Sliding Mode Control Technology Research About Underwater Vehicle Servo

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Abstract. To improve the mobility of underwater vehicle and interference capability of servo control system, the paper designed the variable structure control rate of underwater vehicle servo with the sliding mode variable structure control technology. The paper established servo control model and system simulation was carried out as an example of a certain underwater vehicle. Compared with the traditional PID control, the simulation results show that the control system using sliding mode variable structure has fast response speed, small overshoot and strong anti-interference ability, better stability. The results show that this method can improve the performance of servo control system.

Introduction

The servo as the executing agency of control system underwater vehicle, provide steering torque for underwater vehicle, so as to control the underwater vehicle sailing posture. The servo is received from a control computer output steering commands, according to the requirements of the quality control steering shaft to rotate, drive the rudder deflection to the specified location, completing the underwater vehicle attitude control [1].

While conventional DC motor has good speed performance, because of the kind of motor has a commutator and brushes and other mechanical contact member, which brings easily spark, poor reliability during operation, the motor speed and output power is restricted at the same times. However, permanent magnet brushes DC motor applications well solves this problem, which can eliminate electromagnetic interference caused by the commutation spark as well as the friction torque because of no commutator and brush, which reduce the maintenance cost of motors. In addition, brushless DC has the advantages of light weight, small volume, high efficiency, high torque / weight ratio, high rotating inertia, high power factor, can be made into high speed, large torque and high power motor [2].

PID control theory representing the classical underwater vehicle servo control is simple in structure and easy to be realized in engineering. However the classical PID control system is difficult to reconcile the contradiction between rapidity and stability, and the stability is poor when the parameters change and outside interference.

In order to improve the control of the classical PID control, the variable structure control theory is introduced into the field of motor control. As a modern control method, variable structure control is relatively simple and can be used to coordinate the dynamic and steady state performance. In addition, it has the invariance and robustness at the change of the parameters and the disturbance of the outside world [3]. In this paper, the control system of the underwater vehicle is designed by variable structure control method. The MATLAB/SIMULINK module is used to model the system. The system simulation is carried out with a underwater vehicle servo as an example [4].
Mathematical Model of Underwater Vehicle Servo

Underwater vehicle servo control circuit is mainly composed of a brushes DC motor, reducer and a feedback potentiometer, underwater vehicle closed-loop servo and actuator loop structure diagram is shown in Fig. 1.

![Servo and rudder loop structure diagram.](image)

Mathematical Modeling of Motor

Electrical schematic of motor is shown in Fig. 2.

![Motor electrical schematics.](image)

According to Fig. 2, the motor speed is controlled by the armature voltage $u_a$, Kirchhoff theorem to write the circuit equation is:

$$ L_a \frac{di_a}{dt} + R_a i_a + u_b = u_a $$

(1)

When the armature rotates, armature induced voltage is:

$$ u_b = K_a \omega $$

(2)

According to moment of momentum theorem, rotor torque equation is:

$$ J \frac{d\omega}{dt} + f \omega + M_{ed} = K_e i_a $$

(3)

Where:

- $u_a$ —— Armature voltage (steering instruction), the unit V;
- $u_b$ —— Motor counter electromotive force, the unit V;
- $R_a$ —— Armature winding resistance, the unit Ω;
- $L_a$ —— The inductance of the armature winding, the unit H;
- $\omega$ —— Motor speed, the unit rad / s;
- $f$ —— Viscous friction coefficient, the unit kg · m² / s;
- $M_{ed}$ —— Load torque, the unit N·m;
- $K_e$ —— The motor torque constant, the unit N·m/A;
- $K_a$ —— Counter electromotive force constant, the unit V·s/rad.
Motor Simulation Model

Considering the actual motor viscous friction is small, it will not be considered when modeling. According to Equation 1 to 3 and the motor working principle can create Simulink model. Simulation model of the motor is shown in Fig. 3.

![Motor Simulation Model Diagram](image)

Where:

- $u_a$ —— Steering commands, the unit V;
- $R_a$ —— Armature winding resistance, the unit $\Omega$;
- $L_a$ —— The inductance of the armature winding, the unit H;
- $K_e$ —— Torque constant, the unit N·m/A;
- $K_a$ —— Electromagnetic constants, the unit $V/\text{rad/s}$;
- $J$ —— Motor inertia, the unit $kg\cdot m^2$;
- $M_{ed}$ —— Rated load moment, the unit N·m;

Where the electromagnetic constant: $K_a = \frac{V_{ed}}{n_0} = 0.1$, Torque constant: $K_e = \frac{M_{ed}}{A_{ed}} = 0.068$.

Derivation of Variable Structure Control Law

From the theory of variable structure control, the key to design variable structure control system is to design variable structure control law to make the system status along state space sliding mode tend origin [5].

Taking into account that the servo system is actually a position follower, the system output position is required to track the input position, so the error signal $e$ of the system and its first derivative $\dot{e}$ are the state variables:

$$x_1 = \theta_m - \theta = e$$

$$x_2 = -\dot{\theta}_m - \dot{\theta} = \dot{e}$$

The equation of state of the motor:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & \frac{1}{T_m} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{K_a K_e}{T_m} \end{bmatrix} u + \begin{bmatrix} 0 \\ d \end{bmatrix} f$$

Where $K$ is the motor transfer coefficient, $f$ is the system interference term. Sliding mode equation system is set:

$$s = cx_1 + x_2 = 0$$
Where $c$ is the sliding mode parameters, equation (7) is derivative of the both sides, and the formula (6) into the following:

$$
\dot{s} = -(c + \frac{1}{T_m})x_s + \frac{K_m K}{T_m} u = c(c + \frac{1}{T_m})x_i + \frac{K_m K}{T_m} u - (c + \frac{1}{T_m})s
$$

(8)

Variable structure control system can reach condition (sliding mode exists) as follows:

$$
\ddot{s} \leq 0
$$

(9)

There:

$$
[c(c + \frac{1}{T_m})x_i + \frac{K_m K}{T_m} u]s - (c + \frac{1}{T_m})s^2 \leq 0
$$

(10)

Select the appropriate sliding mode parameter $c$, so:

$$
c + \frac{1}{T_m} \geq 0
$$

(11)

Thus, the left of the second term of the formula (10) is constant less than zero, then the sliding mode existence conditions can be written as:

$$
c(c + \frac{1}{T_m})x_i s + \frac{K_m K}{T_m} u s \leq 0
$$

(12)

According to the above formula can be deduced electric steering system variable structure control law is:

$$
\begin{cases}
    u < -\frac{T_m c}{K_m K} (c + \frac{1}{T_m})x_i, s > 0 \\
    u > -\frac{T_m c}{K_m K} (c + \frac{1}{T_m})x_i, s < 0
\end{cases}
$$

(13)

Make:

$$
\psi_0 = -\frac{T_m c}{K_m K} (c + \frac{1}{T_m})
$$

(14)

Then:
\[
\psi = \begin{cases} 
\psi_1 < \psi_0, s > 0 \\
\psi_2 > \psi_0, s < 0
\end{cases}
\]

(15)

Thus, the derived variable structure control law is:

\[ u = \psi x_1 \]

(16)

It can be known from the analysis of type (13), the motor need a large starting voltage to get started, when the servo system position error \( x \) decreases to a certain extent, the control \( u \) will fall into the dead zone, the system brings static error, and reduce the system's anti-interference ability. The speed of the motor is not fully realized, and it also has some difficulty in the circuit realization. Based on this, the variable structure control law (13) should to be simplified. Assume that the motor rated input voltage is \( \pm U \), due to mechanical limit of the rudder, maximum error \( \max (|x1|) \) of servo system is exist. Consider the most extreme case, \( \max (|x1|) \) is the difference of positive and negative mechanical limit angle. Thus, there is always a sliding mode parameter \( c \), which makes the following type be set up for arbitrary values of \( x_1 \):

\[
U \geq \frac{T_m c}{K_m K_T} \left( c + \frac{1}{T_m} \right) x_1
\]

(17)

Therefore, the variable structure control law formula (13) can be simplified as follows:

\[ u = -U \text{sgn}[s(x_1, x_2)] = -U \text{sgn}(c x_1 + x_2) \]

(18)

According from formula (18), the motor is still running at the rated voltage when the servo state changes, so that the effect of the dead zone can be eliminated, the accuracy, the rapidity and the anti-disturbance of the servo system is improved.

The control system designed by variable structure control law is designed to improve the system's rapidity, stability and anti-disturbance, however, the high frequency chattering of the system is also brought out [6]. In this paper, a small linear region is added to the system to eliminate the chattering, which range is determined by the requirements of the actuator.

The selection of sliding mode parameter \( c \) needs to consider all kinds of factors, the higher the absolute value of \( c \), the faster the convergence of the system. However, due to the motor speed is limited, the value of too large \( c \) will make more time to enter the sliding mode from the initial state.

In this paper, the \( c \) value which makes the adjustment time is short, the overshoot is small, as the sliding mode parameter value of the system and the \( c \) values of different motor conditions are required in the practical use.

**System Simulation**

After adding variable structure control rate, simulation schematic of variable structure control system is shown in Fig. 4.

![Figure 4. Underwater vehicle servo system simulation schematic.](image)
Model Validation

First, simulate the model in the idling state and the rated load state. The simulation process, set the steering command voltage is 38V, the sampling time is 1ms, the simulation results of the two states are shown in Fig. 5 and Fig. 6.

![Figure 5. Motor speed without load.](image1)

![Figure 6. Motor speed with rated load.](image2)

Simulation results show that the motor idling speed is 3623rpm, rated load speed is 3142rpm, consistent with an underwater vehicle motor speed indicators.

Assuming the motor steering angle output is 4°, respectively, PID control system and variable structure control system simulation, results are shown in Fig. 7 and Fig. 8.

![Figure 7. Rudder angle output curve with PID control system.](image3)

![Figure 8. Rudder angle output curve with variable structure control system.](image4)

The results show that the system response speed faster using variable structure control, rudder angle output error is small.

For comparing with interference the traditional PID control system and variable structure control system, adding random white noise term 5V in the system, observe the rudder angle of the output curve is shown in Fig. 9 and Fig. 10.

![Figure 9. Rudder angle output curve with PID control system.](image5)

![Figure 10. Rudder angle output curve with variable structure control system.](image6)

The simulation results show that the variable structure control system is more anti-jamming capability, the system more stable.

Conclusions

This paper designed underwater vehicle servo control system with variable structure control method, simulation analysis carried out for a certain type of underwater vehicle system. Compared with conventional PID control system, the results show that the system fast response, small overshoot, anti-jamming capability, better stability with variable structure control.
References


