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Simulation of Micro-EDM Servomotor for Machining Micro Pits on Hip Implant

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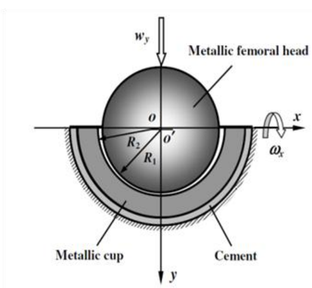
Graphical abstract



Abstract

Metal-on-metal articulation of hip implant suffers from friction due to the moving metal surface. Thus it would shorten the lifespan of the joint. One of the significant current discussions in biomedical field is to reduce the friction between the articulations surface. It was found that lubrication technique is applicable in order to reduce the friction. A surface texture which micro pits formation on the metal surface of hip implant then was found to benefits the lubrication performance. Due to many advantages offered by electrical discharge machining especially in micro machining, it is utilized for machining the micro pits in this research. Thus, this paper is proposing on machining and control method for this purpose in terms of workpiece placement, coordination and orientation related to the electrode of the electrical discharge machining system. In this paper, a design of motor control simulation has been made using DC motor, Proportional-Integral controller and particle swarm optimization in order to get a better performance of micro-machining positioning for this purpose. From the simulation, the result obtained showed that the model could give a better positioning when using particle swarm optimization technique.

Keywords: Hip implant; lubrication; micro pits; electrical discharge; DC motor; PI controller; particle swarm optimization

Abstrak

Artikulasi antara bahan logam yang terdapat pada implant di bahagian pinggul mengalami geseran akibat daripada permukaan logam yang bergerak dan ini akan memendekkan jangka hayat sendi tersebut. Salah satu isu penting masakini dalam bidang bioperubatan adalah mengurangkan kesan geseran permukaan artikulasi. Didapati pelinciran merupakan satu kaedah untuk mengurangkan geseran. Permukaan yang ditekstur di mana lubang-lubang kecil yang bersaiz mikro yang dimesin pada permukaan logam permukaan implant didapati pelinciran tersebut. Oleh kerana banyak kelebihan yang ditawarkan oleh *electrical discharge* dalam pelbagai industry pembuatan yang bersaiz mikro, ianya digunakan dalam kajian ini. Kertas kerja ini mencadangkan kaedah pemesinan dan pembuatan lubang-lubang kecil ini menggunakan mesin *electrical discharge* dari segi kedudukan, koordinat dan orientasi bahan logam yang dimesin tersebut. Dalam kertas kerja ini, rekabentuk sistem kawalan adalah menggunakan motor arus terus, pengawal kamilan kadar terus dan *Particle Swarm Optimization* untuk mendapatkan kedudukan pemesinan mikro yang lebih baik. Berdasarkan simulasi, keputusan menunjukkan bahawa model tersebut boleh menentukan kedudukan yang lebih baik setelah menggunakan teknik *Particle Swarm Optimization*.

Kata kunci: Implan pinggul; pelinciran; lubang kecil; electrical discharge; motor arus terus; pengawal kamilan kadar terus; *particle swarm optimization*

1.0 INTRODUCTION

Hip replacement is one of the solutions that become significant nowadays which help to improve the quality of life for patients material has been introduced to reduce wear compared to UHMWPE. Metal-on-metal (MOM) hip implant which consists of a metallic femoral head articulation with an acetabular cup was introduced as an alternative material combination to avoid the who suffer from joint disease. Material used in the early hip implant is an Ultra High Molecular Weight Polyethylene, UHMWPE. This type of material results in failure since its produces more wear [1] and aseptic loosening. Then, metal polyethylene wear particles and several researches have been conducted by [2-4] on the effects of MOM hip implants to patients. Problems regarding friction and wear of this metal material are still the crucial issues in implant field. In order to reduce wear and friction that occurs between the articulating surfaces in hip implant, lubrication activity must be presented. Naturally, hip joints are lubricated by synovial fluid. The fluid is an electrolyte solution that contains proteins, lipids and hyaluronic acid which is produced by the synovial membrane and cartilage. When a person undergo for hip implant surgery, the synovial membrane eventually reforms and produce a liquid similar to synovial fluid that help to lubricate the implanted devices. However, regarding to Linstorm [5], there was no room or space for the lubricant to be sustained into the space between cup and head of the implant thus causing a constant pain faced by patient.

It was found by [6] that surface texturing or micro pits which is known as dimples, holes, oil pockets or cavities formation on the material surface would give beneficial effect in reducing wear and friction for hip implant. Since the size of pits requirement are too small, thus it requires micro-machining process with good surface finish. An Electrical Discharge Machining (EDM) has been applied in many manufacturing industries as its ability to remove an extremely hard and brittle material that cannot be machined using traditional machining. This is due to its efficiency to machine an advanced difficult-to-machine material with high precision, complex shapes and high surface quality. Hence, it is utilized in this research for machining micro pits on metal-on-metal hip implants. Section 2 will further reviews on the existing EDM system and the proposed mechanical structure of EDM. In this paper, a new workpiece positioning system of EDM structure has been proposed as discussed in section 3. A DC motor of EDM system was modeled and a controller called Particle Swarm Optimization (PSO) technique has been incorporated to achieve better accuracy in positioning system that would give significant benefits in manufacturing hip implant application. Section 4 refers to results and discussion and lastly, section 5 for conclusion.

■2.0 ELECTRICAL DISCHARGE MACHINING SYSTEM

2.1 Electrical Discharge Machining Research

EDM is a non-contact process based on thermoelectric energy where the workpiece and the tool are both placed in position so that they do not touch between each other. In EDM, both electrode and workpiece must be electrically conducted and immersed in a dielectric fluid so that the gap remains between the electrode and workpiece are filled with the dielectric fluid in order to complete the process. Dielectric fluid is an insulator and act as electrical conductor in a certain voltage. When a small gap (about 25 micrometer) is achieved, a spark occurs between the tool and workpiece. Thus, small quantities of metal material will be evaporated due to high temperature at the spark point [7].

Recently, EDM technology has become more significant and high demand in mold and dies manufacturing. The machining method has drawn interest on many researches due to its broad industrial applications such as in aerospace, automotive and medical devices manufacturing. Many inventions have been made in order to improve its machining time, surface quality and integrity, material removal rate and tool wear. In industry, micro hole with diameter less than 0.5 mm has a wide range of applications such as ink-jet printer nozzles, orifices in biomedical devices and diesel fuel injector spray holes. For this purposes, micro-EDM is commonly chosen due to its ability to machine with high repeatability without burrs and material alteration[8-10]. For EDM mechanical structure, most of the previous research has been focused on the development and improvement in movement of the tool (electrode) in Z direction [11] and table in X and Y direction.

2.2 Proposed Machining Method and Mechanical Structure

Metal-on-metal (MOM) hip implant consists of a metallic femoral head articulation with an acetabular cup. Figure 1 shows the main components of hip implant while Figure 2 shows a model of a ball in socket configuration for hip implant which the cup is positioned horizontally under the vertical load and the flexion-extension motion around the x-axis.

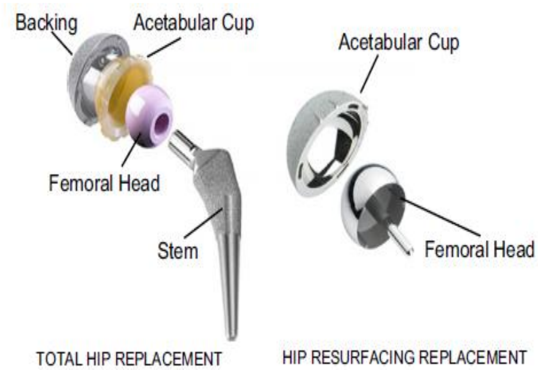


Figure 1 Main component of artificial hip joint [12]

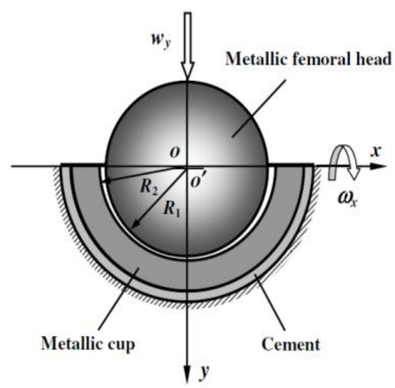


Figure 2 A ball and socket configuration in hip implant [4]

In order to produce micro pits on the curvy metal surface, the angle of machining is one of important factor that need to be considered. From the previous research conducted by [13], it shows that there are an obvious trend between the crack length and the drilling angle which the crack produced can be reduced by increasing drilling angle to surface.

Therefore, it is beneficial to machine the pits perpendicularly to the curvy surface of the metal workpiece to reduce crack formation such as illustrated in Figure 3. Instead of moving electrode, it is quite impractical in micro-EDM machining due to the size of electrode ram [14]. Hence, the workpiece positioning in micro-EDM can be considered for this purpose and the proposed mechanical servo system of the workpiece positioning can be represented by Figure 4.

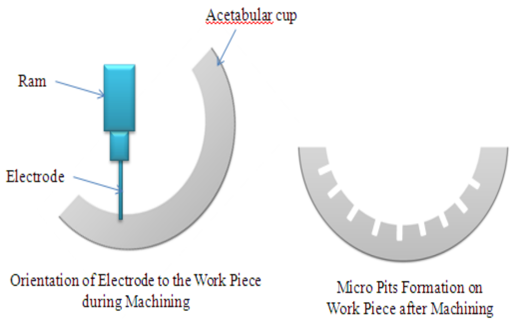


Figure 3 Electrode positioning of the workpiece table [14]

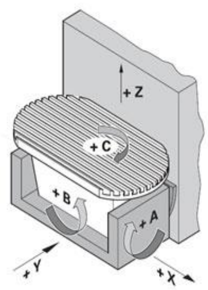


Figure 4 Mechanical structure of workpiece table

■3.0 CONTROLING METHODS FOR EDM

3.1 DC Motor Control Technique

In EDM servo mechanism, DC motor is usually used to control the gap between electrode and workpiece because of its capability to provide excellent speed control for acceleration and deceleration with effective and simple torque control. As the power supply of a DC motor is connected directly to the field of the motor, it can be used to accurately control the speed and torque. Thus, it may be a part of closed loop control systems for precise positioning of a driven machine.

Furthermore, for a small DC motor such as DC motor with 12V operation condition, it is more easier to interface with control electronics [15]. Therefore, DC motor was chosen in this research in order to control the workpiece positioning. Figure 5 is the schematic diagram of DC motor model and its dynamic equations.

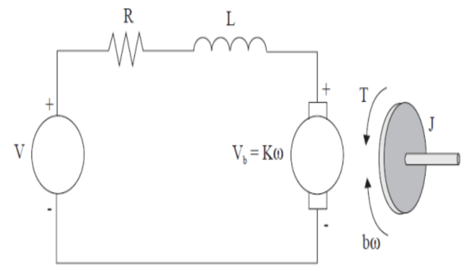


Figure 5 Schematic diagram of DC motor

$$T = Ki \quad (1)$$
$$V_b = K\omega = K\frac{d\theta}{dt} \quad (2)$$
$$J\frac{d^2\theta}{dt^2} + b\frac{d\theta}{dt} = Ki \quad (3)$$
$$Ri + L\frac{di}{dt} = V - K\frac{d\theta}{dt} \quad (4)$$

From equations (3) and (4), the transfer functions are:

$$Js^2\theta(s) + bs\theta(s) = KI(s) \quad (5)$$
$$LsI(s) + RI(s) = V(s) - Ks\theta(s) \quad (6)$$

Combine (5) and (6),

$$I(s) = \frac{V(s) - Ks\theta(s)}{R+Ls} \quad (7)$$

Substitutes (7) into (5),

$$Js^2\theta(s) + bs\theta(s) = K\frac{V(s) - K_s\theta(s)}{R+Ls} \quad (8)$$

After simplification, transfer function for the ϴ(s)/V(s) is as follow:

$$\frac{\theta(s)}{V(s)} = \frac{K}{s[(R+Ls)(Js+b)+K^2]} \quad (9)$$

Then, the transfer function for a linear system of the DC motor can be represented as depicted in Figure 6 where DC motor parameters that was used in the simulation is shown in Table 1.

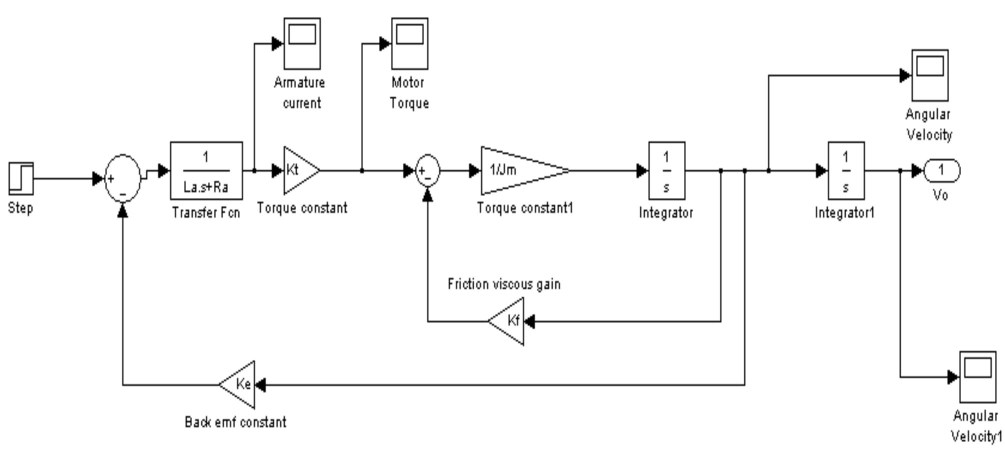


Figure 6 Linear motor model

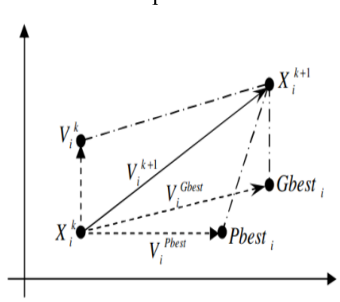
Table 1 Quantum NEM17 DC Motor Parameters

Motor parameters	Symbol	Units	Value used in simulation
Armature Resistance	R_a	Ω	1.51
Armature inductance	L_a	H	0.55×10^{-3}
Inertia of motor	J_m	Kgm2	1.10×10^{-6}
Torque constant	K_t	Nm	0.027
Back emf constant	K_e	V/rad/s	0.027
Friction viscous gain	K_f	Nm/rad/s	5.06×10^{-6}

However, controlling DC motor using feedback control itself does not satisfy to produce desired output. Therefore, controller such as PI and PID are often used in EDM servomechanism system because of its robustness. Gain such as K_p, K_i and K_d will be determined by the controllers and this parameters need to be tuned appropriately so that it can give a desired output.

3.2 Particle Swarm Optimization Algorithm

As mentioned above, the gain value of the PID controller must be tuned appropriately. With the existence of various artificial intelligence techniques such as Ziegler-Nichols, Genetic Algorithm, Artificial Neural Network, Ant Colony Optimization and Differential Evolution could help to tune and search for optimal value of the controllers parameters and get to improve the system response. More recent, a new optimization technique has been introduced which is Particle Swarm Optimization technique that was introduced by Dr. Eberhart and Dr. Kennedy in 1995. This technique is inspired by social behavior of bird flocking or fish schooling which is initialized with a population of random solutions and searches for optima by updating generations using a population of particles, corresponding to individual. Fig 7 illustrates the concept of modification of a searching point by PSO in which P_{best} indicates that each particle adjust its trajectory best on its best solution (fitness) that it achieved so far while G_{best} indicates that each particle also modify its trajectory towards the best previous position attained by other neighborhood particles [16]. Figure 8 is the SIMULINK block diagram that illustrate PSO implementation in the control system while Figure 9 shows flow chart of PSO implementation in DC motor system.



X^k: current position,
X^{k+1} : modified position,
V^k: current velocity,
V^{k+1}: modified velocity,
V^{Pbest}: velocity based on Pbest,
V^{Gbest}: velocity based on Gbest.

Figure 7 Modification of a searching point by PSO [17]

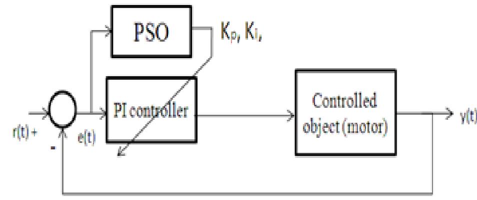


Figure 8 Block diagram of PSO implementation for DC motor control [14]

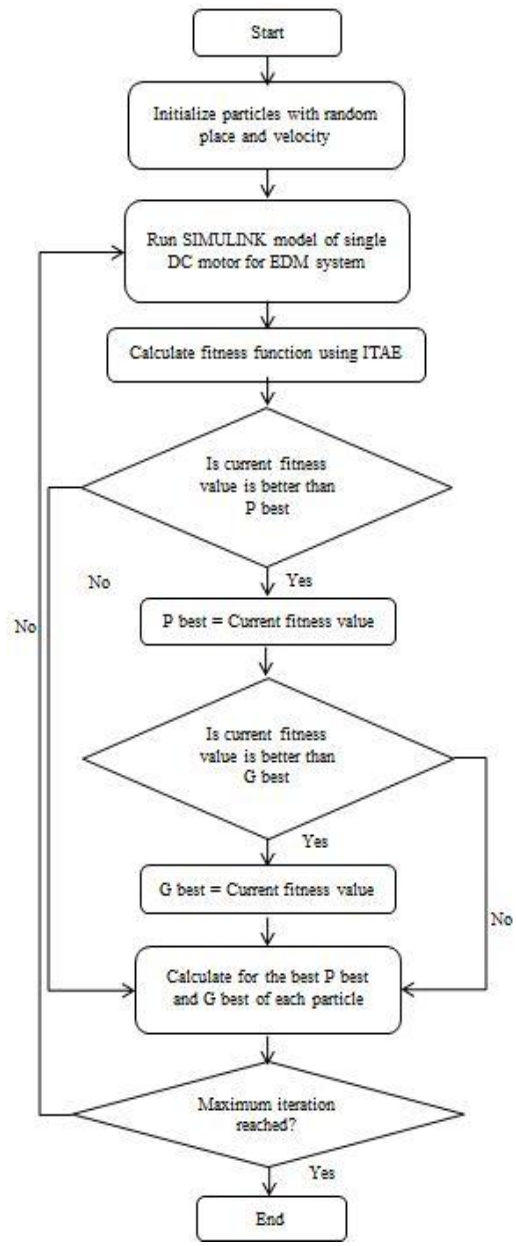


Figure 9 Flow chart of PSO implementation for DC motor in EDM

3.2.1 Performance Evaluation Criteria

Quantification of system performance when implementing PSO algorithm is achieved through a performance index. Performance index which is objective function was used in this simulation is based on error criterion. There are several error criterions that exist, which a controller's performance can be evaluated in terms of:

Integral of Absolute Errors (IAE) criteria:

$$I_{IAE} = \int_0^T |e(t)|dt \qquad (10)$$

Integral Square of Errors (ISE) criteria:

$$I_{ISE} = \int_0^T e^2|(t)|dt \qquad (11)$$

Integral of Time multiplied by Absolute Errors (ITAE) criteria:

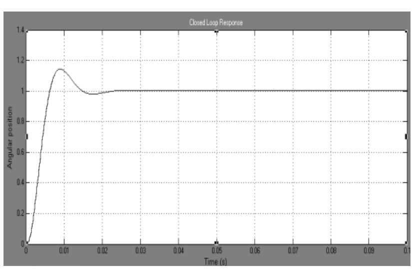
$$I_{ITAE} = \int_0^T t|e(t)|dt \qquad (12)$$

Performance index that was used in this system is Integral of Time Multiplied by Absolute Error (ITAE) in order to calculate the fitness function. Therefore, PI controller is proposed with the optimal parameters derived from PSO algorithm which the value of ITAE is minimized. The comparisons of the system performance between PI controller with and without implementing PSO have been observed. Besides, a comparison between each evaluation criterion also has been made.

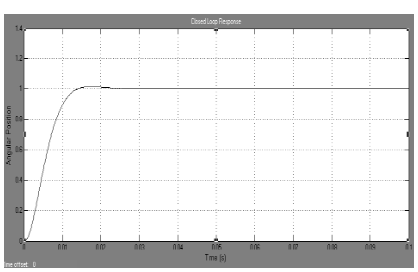
■4.0 RESULTS AND DISCUSSION

As a positioning system is an important issue in this research, this simulation was carried out to determine a better positioning system in controlling DC motor for EDM servomechanism. Several comparisons have been made between PI controller with and without implementing PSO, and PSO fitness calculation using ITAE, ISE and ITE has been made.

For a closed loop time response, the output from angular position was taken and it shows a slight different in rise time between PI with PSO and PI without PSO. However, the overshoot was obviously reduced from 1.1446 to 1.0144 using PSO which reducing overshoot is significant in order to achieve an accurate workpiece positioning in micro-EDM system. Figure 10 illustrates the step response while Table 2 shows the performance criteria of the system positioning with and without implementing PSO.



(a)



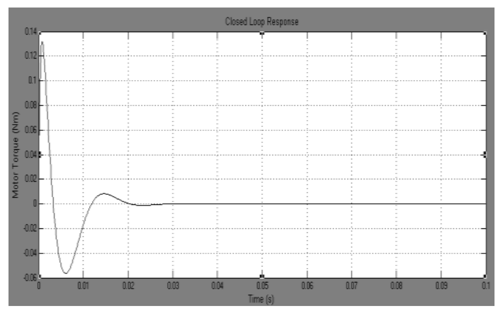
(b)

Figure 10 Closed loop response for angular position of DC motor (a) without implementing PSO, (b) with PSO implemented

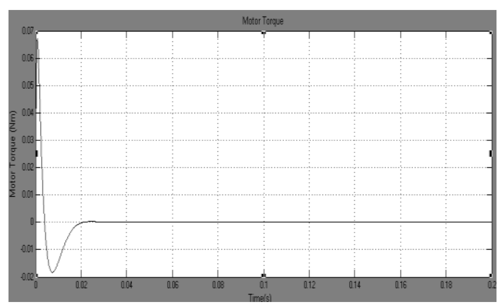
Table 2 Performance criteria micro-EDM system

	PI Controller without PSO	PI Controller with PSO
K_p	9.5256	4.8527
K_i	3.9876	0.0445
Rise time (sec)	0.0091	0.0140
Settling time (sec)	0.0485	0.0276
Steady state error	0.0015	0.0001
Overshoot	1.1446	1.0144

The motor torque shows a reduction in settling time to 0.0195s from 0.043s and maximum overshoot of the motor torque is reduced too from 0.1317 Nm to 0.0671 Nm. These results are shown in Figure 11 (a) and Figure11 (b).



(a)

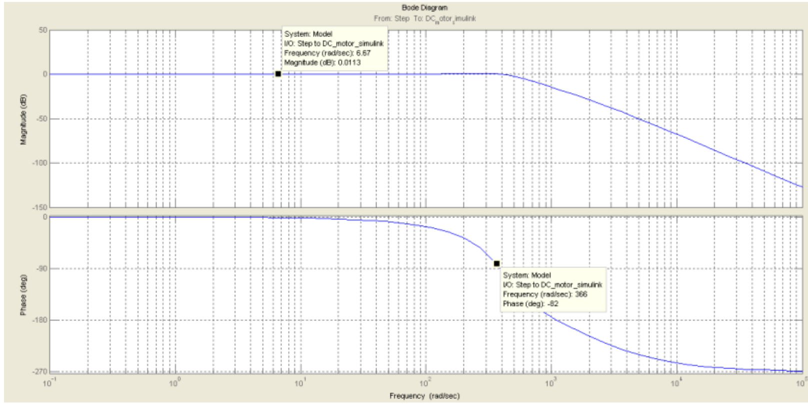


(b)

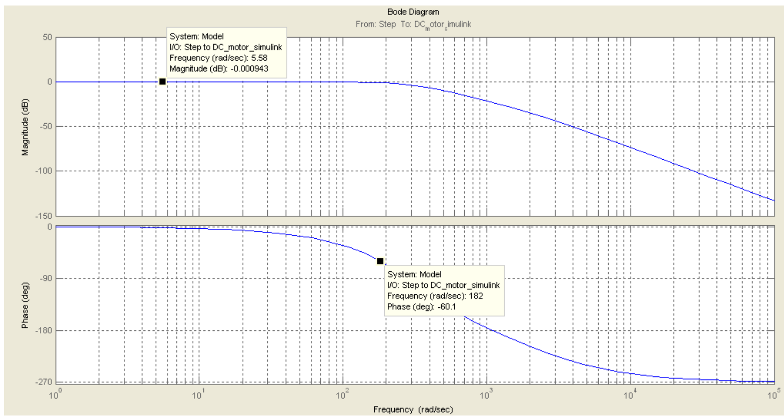
Figure 11 Closed loop response for motor torque of DC motor (a) without implementing PSO, (b) with PSO implemented

In terms of frequency domain, bode plots are very useful way to represent the gain and phase which refers to frequency domain behavior of a system. Figure 12(a) and Figure 12(b) show the frequency response of the micro-EDM positioning system without and with implementing PSO.

Further comparison of performances criteria using PSO technique between ITAE, IAE and ISE has been made. From the simulation, it was observed that ITAE could give a betterperformance for this system which it could optimize the value of PI controller parameter and give a better step response of angular position. Figure 13(a), (b) and (c) show the step response while Table 3 shows the closed loop response of the system using the different performances criteria.

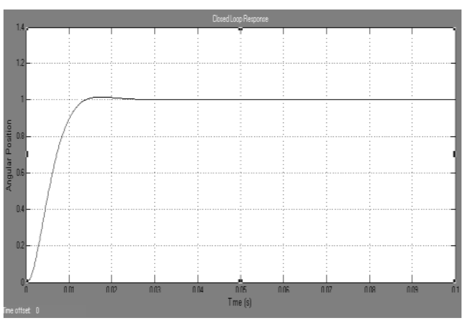


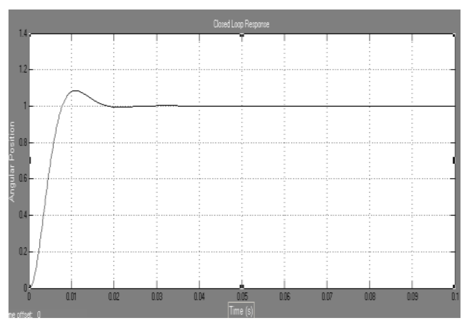
(a)



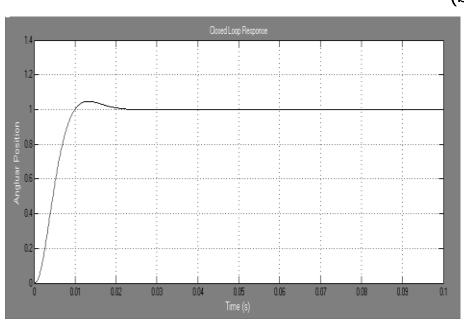
(b)

Figure 12 Frequency response of DC motor positioning with PI controller (a) without implementing PSO (b) with PSO implemented





(a) (b)



(c)

Figure 13 Closed loop response using PSO for (a) ITAE performance index (b) IAE performance index (c) ISE performance index

Table 3 Closed loop responses of DC motor system using different performance index

	ITAE	IAE	ISE
Kp	4.8527	7.4319	6.0709
Ki	0.0445	3.3831	2.5374
Rise time (s)	0.0140	0.0007	0.0008
Settling time (s)	0.0276	0.0435	0.0312
Steady state error	0.0001	0.0005	0.0018
Overshoot	1.0144	1.0859	1.0470

■5.0 CONCLUSION

This paper proposed a new design of mechanical structure of workpiece positioning and the controlling model in EDM for machining micro pits on hip implant devices. The PI parameters in the model of workpiece positioning system of micro-EDM servomotor have been successfully tuned with implemented PSO algorithm that search for optimal value of the controller for ITAE index performance. The simulation shows this method can reduce overshoot, settling time and steady state error of the system which are needed for machining micro pits on the hip implant devices.

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