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Materials challenges in the design of an insect-like flapping wing mechanism based on a four-bar linkage

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Abstract

This paper describes materials challenges, and how they were met, in the design of a four-bar linkage mechanism driving a test-bed for an insect-like flapping wing micro air vehicle. In the design process, both aerodynamic and dynamic simulations were made, but could not resolve all uncertainties regarding the forces acting on the mechanism. This difficulty was resolved by a combination of: (1) a simulation parametric study; (2) an experimental programme devised according to the results of the study; (3) by the use of carbon/epoxy composite for critical elements. Application of carbon/epoxy composites not only allowed to overcome uncertainties, but also provided a potential for future research and development. A complete mechanism was manufactured, assembled and tested; it works reliably and generates useful data for further aeromechanical research.
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1. Introduction

Micro air vehicles (MAVs) are defined here as flying vehicles ca. 150 mm in size (hand-held), weighing 50–100 g, and are being developed to reconnoitre in confined spaces (inside buildings, tunnels, etc.). A detailed discussion of the future utility of MAVs and the advantages of considering insect-like flapping wing propulsion have been presented elsewhere, see [1–4]. Here, we only mention that the main mission of the MAVs is indoor reconnaissance, i.e. flying in confined spaces inside buildings, shafts, tunnels, machine rooms, etc. This requires power-efficient, highly manoeuvrable, low-speed flight with stable hover. Such performance is routinely exhibited by flying insects and hence the focus on emulating insect-like flapping by engineering means. In particular, true flies, or *Diptera*, are attractive reference insects, because they are excellent fliers and achieve that with one pair of wings. Aeromechanical analysis and design of two interacting pairs of wings is more involved, while not necessarily offering improved flight performance.

In general, *Diptera* fly by oscillating (plunging) and rotating (pitching) their wings through large angles, while sweeping them forwards and backwards. The wingbeat cycle (typical frequency range: 150–250 Hz) can be divided into two phases: downstroke and upstroke (see Fig. 1). At the beginning of down-stroke, the wing (as seen from the front of the insect) is in the uppermost and rearmost position with the leading-edge pointing forward. The wing is then pushed downwards (plunged) and forwards (swept). At the end of the down-stroke, the wing is twisted rapidly, so that the leading-edge points backwards, and the upstroke begins. During the upstroke the wing is pushed upwards and backwards. At the highest point, the wing is twisted again, so that the leading-edge points forward and the next downstroke begins.

Insect wing flapping occurs in a stroke plane that generally remains at the same orientation to the body, see

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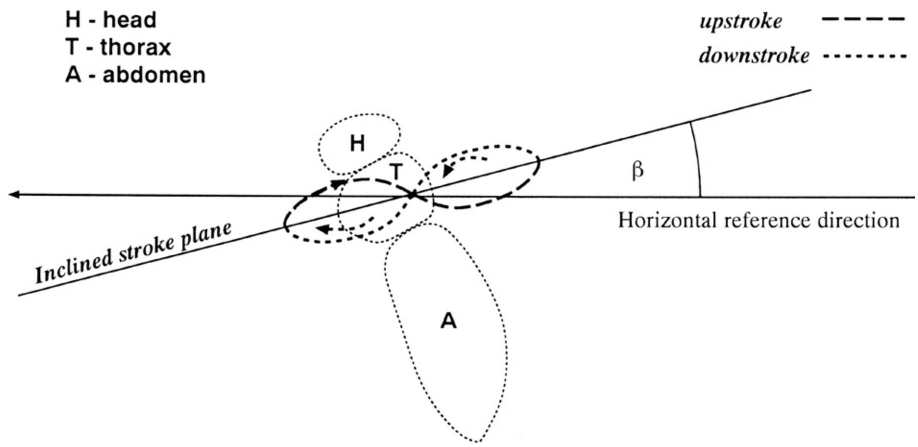

Fig. 1. "Generic" kinematics of insect in hover: the wing tip traces a 'figure-of-eight', when seen from the insect side.

Fig. 1. Thus, forward flight is achieved by rotating the stroke plane together with the body. The work presented here focuses on hover, when stroke plane is nearly horizontal.

Since each half-cycle starts from rest and comes to a stop, the velocity distribution of the flapping is non-uniform making the resulting airflow complex. Not only are insect-like aerodynamics quite complex, but their observation and measurement in nature is very challenging [5–8]. This motivated the development of aerodynamically scaled flapping mechanisms, most notably Ellington's flapper [9,10] and Dickinson's Robofly [11]. These devices allowed remarkable progress in gathering experimental data on insect-like aerodynamics [12,13]. However, they tend to be bulky constructions not suitable for developing into light-weight, 150 mm versions suitable for a future flapping wing MAV.

On the other end of the scale, Fearing [14,15] aims at building an insect-like flapping robot weighting a tenth of a gram and having 25 mm wing span. This approach is based on MEMS technology, as the expected forces (and payloads) are below 1 g.

In order to design an insect-like flapping wing MAV on the 150 mm scale in a systematic and rational way, a good understanding of the underlying aerodynamics is necessary. This can be done through theoretical modelling, e.g. [16], but all mathematical models must be verified experimentally.

The pioneering and useful experiments of Ellington and Dickinson, mentioned above, are not sufficient for detailed verification of the MAV aerodynamics, since they were performed with mechanisms on a scale much larger than the MAV size of 150 mm and the design flapping frequency of 20 Hz. This creates uncertainty whether the flow observed in those experiments is dynamically similar to the real flow on the required 150 mm/20 Hz scale. For example, Dickinson's Robofly is an application of Ellington's approach to aerodynamic scaling of the fruit fly *Drosophila melanogaster*, an insect whose typical size is 2.5 mm. Robofly has a 60-cm wingspan, typically flaps[1] five times a second, and is immersed in 2 tons of mineral oil. These geometric and kinematic parameters, together with the use of the oil, satisfy the Reynolds flow similarity criterion. The criterion is expressed in terms of the mean flow velocity, wing size and kinematic viscosity and is the most fundamental characteristic of the flow. However, in insect-like flapping periodic vortex generation and shedding is very important. Thus, the vortical phenomena should be preserved in dynamic scaling and can be done by complying with the Strouhal similarity criterion. In general, it is not possible to satisfy both similarity criteria simultaneously and this, unfortunately, applies to the case of Robofly. Hence, despite significant progress in the understanding of insect's flight principles, there is lack of a fully reliable method to predict dynamic loads acting on flapping mechanism on the MAV scale of 150 mm/20 Hz. The first motivation for the work described here was to create a mechanism which would provide reliable data on the required scale directly (no re-scaling involved). The second main reason for this research was to design a feasible electromechanical precursor of a flapping wing MAV prototype. It was decided to design it as a robust test rig rather than a lightweight mechanism optimised for flight, because of the fundamental aerodynamic uncertainties, mentioned above, and the need of extensive laboratory testing.

This paper is organised as follows. Section 2 gives a brief summary of the predicted aerodynamic forces acting on the flapping wing. The flapping mechanism itself is described in Section 3. This description consists of loading analysis in Section 3.1, wing design description in Section 3.2, strength analysis in Section 3.3 and the frames design in Section 3.4. Section 4 outlines tests conducted with complete mecha-

[1] Six computer-controlled motors specify the three rotational angles of each wing. The wings are equipped with sensors for measuring instantaneous aerodynamic forces, see http://www.dickinson.caltech.edu/.

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