The Design and Implementation of Control and Driving system with Double Position Feedback for Submarine Steering

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Abstract—With the well improvement of motor and power electronic technology, the technology of Electro-mechanical actuator (EMA) has come into a new stage. A high-reliability driving and controlling technology with a double redundancy feedback loop is described in this paper. In this method, the position of electromechanical actuator and the resolver position of motor can be back up for each other by some compensate algorithms. This method can improve the reliability of the control system without extra hardware and increasing cost.

1. Introduction
The ship steering system is an important equipment to ensure ship navigation. The traditional hydraulic steering system has shortcomings such as large noise and large size, which not only seriously affects the work and life of the crew, but also brings difficulties in the use and maintenance of the product \cite{1}. With the development of permanent magnet materials and AC speed control technology, permanent magnet synchronous motors have attracted widespread attention and in-depth research with their obvious advantages such as small size, low noise, and convenient use and maintenance, which also makes electric servo technology popular in the submarine field. It is possible to expand the application.

The electric steering device is mainly used to change or maintain the speed, attitude, heading and depth of the ship, and the control drive system, as the nerve center of the electric steering, is an important component to ensure the ship's heading and track. Therefore, the reliability of the control system can greatly improve the economy and safety of the ship during the voyage. In order to improve the reliability of the system, a mechanical redundancy structure or an electrical redundancy structure is generally used \cite{2}, but these redundancy methods will increase the complexity of the system hardware and increase the weight and volume of the electric steering \cite{3-6}. For the application of quiet and high-reliability electric steering on ships, a control drive system for electric steering is designed. The dual redundant feedback loop design scheme of permanent magnet synchronous motor rotary transformer and electromechanical actuator position sensor is proposed, and the dual redundant control method of the position loop is realized. This solution does not need to add any hardware, and only needs to
design the control algorithm, filtering and compensation in the software to increase the feedback loop to double redundancy and improve the reliability of the system.

2. The composition and working principle of electric steering system

The electric steering system includes a control driver, an electromechanical actuator (including a permanent magnet synchronous motor), and a set of servo cable network, as shown in Figure 1. The submersible vehicle control system sends the control signal to the servo control driver through the CAN bus. The servo control driver receives the rudder swing angle command, runs the closed-loop control algorithm, and controls the servo motor to act according to the command. The lead screw converts the rotary motion of the motor into linear motion, pushes the rudder surface, and finally achieves the purpose of controlling the rudder attitude of the submersible. At the same time, the control driver feeds back the status data of the electric steering system to the submersible control system.

![Fig.1 The structure of Electro-mechanical actuator](image)

Fig. 1 The structure of Electro-mechanical actuator

3. Vector control requirements for linear displacement accuracy

Due to the high accuracy of the resolver, the motor makes one revolution and the code value is represented by a 14-digit number. When the lead screw is 4 mm/r, the linear displacement accuracy calculated by the resolver is 0.0002 mm, which is far higher than the application requirements. Therefore, this paper mainly calculates the accuracy requirements of using the actuator linear displacement to realize the redundant function of the resolver.

The vector control system studied in this paper is an id=0 control strategy based on the current loop, and its basic control principle is shown in Figure 2. The rotor position $\theta$ of the motor is measured by the resolver. $\theta$ is used for coordinate transformation. The three-phase stator current output by the motor is obtained through Clark transformation, and then id and iq are obtained through Park transformation. id and iq participate in current loop control and are controlled by PI regulator. After the coordinate transformation, the output voltage reference value is input to the SVPWM module, and six PWM signals are generated and input into the three-phase inverter. The inverter outputs the three-phase voltage to the motor by controlling the on and off of the switch tube [7].

![Servo control drive circuit](image)

Fig. 2 Structure of control system for PMSM based on vector control

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From the above analysis, it can be seen that the motor space voltage vector control is completed in the d-q coordinate system. The Clark transformation first transforms the three-phase stationary coordinate system into a two-phase stationary coordinate system, and the transformation matrix is

$$
\begin{pmatrix}
\alpha \\
\beta
\end{pmatrix} = \sqrt{3} \begin{pmatrix}
-\frac{1}{2} & -\frac{1}{2} \\
-\frac{1}{2} & \frac{1}{2}
\end{pmatrix} \begin{pmatrix}
A \\
B
\end{pmatrix}
$$

(1)

Park transformation converts the two-phase stationary coordinate system into id and iq two-phase rotating coordinate system, namely:

$$
\begin{align*}
\frac{i_d}{i_q} &= \frac{i_\alpha \cos(\theta) + i_\beta \sin(\theta)}{-i_\alpha \sin(\theta) + i_\beta \cos(\theta)} \\
\frac{i_d}{i_q} &= \frac{-i_\beta \sin(\theta) + i_\alpha \cos(\theta)}{i_\alpha \cos(\theta) + i_\beta \sin(\theta)}
\end{align*}
$$

(2)

It can be seen that the measurement accuracy of the angular position of the motor rotor directly affects the accuracy after the current conversion. It is assumed that the detected rotor position has a deviation, namely:

$$\theta' = \theta + \Delta \theta$$

(3)

$\theta'$ is the detected rotor position; $\theta$ is the actual rotor position. This article adopts the id0=0 control strategy, so the instruction idref=0, when the iq instruction is iqref, substituting equation (3) into equation (2), after calculation, the actual current error obtained is [8,9]:

$$
\begin{align*}
\Delta i_d &= i'_d - i_d = i_{qref} \sin(\Delta \theta) \\
\Delta i_q &= i'_q - i_q = 2i_{qref} \sin(\Delta \theta/2)
\end{align*}
$$

(4)

For a linear electromechanical servo mechanism driven by a ball screw, the stroke of the mechanism is ±y, the number of pole pairs of the motor is pn, and the linear displacement sensor is used to detect the rotor position of the motor, and when the space vector control is performed, the linear displacement sensor The minimum precision is

$$\sigma = \frac{\Delta \theta \times p}{360 \times p_n \times y}$$

(5)

| parameter name                  | symbol | Numerical value |
|---------------------------------|--------|----------------|
| Number of motor pole pairs      | $p_n$  | 4              |
| Lead screw / (mm·r⁻¹)           | $p$    | 4              |
| Institutional itinerary /mm     | $y$    | ±80mm          |

At present, the linear displacement sensor adopts the displacement sensor of MTS company, and the accuracy of its product is ±0.02%, so it can bring the maximum deviation of the motor angle:

$$\Delta \theta = 4$$

(6)

Substituting formula (6) into formula (4), we can get:

$$
\begin{align*}
\Delta i_d &= i'_d - i_d = 0.07i_{qref} \\
\Delta i_q &= i'_q - i_q = 0.002i_{qref}
\end{align*}
$$

(7)

The current error can meet the accuracy requirements of motor control.
4. Redundancy control strategy

4.1 Feedback loop double redundancy control

The closed-loop control principle of the common electromechanical servo system with permanent magnet synchronous motor as the actuator is shown in Figure 3. The linear displacement sensor of the electromechanical actuator is responsible for the position loop displacement feedback detection, and the space vector control of the permanent magnet synchronous motor is required. The actual position of the rotor of the motor is measured by the resolver installed at the tail of the motor, and the position signal is differentiated to obtain the actual speed of the motor, which is used for the speed control of the electromechanical actuator.

Both linear displacement and resolver are single-point faults. Once damaged, the motor will not be able to commutate normally, and the motor current will increase sharply. In severe cases, it will cause damage to the motor and the drive. The idea proposed in this study is to back up the rotation position of the resolver and the position feedback of the actuator position sensor, and form a double redundancy control of the PMSM feedback loop after a certain calculation and compensation, as shown in Figure 4. After the position feedback of the actuator is calculated by the difference value, the rotor position signal of the motor can be approximated, which is provided to the space vector algorithm (SVPWM) for electronic commutation. At the same time, the linear velocity of the actuator is obtained through differentiation, which is used as the feedback to perform the operation. The speed of the actuator is closed loop; the motor rotor position signal provided by the resolver can correspond to the position output of the actuator one to one, and it can replace the position feedback of the actuator when necessary.
By design, there are three working modes of the feedback loop, namely: normal mode, when the resolver or its signal conversion circuit is open or short-circuited, and when the linear displacement sensor used as the actuator fails. In these three working modes, the signal sources of the feedback loop are shown in Table 2.

| Failure mode          | Rotor position information | Speed closed loop control | Actuator position feedback |
|-----------------------|----------------------------|---------------------------|---------------------------|
| Normal mode           | Resolver                   | Resolver calculation      | Linear displacement       |
| Resolver failure      | Linear displacement        | Linear displacement       | Linear displacement       |
| Linear displacement   | Resolver                   | Resolver calculation      | Resolver calculation      |

4.2 Line displacement signal failover operation mode

4.2.1 Fault monitoring strategy

The linear displacement sensor selected in the system is the displacement sensor of MTS Company, and its output is an SSI signal. When the line displacement cable is disconnected or the communication is interrupted, the collected displacement value will suddenly change to the maximum value of the entire range. The linear displacement code value read each time is compared with the code value at the previous moment for difference. The interval between two readings is 1 ms. Since the maximum actual operating speed of the actuator is 18 mm/s, the theoretical difference is the maximum 0.018 mm. Taking into account the existence of special circumstances such as speed overshoot, 2 mm is selected as the comparison value. When the difference is greater than 2 mm, it is considered that the linear displacement signal is faulty.

4.2.2 System reconfiguration

When the linear displacement signal fails, the resolver signal is used to calculate the displacement. For a linear electromechanical servo mechanism driven by a ball screw, set its lead as $p$ and displacement as $d$.

The resolver signal is a 16-bit value $m$. When the motor position changes from $0^\circ$ to $360^\circ$, $m$ changes from 0 to 16384. The $m$ value read each time was compared with the $m$ value at the previous moment and make the difference. The actual maximum speed of the motor is 270 $r/min$, and the interval between two readings is 1 ms. In theory, the maximum difference between the two $m$ values is 74. Taking into account the existence of special circumstances such as speed overshoot, 5000 is selected as the comparison value. When the $m$ difference is absolutely greater than 5000, it is considered that the resolver signal has a zero-crossing change from 0 to 16384 (or from 16384 to 0). Increase the circle value $i$ by 1 (or subtract 1). It can be concluded that the displacement signal $d$ at this time is

$$d = (i + \frac{m}{16384})p$$  \hspace{1cm} (8)$$

The process of linear displacement signal fault monitoring and system reconstruction is shown in Figure 55.
4.3 Resolver signal failover operation mode

4.3.1 Fault monitoring strategy
The resolver decoding circuit in the controller uses AD’s chip AD1210. The chip has two fault signal output pins DOS and LOT, which can detect the resolver signal disconnection, over-range input signal, input signal mismatch or position tracking loss. When a fault occurs, the DOS and/or LOT output pin goes low.

4.3.2 System reconfiguration
In the reconstruction of the velocity loop, the linear displacement signal \( d \) is differentiated to obtain the linear velocity of the actuator, which is used as feedback to close the velocity loop of the actuator.

In the reconstruction of the current loop, theoretically, the displacement of the mechanism corresponding to one rotation of the motor is fixed, which can be obtained from equation (8):

\[
m = (d_i p - i) 16384
\]  

(9)

During the reciprocating movement of the mechanism, the "0" position of the resolver corresponds to the displacement value of the mechanism and is unique for each revolution of the motor. In fact, through testing, the displacement of the mechanism corresponding to one rotation of the motor is not fixed. Due to the influence of mechanism stiffness, tooth gap, etc., the mechanism displacement value corresponding to the "0" position of the resolver changes greatly when the mechanism moves in different directions, speeds, and load conditions. However, through the averaging process, it can still be ensured that the position of the motor rotor detected by the displacement sensor is within the allowable error range.

Through the reciprocating motion test and averaging processing, a set of mechanism displacement values corresponding to the "0" position of the resolver can be obtained, referred to as "zero position array". The difference between two adjacent displacement values in this array is the mechanical angle change value of one revolution of the motor, that is, 360°, and any displacement value between the two adjacent displacement values has a linear corresponding relationship with the mechanical angle of the motor.

![Flow chart](image-url)
When the redundant resolver of the displacement sensor performs closed-loop control, each time the displacement value of the mechanism is read, the interval in the zero position array is queried, and then the mechanical angle and electrical angle of the motor at this time are calculated through linear correspondence.

The process of resolver signal fault monitoring and system reconstruction is shown in Figure 6.

5. Hardware implementation and test verification

5.1 Hardware system architecture

The servo control driver is mainly composed of: MCU processor circuit, power drive circuit, power conversion circuit, resolver decoding circuit, line displacement signal receiving circuit and CAN bus interface circuit. The electrical principle is shown in Figure 7.
The servo control driver uses an MCU from TI as the core controller, the specific model is TMS570LS3137, with 32-bit floating-point arithmetic precision and processing capacity up to 180MIPS. The control drive and the submersible control system realize communication through two non-similar redundant mechanisms of CAN digital communication and analog communication. After the control driver receives the swing angle control command issued by the submersible vehicle control system, it collects the actuator linear displacement signal and the permanent magnet synchronous motor state data, runs the closed-loop control algorithm, and controls the electromechanical actuator to drive the actuator to act according to the instruction. At the same time, the drive controller feeds digital signals such as rudder swing angle, motor speed, motor current, bus voltage, driver temperature, motor temperature and other digital signals to the boat control system through the CAN bus, thereby completing the self-inspection and testing functions.

5.2 Test results
The experimental system is shown in Figure 8. The left side is the simulated load platform, and the right side is the electric steering actuator. Control driver input DC voltage of 450 V, the maximum output power of 15 kW, PWM modulation frequency of 10 kHz, a permanent magnet synchronous motor driven by the lead screw driven actuator operation control circuit to achieve steering mechanism.
Use this product to carry out the position characteristic test, and the command adopts a sine wave with an amplitude of 40 mm and a frequency of 0.02 Hz. Figure 9a is the comparison of Iq current waveforms in the load position characteristic test between the normal working mode and the resolver redundant linear displacement mode; Figure 9b is the comparison of the current waveforms in the load position characteristic test iq between the normal working mode and the linear displacement redundant resolver mode.

![Diagram](image)

- Normal working mode
- Linear displacement failure mode

- Normal working mode
- Resolver failure mode

**Fig. 9** The waveforms of iq in different modes

It can be seen from the above test results that the q-axis current under the two redundancy modes is basically the same, which is slightly larger than that under the normal working mode, which can meet the index requirements.

A failover experiment was carried out during the operation of the system. The resolver signal and the linear displacement signal were disconnected in the rudder test of the full-stroke simulation of the submersible to simulate the failure of the resolver failure and the failure of the linear displacement sensor, as shown in the figure. As shown in 10 and 11, the actuator runs smoothly, and the displacement curve can follow the instruction to run as required, and there is no obvious position jump, which can meet the requirements of use.
Failover point — Command — Position feedback — Position by resolver calculation
time/ms
position/mm

Fig. 10 The waveforms of position during the switching process to position sensor failed mode

Fig. 11 The waveforms of position during the switching process to resolver failed mode

6. conclusion
This paper designs an electromechanical servo control drive system for electric steering. A double redundancy control method of feedback loop is designed. The redundancy design scheme of mutual backup of resolver and electromechanical actuator position sensor is adopted. No hardware and sensors are added on the basis of the existing electromechanical actuator. It improves the working reliability of the system, and at the same time well controls the cost and volume of the entire system. It is a control scheme with practical value.

References
[1] Li Xch, Wu Wy, Zhang B. Analysis and Control on Vibration and Noise of Pipeline in Submarine Hydraulic System[J]. Technological Innovation and Application, 2015(12): 127.
[2] Xiong Y. Research and Discussion of Reliability on Mechanical and Electrical Products [J]. Environmental technology, 2009(03): 32-37.
[3] Li Q, Wu H, Feng Lm, Zhou hp. Three-redundant electromechanical servo mechanism and its fault isolation and reconstruction technology [J]. Micromotor, 2014(12): 40-44.
[4] Zhang HT. Design of High-precision and Dual-Redundancy Rudder Servo System [D]. Xi'an: Northwestern Polytechnical University, 2007.
[5] Ding HY, Jiao WW, Wang XL, Liu Sh. Research on Double-Motor High-Reliability High-Power Servo Mechanism Based on the Space Vector Algorithm[J]. Missile and space delivery technology, 2017(2): 53-65.

[6] Luo ZhQ, Liang DL. Mathematical Model and Characteristics of Double Redundancy Electromechanical Actuation Servo System [J]. Journal of Electrotechnical Technology, 2014(1): 165-173.

[7] Guo QD, Sun YB, Wang LM. Modern AC Servo System of Permanent Magnet Motor [M]. Beijing: China Electric Power Press, 2006.

[8] Capponi F G, De Donato G, Del Ferraro L, et al. AC brushless drive with low-resolution hall-effect sensors for surface mounted PM machines[J]. IEEE Transactions on Industry Applications, 2006, 42(2): 526-535.

[9] Shen J X, Zhu Z Q, Howe D. PM brushless drives with low cost and low-resolution position sensors[C]. Xian, China: Intreational Power Electronics and Motion Control Conference, 2004.