such that the encoder Index pulse occurs when the wing is at the left-most position \((\xi = -\psi / 2)\). A typical sequence starts with powering up the DC motor to crank the wheel, Fig. 4. The LabView data acquisition is then initiated, which begins when the encoder Index pulse, generated once every revolution of the motor shaft, is received. With the encoder Index pulse as the time reference, LabView generates a pulse of appropriate delay, frequency and duty cycle to trigger the servo at the desired instant. The servo turns when this trigger pulse goes from low to high or high to low.

![Figure 5. Left: wing motion profile. Right: Wing motion control and data acquisition flow diagram.](image)

![Figure 6. DC motor, encoder and wheel arrangement (left). Servo controller timing diagram (right).](image)

The force transducer design requires careful consideration because of the low level forces generated and their dynamic nature. A full Wheatstone bridge configuration is used to increase resolution and provide good dynamic response. This force transducer design yields the z-component (Fig. 7) of the force regardless of its point of application along the spanwise axis. In the present experiments, the wing was mounted to sense the force normal to the wing surface. Our analyses have shown that the tangential force along the wing surface due to skin friction will be < 1% of the normal force. For an initially balanced bridge with equal resistances in the 4 arms and constant applied voltage \(V\), the output/input voltage ratio is as follows.

\[
\frac{\Delta E}{V} = \frac{1}{4} \left[ \frac{\Delta R}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4} \right]
\]  

(1)

For the gage arrangement shown in Fig. 7, the above equation reduces to

\[
\frac{\Delta E}{V} = \frac{S_c CPS}{2}
\]

(2)
in which $S_g$ is the gage factor, $C$ is a constant that depends on the beam geometry and the modulus of elasticity of the beam material, $s$ is the distance between the gage locations, and $P$ is the force. A critical dimension for selecting the force range is the web thickness. Note in Eq. 2 that the output voltage is independent of the distance to the point of application of the force $P$. Therefore, this configuration can be used to measure the force without knowing the center of pressure location. Sensitivity can be increased by increasing $C$ by choosing an appropriate material and geometry, but limiting the maximum strain well below the gage’s fatigue limit.

The force transducer dynamic range can be improved by proper choice of the strain gage, and designing for the expected load range. Special purpose strain gages having high gage factor and extended fatigue life suitable for dynamic measurements are available commercially. Typical strain gage specifications are as follows: strain range: $±2\%$, fatigue life: $∼10^7$ cycles at 2200 microstrain. The present force transducer specifications are as follows: nominal rated output: 2 mV/V; zero balance: 3% rated output; nominal bridge resistance: 1000 Ω; non-linearity: $+/−0.05\%$ rated output; hysteresis: $+/−0.05\%$ rated output; creep: $+/−0.05\%$ load; and mass: 30 g. The transducer was designed for a maximum load of 1N. The signal was processed through a signal conditioner/amplifier and filtered using a lowpass filter with the cut-off frequency set at 3 Hz. The filtered output was input into the data acquisition board and also monitored on an oscilloscope. The transducer was calibrated statically using weights. To ascertain if the point of application of the force in the spanwise direction has any influence on the output, tests were repeated by placing the weight at different spanwise locations and monitoring the output. No differences were observed within the accuracy of the digital voltmeter display. Calibration was repeated after the experiments were completed to detect any drift. The calibration constants obtained before and after the experiments spanning 3 months, differed only by 0.3%.

IV. Experimental Uncertainty Analysis

The flapping and pitching wing experiment using small wings as in the present study (50mm x 150 mm) has some unique challenges posed by the low force levels (~1 N), and the cyclic wing motion. The low force levels require careful selection and/or design of transducers that will ensure good signal-to-noise ratio. Wing motion introduces systematic errors that must be accounted for. Depending on the experiment configuration and force transducer placement, gravity and inertia forces may contribute to the signal. Because of these concerns, a systematic error analysis is necessary to establish error bars for the data. Using wings of different materials and repeating the experiments in air are two ways in which wing inertia forces can be estimated and subtracted from the force sensed by the transducer. It is also possible to calculate the forces due to inertia and gravity by analytical/numerical calculations. We have written a computer program for this purpose. For a wing having uniform mass distribution along the length, the inertia and gravity force terms may be calculated as respectively, the first and the second term on the right hand side of the following equation.

Figure 7. Wheatstone bridge circuit (left) and force transducer

Figure 8. Inertia and gravity forces on a 50 mm x 150 mm, semi-elliptical wing flapping in the vertical plane. stroke angle, $\psi$ (Fig. 1) = 160°. Frequency, $f$ = 2 Hz. Results from numerical quadrature of the equation of motion.
\[ F_z = \rho_{\text{wing}} A \omega^2 \frac{L_w}{2} \xi - g \rho_{\text{app}} A l_c \sin \xi \]  

where: \( \rho_{\text{wing}} \) – wing material density, \( A \) – wing cross sectional area, \( \omega \) – flapping frequency, \( \xi \) – angular displacement, \( \rho_{\text{app}} = \rho_{\text{wing}} - \rho_{\text{liquid}} \). For a wing with variable mass distribution, the above force must be calculated by numerical quadrature.

A sample result from the numerical calculations is shown in Fig. 8 for a semi-elliptic wing in harmonic motion. The force transducer is designed to sense the force in the z-direction, Fig. 7. When pitching is present, the inertia and weight components in the z-direction must be calculated for each orientation the wing sees during the cycle. For a wing flapping in the horizontal plane, the weight contribution does not change during the stroke cycle and it can be easily subtracted from the transducer output signal. For a wing translating in the vertical plane in the plunge-pitch mode, weight will not influence transducer response in our design. For a pitching wing with a pitch axis different from an axis of symmetry, additional inertia forces must be considered. This can also be done through calculations, or by doing the experiment in air and subtracting the result from the water experiment.

Electronic noise is another source of error in transducers. Electrical wires were shielded, and other recommended practices followed as much as possible to reduce noise. A lowpass filter with cut off frequency, equal to ten times the flapping frequency, as done by Anderson et al. [42], can be used to increase signal-to-noise ratio. Effect of water tank walls, another potential source of error, can be minimized by having a tank large enough such that the tank side walls are at least 6 chord lengths away from the wing. The bottom wall also should be sufficiently far from the wing tip. In the present experiments, the bottom wall was two wing lengths away from the wing tip. Motion of the liquid free surface, if present, can introduce error in the measurements. One way to alleviate this is to cover the surface by a rigid wall to prevent surface wave formation as discussed by Ol et al. [56]. Additional sources of error include out-of-plane motion of the wing, flexure of the wing-rod-mounting bracket assembly, and errors in synchronizing the flapping and pitching motion. We estimate that, after correcting for the systematic errors due to weight and inertia, the remaining errors introduce a total of approximately +/-10% uncertainty in the presented results.

V. Scaling Parameters and Force Components

Two important non-dimensional parameters, chord Reynolds number \( (\text{Re}_c) \) and reduced frequency \( (k) \), can be used to study performance of a flapping wing. Using the mean translation speed at the wing midspan, \( \bar{U} \), these can be expressed in terms of the chord length, \( c \), the distance from the hinge point to the wing midspan, \( l_c \), and the stroke angle, \( \psi \) (Fig. 1). The mean translational velocity at midspan can be expressed in terms of the wing beat frequency, \( f \), as follows

\[ \bar{U} = 2l \psi f \]  

A Reynolds number can be defined as

\[ \text{Re}_c = \frac{\bar{U}c}{\nu} \]  

where \( \nu \) is the fluid kinematic viscosity. Substituting for \( \bar{U} \) from Eq. (4) gives the following for \( \text{Re}_c \).

\[ \text{Re}_c = \frac{2l \psi fc}{\nu} \]  

The reduced frequency is defined in terms of the wing beat frequency, \( f \), as

\[ k = \frac{fc}{\bar{U}} \]  

Combining the above expression with Eq. (4) yields the following.

\[ k = \frac{c}{2l \psi} \]  

Note that the wing beat frequency, \( f \), does not appear explicitly in Eq. (8) for the reduced frequency. For a given wing assembly it varies inversely as the stroke angle, and \( \text{Re}_c \) is proportional to the product of stroke angle and the beat frequency. The above analysis illustrates the importance of matching both the Reynolds number and the reduced frequency of the insect and a laboratory model.
Discussing the forces in terms of lift and drag as used in conventional aerodynamics may not be as useful for flapping wing flight. The forces that are important in flapping flight are the vertical component that balances the weight and the horizontal component that represents thrust/drag. These two components can be expressed using the lift and drag components, for the down stroke and up stroke, respectively, as:

\[
\begin{align*}
F_d &= L_d \cos(\gamma_d) - D_d \sin(\gamma_d), \\
F_u &= L_u \cos(\gamma_u) - D_u \sin(\gamma_u),
\end{align*}
\]

where \(L\) and \(D\) are, respectively, the lift and drag forces, perpendicular and parallel to the stroke plane. \(\gamma\) is the angle that the stroke plane makes with the horizontal. Subscripts \(d\) and \(u\) denote down stroke and up stroke, respectively.

\[
\begin{align*}
F_d &= L_d \sin(\gamma_d) - D_d \cos(\gamma_d) \\
F_u &= L_u \sin(\gamma_u) + D_u \cos(\gamma_u)
\end{align*}
\]

VI. Results

We used a flat plate wing made of Lucite (density = 1200 kg/m\(^3\)) for the present experiments. The wing planform is a semiellipse with a length-to-chord ratio, \(l_w/c = 3\). The wing root chord, \(c = 50\) mm, and thickness, \(t = 2.1\) mm. The edges have been rounded using fine-grit sand paper. Torres and Mueller [26] have discussed the effect of edge radius on the dynamic vortex. The experimental conditions of the presented results are given in Table 2. The wing was flapped about the pivot axis shown in Fig. 4 at two frequencies, \(f = 0.22\) Hz and 0.29 Hz, and a nominal stroke angle (see Fig. 1), \(\psi = 60^\circ\). The distance from the pivot point to the midpoint of the wing, \(l_c\), was 0.260 m (10.25 in). The pitching servo motor was mounted below the pivot, followed by the force transducer. One end of a 10 mm diameter rod was attached to the force transducer, and the wing was attached to the other end (Fig. 4). The water in the tank was kept at a level such that the highest point on the wing at strokes extremities was about 1 cm below the water surface. For all the present cases, the wing was pitched at a constant angular velocity, \(\omega = 5.236\) rad/s. The pitching was symmetrical about the stroke extremities, and at the end of the pitching motion, the wing assumed a constant angle-of-attack orientation with respect to the stroke plane. Figure 5 shows the wing orientation at different locations during a stroke cycle. The pink-shaded rectangular end regions indicate pitching phase and the green middle region indicates constant orientation with respect to the stroke plane. Experiments were run at two angles-of-attack, \(\alpha = 30^\circ\) and \(45^\circ\). In order to estimate the extend of deviations from symmetry between the down and up strokes, and the effect on the transducer force output when the loading direction was reversed, the experiments were repeated for all the present cases with \(\alpha\) being negative during the down stroke (Fig. 5) and positive during the up stroke. Except for the transducer signal changing sign, no significant differences were noticeable. The leading edge (LE) and the trailing edge (TE) of the wing, differentiated by the pink dot, switch roles during the down and up strokes. This motion was chosen with future cambered wing experiments in mind. One of the goals of this investigation is to compare results from the above wing rotation mode to that which results in the leading and trailing edges not switching roles, as done in many previous studies.

<table>
<thead>
<tr>
<th>Case</th>
<th>Flapping Frequency, (f) (Hz)</th>
<th>Angle-of-attack, (\alpha) (deg)</th>
<th>Reduced Frequency, (k)</th>
<th>Reynolds Number, (Re_c)</th>
<th>(C_L)</th>
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<tr>
<td>1</td>
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<td>30</td>
<td>0.092</td>
<td>5402</td>
<td>1.68</td>
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<td>2</td>
<td>0.29</td>
<td>30</td>
<td>0.092</td>
<td>7054</td>
<td>1.43</td>
</tr>
<tr>
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<td>0.22</td>
<td>45</td>
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<td>5402</td>
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<td>45</td>
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<td>7054</td>
<td>1.57</td>
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</table>

Figure 9 show the instantaneous fluid dynamic force during one complete cycle for \(\alpha = 30^\circ\) and two flapping frequencies, 0.22 Hz (left) and 0.29 Hz. Figure 10 shows results for the same two frequencies, but for \(\alpha = 45^\circ\). These results were obtained after applying analytically determined corrections for inertia and weight, as described elsewhere. The wing is mounted such that the transducer senses the force normal to the wing surface. The force perpendicular to the stroke plane (defined as lift) and tangential to the stroke plane (defined as drag) can be calculated by taking respective components of the forces shown in Figs. 9 and 10. For reasons discussed earlier, the skin friction force tangential to the surface was neglected in the lift and drag calculations.
The four included cases cover two values of the Reynolds number and two values of the flapping frequency. Results shown are three-run averages for one stroke cycle taken from transducer signals acquired at a data sampling rate of 1 kHz over a ~30 s duration. The signals showed good cycle-to-cycle repeatability. The green vertical bars indicate the approximate rotation phase. The region between the first and the second green shaded bars is named down stroke and the following one is named up stroke. For pure harmonic flapping motion with pitching symmetry about the stroke end points, one might expect symmetry between the down stroke and up stroke forces. The four plots in Figs. 9 and 10 indicate some asymmetry. This may be due to a number of reasons. It is possible that the servo motion was not exactly symmetrical about the stroke end points because of inaccuracies in servo operation. The flapping motion was only near-harmonic, as was determined from an analysis of the kinematics. Though not detectable in simple visual observations, there might exist a certain degree of out-of-plane motion during the stroke cycle. Even though the above factors might have introduced asymmetry, overall, the differences between the two halves of a full cycle are not significant in the four cases shown.

The force normal to the wing shown in Figs. 9 and 10, averaged over one cycle ($F$), is resolved as follows to calculate lift and drag [57].

$$ L = F \cos \alpha \quad \text{and} \quad D = F \sin \alpha $$

The lift coefficient, $C_L$, and the drag coefficient, $C_D$, are defined as

$$ C_L = \frac{L}{0.5 \rho \bar{U}^2 S} \quad \text{and} \quad C_D = \frac{D}{0.5 \rho \bar{U}^2 S} $$

where $\rho$ is the density of water, $\bar{U}$ the mean speed midway between the wing root and wing tip defined earlier, and $S$ the wing planform area.

Case 1, Table 2, force curve is shown in Fig. 9, left. The force peak is about 0.15 N. The down stroke peak on the left and the up stroke peak are nearly at the same level. As noted previously, the down stroke and up stroke show slight force asymmetry. The force can be seen to follow the velocity variation which has a maximum when the wing is vertical, where the angular displacement, $\xi = 0$. As expected, at the two end-of-stroke locations, where the speed is zero, the fluid dynamic force also is near zero. The corresponding lift coefficient, $C_L = 1.68$ (Table 2). The $C_L$ values are of the same order as in previous studies (32,35). However, a more direct comparison of the values from different studies is difficult because of the differences in the non-dimensionalization schemes used to define lift coefficient. To illustrate, the above $C_L$ will be reduced by 40% if the tip mean speed is used to calculate the dynamic pressure instead of the midpoint mean speed. Of the four plots in Figs. 9 and 10, those for the higher frequency, $f = \ldots$
0.29 Hz have better symmetry between the down stroke and the up stroke compared to those for the lower flapping frequency. This may be due to the force transducer, rated for 1N force, operating in a more optimal range. The Case 3 force variation for the up stroke in Fig. 10 has a shoulder not seen in the other plots. This was observed in all the cycles of the runs to which it belongs. It is probably caused by a slight asymmetry in the pitching motion. However, this needs to be further investigated with more experiments under the same conditions. The trends in the force magnitudes are as expected. Force levels are higher for the higher angle-of-attack and higher flapping frequency. The $C_L$ values are, however, lower at the higher flapping frequency for both values of $\alpha$. This may be a Reynolds number effect. The improved performance of flapping wings are pronounced at insect flight Reynolds numbers (~100 to 1000). The above likely Reynolds number effect needs to be confirmed with more experiments covering a wider range, planned for future studies.

Another motivation for the present work is to experimentally investigate the reduced frequency optimum proposed by the authors’ in a previous study based on two-dimensional flow simulation [49]. The reduced frequency, $k = 0.092$ in the present study. Limitations of the experimental setup did not allow easy variation of the reduced frequency. The flapping mechanism is presently being modified to allow for wider Reynolds number and reduced frequency ranges.

The shape of the force curve in the present study is quite different from those in previous studies. Dickinson et al. (19) have a flatter profile for the force variation compared to the present results. These differences can likely be attributed to the differences in the motion profile. The angular displacement of the flapping motion in the present work is near-sinusoidal, which is different from the motion profile used by Dickinson et al. [19] With future study of cambered wings in mind, we also switched the leading edge (LE) and trailing edge (TE) between the two halves of the stroke cycle (see Fig. 5). To completely understand the effect of this mode of pitching motion on force generation, a larger parameter space must be considered. However, the present $C_L$ values suggest that LE/TE switching may not introduce any performance degradation when used for cambered wings, and may even have advantage over pitching mode in which the edges do not switch. A limited comparison of the present results with another recent work by Milano and Gharib (35) can be made. Their reported force curve is for a starting wing in plunge-pitch motion. Our force curve is over one cycle taken from data spanning several cycles. Care was taken to avoid starting and stopping effects by omitting data belonging to the first and the last cycles. For these reasons, quantitative comparison of the two results may not be appropriate. Moreover, there are also significant differences in the investigated flow regimes. The two-dimensional results of Sunada et al. (32) for a plunging-and-pitching airfoil provide another source to compare the present results. After allowing for the differences in the non-dimensionalizing schemes, their force coefficient seems to be much larger than the present values.
VII. Conclusions and Future Work

The present experimental work is a follow up of our previous flow simulation work on two-dimensional airfoils. Techniques such as leading edge/trailing edge (LE/TE) switching and frequency tuning were proposed to improve performance based on the results from the simulations. The experimental work was initiated to further seek validity for the suggested mechanisms. The present results show that the force curve for the stroke cycle closely follow the velocity variation. The flat plate wing of semi-elliptic planform undergoing near-harmonic flapping motion and pitching about the axis of symmetry do not produce end-of-stroke peaks and troughs in the force curve. The results clearly show that the previously proposed LE/TE switching is a viable and perhaps preferred option for pitching, and makes it feasible to use cambered wings to increase performance as in the case of many insects. This is a significant finding because of its implications in airfoil selection. Due to limitations of the present experimental setup, experimental verification of another previous suggestion, that frequency tuning may lead to enhanced performance, is possible only by doing additional experiments over a range of reduced frequencies. The experimental setup is presently being modified for this purpose.

Systematic and random errors in the data are discussed, and analytically determined corrections have been applied for the systematic errors due to wing inertia and weight. Care was taken to select force transducer parameters appropriate for the low force levels (~1N). Overall experimental uncertainty due to other factors such as electrical noise, imperfections in fabrication and assembly of the apparatus, and deviations from the design motion profile, has been estimated.

Ongoing and immediate future work include investigation of a range of reduced frequencies, use of cambered plate airfoils, flow field investigation using digital particle image velocimetry (DPIV), and investigation of other motion profiles for flapping as well as pitching.

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IX. References