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Finite-Element Analysis of Nodus-Driven Flexibility in Dragonfly Wings for Micro-Air Vehicles

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Summary:

We investigate how the stiffness of the nodus joint affects deformation of a dragonfly forewing under a static distributed pressure load, using a full-wing finite element model in COMSOL Multiphysics. A simplified triangular model was initially used for calibration. In the final model the forewing is represented by shell/beam elements with material properties of insect cuticle and a spring at the nodus to simulate the hinge stiffness. Under uniform pressure the tip deflection is highly sensitive to the nodus rotational stiffness: lower stiffness yields larger deflections. Results are quantified by a deflection–stiffness curve. Our findings indicate that a more compliant nodus markedly increases wing flexibility, whereas a rigid nodus limits deflection, consistent with insect wing biomechanics in the literature.

Keywords: dragonfly wing, nodus joint, finite element model, beam–shell coupling, rotational spring, wing deformation, MAVs

Introduction

Dragonfly wings exhibit complex venation and specialized joints (e.g. nodus) that modulate flexibility. Prior work has shown that insect wing stiffness depends strongly on venation pattern and scale[1]. In particular, the dragonfly wing nodus is a vein discontinuity containing soft (resilin) and hard cuticle that acts like a one-way hinge [2]. Experimental studies report that the nodus greatly influences wing compliance: a flexible ("open") nodus increases bending flexibility, whereas a stiffened ("closed") nodus maintains rigidity [3]. Similarly, it was found that fliers tend to have less soft resilin at the nodus, implying a stiffer joint to avoid excessive wing deflections [4]. Finite-element modeling of insect wings has been used to probe these effects: for example, [5] constructed a 3D dragonfly wing FEM (beams and shells) to predict deformation under loads and included soft vein joints in a 3D wing model to study passive deformation. In this work we extend such analysis [6]by systematically varying the nodus rotational stiffness and quantifying the resulting wing deflection under static pressure.

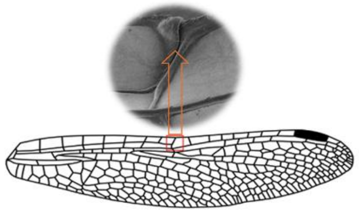

Fig. 1. Nodus Joint Highlighted in Dragonfly Wing

Materials and Methods

The dragonfly forewing geometry (planform and vein layout) was taken from published measurements and digitized for modeling [7]. The wing is modeled as a thin corrugated shell with embedded beam elements for major veins, following [5].

A rotational spring at the nodus enforces a moment rotation relation denoted by eq. (1) where K_{nodus} is varied as a parameter. The wing root is clamped at four points near the base fig.1, and a uniform static pressure load is applied on the wing surfaces to simulate aerodynamic loading. Material properties for cuticle and resilin are based on insect wing literature [5]. A representative set of mechanical properties is given in Table 1. All simulations were performed in COMSOL Multiphysics using linear elasticity (small deflection) assumptions.

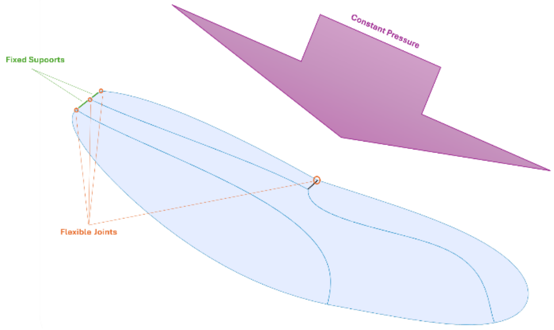

Fig. 2. Wing Model illustrating Boundary conditions

Tab. 1: Material properties used in the wing model.

Material	Elastic Modulus (GPa)	Poison Ratio	Density (kg/m^3)
Membrane	2.0	0.3	1200
Veins	5.0	0.3	1200
Nodus	0.002	0.49	1200

These material properties were adapted by a thorough literature review especially from [8]

Equations

The structural response is governed by linear elasticity. For bending dominated deformation of wing veins/shells, a one-dimensional approximation (Euler–Bernoulli beam) can be expressed as:

$$EI\,\frac{d^4w}{dx^4}=q(x) \tag{1}$$

where E is Young's modulus, I the second moment of area, w(x) the deflection, and q(x) the distributed load. In our FEM implementation the equivalent plate/shell equations are solved in COMSOL. The nodus is idealized as a hinge with torsional stiffness, i.e. the bending moment at the joint is proportional to the angular deflection

$$M_{nodus}=K_{nodus}\cdot\Delta\theta \tag{2}$$

This rotational spring eq (2) is key to assessing how variation in K_{nodus} alters the global wing compliance. The COMSOL model solves the full 3D elasticity equations subject to these boundary and joint conditions.

Results and Discussion

The tip deflection under a uniform pressure load was found to vary strongly with K_{nodus}. Fig. 3 shows the calculated wing tip deflection (mm) as nodus stiffness is increased.

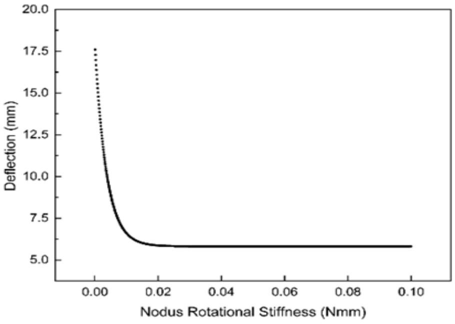

Fig. 2 illustrates the relationship between Nodus stiffness and max deflection at tip

A sharp decrease in deflection occurs for small value of rotational stiffness, a completely floppy nodus yields ~18 mm tip deflection, while a very stiff nodus limits deflection to ~5.5 mm. This nonlinear trend reflects the coupling of wing sections at the nodus: as reported experimentally, making the nodus stiffer greatly reduces overall wing bendability [1] In fact, the deflection–stiffness curve is qualitatively consistent with beam theory (inverse relation) and supports the idea that the nodus acts as a compliance regulator.

Under load, wing model exhibits camber and twist phenomenon as shown in Fig. 3. The red and black outline curves highlight the induced spanwise twist and chordwise chamber of the wing. The wing twists along its span and develops camber, as is typical in real dragonfly wings; here the nodus stiffness was set to an intermediate value. Most bending occurs toward the tip (where the red line deviates most), while the proximal wing remains relatively rigid. Such coupled bending-twist behavior is characteristic of insect wings under pressure and was noted in earlier structural analyses.

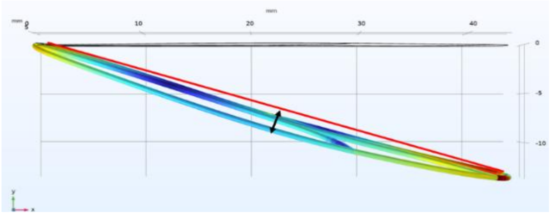

Fig. 3 Red & Black lines illustrate the spanwise twist and chordwise camber.

The displacement field (magnitude in mm) is shown in Fig. 4 for a representative case. Maximal displacement (red) occurs at the wing tip and leading edge, tapering to near zero at the fixed root. This pattern is expected for a cantilevered wing and indicates that much of the wing stiffness is concentrated near the root. Gradual gradient also shows that the membrane and vein stiffness was smoothly distributed in the model. A stiffer nodus shifts more load toward the root, reducing tip motion, Fig. 2, whereas a floppy nodus yields larger tip deflection as seen here.

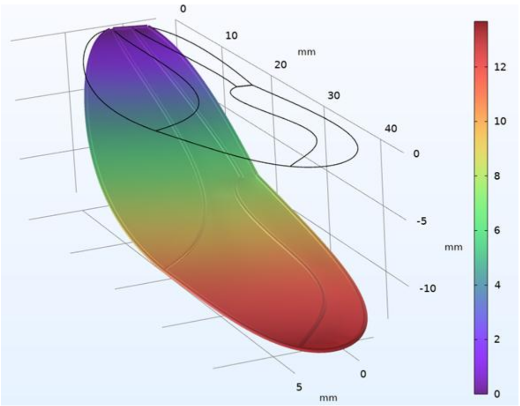

Fig. 4 Distribution of Displacements in Beam & Shell Elements Combined

The von Mises stress distribution is plotted in Fig. 5. Stress concentrates strongly at the nodus joint and at the wing root (dark red regions), while mid-span veins carry moderate stress (green blue). Notably, the nodus sees a stress peak due to the bending moment it transmits, consistent with prior findings that the nodus and pterostigma are mechanical hotspots [5] Insects may mitigate such stress by local material adaptations; for example, the presence of a nodus protrusion (knot) was hypothesized to limit rotation and protect against overload. In our model, as K_{nodus} increases, the stress at the nodus rises further, reflecting the stiffer joint transmitting more moments.

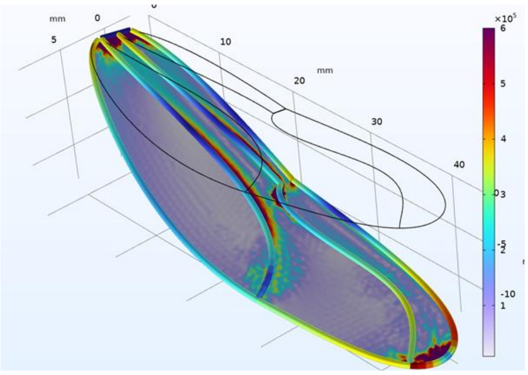

Fig. 5 Distribution of Stresses in Beam & Shell Elements Combined

Conclusion

A full-wing finite-element model in COMSOL was used to quantify the effect of nodus rotational stiffness on dragonfly wing bending. The simulations show that tip deflection under a given load decrease sharply as the nodus stiffness increases. In other words, a flexible nodus greatly enhances wing flexibility, whereas a rigid nodus maintains wing rigidity. Stress analysis reveals the nodus as a stress concentrator, explaining why insects often reinforce or limit motion there. These findings provide insight into how nodus mechanics influence overall wing behavior, with implications for the design of adaptive flapping wings.

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