Hydrodynamic Characterization and Performance Evaluation of Polypyrrole Actuator Propulsor

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Abstract. Polypyrrole, a special class of smart material has gained attention as artificial muscle actuator propulsor due to its promising properties like light weight, flexibility, large dimensional changes with low operating voltage and natural muscle like working and performances. In this paper, a Polypyrrole actuator is fabricated and studied its behaviour and performances in underwater environment experimentally. The actuator is synthesized by electrochemical polymerization and fabricated as a trilayer strip actuator by using layer by layer deposition technique. Following the fabrication, the hydrodynamic bending performances like tip displacement, force and frequency and propulsion characteristics like thrust, power and efficiency are estimated by carried out the bending experiment in a water tank with zero flow velocity. Here the stiffness of the actuator also estimated from dynamic mechanical analysis as it is one of the key parameter which affects the thrust generation. The operation life of the actuator is estimated for underwater operation and analyzes the various parameters and their relation with PPy actuator performances to find the primary controlling parameters. Finally, the present actuator is compared with existing smart material based underwater actuator to study the feasibility of the actuator. From the present study, it can be believe that the proposed PPy actuator propulsor is suitable for underwater bio-inspired robotics motion and may use for various applications like scanning, surveillance and exploration.

1. Introduction
Polypyrrole (PPy), an Electroactive Conducting Polymer has emerged as smart materials due to its promising combination of properties like light weight, flexibility, metal like conductivity and actively changes its shape and size upon applying electric potential. Further its similarity with natural muscle in terms of working and performances makes it potential candidate for used as biomimetic artificial muscle material based sensor, actuator and energy harvesting systems [1-4]. Including the, the large bending displacement and high work density makes it suitable for underwater bending and propulsion systems [5-9]. Although the PPy actuator has been developed for various macro to micro scale underwater applications, miniaturized mobile swimming robots has gained attention for scanning, surveillance, exploration and mapping of largely unknown underwater environment. For a real time mobile robot, an efficient propulsion system is essential as it primarily affect the desired speed, thrust and manoeuvrability. It is believed the smart materials particularly Polypyrrole actuator based propulsor may achieve the goal by developing efficient underwater propulsive system.

Polypyrrole is an organic polymer with ring like conjugated structure having alternate double bonds which facilitate the mobile ions hence exhibit conductivity. One applying electric potential to Polypyrrole, the electrons move out from the PPy matrix due to oxidation and simultaneously the ions from the surrounding electrolyte enter into the PPy matrix due to reduction to make it neutral. Due to
the simultaneous oxidation-reduction reaction, the PPy experiences the volumetric change which leads to generate mechanical output. By using this working mechanism, if a strip like actuator with one end fixed, the actuator experience cantilever like bending behaviour which may analogous to fish tail like movement. Earlier work shows that by adopting this bending behaviour, various PPy based actuator has been developed for underwater mobile robots [10-14].

As per the available literature, at first the underwater operation of PPy actuator is experienced by developing a crab like underwater robot [15] but it is limited to operate only in propylene carbonate. Then a fish like underwater robot has been developed by using trilayer PPy actuator which can operate in salt water for long time however it has very low speed of 1-2mm/sec [16]. Similarly various bio inspired (Tadpole, Snake, Eel, Jellyfish, Tuna etc) underwater robots like have been designed and developed by using PPy actuator [9-16] for wide range of applications. Recently a PPy based swimming robot is limited to certain type of electrolyte solution and exhibited low life cycle [17]. It has been observed that either of the model has at least one of the major limitations like speed, thrust, low bending displacement in non electrolyte medium, slow response, low life and high cost, which restricts their real time application and commercialization till now.

The present work is focuses on estimation and study of underwater bending, hydrodynamic and propulsion performances and behavior of Polypyrrole actuator fabricated in laboratory. At first, the PPy actuator is fabricated by electrochemical polymerization and layer by layer deposition technique. Following that, the underwater bending experiment is demonstrated in an open face water tank to estimate the bending displacement, tip force, thrust, speed, power consumption and efficiency of PPy actuator and study their correlations with material properties like stiffness. Also find the primary controlling or tuning parameter which affects the work output and efficiency of the actuator. Finally estimate the life cycle of the actuator and compared the present actuator performances with published results on performances of existing actuator to show its feasibility for underwater operations.

2. Synthesis and Fabrication of PPy Actuator

This section briefly discusses the materials and methods are used in PPy actuator fabrication followed by the suitable configuration of actuator.

2.1 Actuator Configuration

The structure of the actuator is fabricated here as a trilayer strip actuator as trilayer actuator as the rate of actuation is faster and bidirectional bending occur in trilayer actuator [16]. Hence the trilayer actuator regarded as bimorph actuator. The bidirectional bending is analogous to fish tail like movement hence suitable for underwater mobile robots. The configuration of present actuator is shown in Fig.1. In this trilayer, the middle layer is a poros membrane used as solid polymer electrolyte (SPE) as it traps electrolyte during synthesis process, hence can be used in any non electrolyte fluid medium. The top and bottom layers are PPy layer which acts as working and counter electrode during operation. The interface between SPE and PPy layers are made conductive to maintain the voltage across the actuator during operation. On applying electric potential at one end of PPy actuator, the ion exchange occur between SPE and PPy layers generates strain and induces bending in strip actuators.

2.2 Material Required

Pyrrole (Py) (pure grade), Sodium Dodecyl-benzene-sulfonate (NaDBS) (reagent grade), MilliQ Deionized water, PVDF membrane (110 µm thickness), Gold (Au) All the materials are purchased from Sigma-Aldrich except Gold (Au) (Tanishq, India) and experiments were carried out in IIT Guwahati, India.

2.3 Fabrication Method

The fabrication process starts with Gold coating (5000A°) of PVDF membrane by using Vacuum Coating Technologies. This coating maintains the porosity and uniform voltage distribution throughout the actuator. The vacuum coating method is cheap as compared to sputter coating method
which helps to lower the fabrication cost. As the pyrrole is a volatile liquid, distilled and stored in a dark and low temperature place prior to use.

For fabricating the PPy actuator, layer by layer electrochemical synthesis and deposition method has been adopted as the fabrication parameters can be controlled and tuned unlike the single layer continuous deposition method [18-19]. The synthesis is carried out in a 3 – electrode electrochemical setup (Gamry Inc) where the Au-PVDF membrane would be act as working electrode where PPy will be deposited. The Glassy carbon and Ag/AgCl are used as counter and reference electrode respectively. All the three electrodes are suspended vertically in the electrochemical cell and the others ends were connected to the Potentiostat/Galvanostat and PC. It should be ensure that the electrodes are placed at equidistance position firmly and there should not be any movement during synthesis. After the complete setup the electrochemical solution, a mixture of separately prepared aqueous solution of each of Pyrrole and NaDBS pour into the cell slowly. A constant current density of 0.15 mA/cm$^2$ is supplied to the electrochemical setup in room temperature (22°C-30°C) for nearly 3 h. The same process is followed for five times with freshly prepared solutions alternatively the total fabrication process is carried out in five individual layers of deposition unlike continuous deposition for 15 h. Finally, the PPy deposited working electrode is removed from the electrochemical solution, rinsed thoroughly with water to remove bulk polymerizations, dried and stored in a glass box at room temperature. The final product is a trilayer PPy actuator (PPy-Au/PVDF-PPy) having thickness of 150 μm. Tough the thickness of each layer is nearly 23 μm, nearly 2 – 3 μm thickness of each side PPy layer insert into the PVDF layer during synthesis process. The final product obtained from fabrication process is shown in Fig.2.

3. Experimental Techniques for Characterization

In this section, the experimental methods and setup have been used for studying hydrodynamic performances of PPy actuator is explained in detail. Prior to the experiment the PPy actuator is cut into the desired dimension of $40 \times 8 \times 0.15 \text{ mm}^3$ where the free length and the portion fixed with electrode is 35 mm and 5 mm respectively. Hence the dimension of the actuator $35 \times 8 \times 0.15 \text{ mm}^3$ is considered for bending experiments.

3.1 Modulus of PPy Actuator

At first the modulus and stiffness of the actuator is estimated from dynamic mechanical analysis (DMA) as PPy is exhibited viscoelasticity. The DMA (EXSTAR DTMA /SS 6000, SII Seiko Instrument Inc) test is conducted in open environment in tensile mode with the frequency 0.1 Hz and constant heating rate at 2°C/min [20].
3.2 Hydrodynamic Bending and Propulsion Characterization

The underwater bending displacement and tip force are calculated from underwater bending operation experiment carried out with in-house setup as shown in Fig. 3. The actuator is placed inside a quiescent water tank having dimension 75x60x60 cm$^3$. One end of the actuator is fixed while the other end is free like a cantilever beam. The fixed end is connected with voltage source which is connected to the function generator and PC. A rotational laser vibrometer (RLV-5500, Polytec, GmbH) and a high speed camera (SONY Cybershot) with ImageGrab software is used to estimate the hydrodynamic parameters. The load cell will be used for thrust measurement and a sharp needle will place behind the actuator tip to block the bending and measure tip force. The bending experiment is recorded with high speed camera of 100 fps to study the bending motion of the PPy actuator.

![Schematic Diagram of laboratory setup for underwater bending experiment.](image)

The sinusoidal voltage is used to generate cyclic bending in the actuator. The bending displacement and tip force is recorded for 1.3V of amplitude [18] with a range of frequencies of 0.1Hz ~ 10Hz.

Power Consumption by the actuator can be estimated by carried out the bending experiment in air as well as in water medium with same input voltage. In the underwater experiment the laser sensor is measured the tip displacement and an oscilloscope is used to plot the graph for tip displacement. From the oscilloscope data recorder, the input voltage and output current of PPy actuator during underwater experiment is recorded. By using this voltage and current the average power consumption of PPy actuator is calculated by using the formula [21], as follows

\[
\bar{P} = \frac{1}{f} \int_{t_r}^{t_r+4/f} (V_i I_o) dt
\]

Where $\bar{P}$ is the average power consumed by PPy actuator for underwater bending, $t_r$ is any random time during PPy actuator operates in underwater medium, $V_i$ is the input voltage and $I_o$ is the output current, $f$ is the frequency of operating voltage.

The effectiveness of the PPy actuator propulsor is estimated quantitatively from the ratio of average thrust generated to average power requirement for one cycle of actuation [22].
4. Results and Discussion

4.1 Modulus of PPy Actuator

The modulus of PPy actuator obtained from DMA analysis is shown in Fig 4. The storage and loss modulus varies with temperature and hence time. It has shown as temperature rises more than 90°C the modulus is gradually decreases hence it can be believe that the PPy actuator operates effectively in underwater environment with storage elastic modulus nearly 320 MPa. The loss or viscous modulus is nearly 5MPa while the loss factor is nearly 1 which shows its viscoelastic property. The viscoelastic behavior of the PPy actuator has shown good agreement with the published results and it has been seen the modulus is significantly high which makes it suitable for underwater operation [17,23].

![Fig. 4 Visco-elastic modulus Vs Temperature (left) and Vs Frequency (right) of the PPy actuator](image)

4.2 Hydrodynamic Bending Performances

The bending displacement and force are measured for a time period of 25 sec with voltage amplitude of 1.3V as shown in Fig. 5(a). As the input voltage is sinusoidal, the displacement and force is also sinusoidal in nature. The maximum bending displacement recorded as 5.4mm and force is 4.2Nm extracted from the video recording which is same as the displacement obtained in our previous work with DC voltage [18]. From the frequency response data of bending experiment as shown in Fig.5(b), the displacement amplitude and magnitude of force is estimated is same as recorded by camera.

![Fig.5 Bending performances of the PPy actuator with AC voltage in underwater medium](image)
Further it has been seen the displacement and force is maximum nearly at 1Hz and it decreases with increase in frequency. At higher frequency the ions cannot reach upto the depth of polymer chain while at lower frequency it takes a lot of time to reach the depth, hence the strain is less and PPy actuator exhibit

### 4.3 Propulsive Performances

Although recently various smart material actuators based propulsion systems have been developed for underwater applications, bio-inspired actuators are still under research. PPy actuator based propulsor can be used as efficient bio-inspired propulsor as it exhibited promising hydrodynamic bending displacement. The primary propulsive performance i.e. thrust force is measured with respect to time and frequency as shown in Fig. 6. The maximum thrust is measured as nearly 1mN and average thrust is obtained as 0.84mN and the trends has shown good agreement with the existing actuator. The frequency response of thrust has revealed that the dominant resonance is at 1Hz and this frequency the maximum thrust can be observed. Further it can be observed that at zero displacement the thrust is also zero and the thrust frequency is twice of actuation frequency. The thrust is follow the same behaviour as the displacement i.e. one can observe the maximum thrust nearly at the displacement peak and the phase lag is same as of displacement with input voltage.

![Thrust force Vs Time for PPy actuator](image1)

(a)Thrust force Vs Time for PPy actuator

![Thrust force Vs operating frequency](image2)

(b) Thrust force Vs operating frequency

Fig.6. Propulsive performance of PPy actuator in water medium with operating time and frequency

The power consumption of PPy actuators is primarily dependent on the input voltage, size of mobile ion due to which the actuation occurs. The actuation voltage of the PPy actuator is found as 0.54 V but at this voltage the redox reaction is very slow which generates very low displacement. However the maximum and steady displacement is produced at a voltage of 1.3V and 1Hz, beyond this point the performances are not steady due to loss of material leads to increases the output current, hence the power consumption increases. The power consumption is calculated as average power as the data recorded for eight to ten actuation cycle to enhances the accuracy. The resulting power consumption for the PPy actuator is shown in Fig. 7. With the increase in frequency, the power consumption increases subsequently lowering the performance of the PPy actuator.

The effectiveness of the PPy actuator propulsor shows the good agreement and significantly improved as compared to the earlier developed EAP actuators [15, 21, 22, 24-29]. Tough the effectiveness is primarily depending upon thrust and power consumption; it varies with the frequency of operating voltage.

From the present study it can be summarized that, the bending and propulsive performances of the actuator can be monitored and controlled by controlling the frequency alone and it will help to develop precise control system for any real time applications.
5. Conclusion

This paper presents the hydrodynamic bending behavior and propulsive performances of a PPy actuator by performing underwater bending experiment. The actuator is fabricated by using electrochemical polymerization and layer by layer deposition method. The important parameters for underwater operation such as modulus, tip displacement, blocking force and propulsion performances like thrust force, power consumption and effectiveness of the PPy actuator have been estimated and shown the feasibility of the PPy actuator to operate in fluid particularly in water medium.

The specific outcomes of the present works are as follows.

- An efficient underwater operated PPy actuator is fabricated from aqueous solution of Pyrrole (Py) and Sodium dodecyl-benzene-sulfonate (NaDBS).

- The PPy actuator shows viscoelastic nature with elastic modulus of 320 MPa which makes it suitable for underwater operation.

- The actuator is exhibited significantly large underwater bending displacement of 5.4 mm and tip force of 4.2 mN upon applying sinusoidal input voltage amplitude of 1.3 V and frequency of nearly 1 Hz.

- The present actuator can generate maximum thrust force upto 1mN and average thrust of 0.84 mN, may be effectively used in small mobile robot for underwater operations.

- The PPy actuator developed here consumes very low power and hence shows highly effective for underwater operation.

- The frequency response analysis shows, the hydrodynamic performance parameters are varies according to the input voltage frequency, hence it can be used as the primary control parameter to monitor.

It has been seen that the behaviors of the present actuator good agreement and the performance parameters follow the similar trends with the earlier developed actuators. The data obtained here has been validated with the published work. The present actuator has shown the improved performances hence may extend its application in underwater mobile robots for scanning, surveillance and exploration.
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