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Design Elements of a Bio-Inspired Micro Air Vehicle

Jennifer L. Palmer*, Malcolm B. Jones, and Jan Drobik*****

Defence Science and Technology Organisation, Fishermans Bend, VIC 3207 Australia
**(Tel: 61-3-9626-7000; e-mail: jennifer.palmer@dsto.defence.gov.au)*
***(e-mail: malcolm.jones@dsto.defence.gov.au)*
****(e-mail: jan.drobik@dsto.defence.gov.au)*

Abstract: A multi-tiered approach to the study of the aerodynamics of a biologically inspired micro air vehicle (MAV) is described. The goal of work is to develop the aerodynamic tools necessary to design a mission-capable MAV. Analytical, experimental, and numerical investigations yielding insight into the bio-inspired design elements that could be employed to advantage in an engineered flapping-wing MAV are documented; and it is shown that a four-wing device with a relatively simple wing design and a single active flapping axis for each wing could form the basis of a viable flapping-wing MAV.

Keywords: Flapping flight, micro air vehicle, unmanned aircraft system, bio-inspiration, aerodynamics.

1. INTRODUCTION

The scientific and technical challenges involved in the design of an autonomous 'micro' air vehicle (MAV) with the desirable flight characteristics of insects and useful surveillance capabilities are numerous. The manoeuvrability, speed, control authority, and hovering ability of insects in the Diptera, Hymenoptera, and Odonata orders have inspired researchers worldwide to attempt to reproduce insect flight with mechanical systems; and several prototypes capable of hovering have been developed (Pornsin-sirirak et al. 2001; Avadhanula et al. 2003; Zdunich et al. 2007; de Croon et al. 2009; Keennon et al. 2012), though none matches the endurance, compact size, and agility of biological hoverers.

The work presented in this paper focuses on the aerodynamic features of a bio-inspired MAV, i.e., the loads (forces and moments) generated by the wings for a given set of wing shapes, structures, and motions, and their impact on the design and control of such a device. The aerodynamic system fundamentally constrains a platform's mission capabilities, such as endurance, manoeuvrability, survivability, stability, and controllability. To achieve a mission-capable autonomous system, each of these capabilities must be adequately addressed. Further, for a flapping-wing air vehicle to provide an advantage over competing fixed- and rotary-wing systems, its capabilities must be demonstrated to be superior to those of more-conventional systems.

The development of miniaturised avionics, navigation and guidance, power, and payload systems needed for a compact, biologically inspired autonomous air vehicle is complex; and novel approaches, different to those employed on larger unmanned aircraft systems, are required (Wu et al. 2003; Garratt 2007; de Croon et al. 2009; Chahl and Mizutani 2011). Similarly, the aerodynamicist and airframe designer is presented with significant challenges, including the design, development, selection, and/or optimisation of

- the wing arrangement (positioning and number), materials, structure, load compliance, planform, and kinematic envelope (degrees of rotational freedom and the choice of active or passive control and range of motion in each);
- the flapping mechanism, which must achieve the desired wing kinematics and flapping rate with minimal power to maximise the MAV's endurance; and
- the actuator-control system, which must appropriately and precisely govern the wings' motion to achieve controlled forward flight and stable, efficient hovering, as well as manoeuvrability.

Recent progress has been made on some of these elements, while others lag behind and require new scientific insight and original technical approaches. The vast and interconnected design space necessitates a systematic research strategy, such as the one pursued by DSTO and described here, which aims to identify and to gain an understanding of the fundamental aerodynamic phenomena of flapping wings. The research forms the basis for an aerodynamic-design methodology through which this understanding can be implemented in engineered, bio-inspired solutions.

2. BIO-INSPIRED SIZING AND CONCEPTUAL DESIGN

A scaling analysis of biological species capable of hovering flight provides some basic rules for flapping-wing MAV designs, gives an indication of the feasibility of proposed designs, and points to the maximum performance that may be expected (Harvey and Palmer 2010). The process is akin to an initial sizing analysis in traditional aircraft design and may be complemented by other conceptual-design analyses tailored for flapping-wing MAVs (Whitney and Wood 2012).

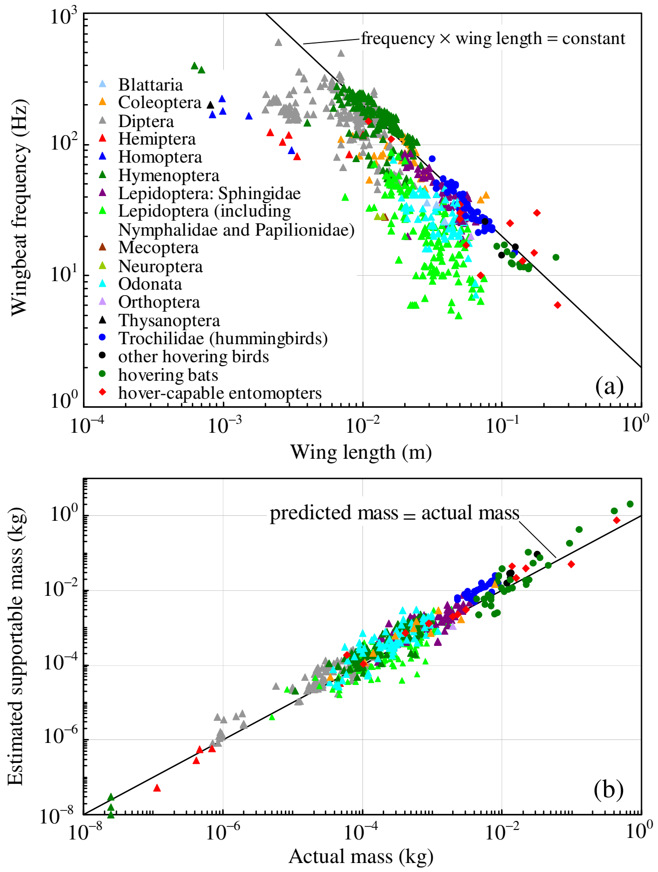

Fig. 1. (a) Wingbeat frequency vs. wing length for individual hoverers and (b) estimated mass supportable by each flyer's wings vs. its actual mass (Harvey and Palmer 2010).

The relationship between wing length and flapping frequency for many individual insects, hovering birds and bats, and hover-capable flapping-wing MAVs is shown in Fig. 1(a). The data for each group of natural hoverers, though scattered, can be roughly fitted by assuming that the product of flapping frequency and wing length is constant (Greenewalt 1960). The variations amongst the groups observed in Fig. 1(a) correlate with their control authority. For instance, butterflies (orders Nymphalidae and Papilionidae) flap their wings more slowly than do dragonflies (Odonata) and hummingbirds and demonstrate commensurately less control authority; whereas mechanical hoverers usually require a higher flapping frequency for a given wing length than other flyers, suggesting that, because they support a similar mass with wings of a given size, they are less efficient aerodynamically.

An expression derived by Ellington (1999) for the lift created by wings performing 'normal hovering', the kinematics used by most insects and by hummingbirds, was also examined to determine its utility for sizing a flapping-wing MAV (Harvey and Palmer 2010). The mass supportable by wings of a given length and aspect ratio, undergoing harmonic motion in a horizontal plane at a given flapping frequency and stroke amplitude (minimum to maximum flapping angle) was estimated by use of Ellington's expression with an assumed mean lift coefficient of 2. The result for each hovering insect, bird, bat, and MAV was compared with its actual mass, as shown in Fig. 1(b); and the agreement was found to be within a factor of three in most cases and often better. Interestingly, this included flyers with multiple wing pairs, for which the estimated lift created by each wing pair was summed, and many that do not utilise normal-hovering kinematics (e.g., dragonflies and clapping-wing MAVs).

3. BASIC AERODYNAMIC CHARACTERISATION

The design of a viable flapping-wing MAV requires an ability to perform aerodynamic characterisation and to identify technological areas needing additional focus. DSTO researchers developed this capability through experimental testing and analysis of commercial-off-the-shelf (COTS) flapping-wing devices that are not necessarily representative of a future MAV prototype. The efforts, however, provided insight into the features of various flapping actuators commonly used in MAVs. The construction of a wing-design and -development testbed has also been undertaken, supported by the implementation of methods that permit the quantitative characterisation of flexible flapping wings.

3.1. Aerodynamic Measurements and Modelling

Several bird- and insect-inspired flappers have been used as surrogates for flapping-wing MAVs in DSTO's laboratories. A 0.65-m-wingspan, 0.32-kg flapper undergoing wind-tunnel testing is shown in Fig. 2(a) (Valiyff et al. 2010). A high-precision balance capable of measuring three-dimensional (3D) forces and moments was used to quantify the horizontal force (thrust) created by the wings in a steady airflow. Its temporal variation was measured at different flapping frequencies and wind speeds. The results for mean thrust, evaluated over many flapping cycles under steady conditions, are shown in Fig. 2(b).

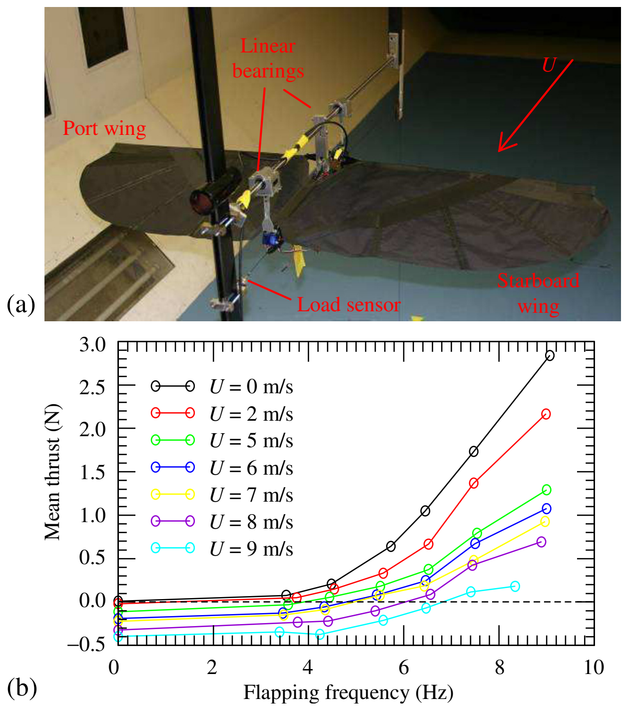

Fig. 2. (a) A bird-like flapper characterised aerodynamically in DSTO's Low-Speed Wind Tunnel and (b) mean horizontal force (thrust) vs. flapping frequency for a range of flow speeds, U (Valiyff et al. 2010).

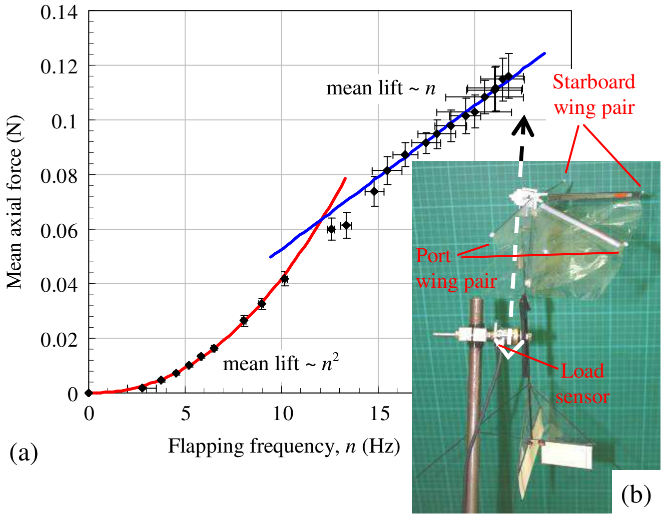

Fig. 3. (a) Mean lift force vs. flapping frequency generated by (b) a small clapping-wing device (Palmer *et al.* 2011).

Another COTS flapper, utilising two pairs of clapping wings, was characterised in quiescent air to investigate a lift-generating mechanism, 'clap-fling', used by biological flyers when high lift is required (Palmer et al. 2011). The small, insect-inspired hoverer, pictured in Fig. 3(b), had a wingspan of 0.28 m and a mass of 0.012 kg. Temporally resolved measurements of the unsteady forces and moments generated by the wings were recorded for a wide range of flapping frequencies.

The mean axial force (lift) is plotted as a function of flapping frequency, n, in Fig. 3(a), where it can be seen to be proportional to the square of the flapping frequency at low frequencies. This agrees with the dependence anticipated theoretically (Ellington 1999); however, at higher flapping rates, the lift was found to increase linearly with flapping frequency, likely due to deflections of the wings' leading-edge spars and the flexibility of their unsupported surfaces.

3.2. Experimental Wing Optimisation

A wing-design testbed, shown schematically in Fig. 4, has been constructed in DSTO's laboratories to permit rapid assessments of wing geometry, structure, materials, and kinematics (Jones et al. 2011). The rig enables the exploration of the vast parameter space in which MAV wings may be designed. Such studies are necessary for the development of prototype wings and for aerodynamic optimisation once a structure or material is chosen.

The rig was designed to test wings less up to 0.3 m long at a maximum flapping rate of 10 Hz, a target value determined from the scaling analysis described in §2. Alternatively, the flapping rate may be adjusted to match a desired test condition, for example, the Reynolds number, Re, of a biological hoverer. ($Re = c\overline{V}/\nu$, where c is the wing chord length, $\overline{V}$ is the mean tangential velocity at the wing's mid-span or tip, and ν is the kinematic viscosity of the fluid, air.)

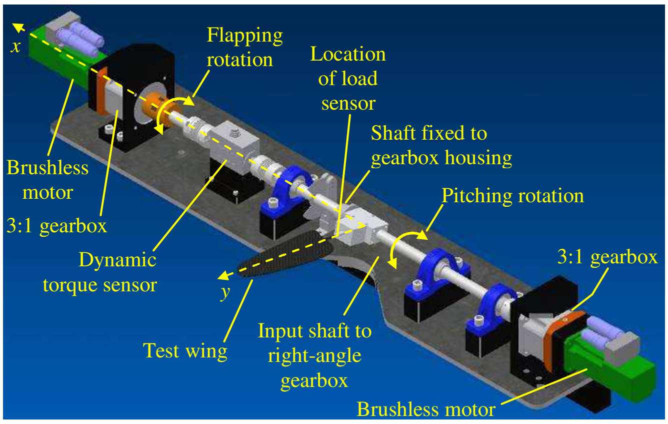

Fig. 4. Testbed used to aerodynamically characterise subject wings with variable kinematics (Jones et al. 2011).

The aerodynamics of wings with arbitrary kinematics in two rotational degrees of freedom (DoF) can be assessed with this rig, which is intended for studies in quiescent air. The kinematics may be chosen to mimic those of a biological species with, for example, a non-sinusoidal flapping profile (Palmer et al. 2011) and leading or lagging pitch reversal at the stroke extremes. Simultaneous motion tracking of the wing surface may be performed to permit the isolation of the 3D, temporally varying aerodynamic loads from the total forces and moments, to which inertial loads generated by the wing motion may contribute substantially (Jones et al. 2012). Motion-tracking data may also be used to examine the aerodynamic influence of wing flexibility through fluid–structural interactions (Valiyff et al. 2011; Jones et al. 2012).

4. INVESTIGATIONS OF COMPLEX, BIO-INSPIRED AERODYNAMICS

Beyond the development and validation of aerodynamic measurement techniques, DSTO researchers have also undertaken detailed numerical and experimental studies of phenomena likely to be important in the design of a practical bio-inspired flapping-wing MAV. These include investigations of the effects of wing topology and fluid–structural interaction and the aerodynamic performance and control achievable with tandem wing-pair configurations.

4.1. Wing Topology

The aerodynamic implications of the corrugations present in insect wings have been studied to assess the benefits they may provide a bio-inspired MAV. The flow surrounding a two-dimensional (2D) wing undergoing kinematics similar to those of a dragonfly in hovering flight was modelled by use of a computational fluid dynamics (CFD) technique (Premachandran and Giacobello 2010). As indicated in Fig. 5, simulations were performed with several different wing-section geometries.

As can be seen in Fig. 5(a), thinner aerofoils were found to produce higher mean lift than thicker sections; and corrugated sections performed similarly regardless of the size of the peaks and the orientation of the leading edge. Although, in gliding flight, corrugations delay the onset of stall (Kesel

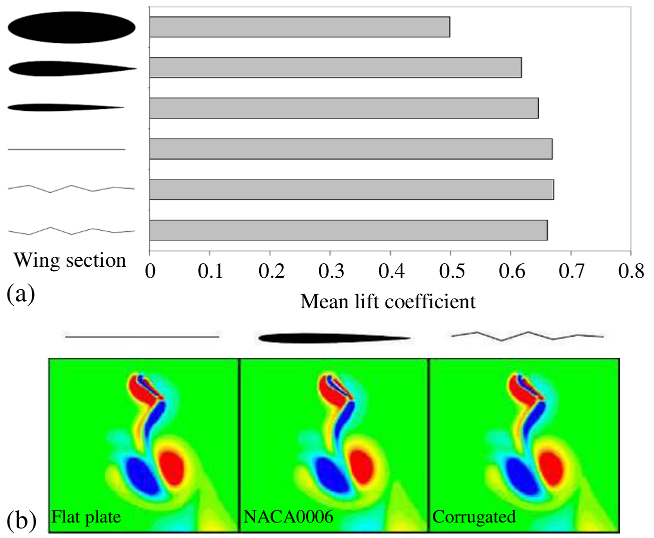

Fig. 5. (a) Mean lift coefficients and (b) instantaneous vorticity fields for different wing-section geometries obtained from CFD simulations of hovering flight with different 2D wing-section geometries undergoing dragonfly-like kinematics (Premachandran and Giacobello 2010).

2000; Murphy and Hu 2010), no major differences were observed in the flowfields surrounding the various wing sections at any point in the stroke cycle, as shown in Fig. 5(b) for the instant when the wing is at the top of its stroke. It was concluded that wing corrugations produce no increase in vertical force for the kinematics studied; however, their impact on the efficiency of flapping (lift-to-power ratio) and their structural benefits to lightweight wings may prove significant and warrant further study.

4.2. Fluid–Structural Interaction

Interactions between wing structures and the surrounding air are expected to significantly influence the aerodynamics of a viable flapping-wing MAV; and such effects may detrimentally affect the flight behaviour of larger aircraft through, e.g., buffet and aeroelasticity. Thus, experimental and numerical methods applicable to the study of fluid–structural interaction have recently been applied by DSTO to a canonical problem to validate their usage (Levinski et al. 2013).

As a first step to understanding the influence that compliance of the wings of a MAV may have, the effects of spanwise twisting (Premachandran and Giacobello 2012a) and chordwise flexure (Premachandran and Giacobello 2012b) have also been examined through CFD simulations.

The vertical force (lift) created by a wing undergoing a prescribed spanwise twisting motion, and thus feathering with the flow, while flapping horizontally in a sinusoidal motion, was compared with that generated by a rigid wing (Premachandran and Giacobello 2012a). The geometry of the dynamically twisting wing, which had an aspect (length-to-chord) ratio of five, and its insect-like kinematics are indicated in Fig. 6(a). The feathering angle was varied linearly from the root to the tip of the wing, and its magnitude was adjusted to examine its effect on the lift generated and on a

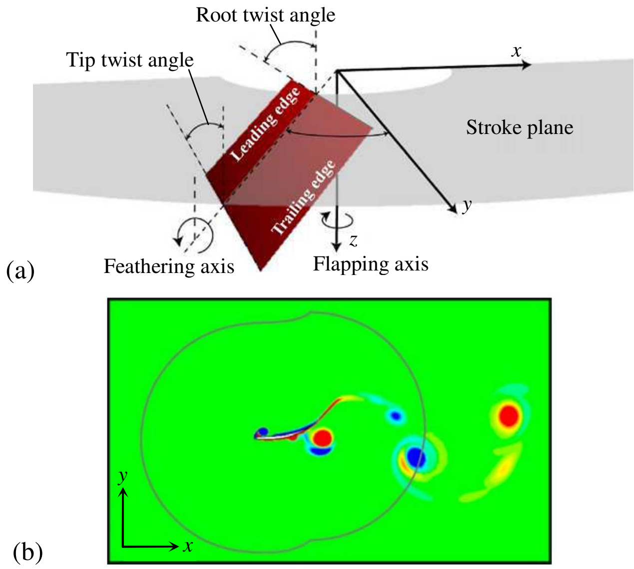

Fig. 6. (a) Geometry and kinematic parameters used in a CFD study of spanwise wing twisting (Premachandran and Giacobello 2012a) and (b) the vorticity field predicted by use of CDF around a 2D wing heaving vertically and experiencing chordwise flexure (Premachandran and Giacobello 2012b).

metric of efficiency (i.e., the ratio of the lift force to the power required to overcome the aerodynamic forces).

The findings of the study are likely to be useful in the initial design of a wing appropriate for a bio-inspired MAV, which can then be optimised using the equipment and methods described in §3.2. They also point to possible simplifications in a flapping actuator through the removal of superfluous DoF (e.g., the elimination of active wing-pitching control).

Fig. 6(b) shows a snapshot of the flow around a 2D flapping (heaving) wing undergoing a prescribed chordwise flexure in a steady on-coming flow (Premachandran and Giacobello 2012b). The flexure profile was varied to determine its impact on the thrust generated by the wing and the power required to overcome aerodynamic forces. The highest efficiency (thrust-to-power ratio) was obtained with a linear chord; thus, it was concluded that for simple flapping kinematics, the best thrust performance may be obtained with an uncambered wing that is free to pitch passively about its leading edge, similar to the wings of the bird-like flapper shown in Fig. 2(a).

4.3. Tandem Wings

DSTO recently extended its investigations to a tandem-wing configuration inspired by the dragonfly. Observations of dragonfly wing kinematics for a range of flight conditions suggest that the phase relationship between the flapping of the fore- and hind-wings plays an important role in their aerodynamics (Alexander 1984; Thomas et al. 2004). Thus, experiments were conducted in the DSTO Low-Speed Wind Tunnel to investigate the feasibility of achieving flight control for a MAV through the interactions of tandem wing pairs (Devlin et al. 2013).

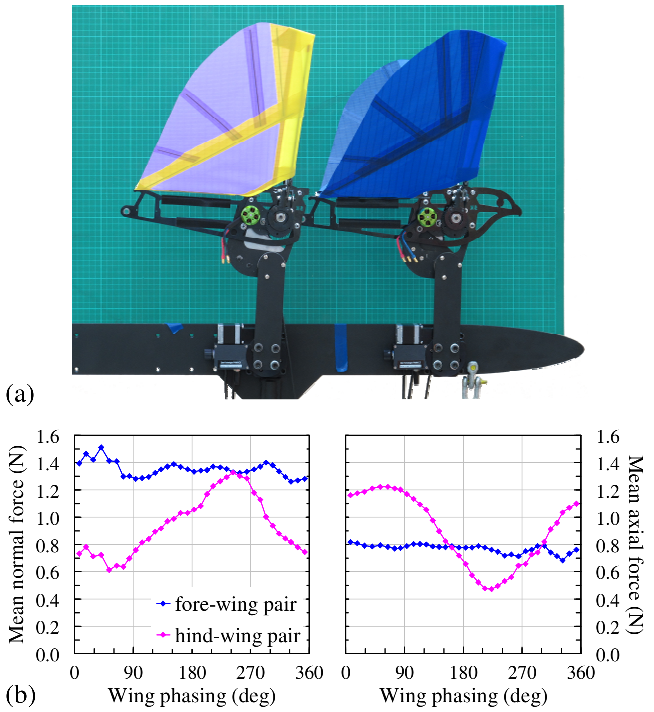

Fig. 7. (a) Experimental arrangement used to quantify the aerodynamics of tandem wings and (b) the mean forces on each set of wings as functions of the phasing between the wing pairs (Devlin et al. 2013).

The test article, shown in Fig. 7(a), was constructed from two COTS flappers; and measurements of the loads on each wing pair were made as the phase angle between them was varied, at different flapping rates and for different on-coming flow speeds. The wings were mounted on a common axis, but the angle of each flapping axis could be adjusted so that the stroke planes of the wing pairs could be varied independently, as could the distance between the wing pairs.

The measured mean normal and axial forces on each wing pair are shown in Fig. 7(b) for a case in which both flapping axes were tilted 5° above the horizontal and each wing pair flapped at 5 Hz in a steady flow of 4 m/s. Significant changes in the forces on the hind-wing pair occurred as the phase difference between its flapping motion and that of the fore-wing pair was varied over a range of 0–360°. This suggests that adjustments to the phasing of the wing pairs could be used to control the flight speed of a tandem-wing MAV by changing the total thrust produced by the system. Although not possible in this test case, it is feasible that if the stroke planes were inclined significantly from the vertical, hovering flight could be sustained, with minimal forward thrust and maximum lift.

5. FLAPPING-MECHANISM REQUIREMENTS

5.1. Actuation and Control

An actuator capable of providing an envelope of wing motions suitable for efficient forward flight and hovering, along with adequate control, stability, and manoeuvrability, is a necessity for a viable flapping-wing MAV. Each wing of a MAV equipped with tandem wing pairs (four wings) could potentially be controlled independently. If each wing had three DoF, i.e., flapping, pitching, and yawing, and could be operated at a variable flapping frequency and phasing relative to the others, the overall system would have up to nineteen DoF. Such a device might well prove impractical to build or fly, however, because of the intricacy and/or relative mass of the mechanism and the power required to drive it.

The aerodynamic studies described in §4 provide guidance to the aircraft designer that can be used to significantly reduce the electromechanical complexity for a controllable flapping-wing mechanism and ultimately a viable MAV. Discarding three-DoF control of each wing, by relying on passive pitching (feathering) of an aeroelastic membrane wing and eliminating wing-yawing motion, would still result in a device with a large number of DoF (and likely good controllability).

For example, each wing of a MAV with two tandem wing pairs could be driven by a motor at a variable flapping frequency and amplitude, and the phasing of each wing with respect to the others could be adjustable. This would provide seven DoF. Roll control could be achieved through port–starboard flapping asymmetry, either in the flapping rate or amplitude. The stroke angle of the wing pairs could also be controlled passively, as demonstrated by flapping devices that transition from bird-like, nearly vertical flapping when in forward flight to insect-like wing motion in a horizontal plane (normal-hovering kinematics) while hovering (de Croon et al. 2009; Palmer et al. 2011).

5.2. Resonant Drive and Energy Recovery

Computations performed when designing the wing testbed described in §3.2 highlighted that inertial loads generated by a flapping wing may require high torque and power input from the driving motor (Jones et al. 2011). A 20-g wing with a length of 0.25 m and an aspect ratio of six, executing dragonfly-like kinematics with a flapping amplitude of 120° at 10 Hz, was found to require a maximum input torque of 1.6 N·m and a maximum power of 62 W to overcome the inertial and aerodynamic loads on the wing. The maximum aerodynamic load requires only 30% of the total torque and 47% of the power. In contrast, a comparable wing with a mass of 5 g would require that the motor supply a torque of only 0.6 N·m and a maximum power of 35 W, meaning that the torque and power supplied are largely needed to overcome aerodynamic forces and moments, rather than inertial loads.

A solution to the problem of powering inertial loads on a flapping-wing MAV may be found in biological flyers that use energy-recovery mechanisms to minimise the input torque and power required to drive their wings (Weis-Fogh and Jensen 1956; Chai et al. 1998). Many insects utilise a resonant flapping system, in which energy is stored in an elastic material (resilin) in an insect's thorax during the portions of the wing-stroke cycle when the wing is decelerating (just before the extremes of the stroke) and then expended when the wing accelerates in the opposite direction (Weis-Fogh and Jensen 1956).

Several authors have described flapping-wing actuators utilising resonant mechanisms to drive wings suitable for MAVs of various sizes (Cox et al. 1998; Raney and Slominski 2004; Madangopal et al. 2005; Baek et al. 2009; Bolsman et al. 2009; Khan et al. 2009), though no wholly satisfactory and generalisable system has been devised. Animals with resonant wing-driving mechanisms have narrow ranges of flapping frequency and tend to increase their total lift, when necessary, by increasing the flapping amplitude of their wings. MAVs utilising such mechanisms would likely have similar restrictions, and these would need to be considered in the design of the flapping actuation and control system. Whether or not flapping-energy recovery is used, it must be concluded that the wings of a viable flapping-wing MAV will be as light as practicable, while maintaining the desired aerodynamic characteristics.

6. CONCLUSION

The experiments and numerical simulations described in this paper are isolated realisations within the large design space encompassing possible flapping-wing MAVs, parts of which are still not well understood scientifically. The purpose of the work was to develop techniques that permit insight into the fundamental physics of flapping flight and, by sampling across the design space, to determine which bio-inspired elements may provide significant aerodynamic and construction benefits to an engineered flapping-wing MAV.

The detailed analyses DSTO has undertaken are necessary for the creation of a mission-capable flapping-wing MAV, because, as has been demonstrated, efficiency will be required at all levels of such a device. Optimisation of the aerodynamics and actuator design are priorities, because the ‘brute force’ of increasing the size of the battery or fuel tank, often applied to small, fixed-wing unmanned aircraft to improve performance (i.e., range and endurance), will not produce a feasible flapping-wing MAV.

It has been shown here that the use of two tandem wing pairs could provide aerodynamic properties to enable a viable MAV with insect-like properties. Extensive information and techniques are now available for use in benchmarking, designing, and analysing such a device, though requirements beyond those related to aerodynamics, as considered in the current discussion, will need to be reflected in the design of a flapping-wing actuator. Essential and nontrivial inputs from the community of scientists working on appropriate navigation and guidance, communications, and sensor technologies are also needed to complete a future prototype.

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