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Design of Self Adaptive Fuzzy Sliding Mode Controller for Robot Manipulators

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Abstract - **This paper intends to design and develop an adaptive fuzzy sliding mode controller (SMC) for robotic manipulator. Since it is not viable to pair the SMC operations with the system model every time, this paper adopts a Fuzzy Inference System (FIS) to replace the system model. It effectively achieves the experimentation in two phases. Accordingly, in the first phase, it attains the accurate features of the system model based on varied samples to characterize the robotic manipulator. In the second stage, it represents the derived fuzzy rules based on adaptive fuzzy membership functions. Moreover, it establishes the self-adaptiveness using Grey Wolf Optimization (GWO) to attain the adaptive fuzzy membership functions. The analysis distinguishes the efficiency of the adopted technique with the optimal investigational scheme and the traditional schemes such as SMC, Fuzzy SMC (FSMC) and GWO-SMC. Moreover, the comparative analysis is also performed by including the noise and validates the effectiveness of the proposed and conventional models.**

Index Terms— Sliding Mode Control; Robot manipulators; Controller; Noise;

1. Introduction

In general, robotic manipulators are widely applied in the industrial environment for executing dangerous or routine works. Robotic manipulators have been encounter nonlinearities and various uncertainties in their dynamic models, such as friction, disturbance, load change due to which it is very difficult to reach excellent performance when the control algorithm is completely based on the robotic plant model [1]. The trajectory tracking accuracy is the most important function of an industrial manipulator. Thus, a robot motion tracking control is one of the challenging problem due to the highly coupled nonlinear and time varying dynamics. Robotic control system design has been an important issue in control engineering. Several kinds of control schemes have already been proposed in the field of robotic control over the past decades [2]. Feedback linearization technique can compensates some of the coupling nonlinearities in the dynamics. Although a global feedback linearization is theoretically possible, a practical insight is restricted. Uncertainties also arise from imprecise knowledge of the kinematics, dynamics and also due to joint and link flexibility, actuator dynamics, friction, sensor noise, and unknown loads [3].

These dynamical uncertainties make the controller design for manipulators a difficult task in the framework of classical control method. Conventional control techniques for robotic manipulators include the computed torque control, adaptive control, sliding mode control, and fuzzy control [4]. The adaptive control has a fixed structure and adaptable parameters and is very effective in coping with structured uncertainties and maintaining a uniformly good performance over a limited range, but it does not solve the problem of unstructured uncertainties. The sliding mode control is a robust nonlinear control scheme that is effective in overcoming the uncertainties and has a fast transient response. However, chattering problem is a major drawback of sliding mode control. Hence boundary layer is used to avoid chattering phenomenon [5].

Recently the development of artificial intelligent control for robotic manipulators has received considerable interest. The most popular intelligent-control approaches are the neural network control and fuzzy control. The merit of the fuzzy control is that it can explicitly use human knowledge and experience in its control strategy. The drawback is the less theoretical analysis of stability for the general fuzzy controllers [6]. To overcome the demerits and take advantage of the attractive features of conventional control and intelligent control, this research proposes an adaptive fuzzy sliding mode controller (AFSMC) for the trajectory control of robotic manipulators. Besides advantage of stability and robustness of sliding mode control, the proposed method suppresses the input chattering in sliding mode by using the fuzzy control with adaptive tuning algorithm [7].

Sliding Mode Controller has been widely applied to various types of non-linear systems. SMC's popularity is due to its robustness against the change in parameters and the external disturbances in both theoretical and practical applications. However, the action of discontinuous part in traditional SMC leads the whole controller to face a troublesome condition known as "chattering" and the traditional type of SMC requires the whole dynamic functions of the system. Moreover, in order to achieve the non-chattering SMC, the sign function should be changed to saturation function to employ the adaptation of a thin boundary layer close by the sliding manifold to minimize or attenuate the chattering. However, this method damages the perfect tracking of the SMC; hence, the steady state error will always exist [8]. Furthermore to overcome the mentioned problem, some adaptive strategies recommended which can compensate the disturbances in order to increase the tracking performance.

In recent decades, the Fuzzy Logic as a technique based on expert knowledge has been applied to a wide range of controllers for solving the complex problems. Although Fuzzy controller is free from huge mathematical operations but sometimes more mathematical treatment is needed. However it should be noted that sometimes Fuzzy Logic Controller is much more tranquiller [9]. Today's, applying techniques that combine the fuzzy theory with nonlinear controllers, for instance using fuzzy sliding mode controller are most common. The applications of fuzzy logic controller can not only be used in the systems with hard modeling, but they can also be used for systems with high mathematical analysis. The robust model of fuzzy combination, so called adaptive fuzzy sliding mode was introduced to reject the chattering phenomenon and compensate unknown dynamic parameters in the systems by another fuzzy logic controller [10].

2. Literature Review

For tracing control of non-linear structure, Kung and Liao [7] had presented the strategy of fuzzy SMC. In the hitting stage of unadventurous SMC, the chattering singularity is reduced by the fuzzy SMC and the sensitivity is reduced to plant uncertainties.

For nonlinear MIMO systems, Lin and Chen [8] had developed the adaptive fuzzy SMC. The main objective of this study is to solve the issue of controlling an unknown MIMO nonlinear affined system. With unknown nonlinear dynamics, Fuzzy controller is employed for the route tracing of MIMO system according to the sliding mode.

The adaptive fuzzy SMC scheme was developed by Kao et al [9]. Moreover, the distance based fuzzy sliding mode controller (D-FSMC) was presented in this work. Through Lyapunov stability system, the stability of the intended control structure is verified.

Using SMC, the design of robust control system was established by Ha [10] which utilizing a fuzzy tuning approach. The switching control, equivalent control and fuzzy control is superposed by the law of control. By the way of pole placement, a corresponding control law is intended. In the occurrence of constraint and disturbance hesitations, the Switching control is included to assurance the state reaches the sliding mode. In the sliding mode, to decrease the chattering and to enhance the control performance. The fuzzy tuning approaches are utilized.

For robotic manipulators, an adaptive FSMC was developed by Guo and Woo [11]. Through Lyapunov technique, the constancy and the conjunction of the entire structure is verified. In the classical SMC, it is a better solution to the issue of chattering. Moreover, it is considered that the designated components of the controller have influence on the network performance.

3. The Proposed Self Adaptive FSMC Controller

AFSMC is a controller that controls the uncertainties of non-linear systems without high-frequency switching. AFSMC helps to enhance tracking performance [8]. It is a widely used technique. It adjusts the SMC key parameters, in

order to eliminate or minimise the chattering. AFSMC improves the system robustness and get rid of the parameter perturbation [7][9]. The structure of AFSMC is represented in figure 1

A Design of an AFSMC

A 1.1 Design of sliding surface

The error state can be represented as [8],

$$c_i = a_i - b_i \tag{1}$$

Where i =1, 2, 3 …

$$\mathrm{P}(c_1, t) = \mathrm{P}_a(a_1, t) - \mathrm{P}(c_1 + a_1, t) \tag{2}$$

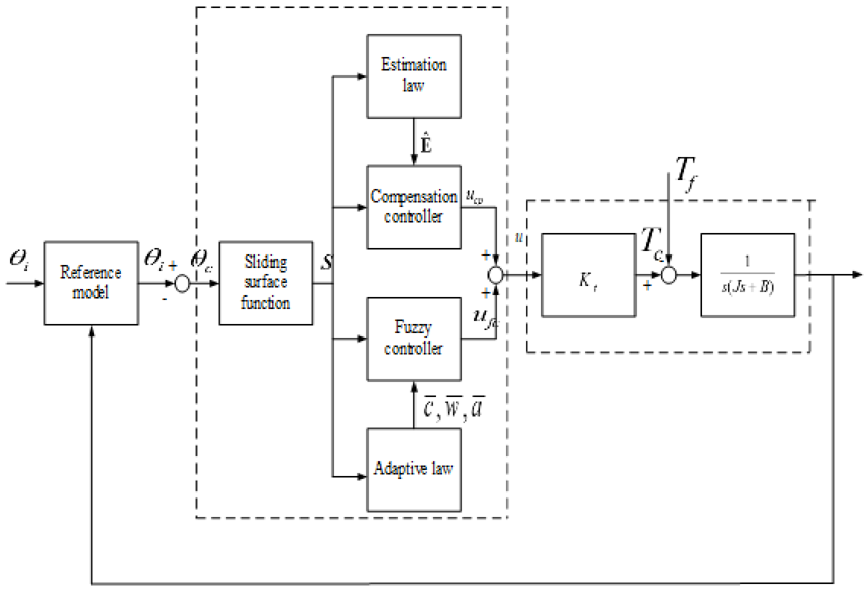

Figure 1: Structure of adaptive fuzzy compensate control

$$\Upsilon() = \Upsilon_a(t,a) - \Upsilon_b(t,b) \qquad (3)$$

The equations of error dynamic are:

$$\dot{c}_1 = c_2 \qquad (4)$$

$$\dot{c}_2 = c_3 \qquad (5)$$

$$\dot{c}_3 = -xc_3 - c_2 + \mathrm{P}(c_1,t) + \Upsilon(\cdot) - v \qquad (6)$$

Standardized state space equations of error states can be found as,

$$\dot{c}_1 = c_2 \qquad (7)$$

$$\dot{c}_2 = c_3 \qquad (8)$$

$$\dot{c}_3 = -xc_3 - c_2 + \mathrm{P}(c_1,t) + \Upsilon(\cdot) - v = c_4 \qquad (9)$$

$$c_4 = -xc_4 - c_3 + \mathrm{P}(c_1,t) + \dot{\Upsilon}(\cdot) - \dot{v} \qquad (10)$$

The sliding surface is given by,

$$u = c_4 - c_4(0) + \int_0^t \sum_{k=1}^{4} e_k c_k \, dt = 0 \qquad (11)$$

Where $c_4(0)$ represents initial state of c_4 Differential of the equation (13) can be written as,

$$\dot{c}_4 = -\sum_{k=1}^{4} e_k c_k \qquad (12)$$

The following is the matrix that defines the error states in equation (12).

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$$\underset{-}{\dot{c}} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -e_1 & -e_2 & -e_3 & -e_4 \end{bmatrix} c = \mathrm{M}e \tag{13}$$

Where $\underset{-}{\dot{c}} = [c_1 \quad c_2 \quad c_3 \quad c_4]^T$. c_j can be found by selecting the eigen values of M in which the characteristic polynomial

$$\mathrm{H}(c) = \dot{c}_4 + \sum_{k=1}^{4} e_k c_k \tag{14}$$

$H(c)$ is Hurwitz. Speed of the system response and eigenvalues are relative.

A 1.2 Design of adaptive SMC

The control law is designed as,

$$r = r_{eq} + r_{afz}(t) \tag{15}$$

Where r_{afz} represents the AFSMC and r_{eq} represents hitting control. Sliding surface, u and derivative of sliding function, $\dot{u}$ serves as the input to the fuzzy controller. Overall AFSMC is chosen as,

$$r_{afz} = \hat{\beta} F(\dot{u}, u) \tag{16}$$

Where $F(\dot{u}, u)$ indicates the functional characteristics of fuzzy linguistic decision schemes. $\hat{\beta}$ represents estimated value. The estimated error can be defined as,

$$\underset{-}{\dot{c}} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -e_1 & -e_2 & -e_3 & -e_4 \end{bmatrix} c = \mathrm{M}e \tag{17}$$

Where $\underset{-}{\dot{c}} = [c_1 \quad c_2 \quad c_3 \quad c_4]^T$. c_j can be found by selecting the eigenvalues of M in which the characteristic polynomial

$$\mathrm{H}(c) = \dot{c}_4 + \sum_{k=1}^{4} e_k c_k \tag{18}$$

$H(c)$ is Hurwitz. Speed of the system response and eigenvalues are relative.

$$\tilde{\beta} = \hat{\beta} - \beta \tag{19}$$

Estimation law is designed as,

$$\hat{\beta} = \gamma \left| F(\dot{u}, u) \right| \tag{20}$$

Where γ represents a positive constant. The reaching law can be determined as,

$$\dot{u} = -\hat{\beta} F(\dot{u}, u) \tag{21}$$

From equations (13) and (18),

$$\dot{u} = \dot{c}_4 + \sum_{k=1}^{4} e_k c_k = -\hat{\beta} F(\dot{u}, u) \tag{22}$$

and control input of slave system

$$v = \int_0^t \left[-x c_4 - c_3 + \mathrm{P}(c_1, t) + \Upsilon(\cdot) \right] dt + \int_0^t \left[\sum_{k=1}^{4} e_k c_k + \hat{\beta} F(\dot{u}, u) \right] dt \tag{23}$$

4. Results and Discussions

A. Experimental Procedure

This paper introduces a fuzzy system model that restores the system model. Mainly the proposed work helps to achieve the objectives. The optimization of each mechanism is used to determine the performance parameters of the proposed controller. This system includes a self-adaptive property into the GWO technique [12]. The SAGWO-FSMC scheme helps the fuzzy model to support the SMC model in the robotic manipulator. It is stimulated based on MATLAB, and the output is obtained. To analyze the efficiency of the proposed method, it is compared with the conventional experimental technique such as SMC, FSMC, and GWO-SMC [12].

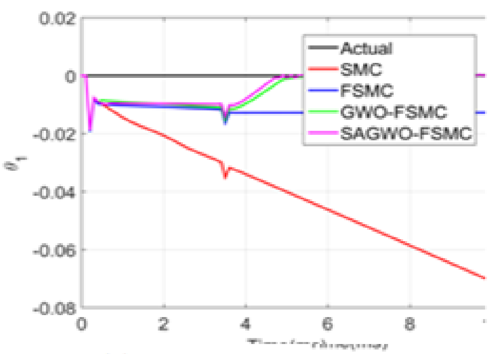
In this SAGWO-FSMC system, the required characteristics are acquired based on fuzzy rules. Then obtained fuzzy rules represent in the form of adaptive fuzzy membership functions. During the procedure establishment, the number of iteration assigned for this model is 100. Then the required parameters are set based on the algorithm. Then its performance is compared with known methods.

B. Analysis on Angles

Performance analysis in terms of three joint angles such as θ_1, θ_2 and θ_3 is conducted and illustrated in Fig. 2. The analysis was limited to 10 ms and the movement of joint angles to be controlled were observed. On comparing the actual joint angle θ_1 with the desired θ_1 as shown in Fig. 2(a), the performance of SAGWO-FSMC is 1%, SMC is 3%, FSMC and GWO-FSMC is 1.9% varied from the desired angle θ_1. Thus SAGWO-FSMC model resembles the desired model than the conventional GWO-FSMC in controlling θ_1. Likewise, from the analysis on joint angle θ_2 as shown in Fig. 2(b), the actual θ_2 of SAGWO-FSMC is 4.41% deviated from the desired θ_2, which is better than the other models. Furthermore, the actual θ_3 of SAGWO-FSMC is4.41% deviated from the desired θ_3, as given in Fig. 2(c). Therefore, the proposed SAGWO-FSMC controls the joint angles that exhibit high correlation with the desired joint angles and so it records the superiority over the conventional SMC methods.

C. Analysis on displacement

Consider three displacements such as X, Y, Z, and the analysis on these three displacements is shown in the figures given below. The implemented SAGWO-FSMC system displacement performance is compared with traditional models like SMC, FSMC, and GWO-FSMC. The measured values will be near to the displacement of desired model.



(a)

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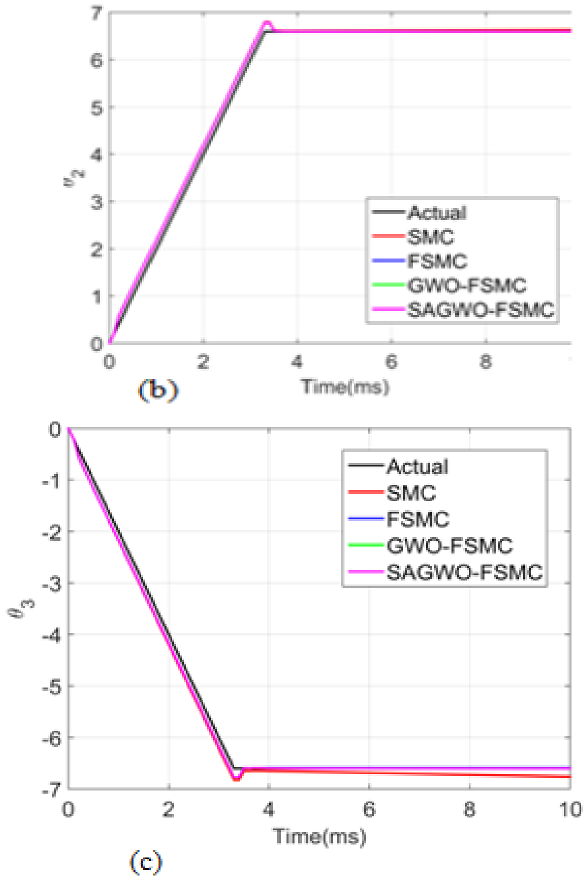

Fig 2. Performance analysis on three angles of joints with respect to time namely, (a) (b) and (c) θ_1, θ_2 and θ_3

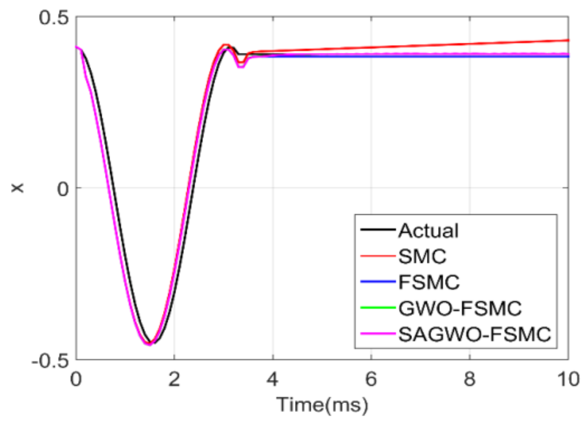

Figure 3: Analysis on displacement x with respect to time

Consider the case of displacement X from figure 3, the difference from desired displacement performance for SMC is 9.52% and for FSMC is 2056% and for SAGWC-FSWC is 2.56%. Thus it shows that the SMC produces a movement far away from the actual value, while other methods are close to the actual value.

Similarly, in the case of displacement y from figure 4 the difference from desired displacement performance for SMC is 1%, FSMC, GWO-FSMC, and SAGWO-FSMC is 0.04%. From this analysis the placement Y shows that the FSMC, GWO-FSMC, and SAGWO-FSMC are near to the actual value, and it shows that the proposed method is superior to other methods.

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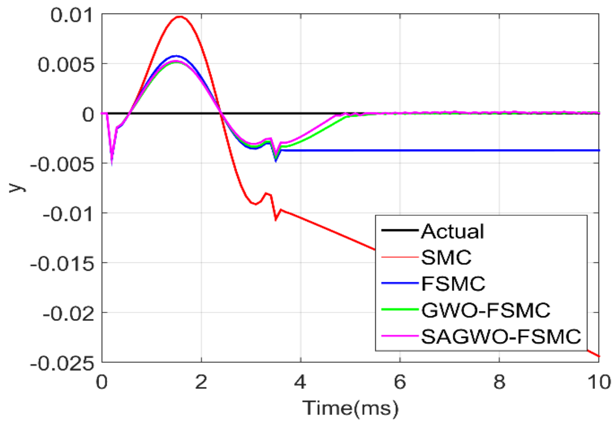

Figure 4: Analysis on displacement Y with respect to time

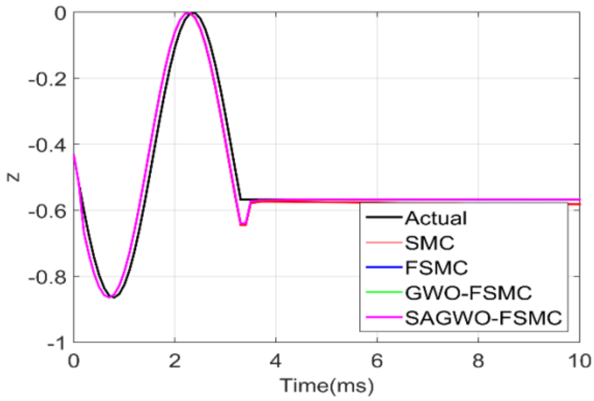

Figure 5: Analysis on displacement Z with time

Besides in the case of displacement z from figure 5, the deviation from displacement performance for SAGWO-FSMC is 14.49%. Therefore the desired displacement will be near to the displacement of the original model. While the displacement of SMC is away from the actual value. It shows that the suggested model should be closer to the desired model to assuring the performance. For better displacement performance the SAGWO-FSMC model is used.

D. Impact of Noise

The three displacements X, Y, and Z with respect to time can be varied by the presence of noise, and is shown in figures given below. By the analysis of figure 6, at 10ms, the original displacement value is 0.4 and the suggested work has achieved a displacement of 0.3. Therefore the proposed model found the displacement near to the actual value. From this, it shows the enhancement of proposed model. The proposed method is superior to other conventional method.

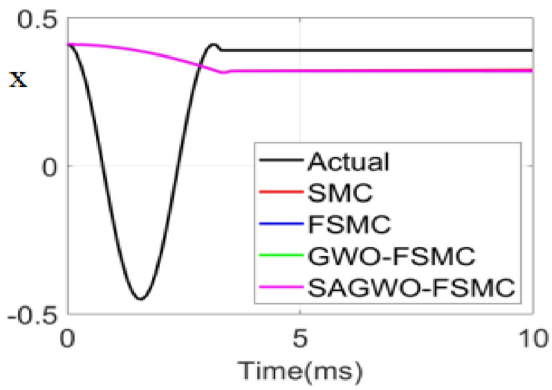

Figure 6: Analysis on displacement X based on impact of noise

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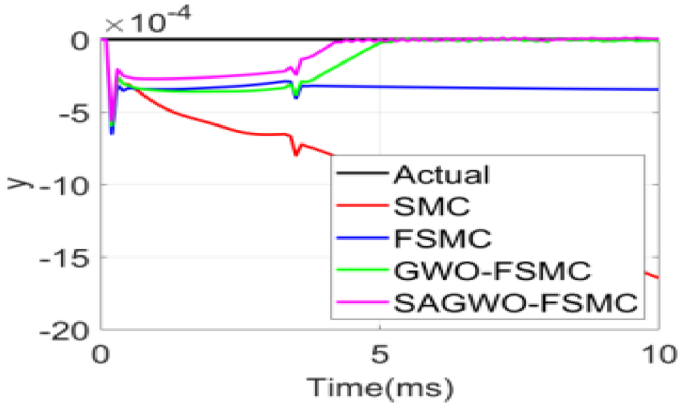

Figure 7: Analysis on displacement Y based on impact of noise

Likewise, from figure 7, at 2ms, the original displacement value is 0, the SMC, FSMC, and GWO-FSMC have achieved a displacement of -4×10^{-4}, While the suggested SAGWO-FSMC has achieved a displacement of -3×10^{-4}. The displacement Y shows the proposed method is superior to other convolutional methods. The SMC produce a movement far away from the actual value, while other methods follow a constant movement nearly to the actual value.

Similarly from figure 8, at 0ms, the original displacement value is -0.43, and the suggested SAGWO-FSMC has achieved a displacement equal to the original value. So, the suggested model displacement value is closer to the original displacement value in the presence of noise, shows the superiority over the traditional method. If there is a presence of noise, the proposed technique follows a constant movement which is near to the actual value.

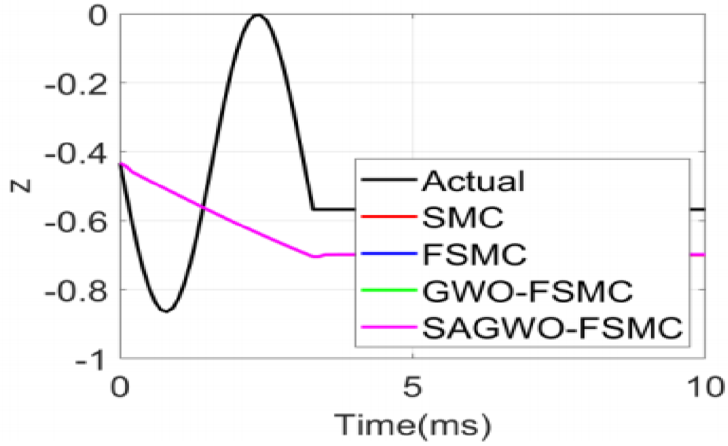

Figure 8: Analysis on displacement Z based on impact of noise

5. Conclusion

Adaptive FSMC was implemented for the robotic manipulator. In general, a system model was not possible to combine with the operation of SMC every time. Hence, fuzzy interference system was employed here to replace the system model. Here, the experiment was performed based on two stages. The accurate characteristics from the system model under various samples were acquired in the first stage to represent the robotic manipulators, where the acquired characteristics were assigned as fuzzy rules. On the contrary, adaptive fuzzy membership function was used to determine the derived fuzzy rules in the second stage, using the SAGWO algorithm. To the next, the performance of the SAGWO-FSMC was compared with the desired experimental model and the conventional methods like SMC, Fuzzy SMC (FSMC) and GWO-SMC. Thus the experimental analysis has revealed the superior performance of SAGWO-FSMC, in tuning the optimum joint angles in the robotic manipulator. Adaptive FSMC was executed for the robotic manipulator on concerning the external noise. Finally, the valuable comparative analysis was done by validating the performance of proposed over conventional models while adding external noise in the manipulator.

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