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Biomimetic Design of a Flexible Wing

Joseph Marrocco, Satchi Venkataraman,
and Luciano Demasi

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ACCESS Proceedings:
Biomimetic Design of a Flexible Wing

Joseph Marrocco
Mentors: Dr. Satchi Venkataraman and Dr. Luciano Demasi

The practical application of relatively small, and light weight micro air vehicles (MAV), is of great interest to the engineering community. Innovative and interesting approaches are being utilized to address the many constraints that arise from attempting to design a flapping MAV. The goal of this research is to investigate the structural and mechanical properties of the dragonfly, that give it its unique flight capabilities, and mimic the design in a finite element model to simulate the wings structural dynamics for analyses.

Introduction: The Dragonfly's Wing

The first ancestor of order Ordonata, or dragonflies, as they are more commonly known first appeared on Earth about 280-360 million years ago. For hundreds of millions of years Mother Nature has been making improvements and tinkering with the initial design, until you arrive at the highly evolved and specialized flight organs that you see today. A design that is drastically different than most man made airfoils.

Dragonfly wing's are able to absorb and endure the inertial forces imposed upon them by the surrounding air, caused by acceleration and decelerating their own weight, as well with interactions with the local environment and other members of their species.[8,14,19,20,21] They are able to achieve an assortment of different flight patterns such as gliding, synchronized-stroking of both sets of wings that maximizes thrust to change direction quickly, phased-stroking, and the very efficient counter-stroking. During counter-stroking the front and hind wings are beating in opposite directions to maximize lift. These ultra light flexible airfoils perform all of these roles extremely well, despite the fact that they are largely passive flight structures. [20, 21] All muscular control is located at the base of the wing. This means that any change or deformation of the wing in flight is caused solely by the wings innate properties. A dragonfly's wing is like any other organ, it has different parts that perform different functions. The *Costa*, *pterostigma*, and *nodus* are external components that assist in the wing function and structure. The wing is composed of a network of tubular veins that are the main structural units of the wing acting like cantilever beams.[10,12,22,24] They are buttressed by many cross veins running orthogonal to the tubular veins and a thin membrane that aids in support of the wing against aerodynamic and environmental forces.[5,12,23,24] The membrane is corrugated which is designed to absorb stress and allow deformations to occur.[12,22,23] At the core of both the venation and the membrane are many structural proteins and polymers. All of these elements give the dragonfly wing it unique abilities.

This tubular pleated membrane, responds similarly whether loaded form above or below, deforming with the increase in horizontal or vertical forces. [11,13,22] Dragonfly wings have developed to deform to aerodynamic forces, yielding briefly, without damage, and to recover immediately. In combining rigidity to span wise bending under normal conditions with the capability of yielding reversibly under excessive loads, the pleated, densely veined wings of Dragonflies demonstrate an elegant solution to insects' stringent requirement for stiff, durable, ultra-light wing for high-performance flapping flight.

Finite Element Model

The different components of a dragonfly wing were modeled in FEMAP (see Figure 1). The complex geometry of the dragonlfy wing was imported using an existing wing picture. Beam and plate elements were used to model the viens and membranes, respectively. The goal of this work was not to replicate the dragonfly wing, but model some of its structural components. Therefore, the materials used were not the same as that of the dragonfly's. Materials of known properties, steel for the viens, and aluminum for the membranes, were used. The corruagtion or flexible components were not yet integrated into the model, and as such the model is planar.

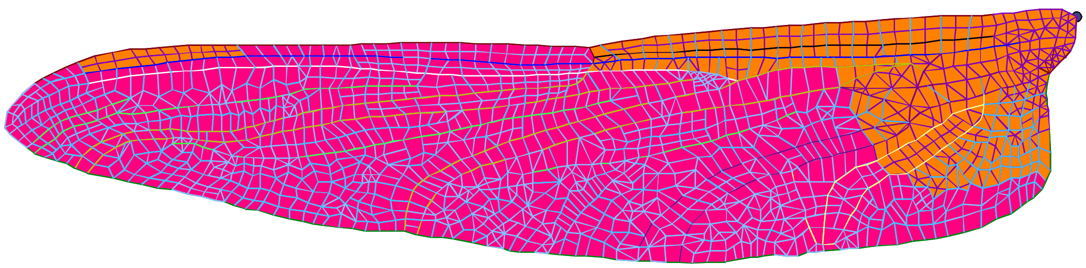

Figure 1

The orange and pink zones (see Figure 1) of the model represent areas of different thickness. The orange zone, is 12 μm thick, and the pink zone is 4 μm thick. The orange zone is thicker, because it is located at the base of the wing and will have to withstand more force than the rest of the span of the wing. The viens have ten different diameters and thickness, depending on their location on the wing, and have different colors associated with those diameters and thickness. The viens at the front and base of the wing are thicker than the those at the tip or back of the wing. Again, this is because of the increased forces occuring at these areas of the wing. The vien's have diamters ranging from 0.466 mm to 0.217 mm, and thickness' range form 0.060 mm to 0.040 mm. The wing span length is 750 mm.

FEMAP was used to generate the finite element model. NX NASTRAN was the finite element solver. Finite element Analysis (FEA) is a numerical technique for finding approximate solutions of partial differential equations (PDE) as well as of integral equations. NASTRAN was used to calculate the natural modes and frequencies of the dragonfly wingA physical object, has a set of normal modes (and corresponding frequencies) that depend on its structure stiffness and mass distributions. In the finite element discretization the continuous system representing the wing is approximated with a finite set of second order ordinary differential equations in the time domain (equations of motion) as follows:

$$K \cdot U + M \cdot d^2U/dt^2 = 0 \tag{1}$$

The finite element stiffness matrix is represented by K. U is the vector of nodal displacements, with 6 degrees of freedom for each node (3 rotations and 3 translations). M is the finite element mass matrix. Setting,

$$U = \Phi e^{i\omega t} \tag{2}$$

and substituting it into the equation of motion (equation (1)), the following eigenvalue problem is obtained:

$$[K - \omega^2 \cdot M]\Phi = 0 \tag{3}$$

Where Φ is the generic eigenvector (mode) and ω is the associated eigenvalue (frequency). NASTRAN calculates the modes and frequencies. FEMAP reads the NASTRAN's outputs and plots the modes. The mode shape is dependent on the boundary conditions.

Results

The front of the wing have little displacement (see Figure 2), this is from the increased strength from the thicker longitudinal located at the front of the wing. Throughout the first four modes the majority of the displacement occurs across the span of the wing, where there is less a dense concentration of viens.

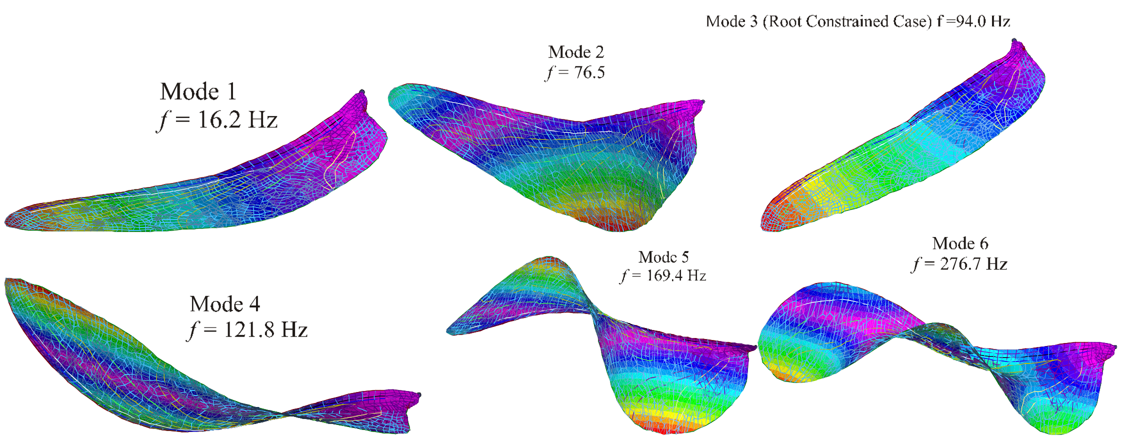

Figure 2

A second set of analyses were perfromed, with a changing pterostigma mass. The pterostigma is a thickened membrane structure on the front edge of the wing, close to the tip. It is believed to increase the stability of the wing during flight, by moving the wing's center of gravity to the front edge, and maintains the wings functional angle of attack. [15, 21, 24] It is believed by a few researchers that the pterostigma reduces flutter during gliding, and therefore maximizing speed while gliding. [1,21]

The mass of the pterostigma was modeled by adding masses (form 0% to 30% of the dragonflies mass. The change of the first four frequencies has been analyzed (see Figure 3).

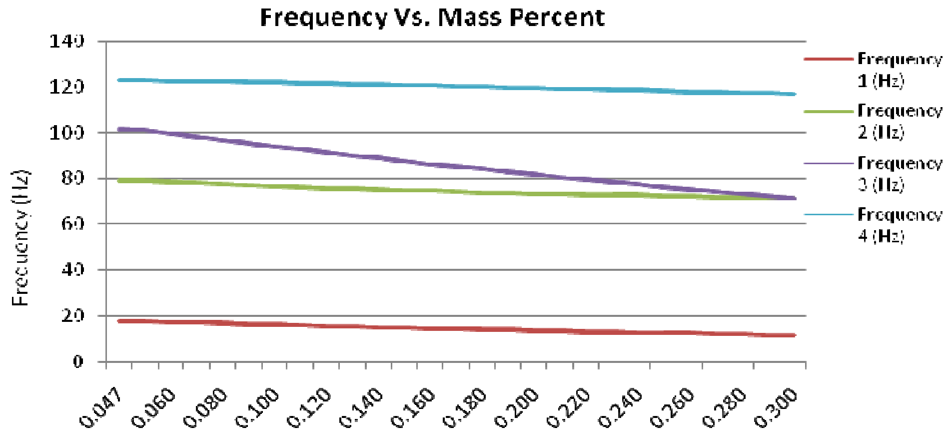

Figure 3

From the graph, as the mass of the pterostigma increases, the frequency of all first four modes decreases. The second and third mode reach the same frequency.

Conclusion

The structural dynamics of the dragonfly hindwing was modeled with a planar finite element model. It demonstrates the bluk of the structural strength of the wing lies along the leading edge of wing. The energy from aerodynamic forces acting on the wing is transferred along the leading edge of the wing, too the base of the wing. The increase of the pterostigma mass, does decrease the natural frequency's of the wing, and possibly increase the wings stability during flapping flight. For future work the corrugation and flexible elements of the wing will be included, to see their effects on the structural dynamics of the wing.

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