Hydraulically-Actuated Asymmetric Flexible Hinge: A Bio-Inspired Design Principle

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Abstract

Insect wings are composed of thin, highly flexible, double-layered elastic membranes. Veins form where these layers separate, often creating campanulate cross-sections. The vein walls are also elastic structures, making the entire wing an interconnected elastic continuum. One can think of a wing membrane as a set of flexible 'panels' connected by flexible struts (veins). Many species of insect can fold, unfurl, and adjust the shape of their wings during flight. Although such shape control is primarily exerted by basal wing muscles, changes in wing shape are observed throughout the wing. However, unlike those of birds and bats, insect wings lack internal musculature.

While the potential for hydraulic contributions to this control has been long hypothesised, it remains largely unexplored. Insect veins contain hemolymph, a fluid circulated by thoracic 'wing hearts.' Hydraulic pressure has been implicated in the folding/unfolding of hindwings in beetles and other insects. It is plausible that vein rigidity could be actively controlled through pressure variations, either synchronised with wingstrokes or maintained over multiple wingbeats.

We propose a novel mechanism for active wing shape control: hydraulic distortion of vein cross-sections, which exert leverage on adjacent cross-veins and membrane. Insect veins exhibit a wide range of cross-sectional shapes and wall thicknesses. Some sections, particularly in dragonflies, appear visually capable of deformation in response to lateral pressure. Hydraulic distortion of such vein cross sections can induce wing shape changes by varying relative orientation of adjacent membrane panels. This mechanism holds significant technical potential, with applications in deployable structures and micro aerial vehicle wing design.
An assumption of translational invariance along the vein's length allows us to simplify the analysis and consider the deformation of the vein's cross section. We model the vein cross-section as a cavity bounded by two elastic curves (elasticae) of different lengths, this difference captures the asymmetry of the cross-section shape. Hemolymph pressure is approximated as a differential normal pressure acting on the boundary of the cross-section.

Our model may be considered as a generalisation of the 'elastica hypoarealis' – a classical problem involving the deformation under a uniform distributed normal force of a single elastica bent into a smoothly closed loop. It has attracted occasional interest since the end of

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19th century, yet remains the subject of active research. Our model differs from that because the boundary is now not differentiable in two points, where the two membrane layers separate.

The force and moment balance equations, expressed as a system of nonlinear ordinary differential equations, describe how the vein cross-section quasi-statically deforms under differential pressure and forces caused by wing membrane panels. A boundary value problem is formulated to obtain the equilibrium configurations of the two elasticae under pressure. The pressure, force, and moment acting on the end points influence the deformation of the vein cross-section and the subsequent deflection of adjacent wing panels. This deflection is characterised by a relative orientation angle and relative displacement. Numerical methods are employed to solve the boundary value problem.

This model accounts for large deformations and sudden shape changes, such as the snap-buckling observed during wing folding and unfolding. Asymmetry, a key factor in snap-buckling, is inherent in the non-circular cross-sections of many insect veins. We explore the relationships between haemolymph pressure, vein cross-sectional geometry, wall stiffness, and resulting deformations. Design criteria for triggering wing folding/unfolding are formulated. Graphical representations of key parameter relationships provide a benchmark for experimental studies and biomimetic design.