Observer Sliding Mode Control Design for lower Exoskeleton system: Rehabilitation Case

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Abstract—**Sliding mode (SM) has been selected as the controlling technique, and the state observer (SO) design is used as a component of active disturbance rejection control (ADRC) to reduce the knee position trajectory for therapeutic purposes. The suggested controller will improve the needed position performances for the Exoskeleton system when compared to the proportional-derivative controller (PD) and SMC as feed-forward in the ADRC approach, as shown theoretically and through computer simulations. Simulink tool is used in this comparison to analyze the nominal case and several disruption cases. The results of mathematical modeling and simulation studies demonstrated that SMC with a disturbance observer strategy performs better than the PD control system and SMC in feed-forward with a greater capacity to reject disturbances and significantly better than these controllers. Performance indices are used for numerical comparison to demonstrate the superiority of these controllers.**

Keywords—Exoskeleton system; ADRC; robustness; disturbance rejection, SMC.

I. INTRODUCTION

Exoskeleton and orthotic devices of various kinds have been created recently to help with lower-limb movements. These devices are typically used for one of two major types of rehabilitation: (1) enhancing healthy subjects' muscular force or (2) treating patients with movement disorders. The majority of the currently used implementations in the first category are designed [1]. The fundamental challenge in employing an exoskeleton to improve the agility of leg motions is that the mechanism of the exoskeleton adds additional resistance to the legs. The legs should therefore move slower rather than faster as a result of the mechanism alone. Furthermore, while the weight and friction of the mechanism can be effectively concealed by control, it is much more challenging to account for the inertia of the mechanism because of stability problems [2, 3].

There are a variety of control strategies for the Exoskeleton's lower knee position, starting with the conventional PID controller [4, 5], which can reduce the discrepancy between desired and actual trajectories but responds poorly to disturbances. In another study, the robot's posture was managed via model predictive control, and the author claims to have accomplished the specific objective of raising a human body that was lying down while doing so [6]. In order to achieve the necessary accuracy, another author used iterative linear quadratic regulator control as a feedback controller [7] and created a comparison of LQR and adaptive PD control for lower limb exoskeleton devices. The performance of the Adaptive-Fuzzy-PD was compared with the fuzzy logic controller (FLC) and FLC-proportional derivative (FLC-PD) algorithms in [8] robust adaptive fuzzy PID Control method used to control the actuated exoskeleton for improving the position trajectory.

A new control strategy (ADRC) has been used recently to cancel these effects due to the impact of internal and external disturbances on the position trajectory of the Exoskeleton system [9-11]. There are numerous ways to build an ADRC, both linear and nonlinear, and the feed-forward controller may use a variety of techniques, including fuzzy control, artificial intelligence control, classical PD, and fractional PD [11–15]. Each of these approaches has benefits and drawbacks in terms of performance robustness against rejection disturbances. Due to its straightforward design process, an SMC is one of the most well-known and reliable nonlinear control strategies for uncertain systems [16]. Prior attempts at using the ESO-based SMC [17, 18] techniques failed to address problems, including chattering in SMC, reaching phase elimination, non-integral chain form, mismatched systems, and accurate disturbance estimate. In this research, an extended state observer (ESO) for the ADRC scheme is built from the estimated states. In a simulation study, a lower knee position model is utilized as a nonlinear example to build and implement ESO-based SMC. Comparing this suggested controller to two other controllers (PD-LESOADRC and (SMC-LESOADRC).

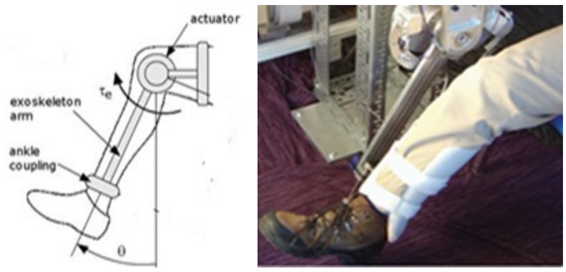
These aspects of the study's contribution to the paper can be outlined:

- An improved ADRC was built by modifying the ESO for traditional ADRC depending on nonlinear function sliding mode trajectory response with two design parameters.
- The proposed controller is compared with different ADRC configurations techniques to show the effectiveness of anti-disturbances rejection and its robustness of it.
- Study the robustness of modified ESO for estimation and cancellation of total disturbances by different performance indices and new index integral absolute control signal for required torque.

The arrangement of the remaining text is as follows. First, a mathematical model to represent the dynamic properties of the lower knee Exoskeleton system was developed in the following section. For the purpose of limiting plant uncertainties, an SMC law with disturbance observer compensation was created in Section 3. This allows us to choose a smaller value for the switching gain of the SMC law and reduce chattering on the sliding mode plane. To evaluate the suggested controller activities, compare the 4 results and discussions across all controllers. The paper's key conclusions are outlined in section 5.

II. Dynamic Model Of Exoskeleton System

Exoskeletons are motorized joints equipped with wearable electromechanical devices that are attached to the user's body to improve performance. The importance of the Exoskeleton has increased recently as a result of the sharp rise in the number of older persons. This technology is mostly used to repair or improve people's capacity to walk or carry standard objects because lower-limb neurological injuries, hemiplegia, lower-limb weakness, and movement disorders are on the rise due to unhealthy lifestyles, traffic accidents, and sports injuries [19, 20]. The majority of knee exoskeletons use this type of pin-joint, which has only one DOF and a fixed rotation axis, as their representation of the knee joint [21]. The Exoskeleton system is seen in Fig. 1.



(a) (b)

Fig. 1. 1-DOF exoskeleton coupled to a subject's leg, (a) schematic diagram, (b) Practical diagram

The mathematical model is represented by the following equation using the Lagrange implementation [9], [11], [22] as

$$J\ddot{\theta} = -\tau_g \cos\theta - A sign\dot{\theta} - B\dot{\theta} + \tau_e + \tau_h \quad (1)$$

where (θ) joint angle, (τ_e) exoskeleton torque, (τ_h) human torque, and (τ_g) gravitational torque of the shank/foot section is all taken into account. Inertia, solid friction coefficient, and viscous friction coefficient are represented by (J), (A), and (B), respectively. Knee extension and flexion movements are considered synchronous and simultaneous since the exoskeleton and the wearer's joints are safely coupled in the model. The use of rehabilitation robots by therapists provides new opportunities to enhance the rehabilitation process [11], [23].

III. State Observer Sliding Mode Control with ADRC

Han made the initial suggestion for ADRC [24]. To estimate the total disturbance and rejection in the subsequent state, the profile generation (PG), the linear feedback controller C(s), and the extended-state observer (ESO) can be combined to create the ADRC, which has the appearance in Fig. 2 [25].

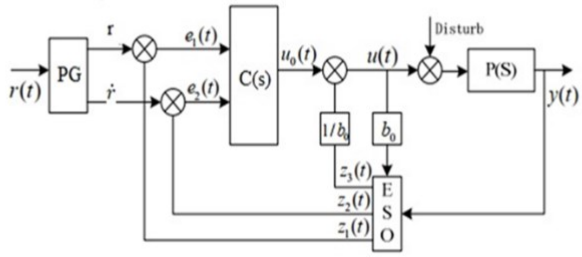


Fig. 2 ADRC structure

ESO has a straightforward structure and can frequently estimate unmolded dynamics with high accuracy. A class of nonlinear ESOs is created to estimate the total of the states and external disturbances in the context of ADRC [24]. Following that, GAO [26] introduced a class of linear ESOs (LESO) and offered advice on how to select the best controller design settings. In the control system nowadays, ESO is mostly utilized to estimate disturbances and compensate them using a feed-forward cancellation mechanism [27]. In the past 20 years, numerous observers, such as high gain and disturbance observers, have been developed [28].

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= f + b\,\tau_e \end{aligned} \quad (2)$$

where, $b = 1/J$ and f represents the lumped term of uncertainties and nonlinearities (total disturbances), which is given by

$$\frac{1}{J}\left[\tau_g \cos(x_1) - f_v\, x_2 - f_s\, sign(x_2) + \tau_h\right] \quad (3)$$

Rewrite (2) after adding an extra state (x_3) that represent the total disturbances as

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= x_3 + b_o\,\tau_e \\ \dot{x}_3 &= \dot{f} \\ y &= x_1 \end{aligned} \quad (4)$$

The proposed structure of observer dynamics for the system described by (4) is

$$\begin{aligned} \dot{\hat{\boldsymbol{z}}} &= \boldsymbol{A}\hat{z} + \boldsymbol{B}\tau_e + \boldsymbol{\beta}(y - \hat{y}) \\ \hat{y} &= \boldsymbol{C}\hat{\boldsymbol{z}} \end{aligned} \quad (5)$$

where, $\hat{\boldsymbol{z}} = [\hat{z}_1\ \hat{z}_2\ \hat{z}_3]^T$ are the vectors of estimates of y, $\dot{y}$, and f, respectively. The observer described above is known as the Linear ESO, and $\boldsymbol{\beta}$ is termed as the observer gain matrix. The elements of observer gain matrix $\boldsymbol{\beta}$ can be obtained using the pole-placement method. When properly designed and implemented, the estimated states of the observer will track that of the plant defined by (4). Based on the pole-placement control technique [29], one can establish the following characteristic equation based on the structure of the extended state observer

$$Q(s) = |s\boldsymbol{I} - (\boldsymbol{A} - \boldsymbol{\beta}\boldsymbol{C})| = (s + \omega_o)^3 \quad (6)$$

The observe gain matrix can be evaluated as follows

$$\boldsymbol{\beta} = [3\,\omega_o \quad 3\,\omega_o^2 \quad \omega_o^3] \quad (7)$$

Only the bandwidth ω_o of LESO is necessary to determine the elements of the observer gain matrix. This easy tuning strategy by using the pole-placement method [29]. For SMC structure, there are two phases, firstly is the sliding surface, which is

$$s = \dot{e} + ce \quad (8)$$

The sliding surface coefficient (c) is a design parameter, and (e) is the error as

$$e = r - y \quad (9)$$

The second part of SMC is the switching control as

$$U_{sw} = -Ksign(s) \quad (10)$$

The switching controller gain K is another design parameter. Sub. (8) in (10) and rewrite as

$$U_{SM} = -Ksign(\dot{e} + ce) \quad (11)$$

In this paper, the control law (u_o), as shown in Fig. 2, can take three configurations for comparison purposes.

A. PD Controller with linear ESO (LESO)

In this case, using (5) as LESO and

$$u_o = K_p\,(r - \hat{z}_1) + K_d\,(\dot{r} - \hat{z}_2) \quad (12)$$

So that the required torque signal (u) to move the exoskeleton is

$$u = \frac{(u_o - \hat{z}_3)}{b_o}$$
$$u = \frac{[K_p\,(r - \hat{z}_1) + K_d\,(\dot{r} - \hat{z}_2) - \hat{z}_3]}{b_o} \quad (13)$$

Where $\hat{z}_1$ is the estimated feedback signal tracking (y) and $\hat{z}_2$ is the derivative of $\hat{z}_1$ tracking $(\dot{y})$, while $\hat{z}_3$ is estimated the total disturbance (f).The values of controller gains are given by [29], [30]:

$$k_p = \omega_c^2; \quad k_d = 2\,\omega_c \quad (14)$$

Where ω_c is the control loop bandwidth. This controller is called (PD-LESOADRC).

B. SMC with LESO

In this case, using (5) as LESO and (11) as control law u_o so that:

$$u = \frac{[-Ksign(\dot{e} + ce) - \hat{z}_3]}{b} \quad (15)$$

This controller is called (SMC-LESOADRC). The two parameters (c) and (K) must be calculated by an optimization technique.

C. The Proposed Controller

In this case, return to (5) as LESO with SMC and rewrite with modified [31] as

$$\dot{z}_1 = z_2 + \beta_1 g(e)$$
$$\dot{z}_2 = z_3 + \beta_2 g(e) + bu \quad (16)$$
$$\dot{z}_3 = \beta_3 g(e)$$

where

$$g(e) = \{K_1|e|sign\;e + K_2|e|e\} \quad (17)$$

where e is defined in (9) and K_1, K_2 two parameters must be calculated by an optimization technique. The proposed controller is called (PD-SMCESOADRC). Fig. 3 shows the ADRC-based SMC structure. While Fig. 4 shows the details of SMCESO.

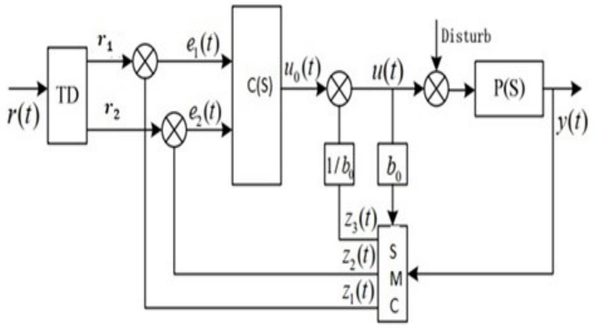


Fig. 3. Show ADRC-based SMC structure

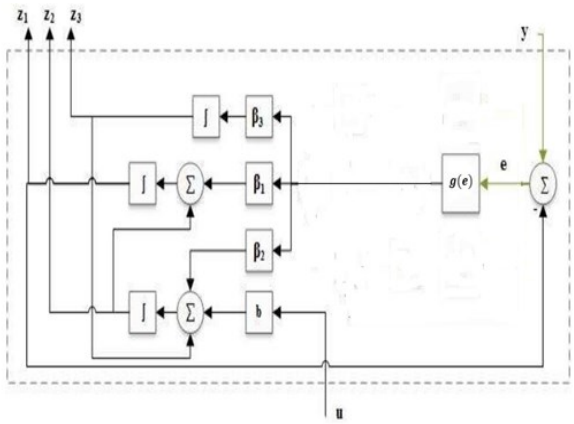


Fig. 4. Show the details of the SMCESO structure

IV. NUMERICAL SIMULATION AND DISCUSSION

To demonstrate the effectiveness of the proposed ESO-based sliding mode learning controller, a numerical simulation is considered in this section. The parameters of (1) are chosen as follows [9], [11], $J = 0.348\,kg.m^2$, $A = 0.998\,N.m$, $B = 0.872\,N.m.sec.rad^{-1}$ and $\tau_g = 3.445\,N.m$.

The optimization algorithm based on PSO [32-40] results in optimal design parameters for SMC and finding the optimal values of $(c = 0.1)$, $(K = 40)$ for (15) and $(K_1 = 6.93)$, $(K_2 = 600.59)$ for (17). The values of (K_p), (K_d), (β_1), (β_2) and (β_3) are calculated according to (7) and (14) when choosing $(w_c = 24.5\,rad/sec)$ and $(w_o = 4w_c)$. The Root Mean Square Error (RMSE), Integral square error (ISE), Integral absolute error (IAE) and Integral absolute control signal have been chosen as the performance indices for comparison purposes [9], [11], [41, 42]. The reference input trajectory to the Exoskeleton system is a sine wave as; $r = -0.785\sin(1.75\,\pi\,t)$.

A. No disturbance scenario

In this case, the human effect considers null or ($\tau_h = 0$). The simulation results of (13), (15), and (16) based on PD-LESOADRC, MC-LESOADRC, and PD-SMCESOADRC are shown in Fig. 5. The position trajectory of the proposed controller is very approximate to the desired signal with minimum error as shown in Fig. 6. when compared with others controllers. To study the controller's effects and the required torque signal, Fig. 7 shows the control torque required for each controller scheme. Table I shows the numerical performance indices for comparison purposes. As seen in Fig. 7, the PD-SMCESOADRC and PD-LESOADRC control methods produce the smallest measure of chattering reduction in the control signal index (IAU) and are almost equal (IAU=28 N.m). Because of the effect of the sign function in the forward path of the system, the SMC-LESOADRC response torque has more chattering (IAU=100 N.m). This has no effect on knee position tracking. To check the estimation of total disturbances (in this part, the internal dynamics effect of J, A, B, τ_g) and cancellation with the extra state ($\hat{z}_3$), Fig. 8 shows the smallest error between them.

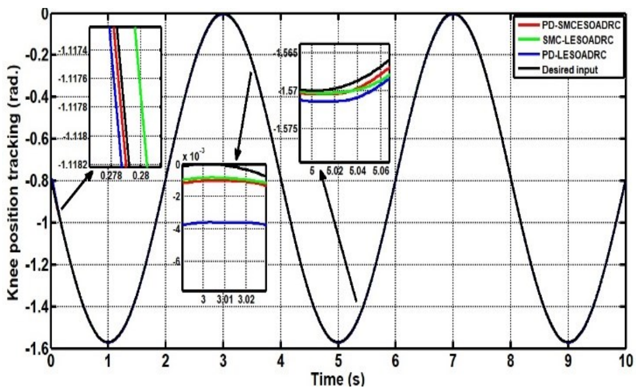


Fig. 5. Simulation results of the three controllers based ADRC without disturbance

TABLE I. PERFORMANCE INDICES FOR ALL CONTROLLERS BASED ADRC WITHOUT DISTURBANCE

Control Methods	R.M.S.E(rad.)	IAE (rad.)	ISE (rad.)	IAU (N.m)
PD-LESOADRC	0.0038	0.03108	0.00014	28.36
SMC-LESOADRC	0.0023	0.01218	0.00005	100
PD-SMCESOADRC	0.0019	0.01046	0.00003	28.71

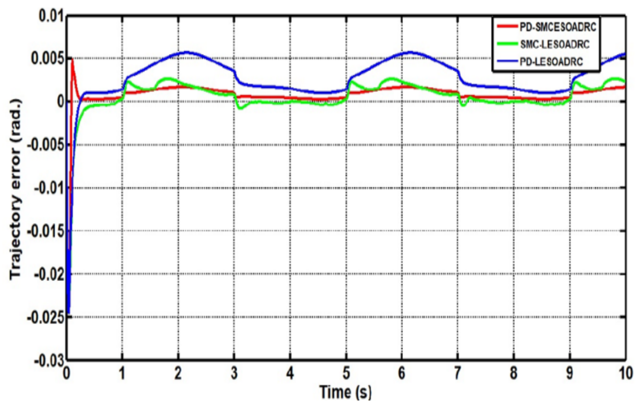


Fig. 6. Comparison of trajectory error results of the three controllers based ADRC without disturbance

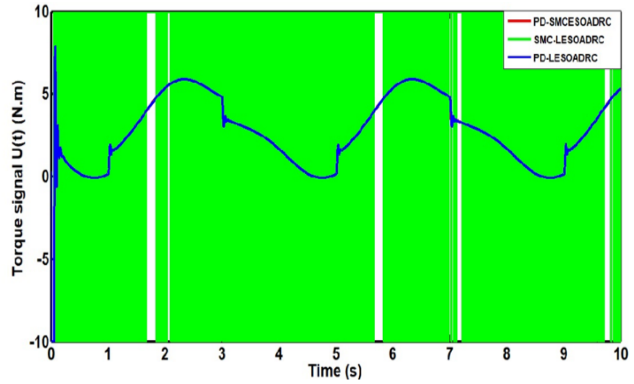


Fig. 7. Required torque signal of the three controllers based ADRC without disturbance

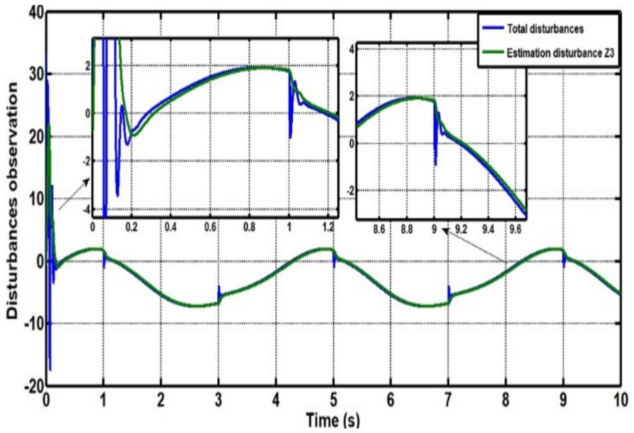


Fig. 8. Shows total disturbance (internal dynamic effects) and its estimation

B. With disturbance scenario

Consider the human effect $\tau_h \neq 0$ or during the training, the patient reacts to the Exoskeleton motion. Suppose this effect is like external vibration disturbance with magnitude (± 0.05) and frequency ($25\, rad/sec$). Fig. 9 shows the position trajectory of the proposed controller is very approximate to the desired signal with minimum error, as shown in Fig. 10 when compared with other controllers. To study the controller's efforts and the required torque signal, Fig. 11 shows the control torque required for each controller scheme. Table II shows the numerical performance indices for comparison purposes. As seen in Fig. 11, the PD-SMCESOADRC and PD-LESOADRC control methods produce the smallest measure of chattering reduction in the control signal index (IAU) and are almost equal (IAU=35 N.m). Because of the effect of the sign function in the forward path of the system, the SMC-LESOADRC response torque has more chattering (IAU=100 N.m). This has no effect on knee position tracking. To check the estimation of total disturbances (in this part, the noise effect) and cancellation with the extra state ($\hat{z}_3$), Fig. 12 shows the smallest error between them.

TABLE II. PERFORMANCE INDICES FOR ALL CONTROLLERS BASED ON ADRC WITH DISTURBANCE

Control Methods	R.M.S.E(rad.)	IAE (rad.)	ISE (rad.)	IAU (N.m)
PD-LESOADRC	0.0181	0.07316	0.00328	35.08
SMC-LESOADRC	0.0186	0.06646	0.00346	100
PD-SMCESOADRC	0.0124	0.05803	0.00153	34.87

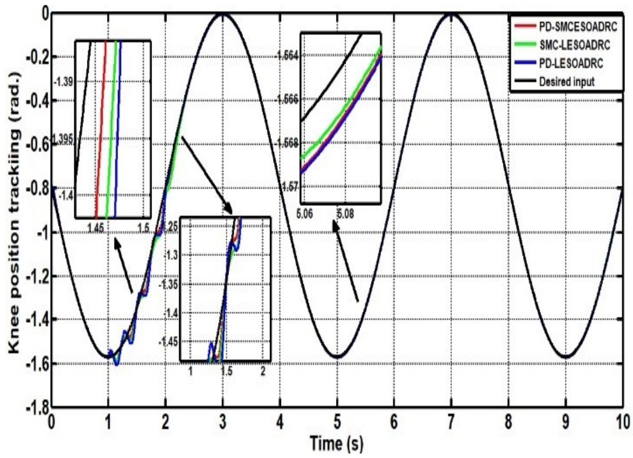


Fig. 9. Simulation results of the three controllers based ADRC with noise disturbance

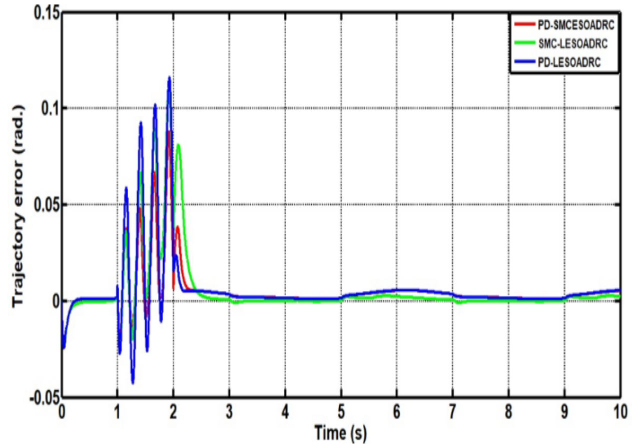


Fig. 10. comparison of trajectory error results of the three controllers based on ADRC with noise disturbance

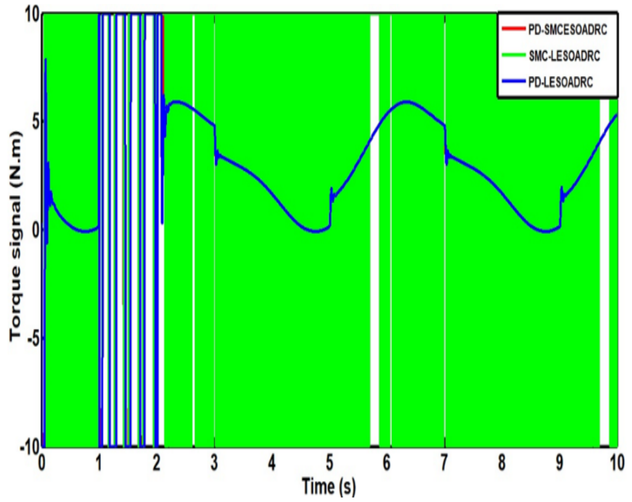


Fig. 11. Required torque signal of the three controllers based ADRC with noise disturbance

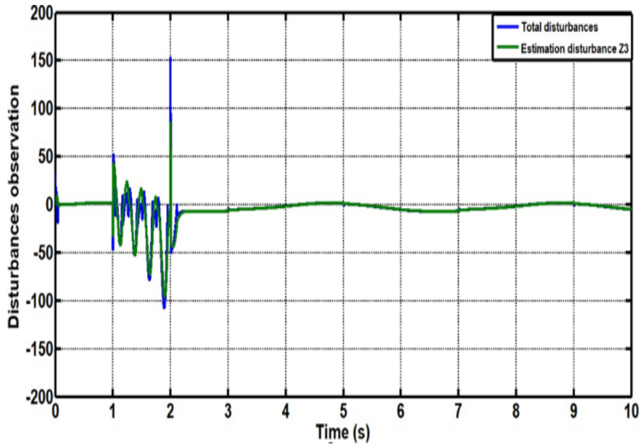


Fig. 12. Shows total disturbance and its estimation with the noise effect

V. CONCLUSIONS

A knee extension experiment is used to confirm the suggested control algorithm's impact on a healthy individual. The Exoskeleton is adjusted to change the joint angle more precisely with the suggested algorithm than with existing controllers, according to the results, and the steady-state R.M.S.E. is no more than 0.0019 rad. The control system may dynamically change the input amplitude even in the face of disturbances to produce precise movement with R.M.S.E=0.0124rad. Generally, the proposed nonlinear control technique is best experimentally verified. When using the trial-and-error method, it was observed that raising the sliding surface parameter (c) enhanced tracking performance but increased control signal chatter. Additionally, using a sufficiently high switching controller gain K might lessen chattering, but performance would suffer. The ideal values for these parameters are displayed using the PSO optimization process. The gains (K_1, K_2) can be said to support this conclusion. When sliding-mode control is used, a reliable controller that doesn't rely on intricate muscle models is produced. This controller also promises to be applicable in subsequent control sessions without needing time-consuming re-tuning. The 1-DOF basic model used, however, has a restricted tracking performance. Strongly chattering control signals, which are invariably necessary for high tracking performance, may not be ideal for this application. The efficiency and robustness of our applied control are a result of the sliding mode technique used in LESO-ADRC, which efficiently absorbs disturbance and parametric variations. The SMC law's switching gain can be modified to a lower value with the use of the disturbance observer, which will help to suppress the chattering issue. Implementing the suggested controller in a practical situation utilizing Arduino tools or other embedded hardware designs could be another development of this research [43], [44]. To perform a comparative study for this therapeutic purpose, several control methods could be recommended [45]-[50]. Controlling the knee and hip muscles is when the difficulty first appears at (2-DoF), and this was considered the future task.

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