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Not gone with the wind: Active microscale flight with highly porous bristled wings

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The finesse of sub-millimeter insect flight with comb-like bristled wings raises intriguing questions, not only on fluid-structure interactions (FSI) but also on the mechanical behavior of the underlying, highly porous structures. Farisenkov et al. characterized the morphology and kinematics of one of the smallest flying insects, the featherwing beetle *Paratuposa placentis*. Their simulations of this beetle in flight quantified crucial aspects of its aerodynamics, explaining why porous bristled wings enable flight and how they produce unexpected speeds and accelerations.

Nature reigns with elegance, ingenuity, and robustness when it comes to finding a balance between lightweightness, strength, and function. Bio-inspired designs and biomimetics have often been at the forefront of new engineering developments. Still, to be inspired by nature, one must first be its keen observer. An overarching design solution is porosity, which permeates natural materials and structures across a wide range of length scales and geometries, facilitating diverse physical and chemical phenomena, and biological functions. Examples range from roots, branches, and seeds of plants, to hair, feathers, and other animal appendages, to bones, shells, and other biological tissues.

Porous biological structures at small length scales can be especially striking and thought-provoking. In the evolutionary process of miniaturization,[1] some organisms have evolved much-reduced body sizes, requiring extreme adaptations in morphology and the underlying physical mechanisms. Some fascinating examples are found in miniature insects (Figure 1A). The title of the smallest known winged insect goes to some species of parasitoid wasps, commonly known as fairyflies (Figure 1A). One of the smallest free-living flying insects is the featherwing beetle *Paratuposa placentis*, measuring $\lesssim$ 400 μm, smaller than an ameba (Figure 1B).

Whereas the fluid mechanics and fluid-structure interactions (FSI) in viscosity-dominated (small values of the Reynolds number, $Re \ll 1$) or inertia-dominated ($Re \gg 1$) regimes are well established, intermediate cases with $Re \gtrsim 1$ are far more challenging to tackle. For flying miniature insects, the Reynolds numbers in flight are on the order of 10, where viscous forces dominate, but inertia effects cannot be neglected. In this flow regime, miniature insects must minimize the inertial load from the body and wings while maintaining sufficient muscle to supply power to the flight. In addition, other mechanisms in the flapping flight of larger insects (e.g., the leading-edge vortex) become ineffective at generating lift due to viscous dissipation. To stay airborne, miniature insects would need rather different flight kinematics from larger insects.[3]

Facing the above challenges, some downright bizarre solutions have evolved, e.g., eliminating whole organs and organ systems.[1] The highly porous wings are perhaps the most visually striking adaptation to the diminished sizes. Unlike membranous wings in larger insects, the wings at the smaller scales are often donned with bristles, hair-like micro-structures made out of chitin, the same material of insect exoskeleton.[4] These bristles emanate from a central membranous part, which can itself be extremely slender in some miniature insects; they are arranged with regular spacing, conferring the wings with a strange, comb-like look (Figures 1A and 1B).

At first sight, the highly porous bristled wings seem too leaky to be any good for flying. Surprisingly, in the case of *P. placentis*, they not only can fly but excel at fast maneuvers (with relatively high speeds and accelerations), rivaling similar rove beetles three times as large.[5] How do these minuscule insects achieve this exquisite feat? What is the role of porosity of their underlying material structure in flight?

A recent paper published by Farisenkov et al.[6] provides valuable insights into the flight kinematics and aerodynamics of *P. placentis*, whose porous wings have a peculiar structural layout, bearing much surprise and inspiration for their extreme scale and complex function. The study combined light, confocal, and electron microscopy imaging to construct a detailed morphological model of the beetle, including the body, the elytra (wing cases), the wings, and even the secondary outgrowth on the bristles (Figure 1B).

Whereas past high-speed videography had revealed that these miniature insects use a gait different from the "clap-and-fling mechanism" typically associated with larger insects,[3] it remained unclear until now how the extremely porous wings of *P. placentis* engage in flight. By filming the tiny beetles in a specially designed chamber with high-speed cameras operating at nearly 4000 frames per second, it was

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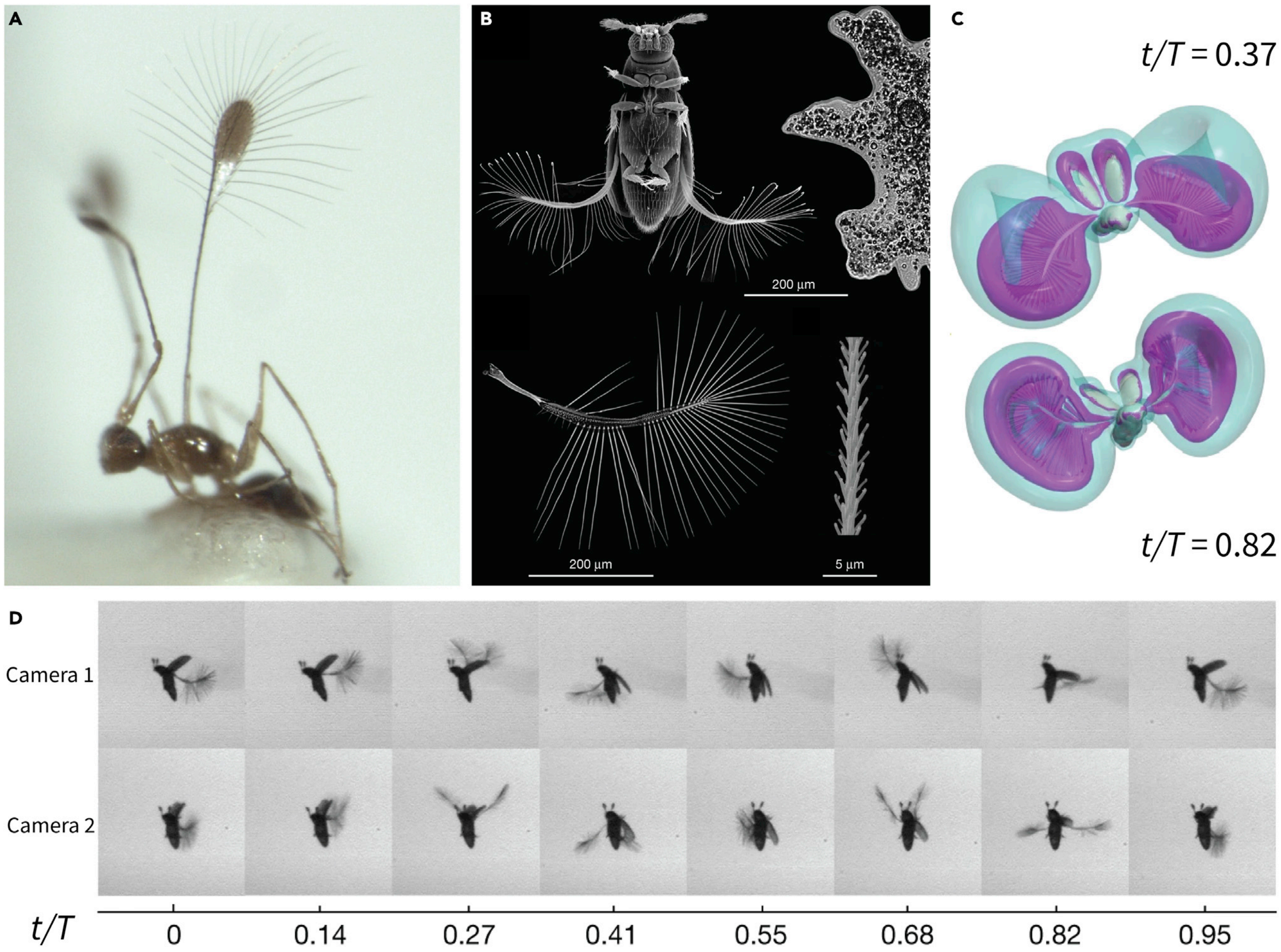

Figure 1. Morphology, flight kinematics, and aerodynamics of miniature insects

(A) An adult female specimen of Mymaridae sp. from New Zealand. Image credit: S.E. Thorpe, Wikipedia.

(B) SEM images of *P. placentis*, compared with a single-celled organism *Ameba proteus*. Bottom shows details of the wing and a single bristle.

(C) Snapshots of simulated *P. placentis* in flight; colors indicate vorticity magnitude.

(D) Snapshots of the high-speed video of *P. placentis* in flight. (B–D) Adapted from Farisenkov et al.[2] with labeling modifications. Copyright ©2022, Farisenkov et al.

possible to visualize, for the first time, how these beetles fly: they flap their wings in a figure-eight fashion at about 180 Hz, clapping above and below the body at the end of each stroke (Figure 1D). The high-speed videos of the study also unveiled an unexpected function of the elytra in providing a counterbalance to the wing motion for stabilization.

To investigate the generation of aerodynamic forces and the power consumption of the tiny beetle in flight, Farisenkov et al.[6] turned to three-dimensional FSI simulations. Here, a major challenge is the separation of length scales in the bristled wings—the wings are two orders of magnitude larger than the individual bristles. FSI simulations of a multiscale structure like this require advanced numerical techniques in meshing, solving unsteady Navier–Stokes (N–S) equations, and coupling fluid and solid phases. Leveraging the open-source solver WABBIT[2] designed for simulating insect flights, the authors constructed a faithful full model of the animals based on detailed morphological data and applied the flight kinematics in near-hovering flight (low velocity in both horizontal and vertical directions) to actuate the wings and the elytra (Figure 1C). At the relevant fluid regime ($Re \sim 10$), the simulated wings were found to generate nearly 70% as much mean vertical force as their membranous counterparts while weighing as little as 13%. (The horizontal thrust was not reported in the work.) Consequently, the bristled wings consume significantly less power than the membranous counterparts and require no elastic energy to be stored in the flight muscles; both of these features are highly advantageous for creatures so minute.

Beyond the work highlighted here, there is an increased interest in miniature flight.[7] Recent advances include studies on the material and mechanical properties of bristled wings,[4] the fundamentals of the aerodynamics of flow past bristles,[8] and flapping flight at low Reynolds numbers.[3] These studies often comment on the inspiration miniature flying insects may have on the design and engineering of microscale aerial vehicles (MAVs). In comparison, the state-of-the-art MAVs (e.g., the RoboBee[9]) are still orders of magnitude larger, not to mention their relative primitiveness in control, power, and functionality. Still, unraveling the physics of bristled-winged flight, and applying it to the engineering design of micro-devices, will require further advances in experiments, theoretical modeling, and computation.

Some recent efforts on idealized porous structures and their FSI demonstrate that there is much that defies our intuition, long built up from observations at larger scales and in non-porous solids. On the structural mechanics side, *porosity* plays the dominant role in dictating the mechanical properties (e.g., the bending stiffness) of a perforated plate, regardless of individual pore sizes, shapes, or their distributions, as recent work on the homogenization of porous structures has demonstrated.[10] When coupled to fluids, *permeability* becomes another important variable, determined by the geometry and arrangement of the pores. Note that, in general, porosity and permeability may not necessarily be directly related. In another example closer to biology, separated, steady vortex structures in the wake of a dandelion seed were predicted by idealizing the seed as a homogenized rigid porous disk, and so was the critical porosity threshold for a stable wake.[11]

Perhaps the most surprising theme emerging from these studies is the effectiveness of homogenization theory in describing the porous solid phase alone, or the FSI coupling, of these slender poroelastic structures. There is an added difficulty that the pore sizes can be on par or larger than the length scale of the structure,[10,12] which defies standard homogenization assumptions. Experimentally, it is nontrivial to fabricate and characterize the mechanics of small-scale slender structures with precisely designed porosity and permeability. Future experimental, theoretical, and computational research in these directions, coupled with advanced techniques for synthesizing and fabricating porous materials and structures, could unlock an exciting playground for novel FSI mechanisms and bio-inspired designs at a small scale.

WEB RESOURCES

https://commons.wikimedia.org/wiki/File:Mymar_female.jpg

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