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Aerodynamic Analysis of Ornithopter

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Abstract—*An Ornithopter is said to be different from a fixed wing aircraft in the following areas such as Kinematics, Aerodynamics, navigation,..etc. There are various aerodynamic parameters which also includes reduced frequency, Strouhal number are studied along with vortex wake theory. The mechanics of flapping wing micro aerial vehicle MAV which utilizes the flapping, feathering motion of the bird pigeon (Columbia Livia) . A comparative study is carried out between UAV (Unmanned Aerial Vehicle) and MAV(Micro Aerial Vehicle). On the basis of design of unsteady aerodynamics of flapping wing that has been encountered with modified strip theory approach. The application of MAV includes in the vast areas of surveillance, target seeking, etc.*

Keyword: *Micro aerial vehicle, flapping wing, vortex*

1. INTRODUCTION

There is a long term human desire to replicate the way bird fly in the sky. There has been an evolution of different types of system and modeling of aircraft which has now given rise to autonomous ornithopter unmanned air vehicle (UAV). Ornithopter is said to be different from a fixed wing aircraft in the following areas such as kinematics, aerodynamics navigation and stability. These are said to be complicated when compared . A study of such parameters and by different methods by which optimization of design parameters and characterization of behaviour in the aerodynamic performance and flight control is carried out. It promotes reduction of human work in civil and military field.

There are many theories proposed namely in Vortex wake Theory, a shed vortex wake analysis are done through which lift calculation by moving the production of a new downward momentum in the wake, while the induced drag must be equal to the wake's kinetic energy per unit .From the researches there remains a conclusion that there are two types of wake ,one for low speed and another for high speed. A deep study for the propulsive efficiency in the case of UAV and the average lift and thrust parameters are studied in the following .

2. NON CONVENTIONAL AERODYNAMIC PARAMETERS

As in the case of fixed wing flight, there are import on dimensional parameters that provide in depth understanding about flapping flight aerodynamics and performance.

1. Reduced Frequency

It is denoted by "k" (frequency), a ratio of flapping velocity to the reference velocity.

$$k = \left[\frac{(W)C_{ref}}{2(U_{ref})} \right]$$

where
C_{ref} = Wings reference chord
U_{ref} = Reference velocity which is the forward flight velocity
W = Angular velocity of flapping wing

Reduced frequency indicates the degree to which unsteady aerodynamic effects are presents. As "K" approaches zero the wing tends toward a quasi steady state while that of a slow forward flight with large flapping frequency that results in a unsteady flow.

2. Strouhal Number

Another non dimensional parameter that describes kinematics of flapping flight is the Strouhal Number, which describes flapping frequency "F" and vertical wing tip amplitude "A" by a forward vehicle speed "V". It indicates propulsive efficiency, a measure of mechanical Power input to power output.

$$St = \frac{FA}{V}$$

Efficiency of 70% was achieved within Strouhal Number range as follows

$0.2 < St < 0.4$
with a peak efficiency at St = 0.3 (approx.). When the kinematics cause maximum amplification of the Shed vortices in the wake and an average velocity profile equivalent to a jet.

What type of UAV to be used?

Some of the factors which are said to be dominating are as follows.

- Payload weight
- Altitude
- Flight speed
- Duration to stay aloft
- Maneuverability
- Controlling
- Type of launch
- Type of landing

Fixed wing

This is the traditional modeling criteria of UAV that was sustained for a long period of time since it provides a stable, controllable system for various range of aircraft size and missions.

These fixed wing aircraft are said to be found difficult to maintain at low Reynolds number.

This is due to the limited usage of span which increases the wing loading and decreases lift produced. To avoid such problems wing chord is said to be extruded and thereby tends to become a plan form "of flying wing" geometric configuration. This plan form decreases the aspect ratio and increase induced drag with the condition of downwash often affecting more than lay the wing span adversely.

Most of the fixed wings cannot perform VTOL (Vertical take off landing) or hover over a target without a specialized propulsion system.

In this paper a design oriented model for the unsteady aerodynamic of a flapping wing has been studied using a model strip theory approach.

The analysis is said to be design oriented, capable of being readily implemented for the performance prediction of a variety configurations. Most of the previous work falls into two categories. The first is the quasi – steady model where unsteady wake effects are ignored. That is, flapping frequencies are assumed to be slow enough that shed wake effects are negligible, although such an assumption gives a great simplification to the aerodynamic modeling. One of the simplest examples is given by Kuchemann and von Holst where a rigid elliptical – planform wing is assumed to be performing span wise uniform motions, whereas Schmedilder presents a much more detailed analysis using lifting- line theory to predict the performance of a root – flapping wing. One of the most refined versions of the lifting – line approach is offered by Betteridge and Arcer, where they use their analysis to investigate the possibility of optimized flapping behaviour.

The quasi-steady approach also includes models of intermediate complexity, where the aerodynamic points on the wing. Walker chooses three points along the semispan of a root- flapping wing, and assumes the motion to be such that the lift and drag are constant values on the down stroke and different constants on the upstroke. Norberg chooses a single representative point, at 70% of the semispan, performing sinusoidal motion with constant lift – curve slope coefficients throughout the flapping cycle.

The second category accounts for the unsteady aerodynamic effects by modeling the wake in a variety of ways. Among those analyses that include the mean lift required for equilibrium flight (as compared with studies of animal swimming), Philips, East, and Pratt represent the unsteady wake of a root – flapping non twisting rigid wing with discrete nonplanar vortex elements which include spanwise vortices spaced one per half cycle aft of the quarter – chord bound vortex. A similar model was developed by Blackwell and Archer for their study of the propulsive characteristics of a twisting wing, root flapping with constant, but unequal, upstroke and down stroke motions ("saw tooth motion")

The present analysis does not assume a variable span. Since the motivation was to study the feasibility of mechanical flapping wing flight, it was felt that an important first step was to see if this was achievable without having to envision a span variation mechanism. However, the kinematics do allow for span wise bending and twisting.

3. CASE STUDIES

Case 1

Methods of Analysis for UAV

The kinematics for each section of the wing are said to be analyzed from the Fig. 1.1 on using the leading edge as a reference point, the section's motion consists of a plunging velocity, *h*, and a pitch angle, θ, where *h* is not necessarily perpendicular to the mean stream velocity, *U*.

$(dN_c)_{sep}$ = The midchord cross –chord force
$(dN_a)_{sep}$ = An apparent- mass force that is assumed to be 1/2 dN_a
(dN_a) = Apparent mass force normal to the chord at the 1/2 chord location .

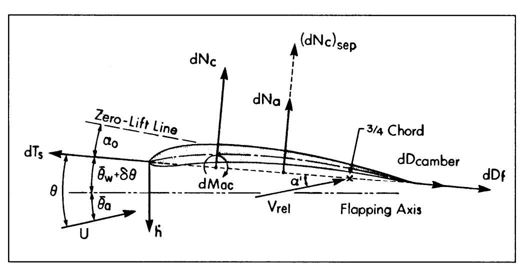

Fig. 3.1: Aerodynamic forces of wing section and motion variables

If the wing is root flapping, as shown in Fig.1.2, then *h* would be perpendicular to the flapping axis.

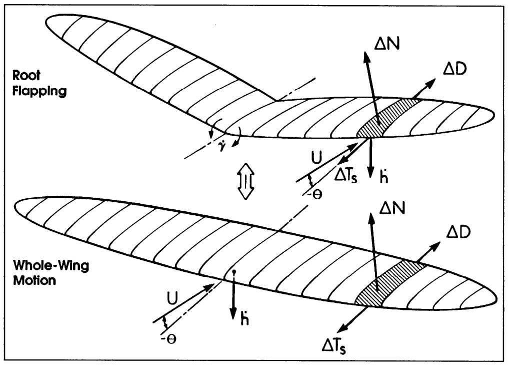

Fig. 3.2 Assumed strip theory equivalence to whole wing motion

The wing's aspect ratio is assumed to be large enough that the flow over each section is essentially chord wise (in the mean – stream direction). Therefore, the section's circulatory normal force is given by

$$dN_c = \frac{\rho UV}{2} C_n(y)\, c\, dy \qquad (1)$$

V is the flow's relative velocity at the 1/4 –chord location, and

$$Cn(y) = 2\pi(\alpha'\alpha' + \bar{\theta}) \qquad (2)$$

The parameters in Equation (2), are illustrated in Fig.3.1, where it is seen that the angle of the zero lift line, α_0, is a fixed value for the aerofoil, and is the section's mean $\bar{\theta}$ is the section's mean pitch angle. Further, $\bar{\theta}$ is given by the sum :

$$\bar{\theta} = \bar{\theta}_a + \bar{\theta}_w \qquad (3)$$

Where $\bar{\theta}_a$ is the angle of the flapping axis with respect to the mean – stream velocity *U* and $\bar{\theta}w$ is the mean angle of the chord with respect to the flapping axis. Note that if the wing does not have a flapping axis (such as for whole – wing motions), the $\bar{\theta}$ is the wing's mean pitch angle.

The reaming angle in Equation (2), α', is given by

$$\alpha' = \left[\frac{ARC'(k)}{2+AR}\right]\alpha - \frac{w_0}{U} \qquad (4)$$

Where α is the relative angle of attack at the ¾ - chord location due to the wing's motion :

$$\alpha = \frac{\left(h\cos(\theta - \bar{\theta}_a)\right) + \frac{3}{4}c\theta + U\left(\theta - \bar{\theta}\right)}{U} \qquad (5)$$

The coefficient of α in Equation (4) accounts for the wing's finite span unsteady vortex wake by means of a strip theory model. As in Fig 3.2, each chordwise strip on the wing is assumed to act as if it were part of an elliptical planform wing, of the same aspect ratio, execution of simple harmonic whole wing motion identical to that the strips. For such a wing, on deviation of the unsteady normal – force coefficient, δC_n is given by

$$\delta C_n = 2\pi C(k)_{jones}\alpha \qquad (6)$$

Where $C(k)_{Jones}$ is a modified The odorsen function for finite AR wings and k is the reduced frequency, given by

$$k = \frac{c\omega}{2U} \qquad (7)$$

$C(k)_{Jones}$ is a complex function, and it was found convenient to use Scherer's alternative formulation :

$$C(k)_{Jones} = \frac{ARC'(k)}{(2+AR)} \qquad (8)$$

Where, for the complex term given by

$$C'(k) = F'(k) + iG'(k) \qquad (9)$$

Scherer presents the approximate equations :

$$F'(k) = 1 - \frac{C_1 k^2}{\left(k^2 + C_2^2\right)}$$

$$G'(k) = -\frac{C_1 C_2 k}{\left(k^2 + C_2^2\right)}$$

$$C_1 = \frac{0.5AR}{\left(2.32 + AR\right)}$$

$$C_2 = 0.181 + \frac{0.772}{AR}$$

Upon noting that the assumed motion is given by

$$\alpha = Ae^{i\omega} \qquad (10)$$

One obtains, when Equations (7), (9), and (10) are substituted into Equation (4), that

$$\alpha' = \frac{AR}{\left(2+AR\right)}\left[F'(k)\alpha + \frac{c}{2U}\frac{G'(k)}{k}\alpha\right] - \frac{w_0}{U} \qquad (11)$$

The downwash term, w_0 / U, is due to the mean lift produced by α_0 and $\bar{\theta}$, stay consistent with the strip theory model assumed for the unsteady aerodynamic terms, the w_0/U could be approximated by the downwash for an untwisted elliptical planform wing,

$$\frac{w_0}{U} = \frac{2(\alpha_0 + \bar{\theta})}{2 + AR} \quad (12)$$

However, if the wing has significant span wise variation of $\alpha_0 + \bar{\theta}$, then one may wish to calculate w_0/U by a more accurate method, such as the extended lifting – line theory for twisted wings,

Returning to Equation (1), note that the flow velocity, V, must include the downwash as well as the wing's motion relative to U. This accomplished by including α' along with the kinematic parameters:

$$V = \left\{ \left[UCos\theta - hSin(\theta - \bar{\theta}_\alpha) \right]^2 + \left[U(\alpha' + \bar{\theta}) - \frac{1}{2} c\theta \right]^2 \right\}^{\frac{1}{2}} \quad (13)$$

An additional normal force contribution comes from the apparent mass effect, which acts at the midchord (shown Fig.1.1) is given by .

$$dN_\alpha = \frac{\rho\pi c^2}{4} v_2 dy \quad (14)$$

Where v_2 is the time rate of change of the midchord normal velocity component due to the wing's motion:

$$v_2 = U_\alpha - \frac{1}{4} c\theta \quad (15)$$

Therefore, the section's total attached flow normal force is

$$d/V = dN_c + dN_a \quad (16)$$

The section's circulation distribution likewise generates forces in the chordwise direction, as illustrated in Fig.1.1 From De Laurier, the chordwise force due to camber is given by

$$dD_{camber} = -2\pi\alpha_0 (\alpha' + \bar{\theta}) \frac{\rho UV}{2} cdy \quad (17)$$

Garrick's expression for the leading edge suction of a two dimensional aerofoil may be applied to the present strip theory model by extending it with Equation (4) to obtain

$$dT_s = \eta_s 2\pi \left(\alpha' + \bar{\theta} - \frac{1}{4} \frac{c^\theta}{U} \right)^2 \frac{\rho UV}{2} cdy \quad (18)$$

The efficiency term, η_s, accounts for the fact that most aerofoils, due to viscous effects have less than the 100% leading edge suction predicted by potential – flow theory.

Viscosity also gives a chordwise friction drag

$$dD_f = (C_d)_f \frac{\rho V_x^2}{2} cdy \quad (19)$$

where V_x is the flow speed tangential to the section, approximated by

$$V_x = UCos\theta - hSin(\theta - \bar{\theta}_\alpha) \quad (20)$$

And $(C_d)_f$ is the drag coefficient due to skin friction, for which expressions may be found in Hoerner. Thus the total chordwise force is

$$dF_x = dT_s - dD_{camber} - dD_f \quad (21)$$

An advantage of the strip theory model is that it allows for an approximation to localised post stall behaviour. The dynamic stall angle is obtained from Prouty.

$$\alpha_{stall} = (\alpha_{stall})_{static} + \xi \left[\frac{c\alpha}{2U} \right] \frac{1}{2} \quad (22)$$

And is chosen to apply at the leading edge. Therefore, the criterion for attached flow over the section is

$$(\alpha_{stall})min \le \left[\alpha' + \bar{\theta} - \frac{3}{4} \left(\frac{c\theta}{U} \right) \right] \le (\alpha_{stall})_{max} \quad (23)$$

When the attached flow range is exceeded, totally separated flow is assumed to abruptly occur, for which condition all chordwise forces are negligible:

$$dD_{camber}, dT_s, dD_f = 0 \quad (24)$$

and the normal force is given by

$$dN = (dN_c)_{sep} + (dN_a)_{sep}$$

$(dN_c)_{sep}$, shown in Fig.1, is due to cross flow drag:

$$(dN_c)_{sep} = (Cd)_{cf} \frac{\rho VV_n}{2} cdy \quad (26)$$

Where

$$V = \left(V_x^2 + V_n^2 \right)^{\frac{1}{2}} \quad (27)$$

And V_n is the midchord normal velocity component due to the wing's motion (note that v_2, in Equation (15), is the linearised time – derivative of V_n):

$$V_n = hCos(\theta - \bar{\theta}_a) + \frac{1}{2} c\theta + USin\theta \quad (28)$$

Also, $(dN_a)_{sep}$ is due to apparent – mass effects, assumed to be half that of the attached flow value in Equation (14) :

$$(dN_a)_{sep} = \frac{1}{2}dN_a \tag{29}$$

Now, the equations for the segment's instantaneous lift and thrust are

$$dL = dN\cos\theta + dF_x\sin\theta \tag{30}$$

$$dT = dF_x\cos\theta - dN\sin\theta \tag{31}$$

These may be integrated along the span to give the whole wing's instantaneous lift and thrust :

$$L(t) = 2\int_0^{\frac{1}{2}}\cos\gamma \tag{32}$$

$$T(t) = 2\int_0^{\frac{b}{2}} dT$$

where $\gamma(t)$ is the section's dihedral angle at that instant in the flapping cycle.

$$\phi = \omega \tag{33}$$

where ϕ = cycle angle t= that instant of time

so that the average lift and thrust are expressed as

$$\overline{L} = \frac{1}{2\pi}\int_0^{2\pi} L(\varphi)\,d\varphi$$

$$\overline{T} = \frac{1}{2\pi}\int_0^{2\pi} T(\varphi(\,d\varphi \tag{34}$$

To obtain the instantaneous power required to move the section against its aerodynamic loads. For attached flow, this is given by

$$dP_{in} = dF_x\, h\sin\left(\theta - \overline{\theta}_a\right) + dN\left[h\cos\left(\theta - \overline{\theta}_a\right) + \frac{1}{4}c\dot{\theta}\right]$$

$$+dN_a\left[\frac{1}{4}c\dot{\theta}\right] - dM_{ac}\,\dot{\theta} - dM_a\dot{\theta} \tag{35}$$

where dM_{ac} is the section's pitching moment about its aerodynamic centre, and dM_a includes apparent –camber and apparent – inertia moments:

$$dM_a = -\left[\frac{1}{16}\rho\pi c^3\dot{\theta}U + \frac{1}{128}\rho\pi c^4\ddot{\theta}\right]dy \tag{36}$$

For separated flow, the input power expression becomes

$$dP_{in} = dN_{sep}\left[h\cos\left(\theta - \overline{\theta}_a\right) + \frac{1}{2}c\dot{\theta}\right] \tag{37}$$

The instantaneous aerodynamic power absorbed by the whole wing is found from

$$P_{in}(t) = 2\int_0^{\frac{b}{2}} dP_{in} \tag{38}$$

and the average input power, throughout the cycle, is given by

$$\overline{P}_{in} = \frac{1}{2\pi}\int_0^{2\pi} dP_{in} \tag{39}$$

Upon noting that the average output power from the wing is

$$\overline{P}_{out} = \overline{T}U \tag{40}$$

the average propulsive efficiency may be calculated from

$$\overline{\eta}_p = \frac{\overline{P}_{out}}{P_{in}} \tag{41}$$

Case 2

Method of Analysis for MAV

There are four degrees of freedom in each wing that are used to achieve flight in nature namely flapping, lagging, feathering, and spanning. Flapping is an angular movement of the wing about an axis in the direction of flight. Lagging is an angular movement of the wing about a vertical axis which effectively moves the wing forward and backward parallel to the body. Feathering is the angular movement about an axis in the wing which tilts the wing to change its angle of attack. Spanning is the expanding and contracting of the wing span.

These motions somehow requires a universal joint similar to the shoulder of a human being. But not all flying animals implement all of these motions. Most insects for instance do not use the spanning technique. Thus, flapping flight is possible with possible few combinations of these four degrees of freedom. Flapping flight is actually possible with only one degree of freedom by using "flapping" alone.

Several studies have been made on flapping flight using this one degree of freedom. From the work of Vest and Katz they pointed out that one-degree of freedom flapping MAV, modeled after a typical pigeon (*Columba livia*), can develop sufficient thrust to propel itself in a steady forward flight .

Of the four degrees of freedom available in flapping flight in nature, it is the combination of the flapping and feathering motions that makes the most significant contribution to the lift and thrust production. It is therefore practical to just utilize these two degrees of freedom in designing and building an effective bird-like MAV. Using these two degrees of freedom there are four important variables with respect to wing kinematics: (1) wing beat frequency, (2) wing beat amplitude, (3) wing feathering as a function of wing position, and (4) stroke plane angle. When properly coordinated, these motions can provide lift not only during downstroke, but also during upstroke. The ability to generate lift on both strokes leads to the potential for hovering flight in insect-like (entomopter) and bird-like (ornithopter) micro aerial vehicle.

Coupled flapping – feathering motion

With the aid of the analysis of the flow around a 2D airfoil in a combined plunging and pitching motion, the kinematics of the coupled flapping and feathering motion coupled be well established as described in Fig.3.3

The flapping angle, θ (the angle of inclination against the horizontal X- Y plane), and the feathering or pitching angle "α" and the plunging position "Z" are given by the following relationships,

$$\theta(t) = (\theta_0)\cos(2\pi ft) \quad (1)$$

$$\alpha(t) = (\alpha_0) + (\alpha_1)\cos(2\pi ft + \phi) \quad (2)$$

$$z(t) = (z_l)\cos(2\pi ft) \quad (3)$$

where f is the oscillation frequency, φ is the phase angle, and α_0 is the mean angle of attack.

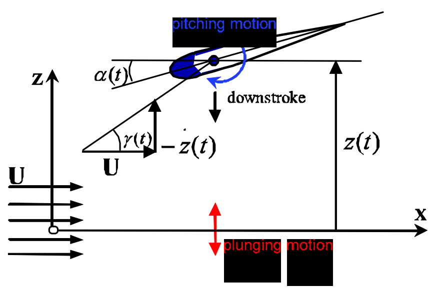

Fig. 3.3: Coupled plunging in and pitching motion

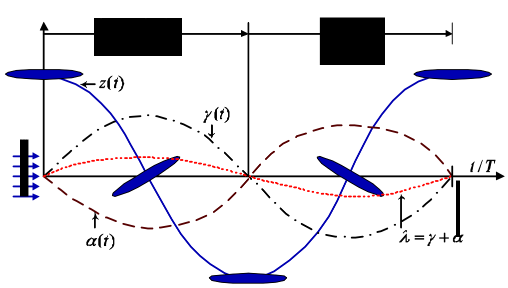

Fig. 3.4: Motion coordination by phase angle

where f is the oscillation frequency φ is the phase angle, and α0 is the mean angle of attack. The pitching motion defined in Eq.(2) consists of a time – dependent part with amplitude α_1.

The momentary pitching angle α(t) is counted from the horizontal parallel to the X – axis and the pitching motion can vary in phase φ relative to the plunging motion. The oscillation frequency 'f' is most often expressed in non – dimensional form as the reduced frequency (k),

$$k = \frac{\pi fc}{U_\infty} \quad (4)$$

Where U_∞ is the free stream velocity and C is the chord length. The reduced frequency, together with the dimensionless plunging amplitude (Z_l, /C) influences the angle of attack (γ) caused by pure plunging as shown in the Fig. and is given by,

$$\gamma(t) = \mathrm{Tan} - \frac{-z(t)}{U_\infty} \quad (5)$$

The maximum angle of attack through pure plunging for small values of k and Z_l/C is approximately,

$$\gamma_l \approx \frac{2kzl}{c} \quad (6)$$

where γ_l = Tan - γ

The momentary effective angle of attack, λ (γ ±α), can be enlarged or diminished depending on phase shift ϕ of the super imposed pitching motion in Eq.(2), and shown in fig.3.4 where the phase angle $\varphi = 90^o$. In order to ensure attached flow throughout the entire flapping cycle, λ is to be kept below 12^o to 15^o.

Basic aerodynamics

A flapping wing generates lift and thrust mainly by virtue of the so-called Knoller-Betz effect that is, the wing oscillations induce vertical lift force and longitudinal thrust force components of the aerodynamic force (the force normal to the direction of the free stream velocity relative to the flapping wing), and by the complex effects of the generated vortex structures which enable high lifting and propulsive properties. Lift and thrust generation can be increased by increasing the flapping amplitude or the flapping frequency as long as the flow remains attached to the airfoil. The aerodynamic lift, drag, and thrust coefficients can be expressed as follows:

$$C_L = \frac{L}{\frac{1}{2}\rho U^2 S}, \quad C_D = \frac{D}{\frac{1}{2}\rho U^2 S}, \quad C_T = \frac{T}{\frac{1}{2}\rho U^2 S}, \quad (7)$$

where *L, D, T, U, S,* and ρ are lift, drag, thrust, flight speed, wing planform area, and air density, respectively. In steady level flight, the lift force equals the body weight, W_g, and so the wing loading can be expressed as

$$L = W_g = \frac{1}{2}\rho U^2 S C_L \Rightarrow W_g/S = \frac{1}{2}\rho U^2 C_L \quad (8)$$

Power Requirement

It depends on

1) Weight of MAV
2) Flight speed
3) Aerodynamic parameter (C_L/C_D)

As the size reduces MAV becomes lighter and small physical size with low flight speed that results in lower Reynolds number, this causes (C_L/C_D) to decrease.

In a steady level flight, the average power output is given by

$$\overline{P_{out}} = \overline{T}U \quad (9)$$

$\overline{T}$ = Average thrust

U = Flight speed

The propulsive efficiency, η_P, for one flapping cycle. This

η_P measure the transformation essential parameter since it measures how well the input where

$$P_{in} / P_{out} = \eta_P \quad (10)$$

From the formulas by Rayner and Gordon for birds in continuous vortex wake model, the estimation of power to mass ratio for machines that can attain performance compared to birds.

Maximum range speed

$$Vmr(m/s) = 10.00 M^{0.413} B^{-0.553} S^{-0.095} \quad (11)$$

Mechanical power at that speed

$$P_{mr}(W) = 27.21\ M^{1.590} B^{-1.818} S^{0.275} \quad (12)$$

Total power

$$P_{met}(W) = 114.61\ M^{1.145} B^{-1.225} S^{0.523} \quad (13)$$

where

M = mass (kg)

B = Wingspan (m)

S = Wing plan form area (m^2)

The total power for flight in a bird is measured as the total rate of metabolic energy uptake P_{met}

4. CONCLUSION

Through these methods of analysis one shall predict the flight performance of harmonically flapping wings. The major assumptions are that, first, the semi span remains constant throughout the motion; and second, modified strip theory is used to model the aerodynamics. However, general distributions of span wise twisting and first order bending may be specified. Also, certain important real fluid effects are accounted for, such as post stall behaviour and partial leading edge suction. These are features which should be included in any accurate flapping- wing analyses, especially when applied to flying animals which usually have sharp edged wings with little leading edge suction.

This analysis for UAV shows that the constant – semi span model is also capable of efficient flapping – wing flight for certain conditions, such as may be experienced by large animals at high speeds, or ornithopter.

In the case of MAV the wing loading summarizes the opposing action between two classes of forces in flight: (1) the gravitational and inertial forces, and (2) the aerodynamic forces that are responsible for creating lift and thrust. The range of wing loading is limited by physical constraints. As an example, larger birds do not have high flapping frequency since their bones cannot withstand the stresses imposed by moving such a large inertial load.

Another important parameter in forward flight is the reduced frequency, k, which is a measure of the degree of unsteadiness and is given earlier in Eq. (4). The reduced frequency is simply a comparison of the angular velocity and the flow speed. As k increases, so does the flow unsteadiness. $k = 0$ corresponds to a rigid fixed-wing vehicle, while the normal cruising flight of a typical pigeon has $k = 0.25$.

REFERENCE

[1] J.D. DeLaurier, "An aerodynamic model for flapping –wing flight", *Journal of The Royal Aeronautical Society*, April 1993.

[2] Jonathan Maglasang, Koji Isogai, Norihiro Goto, and Masahide Yamasaki, Aerodynamic Study and Mechanization Concepts for Flapping – Wing Micro Aerial Vehicels", *Journal of Faculty of Engineering Kyushu University,* vol.66, No.1, March 2006.

[3] Dr.James E, Hubbard Jr., Department of Aerospace Engineering, "Aerodynamic Modeling of a Flapping Membrane Wing Using Motion Tracking Experiments" Robyn Lynn Harmon, Masters of Science, 2008.

[4] Betteridge, D.S and Archer, R.D.A study of the mechanics of flapping wings, *Aeronaut* Q, May 1974, pp 129-142

[5] Walker, G. The flapping flight of birds, J.R *Aeronaut Soc*, 1927, 31, pp 590-594.

[6] Blackwell, J. and Archer, R.D. Performance Characteristics of Simple Flapping Motion with Application to the Cruising Flight of Birds, University of New South Wales Report, 1985/FMT/1, ISSN 0156 3068.