F0685 1/2012

BORANG FRGS – P3(R)

KEMENTERIAN PENDIDIKAN MALAYSIA

FINAL REPORT
FUNDAMENTAL RESEARCH GRANT SCHEME (FRGS)

Laporan Akhir Skim Geran Penyelidikan Fundamental (FRGS)
Pindaan 1/2015

A

RESEARCH TITLE: Modeling of Radial Contraction of Ionic Polymer Metal Composite (IPMC) Actuated Cylindrical Micro Pump

PHASE & YEAR: 1/2012

START DATE: 1 Jun 2012
END DATE: 31 Mei 2014
EXTENSION PERIOD (DATE): RMC LEVEL:
KPM LEVEL:

PROJECT LEADER: Prof. Madya Dr. Zahurin bin Samad
I/C / PASSPORT NUMBER: 660528-10-6879

PROJECT MEMBERS: 1. Dr. Elmi bin Abu Bakar
(including GRA) 2. Muhammad Farid bin Shaari

Project No: 203/PKMEKANIK/6071237

PROJECT ACHIEVEMENT *(Prestasi Projek)*

B

ACHIEVEMENT PERCENTAGE			
Project progress according to milestones achieved up to this period	**0 - 50%**	**51 - 75%**	**76 - 100%**
Percentage (please state #%)			100%

RESEARCH OUTPUT		
Number of articles/ manuscripts/ books *(Please attach the First Page of Publication)*	**Indexed Journal**	***Non-Indexed Journal***
	4	None
Conference Proceeding *(Please attach the First Page of Publication)*	**International**	***National***
	5	None
Intellectual Property *(Please specify)*	None	

Windows XP Printer Test Page

Congratulations!

If you can read this information, you have correctly installed your HP Universal Printing PCL 6 on IQRAM-PC.

The information below describes your printer driver and port settings.

```
Submitted Time:  10:34:09 AM 31/05/2016
Computer name:   IQRAM-PC
Printer name:    \\IQRAM-PC\hp color LaserJet 5550  UPD PCL 6
Printer model:   HP Universal Printing PCL 6
Color support:   Yes
Port name(s):    DOT4_001
Data format:     RAW
Share name:      HP Color LaserJet 5550  RCMO
Location:
Comment:
Driver name:     unidrv.dll
Data file:       hpcu1606.gpd
Config file:     hpmdp160.dll
Help file:       unidrv.hlp
Driver version:  6.00
Environment:     Windows NT x86
```

```
Additional files used by this driver:
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\hpcui160.dll
(61.160.01.17508)
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\hpcpe160.dll
(61.160.01.17508)
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\hpc6r160.dll
(61.160.01.17508)
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\hpcdmc32.dll        (1, 580, 1,
24357)
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\hpbcfgre.dll        (1, 580, 1,
24357)
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\hpcpu160.cfg
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\hpc6m160.gpd
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\hpcsm160.gpd
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\hpcu1606.xml
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\hpcsc160.dtd
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\hpcu160c.ini
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\hpcst160.dll
(61.160.01.17508)
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\hpcur160.dll
(61.160.01.17508)
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\hpcev160.dll
(61.160.01.17508)
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\pclxl.dll   (6.0.5479.0
(vbl_wcp_d2_drivers.060616-1619))
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\pjl.gpd
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\pclxl.gpd
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\hpchl160.cab
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\unires.dll  (6.1.7601.17514
(win7sp1_rtm.101119-1850))
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\unidrvui.dll        (6.1.7601.21853
(win7sp1_ldr.111102-0703))
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\stdnames.gpd
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\stddtype.gdl
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\stdschem.gdl
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\stdschmx.gdl
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\hpcls160.dll
(61.160.01.17508)
```

HUMAN CAPITAL DEVELOPMENT

Human Capital	Number				Others (please specify)
	On-going		Graduated		
Citizen	Malaysian	Non Malaysian	Malaysian	Non Malaysian	
No. PHD STUDENT	1				
Student Fullname: IC / Passport No: Student ID:	Muhammad Farid Bin Shaari 790722045163 P-CD0097				
No. MASTER STUDENT			1		
Student Fullname: IC / Passport No: Student ID:			Muhammad Aliff Bin Rosly 861217435721 P-CM0015/13(R)		
No. UNDERGRADUATE STUDENT			3		
Student Fullname: IC / Passport No: Student ID:			CH'NG JIN JUN 901120075401 104585 SAW SIONG KEAT 890418075243 104614 BEH RUI HENG 920726075637 111516		
Total	1		4		

EXPENDITURE *(Perbelanjaan) as Borang K1(RMC)*

C

Budget Approved *(Peruntukan diluluskan)*	:	**RM 46,000.00**
Amount Spent *(Jumlah Perbelanjaan)*	:	**RM 29,702.17**
Balance *(Baki)*	:	**RM 16,297.83**
Percentage of Amount Spent *(Peratusan Belanja)*	:	64.6 %

ADDITIONAL RESEARCH ACTIVITIES THAT CONTRIBUTE TOWARDS DEVELOPING SOFT AND HARD SKILLS *(Aktiviti Penyelidikan Sampingan yang menyumbang kepada pembangunan kemahiran insaniah)*

D

International

Activity	Date (Month, Year)	Organizer
International Conference on Robotics, Biomimetics, Intelligent Computational Systems.	25-27 November 2013	Institute of Electrical and Electronics Engineers
4th International Conference on Underwater System Technology: Theory and Applications	5-6 December 2012	Universiti Sains Malaysia

National

Activity	Date (Month, Year)	Organizer
(e.g : Course/ Seminar/ Symposium/ Conference/ Workshop/ Site Visit)		

****
*** TX REPORT ***
****

TX IMAGE SET NOT TO DISPLAY

JOB NO.	3002	
ST. TIME	31/05 10:39	
SHEETS	1	
FILE NAME		
TX INCOMPLETE	-----	
TRANSACTION OK	-----	
ERROR	\\10.201.53.144\CanonScan	Irni

E	**PROBLEMS / CONSTRAINTS IF ANY** *(Masalah/ Kekangan sekiranya ada)*
	There is balance of RM 16,297.83 because some equipment including Load cell, Amplifier, Function generator and DAQ card that have been allocated in Vot 35000 were not purchased using this grant since the have been bought using ERGS grant 203_PMEKANIK_6730008.
F	**RECOMMENDATION (***Cadangan Penambahbaikan***)**
	None
G	**RESEARCH ABSTRACT – Not More Than 200 Words** *(Abstrak Penyelidikan – Tidak Melebihi 200 patah perkataan)*
	Utilization of active materials as micro-pump actuator had been implemented since few years ago through varieties of pump design. The usage of these active materials provides several advantages to the designed micro-pumps such as low electrical energy consumption and less mechanical system complexity. However, many of the developed micro-pumps were based on planar diaphragm model whereby the diaphragm motion actuates in opposite to the inlet and outlet valve. Hence, this research proposes a novel model of Ionic Polymer Metal Composite (IPMC) actuated micro-pump. These IPMC actuators bend towards positive polarity when an amount of voltage is supplied to them and cause the micro-pump to contract. The main goal of this research is to achieve a model of the micro-pump contraction via several investigations on parameters relation. The influential parameters include actuator's dimension, supplied voltage, supplied frequency and pressure. The results show that IPMC thickness has significant influence on the tip force generation and lower input frequency would results wider displacement. Higher supplied current would increase the thrust. By adjusting input power to the actuators, the thrust was optimized to be 113.95 mN at 37.96 mm^2 nozzle size. The recorded results are essential as future reference in developing the propulsion for the underwater robot.
	Date : 31/5/2016 *Tarikh* **Project Leader's Signature:** *Tandatangan Ketua Projek*
H	**COMMENTS, IF ANY/ ENDORSEMENT BY RESEARCH MANAGEMENT CENTER (RMC)** *(Komen, sekiranya ada/ Pengesahan oleh Pusat Pengurusan Penyelidikan)*
	....
	Name: *Nama:* PROF. DR LEE KEAT TEONG Pengarah Pejabat Pengurusan & Kreativiti Penyelidikan Universiti Sains Malaysia **Signature:** *Tandatangan:* **Date:** *Tarikh:* 3/6/16

Windows XP Printer Test Page

Congratulations!

If you can read this information, you have correctly installed your Canon iR-ADV 4045/4051 PCL6 on J06_AFZAN.

The information below describes your printer driver and port settings.

```
Submitted Time: 10:25:12 AM 31/05/2016
Computer name:  J06_AFZAN
Printer name:   Canon iR-ADV 4045/4051 PCL6
Printer model:  Canon iR-ADV 4045/4051 PCL6
Color support:  No
Port name(s):   IP_10.201.53.119
Data format:    RAW
Share name:     Printer9
Location:
Comment:
Driver name:    Cnp60M_DFBC9.DLL
Data file:      iR4045XK.XPD
Config file:    Cnp60MUI_DFBC9.DLL
Help file:      CNP61K_DFBC9.CHM
Driver version: 20.75
Environment:    Windows NT x86
Monitor:        CPCA Language Monitor2
```

```
Additional files used by this driver:
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\iR4045XK.UPD
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\CnP6FBC9.dat
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\Cnp60809_DFBC9.DLL   (20.75)
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\cnxp0log.DLL         (1.0 built by: WinDDK)
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\AUSSDRV.DLL (3, 8, 1, 0)
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\CnxDias2.DLL         (10,2,8,2819)
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\CNLK.PRF
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\CPC10S.DLL  (5.5.6.2)
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\CPC10D.EXE  (5.5.6.2)
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\CPC10Q.EXE  (5.5.6.2)
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\CPC10E.DLL  (5.5.6.2)
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\CPC10V.EXE  (5.5.6.2)
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\CPC1UK.DLL  (5.5.5.1)
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\CPC1UK.CHM
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\cnxpcf32.DLL         (2,4,0,0)
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\cnxpcp32.DLL         (2,4,9,0)
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\CnPXCM32.DLL         (3,6,6,0)
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\UCS32P.DLL  (2.2.2)
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\cnxptn32.DLL         (2.4.0.0)
 C:\WINDOWS\System32\spool\DRIVERS\W32X86\3\iR4045XK_D6865.upd
```

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Tarikh Cetakan : 10/09/2015

UNIVERSITI SAINS MALAYSIA

JABATAN BENDAHARI

PENYATA PERBELANJAAN SEHINGGA 31 DISEMBER 2013

Projek :

No. Akaun : 203.PMEKANIK.6071237.

Vot	Nama Vot	Peruntukan Projek	Perbelanjaan Terkumpul Sehingga Thn Lalu	Baki Peruntukan Tahun Lalu	Peruntukan Thn Semasa	Jumlah Peruntukan Thn Semasa	Tanggungan Semasa	Bayaran Thn Semasa	Jum Belanja Thn Semasa	Baki Projek
221	PERJALANAN DAN SARA HIDUP	1,000.00	0.00	1,000.00	0.00	1,000.00	0.00	0.00	0.00	1,000.00
227	BEKALAN DAN BAHAN LAIN	12,500.00	730.40	11,769.60	0.00	11,769.60	0.00	5,555.48	0.00	6,214.12
229	PERKHIDMATAN IKTISAS & HOSPITALITI	1,500.00	1,400.00	100.00	0.00	100.00	0.00	1,216.29	0.00	-1,116.29
335	HARTA MODAL	19,500.00	5,900.00	13,600.00	0.00	13,600.00	0.00	3,400.00	0.00	10,200.00
	Jumlah	**34,500.00**	**8,030.40**	**26,469.60**	**0.00**	**26,469.60**	**0.00**	**10,171.77**	**0.00**	**16,297.83**

Penyata ini adalah cetakan komputer tiada tandatangan diperlukan

Penyata ini adalah dianggap tepat jika tiada maklumbalas dalam tempoh masa 14 hari dari tarikh penyata

****
*** TX REPORT ***
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TX IMAGE SET NOT TO DISPLAY

JOB NO.	3004
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SHEETS	1
FILE NAME	
TX INCOMPLETE	-----
TRANSACTION OK	-----
ERROR	\\10.201.53.144\CanonScan Irni

UNIVERSITI SAINS MALAYSIA

BORANG PENYERAHAN ASET / INVENTORI

==

A. BUTIR PENYELIDIK

1. NAMA PENYELIDIK : **Prof. Madya Dr. Zahurin bin Samad**
2. NO STAF : AE50127
3. PTJ : Pusat Pengajian Kejuruteraan Mekanik
4. KOD PROJEK : 203/PKMEKANIK/6071237
5. TARIKH TAMAT PENYELIDIKAN : 31 Mei 2014

B. MAKLUMAT ASET / INVENTORI

BIL	KETERANGAN ASET	NO HARTA	NO. SIRI	HARGA (RM)
1.	Water bath		1210027	2,900.00
2.	DIGITAL WEIGHING SCALE 0.0001g-150g	AK00007044	AE428L634	3,400.00
3.	HP PAVILION SLIMLINE S5-1245D DESKTOP PC	AK00006720	4CE2250K22	2,999.00
4.	HP LCD MONITOR W2072a	AK00006722	CNC222PKOX	1.00
	Total			**9,300.00**

C. PERAKUAN PENYERAHAN

Saya dengan ini menyerahkan aset/ inventori seperti butiran B di atas kepada pihak Universiti:

....

(Prof. Madya Dr. Zahurin bin Samad) Tarikh: 10/9/2015

D. PERAKUAN PENERIMAAN

Saya telah memeriksa dan menyemak setiap alatan dan didapati :

- [X] Lengkap
- [ ] Rosak
- [ ] Hilang : Nyatakan..
- [ ] Lain-lain : Nyatakan ....

Diperakukan Oleh :

....

Tandatangan
Pegawai Aset PTJ

Tarikh: 31/5/16

*Nota :

Satu salinan borang yang telah dilengkapkan perlulah dikemukakan kepada Unit Pengurusan Harta, Jabatan Bendari dan RCMO untuk rekod

****
*** TX REPORT ***
****

TX IMAGE SET NOT TO DISPLAY

JOB NO.	3005
ST. TIME	31/05 10:46
SHEETS	1
FILE NAME	
TX INCOMPLETE	-----
TRANSACTION OK	-----
ERROR	\\10.201.53.144\CanonScan Irni

Applied Mechanics and Materials Vols. 490-491 (2014) pp 1099-1104
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doi:10.4028/www.scientific.net/AMM.490-491.1099

2D Contractile Water Jet Thruster Characterization for Bio-inspired Underwater Robot Locomotion

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[2]School of Mechanical Engineering, Universiti Sains Malaysia, 14300 Nibong Tebal, Pulau Pinang, Malaysia.

[a]mdfarid@uthm.edu.my, [b]zahurin@eng.usm.my

Keywords: Contractile water jet thruster, thrust, contraction force, mass flow rate

Abstract. This research was conducted to analyze the thrust performance generated from a two dimensional contractile water jet thruster (CWJT). The main aim of this research is to investigate the relation and reaction between the input parameters of the contractile water jet thruster. The major parameter of this study is the actuating force as the input and the thrust force as the output. In addition to these parameters, nozzle area and fluid velocity influence were also considered in the investigation. Two pneumatic cylinders were applied to actuate the contraction. Thrust force was measured by both experimentally and theoretically. Generally the increment of the contraction force increases the thrust force. However, generated thrust at different contraction force depends on the size of the nozzle.

Introduction

Contractile water jet thruster (CWJT) is being inspired by aquatic animals that utilize the water jet for its locomotion such as squid, jellyfish and octopus [1], [2]. Compared to the typical continuous water jet thruster, CWJT has a deformable body which functions as a pressure generator. Thus, the advantages of this propulsion method are including the feasibility for small underwater robot locomotion and flexibility in maneuvering [3]. Technically, the CWJT deals with fluid momentum, as the consequence from fluid volume differentiation which involves the contraction and expanding process. Some would refer the reaction from the fluid momentum as impulse, where it obeys Newton III law [4], [5]. Unlike the continuous water jet thruster, this CWJT generates the jet periodically, to ensure the fluid is fully encapsulated for a maximum thrust during contraction [6]. Hence, the main challenge to achieve the CWJT's ultimate performance is to optimize the interrelated parameters such as the contraction force, contraction frequency, thrust force, Reynolds number of the jet, fluid volume flow rate as well as nozzle area ratio, that contribute to the jet propulsion. The aim of this research is to investigate the relation between the input parameters in order to achieve the optimum thrust. However, some of the parameters had been neglected as this research focuses on thrusters for mini underwater robot application. In order to observe the morphological effect on the fluid flow behavior, a video camera was employed to record the motion of colored fluid that entered and jetted out from the CWJT. The analysis was conducted by adjusting the nozzle area, contraction force and contraction frequency. In this research, pneumatic cylinders were applied as the lateral actuators for easy control of the contraction force. The result shows that the increasing contraction force increases the thrust. However, it depends on the size of the nozzle. The thrust from measured data was compared to the thrust which was obtained from load cell measurement.

System Modeling

CWJT Design. The proposed 2D CWJT design was based on fundamental of fluid mass reduction from the contraction of a pressurized container. As the main aim of this research is to analyze the

the increment of the contraction force increases the thrust. Most of these relations are in exponential trend. However, the nozzle opening area would provide significant influence on the relation between the contraction force and the thrust. By obtaining the result of these experiments, we could expand them to a more detail optimization by utilizing the design of experiment methods. Some of the potential parameters such as the nozzle tapered angle were neglected in this research due to the design factor which deals with small scale application.

Acknowledgment

The authors would like to address their compliment to the Ministry of Higher Education of Malaysia (MOHE) for the FRGS grant sponsorship, Universiti Tun Hussein Onn Malaysia and Universiti Sains Malaysia for their technical and facilities support as well as Mr. Saw Seong Keat who contributes to the success of this research.

References

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Advanced Materials Research Vol. 983 (2014) pp 161-165
© (2014) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/AMR.983.161

Online: 2014-06-30

Characterization and Parametric Study of Multilayered IPMC Actuator

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Keywords: IPMC actuator, Actuation force, Displacement, Force-to-weight ratio

Abstract. Ionic Polymer-Metal Composite (IPMC) has been utilized as an actuator in several robotic applications such as the actuator for its locomotion and gripper of the end effector. However, due to its low actuation force which is normally less than 10gf (depend on dimension), the application has been limited to small scale robot. Hence, in this research we propose a multilayer structure of IPMC actuator and investigate the actuation force increment. Besides, parametric study was also conducted to determine the force-to-weight ratio and the bending displacement. The obtained results had been compared to single ply IPMC actuator at the same thickness. The result shows that the increment of IPMC layer had increased the actuating force up to 30% for two layers and 40% for three layers. In addition, utilizing multilayered IPMC had reduced the stiffness constraint for thicker IPMC. This finding would be useful in designing stage of a small scale robot that require higher actuation force at a higher bending displacement.

Introduction

Ionic Polymer-Metal Composite (IPMC) is regarded as one of the smart material that can be utilized either as actuator or sensing element. The key mechanism that contribute to this functions is the charge transduction within the membrane in two different conditions [1,2]. In the first condition, if the IPMC is supplied with voltage to its electrode, the free cation inside the IPMC attaches water molecules and attracted to the cathode [3,4]. As the consequence, the IPMC will physically bend towards the anode electrode (Fig. 1). Otherwise, if there is external force acts on the IPMC without external voltage, the transduction charge induces voltage at the electrode and become as a generator [4,5]. As a polymeric family member, the generated actuation force or the blocking force for IPMC is relatively small compared to metal-based smart material such as Shape-Memory Alloys (SMA). Few steps had been taken by researchers to increase IPMC performance such as enhancing the surface electrode, membrane composition as well as increasing the thickness of the IPMC actuator. Surface electrode enhancement requires additional layers on the IPMC surface such as gold, silver or silicate [6,7,8]. Membrane composition enhancement process involving polymeric molecule or ionomer molecule alterations in the membrane, for instance by adding lithium molecules to increase the strength of the osmotic pressure that cause the actuation [9,10]. Meanwhile, increasing the thickness of the IPMC is the simplest technique to increase the actuation force at lower cost compared to the previous enhancement process. However, by increasing the thickness of the actuator would reduce the curvature or bending degree [11,12]. Hence, we proposed a multilayered IPMC actuator to increase the actuation force performance. All IPMC actuators had been fabricated and the multilayered IPMC actuation had been characterized. Performance analysis had been conducted to compare the results with other enhancement techniques. There are two circuit models for the multilayered IPMC actuator which are the series circuit and parallel circuit. In this research, parallel circuit model had been selected to obtain a synchronized actuation for every IPMC strips (Fig. 2). The result showed that increment of the IPMC layer had increased the actuation force by 30%. The main difference with IPMC thickness increment is the displacement rate remains constant.

Acknowledgment

The authors would like to address their compliment to the Ministry of Education Malaysia (MOE) for the FRGS grant sponsorship, Universiti Tun Hussein Onn Malaysia and Universiti Sains Malaysia for their technical and facilities support on this research.

References

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Fabrication and Characterization of IPMC Actuator for Underwater Micro Robot Propulsor

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Keywords: IPMC, Underwater robot, Actuation force, Smart actuator

Abstract. The usage of Ionic Polymer-Metal Composite (IPMC) actuator as the propulsor for underwater robot has been worked out by many scientists and researchers. IPMC actuator had been selected due to its advantages such as low energy consumption, low operation noise and ability to work underwater. This paper presents the fabrication and characterization of the IPMC actuator. The IPMC actuator samples had been fabricated using electroless plating for three different thickness and lengths. The characterization was conducted to determine the influence of the thickness, length, input frequency, drive voltage and orientation angle on the tip force and output frequency. The results show that IPMC thickness has significant influence on the tip force generation and lower input frequency would results wider displacement. The recorded results are essential as future reference in developing the propulsor for the underwater robot.

Introduction

Ionic Polymer-Metal Composite (IPMC) is regarded as one of the smart actuator that suits as a propulsor for various types of underwater robot, especially for biomimetic and small scale underwater robot. For instance, the biomimetic underwater robots that employ IPMC actuators as their propulsor are including fish robot, jellyfish robot and lobster robot [1][2][3][4]. The main reason to this selection is because the IPMC actuator requires water molecules to operate [5][6]. Besides, IPMC actuator consumes low energy between 1V and 3V, depend of type of the task [7]. IPMC actuator has few other advantages such as low noise operation and large bending strain [8]. However, this actuator has constraints that should be considered in order to develop the underwater robot propulsor. Generally, IPMC actuator has relatively low actuating force compared to the other smart actuators. Thus, in this paper the performance of the IPMC actuator had been investigated by varying the dimension of the IPMC and the input parameters. This studies focus on basic IPMC actuator without further treatment that would surplus the fabrication cost. The variation of dimension is including the thickness and length of the IPMC. The thickness would determine the stiffness and strength of the IPMC and the length would influence the displacement and frequency of the IPMC.

IPMC Actuator

Actuation Mechanism. Basically IPMC is constructed by depositing noble metals such as platinum or gold under the base material surface [9]. The micro layer of the noble metals would act as the electrode during actuation (Figure 1). The base material such as Nafion (DuPont) and Flemion (Asahi Glass) has free mobile cation which is known as ionomer. Each ionomer has alkaline metal atom such as Li^+, Na^+ or H^+ at one of its ends that conduct positive charge (Figure 2) [9][10]. When the IPMC is submerged in the water, water molecules will be attached to this positive charge ionomer. As the electrodes are activated by supply voltage, these positive charged molecules would ionomer's alkaline metal but this work would increase the fabrication cost such as the utilization of gold plating. Most of the investigation focus on varying the dimension of the IPMC actuator and observed its relation with the targeted output. From the results, it could be concluded that increasing the IPMC thickness would increase the actuating force tremendously. Longer IPMC actuator has greater actuating force compared to the shorter one but this character needs to be traded off with the displacement. In addition, shorter IPMC actuator has higher output frequency if relatively compared to longer IPMC actuator.

Acknowledgment

The authors would like to address their compliment to the Ministry of Higher Education of Malaysia (MOHE) for the FRGS grant sponsorship, Universiti Tun Hussein Onn Malaysia and Universiti Sains Malaysia for their technical and facilities support on this research.

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2013 International Conference on Robotics, Biomimetics, Intelligent Computational Systems (ROBIONETICS)
Yogyakarta, Indonesia, November 25-27, 2013

Influence of Nozzle Size and Current Input on Thrust of the Contractile Water Jet Thruster

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Abstract—**This paper discussed the thrust characterization of the contractile water jet thruster using Ionic Polymer Metal Composite (IPMC) actuators. In this research, the effects of current input variation on the generated thrust at different nozzle size had been studied. By adjusting input power to the actuators, the optimization of the system which influenced by the nozzle opening area had been determined. The result shows the optimum thrust was 113.95mN at 37.96mm^2 nozzle size. At this small scale dimension, the optimum thrust could be obtained in average was between 35mm^2 and 40mm^2. It was concluded as well that higher supplied current would increase the thrust.**

Keywords-water jet, contractile thruster, IPMC, thrust

I. Introduction

Propulsion system is regarded as one of the vital part in designing and developing underwater robot. Currently the typical propulsion system for most of underwater robot is using blade propeller [1]. However, there are other few propulsion systems that are being under research such as the undulatory, oscillating and water jet propulsion system [2][3]. Those alternative propulsion system mimics either the aquatic animal's propulsion mechanics to generate thrust for underwater locomotion. This research focuses on the water jet propulsion system. This biomimetic system applies the accelerated fluid to produce a thrust that enables the motion. In order to study the characteristics of this propulsion system, a contractile water jet thruster (CWJT) had been developed. The CWJT generates thrust from fluid mass flowrate and being actuated at certain contraction frequency. The types of actuator would be pneumatic cylinder, piezo material actuator or smart material actuators. In this research, IPMC actuators had been selected to drive the CWJT. IPMC actuator has certain advantages such as low energy consumption, light and high shape flexibility. However it has limitations too such as low actuating force and working under limited contraction frequency range. In fact, the actuating force is depending on the supplied voltage, the amount of charge in the actuator, thickness of the actuator as well as the capability to reduce the leaking water molecules from the actuator [4]. Thus, the aim of this research is to define the thrust characterization of the CWJT using two lateral IPMC actuators. The idea was to analyze the relation between the thrust and the input parameters. There were two input parameters that had been considered in this research which were the driving current and the nozzle opening area. A 2D CWJT had been fabricated and the varying thrusts were measured using bending force sensor.

Malaysian Ministry of Education had sponsored this project via ERGS grant 2011.

II. Design and Modeling

A. 2D CWJT Design and Fabrication

The proposed design of the 2D CWJT was based on rectangular shape like box with two lateral IPMC actuators on both sides Fig. 1. The top and bottom plate was fabricated from transparent acrylic plate to ensure the fluid flow could be observed during contraction. Both panels had slot at the nozzle end to make it easier to adjust the nozzle opening area. The fluid inlet and outlet had similar passage which is the nozzle. The overall size of the CWJT prototype was 50mm x 30mm x 7mm (L x W x T). The IPMC actuators were made from Nafion 117 (Sigma Aldrich) membrane as the ion transduction base material. The initial thickness of the Nafion 117 was 200μm. In order to increase it actuating force, the thickness of the Nafion had been increased to 0.45mm. At this thickness the IPMC actuator is able to actuate at 3 to 5gf of actuating force [5]. To increase its thickness, three sheets of Nafion 1117 membrane had been stacked and pressed under certain pressure at 180°C for 15 minute. Then, this membrane underwent electroless plating to form platinum micro layer on its surface to become IPMC. Each IPMC actuator had 35mm x 7mm (L x W) dimension.

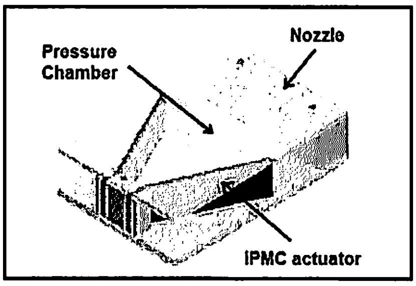
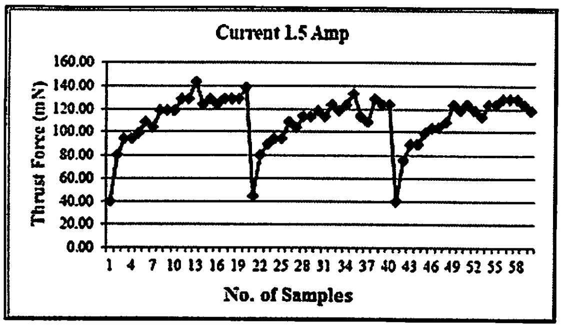


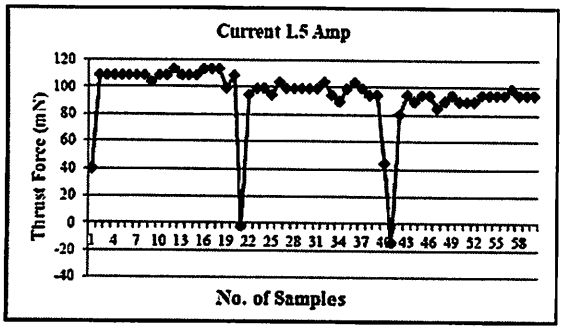
Figure 1. CAD design of the 2D CWJT

B. System Modeling

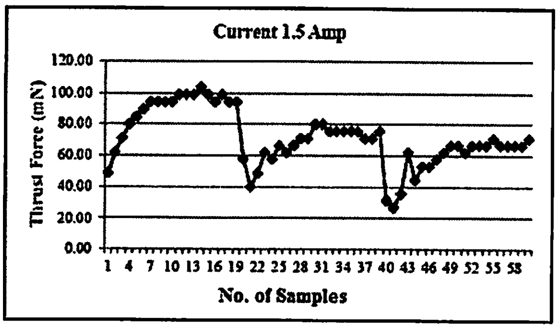
Generally there are two states for CWJT operation, which are inflation and deflation state [6]. During the inflation state, the IPMC actuator bends outward and thus increasing the pressure chamber volume. This condition creates vacuum in the pressure chamber. As the result, the water was entrained. When reach its capacity, the IPMC actuator bends inward and thus forcing the water out from the pressure chamber to create water jet via a nozzle. This process could be recognized as



c) Nozzle size: 37.96mm^2



d) Nozzle size: 50.01mm^2



e) Nozzle size: 62.06mm^2

Figure 6. Data of the averaging thrust measurement at 1.5A current input

V. CONCLUSION

Apparently the increasing current would increase thrust of the CWJT. However, at 1A input, the generated thrust is almost at constant. On the other hand, the increment of nozzle size would not give linear relation to the thrust. The maximum thrust was generated at the nozzle size of 37.96mm^2. A smaller or larger than this size would decrease the thrust. This research had been achieved it target. The results from this research were important in making decision to design any small scale underwater robot.

ACKNOWLEDGMENT

The authors would like to initiate their gratitude to Malaysian Ministry of Education for funding this project via FRGS grant, Universiti Sains Malaysia and Universiti Tun Hussein Onn Malaysia for providing technical service and research facilities.

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Indian Journal of Geo- Marine Sciences
Vol. 42 (8), December 2013, pp. 1023–1027

Preliminary analysis on generated jet pressure from ionic polymer composite actuated radial contraction using balloon manometry technique

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Received 5 December 2012; revised 14 September 2013

Contractile thruster has become a trend for underwater robot propulsion because of its prospective and advantages. However, it is difficult to determine the performance of the generated jet pressure from the small thruster. Thus, in this research an analysis was carried out to observe the radial contraction effects on the jet pressure by applying balloon-manometry technique. Four Ionic Polymer-Metal Composite (IPMC) filament actuators had been utilized as the longitudinal artificial muscle. The lengths of the IPMC actuators were 30 mm, 40 mm and 50 mm. During actuation, the radial contraction differentiated the pressure in the cylindrical shape balloon which was measured by a gauge pressure transducer. The result shows that at 30 mm length, the obtained pressure was almost 0.01psi. The shorter IPMC actuator gave higher contraction force and propulsive pressure.

[**Keywords:** Jet pressure, Radial contraction, IPMC, Manometry]

Introduction

Currently, rotary-blade propeller is widely used as a thruster for underwater robot and vehicle. However, at small scale specification, the blade propeller has maneuverability and propulsion efficiency problem[1-2]. Recent development on contractile thruster for underwater robot propulsion had been an alternative method to rotary-blade propeller. It has several advantages over rotary-blade propeller especially for small scale underwater robot such as lower power consumption, provide better maneuverability for robot and less mechanical complexity which leads to maintenance problem such as blade damage and brush motor problem[1-3]. These advantages are essential criteria for a small underwater robot which has observation and exploring task in robust, high turbidity and complex structure environment such as shipwreck and underwater structure. Inspired by most of the aquatic creatures such as squid, jellyfish and nautilus, this contractile thruster is technically applies water-jet propulsion mechanism. The introduction of deformable smart materials such as shape memory alloy (SMA), piezo material, ionic polymer-metal composite (IPMC) and dielectric elastomer (DE) ensures the designed thruster has near morphological form to the real aquatic animals, whereby those materials had been utilized as active artificial muscle[4-5]. For instance, Wang *et al.* had developed SMA wire actuated artificial squid mantle, Shi *et al.* had developed butterfly inspired thruster and Yeom *et al.* had utilized IPMC as actuator to mimic jellyfish umbrella[6-7-8]. The capability to mimic near morphological design of real system would increase the performance and efficiency of the designed robot. However, it is difficult to determine the performance of the generated jet pressure from the small thruster. Hence, this paper discusses an analysis of the radial contraction actuated by longitudinal IPMC muscles on its resulting jet propulsion pressure under at 3V.

Materials and Methods

In this research, a cylindrical contractile thruster was developed. Four IPMC actuators act as longitudinal muscle for this contractile thruster. Balloon- manometry technique was applied to measure the jet pressure. Observation was made on different actuator's length and the influence of the actuating pressure on the generated thrust.

Theory

Beam shape IPMC filament bends when opposite polarity with an amount of electrical energy between

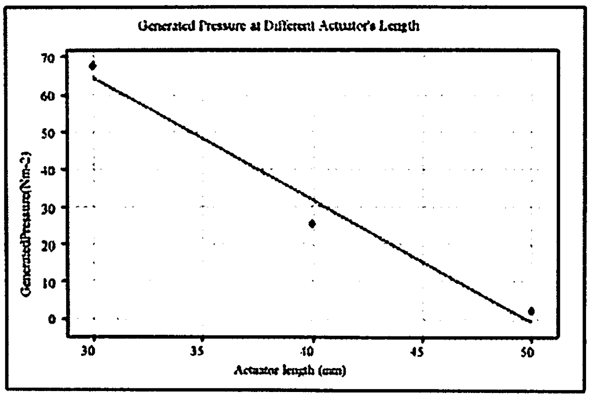

Figure 6 —Generated Pressure at different actuator length

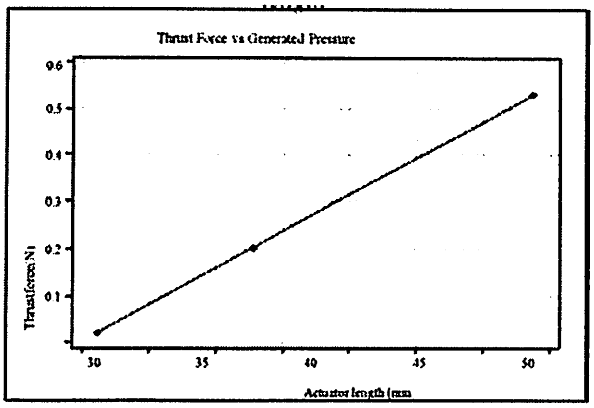

Figure 7 —Thrust force for generated pressure

pressure decreased if the actuator length increased. Therefore, shorter actuator provided better thrust force. Regression analysis using Minitab software shows that the P value of the variables is 0.004. The linear equation for this relation is:

$$T_f(\mathrm{N}) = 0.00282 + 0.00779\, P_j(\mathrm{Nm}^{-2}) \qquad \ldots (8)$$

Conclusion

Generally, higher tip force actuation gives better radial contraction and thus the jet pressure. In this experiment, the generated pressure was relatively small, which was around 0.0098 psi for 3cm IPMC filament length. It varies due to the length of the IPMC actuator. The jet pressure value is vital to determine the thrust force generated by the contractile thruster system. Thus, this method provides fundamental guideline to measure the actual water jet thrust force. In further studies, it is suggested to observe the effect of IPMC actuator slope and allocation degree rather than current orthogonal positions.

Acknowledgments

This project is funded by Ministry of Education (MOE) via its Fundamental Research Grant Scheme (FRGS). Authors are grateful to Universiti Sains Malaysia and Active Materials and Processing Laboratory (AMPL), University of Nevada for providing the facilities to conduct the research works.

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Preliminary Analysis on Generated Jet Pressure from Ionic Polymer-Metal Composite Actuated Radial Contraction Using Balloon Manometry Technique

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Abstract

Contractile thruster has become a trend for underwater robot propulsion because of its prospective and advantages. However, it is difficult to determine the performance of the generated jet pressure from the small thruster. Thus, in this research an analysis was carried out to observe the radial contraction effects on the jet pressure by applying balloon-manometry technique. Four Ionic Polymer-Metal Composite (IPMC) filament actuators had been utilized as the longitudinal artificial muscle. The lengths of the IPMC actuators were 30mm, 40mm and 50mm. During actuation, the radial contraction differentiated the pressure in the cylindrical shape balloon which was measured by a gauge pressure transducer. The result shows that at 30mm length, the obtained pressure was almost 0.01psi. The shorter IPMC actuator gave higher contraction force and propulsive pressure.

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Introduction

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In this research, a cylindrical contractile thruster was developed. Four IPMC actuators act as longitudinal muscle for this contractile thruster. Balloon- manometry technique was applied to measure the jet pressure. Observation was made on different voltage supply at several frequencies. The rest of this paper is organized as follows. Chapter 2 describes the IPMC longitudinal muscle fabrication, cylindrical contractile thruster design and its mechanics of contraction as well as the experimental setup. In Chapter 3, results were presented and discussed. Chapter 4 concluded the analysis and proposes further research works.

Conclusion

Generally, higher tip force actuation gives better radial contraction and thus the jet pressure. In this experiment, the generated pressure was relatively small, which was around 0.0098 psi for 3cm IPMC filament length. It varies due to the length of the IPMC actuator. The jet pressure value is vital to determine the thrust force generated by the contractile thruster system. Thus, this method provides fundamental guideline to measure the actual water jet thrust force. In further studies, it is suggested to observe the effect of IPMC actuator slope and allocation degree rather than current orthogonal positions.

Acknowledgments

This project is funded by Ministry of Higher Education (MOHE) via its Exploratory Research Grant Scheme (ERGS).

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BEST PAPER AWARD

"Analysis on Generated Jet Pressure from Ionic Polymer-Metal Composite Actuated Radial Contraction Using Balloon Manometry Technique"

Muhammad Farid S., Samad Z., Husaini A.B., Arshad M.R., Mahzan S.

USYS'12

The 4th International Conference on Underwater System Technology: Theory and Applications 2012 (USYS'12)

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ORGANISING SECRETARY
UNDERWATER SYSTEM TECHNOLOGY:
THEORY AND APPLICATIONS 2012

Technical Report

Fundamental Research Grant Scheme (FRGS)

Research Title	:	**Modeling of Radial Contraction of Ionic Polymer Metal Composite (IPMC) Actuated Cylindrical Micro Pump**
Project Leader	:	**Assoc. Prof. Dr. Zahurin bin Samad (Universiti Sains Malaysia)**
Project Members	:	**Dr. Elmi bin Abu Bakar (Universiti Sains Malaysia)** **Muhammad Farid bin Shaari (Universiti Tun Hussein Onn Malaysia)**
Project No	:	**203/PKMEKANIK/6071237**
Amount	:	**RM 46,000.00**
Duration	:	**24 months**
Start Date	:	**1 Jun 2012**
End Date	:	**31 Mei 2014**
Phase/Year	:	**1/2012**

1. Abstract

Utilization of active materials as micro-pump actuator had been implemented since few years ago through varieties of pump design. The usage of these active materials provides several advantages to the designed micro-pumps such as low electrical energy consumption and less mechanical system complexity. However, many of the developed micro-pumps were based on planar diaphragm model whereby the diaphragm motion actuates in opposite to the inlet and outlet valve. Hence, this research proposes a novel model of Ionic Polymer Metal Composite (IPMC) actuated micro-pump. These IPMC actuators bend towards positive polarity when an amount of voltage is supplied to them and cause the micro-pump to contract. The main goal of this research is to achieve a model of the micro-pump contraction via several investigations on parameters relation. The influential parameters include actuator's dimension, supplied voltage, supplied frequency and pressure. The results show that IPMC thickness has significant influence on the tip force generation and lower input frequency would results wider displacement. Higher supplied current would increase the thrust. By adjusting input power to the actuators, the thrust was optimized to be 113.95 mN at 37.96 mm^2 nozzle size. The recorded results are essential as future reference in developing the propulsion for the underwater robot.

2. Introduction

Propulsion system is regarded as one of the vital part in designing and developing underwater robot. Currently the typical propulsion system for most of underwater robot is using blade propeller [1]. However, there are other few propulsion systems that are being under research such as the undulatory, oscillating and water jet propulsion system [2][3]. Those alternative propulsion system mimics either the aquatic animal's propulsion mechanics to generate thrust for underwater locomotion. This research focuses on the water jet propulsion system. This biomimetic system applies the accelerated fluid to produce a thrust that enables the motion. In order to study the characteristics of this propulsion system, a contractile water jet thruster (CWJT) had been developed. The CWJT generates thrust from fluid mass flowrate and being actuated at certain contraction frequency. The types of actuator would be pneumatic cylinder, piezo material actuator or smart material actuators.

In this research, IPMC actuators had been selected to drive the CWJT. IPMC actuator has certain advantages such as low energy consumption, light and high shape flexibility. However it has limitations too such as low actuating force and working under limited contraction frequency range. In fact, the actuating force is depending on the supplied voltage, the amount of charge in the actuator, thickness of the actuator as well as the capability to reduce the leaking water molecules from the actuator [4]. Thus, the aim of this research is to define the thrust characterization of the CWJT using two lateral IPMC actuators. The idea was to analyze the relation between the thrust and the input parameters. There were two input parameters that had been considered in this research which were the driving current and the nozzle opening area. A CWJT had been fabricated and the varying thrusts were measured using bending force sensor.

3. CWJT Design and Fabrication

The proposed design of the CWJT was based on rectangular shape like box with two lateral IPMC actuators on both sides Figure 1. The top and bottom plate was fabricated from transparent acrylic plate to ensure the fluid flow could be observed during contraction. Both panels had slot at the nozzle end to make it easier to adjust the nozzle opening area. The fluid inlet and outlet had similar passage which is the nozzle. The overall size of the CWJT prototype was 50mm x 30mm x 7mm (L x W x T).

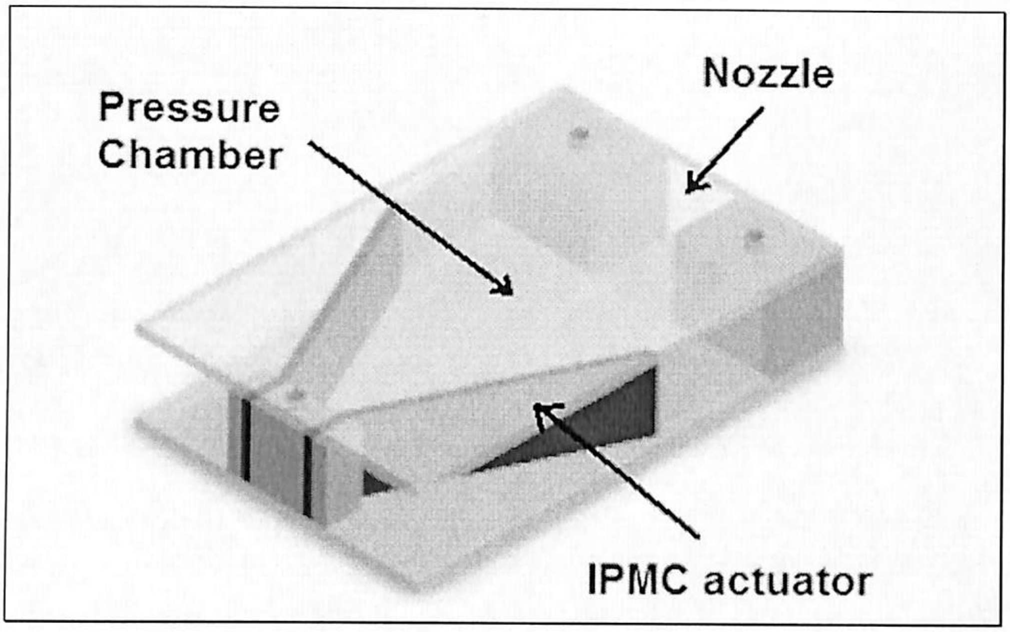

Figure 1: CAD design of the CWJT

The IPMC actuators were made from Nafion 117 (Sigma Aldrich) membrane as the ion transduction base material. The initial thickness of the Nafion 117 was 200µm. In order to increase it actuating force, the thickness of the Nafion had been increased to 0.45mm. At this thickness the IPMC actuator is able to actuate at 3 to 5 gf of actuating force [5]. To increase its thickness, three sheets of Nafion 1117 membrane had been stacked and pressed under certain pressure at 180°C for 15 minute. Then, this membrane underwent electroless plating to form platinum micro layer on its surface to become IPMC. Each IPMC actuator had 35mm x 7mm (L x W) dimension.

4. System Modeling

Generally there are two states for CWJT operation, which are inflation and deflation state [6]. During the inflation state, the IPMC actuator bends outward and thus increasing the pressure chamber volume. This condition creates vacuum in the pressure chamber. As the result, the water was entrained. When reach its capacity, the IPMC actuator bends inward and thus forcing the water out from the pressure chamber to create water jet via a nozzle. This process could be recognized as deflation state (Figure 2). In this research, in order to find the thrust characterization, we focus on the deflation process. The contraction forces initiated by the IPMC actuators vary depend on the inputs magnitude.

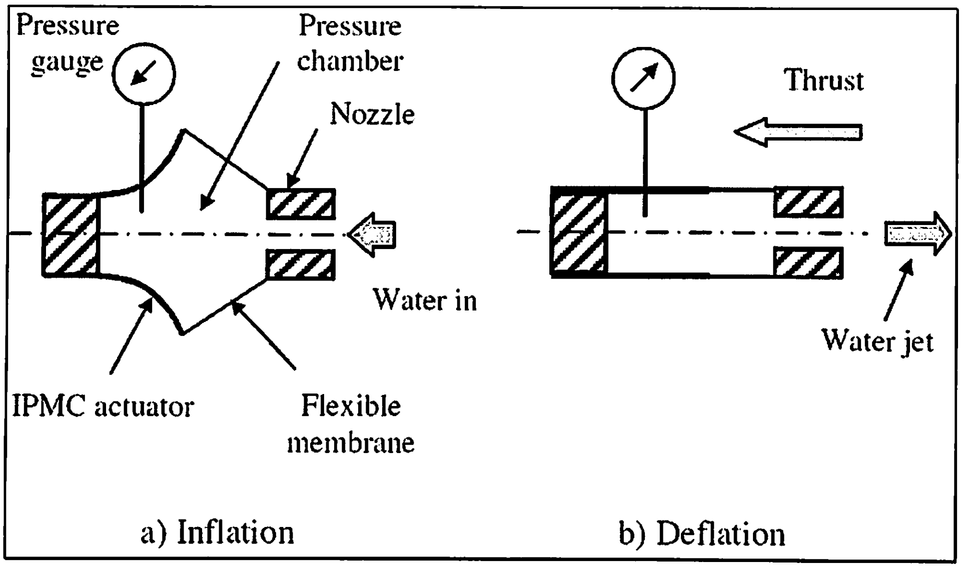

Figure 2: Formation of the water jet propulsion

The inputs could be voltage supply or current supply. The resultant trust would depend on other factors such as nozzle opening area, A_n and actuating frequency, f_{act} [7]. Basically, decreasing the nozzle opening area would increase the fluid velocity, v_j under the same applied pressure, P. The pressure in the pressure chamber increased during the contraction whereby the IPMC actuators bent inward to reduce pressure chamber volume. According to the Boyle's equation, this relation could be described as:

— (1)

where P_{pc} is the pressure in the pressure chamber, V_{pc} is the volume of the pressure chamber and k is the constant. V_{pc} could be determined by:

(2)

where W is the IPMC actuator width, L is the length of the bending IPMC actuator, dL is the length of the clamp, $f_{IPMC}(x)$ is the curvature of the IPMC, δ is the IPMC actuator displacement and L_m is the length of the membrane.

By assuming the total fluid amount is equal to this V_{pc}, the mass flow rate, during contraction period would be the total fluid volume that passes through the nozzle over the contraction time. Hence, the thrust, T could be measured using this equation below:

— (3)

Thrust is an impulse which means the change of momentum during contraction [8]. Referring to the (3), there are two important elements to get the thrust which are the mass flow rate and the changes of jet velocity, dv/dt. By assuming there is no mass change, mass flow rate, is depending on the V_{pc} and the contraction time. Otherwise, the jet velocity has wider range of magnitude and it depends on the contraction force and actuator acceleration.

5. Experimental Setup

Figure 3 depicts the experimental setup for this research. The IPMC actuators were powered by 7 V power supply (model GWInstek PSM 3004) with variation of current input from 1.0 A to 1.5 A. This range was determined by the specification of the IPMC actuator itself where more current would increase the electrolysis process at the terminal contact and thus would damage the actuators. In order to obtain a contractile function, the supply voltage had been attached to a driver which received the actuating frequency signal from a microcontroller (Arduino Duemilanove). This driver functions as H-bridge voltage follower where it gives and amplified signal to the CWJT. To obtain a uniform and averaging result of the thrust, the microcontroller had been programmed to trigger contraction for three times continuously. Data will be recorded for 60 samples in 100 milliseconds cycle.

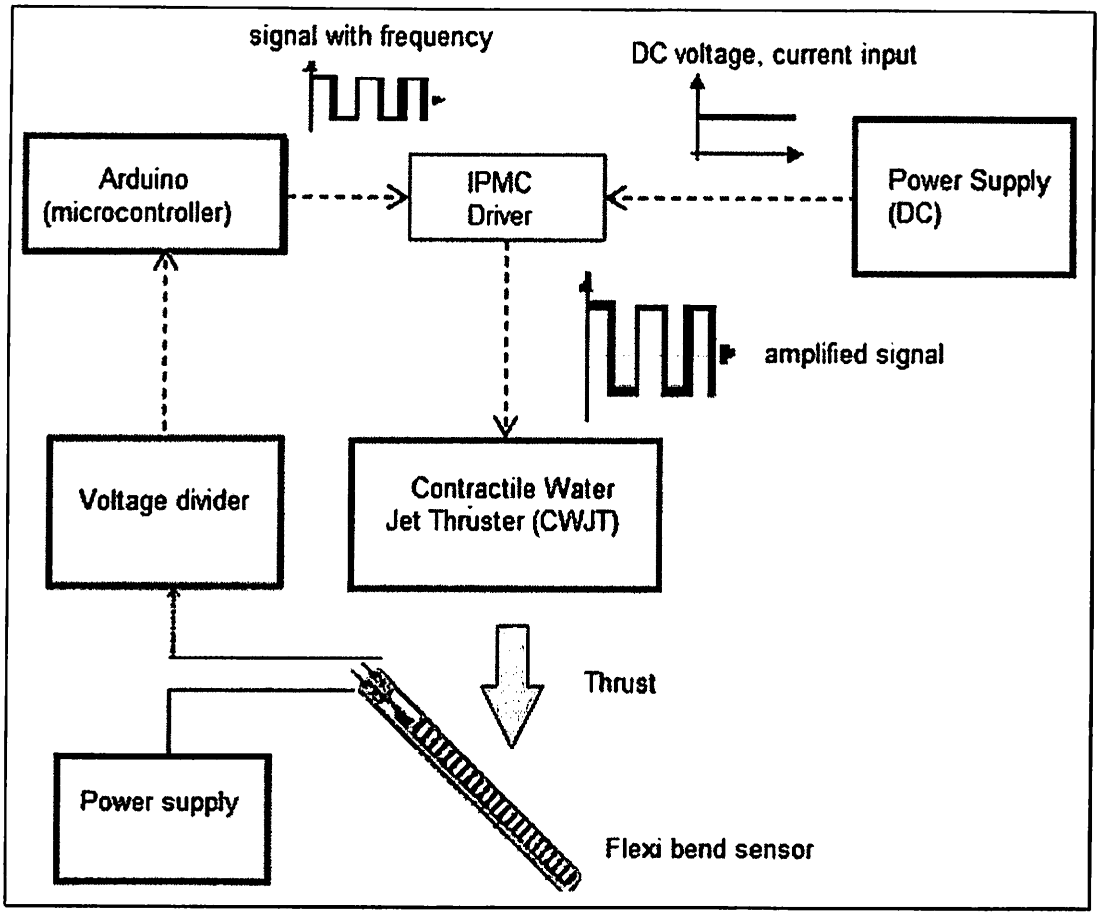

Figure 3: Experimental setup

Thrust had been measured using bending force sensor (Spectralsymbol, model Flexi bend sensor 2.2 inchs). The tip of the thrust had been located in 5 mm in front of the nozzle. The reading output from the flexi bend sensor is in resistant. Therefore a voltage divider was required to convert the readings to voltage so it can be read by the microcontroller. The rectangle nozzle opening area had been varied six size which were; 13.86 mm^2, 25.91 mm^2, 37.96 mm^2, 50.01 mm^2 and 62.06 mm^2. The thrust magnitude had been measured by varying the current input for each of these nozzle opening areas.

A video camera was attached to catch the contraction video from the top of the CWJT. A syringe contains red color dye was attached at the nozzle to observe the jet flow during the contraction as additional surveillance. The results were recorded and logged into a computer. Figure 4 exhibits how the CWJT works during the actuation. The black bending line under the transparent coverage is the IPMC actuator. Figure 4a shows the CWJT during inflation state and Figure 4b shows the inflation state.

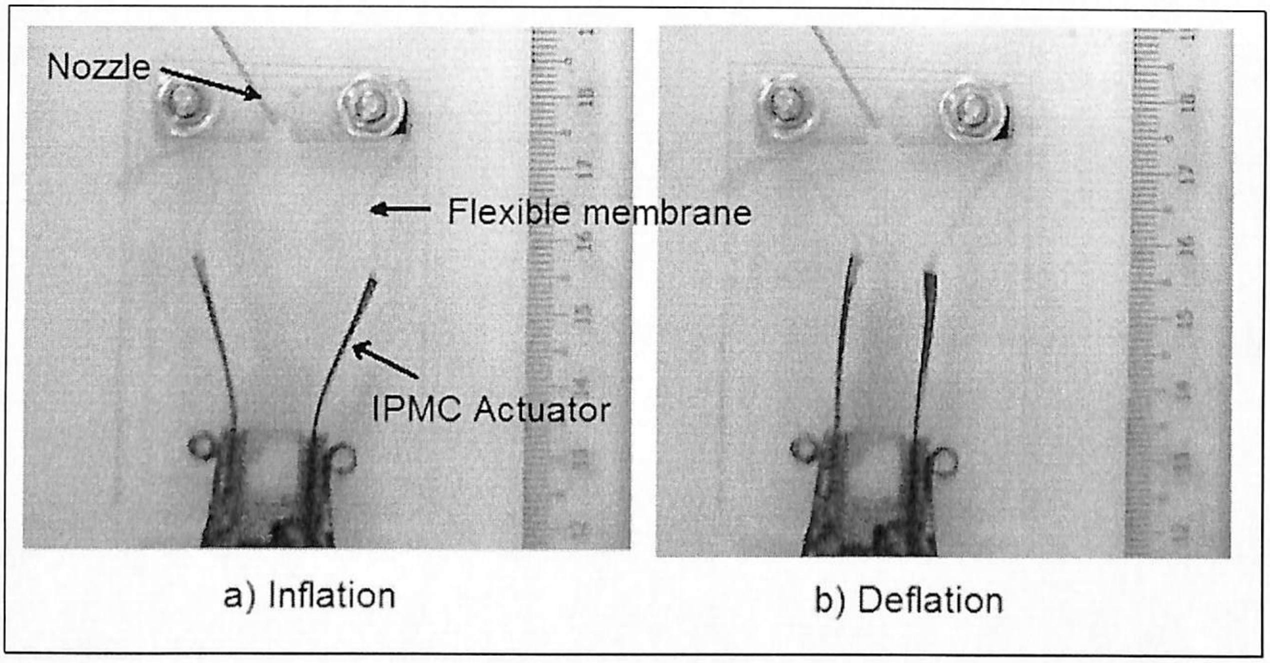

Figure 4: The two states of contractile process

6. Results and Discussion

Basically there were two observations made in this paper. The first observation was the influence of the current input to the thrust and the second observation was the effect of nozzle opening area to the thrust. Figure 5 displays the overall results of the generated thrust force at different nozzle opening area. The trend shows that increasing current input would generally increase the resultant thrust. It was only at 1 A input, the resultant thrust had almost at constant. The optimum curve increase apparently as the current was increased.

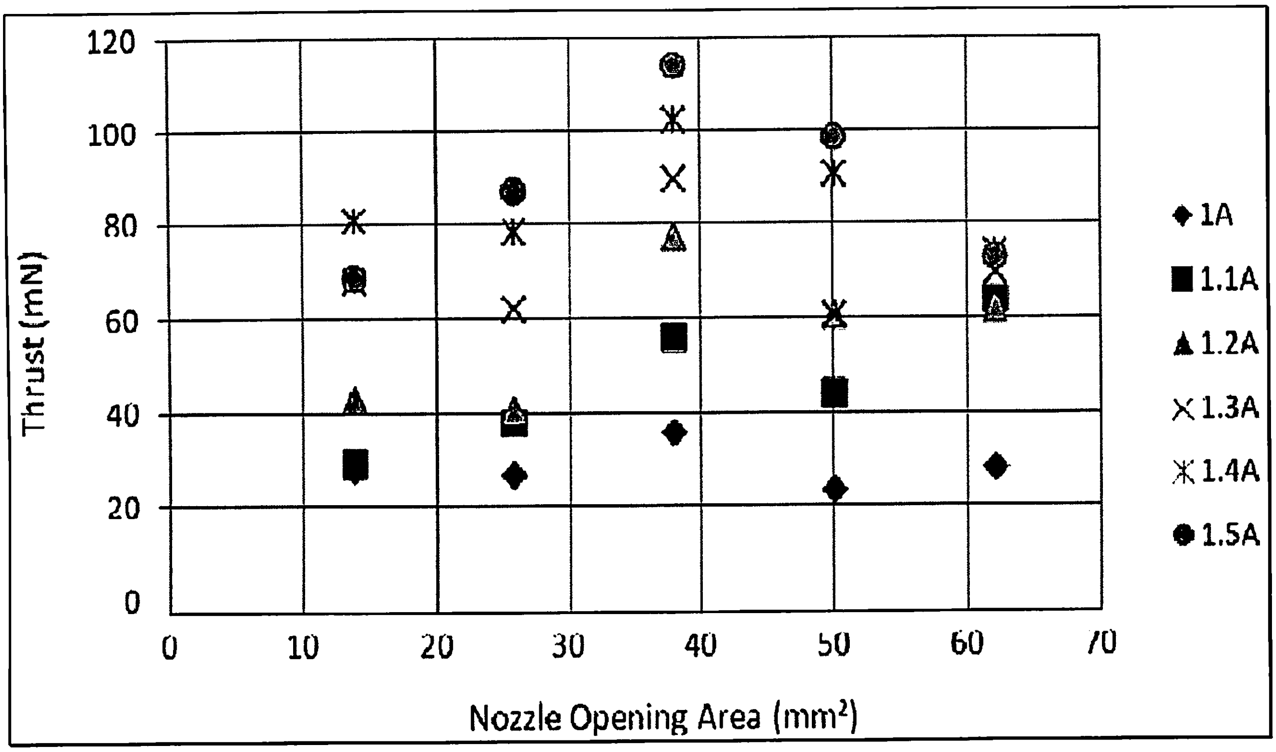

Figure 5: Optimized thrust at different nozzle area and current input

Theoretically, IPMC actuator is definitely influenced by the input voltage and current. This is because IPMC has the fundamental character of both parallel and series RC circuit. Current variation is vital in the analysis especially for parallel RC circuit where actually there are two resistors which are the resistant across the nafion base and resistant because of the capacitance created by the platinum layer under the nafion surface. In addition, when it comes to the series circuit, the resistor value in series varies as the actuator starts to deform. Adequate current is required to overcome the varying resistance.

Single IPMC actuator which has thickness around 0.2 mm to 1 mm normally requires approximately 500 mA for its actuation [9]. In this case, the IPMC actuators were connected in parallel and thus we expected an increment of current demand. Besides, connecting IPMC actuators in parallel would also demands similar specification of the actuator and connecting terminals. Any dissimilarity would influence the performance of the actuator deformation and thus the performance of the thrust.

Another factor that influences the optimization of the thrust is the nozzle size or nozzle opening area. As displayed in Figure 5, the ultimate thrust had been achieved in average at 37.96 mm^2 nozzle size. Smaller nozzle size had lower thrust. At larger nozzle size, the thrust value declined. Though it seems like smaller nozzle size would increase the thrust via jet velocity as stated in (3), the smaller nozzle size reducing the volumetric mass flow. Hence, the limited mass transfer had trading off the increasing jet velocity.

On the other side, having bigger nozzle size would increase the mass flow rate but in contrast it would lowering the jet speed and as the consequent it declining the thrust. Figure 6 to 10 depicts the thrust force at different nozzle size for 1.5 A current input. There were three readings at 60 samples have been taken in 100 milliseconds cycle. The downward spikes represent the inflation stage. Some of the value turned into negative to show that the fluid was entrained into the pressure chamber. Some of the contraction had good response and there were also some contraction that required stability time.

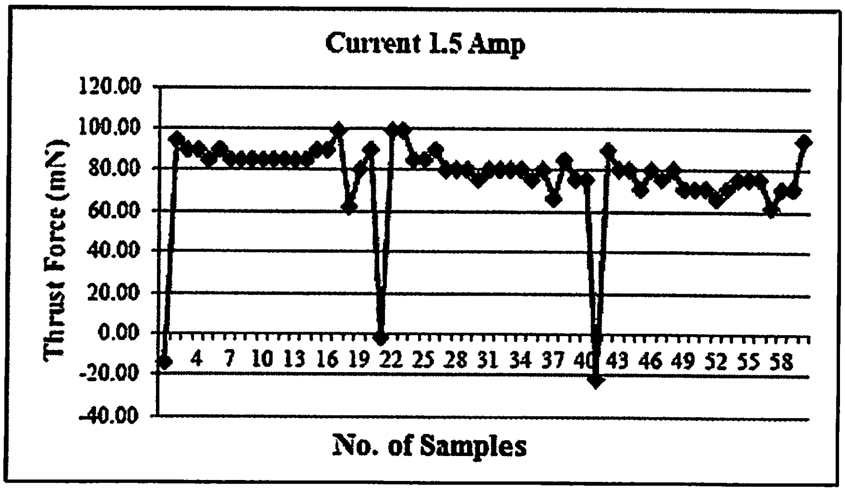

Figure 6: Data of the averaging thrust measurement at 1.5A current input for nozzle size 13.86 mm^2

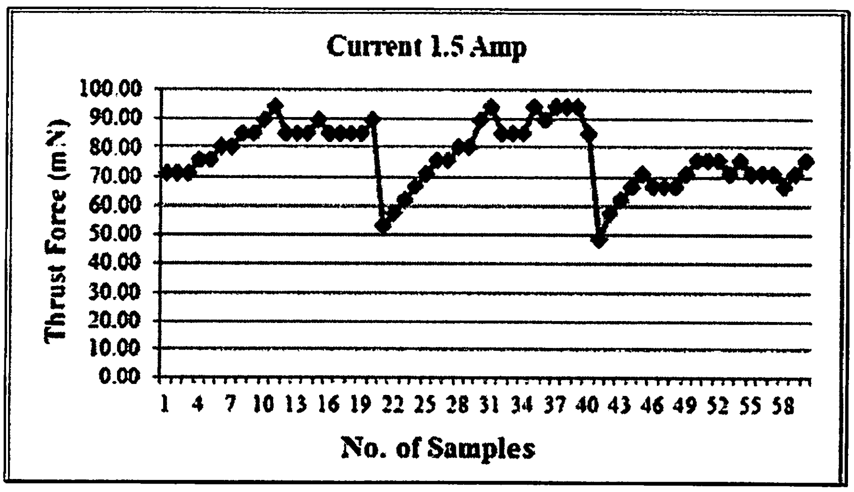

Figure 7: Data of the averaging thrust measurement at 1.5A current input for nozzle size 25.91 mm^2

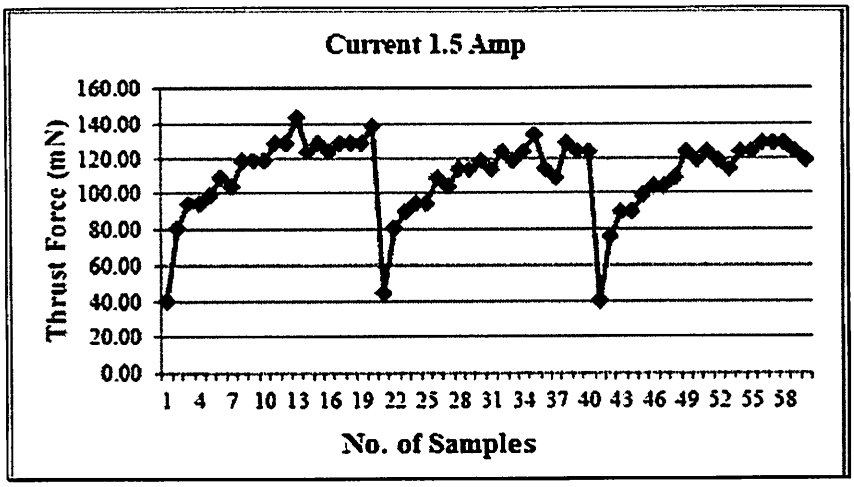

Figure 8: Data of the averaging thrust measurement at 1.5A current input for nozzle size 37.96 mm^2

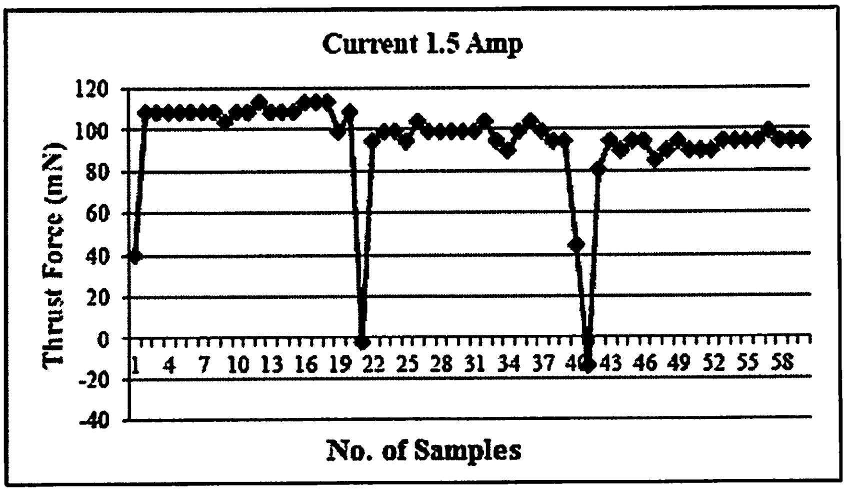

Figure 9: Data of the averaging thrust measurement at 1.5A current input for nozzle size 50.01 mm^2

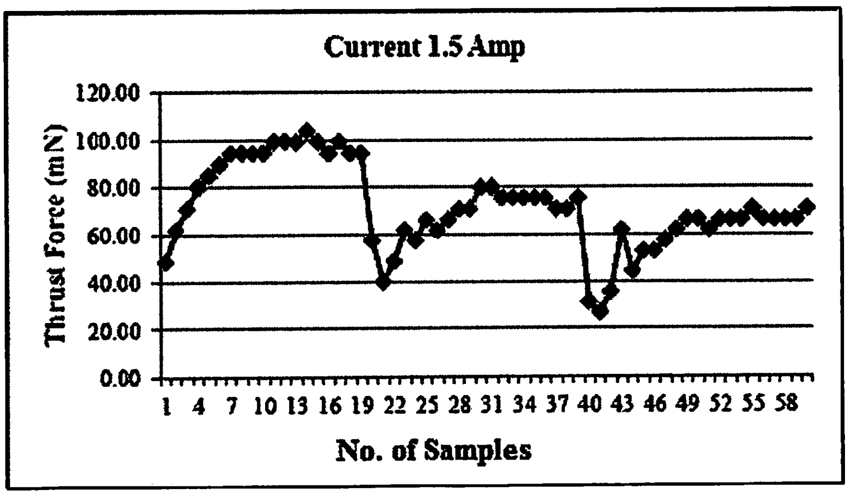

Figure 10: Data of the averaging thrust measurement at 1.5A current input for nozzle size 62.06 mm^2

Though all the data had shown positive results and achieving the aim of this research, there are few things that must be taken into account to improve the result. First, the usage of flexi bend sensor to measure the thrust is actually a reverse thrust measurement process. Generally most of the previous experiments measure the thrust based on 'pushing' method where a load cell is located in front of the thruster.

Secondly, to gain a better result, we need gold plated terminal. The reason to utilize gold at the terminal instead of copper is gold has higher oxidation resistance and thus would give more consistency in voltage supply as well as reducing the terminal damage risk. For further work, we could study the influence of the actuating frequency and nozzle angle effect to the thrust characterization. This is due to obtaining an optimum thrust and determining the potential tradeoff between the factors.

7. Conclusion

Apparently the increasing current would increase thrust of the CWJT. However, at 1A input, the generated thrust is almost at constant. On the other hand, the increment of nozzle size would not give linear relation to the thrust. The maximum thrust was generated at the nozzle size of 37.96 mm^2. A smaller or larger than this size would decrease the thrust. This research had been achieved it target. The results from this research were important in making decision to design any small scale underwater robot.

8. Acknowledgment

The authors would like to initiate their gratitude to Malaysian Ministry of Education for funding this project via FRGS grant (203/PMEKANIK/6071237), Universiti Sains Malaysia and Universiti Tun Hussein Onn Malaysia for providing technical service and research facilities.

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