Smart Structures and Systems, *Vol. 20, No. 4 (2017) 499-508*
DOI: https://doi.org/10.12989/sss.2017.20.4.499

Dynamic modeling and control of IPMC hydrodynamic propulsor

Shivendra K. Agrahari and Sujoy Mukherjee*

PDPM Indian Institute of Information and Technology, Design and Manufacturing Jabalpur – 482005, Madhya Pradesh, India

(Received September 7, 2016, Revised April 22, 2017, Accepted May 26, 2017)

Abstract. The ionic polymer–metal composite (IPMC) is an electroactive polymer material and has a promising potential as actuators for propulsion and locomotion in underwater systems. In this paper a physics based model is used to analyse the actuation dynamics of the IPMC propulsor. Moreover, proportional-integral (PI) controller is used for position control of the tip displacement of IPMC propulsor. PI parameter tuning is performed using particle swarm optimization (PSO) algorithm. Several performance indices have been used as an objective function to optimize the error of the system. Finally, the best tuning method is found out by comparing the results under various performance indices.

Keywords: Ionic Polymer Metal Composite (IPMC); smart materials; propulsor; PI controller; PSO algorithm

1. Introduction

Fishes are very efficient swimmer as they developed in millions of years. Fishes used various modes for underwater propulsion. Studies of these modes demonstrate various swimming mechanism for aquatic locomotion. Fish swimming is broadly classified as body or caudal fin (BCF) movements and median or paired fin (MPF) movements (Sfakiotakis *et al.* 1999). Caudal fin motion can generate more cruising speed and thrust efficiency compare to all other swimming modes. So this mode is highly efficient for propulsion and maneuvering purposes. Conventional robots uses electric motors, hydraulic cylinder and pneumatic cylinder actuator for their actuation but it require high input voltage to work properly (Aureli *et al.* 2010).

Recently, smart material replaces conventional actuator because of its relatively low actuation voltage, higher conversion efficiency and large deformation (Cho *et al.* 2010). Ionic polymer metal composite (IPMC) is a smart material and a bi-directional transducer which converts electrical stimulus to mechanical bending and mechanical bending to electrical voltage (Chen *et al.* 2007, Chen *et al.* 2009). As an actuator it finds many application in robotics, biomedical devices and artificial muscles (Shahinpoor and Kim 2004). A robotic fish propelled by IPMC can be a better replacement of motor driven robotic fish (Guo *et al.* 2003, Shen *et al.* 2015, Karthigan *et al.* 2015).

IPMC is an electroactive polymer which consists of an ion exchange membrane (i.e., Nafion) which is chemically plated with noble metals (gold or platinum) on both surface as electrodes (Kim and Shahinpoor 2003, Weiland and Akle 2010). If an electric field is applied across the IPMC, transport of hydrated cation will take place within the membrane (Mukherjee and Ganguli 2010, Hubbard *et al.* 2014). This redistribution of cation creates the net imbalance of charge density and produces internal stress, due to which bending happens (Shahinpoor and Kim 2001, Tiwari *et al.* 2008). As they have low actuation voltage, very less power consumption, flexibility, low noise it can be used to make a micro size, biomimetic underwater robots. Several studies of underwater robot have been reported which uses several forms of fish swimming modes (Bandyopadhyay 2005). Nasser and Li (2000) developed electro-mechanical response of IPMC. Two presumptions are made in this modeling work. (i) The flux density of ions is zero at the boundary, and (ii) Stress generated is proportional to the charge density. Yim *et al.* (2007) proposed a model to capture dynamic characteristics of single or multi-segment IPMC actuators for underwater propulsor applications. An impedance model with or without surface resistance is presented by Chen and Tan (2008). A speed model of robotic fish propelled by an IPMC caudal fin, was also developed that captures IPMC actuation dynamics and the interactions between IPMC and fluids (Mbemmo *et al.* 2008, Chen *et al*. 2010, Shen *et al.* 2013).

On motion control of IPMC propelled fish, researchers has mainly focused on the open-loop method for swimming performance. Proportional-Integral (PI) controllers is widely used for speed and position control of various applications. Richardson *et al.* (2003) presented control of IPMC actuation and used PI controller since there is no such oscillation in the transient response of system. Recently, optimization algorithms are often proposed to tune the control parameters of PI in order to find an optimal performance (Gaing 2004).

In this work a physics based model is used to analyzed IPMC actuation. Caudal fin motion of the underwater propulsor is studied and speed under frequency range is obtained using Lighthill's theory of slender-body propulsion

*Corresponding author, Assistant Professor
E-mail: sujoy.mukherjee09@gmail.com
[a] M Tech Student
E-mail: shivendraagrahari.7777@gmail.com

ISSN: 1738-1584 (Print), 1738-1991 (Online)

(Lighthill 1970). Further passive fin model is investigated for higher cruising speed. PI controller is then used for position control of the tip displacement of IPMC actuator. For tuning of PI parameter (K_p, K_i), particle swarm optimization (PSO) algorithm is used and results under various performance indices have been compared.

2. Mathematical modeling

In this section, the main goal is to understand the IPMC actuation dynamics in water. The schematic diagram of the robotic fish used for modeling is shown in Fig. 1.

Nemat-Nasser and Li (2000) first derived a model that describes electromechanical response of IPMC considering electrostatic interactions within a polymer. Chen and Tan (2008) expanded the model under two different boundary conditions, one ignoring with surface electrode resistance and the other considering the surface resistance. The model is represented as an infinite dimensional transfer function relating the bending displacement $w(z,s)$ to the applied voltage $V(s)$. As shown in Fig. 1, the IPMC strip is clamped at one end (z = 0) and under actuation voltage $V(s)$ producing the tip displacement $w(z,s)$ at the other end (z = L). The transfer function $H(s)$ relating tip displacement $w(z,s)$ under actuation voltage $V(s)$ is given by

$$H(s) = \frac{w(z,s)}{V(s)} = -\frac{L^2 \alpha_0 K W \varepsilon_e (\gamma(s) - tanh(\gamma(s)))}{2 Y_e I(\gamma(s) + tanh(\gamma(s)))} * \frac{2X(s)}{(1 + r_2 \theta(s))} \quad (1)$$

where α_0 is the stress-charge coupling constant, W is the width of IPMC, ε_e is the effective dielectric constant of the polymer, r_2 is the electrode resistance per unit length in the thickness direction, W is the width of the IPMC beam, Y_e is the equivalent Young's modulus of IPMC in the fluid.

In order to accommodate the vibration dynamics of the beam, $G(s)$ is cascaded to $H(s)$. Since the actuation bandwidth of an IPMC actuator is relatively low (under 10 Hz), it often suffices to capture the mechanical dynamics $G(s)$ with a second-order system (first vibration mode)

$$G(s) = \frac{\omega_n^2}{s^2 + 2\xi w_n + \omega_n^2} \quad (2)$$

where ω_n is the natural frequency of the IPMC cantilever beam in fluid, and ξ is the damping ratio.
So, $H_1(s) = H(s)\, G(s)$.

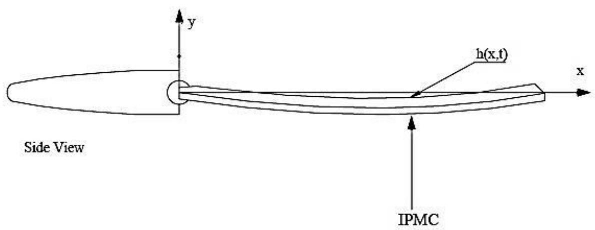


Fig. 1 Schematic of IPMC propelled robotic fish

To couple the actuation dynamics to hydrodynamics, the expression of the transfer function $H_{1d}(z,s)$ relating the slope of the beam $\partial w(z,s)/\partial z$ to the input voltage $V(s)$ can be written as

$$H_{1d}(z,s) = \frac{\frac{\partial w(z,s)}{\partial z}}{V(s)} = \Gamma_{1d}(z,s) G(s) \quad (3)$$

$$\Gamma_{1d}(z,s) = \frac{\alpha_0 W K \varepsilon_e (\gamma - 1)}{Y_e I(\gamma s + K)} \times \frac{\left(\left(\cosh\left(\sqrt{B(s)}z\right) - 1\right) \tanh(\sqrt{B(s)}L - \sinh(\sqrt{B(s)}z)\right)}{\sqrt{B(s)}(1 + r_2 \theta(s))} \quad (4)$$

According to the Lighthill's theory (Lighthill 1970), the fish will reach to a uniform cruising speed U, in the steady state. By giving the input voltage $V(t) = A_m \sin(\omega t)$, U can be expressed as (Mbemmo *et al.* 2008)

$$U = \left[\sqrt{\frac{m \overline{\left(\frac{\partial w(z,t)}{\partial t}\right)^2}}{C_D \rho_w S + m \overline{\left(\frac{\partial w(z,t)}{\partial z}\right)^2}}} \right]_{z=L} \quad (5)$$

where S is the wetted surface area, and C_D is the drag coefficient, m is the virtual mass density at $z = L$, expressed as

$$m = \frac{1}{4} \pi S_c^2 \rho_w \beta \quad (6)$$

where S_c is the width of the tail at the end $z = L$, ρ_w is the fluid density, and β is a non-dimensional parameter close to 1, $\frac{\partial_w}{\partial_t}$ is lateral velocity of the tail and $\frac{\partial_w}{\partial_z}$ is slope at the tail end. One can obtain the fish speed U under the actuation voltage $V(t) = A_m \sin(\omega t)$ by

$$U = \sqrt{\frac{m A_m^2 \omega^2 |H_1(L, j\omega)|^2}{2 C_D \rho_w S + m A_m^2 |H_{1d}(L, j\omega)|^2}} \quad (7)$$

2.1 Model of fish motion with passive fin

The schematic diagram of IPMC caudal fin with passive fin is shown in Fig. 2. Addition of passive plastic fin will increase the width of the tail (S_c) as the virtual mass density (m) is directly proportional to S_c.

Since the passive fin is rigid compared to IPMC, its width $b(z)$ and deflection $w(z,s)$, $L_0 \le z \le L_1$, can be written as

$$b(z) = \frac{b_1 - b_0}{L_1 - L_0}(z - L_0) + b_0 \quad (8)$$

$$w(z,s) = w(L_0, s) + \frac{\partial w(L_0, s)}{\partial z}(z - L_0) \quad (9)$$

Here, Where $L_0 \le z \le L_1$ and $\Gamma(s) \approx 1$ for inviscid water and b_0, b_1,, L, L_0, L_1 are as defined in Fig. 2. For any point z on the IPMC beam, $z \le L_0$, the bending moment generated by the hydrodynamic force acting on the passive fin is

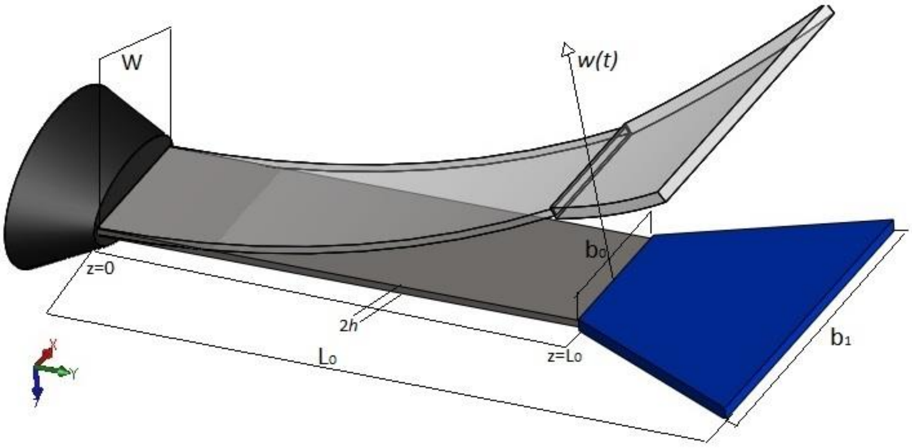


Fig. 2 IPMC actuator with passive caudal fin

$$M_{tail}(z,s) = \int_{L_0}^{L_1} F_{hydro}(\tau,s)(\tau - z)\partial\tau \qquad (10)$$

The deflection $w(z,s)$ of the IPMC is

$$\frac{\partial^2 w(z,s)}{\partial z^2} = \frac{M_{IPMC}(z,s) - M_{tail}(z,s)}{Y_e I} \qquad (11)$$

From the actuation model of IPMC

$$\int_0^z \int_0^\tau \frac{M_{IPMC}(v,s)}{Y_e I}\partial v\partial\tau = \Gamma_1(z,s)V(s) \qquad (12)$$

Integrating, the transfer functions relating $w(L_0,s)$ and $w'(L_0,s) \triangleq \frac{\partial w(L_0,s)}{\partial z}$ to $V(s)$ can be found

$$H_2(L_0,s) = \frac{w(L_0,s)}{V(s)} = \Gamma_2(L_0,s)G(s) \qquad (13)$$

$$H_{2d}(L_0,s) = \frac{w'(L_0,s)}{V(s)} = \Gamma_{2d}(L_0,s)G(s) \qquad (14)$$

$$\Gamma_2(L_0,s) = \frac{(1-F)A + BE}{(1-C)(1-F) - BJ} \qquad (15)$$

$$\Gamma_{2d}(L_0,s) = \frac{(1-C)E + AJ}{(1-C)(1-F) - BJ} \qquad (16)$$

One can obtain the transfer functions relating the bending displacement and the slope at $z = L_1$ to the voltage input $V(s)$ as follows

$$H_3(L,s) = \frac{w(L_1,s)}{V(s)} = H_2(L_0,s) + H_{2d}(L_0,s)D \qquad (17)$$

$$H_{3d}(L_1,s) = \frac{w'(L_1,s)}{V(s)} = H_{2d}(L_0,s) \qquad (18)$$

Input voltage $V(t) = A_m \; sin(\omega t)$, one can find U by

$$U = \sqrt{\frac{mA_m^2\omega^2|H_3(L_1,j\omega)|^2}{2C_D\rho_w S + mA_m^2|H_{3d}(L_1,j\omega)|^2}} \qquad (19)$$

2.2 IPMC Model verification

In this paper, IPMC sample actuator of cross section area of 14.7 × 23 mm and thickness of 0.35 mm is used for simulation. Moreover, Table 1 shows the list of parameter used for numerical simulation. IPMC is clamped with one end and a sinusoidal actuation voltage provided with 3.3 V of amplitude and frequency range from 0.2 to 10 Hz. Fig. 3 shows the bode plot of actuation response magnitude and phase response.

Fig. 4 shows the speed response of IPMC caudal fin under the sinusoidal frequency range from 0.2 to 10 Hz. There is optimal frequency 4.6 Hz at which speed of IMPC propelled robotic fish is maximum after which speed start decreasing abruptly, known as resonance frequency. Resonance frequency can be obtain from equation given below

$$\omega_n = \frac{C_1^2}{L^2}\sqrt{\frac{Y_e I}{2\rho_c W h}} \qquad (20)$$

where $C_1$is a constant related with the first-mode oscillation

Fig. 5 shows the speed comparison of robotic fish with and without the passive fin. It shows that passive caudal fin improves the speed response of robotic fish. The fin dimensions can be found in Table 1. The parameter of IPMC strip is kept constant for both the cases. These results are in good agreement with the results presented by Chen *et al.* (2010). Therefore, the computer implementation of the model is verified.

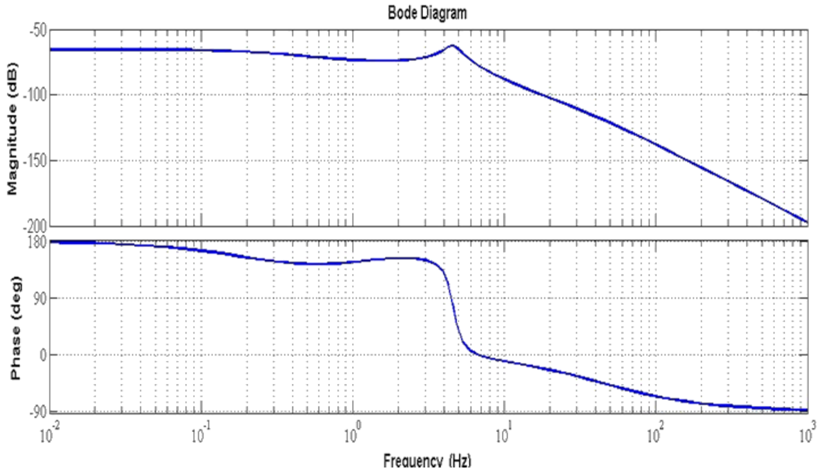


Fig. 3 IPMC actuation response with actuation model predictions

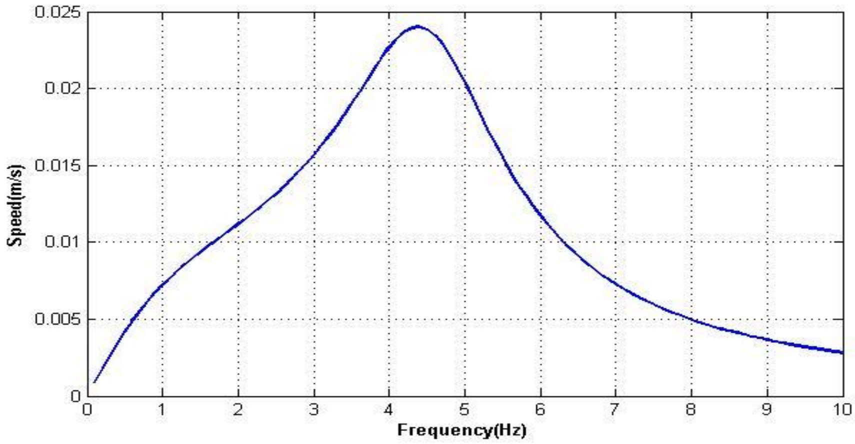


Fig. 4 Speed of robotic fish with passive fin

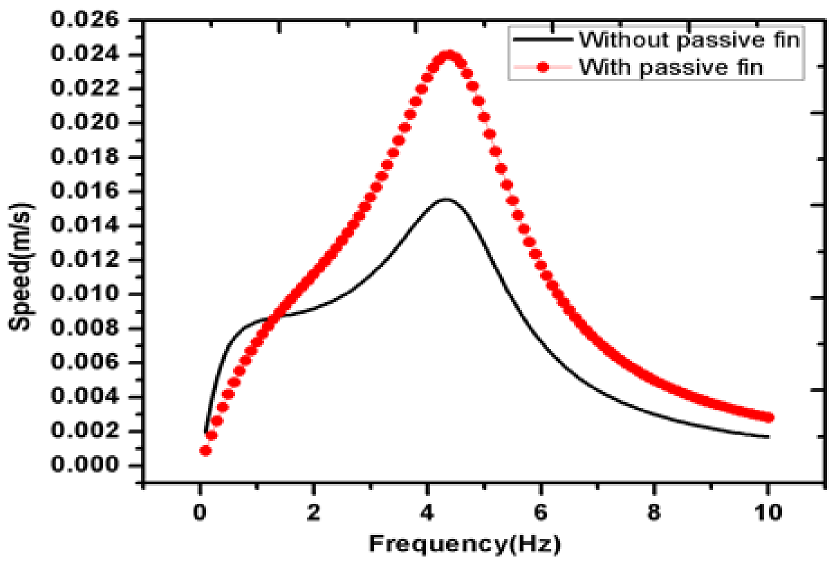


Fig. 5 Speed comparison of robotic fish with and without passive fin

Table 1 Parameter of IPMC actuation model (Chen *et al.* 2010)

Parameter	Value	Parameter	Value
F	96487 (C/mol)	C_1	1.8751
D	$3.38\times10^{-7}(m^2/s)$	ρ_w	$1000\,(kg/m^3)$
C^-	$1091\,(mol/m^3)$	ζ	0.225
R	$8.3143\,(J/mol.k)$	ρ_c	$1600\,(kg/m^3)$
T	300 K	S	$1.52\times10^{-2}m^2$
R_p	$34\,\Omega,m$	L	$23\times10^{-2}m$
Y	$5.71\times10^8\ pa$	w	$1.47\times10^{-3}m$
H	175 μm	A_m	3.3 V
C_D	0.017	b_0	$20\times10^{-3}m$
ε_e	$1.34\times10^{-6}(F/m)$	b_1	$40\times10^{-3}m$
r_1	2.23 (Ω/m)	L_0	$18\times10^{-3}m$
r_2	1.8×10^{-3} (Ω/m)	L_1	$26\times10^{-3}m$
a_0	$0.05\,(J/C)$		

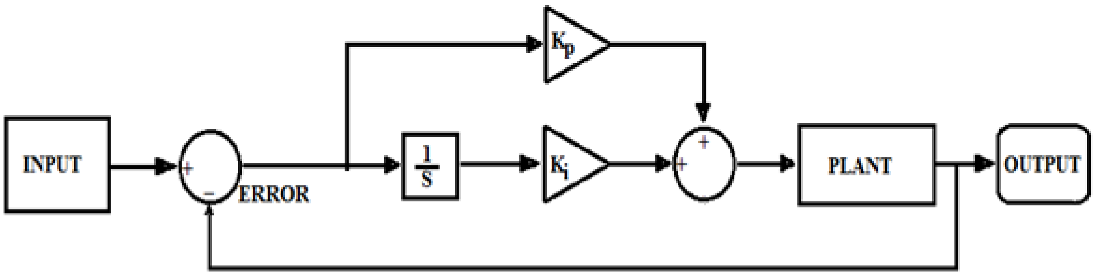


Fig. 6 A common closed loop feedback control system

3. PI Controller

The ability of proportional and integral (PI) controller to compensate the error of the practical process led to wide acceptance in industrial and automation industries. The PI controller generally used to control the process of low to medium order, with small time delay. PI controller is the combination of proportional and integral control; the transfer function of PI controller is given by (Ogata 2010)

$$C(s) = K_p + \frac{K_i}{s} \tag{21}$$

where K_p, K_t are respectively the proportional, integral gains of the PI controller. Simulink model of PI controller is shown in Fig. 6.

3.1 Performance evolution criteria

System performance is achieved through performance indices. To meet the desired specification different performance has to be selected. Our goal is to design an optimal system by efficient controlling of its parameters.

This control action does not change the system parameter, so various performance indices are used to optimize the performance of the system. Performance indices are used in control engineering which includes the Integral Square-Error (ISE) index, Integral of Absolute-Error (IAE) index, Integral of Time multiplied by Square-Error (ITSE) index and Integral-of-Time multiplied by Absolute-Error (ITAE) index (Ogata 2010).

Integral of squared error (ISE)

$$ISE = \int_0^\infty e^2(t)\,dt \tag{22}$$

Integral of absolute error (IAE)

$$IAE = \int_0^\infty |e(t)|\,dt \tag{23}$$

Integral of time multiplied absolute error (ITAE)

$$ITAE = \int_0^\infty t|e(t)|dt \tag{24}$$

Integral of time multiplied squared error (ITSE)

$$\mathrm{ITSE} = \int_0^\infty te^2(t)\,dt \tag{25}$$

3.2 Tuning of PI controller using PSO based optimization

Particle Swarm Optimization (PSO) is an evolutionary optimization technique which uses the movement and intelligence of particles. These particles also known as swarms and this method was developed by Kennedy and Eberhart (1995). Shi and Eberhart (1998) is then proposed a modified PSO to improve the operation of the original PSO. At first, swarms are randomly organized in search space then these swarm moves in the search space to optimize the problem and each swarm has its candidate solution. The fitness function decides the performance of the system which varies with system to system. A new inertia weight parameter is added which has the importance of personal best and global best respectively. Clerc (1999) has reported that this inertia weight parameter decreases linearly with the iteration.

Particle swarm optimization is an emerging algorithm whose solutions are obtained as a point in an m dimensional search space. At first, these randomly organized particle moves in such a way that each particle search for the optimum. Each particle has a particular velocity and position and each particle remembers the best position visited for the solution. This position is its personal best position. These particles then communicate to each other about their best position they have visited so far. Each particle has neighborhood particles and it knows the fitness of its neighborhood particles, and one of these positions is used as best fitness. This position is simply used to adjust the velocity of the particles. A particle moves to a new position at each time. It does this by adjusting its velocity. The particles velocity and position and are updated by the following equations (Shi and Eberhart 1998)

$$v_{id}^{m+1} = w.v_{id}^{m} + c_1.rand().(p_{id}^{m} - x_{id}^{m}) + c_2.rand().(p_{gd}^{m} - x_{id}^{m}) \tag{26}$$

$$x_{id}^{m+1} = x_{id}^{m} + v_{id}^{m} \tag{27}$$

where v_{id}^{m} is the current velocity of i^{th} particle at m iteration, v_{id}^{m+1} is the new velocity of i^{th} particle at next $m+1$ iteration, c_1 is the adjustable cognitive acceleration constants, c_2 is the adjustable social acceleration constant, *rand* () is the random number between *0* and *1*, x_{id}^{m} is the current position of i^{th} particle at m iteration, x_{id}^{m+1} is the new position of i^{th} particle at next $m+1$ iteration, p_{id}^{m} is the personal best of i^{th} particle, p_{gd}^{m} is the global best of i^{th} particle.

Clerc (1999) has suggested the constants values as $c_1 = c_2 = 1.48$ for the best performance. Eq. (26) is used to update the particle's velocity based on the previous velocity and distance traveled by the particle from its best position and group's best position. Then the particle moves toward a new position which can be calculated by Eq. (27). The performance index is used as the fitness function to measure the performance of each particle, which depends on the problem to be optimized. To balance the global and local search capabilities inertia weight is brought into the Eq. 26. It may be positive constant or positive function of time which can be linear or nonlinear in nature. Clerc (1999) set $w = 0.72$ to assure the convergence of PSO and also showed that the different number of particles can have similar performance. Here, swarm size is set to 50 and PSO can be used for tuning of the PI controller to optimize the gain parameter of PI for optimal performance of the system. PSO is used to tune PI gain parameter (K_p, K_i) using the model in Eq. (28). First, it produces a matrix of the initial swarm of particles in search domain. To tune this PI controller, matrices of dimension 2 x swarm size is used to represent position and velocity of the particle. A good set of PI gain parameters can give a good response of the system, and can reduce the performance indices of Eqs. (22)-(25). Recently, tuning methods based on optimization technique is used to ensure good stability and robustness of the system performance.

The plant used here is transfer function H(s) relating tip displacement $w(z,s)$ under actuation voltage V(s).The open loop response of system can be found from Eq. (28) as

$$\mathrm{H(s)} = \frac{0.00335s + 0.0546}{s^2 + 13.65s + 30.44} \tag{28}$$

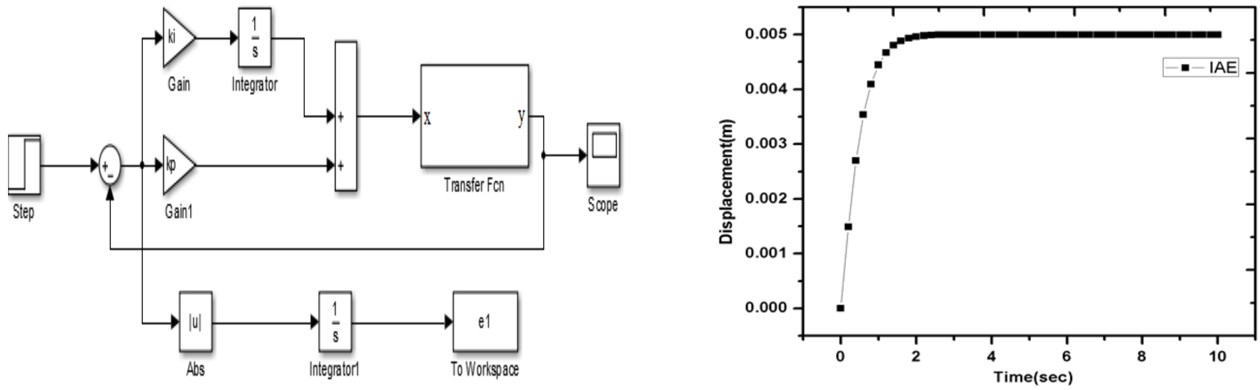
Self-tuning of PI controller for optimal control performance is achieved by PSO algorithm. Tuned PI gain parameters (K_p, K_i) for the model shown in Eq. (28) is evaluated. PI parameters search space is selected in the range of 0 to 100 and the swarm size is taken 50 which are considered a lot enough.

4. Simulation result

To get the system response Simulink® has been used in this work. Simulink® is a graphical tool of Matlab® for modeling, simulating and analyzing complex and dynamic systems. It is generally used in the automatic controlling system and digital system processing. Simulink® model of performance index IAE, ISE, ITAE, ITSE and its output response has been shown in Figs. 7-10 respectively.

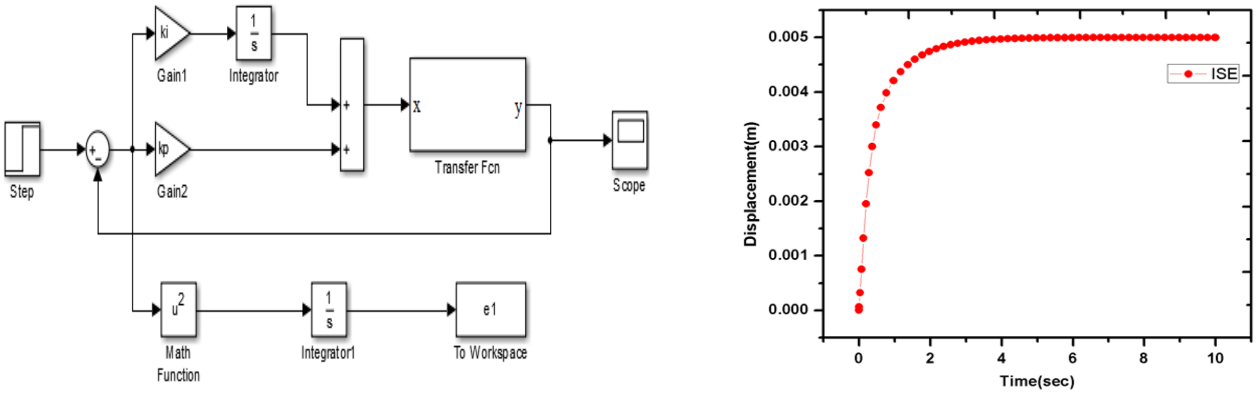
PSO based PI position controller has been used to control the position (displacement) of IPMC actuator with respect to given voltage. It is to be noted that PI tuning is done based on rise time, settling time and SSE (steady state error). Fig. 11 shows the comparative result of PI controller, where step response for different performance indices (IAE, ISE, ITAE and ITSE) have been evaluated.

Fig. 12 shows some snapshots of the movement of particle swarm in a search space. As they moves towards global maxima or minima, at the end of the simulation these swarm gathered to global best solution.



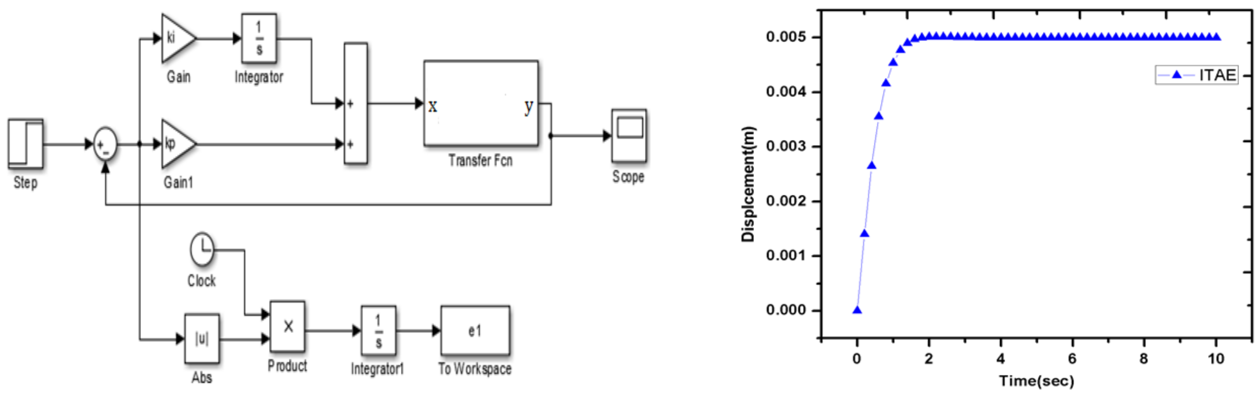
(a) (b)

Fig. 7 (a) Simulink® model for IAE and (b) Step response for IAE



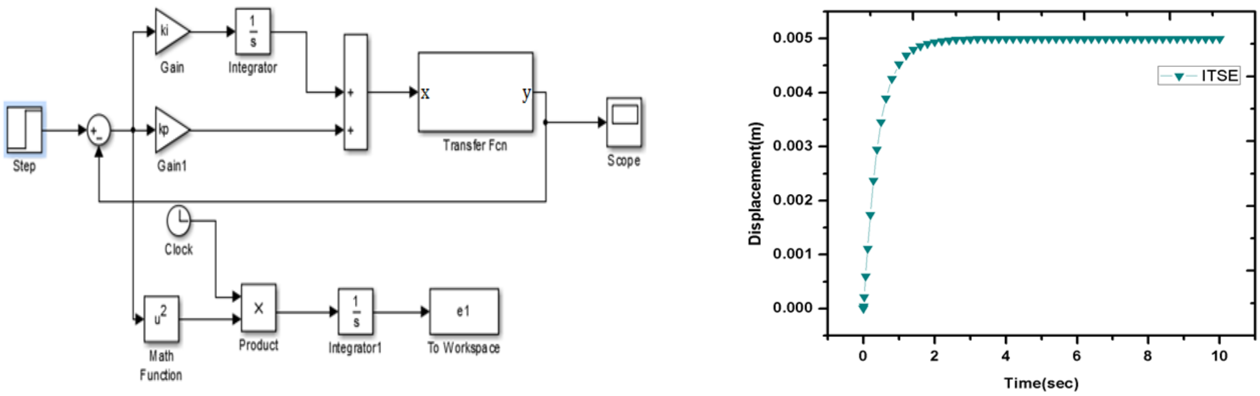
(a) (b)

Fig. 8 (a) Simulink model for ISE and (b) Step response for ISE



(a) (b)

Fig. 9 (a) Simulink model for ITAE and (b) Step response for ITAE



(a) (b)

Fig. 10 (a) Simulink model for ITSE and (b) Step response for ITSE

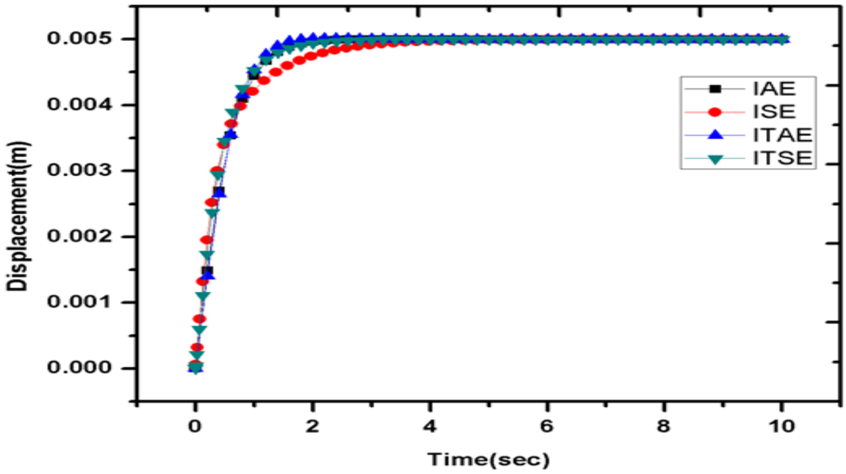


Fig. 11 Comparison of step response of PI controller

Table 2 Step response of PI controller

Tuning Method	K_p	K_i	Rise Time(sec)	Settling Time(sec)	Steady state error (%)
PSO-PI1 (IAE)	383.2975	1167.5	1.069	1.669	0
PSO-PI1 (ISE)	623.3782	1044.2	1.37	2.77	0
PSO-PI1 (ITAE)	345.7893	1221.6	1.0	1.4	3.4
PSO-PI1 (ITSE)	505.5690	1278.9	1.0	1.8	0

It is to be noted that PSO gives the optimum or nearest best solution so that PI parameters (K_p, K_i) will be somewhat different in each run, but they are close in value. Step response performance of PI controller for different error schemes is shown in Table 2.

From the Fig. 11 and Table 2, we can see that ITAE has lesser rise time and settling time compare to other performance indices but it has 3.4% of the steady state error. ITSE has fast rise time but settling time is more. So based on the system performance requirement one can choose the tuning method.

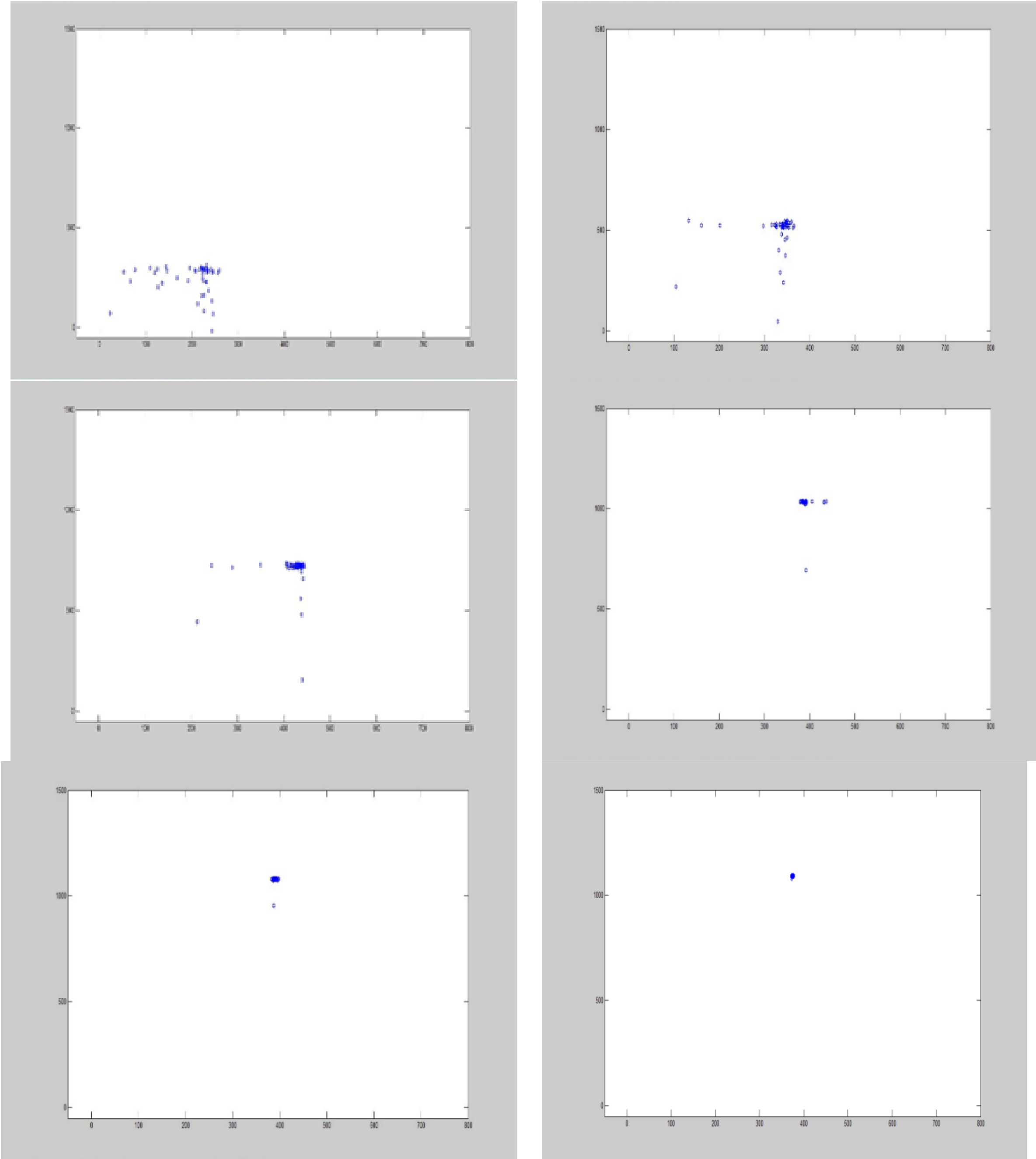


Fig. 12 Swarm movement in search space

5. Conclusions

Dynamic characteristics of an IPMC propulsor is studied using a physics based model. It was found that maximum cruising speed occurred at the resonance frequency of 4.6 Hz. The IPMC propulsor produced maximum cruising speed of 1.5 cm/s without using passive fin. Maximum cruising speed increased up to 2.4 cm/s when a passive fin is used. In order to control the displacement of IPMC propulsor, a PI controller is used. Moreover, to optimize PI gain parameter several performance indices can be used as the objective function such as IAE, ISE, ITAE and ITSE. It is found that ITAE has lesser rise time and settling time compare to other performance indices but it has 3.4% of the steady state error. ITSE has fast rise time but settling time is more. So based on the system performance requirement one can choose the tuning method.

References

Aureli, M., Kopman, V. and Porfiri, M. (2010), "Free-locomotion of underwater vehicles actuated by ionic polymer metal composites", *IEEE/ASME T. Mechatronics*, **15**(4), 603-614.

Bandyopadhyay, P.R. (2005), "Trends in biorobotic autonomous undersea vehicles", *IEEE J. Ocean Eng*., **30**(1), 109-139.

Chen, Z. and Tan, X. (2008), "A Control-oriented and physics-based model for ionic polymer-metal composite actuators", *IEEE/ASME T. Mechatronics*, 13(5), 519-529.

Chen, Z., Hedgepeth, D.R. and Tan, X. (2009), "A nonlinear, control oriented model for ionic polymer–metal composite actuators", *Smart Mater. Struct*., **18**(5), 055008 (9pp).

Chen, Z., Shatara, S. and Tan, X. (2010), "Modeling of biomimetic robotic fish propelled by an ionic polymer–metal composite caudal fin", *IEEE/ASME T. Mechatronics,* **15**(3), 448-459.

Chen, Z., Tan, X., Will, A. and Ziel, C. (2007), "A dynamic model for ionic polymer–metal composite sensors", Smart Materials and Structures, 16(4), 1477–1488.

Cho, S., Jo, H., Jang, S., Park, J., Jung, H.J., Yun, C.B., Spencer Jr. B.F. and Seo, J.W. (2010), "Structural health monitoring of a cable-stayed bridge using wireless smart sensor technology: Data analyses", *Smart Struct. Syst*., **6**(5-6), 461-480.

Clerc, M. (1999), "The Swarm and the queen: towards a deterministic and adaptive particle swarm optimization", *Proceedings of the Conference on Evolutionary Computation*, Washington D. C. USA.

Gaing, Z.L. (2004). "A particle swarm optimization approach for optimum design of PID controller in AVR system", *IEEE T. Energy Conver*., **19**(2), 384-391.

Guo, S., Fukuda, T. and Asaka, K. (2003), "A new type of fish-like underwater microrobot", *IEEE/ASME T. Mechatronics,* **8**(1), 136-141.

Hubbard, J.J., Fleming, M., Palmre, V., Kim, K.J. and Leang, K.K. (2014), "Monolithic IPMC fins for propulsion and maneuvering in bioinspired underwater robotics", *IEEE J. Oceanic Eng*., **39**(3), 540-551.

Karthigan, G., Mukherjee, S. and Ganguli, R. (2015), "Fish inspired biomimetic ionic polymer-metal composite pectoral fins using labriform propulsion", *Mech. Adv. Mater. Struct*., **22**(11), 933-944.

Kennedy, J. and Eberhart, R.C. (1995), "Particle swarm optimization", *Proceeding of the IEEE International Conference on Neural Networks*, Perth, Australia.

Kim, K.J. and Shahinpoor, M. (2003), "Ionic polymer-metal composites: II. Manufacturing techniques", *Smart Mater. Struct*., 12(1), 65–79.

Lighthill, M.J. (1970), "Aquatic animal propulsion of high hydromechanical efficiency", *J. Fluid Mech*.., **44**(2), 265-301.

Mbemmo, E., Chen, Z., Shatara, S. and Tan, X. (2008), "Modeling of biomimetic robotic fish propelled by an ionic polymer-metal composite actuator", *Proceedings of the IEEE International Conference on Robotics and Automation*, Pasadena, CA, United States.

Mukherjee, S. and Ganguli, R. (2010), "A dragonfly inspired flapping wing actuated by electroactive polymers", *Smart Struct. Syst*., **6**(7), 867-887.

Nemat-Nasser, S. and Li, J.Y. (2000), "Electromechanical response of ionic polymer-metal composites", *J. Appl. Phys*., **87**(7), 3321–3331.

Ogata, K. (2010), Modern Control Systems (5th Ed.), Prentice Hall, New Jersey, USA.

Richardson, R.C., Levesley, M.C., Brown, M.D., Hawkes, J.A., Watterson, K. and Walker, P.G. (2003), "Control of ionic polymer metal composites", *IEEE/ASME T. Mechatronics*, **8**(2), 245-253.

Sfakiotakis, M., Lane, D.M. and Davies, J.B.C. (1999), "Review of fish swimming modes for aquatic locomotion", I*EEE J. Oceanic Eng*., **24**(2), 237-252.

Shahinpoor, M. and Kim, K.J. (2001), "Ionic polymer-metal composites: I. Fundamentals", *Smart Mater. Struct*., **10**(4), 819-833.

Shahinpoor, M. and Kim, K.J. (2004), "Ionic polymer-metal composites – III. Modeling and simulation as biomimetic sensors, actuators, transducers and artificial muscles", *Smart Mater. Struct*., **13**(6), 1362-1388.

Shen, Q., Wang, T. and Kim, K.J. (2015), "A biomimetic underwater vehicle actuated by waves with ionic polymer-metal composite soft sensors", *Bioinspiration Biomimetics*, **10**(5), Article No. 055007.

Shen, Q., Wang, T., Wen, L. and Liang, J. (2013), "Modeling and fuzzy control of an efficient swimming ionic polymer-metal composite actuated robot", *Int. J. Adv. Robot. Syst*., **10**, 1-13.

Shi, H. and Eberhart, R. (1998), "A modified particle swarm optimizer", *Proceedings of the IEEE International Conference on Evolutionary Computation*, Anchorage, Alaska, USA.

Tiwari, R., Kim, K.J. and Kim, S.M. (2008), "Ionic polymer-metal composite as energy harvesters", *Smart Struct. Syst*., **4**(5), 549-563.

Weiland, L.M. and Akle, B. (2010), "Ionic polymer transducers in sensing: The streaming potential hypothesis", *Smart Struct. Syst*., **6**(3), 211-223.

Yim, W., Lee, J. and Kim, K.J. (2007), "An artificial muscle actuator for biomimetic underwater propulsors", *Bioinspiration Biomimetic*, **2**(2), 31-41.

HJ