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Knee-joint exoskeleton control system design using adaptive barrier function controller

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ABSTRACT

Exoskeletons and wearable robots are mechatronic devices that are worn by an operator and fit closely to the body to improve daily activities. The adaptive sliding mode control (ASMC) based on the barrier function is proposed in this study to regulate the movement of the knee joint exoskeleton with friction. This controller is implemented without the requirement to know the system model uncertainty and disturbance bounded and does not require the use of the low pass for chattering elimination with keeping the controller's performance. The suggested barrier method can be guaranteed the output variable's convergence and keep it in a preset neighborhood of zero regardless of the disturbance's upper bound, without overestimating the control gain. The simulation results show that the proposed performs well, the system angle following the target angular position with a modest pre-adjusted steady-state error. Furthermore, when compared to a typically strong and stable ASMC developed with the identical actuator; the obtained results reveal superior features. Concluded from the above this control method indicates the robustness of the proposed adaptive controller with barrier function against uncertainties and disturbances elimination.

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1. INTRODUCTION

The most common type of central nervous system damage is spinal cord injury (SCI), which frequently results in motor abnormalities such as paralysis. Because the brain control orders for limb movements cannot be delivered to the limb motor nerve in people with SCI, they lose motion function in their limbs [1]. The exoskeleton knee joints are electro-mechanical devices that are embodied by the limbs and are designed to aid or restore the capabilities of old and dependent persons who have physical limitations [2]. Passive therapy is mostly utilized with spinal cord injury patients to strengthen muscles, expand the joint range of motion, and reduce joint stiffness by continuously moving their damaged limbs [3]. Control of the knee joint exoskeleton system has attracted attention in recent years, because of nonlinear mechanical coupling, external disturbances, and unknown system characteristics. Therefore, it is challenging to achieve desired stability properties and performance specifications for a closed-loop system in the presence of such perturbations [4], [5].

Sliding mode control (SMC), which has improved design efficiency and is widely used in industrial systems, is one of the most successful methods for controlling nonlinear systems with matched disturbances [6]. Despite its advantages, SMC has some drawbacks, including chattering efficacy, reaching phase, and sensitivity to unmatched uncertainty. These problems have been solved by using different strategies of SMC such as integral SMC and adaptive SMC [7], [8] SMC is utilized for exoskeleton control because it is a reliable control method. In the Lokomat robotic orthosis, a basic SMC is used [9]. Banala and Agrawal [10] two controllers are proposed for operating an active gait rehabilitation device for the human body's lower limbs. The first controller employs a basic SMC to move the leg in a predetermined manner. The second one is used the feed-back linearizing controller. This method entails measuring the subject's torque and then adding the additional torque necessary to propel the leg along a chosen trajectory. The non-singular terminal sliding mode (NTSM) technique is another SMC technique that was utilized to achieve a finite time convergence in an actuated exoskeleton [11]. Mefoued and Belkhiat [12] a sliding mode observer-based robust control algorithm was studied. In this method, the authors used a sliding mode observer to control the closed-loop system's velocity and reduce the chattering impacts induced when a traditional sliding mode control is designed. Although the impact of the chattering was little, it is still fussing. For rehabilitation in [13], employed a knee exoskeleton with an adjustable instantaneous rotation center and impact absorption. A mechanism with cross-configuration based on the corresponding degree of freedom was constructed to adjust to the rotation center of the knee joint, and the stiffness of the springs was calculated by combining it with gait motion, leading to the human body's average force being minimized. The tracking error between the real and goal knee joint angle trajectory was between-1 and 1 degree, according to simulation results [13].

An adaptive controller is a device that may change its behavior in response to dynamic changes in the process or disturbance characteristics [14]. This study contributes by designing an adaptive SMC that uses the barrier-function to stabilize the knee joint exoskeleton system. The adaptive controller's key benefit is that it keeps the controller as robust as feasible against parameter uncertainty while keeping the controller gains as minimal as possible to lower the control effort for system performance. Due to the barrier function, the chattering drawback will also be minimized without the use of the saturation function. The suggested controller's goals are to correct for the system's nonlinearity and uncertainty under various variations, to reject external disturbances, and to achieve asymptotic tracking between system and reference model states.

Also, this approach ensures the finitetime convergence of the sliding variable to some neighborhood of zero without big overestimation of the gain. The main drawback of this approach is that the size of the above-mentioned neighborhood and the time of convergence depend on the unknown upper bound of disturbance. The aim of this paper is to propose an adaptive strategy that can achieve the convergence of the output variable to a predefined neighborhood of zero, with a control gain that is not overestimated, and without using any information about the upper bound of the disturbance, nor the use of the low pass filter.

This paper is organized as follows. In section 2 the material and method is given. Section 3 results and descusion. Finally, some conclusions are shown in section 4.

2. MATERIAL AND METHOD

In this section the mathematical model of the knee joint exoskeleton system is consitracted. Besides that, the proposed control strategy is presentd in detail, as are the methods and algorithms used to complement the control design process. Also, the stability analysis of the open loop system is presented based on laypunov theory.

2.1. System modeling

The knee joint exoskeleton system model is given in this section, where the kinematics of the system is derived when the exoskeleton is attached to a human leg (the operating situation). In this case, the system model is obtained for the exoskeleton and leg concurrently. The leg part composed of the knee joint and shank can be thought of as a pendulum driven by an actuator to achieve the required flexion/extension motions of the knee joint [4].

Figure 1 shows a schematic representation of the exoskeleton-leg system adopted for system analysis. In this figure, a fixed inertial frame (x_f, y_f, z_f) and an exoskeleton-leg frame (x_e, y_e, z_e) are used to depict the motion of the knee joint, which is a rotation by an angle θ so that the joint axis y_e remains in the same direction as y_f. Therefore, the system has one degree of freedom specified by the knee joint angular position θ, whose time derivative $\dot{\theta}$ indicates the knee joint angular velocity [15], [16]. Assumption 1 the exoskeleton-leg system elements (the exoskeleton and leg) have an identical degree of freedom because they are associated in motion about the knee joint axis y_e [4].

The euler-lagrange method is used to obtain the dynamic system model, and the exoskeleton-leg system's lagrangian is described as follows [4], [12], [15], [16]:

$$L_i = E_{ki} - E_{gi}; \quad i = 1, 2 \tag{1}$$

where KE_i and GE_i stand for the ith element's kinetic and gravitational energies. Moreover, E_{ki}, and E_{gi} are defined as follows [4], [12], [15], [16]:

$$E_{ki} = \frac{1}{2} J_i \dot{\theta}^2 \quad (2)$$

$$GE_i = m_i g l_i (1 - sin\ (\theta)) \quad (3)$$

where J_i, m_i, and l_i are the inertia, mass, and length of the ith element, respectively. Besides, g denotes the gravity acceleration.

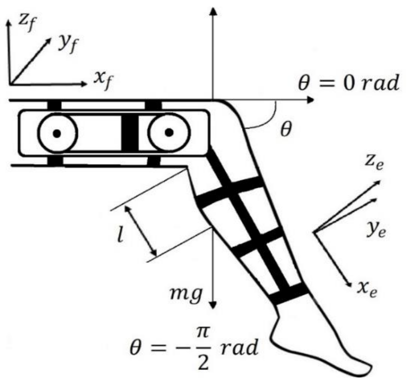

Figure 1. A schematic representation of a knee joint exoskeleton attached to a human leg (exoskeleton-leg system)

Remark 1 the gravitational energy GE_i represents the potential energy generated by the gravity force $m_i g$. Remark 2 the length l_i refers to the length of the section from the knee joint to the center of gravity in each element [4], [15]. Then, the euler-lagrange example is given as [12]:

$$\frac{d}{dt}\left(\frac{\partial L_i}{\partial \dot{\theta}}\right) - \frac{\partial L_i}{\partial \theta} = \tau_i \quad (4)$$

where τ_i denotes the external torques acting on θ. By manipulating (4), yields [15], [16]:

$$J_i \ddot{\theta} + \tau_{g_i} cos(\theta) = \tau_i \quad (5)$$

where τ_{g_i} is the ith element's gravity torque. Hence [4], [14]:

$$\tau_{g_i} = m_i g l_i \quad (6)$$

on the other hand [4], [15]:

$$\tau_i = \tau_{f_i} + u_i \quad (7)$$

where τ_{f_i} and u_i are the friction and actuator (or control) torques applied to the ith element, respectively. Moreover, the friction torque τ_{f_i} is given as follows [4], [12], [15], [16]:

$$\tau_{f_i} = -f_{V_i} \dot{\theta} - f_{S_i} sign(\dot{\theta}) \quad (8)$$

where f_{V_i} and f_{S_i} are the viscous and solid friction coefficients, respectively.

For the exoskeleton-leg system, it is settled that $J = \sum_{i=1}^{2} J_i$`, $f_S = \sum_{i=1}^{2} f_{S_i}$, $f_V = \sum_{i=1}^{2} f_{V_i}$, and $\tau_g = \sum_{i=1}^{2} \tau_{g_i}$. Thus, by substituting (7) and (8) in (5) and taking into account the flexion/extension motions caused by human effort, the model of the exoskeleton-leg system is defined as follows [4], [15]:

$$J\ddot{\theta} = -f_V\dot{\theta} - \tau_g cos(\theta) - f_S sign(\dot{\theta}) + \tau_h + u \tag{9}$$

where τ_h stands for the torque caused by human effort that is assorted as an external disturbance. Letting $x_1 = \theta$, $x_2 = \dot{\theta}$, and $y = x_1$, the system model can be written in state-space representation as follows:

$$\begin{gathered} \dot{x}_1 = x_2 \\ \dot{x}_2 = -a_1 x_2 - a_2 \cos\cos(x_1) - a_3 sign(x_2) + d + a_4 u \\ y = x_1 \end{gathered} \tag{10}$$

where x_1, x_2, and u are the knee joint angular position, knee joint angular velocity, and actuator (or control) torque. In addition, $d = \frac{1}{J}\tau_h$ denotes the human effort (or the external disturbance). Moreover, the coefficients a_1, a_2, a_3, and a_4 are given as (11).

$$a_1 = \frac{f_V}{J}$$

$$a_2 = \frac{\tau_g}{J}$$

$$a_3 = \frac{f_S}{J}$$

$$a_4 = \frac{1}{J} \tag{11}$$

The parameters f_V, τ_g, f_S, and J are considered to be uncertain with ± 20% variation, as in [17], from their nominal values listed in Table 1. As a result, Table 2 shows the bounds and nominal values of system coefficients a_1, a_2, a_3, and a_4.

Table 1. List of system parameters [15]

Parameter	Lower bound	Nominal value	Upper bound
fV	0.8 Nms/rad	1 Nms/rad	1.2 Nms/rad
τg	4 Nm	5 Nm	6 Nm
fS	0.48 Nm	0.6 Nm	0.72 Nm
J	0.32 kg.m2	0.4 kg.m2	0.48 kg.m2

Table 2. List of system coefficients with their brouns and nominal values

Coefficient	Lower bound	Nominal value	Upper bound
a1	1.6667	2.5	3.75
a2	8.3333	12.5	18.75
a3	1	1.5	2.25
a4	2.0833	2.5	3.125

2.2.2. Stability analysis

The Lyapunov function is used to evaluate the stability of the knee joint exoskeleton system in this section. Let $V(t) = \frac{1}{2}\,(x_1^2 + x_2^2)$ positive definite function, the system to be stable in the sense of Lyapunov, the first derivative of the positive definite function must be negative definite. So, let's find the $\dot{V}(t)$,

$$\dot{V}(t) = \dot{x}_1 x_1 + \dot{x}_2 x_2$$

$$\dot{V}(t) = x_2\, x_1 + x_2\,(-f_V x_2 - mgl\cos\cos(x_1) - f_S sign(x_2))$$

$$\dot{V}(t) \le x_2^2 - f_V x_2^2 - mgl\cos\cos(x_1) - f_S|x_2|$$

$$\dot{V}(t) \le x_2^2 - f_V x_2^2 - f_S x_2^2 + \tau_h - mgl(x_1)$$

$$\dot{V}(t) \le -x_2^2\,(f_V x_2^2 + f_S x_2^2) - mgl(x_1)$$

$$\dot{V}(t) \leq 0, when\ (x_1)\ > 0 \therefore the\ system\ is\ stable\ in\ the\ sense\ of\ Lyapunov$$

$$when\ (x_1)\ > 0 \tag{12}$$

2.3. Sliding mode controller (SMC)

Let us assume that the first order dynamic system is given as:

$$\dot{x} = u(t) + D(t) \tag{13}$$

where the control input of the system's states can be denoted as $u(t) \in R$. Also, the system's disturbance is $D(t)$ with a known value i.e $D(t) \leq |d|$, where d is a positive finite integer. By presuming that the system's disturbance boundaries are unknown and to stabilize the system, a first-order sliding mode controller is required, which is given as [18].

$$u(t) = -K(t)\, sig\ n(x) \tag{14}$$

However, there are two key difficulties with the first order sliding mode controller: chattering and gain selection for optimum control. Thus, higher-order SMC is regarded as an efficient technique for resolving chattering, and adaptive SMC is regarded as an efficient strategy for minimizing the gain section of optimum control. Furthermore, barrier function-based adaptive SMC can be employed to address both of the aforementioned concerns [19].

To begin, the ASMC is described in depth in this section. The ASMC's controller gain is gradually lowered until it reaches an acceptable and minimal amount. As with traditional SMC, this acceptable value can keep the system stable and resilient. The goal is to adaptively tune the controller gain without knowing the system's maximum uncertainty bound [18], [20], [21]. The ASMC is organized as:

$$u(s.t) = u_{eq}(x) - k(t) sign\ ((x.t)) \tag{15}$$

where u_{eq} equilibereume controller and k(t) is the gain that varies over time, it can be stated [22], [23]:

$$k(t) = \{\mu\ \ if\ K_{min}\ < \mu < K_{max}\ K_{min}\ if\ \mu \leq K_{min}\ K_{max}\ \ if\ \mu \geq K_{max} \tag{16}$$

$$\mu^{\cdot} = \{p(abs(s(x.t))\ sign\ (abs\big(s(x,t)\big) - \varepsilon)\ if\ K > \mu\ \mu\ if\ K\ \leq\ \mu \tag{17}$$

where $p > 0$ is used to increase or reduce the value of $k(t), \epsilon\ > 0$ is a tiny nonnegative value, and $\mu > 0$ is a small non-negative value. Where μ indicates the beginning value to get only a positive value for k (t).

$K_{min}$is the gain's lowest possible value, K_{max} is the gain's greatest possible value, and $\mu(0)$ is the gain's starting point. If $s(x.t) > \epsilon$ in (17), the gain adjustment law causes the adaptive controller's gain to rise until it reaches a possible value capable of canceling any system instability and disruption, after which $s(x.t) < \epsilon$ the gain adaptation law allows the gain to fall to its K_{min}, which is the minimum value focusing on the first and second conditions in (16). In (16) a third constraint was added to prevent the adaptive gain from reaching an undesirable big value [23], [24]. So that the value of $k(t)$ must be satisfying the condition:

$$K_{min} < (\mu(0) = k(0)) < K_{max} \tag{18}$$

finally, for chattering reducing, instead of utilizing the signum function, the control law will be reformulated using the saturation function.

$$u = u_{eq}(x) - k(t) sat\ (s, \varphi) \tag{19}$$

2.4. Barrier functions (BFs)

Definition: "If some $\varepsilon\ > 0$is known and fixed, the BF can be defined as an even continuous function K_b:x∈[-ε,ε]→k_b (x)ϵ[b.∞] strictly increasing on $[0, \varepsilon]$" [6]. In this paper, two approaches to defining barrier functions are assumed:

– Positive_definite BFs (PBFs): let's assume some fixed $\varepsilon\ > 0$, which leads to a continuous even function $K_b: x \in [-\varepsilon, \varepsilon] \to K_b(x) \in [b, \varepsilon]$ strongly accumulated on $[0, \varepsilon]$. So PBFs will be:

$$K_{PBF}(x) = \frac{\varepsilon \underline{F}}{\varepsilon - |x|}\ i.e., K_{PBF}(0) = \underline{F} > 0 \quad (20)$$

– Positive semi-definite BFs (PSBFs): The PSBF is defined:

$$K_{PSBF}(x) = \frac{|x|}{\varepsilon - |x|}\ i.e., K_{PSBF}(0) = 0 \quad (21)$$

Example (20) and (21) construct a function that delivers adaptive gains depending on PBFs and PSBFs. Therefore when $\varepsilon \to 0\ then\ K \to 0$. If the state is close to the point of origin i. e. $\frac{|x|}{\varepsilon} < 1, then\ K \approx \frac{|x|}{\varepsilon}$ that verifies state x convergence to zero. Also, it should be noted that this method allows the adaptive gain to change depending on the current value of the output variable. When the output variable is heading to zero, the adaptive gain drops till the value which permits compensation for the disturbance. When the disturbance rises and the control gain is less than the absolute value of the disturbance, the output variable grows and the control gain can expand if necessary until the system solution never leaves the region of zero [6], [25].

2.5. Adaptive first-order SMC (FOSMC) with barrier function

For both possible FOSMC gains designs, the following theorem holds: $k_B(s(t)) = k_{PBF}(s(t))$ and $k_B(s(t)) = k_{PSBF}(s(t))$ are the same things [26], [27].
Theorem. Consider the system (13) with the controller and bounded disturbance.

$$u(s.t) = u_{eq}(x) - k(t)sign\ ((x.t)) \quad (22)$$

and with the adaptive-control-gain $K(t, s)$

$$k(t.s(t)) = \{k_a(t) \cdot k^{\cdot}(t) = k^{-}|s(t)|\ if\ 0 < t \leq t^{-}\ k_B(s(t))\ if\ t > t^{-} \quad (23)$$

where: k^{-} to be arbitrary positive constant [28], where k^{-} to be arbitrary positive constant, k_B barrier constant, and: k_B adaptive constant. The controller parameters are tuned by adaptation rule based on barrier function. On the other hand, when the disturbance grows and the control gain is less than the absolute value of disturbance, the output variable grows, and the control gain can grow if it is necessary till the level ensuring that the system solution will never leave the ε vicinity of zero.

3. RESULTS AND DISCUSSION

The simulation results of the proposed ASMC based on barrier function for the knee joint exoskeleton system are presented in this section. The actual and nominal system parameters are listed in Table 1. The controller results of this study are compared with other controllers that were designed as strong_stable_adaptive sliding mod contrl (SS-ASMC)) in [28], and (SS_ASMC) in [29]. Al-Hadithy and Hammoudi [28], [29] the main purpose is to limit controller gains to the minimum achievable value, which reduces controller effort and dampens chattering motion in system performance. The proposed approaches are simulated in the Matlab 2019 a/Simulink program with two cases to demonstrate their activity.

In this study, the signum function is used for both SS-ASMC and ASMC with barrier function, and from the simulation results see that the barrier function had the ability to chattering that a bear on the control action instead of SS-ASMC. Figures 2 and 3 are illustrated the error for each-joint that did not rise over $4*10^{-4}$ (rad) barrier function, while it is more than $7*10^{-4}$ in SS-ASMC. Figure 4, shows the torque action of the controller for both barrier and SS and see that how the barrier can eliminate the chattering and the torque action with a suitable and smooth value depending on the low control action u(t) in contrast with SS as shown Figure 5.

In addition, the low controller gain in barrier guides the joint position to the desired with a very low error less than $4*10^{-4}$ (rad) as shown in Figure 6. These performances (low controller gain with high efforts and more chattering elimination) indicate the controller is more robust and has the ability for disturbance rejection and cancelation. Also for the sliding variable has a smooth response with no chattering in barrier function compared with SS. This is a high indication of robustness as shown in Figures 7 and 8.

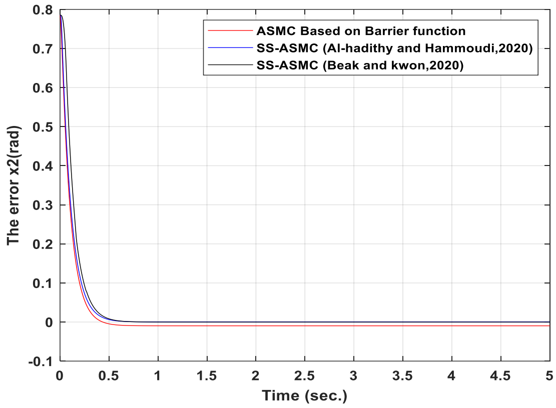

Figure 1. Error of the first joint

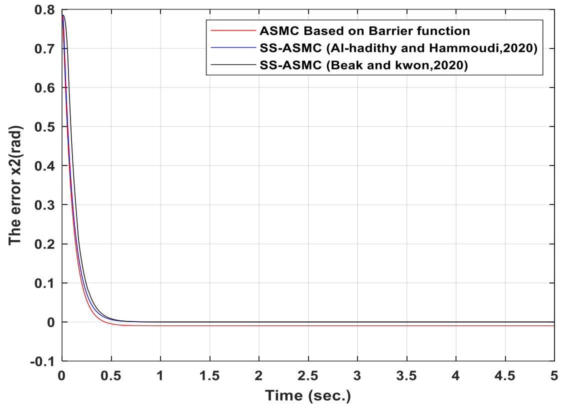

Figure 2. Error of the second joint

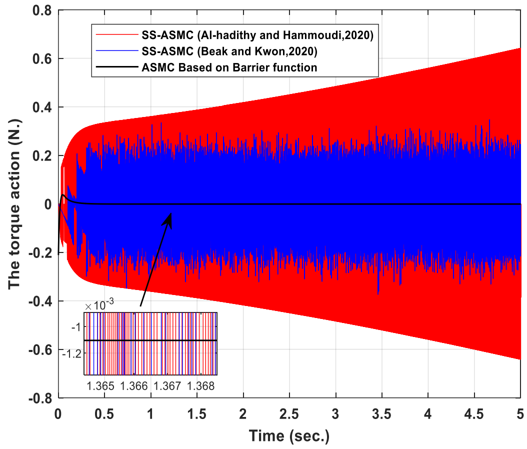

Figure 4. The torque action (N.)

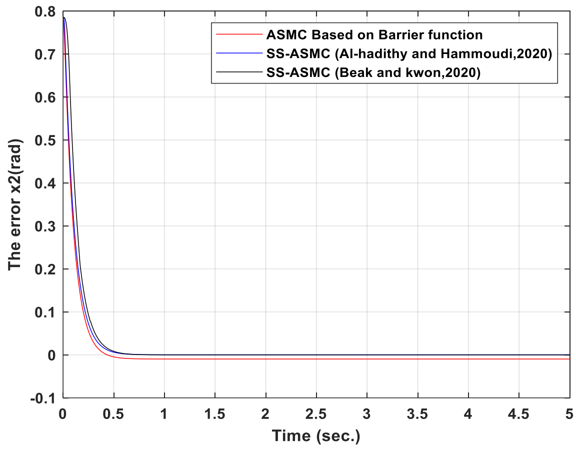

Figure 5. Controller gain k(t)

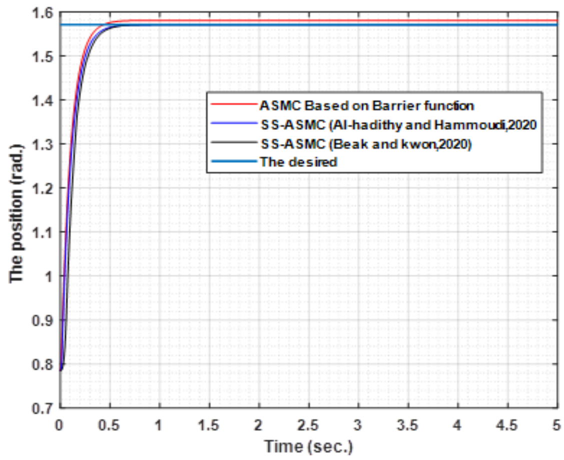

Figure 3. Actual position of knee joint

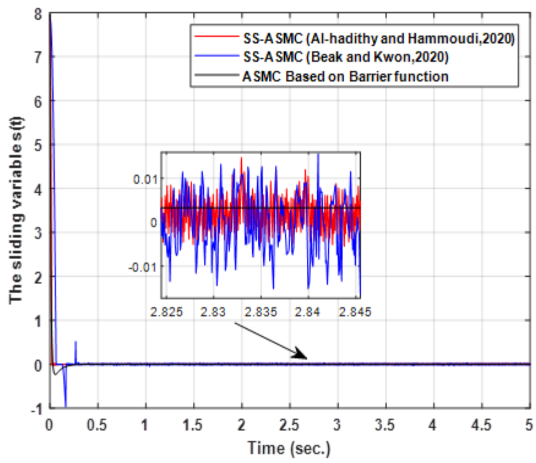

Figure 4. Sliding variable s(t)

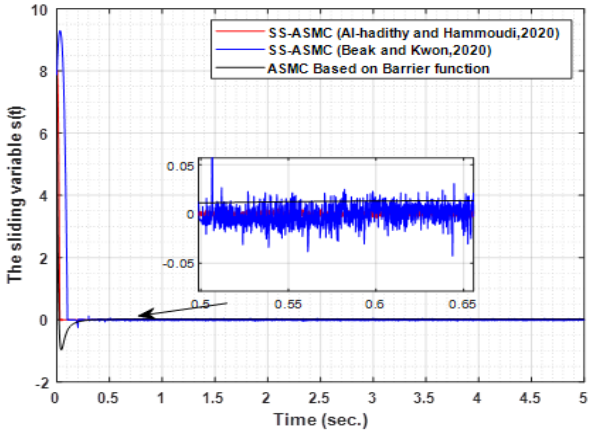

Figure 5. Sliding variable s(t)

4. CONCLUSION

The adaptive approach that relies on barrier function is used to adapt the gain of FOSMC for the knee joint exoskeleton system in the presence of unknown variables, external disturbances, and joint friction. The ASMC-based barrier function is intended to improve CSMC performance by lowering the controller gain to the lowest achievable level. Therefore, the control action is kept low, and the torque action is optimal for the system's performance. As shown in the result the barrier function succeeds in keeping the controller gain and eliminating chattering with the signum function. This indicates that the SMC can be designed without changing the signum function and keeping the sliding variable smooth. Moreover, the adaptive gain in this strategy is not overestimated.

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