

Solid-State Ionic Actuator-Driven Wings for Sub-Millimeter Robotic Fliers

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Primary CNF Tools Used: AJA Sputter Deposition, Oxford FlexAL atomic layer deposition, Oxford 82 reactive-ion etcher, ABM contact aligner, critical-point dryer, and Zeiss SEM

Abstract:

This report describes a sub-millimeter flapping wing powered by solid-state ionic microscopic actuators (SIMAs). Nanometer-scale drive hinges, a lightweight panel, and a passive pitch joint are combined in one lithographically fabricated structure. The wing operates in air from low-voltage input. A microscopic wing with an approximately 250 μm span generated an 80° stroke near 530 Hz and retained motion for about 10^8 cycles. Its output power density was estimated at 1200 W/kg. Aerodynamic and energy estimates indicate that these wings could support a sub-mm flapping robot with small controller and photovoltaics. The work establishes an integrated wing module for future solar-powered microscopic fliers.

Research Summary:

Building a flying robot smaller than one millimeter requires a wing that combines large angular motion, high repetition rate, long life, and microwatt-scale energy use. The structure must also be made by planar nanofabrication and accept signals from a very small control circuit. Existing insect-scale aircraft demonstrate controlled flapping flight, but their actuators and transmissions remain too large for a sub-millimeter platform (1, 2). This project addresses that gap by integrating the actuator, wing panel, electrical leads, and compliant joints into one microfabricated assembly.

The active hinge contains three parallel SIMA strips made from an ultrathin platinum/tantalum-oxide/platinum laminate. The compact actuator serves directly as the active hinge, eliminating a separate transmission. For aircraft integration, the important features are solid-state operation in ambient air, low moving mass, and compatibility with approximately 3-5 V electronics. The actuators supply the main back-and-forth stroke, while

a separate flexible passive hinge allows the wing to change pitch during each cycle.

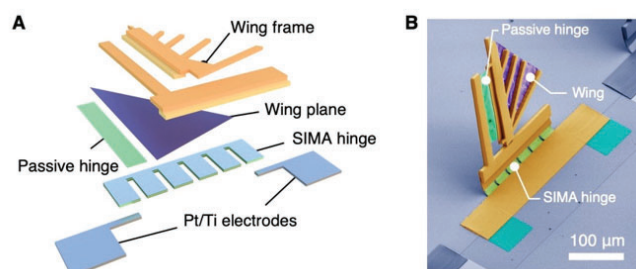


Figure 1: (A) Exploded schematic of a sub-mm flapping wing. (B) False-color SEM image of a sub-mm wing.

The completed wing spans about 250 μm and has a chord near 150 μm (Fig. 1). A titanium film forms the wing surface, while patterned nLOF and SU-8 reinforce the panel with little added mass. A thin tantalum-oxide flexure along the leading edge acts as the passive pitch hinge. The design separates powered stroke from pitch rotation, producing two coupled motions. Fabrication uses CNF processes including sputter deposition, atomic layer deposition, photolithography, plasma etching, and sacrificial release. All layers are patterned on a substrate before release, providing precise alignment of the actuator, panel, frame, and electrical connections.

Alternating voltage moves the released wing between forward and backward positions. At its designed operating point in air, the wing flapped near 530 Hz and swept approximately 80° between the two extremes (Fig. 2). This combination of broad stroke and small span suits the rapid kinematics required at sub-millimeter scale. A second wing from the same fabrication batch continued with substantial amplitude for roughly 100 million cycles, or about one day. From the measured motion and actuator mass, the specific mechanical

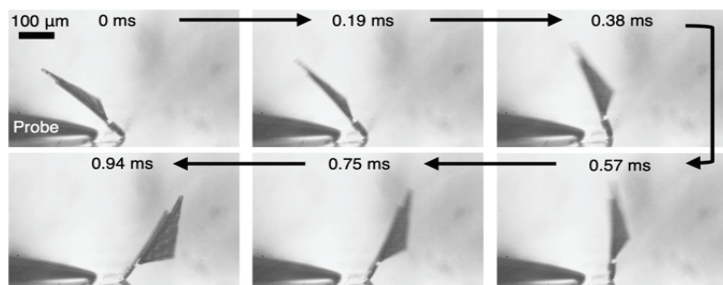


Figure 2: Wing operation in air, showing the stroke extremes, approximately 80° motion near 530 Hz.

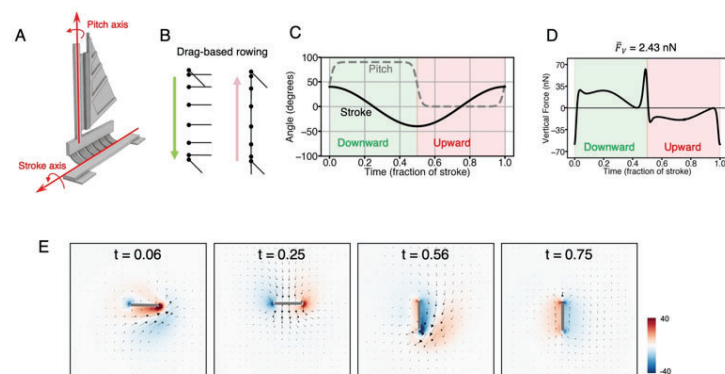


Figure 3: (A) Schematic illustrations of stroke and pitch motions. (B) Wing kinematics for wing chords. The green and pink arrows represent the stroke directions, the black solid circles represent the leading edges and the stick represents the wing chord. (C) Euler angles of pitch and stroke as a function of time over one complete cycle for the three Kinematics. (D) Simulated instantaneous vertical force as a function of time. (E) Vorticity fields (color map) for Kinematics 3, with arrows indicating the flow direction and magnitude (represented by arrow size). The vorticity fields are shown with a color scale ranging from -40 to 40 with blue indicating the clockwise direction and red indicating the counterclockwise direction.

output was estimated at approximately 1200 W/kg, comparable to insect flight muscle and larger robotic flapping actuators (3).

Computational fluid-dynamic calculations evaluated vertical force using the measured geometry and motion: a 250 μm span, 530 Hz wingbeat, and 80° peak-to-peak stroke (Fig. 3). At the resulting low Reynolds number, a drag-based rowing pattern is favorable. The wing plane presents a broad face during the force-producing motion and turns to a narrow profile during recovery (4). With rapid passive pitching, the predicted average force reached about 2.43 nN per wing. Four wings would provide approximately 9.72 nN, greater than the estimated 6.7 nN combined weight of the wings, a 50 μm -scale controller, and thin silicon photovoltaics.

The electrical budget is also close to self-sufficiency. A 30,000 μm^2 photovoltaic area with 20% efficiency is estimated to produce about 6 μW under one-sun illumination. Four wings would consume approximately 5.4 μW , and control electronics are projected to require about 0.2 μW . A complete untethered aircraft has not yet been demonstrated, but the experiments place stroke, durability, force, control, and solar power within one design envelope.

References:

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