Bitten by a Dragonfly

Introduction and Purpose

This is a personal account of an heuristic and pragmatic quest for a life-size scale flying model of a dragonfly. It is NOT a "How-to"!

Originally, a dragonfly was chosen "because it had a long body for a rubber motor" – my first inappropriate notion. Always interested in miniaturization, I eventually centred on a life-size model. That raised more than one challenge:

concealing a flapping mechanism within the envelope of the animal;
understanding the unfamiliar characteristics of four-wing flapping flight;
making so small a model fly at all;
achieving tailless flight stability;
modelling such complex forms, textures and colours;
handling, without damage, such a light and vulnerable sculpture.

No doubt we each have our favourite fascinations. Mine are the mechanics and aerodynamics, but the project defined which problems got resolved and in what order. So Mechanics loomed large, while Aerodynamics hasn't had a look in. Only lately has the difficulty of winding and launching a fragile 1/2gm leggy model become so apparent. Such challenges have not felt daunting, however, and progress was incremental, fairly methodical, continual and I still believe in success – eventually!

The reason for noting it down now was a supposed 18-seconds flight of a test rig. Further technological development would be gilding the lily. The demands had now changed to sculptural, and the technical niceties might soon get forgotten. Also, getting the model to fly at last seems to have disrupted progress. Although its flight is still unpredictable, I'm spellbound that it flies at all! And experiment has halted because I fear to explore further than a slight change of trim. I feel a need for review and for exchanging ideas, so invite comment on any aspect.

Design Philosophy

Working in isolation, like an artist in his garret, I had neither guidance nor constraint. Criteria arose spontaneously and I followed them in the spirit of discovery, like a child intent on play, without concession – eg, to size – or cutting corners because nobody was checking. Those criteria were:

> that flight would be sustained by wings of scale planform and without a tailplane. Here, "flight" means: a) the ability to climb; b) sufficient stability for trimming to a constant turn, despite the falling motor torque; c) a duration of at least 15 seconds (often used for indoor scale fixed-wingers);
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> that the mechanism should reside wholly within the head and thorax – so, eg, there would be no conrods or pins half way out along the LE. A further challenge to mechanism design was to keep the motor hook well forward and so allow the rear anchor to be farther back (but the CG prevented it's being far down the abdomen);

that the appearance represent the essential quality of the Subject, both in static display and in flight characteristics. The motor may be external, but must then be removable for static display. Wing, body and leg surfaces must be durable enough for the rough handling often associated with ornithopters.

Prototypes

The female Brown Hawker, Aeshna grandis was the chosen Subject because of: a) its large size, 102mm span and 73mm length; b) its head being so close to the thorax that there is little necking; c) its thicker waist; d) its being the only British dragonfly with wings that are the colour of condenser paper!

Three test rigs with Brown Hawker planforms have been built, all rubber powered. The wings are arranged with unswept fore LE's and swept-back hind wings (for a CG which allows a long motor). A number of prototypes of non-dragonfly planforms were also flown to test doubtful aspect of the design – eg, a succession of ever smaller conventional models, eventually to a 3" model of about the same wing area as the target dragonfly. All flew, reassuringly.

The first, of 2-foot span, was built with one-piece balsa spars from tip to tip and membranes of condenser paper, with scale TE's. The fore wings were rocked through 140 degrees by a crank and single conrod, while the hind were attached to the body and so rocked by reaction. The effective flapping angles are unknown but will be around 70 degrees. "Veins" (then straight radial balsa spars) were attached to the membranes (originally alternately above and below, to simulate corrugation). To explore the effect of chordwise tension they were spread by wire springs and not attached directly to the structure at the root, so the membrane formed into the conventional Penaud aerofoil – at any rate, on the downstroke. Wing loading was low, so frequency and forward speed were, too. There was no attempt at a scale body profile. A V-tail was fitted for stability. Little flying was done, and nothing deduced from changing the tension, before a structural failure. The model "is going to be rebuilt" ever since.

The rocking of those wings was dubbed "diagonal phasing". Other phasings are used in two life-size test rigs: "counter-phase" (hind wings lag the fore by 180 deg) and "in-phase". A simple non-180 mechanism has proved elusive, so different lags are being explored via the excellent 1-foot (non-scale) "Dragonfly 3" designed by Youhei Takatani. (His models fly really well - I've lost two! See http://homepage1.nifty.com/akatombo/e-product.html/) Those tests indicated an optimum phase lag of between 90 and 120 degrees for that model.

The two life-size 102mm span test rigs, used "aeroelastic" wings instead of membranes, see Life Size Dragonflies.jpg. Their wing profiles are to scale, of cambered 0.008" foam (hind cambers negative), but pivoted on (by light sewing) straight spars (now of carbon, but to be eventually of steamed bamboo). Although they provide (just) enough thrust to fly, more thrust is being sought by slitting in from the LE's (and, soon, TE's) to tailor their torsional stiffnesses, but they will never twist so far as the animal's wings do. (Real wings will be tried as soon as available. Donations of undamaged specimens will be welcomed!) The stroke plane is about 20 degrees forwards/downwards. There is no root seal because the bodies are mostly skeletal.

The in-phase is marginally the heavier and currently flying at 408mg. With a wing area of 19.6cm^2, the wing loading is 0.68oz/ft^2. Frequency averages around 20Hz but the speed has not been measured.

The Mechanism – Flapping the Fore Wings

The smallest detail as well as principles have influenced design. Also, pragmatic licence allows techniques which would not win medals at Model Engineer Contests! Much time lapsed and much sketch paper defaced before a hidden mechanism was devised. One is shown in D'fly Mechanism.jpg.

An early problem was the neck. With the crank placed well forward in the head, its action had to be transmitted back to the high shoulders in the thorax. So a cranked rocker (as seen in side view) was used. To provide for maximum throw, the motor stick is mounted to one side instead of conventionally above the crankshaft. Several rockers were built and flown in more-conventional prototypes for experience – and to seek duration by fitting longer motors

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Another problem concerned the wing mounting. On the large prototype the hinges were on the centreline, but that would not provide for the width of a real body. The animal's wings hinge at the top of the body sides – ie, shoulders – and that turned out best for the model, too.

To obviate the usual conrods out along the LE, the forewings are actuated from the centre. There, they are pivoted to the rocker. As the wings flap, their body hinges have to move in and out slightly to accommodate the arcs of the wing levers – as do the animal's. Two methods of locating the body hinges have been flown: a) one rigid strut rising from the motor stick to one hinge, together with a pivoted link rising to the other hinge; b) two sprung stays rising to the hinges.

Consider method a). If the rigid strut is for the port hinge, the rocker pintle is constrained to move in an arc about it by the port wing lever. The other hinge must therefore swing in an arc about the bottom anchor of the rising link. That implies some asymmetry of flap: the link will swing in an arc so, if the body is held still, the starboard wing angles will theoretically differ slightly from the port's. However, that will not happen in flight because aerodynamic and inertial forces will ensure that both wings flap almost equally in the air. Thus the body will roll cyclically in flight, however that will not be apparent in a small model with a round body rolling through a small angle!

Consider hinge method b). If the two stays spring equally, the rocker pintle will move vertically and the flap angles will be equal. These stays will also provide for a "click" mechanism used by some insects where, by pulling the hinges together, the wings are snapped towards the ends of their strokes. There they "hit the stops" and bounce back, to reverse the stroke without using muscle power or losing energy. Several prototypes have been flown with different preloads, though with no evidence of any advantage so far.

(Re-?)inventing the Conrocker

Now consider the rocker, viewed from the front. Using hinge method b), as just described, the pintle moves vertically while the "little end" orbits with the crankpin.

The axis of the conrocker thus moves in a cone, about its rear bearing. Kinematically, the crankshaft axis should also converge on that rear bearing, too, requiring the motor to be somewhat out of line with the crankshaft. (The rubber becomes a pragmatic UJ.) Thus, viewed from the front, the rocker swings with the action of a conrod. So its combined action is described as that of a "conrocker". Using hinge method a), the pintle does not move linearly, so the "conrod" does not move quite as in an engine, but its action is still kinematic so the term "conrocker" remains apt. The conrocker is my contribution to the art of flying model dragonflies. It is not a large field.

An example of how small detail improvements emerge in a slow project is the reversed crankpin. Instead of bending forwards from the crank arm, it will now bend aft from the conrocker and engage a bearing on the crank arm. The conrocker and the crank arm can thus be moved forwards by the thickness of the retaining collar which would usually have been forward of the conrocker.

Another "lateral" approach to getting the motor well forwards was to mount the head on the conrocker. Then the conrocker can be almost at the animal's face, no thickness or clearance being required. For appearance, the head may be fastened in an appropriate position for static display, when the wings will be in a known position. That it orbits wildly in flight can hardly be seen! Surprisingly, in a brief test neither the cg change nor the added inertia of the head seemed to affect the flight much. The head was of a very low density resilient open-cell foam (polyether, I think).

Almost all the mechanism bearings are wire loops, of 0.008" guitar strings, "tweaked" to minimal clearance in the load direction, yet tolerant of small misalignments – pragmatic ball joints which never wear. Simpler bearings have been tried using loops of thread, tied initially round a slightly oversize greased mandrel and round the frame, then "fixed" with cyano. Carbon rod can be run directly in the resulting bearing. The body frames are of carbon-fibre rod with epoxy joints and all has proved outstandingly robust.

Flapping the Hind Wings

At the root of each forewing was a torque rod back to a bearing on the conrocker behind the hind wing. For in-phase wings, these torque rods were by side above the conrocker, with the hind wings also fixed to them. These torque rods were of split 1/2mm carbon fibre rod and rather flexible. Unfortunately they were of unequal thickness so there is differential wind-up, thus the hind wings had different amplitudes. That wind-up varies with motor torque and might account for some erratic flight.

For 180-degree phase lag, the conrods are arranged vertically above the conrocker so that the hind wings may be fixed to the "opposite" forewing's torque rod. This is not a Good Thing for scale because opposite wings are at different heights. The arrangement has also proved difficult to trim, possibly because of flexible torque rods.

There is the possibility of tuning the wing flexibility/mass to produce resonance for a non-180-degree lag, but that sounds impractical for varying torque and practical flight manoeuvres. One obvious way to produce a 90-degree, say, phase lag would be to use two cranks and two conrockers but that would force the motor hook back somewhat. The possibility of using the swing (in front view) of the conrocker, which is roughly at 90 degrees to its rise and fall, has been considered. So far, this apparently elegant technique has proved hard to employ – requiring 24 bearings.

Flying

Only one observation remains from flying the first lightweight model: cyclic yaw, presumably because of the low frequency of the oppositely-inclined lift forces of the rocking tandem wings. More flying is intended, using higher frequency, curved spars and no tail.

Of the two small models, the in-phase has proved the easier to trim without a tailplane. Both *have* flown, but seldom (in hundreds of launches) and nearly always erratically. Someone timed the in-phase at 18 seconds, recently. Although that was on less than full turns, the model landed with few turns left (so it must have climbed). It was then flying consistently enough to call for its first timing, but trimming is highly critical and that particular trim has not been found since. Later timings suggest that the earlier timing (by wrist watch) might have been 5 seconds in error. The best recent time (mid-April, '03) is 14 seconds, so further flight improvement must be sought to exceed the arbitrary 15-second standard.

Trimming trials are sometimes misleading if the motor bunches and binds against the body. That seems to alter the flight trim, perhaps because the wings tend to dwell at some part of the cycle. Glide trim varies with wing position.

Launching has been uncontrollable, although it is now improving somewhat. Usually both models plunge four feet before finding stability and (rarely) climbing for a brief flight. Changing either: launch speed, flapping before or upon release, launch elevation, angle of attack or bank appears to have no systematic influence on subsequent flight. Launching was little more reliable when fins and tailplanes were fitted.

Manual holding and pre-launch management of such small models is always difficult, while preventing flapping in ornithopters is frequently brutal. So some kind of trigger-released clamp must be devised for winding and launching.

The usual XPE for the body would be too fragile to hold for launching if hollowed out to 1mm wall or less, so polyether (?) foam 'bodies" have been attached to various models for assessment. It's seriously light, sticks well, is tough, paints, and is compatible with organic textures. It proves highly durable but it is difficult to shape. Fisherman flyers tell me they tie flies using it, so I might get some help. An alternative would be a mouldable version.

Legs are a prominent feature and especially vulnerable. Tests on Youhei Takatanis Dragonfly 1, using feather 'Quills" for spars, show how indestructible this material is. It is now favourite for the legs – and the barbs can be trimmed to represent the hairs, too.

The release behaviour, finicky trim and erratic flight suggest that stability is marginal. That view is enhanced by the behaviour after a wingtip just clips an object. The model then goes into a violent tumble, both in roll and pitch (and yaw?), from which I have not seen a recovery. It gives the impression of being driven in tumble by the flapping. Possibly, the tumble is as fast as the flapping.

Directional control is difficult. As with conventional ornithopters, tip weights are more effective at higher torques. These models were acutely sensitive to tip weight. Also, with aeroelastic wings, the chordwise location of tip weights affects the steering. Often, trim correction is contra-intuitive from fixed-wing experience. For example, to correct a left turn, the left forewing's incidence should be *decreased* or the right's *increased*. That has been consistent for both models. I don't know why. A lot of heads have been scratched; drag has been implicated.

CG position affects steering considerably, showing lack of symmetry somewhere. The in-phase model currently pitches in flight at high torque as if near stalling, yet it doesn't and its glide is smooth (whenever it gets that far). Its cg is 9.5mm behind the fore LE. Both models' planforms are similar, yet the counter-phase one is flying (less reliably) at 13mm. However, there are differences other than the phasing: the stitching is of sewing thread instead of monofilament and the hind spar is above the wing. Either might affect turbulation and possible reattachment. No changes have been made to explore this.

It has been frustrating not to be able to vary the phase lag. One possibility for affecting slightly the interaction between fore and hind wings is to alter their relative dihedrals, but this has not yet been tested.

Conclusions

1. Scale dragonfly wings are feasible (in profile, at least), as are a fully hidden structure and mechanism.
2. A life-size scale model can be built to fly, if not elegantly.
3. Stability seems marginal, so facilities for ultra-fine flight trimming and its measurement are required.
4. Lightweight crushable foam is suitable for body parts and can bear an acceptable finish. Bird feathers offer good material for tough hairy legs. The model should prove durable.
5. A quick-release clamp will be essential for winding and launching, before body and legs can be fitted.

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