THE COMPARATIVE EVALUATION OF POWER REQUIREMENTS FOR FIXED, ROTARY AND FLAPPING WINGS MICRO AIR VEHICLES

Maciej Lasek[\$], Jozef Pietrucha*, Krzysztof Sibilski*/**, Maria Zlocka *****
[\$]State Commission of Aircraft Accidents Investigation
***Air Force Institute of Technology, **Department of Aviation Engineering, Wroclaw University of Technology, Poland**
*****Faculty of Mechanics, Energetics, and Aviation , Warsaw University of Technology, Poland**

Keywords: *micro air vehicles, mechanics of flight, flight performance*

Abstract

In this paper we describe power requirements for micro air vehicles. We have researched three flight modes: fixed wing, rotary wing and flapping wing. We have calculated energy and power requirements for the three flight modes. As we can excepted, when there is no hover requirement, fixed wing flight is always most energy efficient for the micro air vehicle. However, if there is a hover requirement, the suitability of flapping or rotary wing flight is dependent on the mission profile and ambient windspeed.

Nomenclature

A	rotor disc area, [m^2]
b	wingspan, [m]
c	wing chord, [m]
C_{D0}	profile drag coefficient
C_{Lmax}	maximum lift coefficient
D	drag, [N]
E	energy, [J]
h	altitude, [m]
L	range, [m]
N	power, [W]
N_a	available power, [W]
N_r	required power, [W]
Re	Reynolds Number, [Uc/v]
S	wing area, [m^2]
S_e	sweeping area of flapping wings, [m^2]
t	time, [s]
T	thrust, [N]
U	free stream velocity, [m/s]
v_i	velocity induced by rotor, [m/s]
V	flight speed (EAS), [m/s]'
V_T	rotor tip velocity, [m/s]'
w_w	wind velocity, [m/s]
Q	MAV weight, [N]
α	incidence, [*deg.*]
Λ	aspect ratio
μ	advance ratio in rotor plane
η	propulsive efficiency
ρ	air density, [kg/nr^3]
σ	rotor solidity ratio
Ω	rotor rotational speed,[rad/s]

1. Introduction

The development of small (less than 6 inches, or hand-held) autonomous flying vehicles is motivated by a need for intelligent reconnaissance robots, capable of discreetly penetrating confined spaces and maneuvering in them without the assistance of a human telepilot. The ability to perform agile flight inside buildings, stairwells, ventilation systems, shafts and tunnels is of significant military and civilian value. The vehicles will fill the gap in the short-distance (less than ten miles) surveillance capabilities, not covered by today's satellites and spy planes. Such capabilities will be useful in battlefields (especially in urban warfare) and against terrorists. The vehicles can also be used in dull, dirty or dangerous (D^3) environments, where direct or remote human assistance is not feasible. Non-military uses of autonomous micro-air vehicles will, in time, exceed in scope and scale the defense applications. They will become standard equipment for law enforcement and rescue services. The ability to explore D^3 environments without human involvement will be of great interest for many industries - the vehicles will allow air quality sampling in no attainment areas, utility inspection (power lines, oil pipes), examination of human-inaccessible confined spaces in buildings, installations and large machines .

Micro air vehicle technology presents a variety of engineering challenges: aerodynamics, micro-electromechanical systems (MEMS). miniature propulsion, small-scale power storage, avionics and flight control, and many others. This paper concentrates on the aerodynamics and power requirements for flight at micro-scale (see [1, 2, 3]).

The shape and form of MAVs will depend very much on their mission requirements. An MAV that must travel appreciable distances at relatively high speed would probably be best suited to a fixed wing design. Alternatively, an MAV with a requirement for hover or agile maneuverability would best benefit from flapping-wing or rotary-motion propulsion. In this paper we provides calculations to estimate the power required for the flight of micro air vehicles, and to compare the advantages and disadvantages of the different flight modes. Our calculations are based on appropriate lift and drag data at low Reynolds numbers. All three flight modes (fixed wing, rotary wing and flapping wing) are considered to determine advantages and disadvantages for typical MAV missions.

2 Fixed wings flight

MAVs encounter Reynolds numbers much lower than conventional aircraft, hence viscous forces are much more significant. An efficient wing design must provide enough lift and sufficiently low drag for a vehicle where aerodynamic behavior is different to that of larger, faster aircraft. Boundary-layer characteristics at small sizes are different to that normally experienced by aeronautical engineers. They tend to be laminar rather than turbulent, so that airflow detaches more easily and laminar separation bubbles very much influence aerofoil behavior.

Nature's airfoils exhibit rounded leading edges and sharp trailing edges. The rounded leading edge is crucial to maintain attached flow around the airfoil over a reasonable range of angle of attack, thus minimizing drag. The maximum camber is near the leading edge suggesting that birds are likely to have flow control devices built into their feather structure.

A number of methods of predicting low Reynolds number aerofoil characteristics are available. The most common predictive method is the viscous/inviscid method. Generally a panel method coupled with Thwaite's method for calculation of laminar boundary layer properties and Head's method for calculation of boundary layer characteristics downstream of transition is used. This, indeed any predictive method, is only successful if the location and nature of transition is accurately calculated.

2.1. Power requirements for fixed wings aircraft

A first approximation of the power requirements for a fixed wing aircraft can easily be made by equating thrust with drag and lift with weight. This results in [4]:

$$N = \frac{1}{2}\frac{\rho V^3 S}{\eta_{prop}}\left(C_{D_0} + \frac{k}{\pi\Lambda}\left(\frac{Q}{S}\right)^2 \frac{2}{\rho V^2}\right) \qquad (1)$$

This is the power required for straight and level flight, which would normally be supplied by a propeller for this size of vehicle, and so the propulsive efficiency of the propeller, η_p, is required.

The low Reynolds numbers at which these propellers operate is likely to reduce their efficiency. Examination of data for man powered flight indicated that an efficiency of 75% was found for a propeller operating at these Reynolds numbers. However, the simple act of gluing a serrated strip turbulator at the 20% chord location of the propeller raised this efficiency to 89%.

The power requirement can be differentiated with respect to V to derive the minimum power velocity, V_{minp}. This can be found from the following expression [4]:

$$V_{minp}^2 = \frac{1}{\rho}\sqrt{\frac{4k}{3\pi\Lambda}}\left(\frac{Q}{S}\right) \qquad (2)$$

In subsequent calculations, C_{D0} was assumed to be 0.04 after examining data for low Reynolds number aerofoils (see ref [16, 17]). The aspect ratio was assumed to be 2..

Equation (1) reveals the following points: reducing the MAV weight whilst keeping the wing loading constant reduces the power requirement in direct proportion. The minimum power requirement flight speed, which is also the maximum endurance flight speed, is constant for constant wing loading, since it is simply a function of the geometry of the aircraft. Also, varying the wing loading at constant aircraft weight changes the maximum endurance speed; increasing the wing loading increases the maximum endurance speed. Increasing the wing loading also increases the power required at this speed. The minimum flight speed that can be achieved is also changed, since increasing the wing area reduces the minimum speed of which the aircraft is capable.

3 Rotary wings flight

Very little is published on rotary-wing aerodynamics at low Reynolds number. Data from nature stems from the performance ot natural rotary seeds (e.g. maple seeds). Papers [8, 9, 12, 13, 15, 16, 17, 18, 19, 21, 22, 30, 39] provides estimated aerofoil characteristics and aerodynamic performance of a variety of such species. For example, the maple seed *Acer diabolicum* has a mass of 006 grams, mean chord 84 *mm*, rotational speed of 100 1/sec. tip speed of 2-9 m/s. The Reynolds number, based on three-quarter radius and three-quarter velocity is 5,500. This is at the low end of the scale for MAVs and yet such seeds are shown to be able to achieve lift coefficients as high as 1-6 at up to angles of attack of 20°. A typical lift and drag coefficient plot [30, 39] for this seed is shown in Fig. 1.

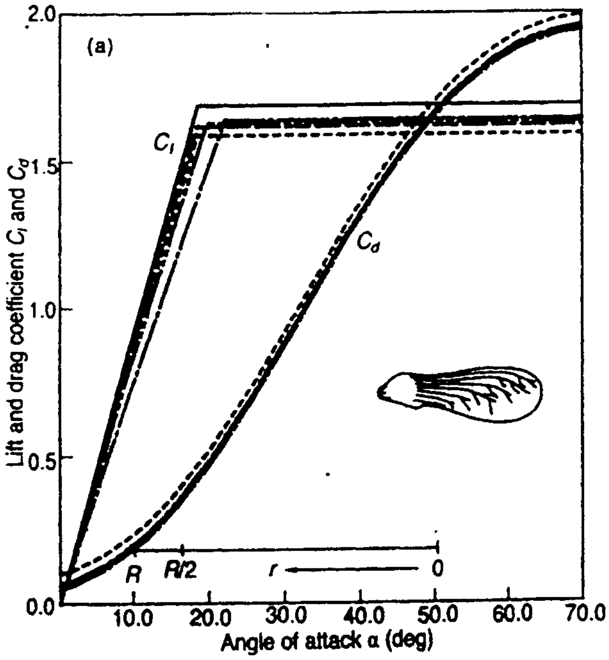

Fig. 1 Lift and drag of a rotary seed (cf. [30])

There are several internet sites on model flying helicopters and autogyros[1]. We found some engineering publications presenting a small scale wind tunnel tests for model propellers. For example we can mentioned papers [31], and [33] in which authors present experimental data for propellers over the range 0.1E6 < *Re* < 0.6E6 at different advance ratios and for RPMs between 3,200 and 6,400, and paper [34] in which authors tested a low Reynolds number aerofoil family for horizontal axis wind turbines over the range 4.0E5 < Re < 1.3E6.

3.1 Power requirements for rotary wings aircraft

The power required by a rotor for forward flight can be estimated using the following equation [43]:

$$N = \tfrac{1}{8}\rho A\sigma V_T^3 C_{D_0}\left(1+3\mu^2\right) + DU + Tv_i \qquad (3)$$

where: D is the drag of the fuselage and T means main rotor thrust (which perpendicular to the rotor disc).

[1] Some useful links could be found at internet address: http://www.rdmac.org.uk/links.htm

This technique utilizes a combination of an actuator disc theory to calculate the induced velocity coupled with blade element theory to estimate the profile power required. There are minima in the resulting Power *vs.* velocity curves for rotorcraft due to the interaction of the three terms in Equation (2). The first term, the profile power, rises as the forward velocity and hence the advance ratio increases. The second term, the parasite power also increases as the forward speed rises. However the final term, which is known as the induced power reduces as the forward speed rises.

In a similar manner to the fixed wing case, increasing the aircraft weight whilst keeping the disc loading constant results in a proportional increase in the power required throughout the velocity range. The minimum power velocity is therefore constant for constant disc loading.

Changes in disc loading have a large effect on the interaction of the three terms. Low disc loadings result in a low power requirement for hover, but there is a rapid increase in the power required at higher flight speeds. This is largely due to the much lower rotational speed that is utilized for a low disc loading. This results in the advance ratio, μ rising rapidly with forward speed and therefore the resulting profile power is large.

4. Flapping wings flight

There is a wealth of information dealing with flapping-wing flight at low Reynolds numbers, though the vast majority of such research has been conducted by biologists and zoologists. There is much information dealing with the aerodynamics of insect and bird flight [35, 36, 37, 38, 44]. However, the research is qualitative, usually in the form of flow visualization, and little is available on classic fixed-wing aerodynamics. Much of the engineering research stems from remarkably few sources. There is some limited work that has been undertaken to evaluate the incidence and velocity of the wing throughout its stroke [36, 37] but there is little that could be used to evaluate numerical models of the aerodynamic phenomena present over birds' wings.

There is a much larger volume of information available regarding the aerodynamics of flow over insect wings. Insect flight can be broadly divided into three areas. The first, and simplest, is the flight mode employed by the Diptera group of insects. The second mode is employed by "high performance" insects such as dragonflies which act as predators. The third and final insect mode of flight is found in creatures such as butterflies and moths. The characteristics of airfoils similar to those found on insects have been examined by Okamoto et all [38]

A number of techniques have been applied to calculate the flowfields over and around flapping wings. One such technique has been applied by Azuma [39]. This employed a "local circulation method" (LCM). This technique described each wing at each point in their motion as an elliptically loaded bound vortex. Although it is somewhat unclear from the description, it appears that any change in lift was described as a wake sheet of shed elements of bound vorticity. These elements, together with elements of trailing vorticity were then attenuated as time passed. No interaction between the vortices was calculated. The influence of the shed vortex wake on the wing was calculated using the Biot-Savart relationship. This technique was used to calculate spanwise loads over the wings during wingbeat cycles.

Hall and Hall [40] used a more sophisticated vortex lattice technique that, however, involved no wake dynamics. The technique was used to evaluate the spanwise load distributions that corresponded with minimum induced power required for a given flight velocity, stroke amplitude and flapping frequency. However, although the results appear plausible and included estimations of the circulation distribution in the wake no comparison with experimental data was made.

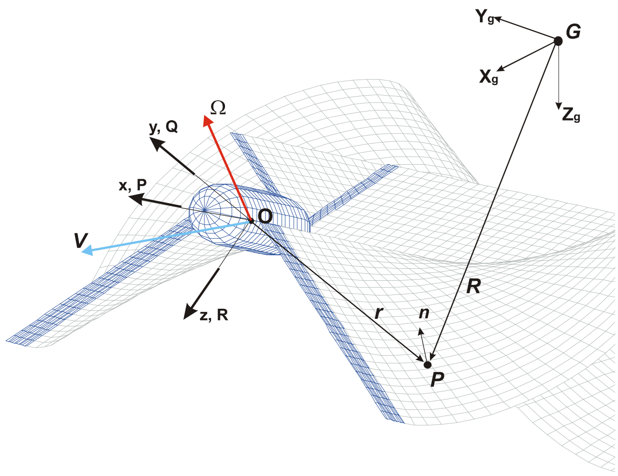

Fig. 2 Distribution of seed vorticity

Lasek et all [32] used an unsteady panel method, calculated the aerodynamic forces of flapping wings MAVs [see Fig. 2]. The results showed good agreement with the experimental data obtained in the vertical force but not in the horizontal force. It is not clear whether the discrepancy was due to the lack of suction force or not.

An alternative approach, aimed at the design of flapping wing vehicles has been attempted by Lasek et. all. [32], and DeLaurier [41]. This utilized a modified strip theory together with a number of semi-empirical equations to estimate the power required by a simply hinged wing of high aspect ratio. The use of a simple strip theory allowed an approximate allowance for post stall behavior to be made. No comparison was made with experimentally derived power

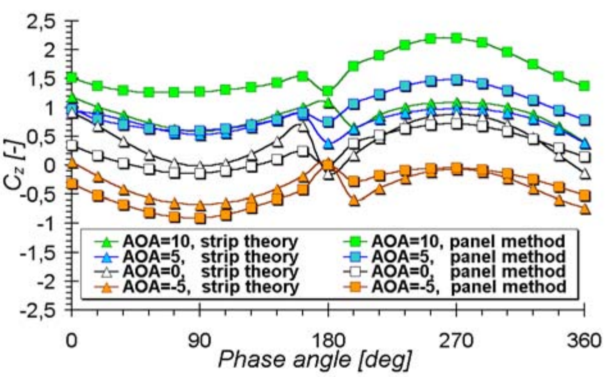

Fig. 3 Modified strip theory vs. panel methods. Lift coefficient [Lasek et all [32]

Figs. 3 and 4 depicts the comparison between results of calculations obtained from panel method and strip theory calculations. Good agreement between results obtained by those methods is shown.

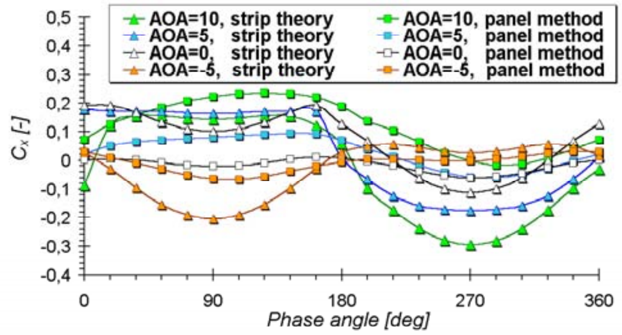

Fig. 4 Modified strip theory vs. panel methods. Drag coefficient [Lasek et all [32]

In order to verify nonlinear panel methods models, as well as modified strip theory approach, experimental investigations in wind tunnel at Institute of Aeronautics and Applied Mechanics of Warsaw University of Technology have been performed. The mechanism of the ornithopter model is shown in Fig. 5.

Fig. 5 Scheme of wind tunnel flapper [32].

It allows two degrees of freedom of wing movement: a) flapping of the wing around the longitudinal axis of model; 2) feathering around the axis of the wing. The ornithopter model was equipped with the rigid wings that data are as follows (for one wing): profile Clark Y; length 0.2 m.; chord 0.08 m.; relative thickness 0.12; mass 0.25 g. The measurements were carried out at the wing flapping frequency 5 Hz.

In experiments, the total flapping angle was admitted β=40 deg around the base position 0 deg. The mean value of the feathering angle ϑ

was taken in the most part of experiments as 10 deg.
Two cases of the amplitude of wing movement at 4 velocities 8, 12, 14 and 16 m/s were studied in the range of weak Reynolds numbers 4.0E10^4 to 8.0E10^4.

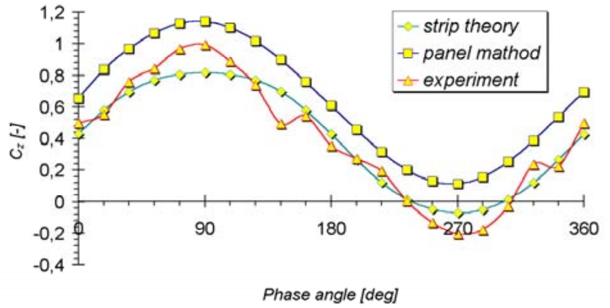

Fig. 6 Comparison between calculations and experimental results. Lift coefficient (cf. [32])

Some results of investigations are shown in Figs. 6 and 7. It can be stated a good agreement between calculations and results obtained from experiment.

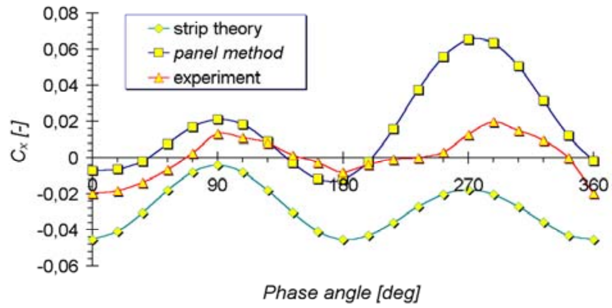

Fig. 7 Comparison between calculations and experimental results. Drag coefficient (cf. [32])

4.1 Power requirements for flapping wings MAVs

The most promising method for initial estimates of the power required for flapping wing flight has been found from Azuma [39]. This uses a simple momentum balance to calculate the "induced power" required that enables sufficient lift and thrust to be generated.
The amount of "profile power" is also estimated. This is simply derived by examining the drag acting on the living body and wings. These are then summed to result in the "necessary power". A simple formula to estimate the power required for flapping flight has been derived [39]:

$$N_n = N_0 + \left[\frac{1}{2}\rho S U^3\left(\frac{C_{L_0}^2}{\pi\Lambda} + C_{D_0}\right)\right] + \left[\frac{2Q^2}{\pi A \rho S U}\left(1 + \frac{2C_{D_0}}{\pi\Lambda}\right)\right] + \frac{Q}{U^5}\left(\frac{2Q}{\pi A \rho S}\right)^3 \quad (4)$$

Necessary Power (N_n) = Parasite Power (N_0)+Profile Powe + Induced Power 'Dram + **Induced Power (Thrust)**

This expression tends to infinity as the flight speed, U tends to zero. This is due to the induced power being based on the mean lift coefficient of the flapping wings (based on forward velocity, U). An alternative expression, also from Azuma [39], is therefore used to estimate the power requirement in hover. This is simply:

$$N_n = N_0 + Q\sqrt{\frac{Q}{2\rho S_e}} \quad (5)$$

where: where S_e is the sweeping area of the wings. In each of these expressions N_0 is the profile power required to overcome the wings friction. It is estimated simply as:

$$N_0 = \frac{1}{2}\rho V_T^2 S C_{D_W} \quad (6)$$

where V_T is the tip speed of the wing.
There are a number of assumptions implicit within this method. The main assumption is that the lift distribution over the wing is elliptical. At higher speeds and scales when the flow is attached this will be approximately true, but as the Reynolds number is reduced separated flow will become apparent. In particular, for insects at low speeds the flow is highly separated and dynamic lift effects are dominant, resulting in unusual spanwise load distributions. Analysis of these effects has not been undertaken in this formulas. However, the results of this technique have been compared with the power requirements for dragonflies [44], and good agreement

has been found. although a limited number of data points have been considered. These values of power in hover compare well with those

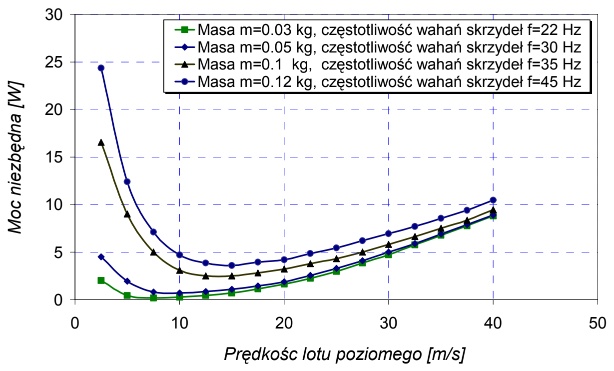

Fig. 8 Variation of flapping wing power requirement with MAV mass and flapping frequency

The effect of MAV mass and flapping frequency on the power required for flapping

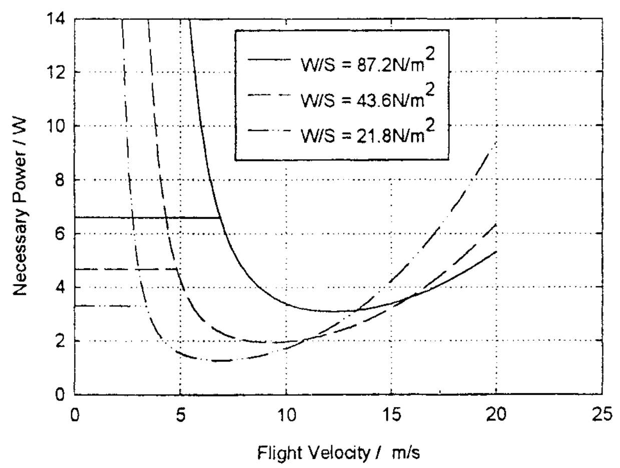

Fig. 9 Comparison of power requirements; mass = 50g (cf. [18])

In contrast to the results for fixed and rotary wing flight, the power required for forward flight does not scale linearly with the mass of the MAV, although the power required at hover does. There is a variation in the forward velocity at which minimum power is required. These results were obtained at constant wing loading.

The effect of wing loading on the power required for flapping wing flight is depicted in Fig. 9. Increasing the wing loading increases both the maximum endurance speed. The variation of necessary power with speed also changes: low wing loadings result in the necessary power rising more rapidly with increasing flight velocity. The weight of the MAVs for these power requirements were constant at 50 g.

5 Comparison of flight modes

A comparison of the power required for the three flight modes are displayed in Fig. 10. It is clear from this that flapping flight is not advantageous for the size of MAVs considered since the power requirements for this flight mode are larger than those required for fixed or rotary wing flight for all flight speeds. However, this is somewhat misleading, since the flapping wing vehicle considered has a very low aspect ratio of 10. Nature's MAVs exhibit aspect ratios much higher than unity, except in butterflies where unsteady aerodynamic effects are dominant.

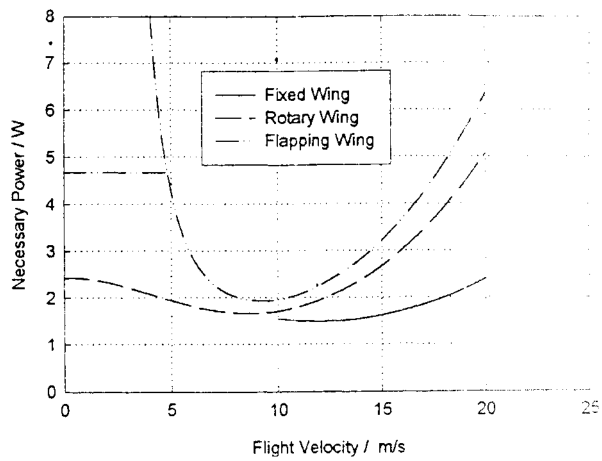

Fig. 10 Comparison of power requirements for three flight modes (cf. [18])

If the effect of aspect ratio on the power required for flapping wing flight is considered a rather different picture emerges. Figure 11 indicates the effect of changing the aspect ratio of the flapping wing whilst keeping the weight of the MAV together with its wing area constant. As is clear from this, the effect of increasing the aspect ratio of the wings is dramatic. The minimum required power drops from 21W to 0.6 W when increasing the aspect ratio from 1.0 to 5.0, a reduction of 71%, but the maximum endurance speed is also reduced from 9 m/s to 5 m/s.

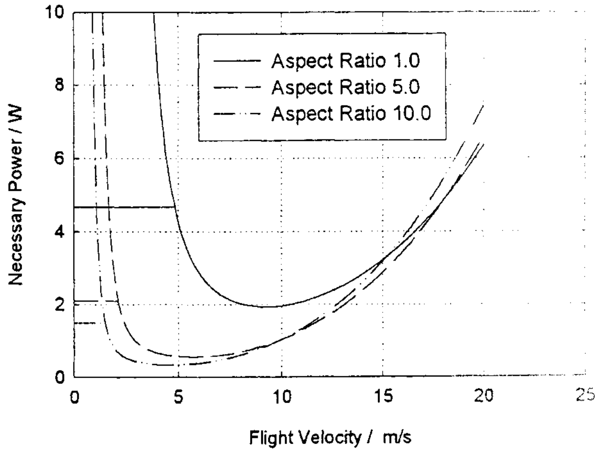

Fig. 11 Effect of aspect ratio on flapping wing flight

If the required power for the various flight modes for higher aspect ratio wings is now considered, as depicted in Fig. 12, it can be seen that flapping wing flight is now advantageous at low speeds, with fixed wing flight being much more efficient at higher flight velocities. However, rotary wing flight offers advantages if higher flight speeds are required in addition to the ability to hover since the rise in necessary power is less rapid as the flight speed increases.

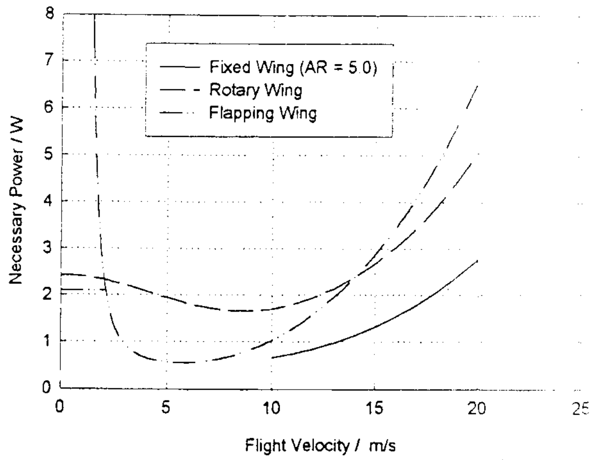

Fig. 12 Comparison of flight modes - mass = 50g (cf. [18]).

6 Conclusions

Power requirements for MAV flight using fixed, flap ping and rotary wing modes of propulsion have been calculated. Three typical MAV scenarios have been chosen.

When there is no hover requirement, fixed wing flight is always most energy efficient for the MAV.

If there is a hover requirement, at low speeds flapping flight is preferable to rotary wing flight. For high speeds rotary wing flight is preferable.

Acknowledgements

The paper was prepared as a part of the project (Grant No. T12C 023 30) financed by the State Committee of Scientific Researches

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