ICIC Express Letters
Volume **16**, Number **11**, November **2022**

ICIC International ©2022 ISSN 1881-803X
pp. 1193–1204

DESIGN OF OPTIMAL SLIDING MODE CONTROL OF PAM-ACTUATED HANGING MASS

Amjad Jaleel Humaidi[1], Saleem Khalefa Kadhim[1], Musaab Esam Sadiq[2]
Saad Jabbar Abbas[3], Ayad Qasim Al-Dujaili[4] and Ahmed Rashid Ajel[4]

[1]Control and Systems Engineering Department
University of Technology
Baghdad 10011, Iraq
{ amjad.j.humaidi; 60014 }@uotechnology.edu.iq

[2]General Company for Grain Processing
Ministry of Trade
Baghdad 10011, Iraq
mesmsi50@gmail.com

[3]AL Rafidain University College
Baghdad 10011, Iraq
saad.jabbar@ruc.edu.iq

[4]Electrical Engineering Technical College
Middle Technical University
Zafaraniyah, Baghdad 10011, Iraq
{ ayad.qasim; dr_ahmed.r }@mtu.edu.iq

Received December 2021; accepted March 2022

Abstract. *The systems actuated by Pneumatic Artificial Muscles (PAMs) are characterized by high nonlinearity and time-varying of their coefficients. Therefore, nonlinear and robust controllers are required to cope with these challenging control problems. This work presents the development of control design for trajectory tracking of PAM-actuated mass based on Sliding Mode Control (SMC). The stability of controlled system has been analyzed and the control law is developed based on Lypunov theorem. The Particle Swarm Optimization (PSO) technique is used to tune the design parameters of the proposed controller for further performance enhancement of controlled PAM system. A comparison study has been conducted in terms of dynamic performances between optimal and non-optimal sliding mode controllers via computer simulation using MATLAB/Simulink.*

Keywords: Pneumatic artificial muscles, Hanging mass, Sliding mode control, Particle swarm optimization, Stability analysis

1. **Introduction.** The pneumatic actuators such as cylinders, pneumatic stepper motors, bellows, and pneumatic engines are commonly used to date. The Pneumatic Artificial Muscles (PAMs) is one type of pneumatic actuators, which are made mainly of inflatable and flexible membrane that works like inverse bellows; i.e., they contract on inflation. The force generated by PAM actuators does not depend only on pressure, but also on the state of inflation, which adds another source of spring-like behavior. These PAMs, which mimic the animal muscle, are characterized by lightweight, since the membrane forms the core element of these actuators. However, they can transfer the same amount of power as cylinders do, where both actuators have the same volume and pressure ranges [1,2].

The PAMs are used in many applications due to light weight, soft, simple construction and high force/weight ratio, direct connection, easy replacement and safe operation. The PAM actuators found their applications in biomechanics, bio-robotics, robotics, artificial limb replacement. Also, since PAMs are noise-free devices, they are applicable in hospital

---

DOI: 10.24507/icicel.16.11.1193

treatments to patients who are sensitive to noise of sounds. Compared to motor, the PAMs do not need to gear mechanism in order to increase power due to their high power/volume ratios. Due to their elasticity, the PAMs are useful for the natural frequency of biped locomotion. Additionally, PAMs are useful for under-water applications due to their water immunity [1,2]. Since the operation of PAM mimicking that of real muscle, PAM is effectively used to implement the humanoid.

Many disadvantages have been reported with PM-actuated systems. Due to antagonistic structure of PMs, one needs a pair of PAMs in order to actuate a load in one Degree of Freedom (DOF), while only one actuator is needed to move the load for the same DOF in case of motor-actuated systems [1,2].

The PAM-based systems are characterized by high complexity and nonlinearity and involve uncertain parameters. Many researchers have presented different control strategies to address the control problems of uncertain mechanical systems actuated by pneumatic muscles. The following researches address the recent control strategies to PAM-actuated systems.

In [3], a new model of operation of PM systems has been developed, which improves the assessment of forces and displacement that can be achieved by the actuator. In [4], a dexterous manipulator powered by 18 Pneumatic Muscle Actuators (PMA) has been designed. The PID controller with suitable feed forward term is used to control the pneumatic system. In [5], the work applied two types of sliding mode control schemes for angular position control tracking of single link robotic arm actuated by pair of PAMs. These control schemes are based on first and second order sliding mode control methodology. In [6], a new control method is proposed to overcome the space problem due to the implementation of actual PAM robot controlled by proportional pressure regulator. The proposed controller is synthesized based on a set of small encoders and pressure switches to be replaced by the commercial proportional pressure regulator, whose size is not suitable to be applied on stand-alone robot. In [7], Lilly and Yang applied the sliding mode techniques for angle tracking of planar PAM-actuated manipulator, which are arranged in an agonist/antagonist set-up, under load exertion. The sliding mode controller is developed for planar elbow manipulator such as to guarantee accuracy in the presence of modeling errors. In [8], an adaptive output tracking controller has been designed for one-link PAM-actuated robot arm. The proposed controller has developed under unknown physical system parameters represented by length of the arm, muscle coefficients, moment of inertia, and mass. In [9], Scaff et al. proposed an optimal conventional PID controller for position control of one Degree of Freedom (DOF) system actuated by McKibben PAM. The terms of PID controller are tuned using Simulated Optimization Algorithm (SOA) to obtain better dynamic performance of PID-controlled system. In [10], Lilly presented an adaptive tracking techniques to enforce the joint angle of PAM-actuated limbs to track a specified reference trajectory. Two configurations have been studied: one based on tricep PM and the other on bicep PM. In [11], Boudoua et al. proposed a novel neural network-based twisting sliding mode controller for control of PAM-actuated robot arm and for chattering reduction in control signal. In [12], Caldwell et al. developed a new high power/weight and power/volume braided Pneumatic Muscle Actuator (PMA). Control of these muscles is explored via adaptive pole-placement controllers.

The Variable Structure Control (VSC) with Sliding Mode Control (SMC) was developed by Emelyanov and his team assistances in the early 1950's [13]. The SMC methodology is an effective tool which aims to design a controller for a nonlinear, complex, high order and time varying systems in the presence of certain or uncertain parameters variations and external disturbances [13,14]. The main advantage of the SMC is that it is low sensitive for system parameters variations and disturbances which restricted the necessity of exact modeling [14]. The SMC replaces the dynamics of a system by application of a discontinuous control signal that forces the system to slide along a stable manifold known as sliding surface [15,16].

The SMC introduces control law which can be distributed into two main parts (equivalent part and switching part). The equivalent part deals with dynamic of the system and sliding surface such as to conduct the trajectory of the states toward the sliding surface. The switching part of control signal is responsible for driving states trajectory to equilibrium point by maintaining the dynamics of the system onto the sliding surface. In the control action of the SMC, there is an undesired phenomenon known as chattering, which is caused by the high frequency oscillation of the sliding variable around the sliding surface, and it is one problem in using sliding mode technique [17-23].

The works, which have been interviewed in above literature, have not addressed the effect of optimization of design parameters on performance of controlled pneumatic system. It has been shown that the setting of design parameters associated with the proposed controller (SMC) has to meet the stabilization requirement of designed controller and they have a direct impact on its performance. The setting based on try-and-error procedure does not lead to optimal performance of controller and hence Particle Swarm Optimization (PSO) algorithm has been suggested for tuning purposes. This modern optimization technique was firstly proposed by Kennedy in 1995 and it was inspired by the behavior of organisms [19]. This optimization tuner is characterized by fast convergence, efficiency of computation and it has the capability to find local and global solutions [24-26].

The present work proposed a controller, represented by SMC to control and guarantee the stability of PAM-actuated hanging system under variation of system parameters. In addition, the PSO technique is introduced for tuning the designed parameters of the proposed controllers to better enhance the performances of the proposed controller. The contributions of the work can be summarized by the following points.

- To develop the SMC algorithm to solve the high non-linearity and time varying inherited in the PAM-actuated hanging mass.
- To better improve the dynamic performance of PAM-actuated hanging mass controlled by the proposed controller by replacing try-and-error procedure with the PSO technique for optimal tuning of controllers' design parameters towards better performance of controlled PAM system.

2. **Model Description.** In this configuration of PAM, a mass is hanged by PAM as indicated in Figure 1. The PAM will consider only the inflation case and the mathematical model consists of a three-elements in parallel, contractile (force-generating) element, spring element, and damping element [7,10].

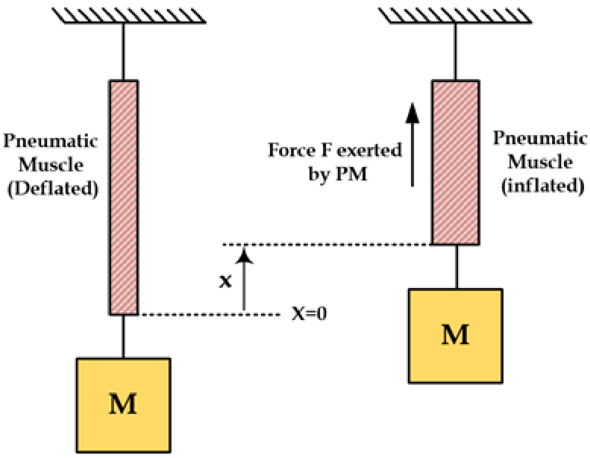

FIGURE 1. Pneumatic artificial muscle [3,6]

The coefficients $B(P)$, $K(P)$, and $F(P)$ represent the coefficient of viscous friction, the spring coefficient and the force exerted by PAM, respectively. All these coefficients depend on the input pressure supplied to the PM. This pressure can be commanded externally by varying the voltage supplied to the inlet valve. According to Figure 1, the equation of motion describing the dynamics of pneumatic artificial is given by [7]

$$M\ddot{x} + B(P)\dot{x} + K(P)x = F(P) - Mg \tag{1}$$

where M is the mass (kg), g represents the acceleration of gravity (m/s^2), B is the coefficient of viscosity (viscous friction), K represents the spring coefficient (N/m), and F is the force exerted by PAM. The functions of coefficients $B(P)$, $K(P)$, and $F(P)$ are assumed to be linearly dependent on pressure as follows [10]:

$$F = F_0 + F_1 P \tag{2}$$

$$B = B_0 \mp B_1 P \tag{3}$$

$$K = K_0 + K_1 P \tag{4}$$

where F_0, B_0 and K_0 represent the nominal values, F_1, B_1 and K_1 define the linear variation in these coefficients with respect to pressure. For the inflation case, the coefficient of viscosity in Equation (3) is given by $B = B_0 + B_1 P$, while in the deflation case, the coefficient of viscosity becomes $B = B_0 - B_1 P$. Combining Equations (1) and (3) it has

$$M\ddot{x} = F_0 - B_0\dot{x} - K_0 x + \left(F_1 \mp B_1\dot{x} - K_1 x\right) P - Mg \tag{5}$$

This can be arranged to become

$$\ddot{x} = \left(\frac{F_0}{M}\right) - \left(\frac{B_0}{M}\right)\dot{x} - \left(\frac{K_0}{M}\right)x + \left(\left(\frac{F_1}{M}\right) \mp \left(\frac{B_1}{M}\right)\dot{x} - \left(\frac{K_1}{M}\right)x\right)P - g \tag{6}$$

Equation (6) can be represented in state variables by letting $x_1 = x$, $\dot{x}_1 = x_2$ and $\dot{x}_2 = \ddot{x}$ and since the input pressure of the PAM is considered as the control signal u, one can write

$$\begin{aligned} x_1 &= x(t) \\ \dot{x}_1 &= \dot{x}\,(t) = x_2 \\ \dot{x}_2 &= \ddot{x}_1 = \ddot{x} = f + bu \end{aligned} \tag{7}$$

In inflation case, f and b can be defined in terms of state variables as follows:

$$\begin{aligned} f &= \left(\frac{F_0}{M}\right) - \left(\frac{B_0}{M}\right)x_2 - \left(\frac{K_0}{M}\right)x_1 - g \\ b &= \left(\frac{F_1}{M}\right) - \left(\frac{B_1}{M}\right)x_2 - \left(\frac{K_1}{M}\right)x_1 \end{aligned} \tag{8}$$

On the other hand, in the deflation case, f and b can be given by

$$\begin{aligned} f &= \left(\frac{F_0}{M}\right) - \left(\frac{B_0}{M}\right)x_2 - \left(\frac{K_0}{M}\right)x_1 - g \\ b &= \left(\frac{F_1}{M}\right) + \left(\frac{B_1}{M}\right)x_2 - \left(\frac{K_1}{M}\right)x_1 \end{aligned} \tag{9}$$

In the present work, the inflation case will be taken into account; that is, Equation (8) will be adopted.

3. Design of SMC Algorithm for PAM-Actuated Hanging Mass.

The desired trajectory in the inflation action of the PAM is assigned to be x_{1d}. Let e be the difference between the actual trajectory x_1 and the desired trajectory x_{1d} as follows:

$$e = x_1 - x_{1d} \tag{10}$$

Taking the first and second time derivatives of error, one can get

$$\dot{e} = \dot{x}_1 - \dot{x}_{1d} = x_2 - \dot{x}_{1d} \tag{11}$$

$$\ddot{e} = \dot{x}_2 - \ddot{x}_{1d} \tag{12}$$

For this system, the sliding surface is assumed to be

$$s = \lambda_1 e + \dot{e} \tag{13}$$

The time derivative of Equation (13) is given by

$$\dot{s} = \lambda_1 \dot{e} + \ddot{e} = \lambda_1 \left[x_2 - \dot{x}_{1d}\right] + \dot{x}_2 - \ddot{x}_{1d} \tag{14}$$

where λ_1 is a scalar design parameter. Using Equation (7), Equation (14) becomes

$$\dot{s} = \lambda_1 x_2 - \lambda_1 \dot{x}_{1d} + f + bu - \ddot{x}_{1d} \tag{15}$$

In the SMC technique, the control law (u) is defined by

$$u = u_{eq} + u_{sw} \tag{16}$$

where u_{eq} and u_{sw} are the equivalent and switching control parts, which are described respectively by

$$u_{eq} = \left(\frac{1}{b}\right)\left[-\lambda_1 x_2 + \lambda_1 \dot{x}_{1d} - f + \ddot{x}_{1d}\right] \tag{17}$$

$$u_{sw} = -\beta_1 sign\left(s\right) \tag{18}$$

where β_1 is a scalar design gain. If the sliding surface is set to zero $s = 0$, then $\dot{s} = 0$, and the control law u will be deduced based on Equation (15) as follows

$$u = \left(\frac{1}{b}\right)\left[-\lambda_1 x_2 + \lambda_1 \dot{x}_{1d} - f + \ddot{x}_{1d}\right] - \beta_1 sign\left(s\right) \tag{19}$$

If the deflation case is considering, the driving of the control law is the same except that the value of b in Equation (19) will be replaced by the value of b in Equation (9) as below:

$$b = \left(\frac{F_1}{M}\right) + \left(\frac{B_1}{M}\right) x_2 - \left(\frac{K_1}{M}\right) x_1 \tag{20}$$

4. **Optimization of Control Design Parameters Based on PSO.** To get the best controller performance of SMC, the design parameters of the proposed controller for PAM-actuated mass have to be tuned. Try-and-error procedure for finding or setting these parameters is cumbersome and it does not lead to optimal solution in terms of better dynamic performance of the controlled systems. As such, the PSO technique has been suggested to find the optimal values of these parameters which could satisfy the perfect performance of the proposed controller towards best dynamic response. In case of SMC, the design parameters are (λ_1, β_1).

In PSO, each particle navigates around the search (solution) space by updating their velocity according to its own and also the other particles searching experience. Each particle must update its velocity and position according to the number of iterations, of course, this job will be done according to some cost functions for minimum or maximum case. In our design, the cost function has to be minimized [27-30].

The velocity of each particle is updated according to the following equation:

$$V_i^{k+1} = w \cdot V_i^k + C_1 \cdot rand \cdot \left(p_{best} - X_i^k\right) + C_2 \cdot rand \cdot \left(g_{best} - X_i^k\right) \tag{21}$$

where w represents the inertia coefficient, C_1 represents the personal acceleration coefficient and C_2 represents the social acceleration coefficient. The position of each particle is updated by the equation

$$X_i^{k+1} = X_i^k + V_i^{k+1} \tag{22}$$

where X_i^k and X_i^{k+1} represent the current and updated vectors, respectively.

The cost function used to evaluate each particle during the search of minimum is chosen to be the Root Mean Square Error function (RMSE). In the present work, the setting of parameters for PSO algorithms is listed in Table 1. Other modern optimization techniques in the literature can be used instead of PSO to tune the design parameters of SMC. Some of these are Spider Social Optimization (SSO), spider monkey optimization, Grey-Wolf Optimization (GWO), and Whale-Optimization Algorithm (WOA) [31-34].

Table 1. List of setting parameters for PSO algorithm

Parameters of PSO technique	**Value**
The inertia coefficient w	1.4
The personal acceleration coefficient C_1	2
The social acceleration coefficient C_2	2
The swarm size (population size)	30
The number of iterations	300

5. **Computer Simulation.** The numerical values of PAM-actuated hanging mass for inflation case are listed in Table 2. The proposed controller and the suggested PAM systems have been modeled using MATLAB/SIMULINK software package. The algorithms of controller and model of system have been coded inside special m-functions. The main structure of the controlled system is synthesized and modeled within SIMULINK environment using SIMULINK library. The simulated results have been run at time of 5 seconds.

Table 2. Numerical values of system parameters

Coefficient description	**Value**
Nominal force exerted by PAM F_0	179.2 N
Variation in force exerted by PAM F_1	1.39 N
Nominal coefficient of viscosity B_0	1.01 (N·s/m)
Variation in coefficient of viscosity B_1	0.00691 (N·s/m)
Nominal spring coefficient k_0	5.71 N/M
Variation in spring coefficient k_1	0.0307 N/M
Mass M	20 Kg
Gravity acceleration g	9.8 m/s^2

Figure 2 shows the open-loop test of PAM-actuated mass. The system is commanded by unit step input pressure for inflation case. It is clear from the figure that the output response, represented by linear displacement x_1, has oscillatory characteristics and the response finally settles after 1800 seconds.

It is worthy to mention that the design parameters of SMC are λ_1 and β_1. The task of PSO algorithm is to tune the design parameters of SMC towards better dynamic performance. The fitness function used to evaluate the iterative particles of PSO algorithm for all control strategies is the Root Mean Square Error (RMSE). The objective of optimization technique is to find the optimal values of design parameters such as to give minimum RMSE. Figure 3 shows the behavior of the cost function for PAM-actuated mass controlled by SMC.

Table 3 gives the two settings of design parameters for PAM-actuated mass system controlled by SMC. The first set of design parameters is based on PSO technique, while the other set of design parameters has been chosen on the try-and-error basis. In the next scenarios, the optimal values of design parameters acquired from PSO process are set to

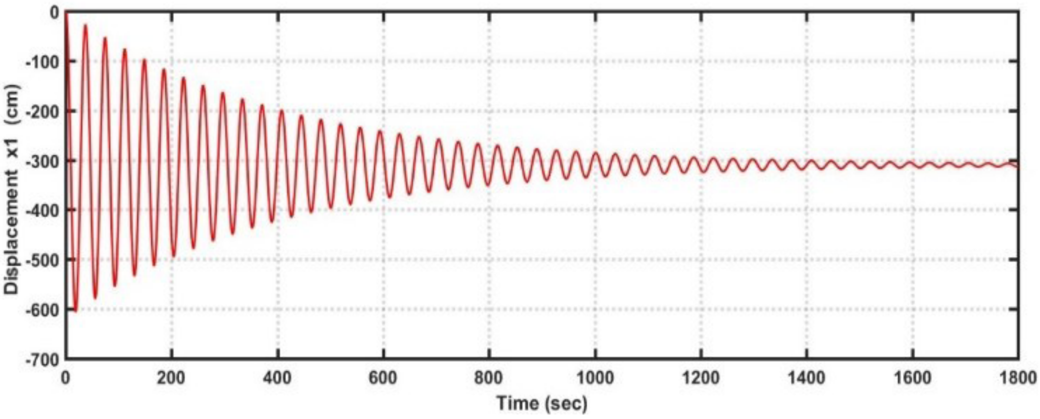

Figure 2. Open-loop response for PAM vertically hanging mass system

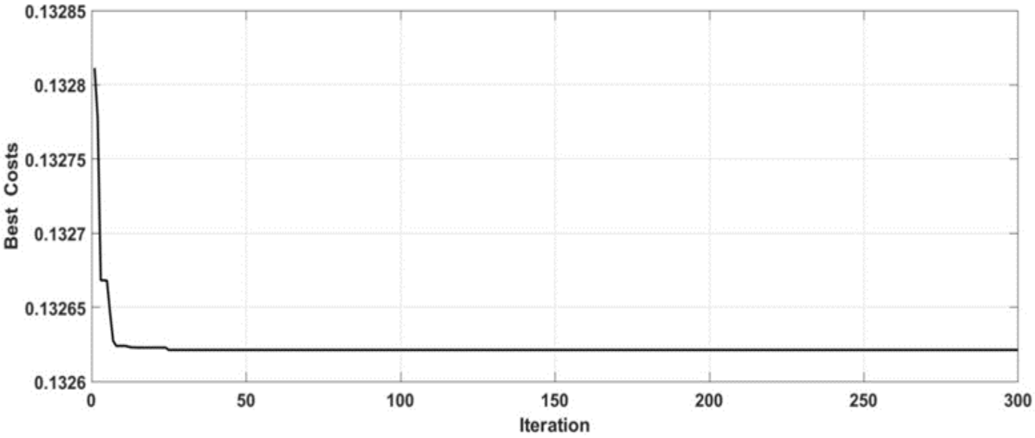

Figure 3. Cost function for the controlled system based on SMC

Table 3. Numerical values of system parameters

Controller	Optimal values		Try-and-error values	
	Coefficient	Value	Coefficient	Value
SMC	λ_1	4.3167	λ_1	1
	β_1	98.0684	β_1	70

their corresponding design parameters of controllers for optimal controlled system. The desired trajectory is assumed to be a unit step input.

Figure 4 shows the behaviors of linear positions based on optimal and non-optimal SMC. Also, Figure 5 demonstrates the behaviors of linear velocities of sliding mode controlled system based on PSO algorithm and try-and-error procedure. It is evident from Figure 4 that the dynamic response obtained by optimal SMC outperforms that based on try-and-error procedure in terms of transient characteristics.

Figure 6 exhibits the corresponding control effects based on both optimal and non-optimal SMCs. It is clear that the requirement of higher control effort is the price of improving the dynamic performance due to PSO algorithm as compared to non-optimal case.

The tracking errors of PAM system controlled based on optimal and non-optimal SMC (e) are illustrated in Figure 7. It is clear from Figure 7 that the tracking error with optimal SMC is less than the case with non-optimal SMC; it is the task of PSO algorithm for such improvement. Figure 8 shows the trace of trajectory on the phase plane coordinates (e-$\dot{e}$).

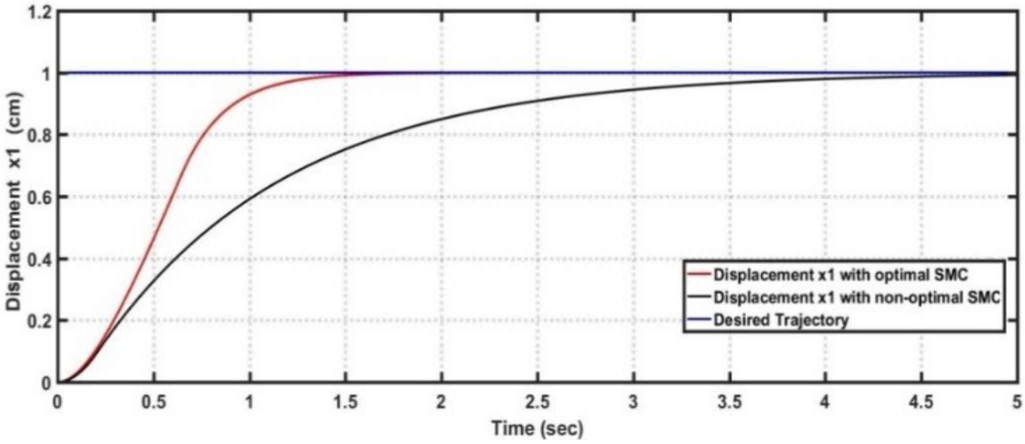

Figure 4. (color online) Tracking performance for the PAM-based system with optimal and non-optimal SMC

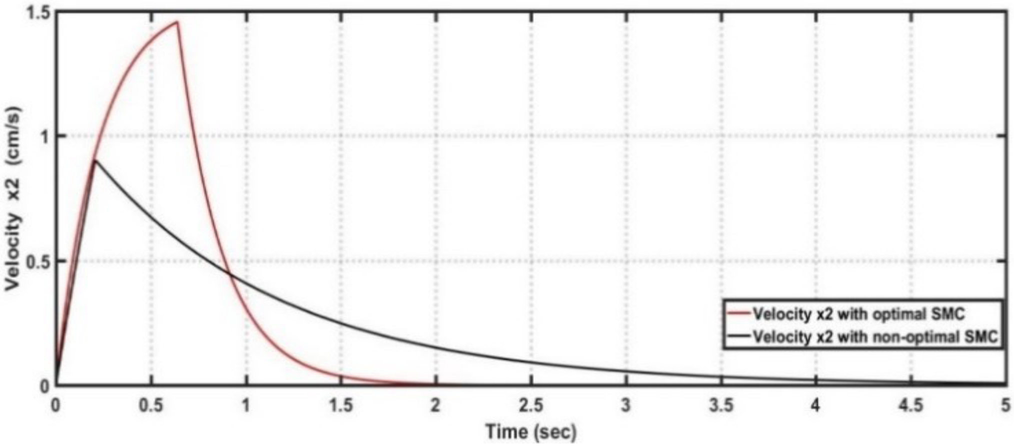

Figure 5. (color online) Linear velocity behaviors of sliding mode controlled system based on PSO algorithm and try-and-error procedure

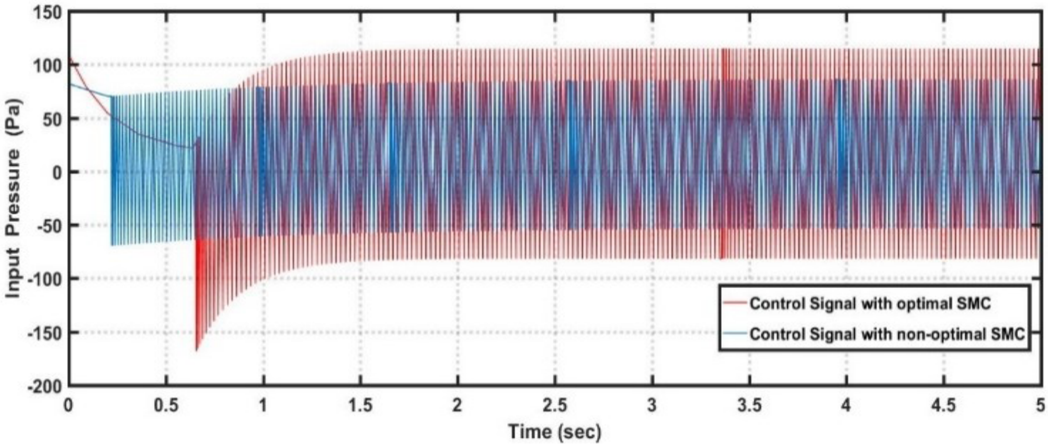

Figure 6. (color online) Behavior of control signal u based on optimal and non-optimal sliding mode controlled PAM system

The trajectory has started at initial state on e-axis and reached the sliding surface by the end of reaching phase and it remained on the surface until the equilibrium point has arrived. The effect of chattering phenomenon due to the SMC is shown in Figure 9.

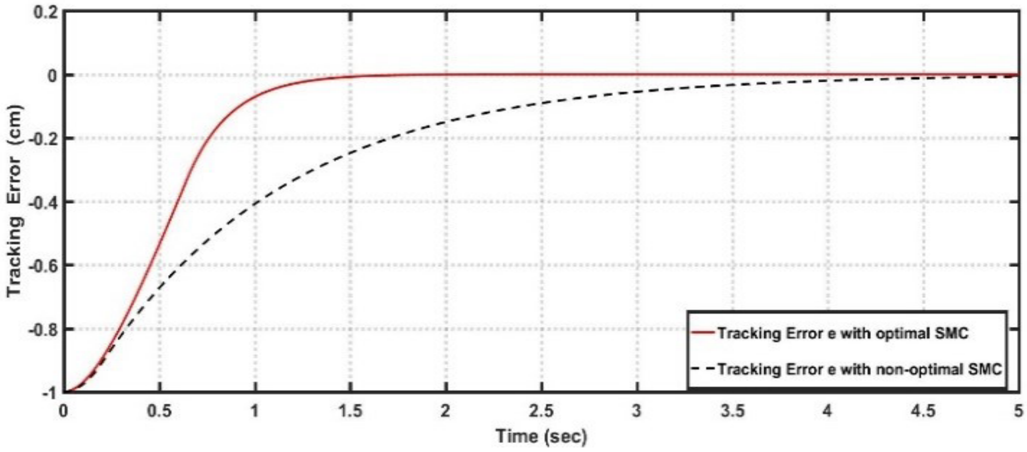

Figure 7. Tracking error

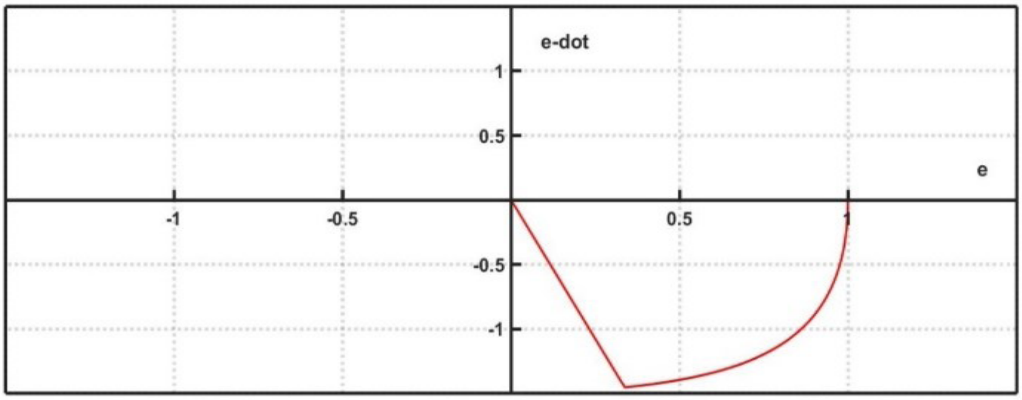

Figure 8. Sliding surface of SMC

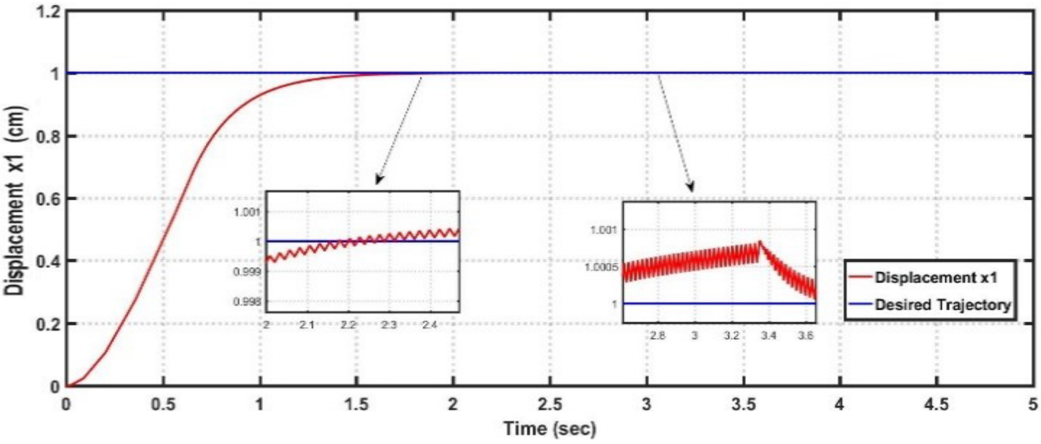

Figure 9. (color online) Chattering phenomenon

6. **Conclusions.** This study presented the design of sliding mode controller for position control of hanging mass, which is actuated by pneumatic muscles. In addition, the PSO is used to tune the design parameters of SMC to further improve the effectiveness of controller.

Based on simulated results, one concludes that sliding mode controller could successfully give good tracking control performance. However, high level of chattering has appeared in both control signals and system output. The PSO technique has better improved the dynamic performance of controlled PAM-actuated system based on SMC as compared to non-optimal controlled system.

This study can be extended for future work by comparing the optimal SMC, which is used in this application, to other control schemes in terms of robustness and transient characteristics [35-40].

REFERENCES

[1] D. B. Rynolds, D. W. Repperger, C. A. Phillpis and G. B. Bandry, Modeling the dynamic characteristics of pneumatic muscle, *Annals of Biomedical Engineering*, vol.31, pp.310-317, 2003.

[2] D. W. Repperger, K. R. Johnson and C. A. Phillips, A VSC position tracking system involving a large scale pneumatic muscle actuator, *Proc. of the 37th IEEE Conference on Decision and Control*, Tampa, FL, USA, vol.4, pp.4302-4307, 1998.

[3] N. Tsagarakis and G. C. Darwin, Improved modeling and assessment of pneumatic muscle actuators, *Proc. of IEEE International Conference on Robotics and Automation*, San Francisco, CA, USA, vol.4, pp.3641-3646, 2000.

[4] D. G. Caldwell, G. A. Medrano-Cerda and M. J. Goodwin, Braided pneumatic actuator control of a multi-jointed manipulator, *Proc. of IEEE Systems Man and Cybernetics Conference – SMC*, Le Touquet, France, 1993.

[5] A. Al-Jodah and L. Khames, Second order sliding mode controller design for pneumatic artificial muscle, *Journal of Engineering*, vol.24, no.1, pp.159-172, 2018.

[6] T. Y. Choi, J. Y. Lee and J. J. Lee, Control of artificial pneumatic muscle for robot application, *Proc. of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Beijing, China, pp.4896-4901, 2006.

[7] J. H. Lilly and L. Yang, Sliding mode tracking for pneumatic muscle actuators in opposing pair configuration, *IEEE Transactions on Control Systems Technology*, vol.13, no.4, pp.550-558, 2005.

[8] K. Tarapong and P. Radom, Adaptive control for a one-link robot arm actuated by pneumatic muscles, *Chiang Mai Journal of Science*, vol.35, no.3, pp.437-446, 2008.

[9] W. Scaff, O. Horikawa and M. D. S. G. Tsuzuki, Pneumatic artificial muscle optimal control with simulated annealing, *IFAC*, vol.51, no.27, pp.333-338, 2018.

[10] J. H. Lilly, Adaptive tracking for pneumatic muscle actuators in bicep and tricep configurations, *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol.11, no.3, pp.333-339, 2003.

[11] S. Boudoua, M. Hamerlain and F. Hamerlain, Intelligent twisting sliding mode controller using neural network for pneumatic artificial muscles robot arm, *International Workshop on Recent Advances in Sliding Modes (RASM)*, Istanbul, Turkey, 2015.

[12] D. G. Caldwell, G. A. Medrano-Cerda and M. Goodwin, Control of pneumatic muscle actuators, *IEEE Control Systems Magazine*, vol.15, no.1, pp.40-48, 1995.

[13] V. I. Utkin, Sliding mode control: Mathematical tools, design and applications, in *Nonlinear and Optimal Control Theory, Lecture Notes in Mathematics*, P. Nistri and G. Stefani (eds.), vol.1932, Springer, Berlin, Heidelberg, 2008.

[14] A. J. Humaidi and A. H. Hameed, Design and comparative study of advanced adaptive control schemes for position control of electronic throttle valve, *Information (Switzerland)*, vol.10, no.2, 65, 2019.

[15] B. Kürkçü, C. Kasnakoğlu and M. Ö. Efe, Disturbance/uncertainty estimator based integral sliding-mode control, *IEEE Transaction on Automatic Control*, vol.63, no.11, pp.3940-3947, 2018.

[16] V. I. Utkin, J. Guldner and J. Shi, *Sliding Mode Control in Electro-Mechanical Systems*, Taylor and Francis Group, LLC, Boca Raton, FL, 2009.

[17] J. Liu and X. Wang, *Advanced Sliding Mode Control for Mechanical Systems Design, Analysis and MATLAB Simulation*, Tsinghua University Press, Beijing and Springer-Verlag Berlin, Heidelberg, 2012.

[18] M. Furat and E. İlyas, Experimental evaluation of sliding-mode control techniques, *Çukurova University Journal of the Faculty of Engineering and Architecture*, vol.27, no.1, pp.23-37, 2012.

[19] A. J. Humaidi, S. K. Kadhim and A. S. Gataa, Optimal adaptive magnetic suspension control of rotary impeller for artificial heart pump, *Cybernetics and Systems*, vol.53, no.1, pp.141-167, 2022.

[20] A. J. Humaidi, S. Hasan and A. A. Al-Jodah, Design of second order sliding mode for glucose regulation systems with disturbance, *International Journal of Engineering and Technology (UAE)*, vol.7, no.2, pp.243-247, 2018.

[21] A. H. Hameed, A. Q. Al-Dujaili, A. J. Humaidi and H. A. Hussein, Design of terminal sliding position control for electronic throttle valve system: A performance comparative study, *International Review of Automatic Control*, vol.12, no.5, pp.251-260, 2019.

[22] M. E. Sadiq, A. J. Humaidi, S. K. Kadhim, A. A. Mhdawi, A. Alkhayyat and I. K. Ibraheem, Optimal sliding mode control of single arm PAM-actuated manipulator, *2021 IEEE 11th International Conference on System Engineering and Technology (ICSET)*, Shah Alam, Malaysia, pp.84-89, 2021.

[23] M. E. Sadiq, A. J. Humaidi, S. K. Kadhim, A. S. Mahdi, A. Alkhayyat and I. K. Ibraheem, Comparative study of optimal nonlinear control schemes for hanging mass actuated by uncertain pneumatic muscle, *2021 IEEE 11th International Conference on System Engineering and Technology (ICSET)*, Shah Alam, Malaysia, pp.78-83, 2021.

[24] J. Kennedy and R. Eberhart, Particle swarm optimization, *Proc. of ICNN'95 – International Conference on Neural Networks*, Perth, WA, Australia, 1995.

[25] A. J. Humaidi and A. F. Hasan, Particle swarm optimization-based adaptive super-twisting sliding mode control design for 2-degree-of-freedom helicopter, *Measurement and Control Journal*, vol.52, nos.9-10, 2019.

[26] A. J. Humaidi and H. M. Badr, Linear and nonlinear active disturbance rejection controllers for single-link flexible joint robot manipulator based on PSO tuner, *Journal of Engineering Science and Technology Review*, vol.11, no.3, pp.133-138, 2018.

[27] A. J. Humaidi, S. K. Kadhim and A. S. Gataa, Development of a novel optimal backstepping control algorithm of magnetic impeller-bearing system for artificial heart ventricle pump, *Cybernetics and Systems*, vol.51, no.4, pp.521-541, 2020.

[28] A. J. Humaidi, H. M. Badr and A. H. Hameed, PSO-based active disturbance rejection control for position control of magnetic levitation system, *2018 5th International Conference on Control, Decision and Information Technologies (CoDIT 2018)*, pp.922-928, 2018.

[29] S. Talukder, *Mathematical Modelling and Applications of Particle Swarm Optimization*, Master Thesis, Blekinge Institute of Technology, Karlskrona, 2011.

[30] A. A. Al-Qassar, A. Q. Al-Dujaili, A. F. Hasan, A. J. Humaidi, I. K. Ibraheem and A. T. Azar, Stabilization of single-axis propeller-powered system for aircraft applications based on optimal adaptive control design, *Journal of Engineering Science and Technology (JESTEC)*, vol.16, no.3, pp.1851-1869, 2021.

[31] A. J. Humaidi, A. A. Oglah, S. J. Abbas and I. K. Ibraheem, Optimal augmented linear and nonlinear PD control design for parallel robot based on PSO tuner, *International Review on Modelling and Simulations*, vol.12, no.5, pp.281-291, 2019.

[32] T. Ghanim, A. R. Ajel and A. J. Humaidi, Optimal fuzzy logic control for temperature control based on social spider optimization, *IOP Conference Series: Materials Science and Engineering*, vol.745, no.1, 012099, 2020.

[33] A. I. Abdul-Kareem, A. F. Hasan, A. A. Al-Qassar, A. J. Humaidi, R. F. Hassan, I. K. Ibraheem and A. T. Azar, Rejection of wing-rock motion in delta wing aircrafts based on optimal LADRC schemes with butterfly optimization algorithm, *Journal of Engineering Science and Technology*, vol.17, no.4, pp.2476-2495, 2022.

[34] A. A. Al-Qassar, A. I. Abdu-Alkareem, A. F. Hasan, A. J. Humaidi, K. I. Ibraheem, A. T. Azar and A. H. Hameed, Grey-wolf optimization better enhances the dynamic performance of roll motion for tail-sitter VTOL aircraft guided and controlled by STSMC, *Journal of Engineering Science and Technology (JESTEC)*, vol.16, no.3, pp.1932-1950, 2021.

[35] A. Q. Al-Dujaili, A. J. Humaidi, D. A. Pereira and I. K. Ibraheem, Adaptive backstepping control design for ball and beam system, *International Review of Applied Sciences and Engineering*, vol.12, no.3, pp.211-221, 2021.

[36] M. Y. Hassan, A. J. Humaidi and M. K. Hamza, On the design of backstepping controller for Acrobot system based on adaptive observer, *International Review of Electrical Engineering*, vol.15, no.4, pp.328-335, 2020.

[37] A. J. Humaidi, A. H. Hameed and M. R. Hameed, Robust adaptive speed control for DC motor using novel weighted E-modified MRAC, *IEEE International Conference on Power, Control, Signals and Instrumentation Engineering (ICPCSI 2017)*, Chennai, India, pp.313-319, 2018.

[38] A. J. Humaidi, E. N. Talaat, M. R. Hameed and A. H. Hameed, Design of adaptive observer-based backstepping control of cart-pole pendulum system, *Proc. of 2019 3rd IEEE International Conference on Electrical, Computer and Communication Technologies (ICECCT)*, Coimbatore, Tamil Nadu, India, pp.1-5, 2019.

[39] A. J. Humaidi and M. R. Hameed, Design and performance investigation of block-backstepping algorithms for ball and arc system, *IEEE International Conference on Power, Control, Signals and Instrumentation Engineering (ICPCSI)*, Chennai, India, pp.325-332, 2017.

[40] A. J. Humaidi and A. I. Abdulkareem, Design of augmented nonlinear PD controller of Delta/Par4-like robot, *Journal of Control Science and Engineering*, vol.2019, 7689673, 2019.

[41] A. J. Humaidi, M. R. Hameed and A. H. Hameed, Design of block-backstepping controller to ball and arc system based on zero dynamic theory, *Journal of Engineering Science and Technology*, vol.13, no.7, pp.2084-2105, 2018.