Sliding Mode Variable Structure Chaos Control for Propulsion Motor of Deep Sea Robot

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Abstract. As the deepwater robot’s dynamic thruster system, the brushless thruster system’s performance will influence the whole system reliability, stabilization, safety. The brushless thruster system will appear chaotic phenomena when its system structure and parameter match badly. The phenomena will lead the deepwater robot out of control, even involved by ocean wave. Aiming the chaos phenomenon of propulsion motor of deepwater robot, this paper proposes the application of sliding mode variable structure control theory to chaos control. The sliding mode variable structure chaotic control of brushless propulsion motor for deep-sea robot is designed, and the controller is designed. The feasibility and effectiveness of the chaotic control are simulated, analyzed and verified. The research result proves that, the gradation sliding mode variable structure using in control of the deepwater robot thruster motor chaotic motion are feasible and effective, i.e. the thruster motor can research the stabilization state from chaotic state and the procedure of control is related to the controller structure, parameter, and control time. And for the example system, the exponent gradation sliding mode variable stature control effect is the better.

Keywords. Chaos control; sliding mode variable structure; simulation; propulsion motor.

1. Introduction
There is rich strategic metals, energy and biological resources in the vast ocean [1, 2]. However, due to some difficult controlled characteristics of the ocean, people have little understanding of the seabed. The development and utilization of the ocean is very limited. Cableless autonomous marine robot can enter the sea floor and provide effective data for people to fully understand the ocean, develop and utilize the ocean and protect the ocean. Most deep-sea robots use brushless propulsion motor [3].

The propulsion motor system of deep-sea robot is a typical multivariable, nonlinear, nonautonomous and time-varying system [4]. It involves the field of chaos research to make a profound study of the dynamic characteristics of this nonlinear system. Chaos control is a very active frontier topic in the field of intelligent control [5]. In this paper, the sliding mode variable structure chaotic control theory is used to control the chaotic motion of propulsion motor system of deep-sea robot.

2. Dynamic Model of Propulsion Motor System
Brushless propulsion motor is mainly composed of motor body, position sensor and electronic control drive circuit. It is similar to ordinary permanent magnet synchronous motor in structure, except that the rotor is no longer equipped with cage winding and other starting devices. The rotor is made of permanent magnet steel according to a certain number of poles [6]. Therefore, brushless propulsion motor can be considered a permanent magnet synchronous motor powered by power electronic converter. The mathematical model of brushless propulsion motor for deep-sea robot is as follows [7].
\[
\begin{align*}
\frac{di_d}{dt} &= (u_d - Ri_d + \omega L_q i_q) / L_d \\
\frac{di_q}{dt} &= (u_q - Ri_q - \omega L_d i_d - \omega \psi_{md}) / L_q \\
\frac{d\omega}{dt} &= [n_p \psi_{md} i_q + n_p (L_d - L_q) i_d i_q - T_L - \beta \omega] / J
\end{align*}
\]

Here \( u_d, i_d, u_q, i_q \) and \( \omega \) are direct axis voltage and current, quadrature axis voltage and current and rotational speed respectively, and \( L_d, L_q, \psi_{md} \) and \( n_p \) are direct inductance, magnet flux linkage and pole pairs respectively.

3. Sliding Mode Variable Structure Chaos Control for Propulsion Motor of Deep Sea Robot

3.1. The Approaching Rate

The motion of sliding mode variable structure control consists of two parts: One is the normal motion of the system in continuous control, its trajectory in the state space is all located outside the switching surface, or limited through the switching surface. The other is the sliding mode motion of the system near and along the switching surface. The generalized sliding mode condition realizes the requirement that the moving point at any position in the state space must reach the switching surface in finite time. In order to improve the dynamic quality of the movement, academician Gao Weibing proposed the method of "reaching law" [8]. This method is simple and effective. It has a good application for complex systems and has been widely concerned all over the world.

3.2. Sliding Mode Variable Structure Control Based on Asymptotic Rate

The Design of the Controller

State equation [9]:

\[
x = Ax + By
\]

The control method of approach law is adopted, and the control law is deduced as follows:

\[
\dot{s} = Cx \\
\ddot{s} = Cx = slaw
\]

Among them, slaw is the reaching law.

The equation of state (2) is introduced into equation (3):

\[
u = (CB)^{-1}(-CAx + \dot{s})
\]

It can be seen that the chattering degree of the controller depends on \( \dot{s} \) the switching term in the reaching law expression.

3.3. Asymptotic Sliding Mode Variable Structure Control and Simulation of Propulsion Motor System

The state equation of propulsion motor system of deep-sea robot is as follows:

\[
\begin{align*}
\frac{d\tilde{I}_d}{dt} &= \tilde{u}_d - \mu \tilde{i}_d + \omega \tilde{i}_q \\
\frac{d\tilde{i}_q}{dt} &= \tilde{u}_q - \tilde{i}_q - \omega \tilde{i}_d + \gamma \omega \\
\frac{d\tilde{\omega}}{dt} &= \sigma (\tilde{i}_q - \tilde{\omega}) + \nu \tilde{i}_q \tilde{I}_q - \tilde{T}_L
\end{align*}
\]
It can be further written into the standard form:

$$\dot{x} = Ax + Bu$$  \hspace{1cm} (5)

Among them,

$$A = \begin{bmatrix} -1 & x_3 & 0 \\ -x_3 & -1 & 19.55 \\ 0 & 5.58 & -5.58 \end{bmatrix}$$  \hspace{1cm} (6)

Different control schemes are designed for different controller parameters, and the control effect of asymptotic sliding mode variable structure control method on chaotic state of brushless propulsion motor system of deep-sea robot is studied through digital simulation [10].

3.3.1. The Parameters of the Controller Are Fixed and the Control Is Applied at Different Times. The controller parameters are as follows:

$$B = [I \ 1 \ 1]^T, \ C = [I 5 \ 1 \ 1]$$

The brushless propulsion motor system of deep-sea robot is in chaotic state, and the control is applied at the 60th second. The chaotic attractor obtained by simulation is shown in figure 1, and the transition process of propulsion motor speed when control is applied is shown in figure 2. The simulation results show that the transition time of the system is 1.16 seconds after the controller is applied.

![Figure 1](image1.png) \hspace{1cm} ![Figure 2](image2.png)

**Figure 1.** Chaotic attractor (\( t = 60s \)).  \hspace{1cm} **Figure 2.** Time for the transition process (\( t = 60s \)).

The digital simulation results of the control process are shown in figures 3 and 4 when the control is applied at the 50th second. The simulation results show that the transition time of the system is 0.96 seconds after the controller is applied.

The digital simulation results of the control process are shown in figures 5 and 6 when the control is applied at the 40th second. The simulation results show that the transition time of the system is 0.98 seconds after the controller is applied.
Figure 3. Chaotic attractor (\(t = 50s\)).

Figure 4. Time for the transition process (\(t = 50s\)).

Figure 5. Chaotic attractor (\(t = 40s\)).

Figure 6. Time for the transition process (\(t = 40s\)).

The above figures show that the brushless propulsion motor can get rid of chaos after adding controller at different times, and the shortest transition time is 0.96s when the controller is applied at 50s.

3.3.2. Change the System Parameters and Observe the Simulation Results

(1) Keep \(C\) unchanged and change \(B\)

\[
B = \begin{bmatrix} 10 & 10 & 10 \end{bmatrix}^T
\]

The control is applied at the 50th second. The change of chaotic attractor in the process of the system out of chaos is shown in figure 7, and the transition time is shown in figure 8.

Figure 8 shows that the transition time is still 0.96s. It can be seen that the change of \(B\) has no effect on the system getting rid of chaos.

(2) Keep \(B\) unchanged and change \(C\)

(a) \(C = \begin{bmatrix} 5 & 1 & 1 \end{bmatrix}\)

The control is applied at the 50th second. The change of chaotic attractor in the process of the system out of chaos is shown in figure 9, and the transition time is shown in figure 10.

Figure 10 shows that the system successfully gets rid of chaos, the transition time becomes 1.1s, and the reduction of \(C\) leads to the extension of the transition time.

(b) \(C = \begin{bmatrix} 50 & 1 & 1 \end{bmatrix}\)

The control is applied at the 50th second. The change of chaotic attractor in the process of the system at 50s.
out of chaos is shown in figure 11, and the transition time is shown in figure 12.

**Figure 7.** Chaotic attractor \( t = 50s, B = [10 \ 10 \ 10]^T \).

**Figure 8.** Time for the transition process \( t = 50s, B = [10 \ 10 \ 10]^T \).

**Figure 9.** Chaotic attractor \( t = 50s, C = [5 \ 1 \ 1] \).

**Figure 10.** Time for the transition process \( t = 50s, C = [5 \ 1 \ 1] \).

**Figure 11.** Chaotic attractor \( t = 50s, C = [50 \ 1 \ 1] \).

**Figure 12.** Time for the transition process \( t = 50s, C = [50 \ 1 \ 1] \).
The simulation results show that the system can still get rid of chaos, and the transition time is 0.995s. Obviously, the increase of C also leads to the longer transition time.

The digital simulation results show that the change of parameter C slows down the transition process and reduces the rapidity index.

4. Conclusion
The experimental results show that the design of appropriate sliding mode variable structure controller can help the propulsion motor of deep-sea robot get rid of chaos. When the controller is applied at different time, the time to get rid of chaos is different. When the controller is applied at the 50th second, the transition time of the system is the shortest. In other words, at the 50th second, the optimal time for the robot propulsion motor system to get rid of chaos is to apply the gradual sliding mode variable structure controller. Whether the controller parameter C becomes larger or smaller, the transition process becomes slower with $C = [15 1 1]$ more appropriate only. Obviously, when designing the adaptive controller, it is very necessary to select the appropriate control time and parameters in order to achieve the ideal control effect.

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