A Sliding Mode Control Algorithm of Improved Reaching Law in Lower Limb Exoskeleton System

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Abstract. The lower limb exoskeleton system is widely used in real life and production, and the lower limb exoskeleton system designed in this paper is mainly aimed at the movement of people with lower limb movement difficulty. The control driven system adopts sliding mode controller to drive brushless DC motor. Based on the improvement of traditional reaching law sliding mode control algorithm, this paper designs an improved reaching law sliding mode controller with high control precision and good control quality. Experiment model simulation is analyzed in Matlab/Simulink software environment, and four tests compare the performance of system dynamic and steady-state in classical PID control, general reaching law sliding mode controller, and improved sliding mode controller algorithm. The results prove that improved reaching law sliding mode controller can promote response speed and control precision, and solve fluency, safety and comfort when a person wears lower limb exoskeleton equipment.

1. Introduction
The main function of the lower extremity exoskeleton is to provide help for human movement gait [1]. The core part is the control system which output signal to control driving system. According to the control signal, the brushless motor and the harmonic reducer magnify the torque, provide operation support for the lower extremity joints, and drive the system through the operation of the joints [2]. As far as the current research is concerned, the vast majority of experiments focus on the problem of controlling the correction error and torque fluctuation suppression of the brushless motor system. For the lower extremity exoskeleton system, the dynamic performance of the motor output torque has a direct impact on the performance and quality of the wearable equipment. This paper mainly focuses on the research and discussion of this problem, through improving the lower extremity exoskeleton in the dynamic process if the output moment curve is not smooth and the response speed, so that when people wear sports, there will be no Catton phenomenon.

2. Basic Methods
Sliding mode control system is different from the normal switch control system, but it is similar to the switch control system. It is essentially a class of nonlinear control with variable structures. It is essentially a class of nonlinear control with variable structures. The control action is not continuous under the switch of the switching function. In the process of control system movement, according to the current state of the system, the switching function acts as a switch. Under ideal conditions, the state space structure of the system is changed instantaneously, so that the system moves according to
different state trajectories. The state's motion trajectory is the so-called control law. After the state moves to the sliding surface, it continues to slide along the surface until the equilibrium point.

In general, there is a state space, and the state space is described as \( x = f(x, u, t) \), \( x \in R^n \), \( u \in R^m \), \( t \in R \) (1)

There is a switching surface in this state space \( s(x) \). According to its switching characteristics, the space is divided into two parts. The initial state of the system may be scattered throughout the state space. The role of the sliding mode controller is to run these state variables that do not appear on the sliding mode control surface to the sliding mode surface, and do sliding mode movement along the surface.

If the state variables are considered as motion points, there are three conditions for the motion state of these motion points on the face of the cut surface. As shown in Figure 1, they are called constant points, starting points, and stop points. The trajectory of the constant point and the starting point are away from the face of the cut, and they can not stay. Such state research is meaningless, and the stop point can stay on the switching surface. This makes once there is a state close to this area, it will be attracted to the area. And the cut surface composed of these stops is called the sliding die surface. The motion of the system state in the sliding modal area is called sliding modal motion [1].

![Figure 1. Characteristic diagram of the three points on the switching surface](image)

Toggle function is defined as following:

\( s(x), d \in R^m \) (2)

The control law is

\[
\mu = \begin{cases} 
\mu^+(x) & s(x) > 0 \\
\mu^-(x) & s(x) < 0 
\end{cases}
\]

(3)

According to Lyapunov's stability theory, we can see that the state up condition in the state space of the system is \( s < 0 \). Accessibility is that states other than the surface of the state space can reach the sliding surface in a limited time and do sliding mode movement on the sliding surface, and it's stable eventually.

3. Proposed Algorithm

3.1. Improvement of Sliding Mode Controller Based on the Law of Convergence

Using the law of convergence to suppress the jitter problem of sliding mode controller, as far as the research goes. The exponential approach law is used as the control method. When the coefficient \( k \) is large, the response can be accelerated. But the system will lose control strength, and the selection of the two coefficients will affect each other. In order to get better quality of sliding mode control, an
improved method of index convergence law control is proposed in this paper. By inducting the input bias into exponential phase, the formula (4) is obtained as follows. The variation of the deviation size adjusts the index item size, improves the contradiction between the two parameter sizes, and effectively improves the sliding mode control jitter problem.

\[ s = -\eta |e| \text{sign}(s) - ks \]  

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3.2. Accessibility and Stability of Sliding Modes

In state space, the initial position of the state is arbitrary. If we want the system to perform sliding mode movement, we must allow the state to reach the sliding mode surface in a limited time after the system is running. Otherwise, sliding mode control can not be established. According to the theoretical analysis based on sliding mode control [3]. The maximum condition for sliding mode control is

\[ s \cdot s < 0 \]

Substituting (4) into the reachable condition yields the following formula:

\[ s \cdot s = -s(\eta |e| \text{sign}(s) + ks) = -\eta |e| \text{sign}(s) \cdot s - ks^2 = -\eta |e| ks - ks^2 \]

Because \( \eta > 0, k > 0 \), we get \( s \cdot s < 0 \), the sliding mode of the improved approach law control can satisfy the accessibility. In addition, the stability of the system is the premise that the control system must be satisfied. If the system is unstable and the state reaches the sliding die surface, it is impossible to do the sliding die movement along the sliding die surface until the steady state, and then the design loses its meaning. According to the stability theorem of the control system, the Lyapunov function is:

\[ V = -\eta |e|kes - ks^2 \]

According to the above analysis, it is shown that the improved approach controller is stable in the sense of Lyapunov. It is proved that the system satisfies the reachable condition and the system is stable, which shows that the sliding mode controller based on the improved approach law can be established.

3.3. The Design of the Motion Trajectory of Sliding Mode Control

The driving system of lower extremity exoskeleton equipment adopts the driving mode of motor [4]. The input of the sliding mode controller be \( u = \omega_g - \omega, \omega_g \) is the given speed, \( \omega \) is the actual speed, select a state variable as \( x_1 = u, x_2 = x_1 \), the state space expression is:

\[
\begin{align*}
    \dot{x}_1 &= x_2 = -\omega \\
    \dot{x}_2 &= -\omega = -\frac{k_i}{J} i
\end{align*}
\]

Select switching function

\[ s = cx_1 + x_2, c > 0 \]

We get sliding mode of the improved approach law control as follow,

\[ s = c x_1 + x_2 = -(\eta |e| \text{sign}(s) + ks) \]

The input deviation is the input of the sliding mode controller, the following formula can be obtained:
\[ i = \frac{J}{k_i} \int (\eta |u| \text{sign}(s) + \alpha u + \beta u) dt \]  

(9)

4. Simulation System Design

The simulation model of the exoskeleton control system of lower extremities is designed with double closed loop control. The sliding mode controller adjusts the current output according to the speed deviation. The advanced control algorithm can improve the control accuracy and the overall performance of the system and achieve the expected goal of the design [5].

In this paper, the process of brushless motor controlled by sliding mode is simulated and analyzed by software Matlab. According to the mathematical model of brushless motor, a corresponding model is established for the control system of brushless motor in the Simulink environment. The speed control system of brushless DC motor consists of two closed-loop control. They are the current and speed control. The overall simulation of the system is shown in Figure 2 below,

![Figure 2. Simulink Environmental simulation program](image)

According to formula (6), the corresponding control module is designed. As shown in Figure 3, the suitable parameters of the improved approach sliding mode controller module are selected for simulation experiments. After debugging and comparing the parameters range, the general approach sliding mode controller module is simulated and designed, the three modules are used to compare the performance indicators of the system.

![Diagram](image)

(a) sliding mode controller module of the General approach law
5. Experiment Results

5.1. Analysis of the Phase Trajectory of Sliding Mode Controller

Draws the phase trajectory of the sliding mode controller, as shown in Figure 4, where the x-axis is the velocity deviation and the Y-axis is the derivative of the velocity deviation. In the figure, the red slash is the switching curve. The state should eventually be attributed to the zero point around the switching curve. From the phase trajectory of the two sliding mode controllers, it can be seen that both sliding mode controllers can eventually attribute the state to the equilibrium point, so the two sliding mode controllers both satisfy stability. On the other hand, the improved approach law sliding mode controller enters the switching curve when the rotation speed error is about $70 \text{ r/min}$, and the general approach law controller enters the switching curve at about $200 \text{ r/min}$, and the phase trajectory of the two controllers and the switching curve. The degree of convergence is significantly different. The improved sliding mode controller is farther away from the switching curve. Under the same rotational speed error, the improved sliding mode control has a higher speed error rate than the general sliding mode control, indicating that the response speed of the improved sliding mode control system is faster.
5.2. Test and Analysis of Torque Wave Suppression Performance

Brushless motor has output torque fluctuation because of its phase change characteristics. Excellent control algorithm can improve torque fluctuation. This test mainly reflects the steady-state characteristics of the control system. Intercepting the moment output after the control system enters the steady state, as can be seen from the contrast curves in Figure 5.

Figure 4. Phase trajectory of sliding mode controller
From the contrast curves, it can be seen that the torque fluctuation of the PID controller is about [-0.12, 0.12]. The torque fluctuation of a general sliding mode controller is approximately [-0.10, 0.10], but the torque fluctuation of the improved sliding mode controller is about [-0.05, 0.05]. The steady state characteristic of the improved sliding mode control system is better than that of the other two controllers, and the torque fluctuation range of the control brushless motor is smaller. The deviation is introduced into the exponential coefficient, so that the coefficient of the exponential term becomes variable, and the torque fluctuation is suppressed well.

### 6. Conclusions

Through comparing simulation curves of output torque of three controllers. Comparing the three torque output curves, the torque curve output of the PID controller has obvious fluctuations. This fluctuation will directly affect the feeling of the human lower extremity exoskeleton in use and the safety of the equipment. The general approach sliding mode controller and the improved approach sliding mode controller are compared with the dynamic process of the moment drop, and the improved controller...
output moment curve is smoother, so the improved approach sliding mode controller the control effect is more prominent, the output torque can reach the stability value more quickly.

7. References
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