Polymer Actuated Variable Camber Foils

John D.W. Madden, Bryan Schmid, Ralph Botha, Martin Hechinger, Serge R. Lafontaine, Peter G.A. Madden, Franz S. Hover, Karl McLetchie, and Ian W. Hunter

***Abstract*—Conducting polymer actuators are employed to create actively shaped hydrodynamic foils. The active foils are designed to allow control over camber. Polymer actuator-driven control of camber, when applied to screws, promises to enable low cost blade shape optimization as a function of flow conditions. The design and fabrication of the active foils are presented, the forces are measured and operation is demonstrated both in still air and water. The foils have a span of 240 mm, and an average chord length of 70 mm. The trailing 30 mm of the foil is composed of a thin polypyrrole actuator that curls chordwise to achieve variable camber. The actuator consists of two 30 μm thick sheets of hexafluorophosphate doped polypyrrole separated from each other by a gel electrolyte. A polymer layer encapsulates the entire structure. Potentials are applied between the polymer layers to induce reversible bending by approximately 35 degrees, generating forces of 0.15 N. A linear actuator driven foil has also been developed which relies on a dual cantilever mechanical amplification system to generate similar forces and displacements as are obtained with the bending system. Remaining challenges include increasing force, improving encapsulation, and demonstrating durability through water tunnel tests.**

***Index Terms*—Actuator, Autonomous Underwater Vehicle, hydrodynamics, artificial muscle.**

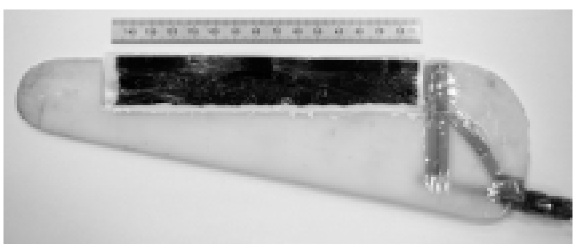

Figure 1: 240 mm long foil with trailing edge at top. The black rectangle is a 150 mm long, 30 mm wide active section that bends under applied potential, resulting in a change in foil camber.

I. Introduction

In large vessels and aircraft it is common to change blade pitch as a function of flow conditions to improve thrust and efficiency, or in order to assist in maneuvering. The mechanisms employed to achieve these changes in blade geometry are complex, expensive and require periodic maintenance. As a result they are seldom used on small vehicles such as Autonomous Underwater Vehicles (AUVs). The ability to modify blade shape nevertheless has great potential benefits for AUVs. Mission lengths in Unmanned, Untethered Submersible Technologies (UUST) are dependent on battery lifetimes, and therefore optimizing propulsion efficiency is particularly beneficial. Low speed maneuverability is often poor in these vehicles. The ability to change propeller shape could enable more effective stopping & acceleration and improve flow over control surfaces at low speeds. Noise reduction is important in naval applications. Variable cambers promise to reduce noise by enabling operation at lower RPM [1] and by reducing cavitation. Therefore an inexpensive mechanism for changing blade geometry could have a major impact on AUV/UUST technology.

Mounting an actuator directly on a rotating propeller shaft or within the blade itself would eliminate the complex transmission systems used to effect changes in propeller geometry. Unfortunately the volume available for the actuators is small, making it challenging to fit a conventional motor (e.g. electric motor) onto the shaft. Furthermore, electric motors require power input to maintain a force, resulting in excessive energy expenditure.

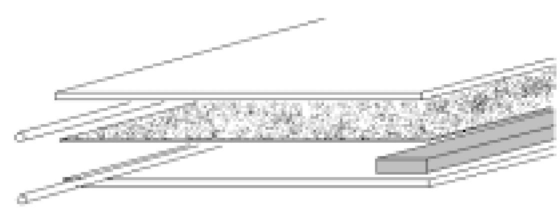

Figure 2: Layered structure of the active section. 30 μm thick PPy sheets (top and bottom), are separated by a paper spacer. A mica shim (bottom right) provides spanwise rigidity and gold wires (left), form electrical contacts. The space between the PPy sheets is filled with gel electrolyte. Total thickness ~ 0.12 mm.

Recently a number of new actuating materials have emerged that generate sufficient force and energy to make them promising candidates for enabling in situ propeller shape changes [2]. Of these, dielectric elastomers, ferroelectric polymers, liquid crystal elastomers (LCE) and conducting polymers have sufficient work density to fit within

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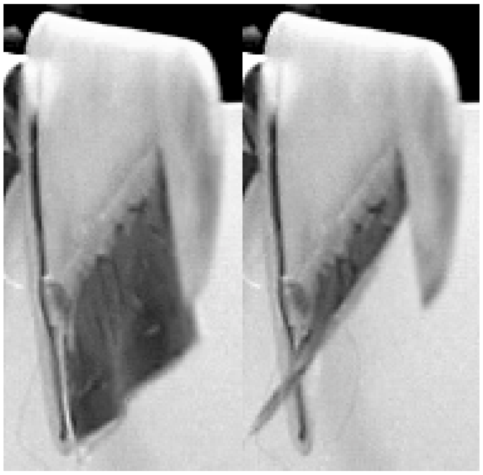

Figure 3: Spanwise view of foil (looking from 'wing' tip at right), showing the neutral (left) and deflected (right) states during actuation in air.

the blade dimensions, and appear to offer the necessary degree of position control. Unlike electric motors they can work against a constant force without requiring energy input.

In this work the objective is to demonstrate polypyrrole actuated variable camber foils. Unlike dielectric elastomers and ferroelectric polymers, conducting polymers operate at low voltages (1-10 V) which are readily provided by on-board battery technology. A disadvantage of polypyrrole, the conducting polymer chosen for this work, is its relatively small strain compared to the other actuator technologies. The 2 % strains need to be substantially amplified to create the required displacements.

Two approaches to mechanical amplification are described. One is a bending trilayer which operates like a bimetallic strip. Two thin sheets of polypyrrole are laminated together, separated by a thin layer of gel electrolyte. Application of a potential difference between them causes one sheet to expand and the other to contract, producing bending. In the second approach linear contraction of the polypyrrole is amplified by two sequential cantilevers to generate the required displacement.

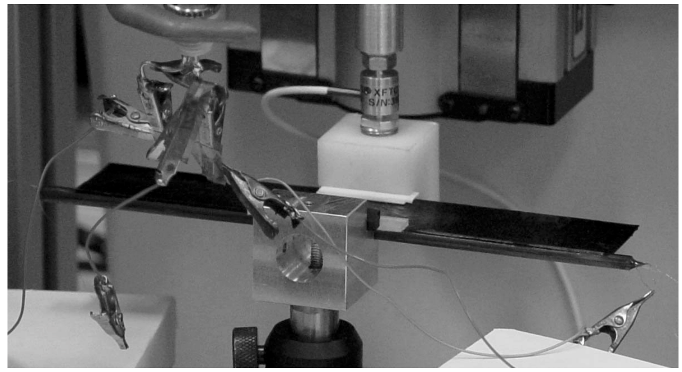

Figure 4: Force measurement apparatus. The bending actuator (black) is held horizontally and clamped on each of its long sides to prevent motion. Electrical activation produces a vertical force, as measured by a load cell (above the center white block).

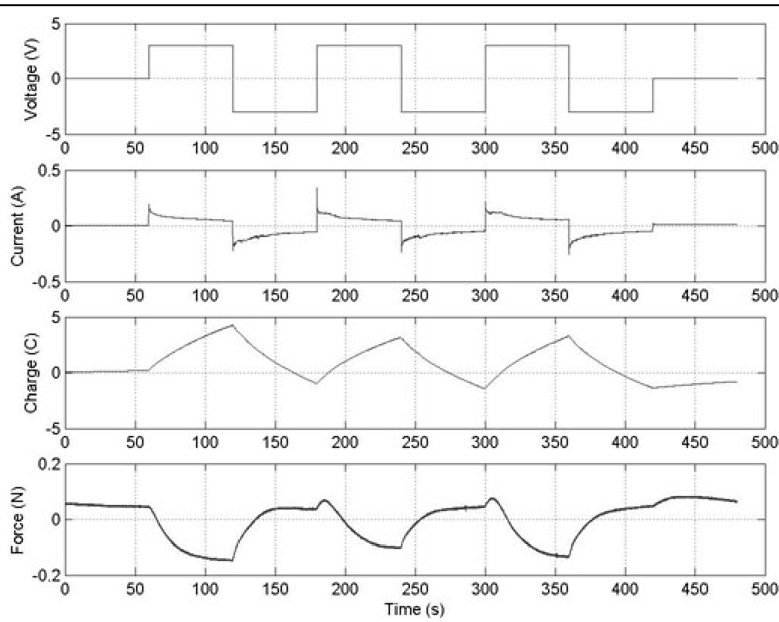

Figure 5: Force generated at the tip of the laminated actuator in the chordwise direction in response to ± 3 V step inputs.

II. Bending Trilayer

Figure 6: Submerged foil operating in shallow water.

The initial objective is to demonstrate the operation of a variable camber foil in air and in pure water. Geometry and flow conditions are chosen to be consistent with those of the MIT water tunnel. A deformable portion at the trailing edge of the wing is designed to act as an aileron, generating torques consistent with flow rates of up to 2 m/s and a 30 degree bending angle. The foil geometry, shown in Figure 1, is approximately NACA 0014 (no camber, thickness is 14 % of chord). The span is 240 mm, the average chord length is 70 mm and the maximum thickness is 34 mm. Camber is varied by deforming a rectangular section that is 150 mm long, 30 mm wide and ~ 0.12 mm thick. Deformation of the trailing edge is achieved using two 30 μm thick, 150 mm long and 30 mm wide sheets of polypyrrole (PPy) separated by gel electrolyte, as depicted in Figure 2. A 3.5 µm thick Mylar® sheet sealed with urethane envelops the structure, providing encapsulation. 75 µm diameter gold wires provide independent electrical contact with each polypyrrole sheet. Mica shims are used to prevent bending in the span-wise direction. The actuating section is inserted into a groove in the foil and fixed in place using polyurethane adhesive.

Equations of a bimetallic strip were adapted for a three layer structure to determine the layer thicknesses necessary to produce the desired 30 degree deflection. The forces required to maintain the deflection given a flow speed of ~ 1m/s were also considered in designing the structure. Calculations based on the flow speed and geometry predict that a force of at least 0.15 N needs to be maintained on the trailing edge. The actuator is designed to achieve this force.

A. Synthesis & Fabrication

The active portion of the foil consists of five main components: 2 layers of PPy, a paper separator (Kodak EK1546027), gold wire providing electrical contact (75 µm diameter), laminated muscovite mica shims, and gel

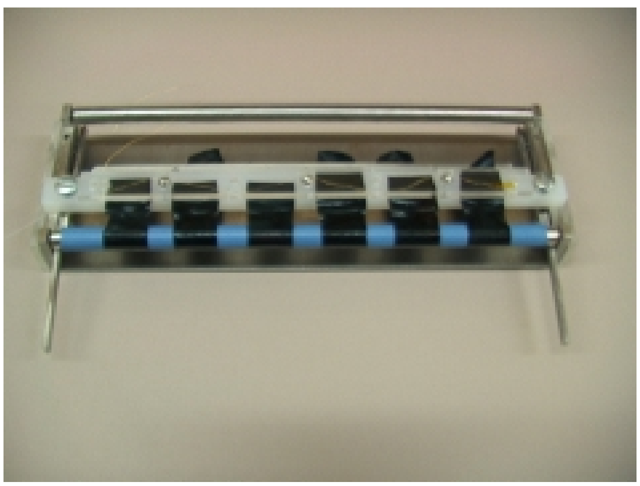

Figure 7: Linear actuator structure. The trailing edge is at the bottom. The two beams extending downwards at the bottom of the page will support a moveable control surface. The black strips are 40 µm thick polypyrrole films, which are held at one end by a plexiglass plate, wrap around the blue roller, and are fixed on the bottom surface of the structure. The actuators contract, tensioning lines that in turn deflect the beams in a direction in and out of the page. (see Figure 8 for a diagram with a side view).

electrolyte. Construction of the bilayer begins with electro-deposition of 30 µm thick films of hexafluorophosphate-doped PPy onto a glassy carbon crucible following a previously described procedure [3]. Once removed from the glassy carbon, two pieces of PPy are cut to the desired geometry (150 mm x 30 mm). Two 150 mm long, 5 mm wide muscovite mica shims (~350 µm thick) are laminated together to serve as a mechanical restraint to span-wise bending. These form the trailing edge of the active portion of the foil. Synthesis of the gel electrolyte is based on a procedure described by Noda and Watanabe [4].

During fabrication, one sheet of PPy is placed on a Teflon surface. Gold wire is placed along one side of the sheet's major axis to provide electrical contact, Figure 2. Next, a sheet of lens paper is laid down. Laminated muscovite mica is placed along the major axis opposite to that of the gold wire. The electrolyte gel is then pored evenly over the paper. A second PPy sheet is placed over the entire sample. A sheet of Teflon is then be placed over the entire bilayer and clamped between two metal plates. The bilayer is placed in an oven and baked at 80 °C for 12 hours. Encapsulation is achieved using a 3.5 µm thick Mylar® film. The Mylar is folded over the bilayer and sealed with a flexible polyurethane (Kalex® D-50, www.elementis-specialties.com). A syringe and needle are used to remove excess air as the urethane seal is compressed.

B. RESULTS

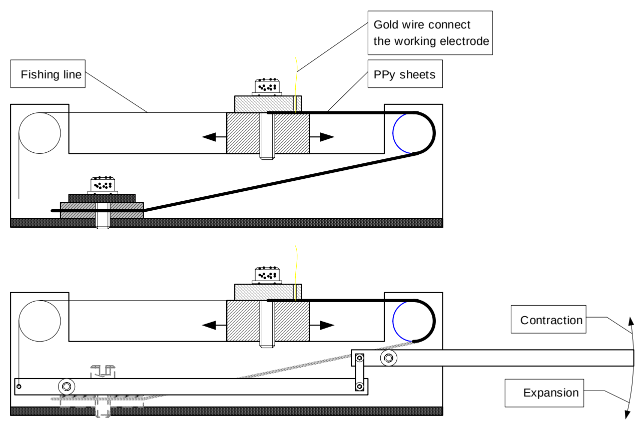

Figure 8: Side view diagram of the linear actuator driven foil. The top diagram shows how polypyrrole strips are fixed to the base at one end. From the base, the strips cross diagonally up to a roller. The strips are then clamped on the top to a moveable truck. Nylon wire extends from the far side of the truck and is wound around another roller (left side). The nylon is attached to a beam. As polypyrrole contracts, the left end of the beam is pulled upwards, rotating it about a hinge. The far end of the beam displaces downwards, with 5 × the displacement, due to the placement of the bearing. The beam pulls a second cantilever, which again has a 5 × amplification factor, with the result that the right hand tip of the second cantilever deflects upwards by 25 × the initial displacement of the polymer.

Step potentials of ± 2.5 V are applied to the polymer actuator in air to actively and reversibly change camber. Figure 3 depicts the foil with the span almost perpendicular to the camera and the chord oriented vertically. Note the change in the camber resulting from the 35° orientation change of the active member (black). Complete deflection is achieved in 4 s.

Force testing is performed by fixing both ends of the active member and applying ±3 V potential steps. A photograph of the force measuring apparatus is shown in Figure 4, and the recorded potential, current and force are plotted in Figure 5. Generated forces exceed the minimum 0.15 N with the actuator held in the undeflected position. Further experiments are required to demonstrate forces as a function of deflection angle. At 5 Hz activation rate the force fluctuates by 10 mN.

Experimentation in water is at an early stage. Figure 6 is an image of the foil submerged in water. Actuation is observed in water, indicating that encapsulation is effective. Tests are now underway in a water tunnel to determine deflection, lift, drag and torque as a function of flow speed.

It has been found that while activation is successful in relatively shallow water, the actuator fails when submerged to depths of greater than ~ 1m, apparently due to seepage of water into the structure.

III. Linear Actuator

The advantage of employing a linear actuator, as opposed to the bending trilayer, is that the linear actuator may sit within the rigid portion of the blade, or even on the shaft. This is an advantage because the larger available volume enables larger forces to be contemplated. The primary drawback of the linear approach is that it requires a mechanical amplification mechanism, adding complexity to the design. Also, unlike the trilayer approach, the actuator only generates work when operating in tension (otherwise it buckles). Where two-way actuation is desired, twice the volume of polymer is required.

The same angular displacement and force is sought with the linear actuator as is obtained with the trilayer.

A. Design

Two cantilevers placed in series produce a 25 × amplification of the contraction of polypyrrole films. The apparatus is shown in Figure 7 and its operation is described in Figure 8. Polypyrrole actuation is achieved by placing the entire apparatus into an organic solvent salt bath and applying potential between the polypyrrole films and a counter electrode. (In the final version, the electrolyte and counter electrode will be encapsulated within the foil structure.) Synthesis of the polymer films follows the procedure described above.

B. Results

Figure 9 depicts the extent of deflection obtained by driving the mechanism using a voltage range of 2.1 V. Forces reach 0.18 N, as measured by holding the position fixed while applying a step change in voltage.

IV. Discussion

An encapsulated polypyrrole trilayer actuator is employed to produce a 35^{o} bend and generate forces of > 0.15 N in the trailing edge of a foil. Operation is demonstrated in air and in water. However the encapsulation was found to leak when the foil was taken to depths of ~ 1 m. A linear actuator driven deflection was also produced, and employs a 25 ×, two cantilever amplifier. The linear actuator produced 40^{o}s of deflection and 0.18 N of force. The actuator has not been encapsulated.

The foil was designed to operate in 1 m/s flows. In order to be applied to higher flow speeds, larger forces will need to be achieved. In reaching higher forces, multiple trilayers are being operated in parallel such that the forces add. Use of parallel films in the linear actuator should also enable increased forces to be achieved, with the total force in both cases scaling linearly with the number of films or trilayers.

Higher forces will enable thicker encapsulation to be applied, which should enable leakage to be eliminated.

This work is the first step towards the demonstration of sea worthy actuators. It is a significant advance, representing the first time an encapsulated conducting polymer actuator has been operated in a liquid environment, and it is the largest conducting polymer actuator yet assembled.

[1] P. R. Bandyopadhyay, *A biomimetic propulsor for active noise control : experiments*, NUWC-NPT Technical Report 11,351, 1 March 2002, Naval Undersea Warfare Center.

[2] J.D. Madden, Nate Vandesteeg, Peter G. Madden, Arash Takshi, Rachel Zimet, Patrick A. Anquetil, Serge R. Lafontaine, Paul A. Wierenga and Ian W. Hunter *“Artificial Muscle Technology: Physical Principles and Naval Prospects”* Proceedings of UUST 2003.

[3] Yamaura, M., Hagiwara, T., and Iwata, K., Ehancement of electrical conductivity of polypyrrole film by stretching: counter ion effect *Synthetic Metals*, vol. 26, pp. 209-224, 1988.

[4] Noda, A. and Watanabe, M., *Electrochimica Acta*, vol. 45, pp. 1265-1270, 2000.