Spatial profiles of wing stiffness in hawkmoths and dragonflies

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Introduction: We describe a method for measuring the spatial variation of flexural stiffness in insect wings. We compare the spatial distribution of wing stiffness in the hawkmoth, *Manduca sexta*, and an aeshnid dragonfly, *Aeshna multicolor.* These insects are both excellent fliers and have wings of similar size, but differ greatly in wing shape and venation pattern (Fig.1). We use the measured stiffness of hawkmoth wings in a static finite element model to examine the effects of the measured pattern of stiffness on wing displacement and strain localization.

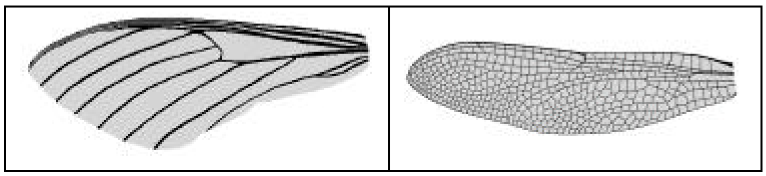

Fig.1: venation pattern of hawkmoth (left) and dragonfly (right)

Background: Flight performance depends strongly on the dynamic geometry of wings. The curvature of the trailing edge, in particular, is a crucial determinant of aerodynamic force generation [1]. While man-made wings attempt to minimize wing defomations (aside from controlled movements of flaps, etc.), all animal wings show a much larger degree of wing deformation. In vertebrates, such as birds and bats, wing bending is actively controlled by the neuromuscular system. However, in insects, wing deformations are almost entirely passive, and wing curvature results from the instantaneous interaction between aerodynamic forces and bending stiffness.

While the effects of changes in wing curvature are well known for steady flight (such as in airplanes), the effects of dynamic wing shape changes in unsteady, flapping flight remain enigmatic. Despite the fact that shape changes are known to have large effects on force production in steady flight, most analyses of animal flight assume that wings are infinitely stiff. Some recent studies have addressed the issue of wing flexibility by incorporating measured wing deformations into numerical flow analyses [2], but there have been few measurements of the stiffness of insect wings and no attempts to understand how wing flexibility interacts with and affects aerodynamic force production.

The complex patterns of supporting veins in insect wings implies that bending stiffness may vary spatially throughout the wing. This suggests a passive mechanism for regional flow control that could affect both force production and aerodynamic stability.

Methodology: We treat the wing as a 2-dimensional beam and measure flexural stiffness (EI) separately in the spanwise (from wing base to tip) and chordwise (from leading to trailing edge) directions. We first measure the surface shape of wings by projecting laser sheets onto the surface and photographing the wing unloaded and with a known force applied to the tip or trailing edge. We calibrate the images to find wing displacement (in the z-axis) along a laser line running from wing base to tip or leading to trailing edge. We pose various EI distributions along these axes (constant, linear, exponential), and use simplex minimization to find the EI distribution that most accurately predicts the measured wing displacement. In hawkmoths, we also load the wings with a range of different loads, repeating each load several times in a random order.

Finally, we use the measured spatial pattern of stiffness in the spanwise and chordwise directions of hawkmoth wings in a finite element model of a simplified wing. We use the Marc finite element program to compare displacement and strain in homogeneous wings vs. wings with the measured stiffness variation. We compare these wings in static tests with a load at the wing tip, a load at the trailing edge, and a pressure load on the surface of the wing.

Results: Despite the morphological differences between hawkmoth and dragonfly wings, we find that the profile of flexural stiffness in the spanwise direction is remarkably similar in both species; stiffness declines exponentially over several orders of magnitude, and the exponent of this decline is similar in both species.

Hawkmoth wings from four different individuals are stiffer in the spanwise direction (Fig.2, solid black lines) than those of three dragonflies (Fig. 2, solid grey lines). This (as well as the variation among individual dragonflies) can be explained by a documented scaling of EI with wing size. In the chordwise direction (Fig.2, dotted lines), hawkmoth and dragonfly wings again decline in stiffness exponentially towards the trailing edge with a similar exponent.

In hawkmoths, we also loaded the wings with a range of loads (Fig.3, one individual- lighter shades indicate increasing loads) and find that the wings behave non-linearly, particularly in the chordwise direction. This non-linearity results in the wings becoming effectively stiffer, particularly towards the trailing edge, as wing deformation increases.

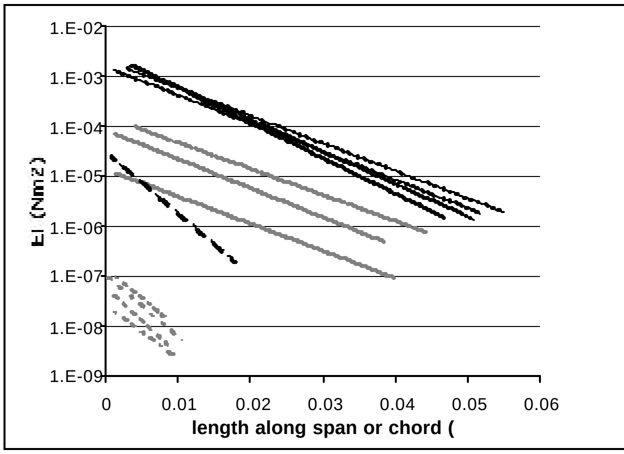

Fig.2: wing stiffness in hawkmoths and dragonflies

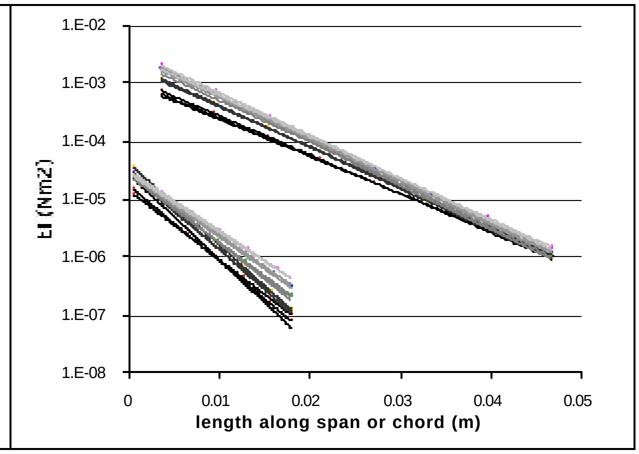

Fig.3: wing stiffness in a hawkmoth- increasing loads

We use the exponential decline in stiffness measured in hawkmoth wings in a finite element model of a simple wing and test first the case of a wing fixed at the base with an applied force at the tip. We find that an exponential decline in spanwise stiffness serves to localize the displacement to the tip and transfer the maximum strain from the wing base to the tip. In a wing fixed at the leading edge with an applied force in the center of the trailing edge, we find that an exponential decline in chordwise stiffness again localizes displacement to the center of the trailing edge and transfers strain from the leading to the trailing edge. Finally, in a wing with exponentially declining stiffness in both the spanwise and chordwise directions and a pressure force applied to the surface, we find that displacement is localized to the distal trailing edge of the wing and strain is transferred from the wing base to this distal region of the wing.

Discussion: The similarity of the measured spatial variation in stiffness between hawkmoth and dragonfly wings is surprising given their vastly differing wing morphologies and the fact that they are distantly related. This suggests that exponentially declining wing stiffness could be a general design principle in insect wings. The non-linear behavior seen in hawkmoth wings in the chordwise direction could possibly serve as a passive control mechanism, preventing excessive deformation.

The results of the finite element model suggest that an exponential decline in wing stiffness could have profound impacts on the localization of strain on the wing. By transferring strain (and thus maximum curvature) from the wing base to the distal trailing edge of the wing, this design may allow the trailing edge to perform similarly to the control surfaces (flaps, etc.) of airplane wings, thus providing passive control over air flow and force generation.

References

(1) **Anderson, J.D. Jr.** *Fundamentals of Aerodynamics*. New York: McGraw-Hill, Inc, 1991.
(2) **Liu, H., Ellington, C.P., Kawachi, K., Van Den Berg, C. and Willmott A.P**. A computational fluid dynamic study of hawkmoth hovering, Journal of Experimental Biology 201**:**461-477, 1998.

Acknowledgements: This work was supported by NSF (KDI), ONR, the MacArthur Foundation, and Joan and Richard Komen.