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Investigating the Structural Dynamics Implication of Flexible Resilin Joints on Dragonfly Wings

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Abstract: The practical application of relatively small, light weight micro air vehicles by biomimicry is of great interest to the engineering community. The goal of this research project is to improve the understanding of the structural construction of insect wings. A dragonfly insect has been chosen, as it has a very revealing structure and is an insect that has unique flight capabilities.

Dragonfly wings are able to withstand the forces imposed upon them by the surrounding air, inertial forces caused by acceleration and decelerating their own weight. The basic design of a dragonfly wing is a pleated membrane stiffened by tubes at the apexes of the pleats, forming a particularly rigid and strong structure. This tubular pleated membrane provides a stiff structure along the length (span wise) direction of the wing and a flexible structure along the width (chord wise direction) of the wing. The tailoring flexibility in the wing is essential as it can play significant role in the aerodynamics wing airfoil shape it can achieve, in addition to the benefits of gust alleviations, and damage tolerance.

The investigation into the material composition and architecture on the dragon fly wings revealed that while a large part of the wing structure is made of chitin protein, there is a regular pattern of joints on the wing made of less stiffer resilin protein. The focus of this effort is to understand the effect and implications of the resilin joints on the structural dynamics of the wing. To achieve this goal a finite element structural analysis tool has been used and a detailed model of the dragonfly wing was created. Main focus of the present analysis is to understand how the presence of flexible resin joints affects the natural vibration and mode shapes of the dragonfly wing.

Keywords: Dragonfly Wings, Resilin, and Flexible Joints.

1. Introduction

The first ancestor of order Odonata-Anisoptera, 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.

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 believed to be caused 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 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 membranes contain randomly oriented micro-tubules that form a composite structure that also aids in stiffening the wing and transferring energy to more robust veins. 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.

While all of these structure and components are extremely interesting, the main focus of this project has been on the flexible elements found in the wings of dragonflies, called resilin. Resilin is very similar to elastin found in humans, but has different charcteristics and composition. [19] It behaves like a swollen isotropic rubber, but is unparalleled by other natural or synthetic elastic materials. [19] Resilin is believed act like a elastic joint and to be involved in mechanical control of wing torsion and elastic energy storage. [7] The goal of this research is to understand the effects and implications of these resilin joints on the structural dynamics of the wing. This task will be accomplished by investigating the natural vibrations and mode shapes of the dragonfly wing with and without the presence of these resilin joints.

This tubular pleated membrane, responds similarly whether loade 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.

2. Method

To accomplish the task of modeling the wing of a dragonfly's wing a finite element structural analysis tool (FEMAP) has been used to model the dragonfly wing's geometry, dimensions, and structural components.

The geometry of an adult dragonfly wing was created by overlaying the wing's image over FEMAP and creating a point and line 2D model. The points were the replaced by nodes and the lines were replaced by tubular beam elements, see figure 1. Ten different dimensions were used for the radius and thickness of the beams. The diameter ranges from 0.466 mm to 0.217 mm, and thickness' ranging from 0.060 mm to 0.040 mm. The properties of the beam elements are as follows: Young's Modulus E = 6.1 GPa, Poisson's Ration V = 0.3, and Mass Density = $1.2E^{-6}$ kg/mm^3. The beam elements were then connected by plate elements, see figure 2. The plate elements properties are as follows: Young's Modulus E = 2.85 GPa, Poisson's Ratio v = 0.25, Mass Density = $2.86E^{-7}$ kg/mm^3.

After the beam and plate elements were incorporated into the model out of plane corrugation was added to the model by changing the displacement in the Z direction of select nodes along particular veins, see figure 2. The max out of plane displacement is 0.9 mm at the front of the wing with an average displacement of 0.3 mm. The corrugation is deeper at the base and leading edge of the wing, and shallower at the tip of the wing.

The resilin mobile joints are modeled by replacing vein beam elements by tube elements along certain veins defined by publications, see figures 3 and 4. The tubes have the same mass, dimensions, and poisons ratio. The elasticity that these elements should contain was achieved by lowering the Young's Modulus to a range of 5 MPa to 28 MPa. The position of these joints was chosen based on the publication of Stanislov Gorb (1999), detailing the chordwise direction and orientation of these joints along certain veins.

Models were created at each stage of the development: planar, corrugated, chord wise joints, and chord wise and span wise joints. Each model incorporates the properties of each previous. This was done so that a comparison of each model could be made, and some insight into the structural dynamics of each element could be achieved.

NX NASTRAN was the finite element solver used in cooradination with FEMAP. 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 wing for each model.

3. Figures

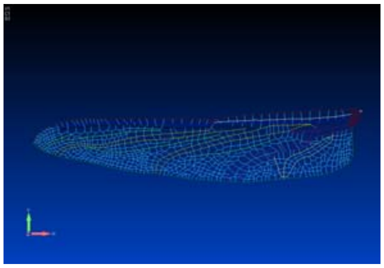


Figure 1: Beam elements of the Dragonfly wing model.

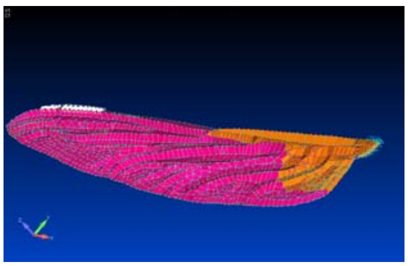


Figure 2: An isometric view of the corrugation and membrane of the dragonfly wing model.

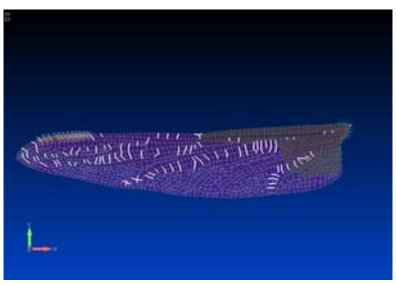


Figure 3: An image of the resilin mobile joints that have a chordwise direction.

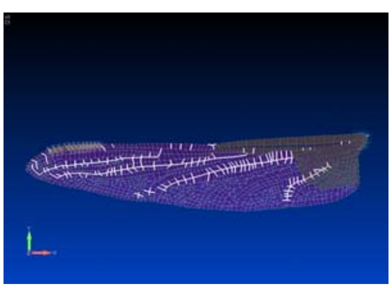


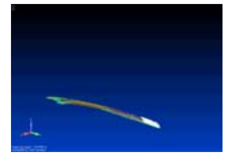
Figure 4: An image of the resilin mobile joints that have both a chord wise and span wise directions.

4. Results

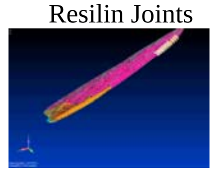
Mode 1

Planar

Non-Planar Corrugated



Chord Wise Resilin Joints

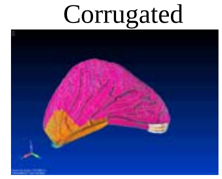


Span/Chord Wise Resilin Joints

Mode 2

Planar

Non-Planar Corrugated

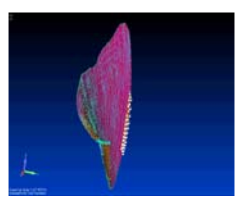


Chord Wise Resilin Joints

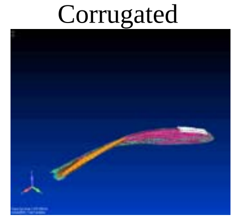
Span/Chord Wise Resilin Joints

Mode 3

Planar

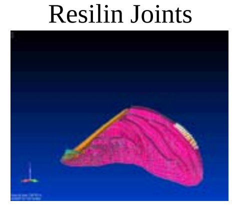


Non-Planar Corrugated



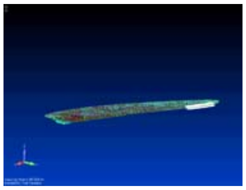
Chord Wise Resilin Joints

Span/Chord Wise Resilin Joints

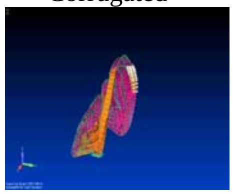


Mode 4

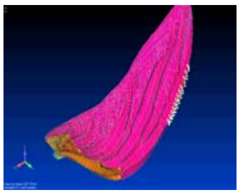
Planar



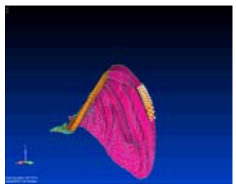
Non-Planar Corrugated



Chord Wise Resilin Joints



Span/Chord Wise Resilin Joints



Once a comparison of the modal shapes was completed it is clear that corrugated model and both resilin joint models modes are very similar in shape and frequency. The first mode is a bending mode in the Z direction and is the same for each model. The second mode is mainly a torsion mode, with the axis of rotation along the leading edge of the wing were there is more corrugation and vein density. The third mode is bending mode in the Y direction with some torsion along the leading edge. The fourth mode is equal in bending and torsion. In the second, third, and fourth mode there is trans-membrane stretching.

The planar model has modal shapes that are completely different from the other three models, other than the first mode. The second mode is primarily a bending mode in an isometric direction, with very little torsion. The third mode is torsion mode, with an axis of rotation located in the center along the span wise direction. The fourth mode is a bending mode in the Y direction.

5. Conclusions

The tubular pleated membrane provides a stiff structure along the length (span wise) direction of the wing and a flexible structure along the width (chord wise direction) of the wing.

The drastic difference between the modal shapes of the planar model and the other models is most likely due to the presence of the corrugation. The corrugation increases the wing s resistance to transverse bending in the Z direction, and allows torsion and chord wise stretching. The second, third and fourth modal shapes of the corrugated models have shapes similar to dragonfly wing’s during flapping.

It appears the addition of resilin mobile joints does not drastically affect the modal shapes of corrugated model, but does affect the max out-of-plane deformation. This is most likely due to the fact that the corrugation is the dominant property of the wing structure. However, the tailoring flexibility of the resilin joints in the wing has to play a significant role in the aerodynamics wing airfoil shape it can achieve, in addition to the benefits of gust alleviations, and damage tolerance.

In future research, we will create simpler geometric wing, were the dimensions and properties of the wing will be identical across the span of the wing. This should allow us the further understand the effects of elastic joints will have on flapping wing system.

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