DEVELOPMENT AND CHARACTERIZATION OF THE IONIC POLYMER METAL COMPOSITE ACTUATED CONTRACTILE WATER JET THRUSTER

by

MUHAMMAD FARID BIN SHAARI

Thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

February 2017

ACKNOWLEDGEMENTS

First of all I would like to express my gratefulness to Allah the Almighty which make me able to finish this project successfully. I would like to dedicate my sincere gratitude and thankful to my supervisor, Associate Professor Dr. Zahurin bin Samad who had supervised me along this time. His passions, guidance and continuous support for this project had led to the accomplishment of my studies. His efforts are muchly appreciated. Secondly, I would like to thank all the supporting staffs, Mr. Norijas Abd. Aziz, Mr. Mohd Ali Shabana Mohd Raus, Mr. Mohd Ashamuddin Hashim, Mr. Hashim Md. Nordin and Mr. Rosnin Saranor who had guided me in dealing with technical stuffs as well as procurement process as well as to all my colleagues; Dr. Cham Chin Long, Mr. Muhammad Alif Rosly, Mr. Muhammad Husaini Abu Bakar, Mr. Lim Chong Hooi and Mr. Ameer Mohamed Abdeel Aziz Mohamed Hanafee who had spent time together in sharing the knowledge and finding the solutions.

I am also would like to thank and address my appreciation to Malaysian Government for providing the IPTA Academic Training Scheme (SLAI) scholarship and Universiti Sains Malaysia for financial support of this project under the Exploratory Research Grant Scheme (ERGS) 2011 (Grant no.: 203/PMEKANIK/6730008). Finally I would like to thank my beloved wife for her continuous support and great sacrifices, my children who always inspired me to complete my studies and also to my family for their supports and prayers. Alhamdulillah.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC	Alternating current
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
AUV	Autonomous Underwater Vehicle
BCA-O	Body/Caudal Actuation-Oscillatory
BCA-U	Body/Caudal Actuation-Undulatory
CAD	Computer Aided Design
CFD	Computational Fluid Dynamic
CNT	Carbon nanotube
CP	Conductive polymer
CWJT	Contractile water jet thruster
DAQ	Data acquisition
DC	Direct current
DE	Dielectric elastomer
DI	Deionized water
DOE	Design of Experiment
DOF	Degree of Freedom
DPIV	Digital Particle Image Velocimetry
EAP	Electro active polymer
EVA	Ethylene Vinyl Acetate
EW	Equivalent weight
FDM	Fused Deposition Modelling
FEA	Finite Element Analysis
gf	Gram force

IPMC	Ionic Polymer Metal Composite
JET	Water jet propulsion
MPA-O	Median/Paired Actuation-Undulatory
MPA-U	Median/Paired Actuation-Oscillatory
PTFE	Polytetrafluoroethylene
ROV	Remotely operated vehicle
SEM	Scanning electron microscope
SMA	Shape memory alloy

LIST OF SYMBOLS

$\frac{\partial V}{\partial t}$	Volume changes in time
μ	Dynamic viscosity of the fluid
A_{AUV}	Fluid-AUV contact area
A_c	Contact area of the actuator on the CWJT
A_n	Nozzle aperture
BL/s	Speed unit in Body-Length per second
C_D	Drag coefficient
C_T	Capacitive ion transduction
D_n	Nozzle diameter
E	Young Modulus
eq	Ion exchange capacity
EW	Equivalent weight
$\mathcal{E}_0$	Lever deformation
F_B	Blocking force
F_b	Reaction force from the body of the CWJT
f_c	Contraction frequency
F_c	Contraction/Actuation force
F_D	Drag force
f_i	Input frequency
F_{wj}	Reaction force from the contraction
Hz	Frequency unit, Hertz
h	IPMC thickness
I	Second moment inertia
k_b	Constant of CWJT body

L	IPMC actuator length
L/D	Length over diameter ratio
L_e	Maximum distance of the ejected fluid
L_l	Length of the force to the strain gage
L_n	Length of the nozzle channel
m_e	Ejected fluid mass
$\dot{m}_e$	Mass flow rate of the ejected fluid
m_i	Initial fluid mass
p	Distributed load of the IPMC
P_{act}	Actuation pressure (Applied pressure by IPMC on CWJT)
P_c	Contraction pressure (inside CWJT)
P_s	Static pressure
P_T	Total pressure
q	Dynamic pressure
Q	Fluid volumetric flowrate
Re	Reynolds number
R_h	Hydrodynamic resistance
R_n	Nozzle radius
R_p	Resistance across the Nafion
R_s	Resistance between electrode and Nafion
R_{ss}	Surface resistance of the IPMC
S	IPMC actuator bending displacement
S_{max}	Maximum IPMC actuator bending displacement
T	Oscillation period
t_c	Contraction time

t_e	Time taken to reach the maximum distance of the ejected fluid
T_f	Thrust
u_b	AUV velocity
u_j	Average jet velocity
V_c	Contraction volume or ejected fluid volume (mm^3) at certain time
V_s	Supply voltage (v)
V_{max}	Maximum contraction volume (mm^3)
$\dot{V}_f$	Contraction volume rate
v_{AUV}	AUV velocity
v_e	Ejected fluid velocity
v_i	Initial fluid velocity
v_k	Kinematic viscosity of water
v_{osc}	Oscillation speed
W	Width of the contraction volume
w	Width of IPMC actuator
Z	Moment second area
Z_w	Nafion induction
α	IPMC actuator bending angle
β	CWJT contraction angle
δ	CWJT mantle displacement
ΔP	Pressure drop
π	pi (3.142)
ρ_f	Fluid density
ρ_w	Water density
$\bar{y}$	Distance between centroid of affected zone and the axis of rotation

PEMBANGUNAN DAN PENCIRIAN PENUJAH JET AIR MENGECUT GERAKAN KOMPOSIT POLIMER – LOGAM BERION

ABSTRAK

Komposit Polimer-Logam Berion (IPMC) merupakan salah satu bahan pintar yang boleh digunakan sebagai penggerak untuk Penujah Jet Air Mengecut (CWJT) yang merupakan penujah jet air alternatif untuk kenderaan bawah air berautonomi (AUV). Kelebihan penggerak IPMC adalah ianya ringan, fleksibel, boleh digunakan dalam air dan memerlukan voltan yang rendah. Walaubagaimanapun daya gerak IPMC yang rendah menghadkan penjanaan daya tujah. Oleh demikian, kajian ini dijalankan untuk menyiasat sifat aliran bendalir yang terhasil daripada gerakan IPMC ke atas CWJT. Siasatan ini meliputi pemerhatian terhadap hubungkait di antara beberapa faktor yang mempengaruhi penghasilan daya tujah seperti saiz muncung jet, bekalan tenaga untuk IPMC dan frekuensi gerakan IPMC. Kajian ini melibatkan kerja-kerja merekabentuk konsep prototaip penujah, fabrikasi dan mencirikan penggerak IPMC, simulasi keadaan bendalir pada rekabentuk prototaip dan juga beberapa ujikaji untuk penentusahan data. Hasil ujikaji dan penentusahan data menunjukkan saiz muncung jet dan frekuensi penggerak merupakan faktor utama dalam pembangunan penujah jet air yang digerakkan oleh IPMC. Frekuensi penggerak yang sesuai adalah di bawah 0.1 Hz. Sebarang nilai frekuensi melebihi 0.1 Hz akan mengurangkan keupayaan pengecutan CWJT. Daya tujahan maksima yang dicapai dalam penyelidikan ini adalah 4.52 mN pada bekalan kuasa sebanyak 6 V. Ini tidak sesuai untuk AUV yang berat dan mempunyai panjang lebih dari 1 m. Walau bagaimanapun, ia sesuai untuk AUV kecil atau AUV mikro yang beroperasi dalam air yang berarus rendah.

DEVELOPMENT AND CHARACTERIZATION OF THE IONIC POLYMER METAL COMPOSITE ACTUATED CONTRACTILE WATER JET THRUSTER

ABSTRACT

Ionic Polymer Metal Composite (IPMC) is a type of smart material that can be utilized as the actuator for contractile water jet thruster (CWJT) which is an alternative thruster for autonomous underwater vehicle (AUV). The advantages of IPMC actuator are light, flexible, able to be utilized underwater and consuming low voltage. However, IPMC low actuation force has limited the thrust generation. Hence, this research had been conducted to investigate the character of the fluid flow generated by the IPMC actuation on the CWJT. This investigation includes the observation on the relation of few factors that influence the thrust generation such as the nozzle aperture size, supply voltage for IPMC actuation and actuation frequency. This research consists of designing the conceptual prototype thruster, fabricating and characterizing the IPMC actuator, simulating the fluid flow of the prototype design and few experiments for data validation. The results and validation from the experiments showed that nozzle aperture size and actuation frequency of the IPMC actuator were influential factors in the development of IPMC actuated CWJT. The feasible actuation frequency was 0.1 Hz. Any higher frequency than 0.1 Hz would decline the CWJT contraction performance. The maximum thrust achieved in this research was 4.52 mN at 6 V supply. It is not feasible for heavy and more than 1 m long AUV. However, it suits for small or micro AUV that works in low current waters.

CHAPTER ONE

INTRODUCTION

1.1 Background

The development of autonomous underwater vehicle (AUV) is simply driven by three major lines of motivation; the underwater biodiversity exploration, environmental ecology concern and the current fast growing sub-ocean industry (Yuh, 2000b; Roper et al., 2010). The related task that requires AUV service regarding these domain of activities including underwater research, oil and gas exploration, underwater construction, water quality monitoring, military activities, sub-ocean mining and eco-tourism. The working environment and nature of the task has determined the design of the AUV. For instance, a linear motion seabed topography scanning requires a torpedo shape AUV design for minimal drag influence. On the other hand, three dimensional seabed pipeline monitoring would utilize a 6 Degree of Freedom (DOF) box shaped AUV design because it has more manoeuvrability and linear speed locomotion is not a priority (Guo et al., 2010; Shi et al., 2013). Meanwhile, Yue et al. (2015) and Guo et al. (2016) had designed and developed a spherical AUV which has the advantage in manoeuvrability, flexibility and outstanding shock resistance.

One of the current trend in the AUV development and has become great attention from many researchers is the small scale AUV that is able to do sensing and observation tasks in various dimension and complex structure (Curtin et al., 2005; Lin and Guo, 2012). In addition, by applying swarm AUV sensing technique, 3D data could be recorded and thus would give a better comprehension on the ongoing investigation (Vasilescu et al., 2005; Campos and Codina, 2015). However, though the AUV technology had been developed since 1960's, researchers and engineers are still struggling to achieve the ultimate swimming performance under the conventional design AUV which is trading off the speed and manoeuvrability of the AUV (Roper et al., 2010). Furthermore, for a small scale sensing AUV which has limited space for energy supply means shortage of operation time. Another concern is the noise from the conventional electric motor is unnecessary. All these constraints had shifted the researchers to the out-of-the-box solution; by getting the inspiration from the nature for design outcome and promoting new actuation techniques (Shi et al., 2013).

Naturally, aquatic animals such as fish, squid and eels are excellent swimmers with high propulsion efficiency in term of both speed and manoeuvrability (Yu et al., 2005). Without rotating propeller, fish for instance manages to move at fast speed (up to 65mph for sailfish) and able to accelerate at difficult angle either to catching its prey or escaping away from its predators (Hingham, 2007). Besides, those aquatic animals manage to move in near silent motion. Ability to move stealthily is a vital characteristic for predator fish. In order to achieve the optimum propulsion efficiency at high manoeuvrability degree and lower drag, researchers had imitated these aquatic animal swimming principles in their AUV design (Chu et al., 2012). This non conventional AUV is known as bio-inspired or biomimetic AUV. In general, there are three main classifications for aquatic animal swimming mechanism which are;

i. Oscillating
ii. Undulatory
iii. Jet propulsion

There are few subcategories between the oscillating and undulatory swimming mechanism or propulsion system as depicted in Figure 1.1 (Colgate and Lynch, 2004).

Almost all aquatic vertebrates such as fish, eels and quite large number of reptile species such as snake, crocodile and iguana utilize oscillating and undulatory swimming mechanics. Only few invertebrates such as squid, jellyfish, octopus and nautilus apply the water jet locomotion. Unlike the oscillating and undulatory swimming mechanism, the water jet propulsion is based on impulse.

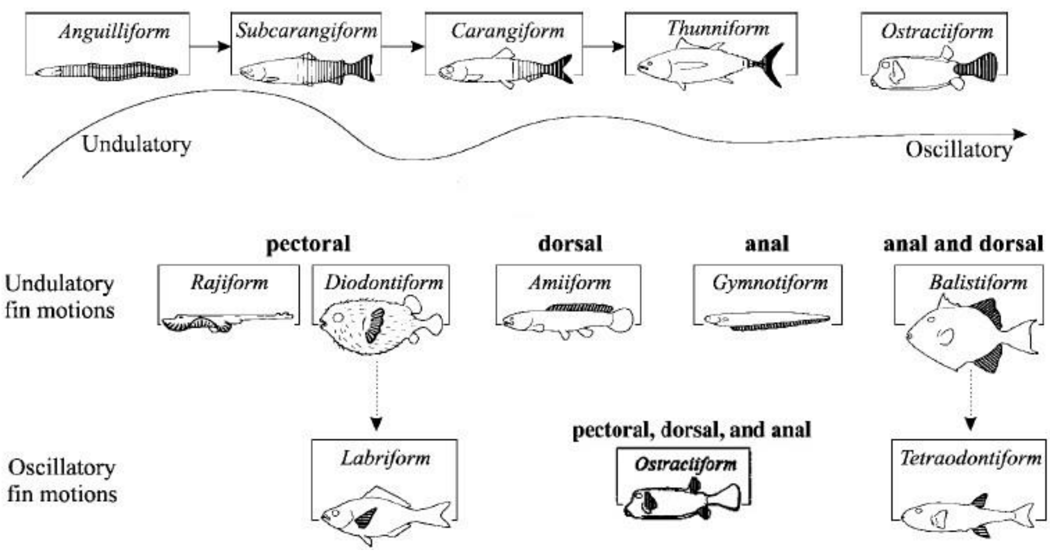

Figure 1.1: Classification of Swimming Mechanism (Colgate and Lynch, 2004)

This impulse is generated from pressurized fluid. Currently, most of the small scale water jet propulsion system is driven by electric motor. The obvious difference between the squid water jet mechanism and the motor powered water jet mechanism is the fluid compression technique. The squid generates water jet pressure using body contraction while the motor powered water jet applies rotary blade compression without body deformation. The utilization of rotary blade compression in commercial thrusters generates noise while the blade propeller induces cavitation in most of the condition and would be harmful for underwater creatures (Wang et al., 2011). The electric motor itself, contribute unnecessary load. Body contraction water jet which is applied by the squid, compresses the fluid by reducing the mantle volume. This contraction is not a continuous process but it is an intermittent process. Thus, the contraction frequency has significant influence on the thrust efficiency. There are few option of actuators that can be utilized to perform the intermittent contraction. In addition to the contraction frequency, contraction force, water inlet and water outlet opening are another few parameters that must be considered to achieve the optimum thrust efficiency.

Hence, in this research the main goal is to developed contractile water jet thruster (CWJT) and conduct parametrical studies to investigate its performance as a thruster for small AUV. A suitable actuator which is more silent, light and compatible to the sensing measurement condition will be adapted. Based on preliminary studies, there are few options of actuators that could be utilized to substitute the fluid compression techniques which is driven by blade – motor integration. The potential actuators would be pneumatic based actuators and smart material actuators. Though the air is compressible and the actuators could be miniaturized, a complete pneumatic system require air reservoir, compressor and control valve which are too bulky for small scale AUV (Nishioka et al., 2011). Smart material actuators seems likely to fit in the actuation system. However, there are numbers of smart materials with various actuation characteristics and input requirements (Mikhrafai et al., 2007).

Basically, smart material is a man-made material that has one or more properties that is being changed due to external inputs such as electric, electromagnetic fields and light (Chopra, 2002). This characteristics had made smart material as an option to fabricate actuators and artificial muscle. Though there is no specific category for this smart material actuators yet, this actuators could be recognized by its based materials, which are metal based, ceramic based and polymer based. Shape Memory Alloys (SMA) is one example for metal based smart material and piezoelectric material is a kind of ceramic based smart material. Dielectric elastomer (DE), Conducting Polymers and Ionic Polymer Metal Composite (IPMC) are few examples for polymer based smart materials. Based on the requirement, IPMC had been selected as the potential actuator for the CWJT. IPMC requires low driving voltage, flexible and able to work underwater (Shahinpoor and Kim, 2001). However, the main challenge for this research is mainly comes from the limitation of IPMC whereby the actuation force is between 1.0 gf and 8.0 gf per actuator, depending on the dimensional geometry (Shahinpoor and Kim, 2001). The research works would involve the design and development of CWJT using smart material actuator and investigating the water jet generation performance at different inputs.

1.2 Problem Statement

Currently most of the commercial thruster available in the market for AUV is developed based on electric motor powered rotary blade. The combination of electric motor and the rotary blade along with batteries requires a rigid and stiff AUV body structure to support those items. Basically, rotary thruster produces thrust in one straight direction which represents one axis of motion. Generally, there are three axis of motions for AUV locomotion which are forward – backward motion or surge, upward – downward motion or heave and right – left motion or sway (Benetazzo et al. 2015). Therefore, to perform these motions AUV will be equipped with at least three thrusters. Rotational motion at every axis which are the roll, pitch and yaw requires another three thrusters. Though this thrusters increases the manoeuvrability degree of