Optimization of Modified Sliding Mode Control for an Electro-Hydraulic Actuator System with Mismatched Disturbance

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***Abstract*—This paper presents a modified sliding mode controller (MSMC) for tracking purpose of electro-hydraulic actuator system with mismatched disturbance. The main contribution of this study is in attempting to find the optimal tuning of sliding surface parameters in the MSMC using a hybrid algorithm of particle swarm optimization (PSO) and gravitational search algorithms (GSA), in order to produce the best system performance and reduce the chattering effects. In this regard, Sum square error (SSE) has been used as the objective function of the hybrid algorithm. The performance was evaluated based on the tracking error identified between reference input and the system output. In addition, the efficiency of the designed controller was verified within a simulation environment under various values of external disturbances. Upon drawing a comparison of PSOGSA with PSO and GSA alone, it was learnt that the proposed controller MSMC, which had been integrated with PSOGSA was capable of performing more efficiently in trajectory control and was able to reduce the chattering effects of MSMC significantly compared to MSMC-PSO and MSMC-GSA, respectively when the highest external disturbance, 10500N being injected into the system's actuator.**

Keywords— electro-hydraulic, mismatched disturbance, modified sliding mode control, particle swarm optimization; gravitational search algorithm

I. INTRODUCTION

The Electro-Hydraulic Actuator (EHA) system, due to its excessive strength to weight ratio and stiffness reaction being more precise, smooth and fast, is one of the crucial force systems in industrial sectors and most engineering practices around the world. Owing to such wide applications, the best overall performance of the electro-hydraulic actuators with regards to its position, force or pressure is necessary. It is however worthy of note that the system is tremendously nonlinear due to many elements, such as leakage, friction, and specifically, the fluid flow expression through the servo valve [1]. Such characteristics, which are prevalent within the system have significantly contributed to the degradation of its overall performance. Upon closely looking into studies such as [2]–[4], it was discovered that the sliding mode control (SMC) as efficient and broadly implemented in comparison with the nonlinear EHA system. It was particularly observed that most of the existing outcomes on sliding surface design have been focused on the matched uncertainties and disturbances attenuation since the sliding motion of conventional SMC is insensitive to matched uncertainties and disturbance [5]. In other words, the uncertainties and disturbances exist within the identical channel as that control input. However, it has been widely proven in related studies that the uncertainties present in many practical systems may not fulfil the so-called matching condition.

In the present study, the dynamic model and design requirement of electro-hydraulic actuator were taken from the National Institute for Aerospace Research, Romania [6]. Within the dynamic model used, the track input disturbance acts on a different channel from the control input. In the case of such systems, the sliding motion of conventional SMC is critically tormented by the mismatched disturbance and the well-known robustness of SMC may no longer preserve anymore. Owing to the importance of attenuating mismatched uncertainties and disturbances with regards to the practical applications, many researchers have committed themselves to the sliding surface design for uncertain systems with mismatched disturbance. Interestingly, it was also discovered that some related studies in the literature had used conventional SMC with some amendment in its sliding surface. One possible reason for such a change is to help enhance the capability of the modified SMC (MSMC).

In the case of [7], it was learnt that the proportional integral type sliding characteristic was used as a modification of conventional SMC. The proposed modified sliding characteristic is capable of improving the steady state and dynamic performance in DC-DC buck converter application. In the study by [8], the sliding mode control approach was modified from the synchronization of a single dynamic system into the synchronization of a complex network. Besides, there were also studies that had made some modifications into the sliding surface[9], [10]. Owing to some of the significant advantages of the MSMC in dealing with the complex situations, the present study has relied on MSMC in electro-hydraulic actuator with mismatched disturbance.

In addition, parameter estimation has been identified as one of the ways, through which the accuracy of MSMC can be improved. Hybrid optimization is quite well-known in many application [11][12]. Several studies have proposed the combination of GSA and PSO it was through such studies, it was learnt that the combination of PSO and GSA is capable of providing improved results for general mathematical functions [13][14]. However, both have looked into the generic algorithms and it has yet to be specifically applied to estimate the parameters of MSMC controller for mismatched disturbance system such as an electro-hydraulic actuator such as the case in the present study[15][14]. More importantly, no studies, at least to the knowledge of the researcher, have considered looking into parameters estimation for MSMC to enhance its accuracy and performance.

Specifically, the present study concerns the performance comparison between MSMC that had been optimized by using PSO, GSA and PSOGSA. In this regard, comparative assessment of this triple optimization method to the system performance is presented and discussed. The main contents of this article are sequenced in the following order: Section II illustrates the mathematical modelling of the developed system. Section III delineates the MSMC algorithm derivation. Moving on, the optimization algorithms used are presented in section IV. The results from observations r are presented, compared and discussed in Section V. Lastly, a brief summary and conclusions are provided in Section VII.

II. ELECTRO-HYDRAULIC ACTUATOR (EHA) MODELING

The actuator dynamic equation of electro-hydraulic actuator servo system with the external disturbance being injected into its actuator is expressed [6].

$$\dot{x}_1 = x_2 \tag{1}$$

$$\dot{x}_2 = -\frac{k}{m}x_1 - \frac{f}{m}x_2 + \frac{s}{m}x_3 - \frac{F_L}{m} \tag{2}$$

$$\dot{x}_3 = -\frac{s}{k}x_2 - \frac{k_l}{k_c}x_3 + \frac{c}{k_c}\sqrt{\frac{P_a - x_3}{2}}k_v \tag{3}$$

Table 1 shows the parameters of electro hydraulic actuator servo system which are represented by (1), (2) and (3).

TABLE I. TABLE TYPE PARAMETER OF EHA SERVO SYSTEM

Parameters	Value	Unit
Load at the EHA rod (m)	0.33	Ns^2/cm
Piston Area (S)	10	cm^2
Coefficient of viscous friction (f)	27.5	Ns/cm
Coefficient of aerodynamic elastic force (k)	1000	N/cm
Valve port width (w)	0.05	cm
Supply pressure (P_a)	2100	N/cm^2
Coefficient of volumetric flow of the valve port (c_d)	0.63	−
Coefficient of internal leakage (k_l)	2.38×10^{-3}	cm^5/Ns
Coefficient of servo valve (k_v)	0.017	cm/V
Coefficient involving bulk modulus and EHA volume (k_c)	2.5×10^{-4}	cm^5/N
Oil density (ρ)	8.87×10^{-7}	Ns^2/cm^4

III. CONTROLLER DESIGN AND STABILITY

The objective of the control design is to achieve a continuous sliding control, u, such that the output of the system tracks the desired input as closely as possible. At given desired position trajectory, x_{id} the control objective is to design a bounded control input, u. Hence the output position, x_p tracks as closely as possible to the desired position trajectory, x_{id}. The design of modified sliding mode control involves two main steps. The first step is to select the appropriate sliding surface for the desired sliding motion. The trajectories are enforced to lie on the sliding surface. The desired position of trajectory is as $x_d = [x_{1d}, x_{2d}, x_{3d}]^T \in R^n$, and defined as $\dot{x}_{1d} = x_{2d}$, $\dot{x}_{2d} = x_{3d}$. In addition, the vector of the system states are assumed measurable and defined as $x = [x_1, x_2, x_3]^T = [x_p, v_p, P_L] \in R^n$. The state error of the system is defined as

$$e_i = x_i - x_{id} \tag{5}$$

where $i = 1 \; to \; 3$ and $e \in R^n$.

In order to ensure that the states of the system successfully tracks the desired trajectories at the same time, the function of a new sliding surface was proposed as in [3].

$$S(t) = x_2 + x_3 + c_1 e_1 + c_2 \int e_1 \tag{6}$$

where $\boldsymbol{c_1}$ and $\boldsymbol{c_2}$ are strictly positive constants. The idea behind the designed controller is that a switching gain is designed to force the states to achieve the integral sliding surface, and then the integral action in the sliding surface drives the states to the desired equilibrium in the presence of mismatched uncertainties, nonlinearities or disturbance. The desired dynamic response for the system is given as $\boldsymbol{S} = \dot{\boldsymbol{S}} = \mathbf{0}$ when the sliding surface is moving. Therefore, it can be obtained as:

$$\dot{\boldsymbol{e}}_{\mathbf{1}} = -\dot{\boldsymbol{x}}_{\mathbf{2}} - \dot{\boldsymbol{x}}_{\mathbf{3}} - \boldsymbol{c}_{\mathbf{2}}\boldsymbol{e}_{\mathbf{1}} \tag{7}$$

The tracking error e_1 is defined as :

$$e_1 = x_1 - x_{1d} \tag{8}$$

In order to obtain the control law, the constant plus proportional reaching law method was applied [16][17]. The reaching law is used to reduce the chattering, since the chattering caused by non-ideal reaching at the end of reaching phase, and also the easy to obtain the control law. The dynamics of the switching function are directly specified by this approach which is described by the reaching function of the form

$$\dot{S} = -Qsign(S) - KS \tag{9}$$

where Q and K are constant with positive value and $sign(S)$ representing the signum function which has a piecewise function as below:

$$sign(S) = \begin{cases} 1 & ; S > 0 \\ 0 & ; S = 0 \\ -1 & ; S < 0 \end{cases} \tag{10}$$

Since the controller is designed to achieve a better tracking accuracy in positioning, a smaller boundary layer is usually required. Hence, an optimal balance between the position error and the level of control chattering can be accomplished by adjusting the thickness of the boundary layer and accordingly, it can be given as

$$\dot{S} = -Qsat(S/\emptyset) - KS \tag{11}$$

In this regard, that the derivative of (6) gives

$$\dot{S} = \dot{x_2} + \dot{x_3} + c_1\dot{e_1} + c_2e_1 \tag{12}$$

The control law is obtained by substituting (1) (2) and (3) in (12). Therefore, the control law can be stated as,

$$u = \frac{k_c}{ck_v}\sqrt{\frac{2}{P_a - x_3}}\Big[-Qat(S/\emptyset) - KS + \frac{k}{m}x_1 + \frac{f}{m}x_2 - \frac{s}{m}x_3 + \frac{F_L}{m} + \frac{s}{k_c}x_2 + \frac{k_l}{k_c}x_3 - c_1\dot{x_1} + c_1\dot{x_{1d}} - c_2x_1 + c_2x_{1d}\Big] \tag{13}$$

If the initial output trajectory is not on the sliding surface $S(t)$, or a deviation of the representative point detected from $S(t)$ due to variations observed in parameter and/or disturbances, the controller must be designed in such a way that it can drive the output trajectory to the sliding mode $S(t) = 0$.

The output trajectory, in such a condition will move towards and reach the sliding surface, and is said to be on the reaching phase. For this purpose, the Lyapunov function can be expressed as

$$V(t) = \frac{1}{2}S^2(t) \tag{14}$$

where $V(t) > 0$ and $V(0) = 0$ for $S(t) \neq 0$. The reaching condition as presented in (15) is considered as necessary as that will help ensure the trajectory moving from the reaching phase to the sliding phase in a stable condition.

$$\dot{V}(t) = S(t)\dot{S}(t) < 0, for\ S(t) \neq 0 \tag{15}$$

By choosing the Lyapunov function candidate as in (14) and (15), the reaching condition is rearranged as

$$V(t) = \frac{1}{2}S^2(t) \ = S(t)\dot{S}(t) \leq -\alpha|S(t)| \tag{16}$$

where $\alpha \in R$ must be a strictly positive design parameter. By means of (6) and (12) by excluding its reaching time function, Equation (16) can be rewritten as

$$\dot{V} = S\dot{S} \leq -\alpha|S| \tag{17}$$

Therefore,

$$S\left[\left[-\frac{k}{m}x_1 - \frac{f}{m}x_2 + \frac{s}{m}x_3 - \frac{F_L}{m}\right] + \left[-\frac{s}{k_c}x_2 - \frac{k_l}{k_c}x_3 + \frac{c}{k_c}\sqrt{\frac{P_a - x_3}{2}}k_vu\right] + c_1[\dot{x}_1 - \dot{x}_{1d}] + c_2[x_1 - x_{1d}]\right] \leq -\alpha|S| \tag{18}$$

$$S\Bigg[\left[-\frac{k}{m}x_1 - \frac{f}{m}x_2 + \frac{s}{m}x_3 - \frac{F_L}{m}\right] + \Bigg[-\frac{s}{k_c}x_2 - \frac{k_l}{k_c}x_3 + \frac{c}{k_c}\sqrt{\frac{P_a - x_3}{2}}k_v\left[\frac{k_c}{ck_v}\sqrt{\frac{2}{P_a - x_3}}\Big[-Qat(S/\emptyset) - KS + \frac{k}{m}x_1 + \frac{f}{m}x_2 - \frac{s}{m}x_3 + \frac{F_L}{m} + \frac{s}{k_c}x_2 + \frac{k_l}{k_c}x_3 - c_1\dot{x_1} + c_1\dot{x_{1d}} - c_2x_1 + c_2x_{1d}\Big]\right]\Bigg] + c_1[\dot{x}_1 - \dot{x}_{1d}] + c_2[x_1 - x_{1d}]\ \Bigg] \leq -\alpha|S| \tag{19}$$

Let assume $\hat{g} = \frac{c}{k_c}\sqrt{\frac{P_a - x_3}{2}}k_v$, $X = -\frac{k}{m}x_1 - \frac{f}{m}x_2 + \frac{s}{m}x_3 - \frac{F_L}{m}$, $Y = \frac{s}{k_c}x_2 + \frac{k_l}{k_c}x_3$, $Z = -c_1\dot{x_1} + c_1\dot{x_{1d}} - c_2x_1 + c_2x_{1d}$,

Therefore;

$$S[X + \big[-Y + \hat{g}\big[g^{-1}[-Qsgn(S) - KS - X + Y + Z]\big]\big] - Z\ ] \leq -\alpha|S|$$

$$S[X - Y + \hat{g}g^{-1}[Y - X + Z] - Z\ ] + \alpha|S| \leq -S[\hat{g}g^{-1}[-Qsgn(S) - KS]]$$

$$S\big[-\beta[-X + Y + Z] + [Y - X + Z]\big] + \beta\alpha|S| \leq Q|S| + KS$$

$$S[(1 - \beta)|-X + Y + Z|] + \beta\alpha|S| \leq Q|S| + KS$$

$$Q \geq [(1 - \beta)|-X + Y + Z|] + \beta\alpha - K \tag{20}$$

The switching gain, Q help ensure the closed loop system to be robust and asymptotically stable upon the control gain and external disturbance. Therefore, in this study, the value of switching gain, Q will be determined by using optimization algorithm.

IV. HYBRIDIZATION OF PARTICLE SWARM OPTIMIZATION AND GRAVITATIONAL SEARCH ALGORITHM

PSO and GSA share some similarities in relation to their formulation. For that reason, another way to hybridize PSO and GSA are to deal with any particle in the swarm as a particle added through PSO and/or GSA by means of making use of the co-evolutionary technique. PSOGSA, is proposed by means of using cooperative behaviours of the particles tormented by both PSO velocity and GSA acceleration to help enhance the performance of the respective algorithms [13]. Therefore, the two phrases the velocity updating formulation in PSOGSA consists of the cooperative contributions of PSO velocity and GSA acceleration.

$$v_i^d(t+1)_{PSO} = w(t)v_i^d(t) + c_1r_1^d(t)\big[pbest\,_i^d - x_i^d(t)\big] + c_2r_2^d(t)\big[gbest\,_i^d - x_i^d(t)\big] \tag{21}$$

$$v_i^d(t+1)_{GSA} = rand_i \times v_i^d(t) + a_i^d(t) \tag{22}$$

$$v_i^d(t+1)_{PSOGSA} = wv_i^d(t)_{PSO} + c_ar_1^da_i^d(t)_{GSA}\big[pbest\,_i^d - x_i^j(t)_{PSO}\big] + c_br_2^d(t)\big[gbest\,_i^d - x_i^d(t)_{PSO}\big] \tag{23}$$

where Equation (21) is obtained from PSO velocity formulation and Equation (22) comes from GSA velocity formulation and Equation (23) is the PSOGSA velocity formulation updated by PSO velocity and GSA acceleration. Determination of control parameters of the designed controller is considered crucial for accurate tracking performance. Therefore, the PSOGSA are applied to determine the most reliable sliding surface and foremost gain of the designed MSMC. Fig. 1 shows the block diagram of the MSMC with PSOGSA algorithm.

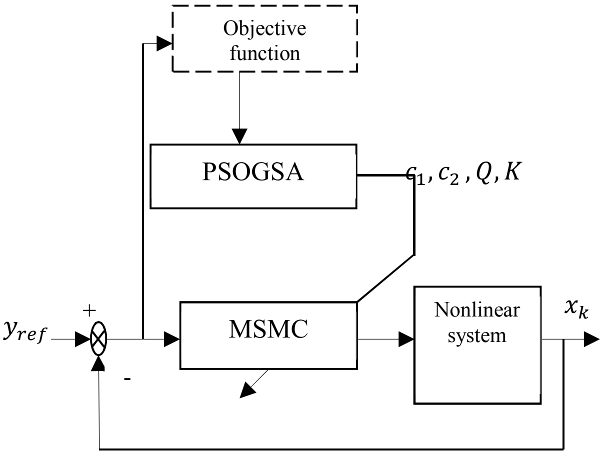

Fig. 1. Block diagram of the MSMC with PSOGSA algorithm

MSMC designed for electro-hydraulic actuator servo system includes four control parameters, c_1, c_2, Q and K. The value of these parameters need to be selected with the intention of minimizing the tracking error. Therefore, in order to enhance the adaptation function of the system, PSOGSA are used to search for the best value of these parameters through the integration of MSMC with this algorithm. PSOGSA caters to this venture primarily based on SSE as an objective function. The formula of SSE is given by

$$SSE = \sum_{k=1}^{n} \left(x_k - y_{ref}\right)^2 \tag{24}$$

where k is the number of iteration, x_k is the system output at k iteration and y_{ref} is the reference input given to the system. The goal of the optimization algorithm is to help minimize SSE.

V. SIMULATION RESULTS AND COMPARISONS

Simulation was carried out by means of using MATLAB/Simulink 2015 software. MSMC is known to help the system track a shaped square wave signal. The references trajectory and the value of external disturbance, 10500 N which was used in this study is similar to that of [18] and [19].

The implementation of optimization algorithms has used the following parameters, i.e., the number of particles, i is set at 5, 10, 15, 20 and 25 particles. The initial value of the number of iteration, t was set at 10 and it was increased to 20, 30, 40 and 50 iterations. As for the presentation of results in this section, the output plot yielded by 5 particles within 10 iterations, 15 particles within 30 iterations and 25 particles within 50 iterations were selected in order to observe the performance of the designed controller with small, medium and bigger number of particles and iterations, respectively. The value of the number of particles and iterations were selected in order to prove that the small number of these parameters will culminate in good tracking performance.

In order to prove the capability of the MSMC, which is not effected on the existence of disturbances for mismatched system, the conventional SMC (CSMC) which was similar to the one used by [20], was utilized for benchmarking and comparison with MSMC. This comparison was performed solely as basic test with the purpose to highlight the primary capabilities of the MSMC. Furthermore, it was designed with the best parameters of CSMC. Parameters for the CSMC were tuned by the same optimization algorithm, namely PSO, GSA and PSOGSA. Moreover, the analysis was carried out through the comparison between MSMC and CSMC in terms of their performances of employing different optimization.

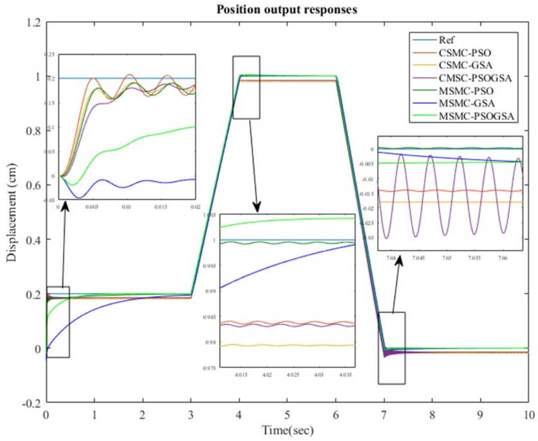

Fig. 2. Position output for CSMC and MSMC, integrated with PSO, GSA and PSOGSA with 5 particles within 10 iterations for external disturbance, 10500N

Based on Fig. 2, through the combination of MSMC with PSO, GSA and PSOGSA, the system output tracked the reference input with different accuracies. Initially, the lowest number of particles and iterations were used, which were 5 and 10 respectively. With this combination, MSMC-PSO was able to exhibit the best system output in comparison to the system output of the MSMC-GSA and MSMC-PSOGSA. This was the inclusion of the values of SSE amounting to 32.4511, 1609 and 147.3797 respectively, as shown in Table 2. In the case of CSMC, the values of SSE for designed controller that which was combined with PSO, GSA and PSOGSA were 232.1030, 370.9705 and 189.8791 respectively. As seen in Fig. 2, at the same external disturbance value, the MSMC shows more accuracy that the CSMC in the aspect of tracking when by 5 particles and 10 iterations are used to find the optimum values of each parameter for both controller. This indicates the lower values of SSE produced by MSMC.

TABLE II. SSE OBTAINED FROM COMBINATION OF MSMC AND CSMC WITH PSO, GSA AND PSOGSA

	CSMC			MSMC		
	PSO	***GSA***	***PSOGSA***	***PSO***	***GSA***	***PSOGSA***
$\boldsymbol{i5, t10}$	232.1050	370.9705	189.8791	32.4511	1609	147.3797
$\boldsymbol{i15, t30}$	232.1031	308.0041	85.9871	32.5014	746.6484	17.1532
$\boldsymbol{i25, t50}$	232.1030	234.5374	80.9007	32.7035	881.2971	19.3152

In Fig. 2, even though the MSMC-PSO produces oscillate output at each corner of the output, but the values of SSE is the lowest and capable of tracking the reference input given accurately with minimal error in comparison with the MSMC-GSA and MSMC-PSOGSA. It clearly shows that PSO managed to comprehend the optimum combination of the parameter with the lowest SSE. The output performance of MSMC-GSA was obviously the worst. The SSE value for MSMC-GSA drastically decreased by from 1609 to 746 and then it went up to 881. However, these values still cannot match the performances outputs that had been shown by MSMC-PSOGSA and MSMC-PSO. The SSE value for MSMC-PSO was still around 32 while the SSE value for MSMC-PSOGSA slightly increased to 19.

Fig. 3 and 4 show the position output for CSMC and MSMC, integrated with PSO, GSA and PSOGSA with 15 particles within 30 iterations and 25 particles within 50 iterations, respectively for external disturbance, 10500N. From both figure, obviously can see chattering occurs along the output response produced by CSMC that been optimized by PSO, GSA and PSOGSA. MSMC-PSO has the tendency to track reference input given with SSE values being 32.5014 and 32.7035 in both conditions. This situation does not change much with previous MSMC-PSO output response when i and t are 5 and 10, respectively.

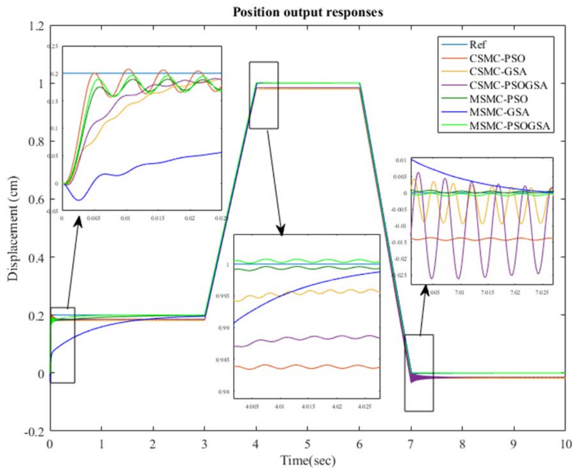

Fig. 3. Position output for CSMC and MSMC, integrated with PSO, GSA and PSOGSA with 15 particles within 30 iterations for external disturbance, 10500N

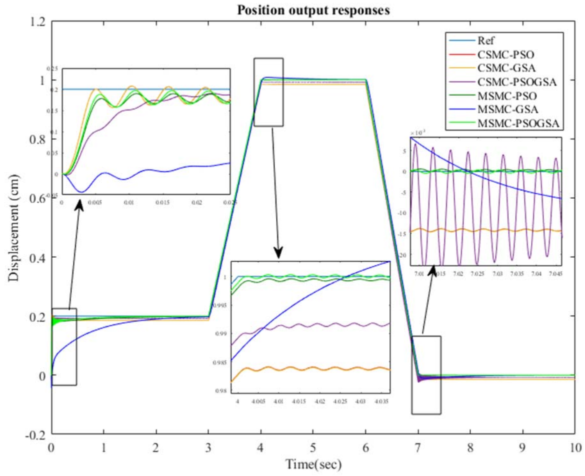

Fig. 4. Position output for CSMC and MSMC, integrated with PSO, GSA and PSOGSA with 25 particles within 50 iterations for external disturbance, 10500N

Meanwhile, the output response for MSMC-GSA was not found to produce chattering and has shown a smooth and steady output response with respect to the reference input given but the SSE value was the largest with 746.6484 and 881 for both conditions. MSMC-PSOGSA output response showed relatively smaller chattering at each corner when the reference input changed its form and the SSE values given by MSMC-PSOGSA were the smallest with 17.1532 and 19.3152 for both conditions, respectively. Although an increase in SSE value of about 2 was observed, but the value was still too small compared to the MSMC-PSO and MSMC-GSA. For GSA, even though no chattering produced but the performance output given was the worst compared to MSMC-PSOGSA and MSMC-PSO. MSMC-PSOGSA revealed an excellent improvement in terms of output response in the event of an increase being observed in the number of particles and iterations compared to MSMC-PSO. However, the SSE produced by MSMC-PSO did not show much improvement with a reduction rate and addition of about 0.1 in comparison with the MSMC-PSOGSA with SSE reduction from 147 to 17. By means of increasing the number of particles and iterations from 5 and 10, to 25 and 50, the performance output of MSMC-PSOGSA was seen as the best compared to another two methods. As the reseachers were looking for the optimum combination which was capable of producing the lowest SSE value among CSMC and MSMC, integrated with PSO, GSA and PSOGSA, therefore the optimum combination number of particles,i and iterations, t for the best performance output which produced the lowest SSE is shown in Table 3.

TABLE III. OPTIMUM COMBINATION NUMBER OF PARTICLES, i AND ITERATIONS, t WHICH PRODUCED THE LOWEST SSE

	CSMC			**MSMC**		
	PSO	***GSA***	***PSOGSA***	***PSO***	***GSA***	***PSOGSA***
Number of particles, *i*	25	25	15	20	20	15
Number of iteration, *t*	50	50	50	40	40	30
SSE	232.10	234.54	72.70	32.66	758.47	17.15

Referring to Table 3, the integration of MSMC and PSOGSA yielded lower SSE value compared to MSMC-GSA and MSMC-PSOGSA. By means of combining both PSO velocity and GSA acceleration, PSOGSA managed to obtain the optimum combination of parameters and the best performance of system output compared to PSO and GSA alone. With the lowest SSE value of PSOGSA (17.1532), the combination of 15 particles/agents within 30 iterations was required. However, compared to PSO, the combination of 20 particles/agents within 40 iterations was required with obtained SSE value of 32.6515, which was almost 15 units bigger than the PSOGSA. It should be noted that the tracking errors of both PSO and PSOGSA were almost non-existent. Besides that, PSOGSA was found to track the given reference smoothly with only minimal chattering at the beginning. This reaffirmed that the optimum combination of parameters can effectively reduce the chattering issue.

VI. CONCLUSION

In this study, a hybrid algorithm of particle swarm optimization (PSO) and gravitational search algorithms (GSA) based modified sliding mode control (MSMC) for solving tracking control accuracy in the mismatched electro-hydraulic actuator are presented. With the presence of large external disturbance, the integration of MSMC with PSOGSA potentially enhances the performance and produces relatively higher accuracy in tracking the reference signal given to the system. Such a development clearly indicates that MSMC-PSOGSA has the potentials to overcome the presence of external disturbance for mismatched system, reduce the chattering effectively and enhances the performance based on the lowest SSE, which is 17.1532 .Future works may have to consider applying MSMC-PSOGSA and looking into its performance with mismatched electro-hydraulic actuator that is injected with uncertainties and nonlinearities to help enhance the complexity of the system and at the same time, to verify the robustness of MSMC-PSOGSA to effectively deal with more complex nonlinear systems.

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