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KINEMATIC AND UNSTEADY AERODYNAMIC MODELLING OF FLAPPING BI- AND QUAD-WING ORNITHOPTER

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Abstract

A flapping quad-wing ornithopter is modeled and analyzed to mimic flapping wing biosystems to produce lift and thrust for forward flight by considering the motion of a three-dimensional rigid and thin quad-wing in flapping and pitching motion with phase lag, based on earlier analysis of bi-wing. Basic Unsteady Aerodynamic Approach incorporating salient features of viscous effect and leading-edge suction is utilized. Parametric study is carried out to reveal the aerodynamic characteristics of flapping quad-wing ornithopter flight and for comparative analysis with various selected simple models in the literature. A generic approach is followed to understand and mimic the unsteady aerodynamics of biosystem that can be adopted in a simple and workable Quad-Wing-Micro-Air-Vehicle (QVMAV) model. Analysis is carried out by differentiating the pitching and flapping motion phase-lag and studying its respective contribution to the flight forces. Further considerations are given to the influence of the Strouhal number on the propulsion generation. Results are discussed in comparison with various selected simple models in the literature, with a view to develop a practical ornithopter model.

1 Introduction

The present work is a part of a series of work to follow a generic approach to model the kinematics and aerodynamics of flapping wing ornithopter, by focusing on a flapping quad-wing ornithopter modeled and analyzed to mimic flapping wing biosystems to produce lift and thrust for forward flight. To this end considerations are given to the motion of a three-dimensional rigid and thin quad-wing in flapping and pitching motion with phase lag following earlier analysis of bi-wing model. Basic Unsteady Aerodynamic Approach incorporating salient features of viscous effect and leading-edge suction will be utilized. Parametric study is carried out to reveal the aerodynamic characteristics of flapping quad-wing ornithopter flight characteristics and for comparative analysis with various selected simple models in the literature, in an effort to develop a simple flapping quad-wing ornithopter model, as exemplified in Fig. 1. A generic approach is followed to understand and mimic the unsteady aerodynamics of biosystem that can be adopted in a simple and workable Quad-Wing-Micro-Air-Vehicle (QVMAV) model.

The most distinctive characteristic of flapping wing motion of ornithopters and entomopters flight is the wing kinematics. Based on Ellington's study [1- 3], the kinematic of flight produced by the generic wing (semi-elliptical wing) can be classified into the inclined stroke plane, where the resultant force produced by the wing can be separated into vertical and horizontal components, which are lift, thrust and drag, respectively throughout the up-stroke and down-stroke cycle; the inclined stroke plane, where a large horizontal thrust component will be produced; and the vertical stroke plane.

Motivated by flying biosystems, flight engineering has been initiated since hundreds of years ago and has gradually grown from the time of Leonardo Da Vinci to Otto Lilienthal's gliders, to modern aircraft technologies and present flapping flight research. Recent interest in the latter has grown significantly particularly for small flight vehicles (or Micro-Air-Vehicles) with very small payload carrying capabilities to allow remote sensing missions hazardous as well as confined areas. Some of these vehicles may have a typical wingspan of 15 cm, with a weight restriction of less than 100 g (Ho et al, [4]). Perhaps the most comprehensive account of insect flight or entomopter to date is given by Weis-Fogh [5], Ellington [1-3], Shyy et al [6-7], Dickinson et al [8], Żbikowski [9] and Ansari et al [10], while one of the first successful attempts to develop birdlike flapping flight was made by DeLaurier [11]. Although our interest in developing a mathematical and experimental model is on more or less rigid quad wing ornithopter, it is also motivated by the fact that insect and hummingbirds have lightweight, flexible wings that undergo large deformations while flapping, which can increase the lift of flapping wings (Rosenfeld [12]). It will be of good interest how wing flexibility can be later on adopted. The flapping wing designs have been created with varied success, for forward or hover mode, but not both, based on observations of hummingbirds and bats (Nicholson et al [13]). According to Maybury and Lehmann [14], the dragonfly has the capability to shift flight modes simply by varying the phase lag between its fore and hind wings. With that observation, a quad-winged flapping system could be conceived as the simplest mechanism that has the capabilities to shift between flight modes [13]. In one of the recent works in developing quad flapping wing micro air vehicle, Ratti [15] has theoretically shown that a flight vehicle with four flapping wings has 50% higher efficiency than that with two flapping wings. Inspired by the flight of a dragonfly, Prosser [16] analyzed, developed and demonstrated a Quad-Wing Micro Air Vehicle (QW-MAV) which can produce higher aerodynamic performance and energy efficiency, and increased payload capacity compared to a conventional (flapping wing) MAV (BW-MAV). However, to develop a generic model of flapping wing ornithopter, Bi-Wing ornithopter will first be reviewed and developed, and then extended to quad-wing ornithopter.

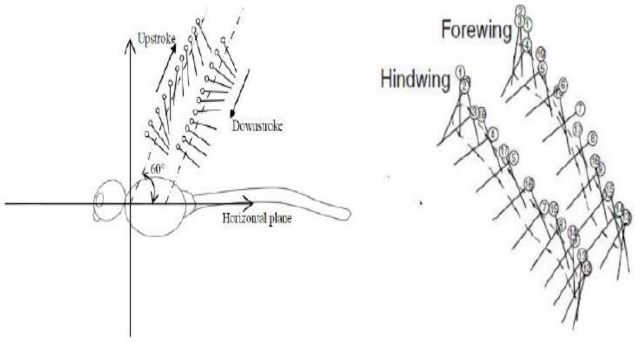
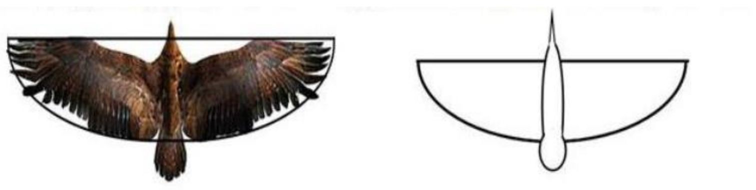


Fig. 1: Upstroke and downstroke motion of dragonfly (Adapted from [17]).

The image displayed in Fig. 1 exhibit a dragonfly, which will later be imitated to take advantage of the quad-wing kinematic and aerodynamic interactions, in the effort of improving the performance of the ornithopter to be developed. Fig. 1 also schematically exhibits the flapping motion of the quad-wing dragonfly, as studied by Wang and Russell [17]. Within such backdrop, a generic approach is followed to understand and mimic the unsteady aerodynamics of Biosystem that can be adopted in the present bi-wing FW-MAV and quad-wing QWMAV, following our previous attempt to develop pterosaur-like ornithopter to produce lift and thrust for forward flight as a simple and workable ornithopter flight model [18]. At the present stage, such model will not take into account the more involved leading edge vortex and wake penetration exhibited by insect flight [1-10].

2 Kinematics of Flapping Wing Motion

The flapping wing motion of ornithopters and entomopters can be generally grouped in three classes, based on the kinematics of the wing motion and mechanism of forces generation; the horizontal stroke plane, inclined stroke plane and vertical stroke plane [5]. As a result of these kinematics, the aerodynamics associated with insect flight are also very different from those met in conventional fixed- and rotary-wing air-vehicle or even bird flight [10]. Based on Ellington's study [1-3], the kinematics of flight produced by the generic wing (semi-elliptical wing) can be classified into the inclined stroke plane, where the resultant force produced by the wing can be separated into vertical and horizontal components, which are lift, thrust and drag, respectively, throughout the up-stroke and down-stroke cycle; the inclined stroke plane, where a large horizontal thrust component will be produced; and the vertical stroke plane.



(a) Top view and outline of an eagle wing (b) The present Baseline Generic Wing Planform.

Fig. 2: A generic semi-elliptical ornithopter wing planform adopted from eagle-wing planform

Insect wings are elegant, impressive and instructive to be considered in the development of small-scale engineering. They are deformable airfoils whose shape is actively controlled by the wingbase articulation while the wing area is subject to inertial, elastic and aerodynamic forces.

3 Theoretical Development of the Generic Aerodynamics of Flapping Wings

Following the frame of thought elaborated in the previous section, several generic flying biosystem wing planforms are chosen as baseline geometries for the ornithopter. Referring to the eagle wing and for convenience of baseline analysis, the semi elliptical wing (shown in Fig. 2) is selected for the current bi-wing baseline study, which will also be utilized for the quad-wing study.

In the present work, analytical approaches of quasi-steady and unsteady model are carefully evaluated in order to deal with the aerodynamic problem. In agreement with the quasi-steady model, it is observed and can be assumed that the flapping frequencies are sufficiently slow that shed wake effects are negligible, as in pterosaur and medium- to large-sized birds so that the unsteady approach attempts to model the wake like hummingbird and insects can be deferred to the refinement stage of the work. The present aerodynamic approach is synthesized using basic foundations that may exhibit the generic contributions of the motion elements of the bio-inspired bi-wing and quad-wing air vehicle characteristics. These are the strip theory and thin wing aerodynamic approach [19], Jones modified Theodorsen unsteady aerodynamics [20, 11], incorporation of leading edge suction [21, 22], and Jones' modified Theodorsen approach which incorporates Garrick's leading edge suction. The computation of lift and thrust generated by pitching and flapping motion of three-dimensional rigid wing is conducted in a structured approach using strip theory and Jones' modified Theodorsen approach without camber, leading edge suction and post-stall behavior. Later, the computational model will take into account certain physical parameters that can be identified via observations and established results of various researchers. Lifting-surface theory [23-26] may later be incorporated. In the present work, unsteady aerodynamics of a flapping wing using a modified strip theory approach as a simplification of DeLaurier's[11] approach is utilized without post-stall behavior. The computational logic in the present work is summarized in the Flow-Chart exhibited in Fig. 3.

To obtain insight into the mechanism of lift and thrust generation, Djojodihardjo and Ramli [27-29] and Djojodihardjo and Bari [30-31] analyzed the wing flapping motion by looking into the individual contribution of the pitching, flapping and coupled pitching-flapping to the generation of the aerodynamic forces. Also the influence of the variation of the forward speed, flapping frequency and pitch-flap phase lag has been analyzed. Such approach will also be followed here through further scrutiny of the motion elements. The generic procedure is

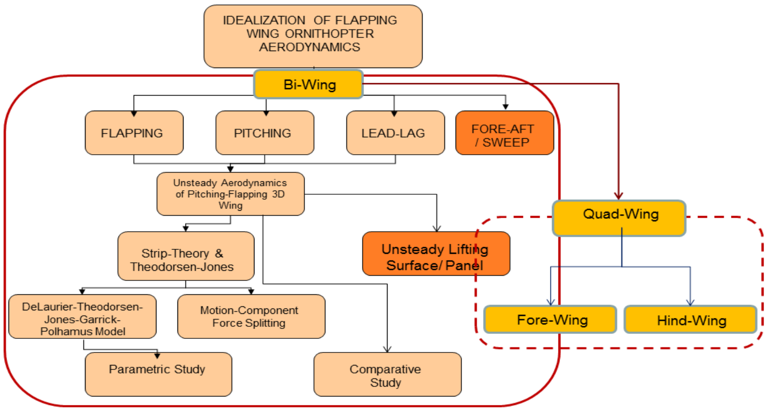


Fig. 3: Ornithopter Flapping Wing Aerodynamics Computational Scheme

synthesized from the pitching-flapping motion

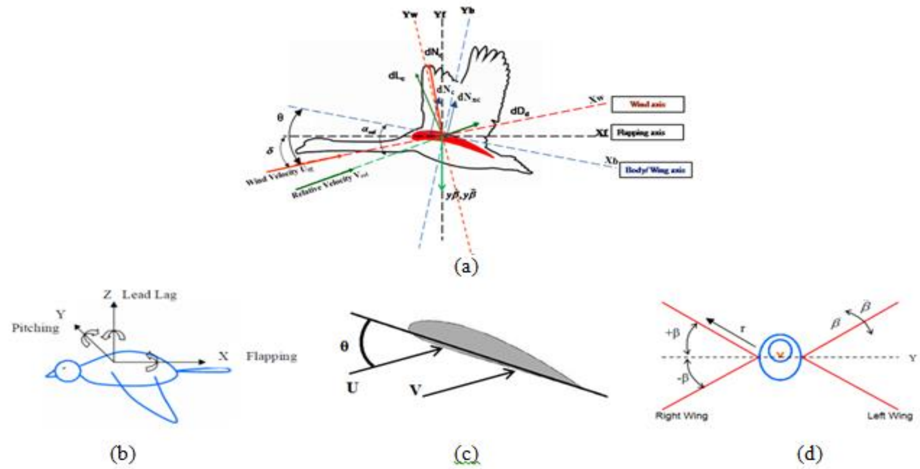


Fig. 4: (a)Forces on section of the wing. (b),(c),(d)Flapping and Pitching motion of flapping wing.

of rigid wing developed by DeLaurier [11], taking into account unsteady aerodynamics of Theodorsen [19], Jones [20], and Garrick [22]. The flapping motion of the wing is distinguished into three distinct motions with respect to the three axes; these are: a) *Flapping*, which is up and down plunging motion of the wing; b) *Feathering* is the pitching motion of wing and can vary along the span; c) *Lead-lag*, which is in-plane lateral movement of wing, as incorporated in Fig. 4. The lead-lag motion could be interpreted to apply to the phase lag between pitching and flapping motion, while the fore-and-aft movement can be associated with the orientation of the stroke plane. The degree of freedom of the motion is also depicted in Fig. 4. The flapping angle β varies as a sinusoidal function and pitching angle θ are given by the following equations.

$$\beta(t) = \beta_0 \cos \omega t \qquad (1)$$

$$\theta(t) = \frac{dy}{B}\theta_0 \sin(\omega t + \phi) + \delta \qquad (2)$$

where θ_0 and β_0 indicate maximum value for each variables, ϕ is the lag between pitching and flapping angle and y is the distance along the span of the wing.

As a baseline, by referring to eq. (1) and eq. (2), β is considered to vary following a cosine function while θ a sine function. Leading edge suction is included following the analysis of Polhamus [32] which has been taken into consideration by DeLaurier's approximation [11] and Harmon [33].

Three dimensional effects will later be introduced by using Scherer's modified Theodorsen-Jones Lift Deficiency Factor [34]. To account for the unsteady effects, Theodorsen unsteady aerodynamics [19] and its three dimensional version by Jones [20] have been incorporated. Further refinement is made to improve accuracy. Thin airfoil approximation based on Prandtl's lifting line theory, i.e. that the circulation is acting on the quarter-chord and the downwash and dominant airflow is calculated at the three-quarter chord point, is also adopted for each strip.

In the present analysis no linear variation of the wing's dynamic twist is assumed for simplification and instructiveness. However, in principle, such additional requirements can easily be added due to the linearity assumption. Assuming small angle approximation, for the plunging displacement or heaving of the wing, the flapping displacement h is given by

$$h \approx y\beta \qquad (3)$$

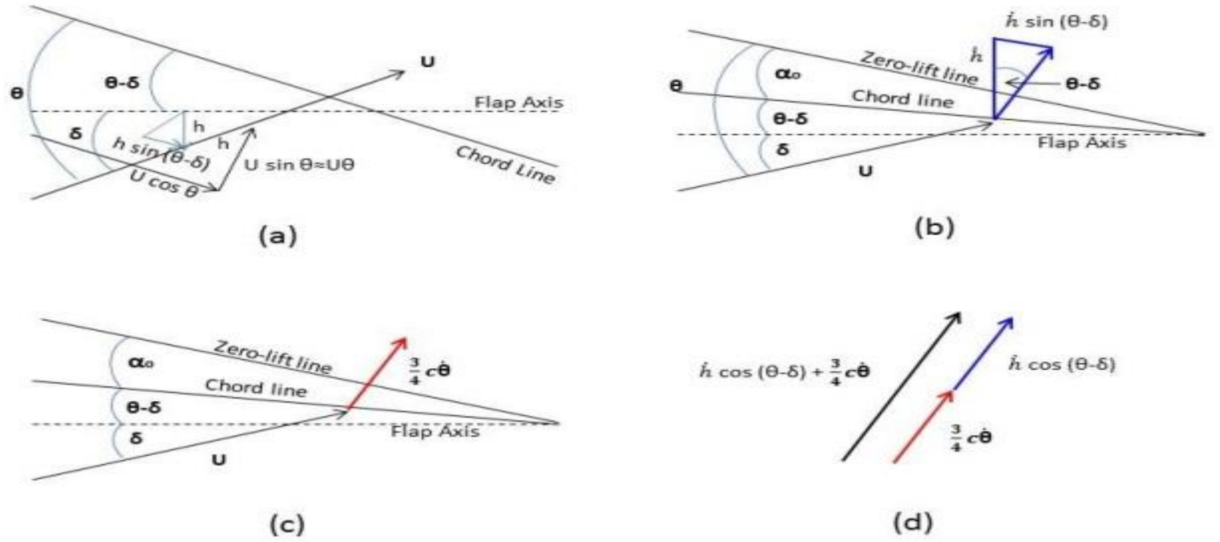


Fig. 5: Schematic diagram of flapping and pitching components of induced velocities at ¾ chord.

The total normal force acting perpendicularly to the chord line and given by

$$dN = dN_c + dN_{nc} \qquad (4)$$

The circulatory normal force for each section acts at the quarter chord and also perpendicular to the chord line and is given by [11]

$$dN_c = \frac{\rho UV}{2} C_n(y) c\, dy \qquad (5)$$

$$dN_{nc} = \frac{\rho \pi c^2}{4} \dot{V}_{mid-chord}\, dy \qquad (6)$$

where

$$\dot{V}_{mid-chord} = U\dot{\alpha} - \frac{1}{4} c\ddot{\theta} \qquad (7)$$

Using these relationships, the relative velocity at three-quarter chord point which is used for the calculation of the aerodynamic forces can be established. The relative angle of attack at three-quarter chord, α, is then given by

$$\alpha = \frac{\left(\dot{h}\cos\left(\theta - \bar{\theta}_a\right) + \frac{3}{4} c\dot{\theta} + U(\theta - \bar{\theta})\right)}{U}$$

(8)

$$\alpha = Ae^{i\omega t} \qquad (9)$$

which is schematically elaborated in Fig. 5.

After considering all of these basic fundamentals, the relative angle of attack at three-quarter chord point α' is given by

$$\alpha' = \frac{AR}{(2+AR)}\left[F'(k)\alpha + \frac{c}{2U}\frac{G'(k)}{k}\dot{\alpha}\right] - \frac{w_o}{U} \qquad (10)$$

which has taken into account the three dimensionality of the wing.

The finiteness of the span of the wing is accounted for by using this factor α' in the unsteady flow calculation, since although strip theory is employed, the present method deals with elliptical planform wing. For such considerations, Jones [20] came up with

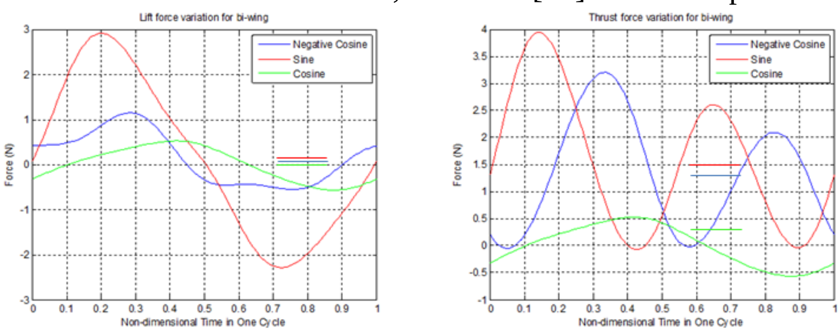


Fig. 6: Lift and thrust for each flapping components

modified unsteadiness coefficient

$$C_n = 2\pi C(k)_{jones}\alpha \qquad (11)$$

where $C(k)_{jones}$ in (11) is the modified Theodorsen Lift Deficiency function for finite aspect ratio which has also been utilized by

DeLaurier in his approach. Accordingly, $C(k)_{jones}$ is a complex function; therefore it is more convenient to use Scherer's [19,20] formulation which takes the following form

$$C(k)_{jones} = \frac{AR\ C(k)}{(2+\mathrm{AR})} \tag{12}$$

$$C(k) = F(k) + iG(k) \tag{13}$$

C(k), F(k) and G(k) relate to the well-known Theodorsen function [19,20] which are functions of reduced frequency, k. In addition, in present study, the interpretation that the real part of C(k) contributes only to the lift whereas the imaginary part for the thrust is adopted. This interpretation follows the methodological philosophy of Theodorsen and Garrick [26,39] and the classical unsteady aerodynamics. Using Complex Analysis, the unsteady lift is expressed as [22]:

$$L = 2\pi b\rho\upsilon C(k)Q \tag{14}$$

where Q is given by $Q = \omega e^{i\omega t}$. Then, substitution Q into eq. (14) gives

$$L = 2\pi b\rho\upsilon C(k)\left(\omega e^{i\omega t}\right) \tag{15}$$

In the Complex Analysis of Theodorsen, Garrick, the convenience of the analysis is to associate the Imaginary part of (14) and (15) with the Lift [22, 35]. The details are elaborated as follows. The reduced frequency is defined as $k = \frac{\omega b}{\upsilon}$, or $\omega t = \frac{\omega b}{\upsilon}\frac{\upsilon t}{b} = ks$. Assuming sinusoidal motion

$$\omega e^{i\omega t} = \omega\left(\cos\omega t + i\sin\omega t\right) \tag{16}$$

or

$$\omega e^{i\omega t} = \omega\left(\cos ks + i\sin ks\right) \tag{17}$$

Combining (13) and (15), one obtains:

$$L = 2\pi b\rho\upsilon\omega\left[\left(F(k)+iG(k)\right)\left(\cos ks + i\sin ks\right)\right] \tag{18}$$

Note that

$$|C(k)| \equiv \mathbf{C}(k) = |F(k)+iG(k)| = \left|\left(F(k)^2+G(k)^2\right)^{-\frac{1}{2}}\right| \tag{19}$$

After algebraic manipulation, Eq. (18) reduces to

$$L = 2\pi b\rho\upsilon\omega \bullet I.P\left[\begin{matrix}\mathbf{C}(k)\cos(ks)\cos\alpha - \mathbf{C}(k)\sin(ks)\sin\alpha \\ +i\mathbf{C}(k)\left(\cos(ks)\sin\alpha + \sin(ks)\cos\alpha\right)\end{matrix}\right] \tag{20}$$

and the imaginary parts of the above equation is

$$\mathbf{C}(k)\sin\left(ks+\alpha\right) \tag{21}$$

Therefore:

$$L = 2\pi b\rho\upsilon\omega\left[\left(F(k)^2+G(k)^2\right)^{-\frac{1}{2}}\sin\left(ks+\tan^{-1}\frac{G(k)}{F(k)}\right)\right] \tag{22}$$

For consistency with the strip theory, the downwash for untwisted planform wing is given by (Anderson [36])

$$\frac{w_o}{U} = \frac{2(\alpha_0+\theta)}{2+AR} \tag{23}$$

From Fig. 5(c), the flow velocity which includes the downwash and wing's motion relative to free-stream velocity, V can be formulated as

$$V = \left[\left(U\cos\theta - \dot{h}\sin(\theta-\delta)\right)^2 + \left(U(\alpha'+\theta) - \frac{1}{2}c\dot{\theta}\right)^2\right]^{\frac{1}{2}} \tag{24}$$

where the third and fourth terms are acting at the three-quarter chord point. The apparent mass effect (momentum transferred by accelerating air to the wing) for the section, is perpendicular to the wing, and acts at mid chord, and can be calculated as [11]

$$dN_{nc} = -\frac{\rho\pi c^2}{4}(U\dot{\alpha} - \frac{1}{4}c\ddot{\theta})dy \tag{25}$$

The term $U\dot{\alpha} - \frac{1}{4}c\ddot{\theta}$ is mid-chord normal velocity's time rate of change due to the motion of the wing.

Apart from normal forces, chordwise forces are also generated due to sectional circulation distribution as in Fig. 6(a). The total chordwise force, dF_x is accumulated by three forces which are leading edge suction, force due to camber, and chordwise friction drag due to viscosity effect. All of these forces acting along and parallel to the chord line as in the Fig. 4(a).

$$dF_x = dT_s - dD_{camber} - dD_f \tag{26}$$

where Garrick's [26,39] expression for leading edge suction, dT_s is

$$dT_s = \eta_s 2\pi\left(\alpha' + \theta - \frac{1}{4}\frac{c\dot{\theta}}{U}\right)\frac{\rho UV}{2}cdy \tag{27}$$

and [11]

$$dD_{camber} = -2\pi\alpha_o(\alpha'+\theta)\frac{\rho UV}{2}cdy \tag{28}$$

$$dD_f = \frac{1}{2}\rho V_x^2 C_f c dy \qquad (29)$$

According to the potential theory, the leading edge suction for most airfoils is predicted to be less that 100% due to viscosity effect, hence the efficiency term η_s is introduced for dT_s. The normal 2D force, dN and 2D chordwise force, dF_x for each section is of the is also changes its direction at every instant during flapping. These forces in the vertical and horizontal directions will be resolved into those perpendicular and parallel to the free-stream velocity, respectively. The resulting vertical and horizontal components of the forces is then given by

$$dL = dN\cos\theta + dF_x \sin\theta \qquad (30)$$

$$dT = dF_x \cos\theta - \mathrm{dNsin}\,\theta \qquad (31)$$

These expressions are then integrated along the semi span, b/2 in order to obtain a three dimensional lift for each wing

$$L = \int_0^{b/2} L_{2D} dy \qquad (32)$$

$$T = \int_0^{b/2} T_{2D} dy \qquad (33)$$

4 The influence of the phase-lag between pitching and flapping motion and the individual motion component on the flight performance

A parametric study is carried out to investigate the influence of the phase lag between pitching and flapping motion to the generation of lift and thrust. As exhibited in Fig. 7, the optimum lift and thrust can also be obtained by appropriate choice of this phase lag. From this study, it is observed that the lift always increases with phase lag angle between pitching and flapping motion, and it reaches its maximum value when the phase lag angle, ϕ = 3π/8. The thrust also exhibits a similar behavior.

Another study is carried out to assess the influence of other flapping wing motion parameters, such as flapping frequency, wing angle of incidence and the effect of total

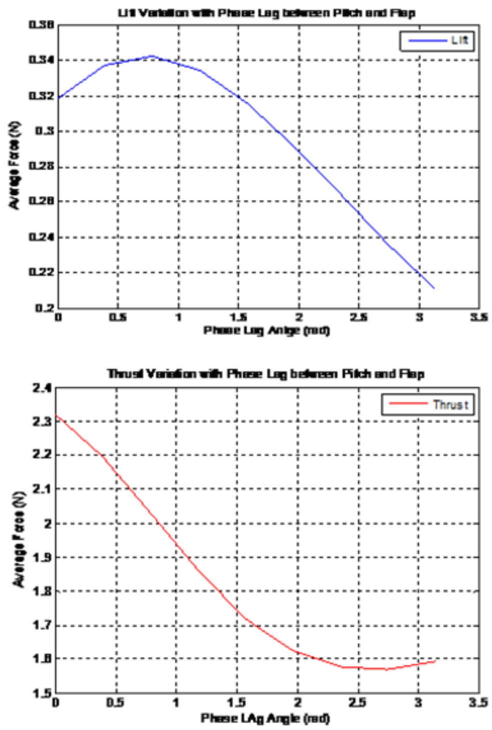


Fig. 7: Variation of Lift (a) and Thrust (b) with phase lag between Pitching and Flapping

flapping angle, to the flight performance desired. Fig. 8 (a) and (b) show the contribution of individual motion component to the lift and thrust including the result using the lifting surface method result obtained by La Mantia and Dabnichki [37] and Spectral Method of Ou and Jameson [38], respectively.

5 Modeling and Parametric Study of the Influence of Leading Edge Vortex (LEV) on Bi-wing Flapping Motion Aerodynamics

To study the influence of a leading edge vortex (LEV) on the flapping flight performance, the oscillatory motion of bi-wing flapping system is simulated by assuming discontinuous motion, by considering the discontinuity to be contributed by instant vortex shedding at the leading edge. To serve as a baseline, the development of the simulation is based on the following rationale:

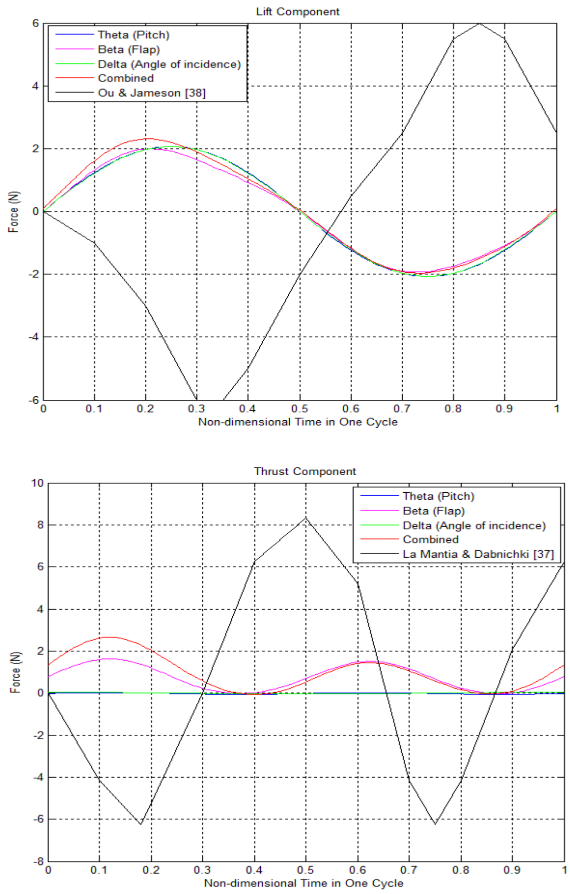


Fig. 8: The contribution of individual motion component to the lift (upper) and thrust (lower); comparison with Lifting surface result of La Mantia and Dabnichki [37] and Spectral Method of Ou and Jameson [38] exhibit similar qualitative behavior

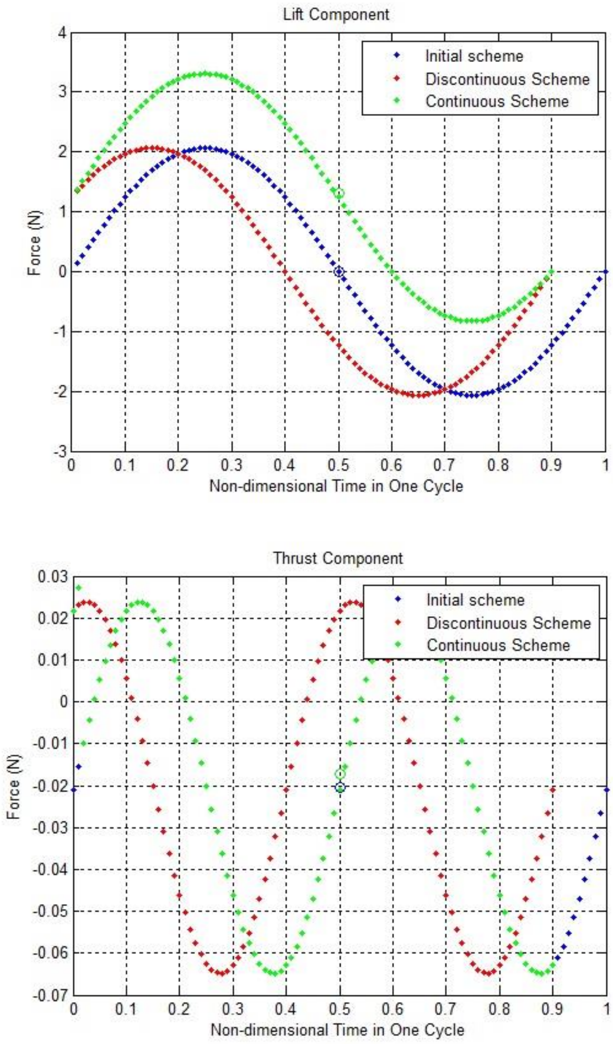


Fig. 9: Lift and thrust due to simulated LEV effect

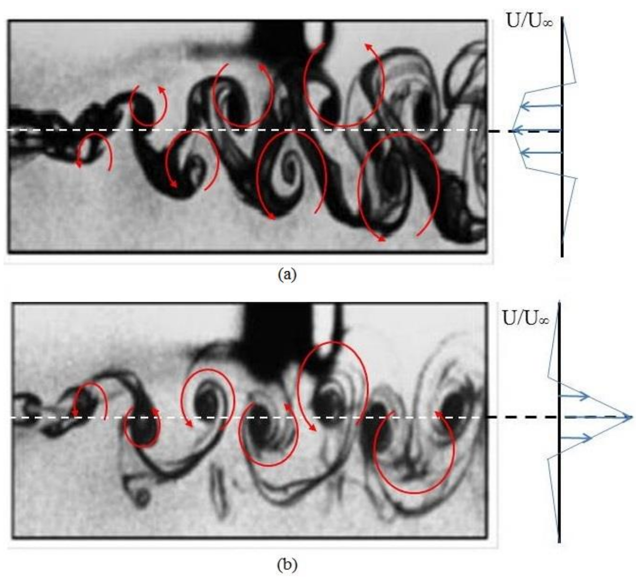


Fig. 10: (a) Drag producing vortex street; (b) Thrust producing vortex street. Adapted from [40]

- LEV is assumed to occur as part of the pitching motion
- LEV is created due to sudden downstroke movement of the leading edge; from biological and performance optimization reason, LEV is assumed not to be created during the upstroke.
- LEV is created during the sudden change of motion which is assumed to take place within a fraction of each stroke. For illustration, without loss of generalities, that fraction is assumed to be in the order of 10%.
- Since the lift and thrust are the two components of the aerodynamic force and thrust of the flapping wing, then this idealized LEV is acting in the same fashion for both lift and thrust.
- These assumptions are only applied to the pitch motion without considering skin friction, three-dimensional effect and

leading edge suction. The effect of these three flapping motion components, from physical reasoning, should be superposed to the resulting discontinuous pitching motion to obtain the total lift and thrust per cycle similar to the procedure followed in the absence of LEV.

Without going through the detail, such procedure is followed to mimic the influence of LEV in a biosystem, to reach the objective of enhancing performance as intrinsic control in biosystem and to allow simple simulation in a mechanized ornithopter. Then a parametric study is carried out to simulate discontinuous motion that will produce better lift and thrust. The result are exhibited in Fig. 9a, which indicates that by performing such discontinuous pitching oscillation, better lift contribution to the flapping aerodynamic performance is produced compared to the original continuous one. However, no significant thrust contribution is indicated (Fig. 9b).

6 Aerodynamic Forces and Strouhal Number Relationship in Bi-Wing

Von Karman and Burgers [39] offered the first theoretical explanation of drag or thrust production based on the resulting vortex street (i.e., the placement and orientation of the wake vortex elements). With respect to flapping airfoil, Jones and Platzer [40] demonstrates that vortex streets characteristic of drag production have a row of vortices of clockwise rotation above the symmetry plane, and a row of vortices of counter-clockwise rotation below the symmetry plane, as exhibited in shown in Fig. 10a. For an airfoil plunging at a low Strouhal number (k = 3.6, h = 0.08, St = 0.29), the vortices induce a velocity or momentum deficit on the centerline indicative of drag, and the wake wavelength, λ, defined here as the distance between vortex centers of same rotation, is shorter than the wavelength predicted by linear theory, $\lambda_{l.t.} = 2\pi/k$, due to the production of drag.

Oscillating the airfoil more energetically the vortex street shown in Fig. 10b is generated (k = 3.0, h =0.20, St = 0.60), which produces thrust. In the present work, the Strouhal number is defined as

$$St = \frac{h_0}{\pi}\frac{\omega}{U} = \frac{h_0}{\pi b}\frac{\omega b}{U} \equiv \frac{h_0}{\pi b}k \qquad (34)$$

For small insects, Yu and Ma [41] noted that the flapping Strouhal number St $\rightarrow$ 1.0, i.e. the reduced frequency $k = 2\pi St \rightarrow 2\pi$, and noted Lighthill's findings, that k = 0.5 is the upper limit of applying the quasi-steady assumption. Pennycuick [42] experimentally derived the correlation of the wing-beat frequency for flapping flight to the body mass, wingspan, wing area and the wing moment of inertia. For birds with the body mass ranging from 20g to nearly 5kg the wingbeat frequency is correlated by the following formula:

Table 1: Average lift and thrust

Parameters	Forces	Phase Lag				
		0	π/4	π/2	3π/4	π
Pitch and Flap Phase Lag	Average lift	0.3631	0.4457	0.3872	0.2394	0.1141
	Average Thrust	3.3661	3.6608	2.8717	1.6295	0.5614
Fore and Hind Pitch Phase Lag	Average lift	0.3631	0.3978	0.3622	0.2828	0.2149
	Average Thrust	3.3661	3.4845	3.0849	2.4597	1.9179
Fore and Hind Flap phase lag	Average lift	0.3631	0.2396	0.1675	0.1884	0.2267
	Average Thrust	3.3661	2.7038	1.9209	1.584	1.8108

$$f = \frac{1.08}{b}\sqrt[3]{\frac{m}{\rho}}\sqrt{\frac{g}{\sqrt{S}}} \qquad (35)$$

where m is the bird's body mass in kg, g is the gravitational acceleration, b is the wingspan, S is the wing area and ρ is the air density. With such correlation, Pennycuick typically found wing beat frequency, which is k, to be ~ 4.14 Hz

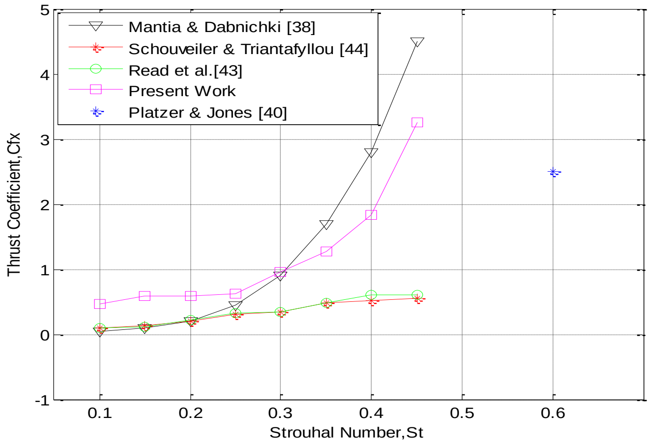


Fig. 11: Thrust - Strouhal Number relationship in comparison with other results from the literature.

or ω =9.8775 rad/sec. Earlier work [27-29] has applied this frequency and obtained reasonable results for bi-wing flapping ornithopter comparable to results derived from the literature and biosystems, using a flapping wing model with chord-length of 0.08m.

By analyzing data from flapping foils, such as those given by [40, 42] it could be surmised it was found that the thrust inducing vortices form optimally when the Strouhal number lies between 0.25 and 0.35. It can be anticipated that efficiency should be at a maximum for these values. Some preliminary experiments at the M.I.T. testing tank [43,44] confirmed that the efficiency of a flapping foil does indeed peak when the Strouhal number is in this range.

Understanding flapping propulsion may imply a far-field analysis of a phenomenon that may also be understood in the near field which can be carried out using simple analysis as the present work or lifting surface simulation. In the following sections we attempt to describe flapping propulsion as related to flapping frequency and/or Strouhal number.

Rewriting the relationship between Strouhal Number and reduced frequency (wing-beat frequency) (33) in the following form

$$k = \frac{\omega c}{2U} = \frac{\pi\, fc}{U} = \frac{fA\pi c}{UA} = St\,\frac{\pi c}{A} \qquad (34a)$$

it can be seen that with flapping amplitude of

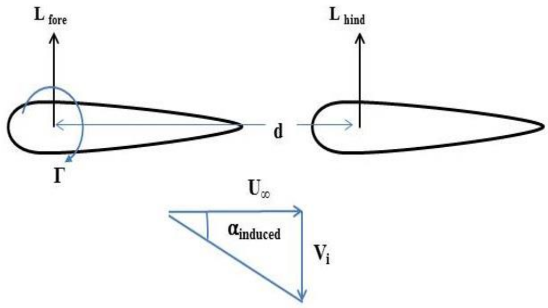


Fig. 12: Schematic diagram of fore wing downwash and induced angle of attack on hind wing

about πc, the two frequency parameters are equal. With Strouhal numbers in the range of 0.3, the quasi-steady assumption may be reasonable when the amplitude is larger than about 3 chords, but not if it is much smaller.

With such background, Fig. 11 is produced from the bi-wing results [27-31] using the present bi-wing computational modeling as a baseline. Comparison made with the panel method results of [38] and experimental results of Read et al [43] and Schouvelier et al [44] show reasonable qualitative agreement. In view of the simplicity of the present bi-wing three-dimensionally modified strip-theory unsteady aerodynamic approach, such agreement is encouraging.

7 Modeling of Quad-wing

Based on modelling and encouraging results obtained from bi-wing, the quad-wing will be modeled. For the quad-wing kinematics and aerodynamics, the present work takes into account the influence of the forewing induced downwash on the hindwing effective angle of attack.

This effect is modeled by assuming that, at any the induced downwash is also calculated at the quarter-chord point of the hindwing, as depicted instant, the circulation Γ of the forewing acts at its quarter-chord point, and in Fig. 12. Following Kutta-Joukowski Law, the instantaneous equivalent circulation generated by the forewing is given by

$$\Gamma = \frac{L_{fore}}{\rho U_\infty} \tag{36}$$

and the induced velocity V_i , following Biot-Savart law is given by

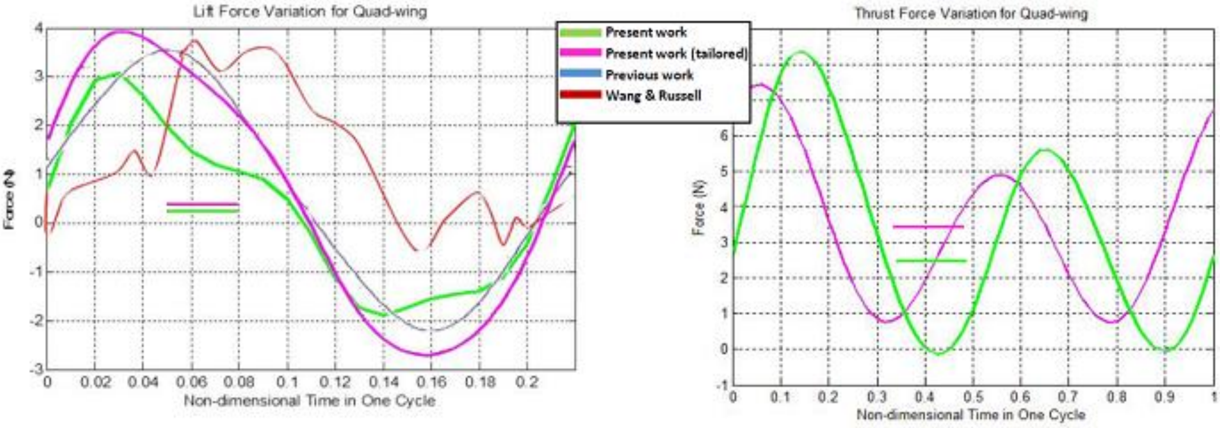


Fig. 13: Computational Results of Lift and Thrust and comparison with Wang & Russel [17] results

$$V_i = \frac{\Gamma}{2\pi d} \tag{37}$$

Following Fig. 11, for small angle of attack, the induced angle is formulated as

$$\alpha_{induced} \approx \frac{V_i}{U_\infty} \tag{38}$$

Therefore the pitching angle of the hind wing is given by

$$\theta(t) = \frac{dy}{B}\theta_0 \sin(\omega t + \phi) + \frac{V_i}{U} + \delta \tag{39}$$

8 Results for Quad-Wing

8.1 Simulation Results

Initial initiative was done with an assumption that the fore and hind wings are closely attached, that is there is no gap between the leading edge of the hind wing and the trailing edge of the fore wing .

Initial initiative was done with an assumption that the fore and hind wings are closely attached, that is there is no gap between the leading edge of the hind wing and the trailing edge of the fore wing .The results in Table 2 are obtained using the following wing geometry and parameters: the wingspan of 40cm, aspect ratio of 6.2, flapping frequency of 7Hz, total flapping angle of 60°, forward speed of 6m/s, maximum pitching angle of 20°, incidence angle of 6° and wing dihedral angle. The results of both methods are compared to appreciate the influence of physical refinements in the computational procedure and for validation purposes. This analysis is also accounts for the induced angle of attack on the hind wing due to downwash of the fore wing. The results are presented in Fig. 13 and Table 3.

Fig. 13 also shows the lift computed using the present simplified and generic model, for 180° phase angle between fore- and hind-wings, compared to previous work [27] Wang and Russell's more elaborate model calculation [17]. This comparison is very qualitative, for proof of concept considerations.

Table 2: The quad-wing average lift and thrust

Forces	Results
Average Lift	0.3631
Average Thrust	3.366

Table 3: Quad-Wing Parametric study results

Forces	Frequency, f			Distance, d			
	5 Hz	7 Hz	9 Hz	No Gap	Half-Chord	One Chord	Two Chord
Average Lift (N)	0.957	0.3631	2.8347	0.3631	0.347	0.3392	0.3316
Average Thrust (N)	1.6417	3.3661	10.4646	3.3661	3.3007	3.2668	3.2322

8.2 Variation of Oscillatory Articulation of the Quad-Wing

Following the procedure and parametric study carried out for bi-wing ornithopter [27-31], the present study also addresses the flapping kinematics accordingly, by taking into considerations what has been learned from bi-wing parametric study. The forewing and hindwing are arranged in tandem without gap, so that the leading edge of the hindwing touches the trailing edge of the forewing, and they are moving simultaneously. The pitching motion of both forewing and hindwing moves sinusoidally, while the flapping motion of both is varied following sine, negative cosine and cosine. The results, as exhibited in Fig. 14, shows that the synchronous sinusoidal pitching and flapping produce the maximum amplitude as well as average values of lift and thrust. These results also indicate one variation only of such oscillatory articulation possibilities that could be further tailored to meet certain objectives.

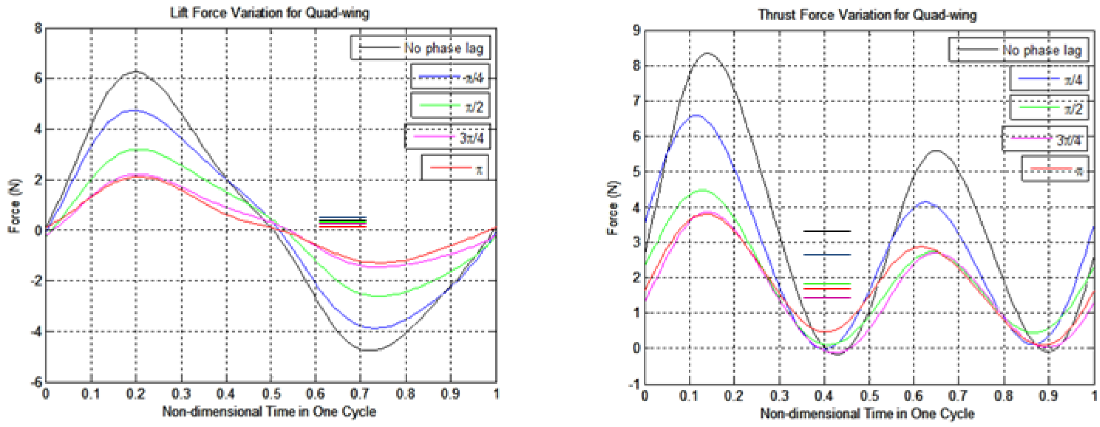


Fig. 15: Lift and Thrust generated by Fore and Hind wing

8.3 Parametric Study for Quad-Wing

A parametric study is carried out to assess the influence of certain flapping wing motion parameters to the flight performance desired. The study considers the following parameters: the effect of forward speed, the effect of flapping frequency, the effect of lag angle, the effect of distance between fore and hind wing and the effect of the total flapping angle. The results are exhibited in Fig. 15 and table 3. In general, the sensitivity of the bi-wing and quad-wing towards these parameters are comparable. Interesting results are exhibited by Table 1 where the combination of pitch and flap of both fore and hind wings are varied.

Results obtained as exhibited in next section show the lift produced for various scenarios involving phase combinations between flapping and pitching motions of the individual fore- and hind-wings. Table 1 summarizes the average forces per cycle for the selected scenarios.

A deduction can be made from the results from Table 1 that the phase lag of $\pi/4$ produces the maximum lift and thrust among the others. However further analysis to optimize the combination of these parameters is still under progress.

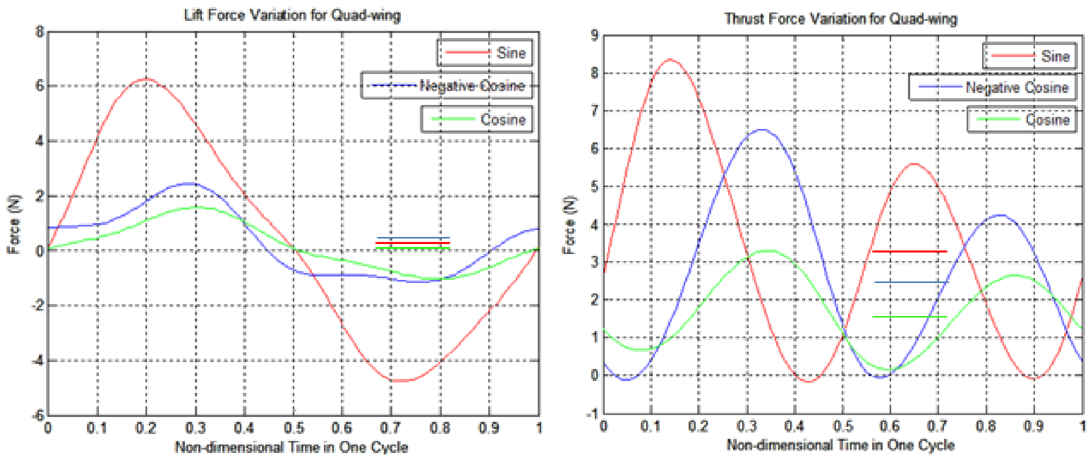


Fig. 14: Lift and thrust for quad-wing for each flapping motion components

9 Conclusion

The present work has been performed to assess the effect of flapping-pitching motion with pitch-flap phase lag in the flight of ornithopter. In this conjunction, a computational model has been considered, and a generic computational method has been adopted, utilizing strip theory and two-dimensional unsteady aerodynamic theory of Theodorsen with modifications to account for three-dimensional and viscous effects and leading edge suction. The study is carried out on semi-elliptical wing planforms. For the quad-wing ornithopter, at the present stage, the simplified computational model adopted verified the gain in lift obtained as compared to bi-wing flapping ornithopter, in particular by the possibility of varying the phase lag between the flapping and pitching motion of individual wing as well as between the fore- and hind-wings. A structured approach has been followed to assess the effect of different design parameters on lift and thrust of an ornithopter, as well as the individual contribution of the component of motion. These results lend support to the utilization of the generic modeling adopted in the synthesis of a flight model, although more refined approach should be developed. Various physical elements could be considered to develop ornithopter kinematic and aerodynamic modeling, as well as using more refined aerodynamic computation, such as CFD or lifting surface methods. In retrospect, a generic physical and computational model based on simple kinematics and basic aerodynamics of a flapping-wing ornithopter has been demonstrated to be capable of revealing its basic characteristics and can be utilized for further development of a flapping-wing MAV. Application of the present kinematic, aerodynamic and computational approaches shed some light on some of the salient aerodynamic performance of the quad-wing ornithopter.

The results have been compared and validated with other literatures within similar unsteady aerodynamic approach and general physical data, and within the physical assumptions limitations; encouraging qualitative agreements or better have been indicated, which meet the proof of concept objectives of the present work. For the bi-wing flapping ornithopter, judging from lift per unit span, the present flapping-wing model performance is comparable to those studied by Byl [37] and Harmon [32].The analysis and simulation by splitting the flapping and pitching motion shows that: (a) The lift is dominantly produced by the pitching motion, since the relative airflow effect prevailed along 75% of the chord length. (b) The thrust is dominated by flapping motion (c) Phase-lag could be utilized to obtain optimum lift and thrust for each wing configurations.

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References

[1] Ellington CP, The Aerodynamics of Hovering Insect Flight, III. Kinematics, Phil. Trans. R. Soc. London B, 305, pp 41-78, 1984.
[2] Ellington CP, The Novel Aerodynamics of Insect Flight: Applications to Micro-Air Vehicles, *The Journal of Experimental Biology* 202, pp 3439–3448, 1999.
[3] Ellington CP, The Aerodynamics of Hovering Insect Flight, I, Quasi-Steady Analysis," *Phil.Trans. of Roy.Soc.London, B, Bio.Sci.*, Vol 35, No 1122, Feb 1984.
[4] Ho S, Nassef H, Pornsinsirirak N, Tai YC and Ho CM, Unsteady Aerodynamics and Flow Control for Flapping Wing Flyers, *Progress in Aerospace Sciences* 39, pp 635–681, 2003.
[5] Weis-Fogh T, Quick Estimates of Flight Fitness in Hovering Animals, Including Novel Mechanisms for Lift Production. *Journal of Experimental Biology* 59, pp 169–230, 1973.
[6] Shyy W, Berg M and Ljungqvist D, Flapping and Flexible Wings for Biological and Micro Air Vehicles, *Progress in Aerospace Sciences*, Vol. 35: pp 455-505, 1999.
[7] Shyy W, Aono H, Chimakurthi S K, Trizila P, Kang C-K, Cesnik C E S and Li H. Recent Progress in Flapping Wing Aerodynamics and Aeroelasticity, *Progress in Aerospace Science*, 2010.
[8] Dickinson M H, Lehmann F O and Sane S P, Wing Rotation and the Aerodynamic Basis of Insect Flight, Science 284, pp 1954, 1999.
[9] Żbikowski R, On Aerodynamic Modelling of an Insect-like Flapping Wing in hover for Micro Air Vehicles, *Phil. Trans. R. Soc. Lond. A* 360, pp 273-390, 2002.

[10] Ansari S A, Żbikowski R and Knowles K, Aerodynamic Modelling of Insect-like Flapping Flight for Micro Air Vehicles, *Progress in Aerospace Sciences* 42, pp 129–172, 2006.
[11] DeLaurier J D, An Aerodynamic Model for Flapping Wing Flight, *The Aeronautical Journal of the Royal Aeronautical Society*, pp. 125-130, 1993.
[12] Rosenfeld N C, An Analytical Investigation of Flapping Wing Structures for MAV, Ph.D. Thesis, University of Maryland, 2011.
[13] Nicholson B, Page S, Dong H and Slater J, Design of a Flapping Quad-Winged Micro Air Vehicle, AIAA-4337, 2007.
[14] Maybury W J and Lehmann F-O, The Fluid Dynamics of Flight Control by Kinematic Phase Lag Variation Between Two Robotic Insect Wings, *Journal of Experimental Biology*, Vol. 207, pp 4707-4726, 2004.
[15] Ratti J, QV-The Quad Winged, Energy Efficient, Six degree of Freedom Capable Micro Air Vehicle, PhD thesis, Georgia Institute of Technology, 2011.
[16] Prosser D T, Flapping Wing Design for a Dragon-fly like MAV, M.Sc. Thesis, Rochester Institute of Technology, 2011.
[17] Wang Z J and Russell D, Effect of Forewing and Hindwing Interactions on Aerodynamic Forces and Power in Hovering Dragonfly Flight, Physical Review Letters 99, 148101, 2007.
[18] Lentink D, Jongerius S R and Bradshaw N L, The Scalable Design of Flapping Micro-Air Vehicles Inspired by Insect Flight, Flying Insects and Robots, pp 185-205, 2010.
[19] Theodorsen T, General Theory of Aerodynamic Instability and the Mechanism of Flutter, NACA Report No.496, 1949.
[20] Jones R T, The Unsteady Lift of a Wing of Finite Aspect Ratio, NACA Report 681, 1940.
[21] Kuethe A M, Chow C-Y, *The Finite Wing, Foundations of Aerodynamics*, 4th ed, John Wiley, New York, pp145-164, 1986.
[22] Garrick I E, Propulsion of a Flapping and Oscillating Aerofoil, NACA Report No.567, 1936.
[23] Ashley H, Landahl M T and Widnall S E, New Directions in Lifting Surface Theory, *AIAA journal*, 3, No.1, 1965.
[24] Albano A and Rodden W P, A doublet-lattice method for calculating lift distributions on oscillating surfaces in subsonic flows, *AIAA Journal*, Vol. 7, No. 2, pp. 279-285, 1969.
[25] Djojodihardjo H and Widnall S E, A numerical method for the calculation of nonlinear, unsteady lifting potential flow problems, 1969, *AIAA Journal*, Vol. 7, No. 2, pp. 2001-2009, 1969
[26] Murua J, Palacios R, and Graham, J M R, Applications of the Unsteady Vortex-Lattice Method in Aircraft Aeroelasticity and Flight Dynamics Preprint submitted to Progress in Aerospace Sciences August 1, 2012
[27] Djojodihardjo H and Ramli ASS, Kinematic And Unsteady Aerodynamic Modelling, Numerical Simulation And Parametric Study Of Flapping Wing Ornithopter, Proceedings, *International Forum on Aeroelasticity and Structural Dynamics*, Bristol, 2013.
[28] Djojodihardjo H and Ramli A S S, Generic and Parametric Study of the Aerodynamic Characteristics of Flapping Wing Micro-Air-Vehicle, *Applied Mech. and Materials*, Trans Tech Publications, Switzerland,Vol.225, pp 18-25, 2012.
[29] Djojodihardjo H and Ramli, A S S, Kinematic and Aerodynamic Modeling of Flapping Wing Ornithopter, *Procedia Engineering* (Elsevier), Vol. 50, 2012, pp 848-863, 2012.
[30] Djojodihardjo H and Bari M A A , Further Development of the Kinematic and Aerodynamic Modeling and Analysis of Flapping Wing Ornithopter from Basic Principles, Submitted to *Aerotech Conference 2014*, October 29-30 2014, Kuala Lumpur, Malaysia
[31] Djojodihardjo H and Bari M A A, Kinematic and Unsteady Aerodynamic Modelling of Flapping Wing. Submitted for publication, 2014 .
[32] Polhamus E C, A Concept Of The Vortex Lift Of Sharp-Edge Delta Wings Based On A Leading-Edge-Suction Analogy, NASA TN D-3767, 1966.
[33] Harmon R L, Aerodynamic Modelling of a Flapping Membrane Wing Using Motion Tracking Experiments, M.Sc. Thesis, University of Maryland, 2008.
[34] Scherer J O, Experimental and Theoretical Investigation of Large Amplitude Oscillating Foil Propulsion Systems, Hydronautics, Laurel, Md, December 1968.
[35] Garrick I E, On Some Reciprocal Relations in the Theory of Nonstationary Flows, NACA Report 629, 1938.
[36] Anderson J D, *Fundamentals of Aerodynamics*, fourth ed., McGraw-Hill, New York.2004.
[37] Ou, K. and Jameson, A., Towards Computational Flapping Wing Aerodynamics of Realistic Configurations using Spectral Difference Method, AIAA 2011-3068, 20th AIAA CFD Conference, 2011
[38] La Mantia, M. and Dabnichki, P., Unsteady Panel Method for Oscillating Foils, in Advances in BE Tech., Gatmiri, Sellier, Aliabadi, BETEQ-2006-part2, 2006
[39] Von Karman, T. and Burgers, J. M.,, General Aerodynamic Theory - Perfect Fluids," Division E, Vol. II, Aerodynamic Theory, Ed. Durand, W. F., 1943, p.
[40] Jones, K.D. and Platzer, M.F., Numerical Computation of Flapping-Wing Propulsion and Power Extraction, AIAA–97–0826-NPS Lib.
[41] Yu, Tong, Ma, An Analytic Approach To Theoretical Modeling of Highly Unsteady Viscous Flow Excited By Wing Flapping in Small Insects, Acta Mech.Sinica, V19, N6, Dec 2003

[42] Pennycuick C J, Predicting Wingbeat Frequency and Wavelength of Birds, *The Journal of Experimental Biology*150, pp 171 – 85, 1990.
[43] Read, Hover and Triantafyllou, Forces on Oscillating Foils for Propulsion and Maneuvering, Journal of Fluids and Structures, 17 (1), pp 163-183, 2003.
[44] Schouveiler H and Triantafyllou, Performance of Flapping Foil Propulsion, *Journal of Fluids and Structures*, 20 (7), pp 949-959, 2005.
[45] Byl K, A Passive Dynamic Approach for Flapping Wing Micro Aerial Vehicle Control, *ASME Dynamic Systems and Controls Conference*, 2010. http://www.ece.ucsb.edu/~katiebyl/papers/Byl10_DSCC.pdf
[46] Norberg, U.M., Hovering Flight of *Plecotus auritus*, L. Bijdr. Dierk 40, *Proc.2nd int. Bat.Res, Conf*., pp 62-66, 1970.
[47] Tedrake R, Jackowski Z, Cory R, Roberts J W and Hoburg W, Learning to Fly like a Bird, *Communications of the ACM*, 2009.
[48] Altshuler D L, Dudley R, Ellington C P, Aerodynamic Forces of Revolving Hummingbird Wings and Wing Models, *J. Zool*, Land., 264, pp 327-332, 2004.
[49] Kesel A B, Aerodynamic Characteristics of Dragonfly Wing Sections Compared with Technical Airfoils, *J. Exp. Biol*. 203,pp 3125-3135, 2000.
[50] Tucker V A, Gliding Birds: The Effect Of Variable Wing Span, *J. Exp. Biology*, 133, 1987.
[51] Mueller D, Bruck H A and Gupta, S K, Measurement of Thrust and Lift Forces Associated with Drag of Compliant Flapping Wing for Micro Air Vehicles using a New Test Stand Design, *Experimental Mechanics* 50, pp 725–735, 2009.
[52] Deng X and Hu Z, Wing-wing Interactions in Dragonfly Flight, A Publication of Ine-Web.Org, 10.2417/1200811.1269, 2008.
[53] Jones K D and Platzer M F, Numerical Computation of Flapping-Wing Propulsion And Power Extraction, *AIAA*−97−0826-NPS Lib.
[54] Triantafyllou M S and Triantafyllou GS, An efficient swimming machine, *Scientific American*; Vol. 272 Issue 3, web.mit.edu, 1995.
[55] Wang J, Dissecting Insect Flight, *Ann.Rev.Fl.Mech*. 2005, 37, pp 183-210.
[56] Jones and Platzer, On the Use of Vortex Flows for the Propulsion of Micro-Air & Sea Vehicles, MP-069(I)-(SYA)-40
[57] Xu B and Wang J, Passive wing pitch reversal in insect flight, *JFM 2007*, Vol. 591,pp 321-327
[58] Phillips N and Knowles K, Formation of the Leading-edge Vortex and Spanwise Flow on an Insect-like Flapping-wing throughout a Flapping Half Cycle, https://dspace.lib.cranfield.ac.uk/bitstream/1826/.../manuscript%20final.p
[59] Warrick D R, Tobalske B W and Powers D R, Lift production in the hovering hummingbird, *Proc. R. Soc.* B 276, pp 3747–3752, 2009

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