

Chapter 15

Springy Shells, Pliant Plates and Minimal Motors: Abstracting the Insect Thorax to Drive a Micro-Air Vehicle

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Abstract The skeletons of the wing-bearing segments of advanced insects show unexploited potential in the design of biomimetic flapping MAVs. They consist of thin, springy, composite shells, cyclically deformed by large, enclosed muscles to flap the wings as first-order levers over lateral fulcra. The wings are light, flexible, membrane-covered frameworks, with no internal muscles, whose deformations in flight are encoded in their structure; they are ‘smart’ aerofoils. Both thorax and wings are apparently resonant structures, storing energy elastically, and tuned to deform appropriately at their operating frequencies. The form of the basic wing stroke is determined structurally, but is modulated by a series of controlling muscles, contracting tonically to alter the positions of skeletal components over the course of several stroke cycles. Fuel economy through lightness, low wing inertia and cyclic energy storage are all desirable in a flapping MAV. Furthermore, the insects’ peculiar combination of structural automation with modulation has great potential in achieving versatile kinematics with relatively few actuators. Aspects of the thoracic functioning of an advanced fly can be simulated in a simple card flapping model, combining the properties of a closed four-bar linkage with the elastic lateral buckling of a domed shell. Instructions for building this are included. Addition of further degrees of freedom, along with biomimetic smart wings, would seem to allow other crucial kinematic variables to be introduced and controlled with minimum actuation, and ways are suggested how this might be achieved in a sophisticated mechanism.

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15.1 Introduction

Insects are superlative micro-air vehicles. This is widely recognised by engineers who have chosen to propel small flying robots by means of flapping wings, and insect flight specialists have been extensively consulted and sometimes actively involved in MAV development. Their contributions, however, have so far mainly been in the areas of flapping flight aerodynamics and of flight control. The mechanical processes and components to drive MAVs – the actuators, transmission and effectors – have tended to follow orthodox rather than biomimetic technology: electric motors or piezoelectric actuators driving novel, often beautifully ingenious mechanisms of stiff components, linked by bearings, and flapping rigid or simple flexible wings ([1, 2, 4, 12, 14–18, 22, 30, 31, 36] and see [4] for a useful classification of types); see also Chaps. 13 and 14.

Insect ‘technology’ is very different. Muscle has no real parallel in our own engineering; and the insect flight skeleton, which provides both the transmission and the wings themselves, is a system of thin, springy shells, plates and frameworks. The thoraxes of advanced insects – flies, wasps, moths, true bugs – can be thought of as flexible monocoques which are deformed cyclically by the muscles, flapping the wings as first-order levers over lateral fulcra. The wings themselves are smart, deformable aerofoils, whose instantaneous shape through the stroke cycle is determined, largely automatically, by the interaction of their structural elasticity and the inertial and aerodynamic forces they are experiencing. Again there are no obvious parallels in our own technology – yet.

There are good reasons for this. Deformation of thin shells and plates under loading often involves buckling, which can be highly non-linear, is difficult to model and is often destructive. Furthermore, cyclical deformation can lead quickly to fatigue failure. These disadvantages can to some extent be overcome by using appropriate polymers and composites and by new computer modelling and optimisation techniques; but in most engineering contexts traditional methods are adequate and considerably more straightforward to use.

Insects, however, overcome these difficulties with ease, and thereby gain considerable advantages. First, thin composite shells and plates have low mass; an advantage in any flying machine, but especially valuable in a flapping system, where the inertia of the moving parts and particularly of the wings needs to be minimised. Second, they are often springy, made of resilient materials in three-dimensional structures that deform elastically and are capable of elastic energy storage – again invaluable in an oscillating system. Elastic storage is a component of some existing MAV mechanisms (e.g. [16, 30, 31]), but achieved in more conventional ways. Third, they seem fairly insensitive to scaling effects; in some prominent groups similar mechanisms operate over a very wide size range, from the unnervingly large to the near-microscopic, with little apparent difference in morphology. These properties should all commend themselves to MAV designers, and it seems possible that insect solutions may have much to offer in the development of small robotic flapping mechanisms. This chapter will therefore explore the possibilities and implications of adopting and adapting aspects of the insect thoracic skeleton in designing the transmissions of small, versatile, manoeuvrable low-speed MAVs with some insect flight characteristics and will also examine how an understanding of insect wing functioning might lead to the development of more effective flapping aerofoils than have so far been employed.

15.2 Some Requirements of a Small, Versatile Flying Machine: How Do Insects Manage?

Flying machines, whether natural or man-made, need a power source, actuators, a control system, a transmission and effectors. The first three are outside the scope

of this chapter; we are concerned with design requirements of the last two. These need the following.

15.2.1 Low Mass

Flapping flight is expensive, especially at low speeds. Power is at a premium; and minimising both weight and the inertial cost of flapping is a major design consideration. The cuticular skeleton of insects, which also serves as a skin forming almost the entire interface between the insect and its surroundings, is suitably light. It consists mainly of an extraordinarily versatile array of composite materials, chemically and structurally related but varying markedly from place to place in the orientation of the fibrous component, which consists of microfibrils of the carbohydrate chitin, and in the composition and degree and nature of cross-linking of the protein molecules that provide the matrix of the composite material. These variations provide a range of mechanical properties – stiffness, toughness, hardness, strength, resilience – apparently optimised everywhere for the forces encountered and for the many local functions that the cuticle serves [20, 23]. In the skeleton of the thorax itself cross-linked cuticle provides areas of rigid, but often springy, plates and curved shells ('sclerites'), which may locally be reinforced by internal ridges or thinned for greater pliancy. Between and continuous with them are areas of soft, compliant cuticle, which may locally include tensile, tendon-like bands joining muscles to plates or plates to plates and sometimes bands or pads of rubbery, elastomeric protein.

The wings themselves consist almost entirely of cuticle, which provides both the supporting, usually tubular, veins and the membrane, whose thickness varies greatly but can be less than 1 μm . With no internal muscles and little contained fluid the wings are usually extremely light with low moments of inertia – important, since flapping frequencies of several hundred hertz are common – and the potential for inertial energy loss is substantial. Rigidity is enhanced by relief: corrugation and camber, raising the second moment of area of cross sections, with little extra cost in material and mass.

15.2.2 Appropriate Kinematics

Appropriate wing kinematics are essential in flapping flight. These become more complex at low speeds or

more precisely at lower values of the advance ratio, J . This is a measure of the ratio of forward speed to flapping speed and is given by

$$J = V/2\Phi nR,$$

where V is the forward velocity, Φ the stroke amplitude in radians, n the stroke frequency and R the wing length [7]. At high J values the wings meet the air at positive angles of attack on both downstroke and upstroke. In fast forward flight the wings of birds and bats undergo minimal change in shape and attitude, and this is also true of the relatively small range of insects, including some butterflies, that fly fast with slow strokes. For this reason it is relatively easy to build a simple fast-flying model whose wings simply flap up and down, and several are available as toys, showing remarkably lifelike flight. The best known are the inexpensive Tim and Timmy birds, by Schylling Toys, whose simply supported wings are flapped by an ingenious variant on the open four-bar linkage driven by wound synthetic rubber loops, widely used in 'ornithopters' by aeromodellers.

However, as the value of J decreases, changes in wing attitude and/or shape between the two half-strokes become increasingly necessary if the upstroke is not to exert adverse forces on the wings, with a net downward component. Slow flight at low J values, and hovering, where $J=0$, hence require the wings to twist and sometimes to change shape between the half-strokes in order to either minimise upstroke forces or direct them favourably. Furthermore, in many insects wing twisting, appropriately timed, is itself responsible for generating bursts of high vorticity and hence high lift around the points of stroke reversal, in a range of unsteady aerodynamic mechanisms that may be essential to support the insects' weight and in the fine control of accelerations and manoeuvres [5, 8, 26].

Insects achieve these kinematic skills by unique methods. In the great majority of species, flapping is achieved by cyclic contraction of opposing sets of 'indirect' muscles, inserted on thoracic sclerites remote from the wings, rather than on the wings themselves as in flying vertebrates. These muscles alternately pull the top of the thorax down, levering the wings up, and cause it to bow upwards by compressing it longitudinally, levering the wings down (Fig. 15.1a,b). Other movements of the whole wing – promotion and remotion, some basal twisting, control of the wing stroke path, folding and extension – are

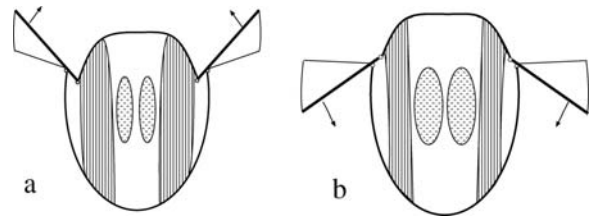


Fig. 15.1 Diagrammatic cross section of a generalised insect thorax showing the action of the flight muscles: (a) upstroke and (b) downstroke

achieved by a series of 'direct' muscles, inserted on, or connected by tensile cuticle bands to sclerites at the extreme wing base. In the great majority of species, the indirect muscles powering the wing stroke are of a physiologically and histologically distinct type, known as 'asynchronous' or 'fibrillar' muscle, and unique to insects, whose contraction frequency is not limited by the frequency of the incoming nerve impulses. This allows the insects to operate if necessary at stroke frequencies far higher than those with orthodox muscle only, which are constrained to values below c. 100 Hz. The direct muscles, on the other hand, appear always to be of the orthodox kind; and in insects with asynchronous power musculature, changes in the wing stroke variables which the former control are achieved by slower, tonic contractions that modify the positions of the basal sclerites during the course of several stroke cycles.

There is some evidence that the direct muscles can influence the shape of the wings at their extreme base, but wing shape is otherwise passively determined from instant to instant during the stroke cycle by the interaction of the wings' elasticity with the inertial and aerodynamic forces that they are receiving. These alterations in shape – twisting, flexion, change of cross section – are an integral part of the flight process, and they are effectively programmed into the wings' structure: in the relief, the form and arrangement of the supporting veins, the distribution of rigid and flexible components. The wings are in effect 'smart' aerofoils, combining remote and automatic shape control in ways which seem to occur nowhere else in nature or in technology [32, 33, 35].

15.3 Biomimetic Possibilities

Biological systems have limitations as well as advantages – see Vogel [24] for a thoughtful analysis. They

have no access to bulk metals or (above the level of bacterial flagella) to rotational joints, so that movement involving rigid components is restricted to oscillation and reciprocation. Their actuators can only pull, not push. Most importantly, their designs are constrained by their ancestry; they have always to develop from those of their immediate predecessors. They cannot, as engineers can, learn from, adopt, combine and adapt the designs of widely separate groups.

Engineers contemplating biomimetic design solutions therefore face a sequence of decisions. Is the naturally occurring solution to the problem in question the best available? If so, is it feasible and sensible to adopt it? If so, to what extent?

Copying the principles of insect thoracic skeletons appears to have real potential in MAV design. It is at present beyond us to emulate the extraordinary versatility of insect cuticle, but combining appropriate tough, fatigue-resistant polymers and composites in an optimally designed thin shell would seem to be a feasible, and ultimately simple and reproducible way of building an effective low mass transmission. MAV wings, too, could usefully copy the smart properties of insect wings; the greater the degree of structure-based automation, the less information needs to be processed from instant to instant, and the fewer actuators are required.

Minimising the number of actuators is a major consideration in MAV development, and insects here give us no cause for optimism. In dragonflies, insects which instinctively appeal to biomimetic engineers because of their appropriate size and superlative flight skills, no fewer than 50 muscles are involved in flight. Even flies (Diptera), which operate with a single pair of aerofoils on one thoracic segment, use 38 muscles [28]. Here at least, close biomimicry seems impracticable. The implications of so many actuators in terms of weight and control in an MAV are obvious, and different solutions are needed.

15.3.1 Kinematic Requirements

A fully manoeuvrable flapping MAV may need to be capable of varying and controlling most or all of the following:

- A. Flapping amplitude: Most insects whose flight has been studied appear to use amplitude change as a means of varying the strength of the net aerodynamic force, though the relationship between amplitude and flight velocity is far from simple [6].
- B. Stroke path: The principal reason to vary the trajectory of the wing stroke is to control the direction and centring of the mean aerodynamic force vector of each stroke, or in low frequency flappers each half-stroke, relative to the centre of mass of the insect; hence inducing and controlling movement around the three rotational axes of space: pitch, roll and yaw. Control of pitch is particularly important, in influencing the angle of the stroke plane to the horizontal: the stroke plane angle – see below. Most insects studied are capable of modifying their stroke path to a considerable extent [3, 7, 10, 25, 27]. The ‘figure of eight’ shape that appears in much of the earlier literature is only one of a range of such paths, and the emphasis on achieving this that has guided some recently published flapping mechanisms is probably quite unnecessary.
- C. Stroke plane angle: In many insects the flapping movement of the wing approximates to a plane. The angle of this plane – calculated as the slope of the linear regression of the vertical component of the wing tip path on the horizontal axis [7] – is a major determinant of the direction of the mean force vector, and hence of flight velocity.
- D. The degree and timing of wing twisting during the stroke: Twisting, as we have seen, is essential at low values of J , and its timing can be important in unsteady lift mechanisms.
- E. The capacity for lateral stroke asymmetry in amplitude, stroke path, the degree or timing of twist, or in any combination of these, to facilitate manoeuvres.

Control of another possible kinematic variable – stroke frequency – is probably less important. Frequency appears to vary little in individual insects and is probably kept close to the resonant frequency of oscillation, where energy expenditure is minimised [6, 13]. For economy any flapping mechanism in an MAV should be designed as a resonant system, and its frequency would then be relatively invariable.

15.4 An Appropriate Thorax Design for Abstraction – Higher Flies

Insect thoraxes are extremely diverse, and the mechanics of very few have been studied in detail. While there

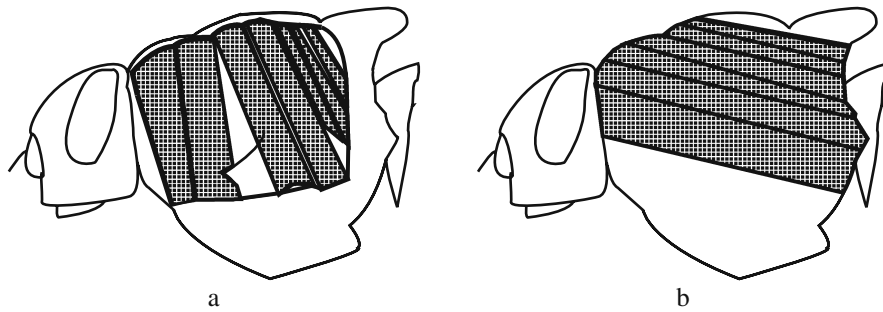


Fig. 15.2 The indirect flight muscles of the blowfly *Calliphora*: (a) the wing elevators and (b) the wing depressors

is nothing to preclude the abstraction and combining of principles from several different groups, I shall base the following on the blowfly *Calliphora*, whose flapping mechanics have been investigated in particular depth [9, 19, 28, 29]. Figure 15.2 shows semidiagrammatically the positions of the flapping muscles in a sagittal section of the blowfly mesothorax – the flapping body segment. Wing elevation is achieved by contraction of an array of large, paired dorsoventral muscles (Fig. 15.2a) inserted dorsally on the notum – the thoracic roof – and ventrally low down on the pleura – the sides of the thorax. Wing depression is brought about by contraction of huge dorsal longitudinal muscles (Fig. 15.2b), inserted broadly on the anterior part of the domed notum, and posteriorly on the vertical back of the notum and an internally extending plate, the phragma. These, together with a pair of small lateral muscles, not illustrated, are ‘indirect’; remote from the wing itself. Three further pairs of small muscles, not shown, serve to tension the thoracic box, and no fewer than 13 further pairs, inserted directly on the

complex of small sclerites around the wing hinge, are concerned with wing folding, in controlling the positioning and attitude of the wing base and in modifying the form of the stroke.

It would be absurd to attempt to copy such a complex actuation system in an MAV. The correct approach would seem to develop a simplified transmission based on the thoracic skeleton and to consider from first principles what actuation would be necessary to achieve the necessary kinematics.

The following account of the deformation of the mesothorax largely follows that in [19, 29]. Figure 15.3a shows the mesothorax from the side. The four round dots represent transverse axes, about which the thorax distorts cyclically under the action of the indirect, flapping muscles. The positions of the anterior and ventral axes are approximate; their presence is betrayed by the cyclic widening and contracting of the adjacent pointed clefts, filled with soft cuticle. Posteriorly two more clefts also widen and narrow by the cyclic elevation and lowering of the processes X and Y.

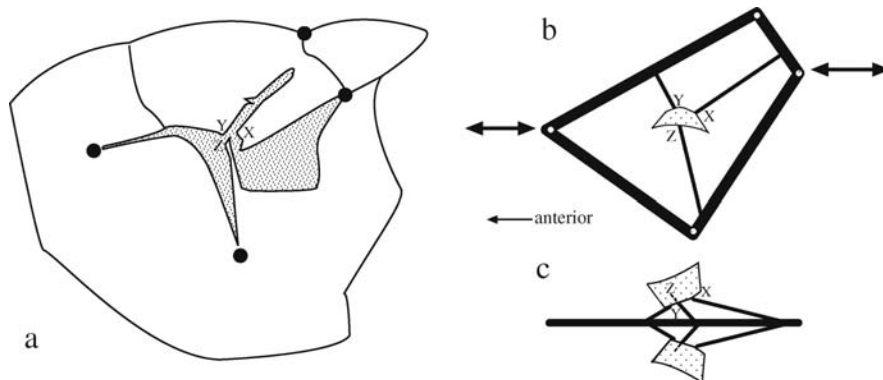


Fig. 15.3 (a) Side view of the mesothorax of *Calliphora*, showing the three principal processes, X, Y and Z, to which the wing attaches and the four rotational axes about which the thorax

deforms in flight. (b, c) The mesothorax treated as a four-bar linkage, with three out-of-plane coupler bars. (b) Side view and (c) from above

These are flexibly linked to the base of the wing; and the latter rests on the process Z, which acts as the fulcrum. In flapping, the up and down movements of X impart some twist to the wing base, so that the latter tends to pronate as the wing is depressed and to supinate as it rises.

The mesothoracic flapping mechanism can be simplified as a three-dimensional four-bar linkage, with fixed coupler bars projecting inwards from three of the four, their ends representing the three processes, X, Y and Z, to which the wing is attached (Fig. 15.3b,c). Z, the fulcrum, is more laterally situated than X and Y; and X is positioned slightly more laterally than Y. The proportions of the bars and the positions of X, Y and Z are critical. If correct, low-amplitude compression at the points indicated by arrows raises X and Y relative to Z and would depress an attached wing. X moves higher than Y, which would tend to twist the wing base and pronate the wing; and Y also moves slightly posteriorly, and closer to X, tending to promote the wing. Hence, as a direct consequence of the structure of the mechanism, a single movement depresses, pronates and promotes the wing; and conversely tension at the indicated points would raise, retract and supinate the wing – all in keeping with actual wing kinematics. Since a four-bar linkage has only one degree of freedom, the system should theoretically be operable with a single actuator, replacing the four sets of indirect muscles in the insect itself.

In the fly the four bars are actually thin shells, and in no case do the ends of the flexible clefts coincide with the axes of rotation, so that some lateral buckling is inevitable. The notum in particular is domed, and Ennos [9] found that contraction of the dorsal longitudinal muscles caused the sides to buckle outwards at the process Y, assisting in wing depression. This is an elastic process, and a potential site of cyclic energy storage.

Figure 15.4 shows a cardboard flapping model that combines these properties and can be worked by simple pressure of thumb and forefinger. Figure 15.5 is a flat design for the model, with instructions for building it. If properly constructed the mechanism produces an automated flapping cycle with a degree of appropriately timed promotion, remotion and pronatory and supinatory twisting and twisting.

For a manoeuvrable MAV, however, a mechanism with a single degree of freedom is inadequate. The only kinematic variables that could be altered in flight

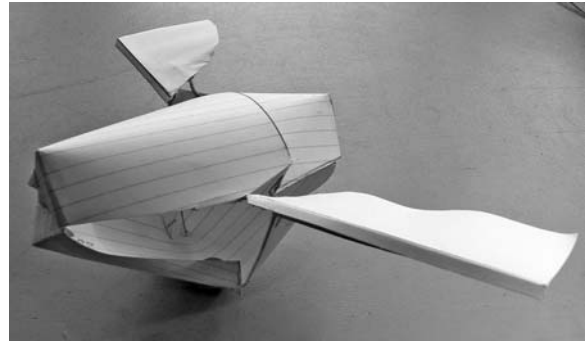


Fig. 15.4 The thorax modelled as a four-plate linkage with lateral elastic buckling

are stroke amplitude and, within the limits imposed by resonance, frequency. To be able to change the stroke path and the stroke plane angle, additional freedom and actuation are required.

Here another insect trick could if necessary be adopted: the tonic contraction of the direct, controlling muscles, acting slowly by altering the positions of thoracic components over several flapping cycles. Two approaches, available to engineers but not to insects, appear to be worth exploring.

1. The stroke path could be made adjustable by introducing active movement to the lateral fulcra.
2. An extra three-dimensional, shell-like bar could be added to the linkage, increasing its mobility to 2 and theoretically necessitating one additional actuator. Interaction of the two actuators, operating at the same frequency, should allow precise instantaneous control of the relative motions of Y and Z, and hence of the wing tip path, and using one actuator 'tonically' to position the mechanism over several cycles is also an option. One feature of the four-bar system is lost. Experiment shows that active twisting of the wing base can no longer be appropriately coordinated with the flapping cycle, so that the bar corresponding to the process X, which causes twisting in the four-bar model, needs to be lost. Promotion and remotion, the other functions of X, are components of the stroke path and hence controllable by the newly acquired mobility of the system.

Active wing twisting would now need separate actuation. However, this may not be necessary. Most of the

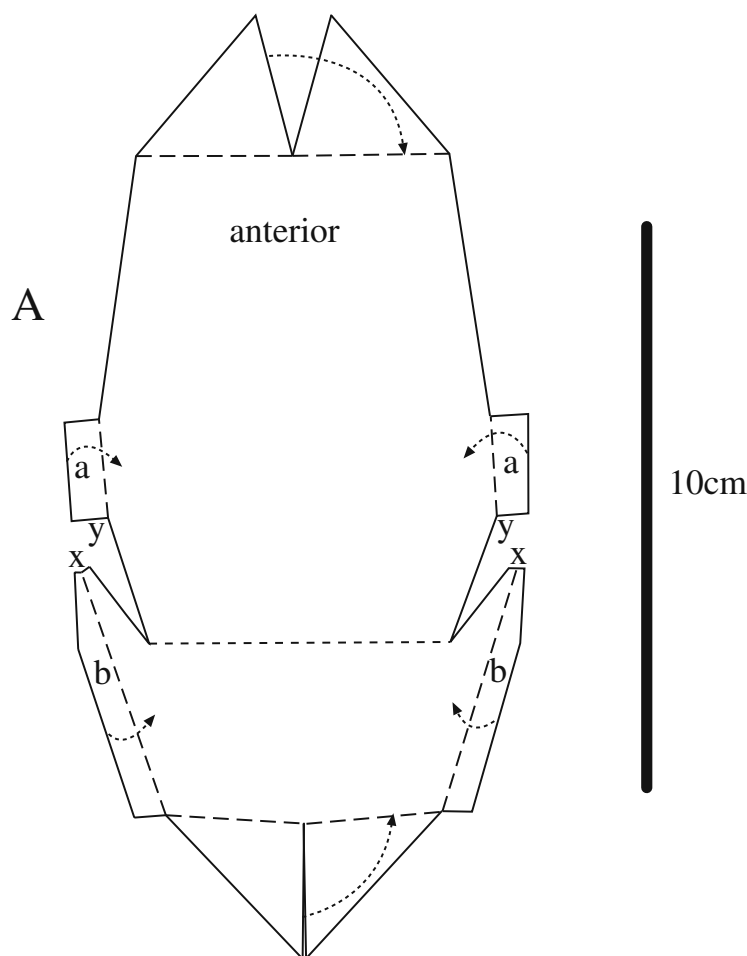


Fig. 15.5 Cut-out design for the thorax model: (A–D) cut-out proformas and (E) diagrammatic detail from Fig. 15.4, showing the positions of the cords at the articulation. *Assembly instructions:* Use thin card, about the thickness of a standard index card. A glue stick is best for adhesive. Paperclips and small staples are useful for the temporary support of glued surfaces, and fine forceps or pliers help in making the wing articulations. Carefully score along the *broken lines*. Those with *longer dashes* are actual fold lines, the *smaller dashes* facilitate the operation of the mechanism. (A) The dorsal component of the model, corresponding to the insect's notum. Bend the triangular tabs at each end until they overlap as shown and glue them together, forming two triangular, boat-shaped ends. Fold in the tabs marked 'a' and 'b', but do not glue them at this stage. (B) The ventral component. Glue together the *triangular/square* tabs at each end, as indicated, creating *diamond-shaped, boat-shaped* ends, with a transverse crease across each *diamond*. Fold back the tabs marked 'c', but do not glue them at this stage. Flex the model along the line 'd–d' through approximately 90° and glue the tabs marked 'e' to the *shaded squares*. (C) The leading edge spar of the wing, and two should be made. Crease along all the broken lines, fold along the middle one and mould the result into a v-shaped cross section, with the small, *cut-out rectangle* on

the concave side of the V, near the pointed end. Glue all but the *shaded area*. Join the dorsal and ventral components of the body (A) and (B) at the ends by gluing the protruding, flexible, triangular part of the diamond-shaped ends of (B) inside the *triangular ends* of (A), making sure that both components are similarly orientated. Allow to dry. Cut four lengths of thin cord, or strong thread, each ca. 4 cm long. On each side, glue ca. 1.5 cm along the fold line of tab a, with the free length protruding posteriorly at point y, corresponding to point Y on the fly thorax in Fig. 15.3. Glue tab a in place, anchoring the cord. Bring the pointed end of the wing spar (C) up to point y and glue the next section of the cord along the concave face, behind the innermost layer, bringing it out through the *cut-out rectangular slot*. Complete the gluing of the spar base, which should now be capable of free rotation about y. Glue the remaining end of the cord down the fold line of tab c in the ventral component of the model. The upper end of tab c, point z, forms the fulcrum for the wing, corresponding to point Z in Fig. 15.3. Both y and z should be in flexible contact with the wing spar, with very little cord showing. Glue tab c in place. Glue ca. 1.5 cm of the next piece of cord along the fold line of tab b, with the free end protruding anteriorly at point x. Glue the tab in place. Cut two of the shapes marked (D) from paper and glue the straight sides

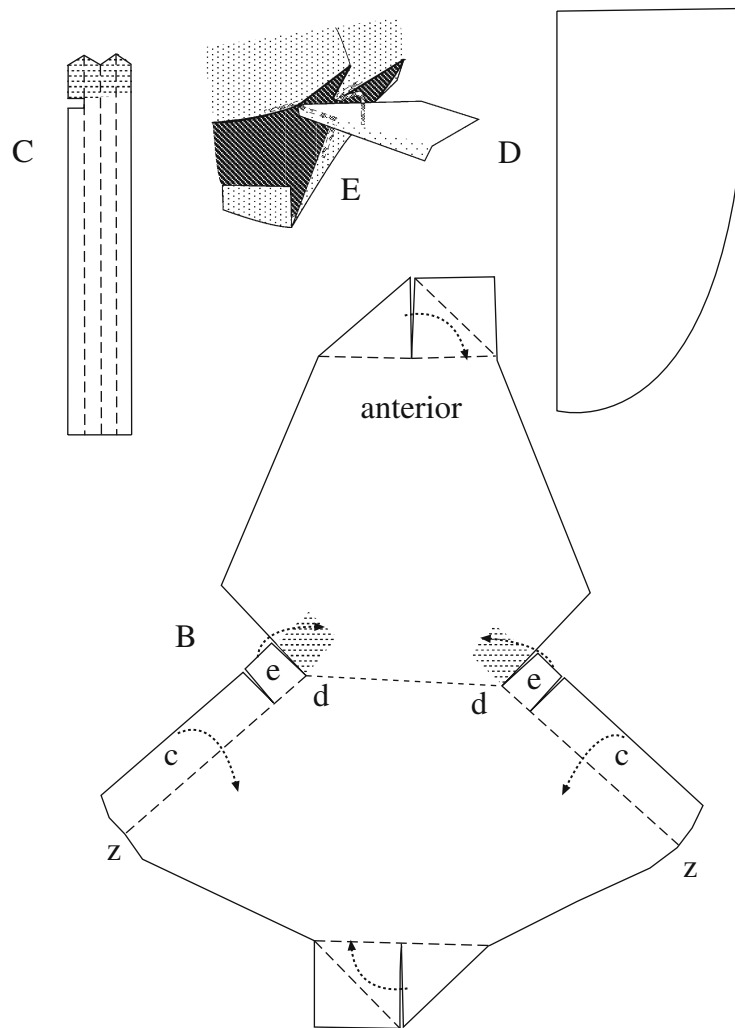


Fig. 15.5 (Continued) to the wing spars. The model is now virtually complete. The wing spars should be level, projecting transversely and slightly above the horizontal. Glue the free ends of the cord extending from point x to the underside of the posterior part of the wing, leaving enough cord between x and the wing to allow free movement. Trim off any surplus cord. To

operate the model, hold the anterior part of the ventral component between the thumb and forefinger of one hand. Support the most ventral part of the model (at d–d) with the thumb of the other hand and gently squeeze repeatedly with the forefinger at the posterior extremity of the ventral component

torsion in insect wings takes place within the span, and appears often to be driven solely by inertial forces on the wings, perhaps with an aerodynamic component. It may well be that in a suitably constructed and tuned wing no active twisting is required.

There remains the need to introduce lateral asymmetry to the wing stroke, in the form of differential amplitude or torsion, in order to manoeuvre. For either of these, additional actuation is essential. Four approaches deserve consideration.

- A. In the movable fulcrum option described above, asymmetry would be provided by separate actuation of the two sides.
- B. It may be possible to achieve the necessary effects by actively stiffening or warping the shell on one side through several stroke cycles. Pressure applied to one side of the model in Fig. 15.4 can alter the form of the stroke on that side, indicating that it may be possible to optimise this effect by careful design.

- C. Another solution available to engineers, though not to insects, may be to allow active movement of the centre of mass of the body relative to the centre of aerodynamic force.
- D. The effects may be achievable by remote control of the instantaneous shape of the wings themselves.

We will explore the last solution.

15.5 Wing Biomimicry

MAV designers have so far paid little attention to the biomimetic possibilities that insect wings offer. Approaches to modelling their unique properties, which combine structural automation of their kinematics with remote control, have been explored by Wootton et al. [35], with reference to much earlier work; see also Chap. 11.

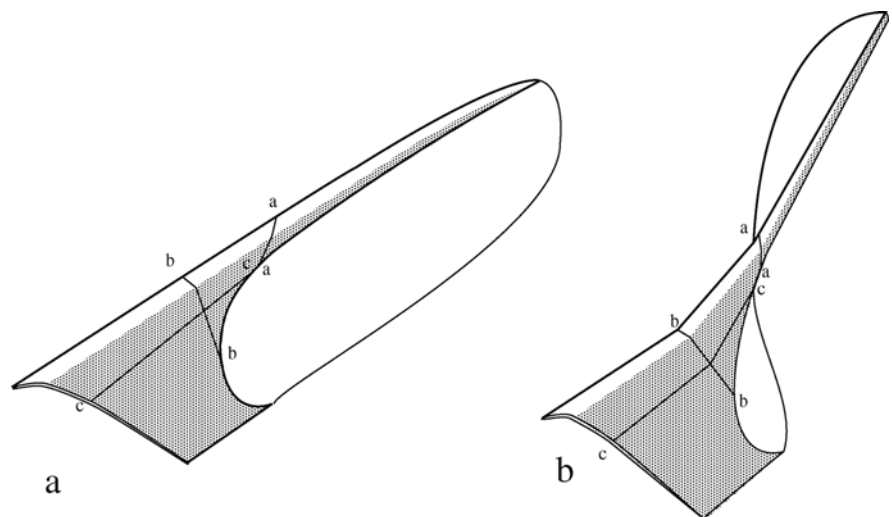
Insects make extensive use of relief to stiffen their wings. This not only minimises mass but also provides differential flexibility in different planes. For example, a wing with longitudinal pleats is flexible along axes parallel to the pleats, but rigid to bending across them. Transverse bending is only possible if the pleats can be flattened or if the pleats on the inside of the curve can bow upwards into the plane of those on the outside [21]. A wing with a cambered section is more rigid than one with a flat section, and asymmetric in its response to bending forces. Force applied

from the convex side flattens the section and allows non-destructive bending with a fairly large radius of curvature, but applied from the concave side tends to increase the camber and hence the rigidity, and eventually leads to local buckling and destructive failure [32]. If the force is centred behind the wing's torsional axis, this asymmetric response to bending leads to asymmetry in resistance to twisting, which combines bending and torsion; and this simple property appears to be extensively used by insects to facilitate passive twisting in the upstroke while resisting it in the downstroke [11, 34].

In many insects with broadly supported wing bases, or whose fore and hind wings are coupled together, upstroke twisting of the distal part of a cambered wing is achieved by ventral bending along an oblique line of flexibility. The amount of bending and angle of twist are related to the height of the wing camber proximally to the line of flexion, and this seems to be actively controllable by muscles at the wing base. Bending and torsion of a cambered or pleated wing involve elastic deformation, and it seems that wings too are resonant structures. Like the thoracic box they need to deform correctly at their working frequency, and one can identify morphological features that seem adapted to tune them to do so.

These principles can readily be modelled physically and could certainly be used in designing wings for an MAV. Figure 15.6 shows one such model. Support is provided by the stippled area, which is made of thin card. The leading edge section is curved ventrally and

Fig. 15.6 A cardboard (a) and paper (b) wing, demonstrating how three flexion lines can allow and control supinatory twisting in the upstroke. Explanation in the text



is crossed by two oblique lines of flexibility, a–a and b–b, made by cutting part way through the card with a sharp blade. The broad basal stippled area is also cambered and is crossed by a longitudinal flexion line c–c that crosses b–b. The rest of the wing is made of paper.

The wing has interesting and unexpected properties, best understood by making the model. The curved section of the leading edge makes it resistant to bending when force is exerted on the ventral, concave side, as it would be in a downstroke. If the force is applied to the convex side, behind the wing's torsional axis, as it would be in an upstroke, the leading edge bends slightly about a–a, and the wing twists readily towards the tip and could easily assume a positive angle of attack and generate useful upward force. Bending about b–b greatly enhances the twisting, but this is controllable by varying the camber of the basal area around c–c. When the base is nearly flat, bending at both a–a and b–b allows the distal part of the wing to twist dramatically (Fig. 15.6b). Steeper basal camber limits bending to a–a and the wing twists far less. A wing so designed would twist automatically to some extent in the upstroke, but the extent could be controlled over a wide range by simple basal actuation.

15.6 Conclusion

It seems possible that a complete system comprising a transmission with the properties of a five-bar linkage in a resonant, springy shell, together with a pair of smart wings with actively variable basal camber, could drive an MAV having mechanical control over all the kinematic variables that we have identified as essential for versatile flight, with a rather small number of appropriately designed and located actuators. The mechanism in Figs. 15.4 and 15.5 and the wing in Fig. 15.6 are naïve examples; a sophisticated design would be a deformable monocoque, optimised using modern modelling software, with similar optimised wings. Such a system would have the added advantages of low weight and inertia and relative economy through cyclic elastic energy storage and release. It should moreover be fairly easy to build and replicate, and be capable in time of progressive miniaturisation, as smaller motors, power stores and control circuits become available.

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