MECHANICAL ENERGY SCAVENGING FROM FLYING INSECTS

Ethem Erkan Aktakka¹, Hanseup Kim¹, Massood Atashbar^{1,2}, and Khalil Najafi¹

¹ Department of Electrical Engineering and Computer Science

Center for Wireless Integrated Microsystems (WIMS ERC), University of Michigan, Ann Arbor, MI, USA

² Department of Electrical and Computer Engineering

Center for Advanced Smart Sensors and Structures, Western Michigan University, Kalamazoo, MI, USA

ABSTRACT

This paper reports the first effort to generate power from a live insect (*Cotinis nitida* - Green June Beetle) during its tethered flight, by utilizing piezoelectric devices in the d31 bending mode to convert mechanical vibrations of a beetle into electrical output. We measured available deflection, force and power output from oscillatory movements at different locations on a beetle with an unmounted piezoelectric beam and showed that up to $\sim 115 \mu\text{W}$ power generation is possible. Two initial generator prototypes were fabricated, mounted on a beetle, and harvested $11.5 \mu\text{W}$ and $7.5 \mu\text{W}$ in device volumes of 11.0 mm^3 and 5.6 mm^3 respectively, from 85 Hz-100 Hz wing strokes. A final prototype was designed to enable minimum disturbance of free-flight while maximizing power output. ANSYS simulations predict an output of $101.6 \mu\text{W}$.

INTRODUCTION

One of the main constraints in the development of Micro-Air-Vehicles (MAVs) is the limited weight and volume reserved on the device for a long-life power source. Studies towards creating cyborg insects have demonstrated reliable tissue-electronics neuromuscular interfaces [1], and flight modulation through an implantable microsystem [2]. These initial implanted systems used batteries to power the microcontroller and muscle stimulator. However energy scavenging from an insect's high frequency body movements would achieve an unlimited source of power over the insect's life-time.

MEASUREMENTS ON BEETLE

Several measurements were performed during tethered flight of a subject beetle, including acoustic measurements to define the average fundamental wing-stroke frequency, 92.1 Hz. Fig.1 summarizes the high speed (6000 fps) camera measurements of deflection and frequency at various body sections. Available force and power output measurements at various locations of the body were performed with an unmounted macro-scale piezoelectric beam (Fig.2-3). Force and power output (directly proportional to Frequency $\times$ Force $\times$ Deflection) increased towards the flight muscle base. These experimental measurements demonstrated $\sim 115 \mu\text{W}$ power generation due to elytra vibration close to the wing base, where both peak force input (35 mN-40 mN) and oscillatory displacement (0.8 mm_{pp}) are considerably large.

INITIAL PROTOTYPE EXPERIMENTS

Two initial back-pack type energy scavenger prototypes were fabricated from $380 \mu\text{m}$ thick PZT-Brass-PZT bimorphs, then mounted and tested on beetles. Prototype-I (Fig.4), stretching from thorax to far abdominal end of elytra, generated $11.5 \mu\text{W}$ in 11.0 mm^3 device volume by delivering $874 \text{ mV}_{\text{RMS}}$ to a $66.6 \text{ k}\Omega$ load. Prototype-II (Fig.5), again mounted on the thorax, generated $7.5 \mu\text{W}$ in a device volume of 5.6 mm^3 from two short piezoelectric beams each actuated by left/right elytra upstrokes.

Figure 1: Deflection and frequency measurements on a beetle in flight.

Figure 2: Measuring available power from a beetle.

Figure 3: Available power measurements on *Cotinis nitida* during its tethered flight using the setup shown in Figure 2.

Figure 4: Prototype-I and output values of both prototypes.

The second prototype provided higher normalized output, (Power/Force/Deflection), 17.5 μ W/mN/mm, as it was hit by a higher force source. Since these initial prototypes had high beam stiffness, their vibrating tips could not be attached directly to the actuation site, therefore a gap between the device tip and the elytra was provided. From these experiments, it was concluded that the final prototype should take advantage of the full deflection of the elytra with a lower spring constant, while keeping maximum beam stress lower than the material yield stress (~ 20 MPa).

Figure 5: Prototype-II and its voltage output on a 200 k Ω load.

FINAL PROTOTYPE DESIGN

A final energy scavenger prototype (Fig.6) was designed to provide a lower spring constant, while still occupying a limited area (5 mm $\times$ 5 mm) and maximizing strain on the piezoelectric layer, by employing a spiral beam geometry. For realization of the device, reliable low temperature solder bonding of piezoceramics was developed, and re-polarization and laser ablation of bulk piezoelectric layers were characterized. ANSYS simulations

indicate that a force of < 2 mN is required for this design, and that 50.8 μ W can be generated per device at the insect's flapping frequency and elytra deflection. Placement of one coil design per wing can provide a total output > 100 μ W, which is greater than the worst case average power consumption (80 μ W) of the wing muscle neural stimulator used in [2]. A direct connection from the device's impact point to the wing base (Fig.7), where the asynchronous flight muscle can supply up to ~ 0.9 N [3], would further improve power output.

Figure 6: Final prototype; conceptual device geometry constrained in a 5 mm $\times$ 5 mm area, and device placement on a beetle's dorsal thorax.

Figure 7: Conceptual device connection to the beetle's wing base, where flight muscles can provide up to 910 mN [3].

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