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Technical aspects of microscale flight systems

G. R. Spedding and P. B. S. Lissaman

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Micro Air Vehicles (MAVs) have excellent potential utility as flight platforms for optical, acoustic, electronic and chemical sensors for operation in hazardous sites with aerial access. The dimensions and performance specifications call for a 100 g take-off mass with 100–200 mm wingspan that must fly at 5–20 m/s for approximately 30 minutes. Owing to the low operating Reynolds number (*Re*), the aerodynamic performance of all lifting surfaces is degraded. The small scales and speeds also mean that atmospheric turbulence has a severe effect, and small thermal cycle engines that could profit from the high energy densities of fossil fuels are unavailable. It is thus difficult to obtain good performance. Studies have been made of wing plus propeller systems, rotor systems and flapping wing systems. In all cases, L/D is in the range of 5–10. Flapping is about as efficient as propeller motion at this *Re*, but more complicated mechanically. The ThrustWing is a configuration derivative of the dragonfly, with characteristics lying between a helicopter and an ornithopter. It has both zero and forward flight capabilities, and appears to have good potential as a MAV configuration. Finally, the effects of atmospheric turbulence are described and shown to fall into four qualitatively different categories as turbulence intensity increases. Due to favourable scaling, the stresses in MAVs will be very low, and although turbulence will cause large G loads on the MAV, no structural damage will result.

G. R. Spedding and P. B. S. Lissaman, Department of Aerospace Engineering, University of Southern Califiornia, Los Angeles, CA 90089-1191, U.S.A. E-mail: geoff@ostrich.usc.edu

Motivation and approach

There is interest in the remote operation of unobtrusive, aerial, miniature, information/communication systems, called Micro Air Vehicles (MAVs). Some of the observables are electronic, optical, acoustic or chemical signals. Due to their small size, there is a relatively low cost per unit, individual units can be considered expendable, and they can therefore operate in high-risk or hazardous areas. The small scales require airfoil surfaces that function at significantly smaller Reynolds number (*Re*) than usual. For a mean chord of 50 mm, flying in air at 5 m/s, $Re = 2 \times 10^4$. The regime is one of reduced lift coefficient, and separation-prone boundary-layers. In considering possible configurations for MAVs, it is natural to consider existing, successful designs. Small animals can fly quite well by flapping wings (see Spedding 1992, for a review). Perhaps MAVs should do the same?

The approach here is in traditional engineering 'forward' mode, where we attempt to construct a workable solution to a given problem, based on physical principles. Note that the criterion for success is 'workable', rather than 'optimum'. Engineering is often described as the art of approximation, and the pursuit of the workable inevitably involves the discarding of intractable, insignificant, or even merely inconvenient quantities. Provided the assumptions and simplifications are correctly noted, their very omission can lead to improved physical insight. At the same time, although demonstrating the sufficiency of a particular engineering solution (such as a functional MAV) is *not* necessarily equivalent to proving its adequacy or significance in other contexts (such as animal flight), there *are* occasions where the comparison and/or combination of the forward and reverse engineering approaches of the engineer and biologist can be instructive to both. Here, we shall deliberately operate almost exclusively (even recklessly) in forward mode, with occasional remarks designed to encourage cross-pollination of ideas in the considerably more difficult analysis of naturally-selected flight systems.

System requirements

There is no single MAV design specification, but some typical figures can be given. Assume a take-off mass of 100 g, with 100–200 mm wingspan. The vehicle should be capable of remaining aloft for 30 min, cruising at speeds of 5–20 m/s, with a total range of 10–20 km. It is useful to consider some of the scaling properties of small flying machines. For geometrically similar *airlines*, the optimal L/D ratio is independent of scale, l, if Re effects are ignored. Thus, the flight speed, U, for a vehicle of weight, W, varies as

$$U^2 \sim \frac{W}{l^2}. \tag{1}$$

For vehicles of the same average *density*, $W \sim l^3$, and so

$$U \sim l^{1/2}. \tag{2}$$

For vehicles with geometrically similar *structure*, the stress, σ, varies as W/l^2. Thus, for vehicles with geometrically similar airlines and structural layout,

$$\sigma \sim U^2 \sim l, \tag{3}$$

indicating that smaller vehicles are less highly stressed, or can operate with modified structural configurations.

Actually, it can reasonably be argued that since neither birds nor mechanical flight vehicles show any marked configurational similarity as scale is changed, power laws based on geometric similarity have little rational basis. Nevertheless, it can provide a framework for comparison, and Fig. 1 shows the wing loading, W/S, plotted against weight for selected insects, birds and fixed-wing aircraft. Note that since the wing area $S \sim l^2$, U and W/S are related by eq. (1), so while U spans two orders of magnitude, W/S varies by four orders of magnitude. The solid line is a fit to the data for $W/S \sim W^{1/3}$. The overall trend appears to fit the data, but in fact most of the interest is in the departures from this line, which become more evident when the graph is partitioned off by horizontal lines that separate the largest insect from the smallest bird, and the largest viable bird from the smallest human-engineered device (see Pennycuick (1975) for the original arguments as to why).

Notable departures to the left of the mean curve fit denote unusually low wing loading, and include the B2 stealth bomber and the Gossamer Condor amongst the aircraft, and several species of seabird. Taken by themselves, the majority of the bird species plotted on Fig. 1 have low wing loadings. There are several reasons for this, but it is worth noting that some of them involve the birds' capacity for changing their effective wing area and span. It is an almost ubiquitous strategy, and one that is completely ignored in the remainder of the discussion.

With a weight of about 1 N, the MAV specified above (the star in Fig. 1) turns out to be an equivalent-starling, an almost perfectly average bird. In principle then, flight at this scale is manifestly a solvable problem. But what are the major engineering problems for a human-designed and built system?

Major challenges for small, flying vehicles

Aerodynamics

The speed and scale of the MAV world involve different realities from conventional low speed aerodynamics. In general, at MAV Reynolds numbers, typically about $1–5 \times 10^4$ based on flightwise lengths, viscous effects have a large influence on the aerodynamic loads and limitations, as has been noted many times (e.g. Lissaman 1983). Since these are in almost all cases deleterious, the MAV will not have the performance or flight configuration similar to the normal winged vehicle. The dominant factors involved in design of most flight vehicles are the structure, the aerodynamics and the propulsion. For the conventional vehicle, the three disciplines interact with roughly equal importance in a classic design trade-off. This is not the case here. Both aerodynamics and propulsion depend on, and suffer from, the normally sluggish low Re flow of this flight regime, but there is a relief in the structural aspect of the small flight vehicle.

Careful note ought to be taken of the scope and assumptions implicit in this position, whose truth is well established for most practical geometries in steady forward flight of fixed wings and propellers – and for almost none involving moderate to large amplitude reciprocal oscillation of lifting surfaces. There are two inter-related points, concerning (i) the effects of viscosity at moderate Re ($Re \in [10^2, 10^4]$), and (ii) the potential benefits of time variation of the airflow over the wings and body. The importance of leading edge separation in insect flight at moderate Re has long been known (e.g. as demonstrated in 3D model experiments by Maxworthy (1979), and recently also by Ellington et al. (1996)), and the debate concerning the relative significance of unsteady effects also has a long history (reviewed in Spedding 1993). In combination, it is entirely conceivable, perhaps even likely, that at some range of scales, in certain flight modes, appropriate wing motions can maintain the viscous flows there (complete with their propensity for separation, complex vortex dynamics, local transition to turbulence, reattachment) at, or close to conditions equivalent to dynamic stall, where local lift coefficients can greatly exceed steady-state values.

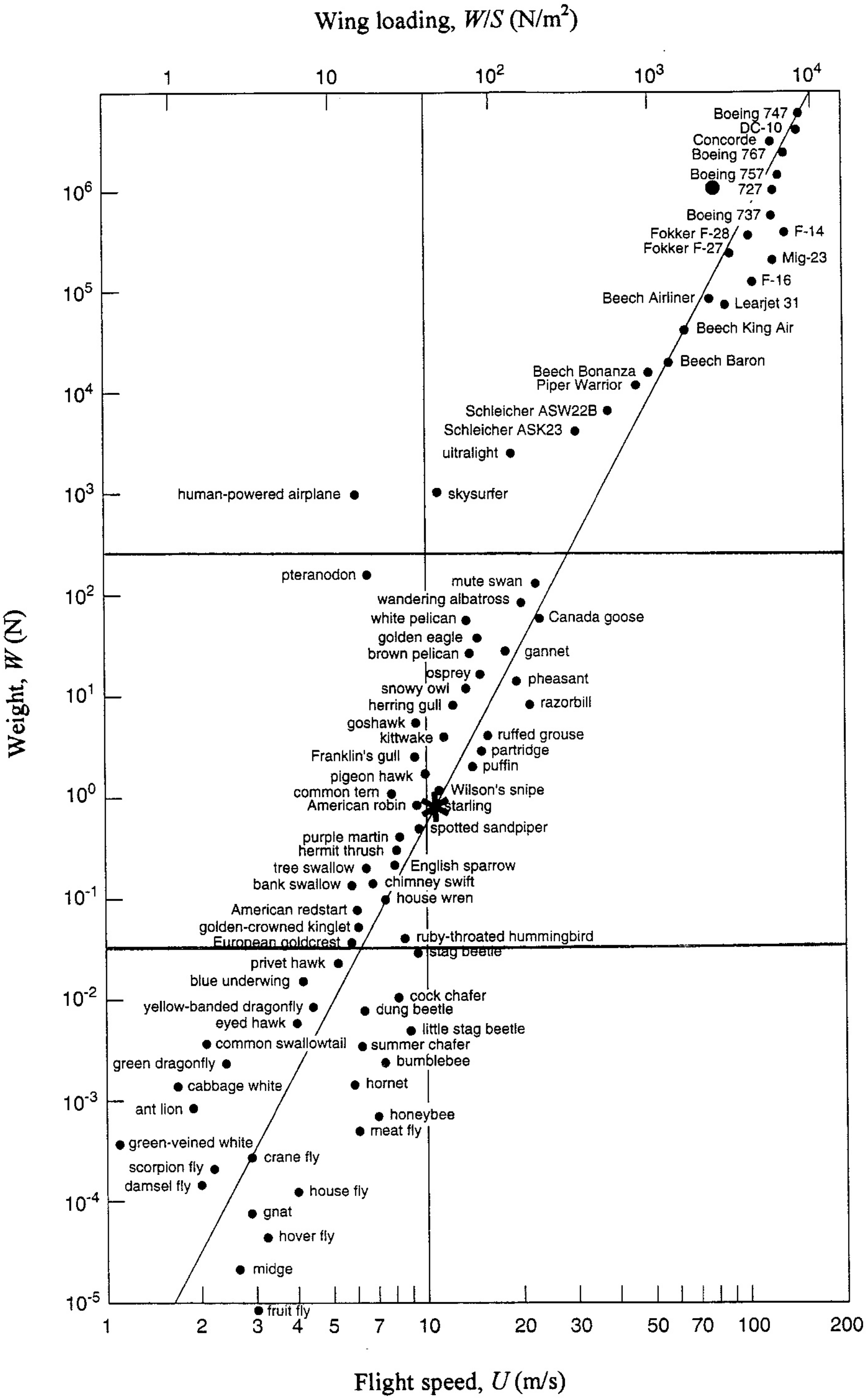

Fig. 1. Variation of wing loading, W/S, with weight, W, over 12 orders of magnitude change in W from insects to large passenger aircraft, where the lower abscissa, U is determined from W/S by eq. (1). The large blot next to the Boeing 727 is the B2 bomber. The star symbol for a MAV configuration coincides with that of the starling. Modified from Tennekes (1996).

While it may seem tempting to invoke such exotic mechanisms to explain the dramatic migratory feats reported elsewhere in this volume (for example the 11,000 km trip from Alaska to New Zealand of the godwit reported by Piersma which stunningly exceeds the humble MAV specifications), steady forward (thus including migratory) flight occurs at parameter values (reduced frequency, or advance ratio) where unsteady aerodynamics are *not* likely to be of great significance. It is much more likely that the formidable power plant has a great deal to do with the notable migration performance, and some of the more remarkable physiological aspects are discussed further in this proceedings (e.g. papers by Piersma, Jenni and Jenni-Eiermann, Lindström and Kvist, and Biebach).

By contrast, unsteady effects are almost certain to be significant in take-off and landing, in slow and hovering flight, and in rapid maneouvres, some, or all of which are included in the MAV specification. Here, the engineering pursuit of the workable must take precedence over the less-constrained contemplation of the possible, and although unsteady and viscous effect are not at all ignored, comparisons are limited to cases where quantitative results can be generalised to practical devices.

Table 1. Energy densities of various storage systems. These can be compared with likely requirements of 360 J/g. Winding a spring or rubber band works well for lightly-loaded model planes in still air, but cannot be used for a MAV. Lithium batteries may suffice – just. Elaborate flywheel mechanisms may be efficient, but have insufficient duration. It would be much more convenient to burn alcohol or gasoline, or to metabolise fat. The former engines are difficult to make small and quiet, and we currently lack the means for production of the latter (at least in a sufficiently controlled manner). A small-scale nuclear-fission reactor would be handy, and is not very far removed from the best possible device (given by the speed of light squared), which, since it does not exist, is given a nominal 10% efficiency.

Storage system	J/g
Steel spring*	1.4
Rubber	10
NiCad battery	1.0×10^2
Lithium battery	3.6×10^2
Kevlar flywheel*	1.6×10^3
Methanol$^+$	2.3×10^4
Fat	3.9×10^4
Gasoline$^+$	4.7×10^4
Plutonium 239	8.3×10^{10}
Matter-antimatter	9×10^{12}

* Steel spring and Kevlar flywheel both assumed to operate under high stress conditions, wound to 2.1×10^3 MPa. $^+$ Numbers for methanol and gasoline do not include the oxygen removed from air in combustion.

Structures

For the MAV, initial studies show that the structural features of the design interact weakly in the configurational design process. This is because the scaling laws show that at small sizes, using modern materials, the airframe will be more than strong enough for any flight loads. In fact, since these vehicles will be constructed of high-strength graphite or fiber glass composites, the main design problems involve the "minimum gage" issue, in essence that the smallest and thinnest MAV structures that can be fabricated from these advanced materials are considerably over-strength. Additionally, the structure weight is not a major component of the gross weight, of which the main part is that of sensor systems and power supplies. This implies that structure is not a dominant issue so that attention can be focused on the flight system, and on the on-board energy requirements which must provide the requisite range and endurance as well as the power for the sensors, flight controls and communication equipment.

Propulsion

Quick calculations suffice to show that the power density requirements of MAVs will pose severe engineering challenges. If a 100 g vehicle flies at 5 m/s with $L/D = 5$, then the power required is around 1 W. If the propulsive efficiency (defined as the ratio of the 'useful', or minimum power required to generate thrust, T at speed U ($= UT$) vs the total power, which includes induced and viscous losses – cf. eq. (6)) is 0.5, 2 W of shaft power must be supplied, and from a 60% efficient motor this corresponds to about 3.3 W of power input. If one quarter of the total mass is occupied by the power plant, the required power density is about 130 mW/g. The power required for a vehicle doing anything other than fly at cruising speed (for example, hovering, climbing, maneouvering) will be significantly greater, and for some reasonable safety margin, we should probably require 200 mW/g. For a 30-min flight duration, the required energy density is 360 J/g. Table 1 shows approximate energy densities from various sources.

NiCad batteries have energy densities of about 100 J/g, which is insufficient, but lithium batteries have 360 J/g. Fossil fuels have about 100 times the lithium battery energy density, however, and pending significant improvements in battery technology, some kind of thermal cycle machine seems attractive. Internal combustion engines may have low thermal efficiencies, but their high power density makes them quite sufficient for MAV propulsion. However, none have been built at this scale, and they are very noisy. Micro heat engines that operate like miniature gas turbines have been proposed, and research in this field is active. It is intriguing to note that fat has approximately the same energy density as fossil fuel, and this extraordinary power source is undoubtedly a key element in the very respectable (or better!) performance of flying animals.

Control

Conventional control surfaces with discrete actuators may impose too large a weight penalty, and distributed and/or integrated microactuators or lifting surface shape change may be required. This decision depends on the propulsion system, and there is strong incentive for integrating the two. Sensors may detect angular acceleration, differential and absolute pressure, magnetic, or optical fields. Local feedback control is frequently advocated, and will require custom microchips and controllers. Clearly, the control aspects must be considered as part of the whole flight systems package.

Certain aspects of the control problem seem to be fore-shadowed by existing strategies in animal flight, but design constraints in engineered and natural flight are not always the same. Abrupt turns and rapid accelerations deemed quite acceptable and routine in natural flight would not be popular on passenger aircraft, for example. However, they may be more tolerable, at least in part, in MAVs, where elegance and smoothness of the flight trajectory may be of secondary (if any) importance.

Flight systems

The overall requirements are small size, low mass, and low power consumption. Infrared and chemical sensors are not currently practicable due to weight constraints. A 1000^2 element CCD array currently requires about 150 mW, and could be used for navigation, control and information acquisition. Transmission of more than one image per second would strain the likely bandwidth of the communications link, and so onboard compression might be desired. Efficient, local artificial neural net (ANN) processing of image information has been demonstrated in research laboratories, and custom ANN chips for image processing exist. It will be several years before a useful custom ANN microchip could be relied upon for the primary information link.

Lift and thrust generation

There are three variants of the lift/propulsion system: first, one in which the two are essentially discrete, that is, separate lift and propulsion systems (like a normal airplane); second, one in which they are integrated through the use of a rotary thruster which serves both the lift and propulsion role (like a helicopter); and finally the reciprocating integrated lift/thruster (like an ornithopter). Here we consider separate or combined rotary mechanisms, while reciprocating lift/thrust mechanisms are considered in the following section.

Fixed wing lift systems

Dealing with the separate lifting surface first, we note that for a given speed and gross weight, scale is everything for this system, in other words, it is always advantageous from the power point of view to use the largest span available. The selection of span, b, weight or lift, L, and dynamic pressure, q, fixes the induced power requirement, which is determined by D_i,

$$D_i = \frac{L^2}{e\pi q b^2}, \tag{4}$$

where e is the span efficiency.

The chord of the wing now enters in, through S, to define the profile power requirements, and the profile drag, D_0 , is given by,

$$D_0 = qSC_{D_0}(Re, \alpha). \tag{5}$$

There is an interesting trade here, not usually encountered in the design of other flight vehicles. It is occasioned by the fact that as the chord is increased, the profile drag coefficient of the airfoil at a given lift can reduce substantially, apparently due to *Re* effects, but more significantly due to the reduced lift coefficient and the associated reduction in lift dependent profile drag coefficient. At a fixed α, increases in chord always result in *increases* in drag, even though the drag *coefficient* will decrease due to the higher *Re*. This can be visualized by noting that any extension of the chord of an airfoil will add drag-developing surface to the airfoil, provided that any separation is ahead of the extension.

A simple parametric study, comparing the effects of independent variation of parameters controlling the wing geometry, loading, and aerodynamic efficiency, was undertaken to determine the performance of a family of MAV wings. These were intentionally taken at the low end of the size/speed spectrum, to demonstrate the scale effects most vividly. It is assumed that the wing is rectangular (this is discussed in a later section), and then, for a flight speed of 5 m/s and wing span of 300 mm, the lift/drag performance, L/D, is calculated for four lift values (25, 50, 75, 100 g), for a number of different airfoils, as aspect ratio is varied. The span effectiveness, e, is also varied from 0.25, 0.50, 0.75, to 1.00.

An important factor in the total drag is the profile drag of the section at the specific *Re* and lift coefficient. Theoretical data are notoriously unreliable so it was decided to use only airfoils for which test data were available in the specific *Re* range. The airfoils utilized (Fig. 2) were: a flat plate of 3% (of chord) thickness, and a cambered 3% plate, both reported in Schmitz (1945), two characteristic low speed airfoils of about 5% thickness, the K-2 and the Eppler 61 (Althaus, 1980) and two truncated NACA airfoils of 22% thick-

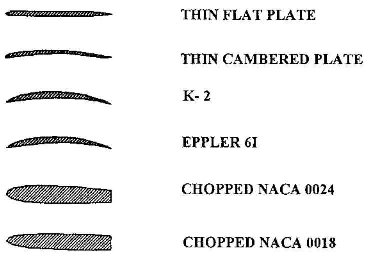

Fig. 2. Airfoils used in performance analysis.

ness tested by Sato and Sunada (1995). The rationale for the choice was that the first two airfoils represent the simplest (effectively) zero thickness airfoil, the second pair represent airfoils designed specifically for high performance at low *Re*, and the last two represent airfoils with significant thickness that could prove desirable for payload storage.

An extensive set of results has been derived from these calculations. The results are not expected to be accurate to within 20%, but give insight on the general performance to be expected and the effect of the various configurations. A selection is given in Fig. 3, which shows the performance of the flat and cambered plates for three lift values. For the flat plate at the lightest load of 25 g, *L*/*D* reaches a value of about 6 but performance degrades severely as the load is increased. For the cambered plate the performance is superior, but at higher lift levels there is a severe increase in drag. This is due to wing stall, and occurs for any airfoil. The important result is that *L*/*D* values in excess of 10 are unlikely, and that the optimal planforms are not very sensitive to aspect ratio. This behavior can readily be interpreted qualitatively, since it reflects the poor performance of the airfoils at high lift coefficients, and as the aspect ratio or lift increases, the profile drag coefficient increases until stall occurs.

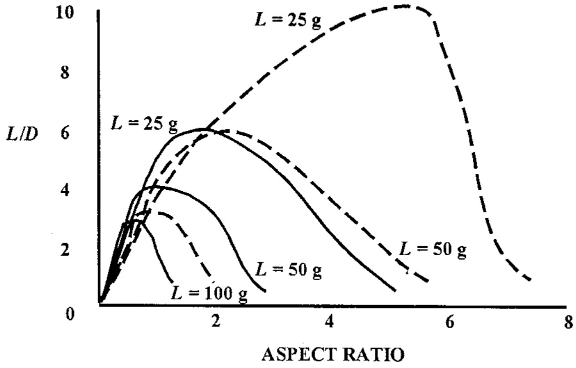

Fig. 3. Wing performance for varying aspect ratio and airfoil cross-section. The solid line is for the flat plate (top of Fig. 2), and the dashed line is for the thin cambered plate shown beneath it in Fig. 2. $U = 5$ m/s, $b = 300$ mm and $e = 0.8$ are fixed in this calculation.

The K-2 airfoil appeared somewhat superior, but similar, to the cambered plate. The improvement, of about 10%, cannot be considered significant, since the drag data for the airfoils came from different sources. The Eppler 61 was superior to the flat plate, but not as good as the cambered plate. The two chopped NACA sections had lower performance than any cambered airfoil analysed.

The approach above is a useful procedure for selecting a suitable wing configuration for the MAV, and the analysis is being refined to give a better representation of the spanwise profile drag variation. CFD procedures will not prove useful here since the 3D separation patterns on the wings are so radical at these *Re* that, to the best of our knowledge, they can not be reproduced with a CFD model. Any proposed CFD model should first be checked against reliable 2D airfoil test data, and when good agreement has been obtained for this simple restricted case, then the 3D features, including spanwise varying wake separations may be introduced.

For the above reasons it is highly recommended that physical tests be conducted with a family of wings of this *Re* range. These can be conducted at higher speeds on smaller models (or vice-versa), but, since the product of speed and scale is conserved for proper *Re* scaling, the loads on a model of any size will still be that of the actual load on the full scale MAV.

As knowledge of the performance of the lifting system develops it will be possible to define more closely the planform and airfoil characteristics. It seems that there will be no magic airfoil providing dramatic improvements in performance beyond that of the cambered or the K-2 airfoil, but probably the existing airfoils can be improved upon slightly. For the planform, the present approach of using a rectangle to fill the allowable area at fixed span seems reasonable. It is likely that a more accurate evaluation of the spanwise profile drag variation will indicate favorable effects by reducing the tip chord, thus producing a low aspect ratio, slightly tapered planform. It will be interesting to investigate the effect of slender wings as exemplified by the delta planform, but it is expected that this will have more drag than a comparable unswept wing of the same span.

Evidently a wing of this type is not capable of zero flight speed, as is sometimes a requirement, but many of the functions associated with hovering flight can be performed by a fixed wing vehicle performing orbital flight about a point.

Rotary thrust systems

The most obvious thrust system for the MAV is a propeller of the conventional type. These propellers have been developed and optimized to a high level of performance in model airplane technology. The propellers used for very light microfilm model airplanes may be a good guide. These are of large diameter and chord, and slow turning. Any propeller suffers the same *Re* problems with scale, as do the lifting surfaces of the MAV vehicle, although it is possible by using a relatively high rotational speed to offset some of the problems associated with the very small chord lengths. Typically, for propeller speeds of about 600 rpm, the advance ratio is about unity so that the blades, at least near the tip, will experience relative flows of about 1.4 times the MAV flight speed. The chord will generally be less than the one quarter of the wing chord, so the *Re* of the propellers will be lower than that of the wing, unless rotation speeds are very high.

There is an interesting technical trade-off here exemplified by the fact that the optimal speed of light electric dc motors will be high, and they will have to be geared down, with weight and power penalties, for use on the propeller, while the viscous losses on the propeller will be proportional to some power of the rotation speed. Thus there are four interrelated factors, the propeller diameter, chord and rpm, the gear box, the motor speed, and the battery capacity. A rational design criterion can be set as the requirement to obtain a given thrust in grams for a given number of minutes from a propeller for the lightest weight of the complete thrust system (propeller, gearbox, motor, battery).

MAV propeller design lends itself to further development. As is the case with wings, it is expected that careful applied aerodynamic calculations will provide insights to the general configuration, and the propellers must then be tested for accurate performance evaluation. General experience for propellers in this size indicates that the propeller efficiency, η, will be about 40% where η is defined as:

$$\eta = \frac{TU}{P}. \tag{6}$$

T is the thrust, P the shaft power, and U the flight speed. A static balance can be used to determine the thrust, rpm and input power. The static thrust/power curve then immediately gives an indication of the dominant viscous effects at this scale. The effect of forward speed can be estimated analytically once the static power curve has been determined.

Lifting thrust systems

The natural step after developing a design family of thrust systems is to consider such devices as lifters, with a small inclination (leading edge of disk down) to provide forward thrust. This is essentially the helicopter principle. It will require thrust of approximately five times the levels considered for the direct propulsive propellers, which will significantly alter the configurational layout, as seen in the difference between airplane propellers and helicopter rotors. Evidently such a system will provide an effective hovering capability, and a somewhat less efficient L/D for forward flight. Performance calculations for such a device have not been made, but the standard helicopter equations, incorporating the low *Re* airfoil features, will provide the fundamental expression.

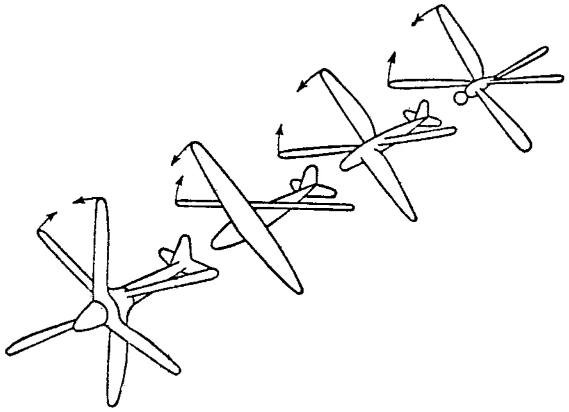

Fig. 4. Development of the ThrustWing (from Küchemann and Weber 1953).

It appears that the small helicopter will be severely handicapped by the forward flight stability problems associated with blade crossflow and that any suitable system will require some form of active blade pitch control which, at this scale, will be delicate and complicated and may preclude the application to MAV. This requires more careful examination.

The ThrustWing

The ThrustWing (von Holst et al. 1942) is an interesting configuration, which avoids the stability problems associated with the helicopter configuration. The conceptual development has been sketched in Fig. 4, which starts with the dragonfly with four high aspect ratio wings flapping in opposition, and is then generalized into a pair of rotating wings, with pitch control provided by a lifting surface mounted on a tail boom. These devices operate in the forward flight mode at very large angles of inclination of the rotation axis to the vertical, and aerodynamically are more like a flapping wing than a rotating propeller. The analysis proposed by von Holst et al. uses the simple theory of rolling wings and thrust-due-to-roll effects to establish the wing performance. Forward flight is achieved with the thruster axis inclined at about 30° to the horizontal and the systems are passively stable. Von Holst et al. report having built and flown rubber-powered versions of a 530 mm diameter ThrustWing (and its intermediate steps) which exhibited excellent stability. The model had an ingenious passive feathering propeller, controlled by offsets from the blade elastic axis and responsive to blade load; today, this might be accomplished more specifically, but less simply, by an actuator.

This configuration may prove to be of great value for MAV, since the hovering capability can readily be accomplished while the forward flight capability is retained, with simplicity in the rotor system. Preliminary calculations at the appropriate scale indicate that, while the efficiency of the system is not higher than either the wing in forward flight or the thruster in hovering flight, this arrangement may provide a simple MAV configuration having both the low and high speed flight capability.

Efficiency of flapping flight

Potential benefits

Numerous and various reasons are given for the possible advantages of flapping wing flight, some aerodynamic, some not. The most compelling of these is the possibility for integrating lift and thrust *together* with stability and control mechanisms. All forces on the surrounding fluid, and all small local corrections to changing conditions, derive from the motions of the same actuators. This kind of integration is likely to be essential in managing the total vehicle weight. Furthermore, visual and radar cross sections and acoustic signatures might all be reduced.

While it is conceivable that such benefits might be realised, the thinking is speculative. The principal motivation seems to be that the capabilities of the birds, bats and insects that surround us are evidently superior in certain respects, such as maneouvrability and agility, and so it would be wise to emulate their example. Furthermore, the proof of concept is already airborne. However, just as submarines are in many respects quite un-fishlike, engineering solutions must respect and profit from human-based constraints and/or opportunities.

Principles

Reciprocally-oscillating wings generate wakes with both trailing (streamwise) and shed (cross-stream) vorticity because there must be a component of wing motion normal to the direction of flight in order to generate thrust as well as lift. A convenient parameter that describes the relative magnitudes of these components is the reduced frequency,

$$k \equiv \frac{\omega b}{2U}, \tag{7}$$

where $\omega = 2\pi/t_{\text{flap}}$ is the radian flapping frequency, $b/2$ is the wing semispan and U is the flight speed. The inverse of k is the advance ratio, $\mu = 1/k$. For a propeller of radius, R, μ can be written

$$\mu = \frac{Ut_{\text{prop}}}{2\pi R}, \tag{8}$$

and so describes the horizontal distance traveled ($X = Ut_{\text{prop}}$, where t_{prop} is the period of rotation) per unit circumference traced out by the blade tip. Similarly, when $k = 2\pi$, a wing flaps once for every semispan of forward travel. For very small k, or large μ, quasi-steady assumptions should work well, but these same assumptions become increasingly tenuous as k increases far beyond 1. Most animal flight occurs in the range $1 < k < 4$.

Current ornithopters

It is one thing to argue about the validity of unsteady aerodynamic theories as useful (however this is defined) animal flight models. However, when the theory must form the basis for practical design and construction of an ornithopter, success, or lack of it, has a rather immediate impact.

Practical ornithopters have been built, and some comparisons of animal and ornithopter flight are given in Spedding and DeLaurier (1996). The most famous ornithopter is the *Quetzalcoatlus northropii* (QN) model developed at AeroVironment (Brooks et al. 1985). QN had a 5.5 m wingspan, and a mass of 17 kg. The performance was marginal, as increased surface roughness imposed by aesthetic considerations (it had to look like a real pterosaur) resulted in extra drag penalties. Recalling Fig. 1, it is most likely that the original pterosaur upon which the model was based was itself a weak flyer. However, it was apparent that QN had excellent stability and control characteristics.

The unsteady strip theory of DeLaurier (1993a) was used in developing a 3 m span ornithopter (DeLaurier 1993b, DeLaurier and Harris 1993) that was capable of sustained level and ascending flight, limited only by the power source. The ornithopter with 250 mm mean chord Mark-8 wing, supported a weight of approximately 38 N at a flight speed of 15 m/s, flapping at a frequency of 3.3 Hz. The relevant dimensionless numbers based on wing chord are $Re = 2.6 \times 10^5$ and $k = 0.19$ (approx. 2 when based on semispan). The combined theoretical analysis and flight tests showed significant contributions from aeroelastic coupling with local wing section bending and twist. These elements are not normally included in flight models.

Again recalling Fig. 1, it can be argued that since such large-scale ornithopters evidently do work, it ought to be *easier* to construct small-scale versions that benefit from the larger surface area/volume ratios, provided the aerodynamic difficulties at lower *Re* can be solved, as discussed above. It should also be clear that assessing the comparative efficiency of flapping wing devices requires a theory that is not limited to very small reduced frequencies.

Parametric studies of flapping flight

Phlips et al. (1981) described an unsteady lifting-line theory where a simplified three-dimensional model of the near and far vortex wake was used in making corrections to the instantaneous values of $\alpha(t)$, the local angle of attack, and $u_r(t)$, the relative velocity on the airfoil. All viscous effects and virtual mass effects were ignored. Some of the main results from the parametric analysis are of interest for a flapping wing ornithopter.

At moderate flapping angles, β (β is the total angle through which the rigid wing flaps), of 90°, the lift coefficient averaged over one wing beat cycle increased by approximately 20%, for $k = 2$. Clearly, when unsteady terms are included, the mean lift can be significantly different from the quasi-steady value. The propulsive efficiency (as defined in eq. (6)) increased from about 0.5 to 0.8 as the aspect ratio ($A = b/c$) rose from 4 to 16 for both rectangular and semiparabolic planforms (for $k = 1$, $\beta = 40°$). In the absence of viscous effects, flapping wings should have high aspect ratio. Finally, Phlips et al. also showed that, for fixed wing shape and A, η decreases roughly from 0.8 to 0.6 as k increases from 1 to 4. The decrease is increasingly marked as β increases from 20°–120°.

Within the limitations of the model, unsteady effects seem to be important at realistic values of k, and flapping wings should also have high aspect ratios. For moderate values of β, between 40–80°, propulsive efficiencies can drop by 20–25% as k increases from 1 to 3. However, a simple extrapolation of these results to MAV design is not possible because viscous effects cannot be ignored at low *Re*.

Hall et al. (1997) formulated a procedure for finding the optimum circulation distribution along the span of a rigid flapping wing that minimises the power requirement for generating a specified lift and thrust. The profile power was estimated from the two dimensional drag polar at each spanwise station. Viscous forces are thus accounted for, but only in a quasi-2D fashion. By assuming that the wings are lightly loaded, it is possible to ignore distortion of the wake by the induced velocities, and the wake geometry is just that prescribed by the trace of the rigid wing motion. The quasi-2D drag polars can be used if A is large, so that a reduced frequency based on semichord is small. This also justifies the neglect of virtual mass effects.

Again, some caution should be exercised in extrapolating the results to MAV conditions, but some of the comparative results are valuable. The same calculation applied to optimally-loaded propellers and flapping wings showed that the propulsive efficiencies were comparable, at about 0.8. The optimum value of k was 5.3, which corresponds to a little less than one wingbeat per semispan of forward travel, and it depended only weakly on the thrust requirement. On the other hand, the optimum flapping amplitude, β, was sensitive to thrust loading, and varied from 40° to 55° for a doubling in thrust coefficient. The optimum power loss actually had a rather broad minimum in k, so the minimum power solution, or close to it, could be achieved at different k by only small changes in β.

Hall et al.'s solutions show rather small viscous corrections in the optimum circulation distribution, but that is probably a consequence of the large *Re* conditions that established the drag polar, and hence, the profile drag coefficients. *Re* was 6×10^6, which is 2 orders of magnitude above the likely MAV range, and far beyond any small-scale airfoil or propeller scale. Viscosity is not very important at such high *Re*, and the high values of η are less surprising when viewed in this light.

To flap, or not to flap?

Should MAVs do it?

If we assume that a flapping bird wing can produce the optimal circulation distribution for minimum power loss, then the aerodynamic efficiency is likely to be comparable to that of an optimally-loaded propeller. An automatically-twisting wing could in principle be constructed, using the design of DeLaurier and colleagues as a starting point, and it may be possible to fabricate a device that comes acceptably close to an optimal circulation distribution. The main incentive for preferring a flapping wing design is that if the entire wing participates in lift and thrust generation, then the reduction in *Re* is not so large as it would have been with a separate, smaller propeller. However reciprocally-oscillating wings are not a necessary condition for combining lift and thrust, and the ThrustWing model has the same benefit with regard to maintaining *Re*, but without the additional complexity of the drive mechanism. Indeed, the primary obstacle is that of constructing a light, robust, maintainable wing articulation and drive mechanism. It is not clear that there are any significant performance benefits that would accrue from the substantial research and design effort required.

Why do animals do it?

The data seem somewhat equivocal concerning the performance advantages of flapping wings vs propellers, and our recommendation to design a ThrustWing is based on the more simple engineering construction with continuously rotating drive shafts. Why are there no ThrustWings in nature? Probably because animals do not have wheels. In general, appendages or body parts that can rotate through more than one revolution are rare in the animal kingdom. Exceptions are notable according to their rarity – certain flagellar motions in microscopic organisms where chemical exchange can occur by diffusion, rolling tumbleweeds and woodlice perhaps. This may be partly due to the lack of suitable precursors, or to plumbing problems in maintaining nutrient flows to living tissue. Furthermore, the arguments based on the observation that flapping and propeller efficiencies are similar in magnitude are quite symmetric, and can be reversed with ease: having evolved a satisfactory (if not even optimal) solution to mechanical and fluid dynamical problems of propulsion and lift, there is probably little or no selective advantage to the evolution of novel rotating devices.

Ambient turbulence and flight control

Atmospheric turbulence can have a marked effect on slow flying vehicles. It is common to experience general wind-generated turbulence having root mean square levels of the order of 1 m/s near the ground, especially when thermal and/or density gradients are unstable, and even small to moderate velocity gradients can lead to sustained overturning motions.

Perturbation magnitudes

Perturbations of this magnitude will have a significant effect on the vehicle aerodynamic flow state. Streamwise turbulence will cause 20% variations in flight speed, corresponding to 40% changes in aerodynamic forces on the vehicle. Cross-stream turbulence will introduce a perturbation of about 10° to the relative flight attitude, which is of approximately the same magnitude as the angle of attack at which the wing will be cruising. The effect of this turbulence has been observed on model airplanes and low speed flight vehicles. In particular, rough observations have been made on the Gossamer Condor and the AV Pointer, both low speed vehicles with very low relative mass ratios (Lissaman et al. 1979, Lissaman 1980). For the vehicles noted, it appeared that even mild turbulence has quite severe effects in reducing the performance. For larger vehicles, for which most stochastic turbulence analysis is conducted, since turbulence has a zero mean, the effects on lift and drag tend to cancel out for most airflow situations that are near linear, unless the turbulence is very strong or the vehicle very large.

The regimes of turbulent perturbations

It is observed that the turbulence effects are not directly continuous with turbulence level, but appear to fall into four different mechanisms as the turbulence increases, with a discontinuous increase in severity as each regime is entered. These flight regimes are described below. For very light turbulence, the main effect appears to be the changes in transition point of the airfoil, resulting in relatively small changes on profile drag, but with consequences which will always slightly increase the mean drag coefficient. No significant changes in lift performance are noted. As the turbulence level increases to the second regime, the effects of turbulent variation in angle of attack can be noted. Most airfoils exhibit an approximately parabolic variation in profile drag coefficient with angle of attack change about the ideal angle. As a consequence the mean profile drag coefficient is increased due to the relatively higher drag coefficients due to positive angle of attack excursions, which are not compensated for at the lower angles of attack. As before the mean lifting performance is unaffected. For more extreme turbulence (the third regime) the angle of attack perturbations can produce flow separations, including actual stalling of the wing and propeller and fuselage separations, with severe increases in drag, and loss of lifting performance. Finally, in the fourth regime, for the most extreme turbulence, the angle of attack excursions can be sufficiently large that wing stall is caused. This can be of sufficient magnitude that the vehicle will experience severe dynamic instability, culminating in a stalled dive and may be out of control of passive or active stability systems for many seconds. If the turbulence has sufficient energy at high wave number to cause different vertical flows on each wing, then this stall can actually occur in an asymmetric fashion, so that the vehicle will drop one wing, and fall off, sometimes entering a spin state. The spin state can on occasion be so stable that normal control authority is insufficient to normalize the flight mode.

All of these turbulence regimes and vehicle responses can be observed with model airplanes, and also with birds. Indeed, it is observed that birds can lose control when flying in high turbulence, and even skilled natural flyers will require many meters of fall before regaining control.

Consequences for MAV design

As noted above, turbulence will clearly have the effect of limiting the vehicle Range/Endurance quotient, and it will be necessary to make a multi-disciplinary trade-off of the advantages of active turbulence alleviation against the lower weight requirements of a simpler passive rough air tolerant vehicle. Higher turbulence levels introduce a further trade-off, relating to whether it is better to placard the vehicle to prohibit flight in turbulence above a certain level, or to take steps to alleviate turbulence excursions by some design means. Both of these options are employed in normal land vehicle technology. For example, an off-road vehicle pays the price of its rough terrain capability by limited freeway cruising speeds and comfort. A sacrifice of performance for agility in different avian species (Lissaman 1973) can be observed. Here, for example, some of the most spectacular flyers, like the albatrosses and the condor, being aerodynamically more narrowly-specialised for cruising flight, experience severe take-off and landing difficulties, and their highly efficient cruise wing planforms cause them to be troubled in turbulence. On the other hand, smaller passerines appear to be comfortable flying in the severe turbulence downwind of buildings and obstacles, their normal flight habitat.

Conclusions and recommendations

The following conclusions may be drawn for MAV development:

1. The primary **lift and propulsion** problems are caused by the poor performance of lifting surfaces at low *Re*.
2. Flight **control** problems are caused by atmospheric turbulence disturbances, which are of large amplitude compared to the flight speed.
3. Because of favourable scaling, **structural strength** will not be a problem.
4. Lightweight, miniature **power sources** in the 2 W power range seem to be restricted to high speed DC motors.
5. **Power storage** may be restricted to batteries, which are relatively inefficient compared with fossil fuel, or fat.
6. Under similar operating conditions, **flapping wings** have about the same propulsive efficiency as **propellers**.
7. The **ThrustWing** may provide a configuration that most *simply* and *effectively* provides both hovering and stable forward speed capability. It is also the only configuration that currently lacks an extensive technology at larger scale.

The conclusions lead to the following recommendations as to how to proceed:

1. Because of the complex viscous flow fields associated with this flight regime, and the consequent unreliability of CFD codes, MAV components should be developed by physical testing combined with appropriate aerodynamic analysis.
2. Complete MAV systems should be flight-tested at the earliest stage.
3. Applied aerodynamic analysis, component and flight testing should be conducted on a ThrustWing configuration.

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