PSO-PID control strategy for ship anti roll slider device under the influence of long peak wave seas

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Abstract: The ship will produce various swaying motions after being affected by wind, waves and other disturbing factors when sailing, among which the transverse swaying motion is the most violent. By the effective control of transverse swaying motion it can improve the safety of ship sailing and the comfort of crew. Thus, in the present study, ship anti roll slider device is chosen as the research subject, and a theoretical analysis on the principle of rocking reduction of ship anti roll slider device is performed. For the problem that the PID controller parameters do not have self-tuning capability, the PID controller parameters are optimized by introducing the PSO algorithm, and the PSO-PID controller is designed on this basis. The PID controller and PSO-PID controller are used to simulate the ship anti roll slider device on Matlab. and the simulation results show that the PSO-PID controller has good rocking reduction effect under different sea conditions, which verifies the effectiveness and superiority of the PSO-PID controller.

1. Introduction

When a ship is sailing and operating at sea, it will inevitably be affected by external environment such as wind, waves, currents and other disturbing factors to produce various swaying movements. In order to reduce the transverse rocking motion, most ships are equipped with rocking reduction devices. Among them, ship anti roll slider device has the characteristics of smaller space required, simple mechanism, convenient and flexible control, etc., and the rocking reduction effect is not affected by the speed of navigation, but the slider control should have high sensitivity and accuracy, so the control algorithm is required to be high.

The most widely used and practical control method in the early days was mainly PID control. Since the parameters of the PID controller cannot be adjusted, the desired rocking reduction effect cannot be achieved. The most important feature of intelligent control is that the parameters of the PID controller can be adjusted so that the output of the controller can be adjusted as in [1], and the mathematical model
of the object does not need to be known exactly as in [2]. Luo proposed an adaptive robust rocking reduction controller based on feedforward neural network as in [3]. Ghassemi used neural networks in combination with PID for cross-swing control to make the controller suitable for any irregular sea conditions as in [4]. Li proposed an adaptive neural network-based ship sway reduction controller as in [5]. At home and abroad, many researchers have done a lot of research on other shake-reducing devices other than shake-reducing fins as in [6-8].

As a population intelligence-based algorithm, the particle swarm optimization algorithm gradually finds the optimal solution by iterative search of individual and population particles. It has the advantages of high solution quality, less parameters to be adjusted, and fast convergence in multi-dimensional space function optimization and dynamic objective optimization, etc. Therefore, this paper uses the particle swarm algorithm to adjust the PID controller parameters. The simulation results have verified that the adjustment of the controller has significantly improved the effect of rocking reduction, and the adaptability and adjustability in different sea conditions have been greatly improved.

2. Long peak wave random model

Due to the influence of sea wind and pressure changes, seawater then fluctuates in all directions, thus forming random waves at sea. Since the phase, frequency and amplitude of waves are random and irregular, a large number of regular waves with different amplitude-frequency characteristics can be superimposed by wave obedience to statistical laws as in [9], and the mathematical model expression for a long-peaked wave at a fixed point at sea level is described as

$$\zeta(t) = \sum_{i=1}^{N} \zeta_{ai} \cos(\omega_{i}t + \varepsilon_{i})$$  \hspace{1cm} (1)

where N is a large enough integer; $\zeta_{ai}$, $\omega_{i}$ and $\varepsilon_{i}$ are the wave height, angular frequency, random initial phase of the i-th unit rule wave; and $\zeta(t)$ is the wave height at the moment of the fixed point.

The wave spectrum is widely used to simulate the mathematical model of long-peaked waves. The wave spectrum density expressions commonly used in the research of ship motion control as in [10] such as P-M spectrum, ITTC spectrum, JONSWAP spectrum, etc. In this paper, we choose the P-M spectrum, which is expressed as

$$S_{\zeta}(\omega) = \frac{81 \times 10^{-3} g^{2}}{\omega^{5}} \exp[-0.74\left(\frac{\omega}{\nu_{w}}\right)^{4}]$$  \hspace{1cm} (2)

Where: $g$ is the acceleration of gravity; $\nu$ is the average wind speed at 19.5m above sea level; and $S_{\zeta}(\omega)$ is the wave spectrum density.

When a random wave acts on a ship, a wave disturbance moment is generated, which depends on the magnitude of the wave inclination. In general, the wave inclination angle can be viewed as a smooth zero-mean stochastic process. The mathematical model for the wave inclination angle at a fixed point on space can be described by

$$\alpha(t) = \sum_{i=1}^{N} \sqrt{\int_{\omega_{i-1}}^{\omega_{i}} S_{\alpha}(\omega) d\omega \cos(\omega_{i}t + \varepsilon_{i})}$$  \hspace{1cm} (3)

Where $S_{\alpha}(\omega)$ is the wave dip angle spectrum; $\omega_{i}$ is the wave angle frequency; and $\varepsilon_{i}$ is the initial phase.

When $\alpha_{w} = k\zeta$, and $k = \omega^{2}/g$, The relationship between the wave inclination angle spectrum and the wave spectrum density can be described as

$$S_{\alpha}(\omega) = k^{2}S_{\zeta}(\omega) = \frac{\omega^{4}}{g^{2}}S_{\zeta}(\omega)$$  \hspace{1cm} (4)

Considering that the width and draft of the ship affect the size of the wave inclination angle, the effective wave inclination angle $\alpha_{\omega e}$ is introduced instead $\alpha_{w}$. Through the ship sway theory can know $\alpha_{\omega e} = K_{w}K_{p}\alpha_{w}$. Where $K_{w}$ is the width of the ship and $K_{p}$ is correction factor of draught. the effective wave inclination angle $\alpha_{\omega e}$ is derived as

$$S_{\omega e}(\omega) = K_{w}K_{p}^{2}\frac{\omega^{4}}{g^{2}}S_{\zeta}(\omega)$$  \hspace{1cm} (5)
When a ship is sailing at sea, the waves are also affected by the speed and direction of the waves, which will make the frequency of the action on the ship and the natural frequency of the waves are not the same, and this frequency is called the encounter frequency $\omega_e$. Their relationship can be expressed as

$$\omega_e = \omega - \frac{\omega^2}{g} V \cos \psi$$  \hspace{1cm} (6)$$

$$S_{ae}(\omega_e) = S_{ae}(\omega)/(1 - \frac{2\omega}{g} V \cos \psi)$$  \hspace{1cm} (7)$$

where $\omega_e$ is the natural frequency of the wave; $V$ is the airspeed; and $\psi$ is the wave direction angle.

Therefore, taking into account the influence of ship parameters and encounter frequency on waves, the mathematical model for the wave inclination angle at a fixed point on space can be described by

$$\alpha(t) = \sin \psi \sum_{i=1}^{N} \sqrt{2 \int_{\omega_{i-1}}^{\omega_i} S_{ae}(\omega_e) d \omega_e \cos(\omega_e t + \varepsilon_i)}$$  \hspace{1cm} (8)$$

Assuming that the wind speed is 10m/s, the speed is $V=16.9$ kn, the simulation frequency interval is $(0.25, 2.4)$, the frequency increment is 0.08, and the encountered wave direction angle is 30°, 60°, and 90°. The simulation results of the long-peaked wave random sea wave inclination angle when the ship is sailing are derived by using Matlab software, as shown in Fig.1.

![Simulation of long-peaked waves with random wave inclination](image)

3. Mathematical model of ship transverse rocking motion and rocking reduction principle

3.1. Mathematical model of ship transverse rocking motion

The Conolly linear transverse sway equation is the most widely used in the field of ship control sway reduction, which is extremely easy to use and has high accuracy. According to Conolly’s theory, when the ship's transverse sway angle is small, equation of motion of ship transverse rocking is expressed as
\[(I_{xx} + J_{xx})\ddot{\phi} + 2N\dot{\phi} + Dh\phi = Dh\alpha \tag{9}\]

Where \(I_{xx}\) and \(J_{xx}\) are the ship's transverse rocking moment of inertia and additional moment of inertia, respectively; and \(N\) is damping moment coefficient of ship transverse rocking; and \(D\) is the displacement of the ship; and \(h\) is the ship at first steady heart high; and \(\alpha\) is the wave inclination angle.

When the ship is in the initial state, The Laplace transformation of Eq. (9) yields the transfer function of the transverse rocking angle with respect to the wave inclination angle, which can be expressed as

\[
\frac{\phi(s)}{\alpha(s)} = \frac{1}{T^2\phi^2 + 2\mu T_\phi \phi + 1} \tag{10}\]

Where \(T = \frac{l_{xx} + J_{xx}}{Dh} = \frac{1}{\omega_\phi} \Rightarrow s = j\omega\).

The inherent period of ship transverse oscillation can be calculated from

\[
T = \frac{2\pi}{\omega_\phi} = 2\pi T_\phi = 2\pi \sqrt{\frac{l_{xx} + J_{xx}}{Dh}} \tag{11}\]

### 3.2. Rocking reduction Principle

The rocking reduction slider reciprocates on the track to produce a control torque to reduce the ship's transverse rocking. In the ideal state, the control moment generated by the motion of the rocking slider is equal in magnitude and opposite in direction to the disturbance moment of the wave on the ship. Thus greatly reducing the ship's transverse rocking amplitude.

During the ship's transverse rocking process, the moments to which the ship is subjected include: recovery moment, damping moment, inertia moment, wave disturbance moment and the control moment generated by the ship anti roll slider device. Ship rocking reduction principle can be calculated from

\[(I_{xx} + J_{xx})\ddot{\phi} + 2N\dot{\phi} + Dh\phi = Dh\alpha - K_c \tag{12}\]

where \(K_c\) is the control torque.

When the right side of Eq. (12) is zero, the control moment \(K_c\) can just offset the wave disturbance moment \(Dh\alpha\). In an ideal state, the expression for the control torque generated by the ship anti roll slider device can be expressed as

\[K_c = A\phi + B\dot{\phi} + C\ddot{\phi} \tag{13}\]

Combining Eqs. (12) and (13), the principle of rocking reduction for ship anti roll slider device can be expressed by the torque control method as

\[(I_{xx} + J_{xx} + C)\ddot{\phi} + (2N + B)\dot{\phi} + (Dh + A)\phi = Dh\alpha \tag{14}\]

### 4. PID controller based on PSO algorithm

#### 4.1. PID controller

PID control is currently the most used control algorithm in ship motion control. In many cases, the ideal PID controller can be expressed as

\[G(s) = \frac{U(s)}{E(s)} = K_p \left(1 + \frac{1}{\tau_i} + \tau_d s\right) \tag{15}\]

Since high frequency signals are extremely susceptible to differential links, indirect differential links will be used instead of regular differential links, which can be expressed as

\[G_D(S) = \frac{K_p\tau_{d1}s}{(\tau_{d1}s+1)(\tau_{d2}s+1)} \tag{16}\]

Combining Eqs. (15) and (16), transfer function of PID controller can be expressed as

\[G_{PID}(s) = K_p + \frac{K_i}{\tau_i s + 1} + \frac{K_p\tau_{d1}s}{(\tau_{d1}s+1)(\tau_{d2}s+1)} \tag{17}\]
4.2. Principle of PSO algorithm

In the PSO algorithm, each bird in a flock is considered as a particle with no volume and mass but only velocity and position. The speed of the particle is influenced by its own flight experience and the flight experience of other particles close to itself during the flight, so that it will constantly adjust its flight speed and direction to bring itself closer to the optimal position.

Assuming that the optimal solution is found in a D-dimensional space of size m particles, the flight speed of the i-th particle can be expressed as

\[ v_{ij} = [v_{i1}, v_{i2}, ..., v_{iD}] \]

and the position of the i-th particle can be expressed as

\[ x_{ij} = [x_{i1}, x_{i2}, ..., x_{iD}] \]

There are two extremes in the PSO algorithm: (1) the individual optimal position \( p_{ij} = [p_{i1}, p_{i2}, ..., p_{iD}] \) represents the current best position obtained by comparing all positions previously searched by the particle. (2) the global optimal position \( p_{g,d} = [p_{g,1}, p_{g,2}, ..., p_{g,D}] \) represents the best position currently found by the whole population. The velocity and position of the particles also change during each iteration, which can be expressed as

\[
\begin{align*}
    v_{ij}(t+1) &= w \times v_{ij}(t) + c_1 \times r_1 \times [p_{ij} - x_{ij}(t)] + c_2 \times r_2 \times [p_{g,d} - x_{ij}(t)] \\
    x_{ij}(t+1) &= x_{ij}(t) + v_{ij}(t+1)
\end{align*}
\]

where \( j(1 \leq j \leq D) \) is dimension; and \( w \) is Inertia weights; and \( c_1, c_2 \) are learning Factor; and \( r_1, r_2 \) are random number, and \( 0 < r_1, r_2 < 1 \).

4.3. Coding of PID parameters

The number of particles of the whole population \( P \) is set to \( m \). Since the three parameters of the PID are used as the position vector of the particles, the dimension of the particle position vector \( D = 3 \), so this population can be represented by a matrix as

\[
P(m,D) = \begin{bmatrix}
K_p^1 & K_i^1 & K_d^1 \\
K_p^2 & K_i^2 & K_d^2 \\
\vdots & \vdots & \vdots \\
K_p^n & K_i^n & K_d^n
\end{bmatrix}
\]

(20)

The initial population can be generated by estimating a range of values for the three parameters of the PID based on a large amount of experience, and then randomly taking numbers within the current range.

4.4. Selection of the fitness function

The performance indicator function used to evaluate the PID controller was selected as the fitness function of the PSO algorithm, and the absolute value of the error multiplied by the time integral (ITAE) was used as the indicator to evaluate the control performance, which can be expressed as

\[
ITAE = \int_0^\infty t|e(t)|dt
\]

(21)

ITAE is relatively easy to implement on the computer, and the PID parameters derived by applying this method can make the system have the advantages of good stability, small overshoot and fast response time, etc.

4.5. Algorithm flow

The algorithmic flow of the PSO algorithm to optimize the three parameters of the PID is specified as follows.

1) First, the algorithm parameters are set. The number of particles in the population is taken as \( m=21 \), and the dimension of the particles is taken as \( D=3 \); In general, the learning factor \( c_1, c_2 \) is taken as \( 2 \); the maximum number of iterations \( M \) is determined as \( 20 \), and the positions and velocities of the particles in the population are randomly initialized. In order to optimize the search capability of the PSO algorithm, this paper uses the adaptive weight method to change the inertia weights, which can be expressed as
\[ w = \begin{cases} 
    w_{\min} + \frac{(w_{\max} - w_{\min}) \times (f - f_{\min})}{(f_{\avg} - f_{\min})}, & f \leq f_{\avg} \\
    w_{\max}, & f > f_{\avg}
\end{cases} \]  

(22)

2) Set the optimal position of particles in the population and the global optimal position.

3) The particles in the population are sequentially assigned to the three PID control parameters \( K_P \), \( K_I \), \( K_D \) and then the control system model built in the Simulink module of Matlab software is run for simulation.

4) Calculate the fitness of each particle in the population according to Eq. (21).

5) The fitness value of each particle is compared with the best position previously stored by itself, and the better side is taken as the current best position of the particle.

6) The fitness value of each particle is compared with the best position previously stored globally, and the better side is taken as the current global best position.

7) Eliminate the particles that do not meet the requirements.

8) Combining Eqs. (18) and (19) updates the velocity and position of the particle, while adjusting the inertia weights \( w \) according to Eq. (22).

9) The new particles are sequentially assigned to the parameters of the PID control, and the new performance index is obtained according to Eq. (21), which is the fitness value of the new position of the particle, and compare it with the original individual optimal value and the global optimal value, and take the better one.

10) The global optimal position is output and the program terminates.

5. Simulation results

In order to verify the control effect of the improved PID controller based on PSO algorithm, a real ship is selected as the controlled object in this paper, and its main parameters are shown in Table 1. The slider design is square, using a slider weight of 30t, a side length of 1.56m and a track length of 14m. The control effects of the PID controller and the modified PSO-PID controller are simulated under different sea states. The simulation results for different wave angles are shown in Fig. 2. Due to space limitation, the simulation results for other different sea conditions such as wind speed and significant wave height are not shown in detail.

| Table 1 Ship parameters of a real ship |
|--------------------------------------|
| Total length of ship | 116m | Length between vertical lines | 105m |
| Type width | 18m | Ship displacement | 5878.8t |
| Type deep | 8.35m | Design Draught | 5.4m |
| Service speeds | 16.9kn | First stable heart high | 1.71m |
| Center of gravity height | 6.45m | Square factor | 0.7464 |

a) Simulation comparison of cross-swing angle under different control when the wave angle is 30°
Simulation comparison of cross-swing angle under different control when the wave angle is 60°

Simulation comparison of cross-swing angle under different control when the wave angle is 90°

Fig.2.Ship cross-swing angle simulation curve

TABLE2 Comparison of cross-swing angles at different wave angles

| Wave direction angle | Original cross-swing angle | Cross-swing angle under PID control | Cross-swing angle under PSO-PID control |
|----------------------|-----------------------------|-------------------------------------|-----------------------------------------|
| 30°                  | -5°~5°                      | -2.5°~2.5°                          | -1.5°~1.5°                              |
| 60°                  | -10°~10°                    | -5.5°~5.5°                          | -2.3°~2.3°                              |
| 90°                  | -15°~15°                    | -9°~9°                              | -4°~4°                                  |

From the above table, it can be seen that the improved PID controller based on PSO algorithm has a more stable control effect and better rocking reduction. It can be obtained from Fig. 2 that the ship's transverse rocking angle based on the improved PID control of PSO algorithm reaches the crest and trough of one cycle faster by about 0.5s, which indicates that the control response speed is improved and is more conducive to maintaining ship stability. In addition, in some time periods, such as 120s-130s in Fig. 2(c), the ship's transverse sway angle under PID control is equal to or even exceeds the original transverse sway angle, which indicates that the PID controller lacks adaptability and regulation capability when the sea state changes. However, the improved PID control based on PSO algorithm will adjust its own control parameters with the change of sea conditions, which makes up for the defects of PID control, so that the ship anti roll slider device system still maintains a good rocking reduction effect.

6. Conclusions

In this paper, the PSO algorithm is introduced to optimize the PID control parameters for the shortcomings that the PID controller of the ship anti roll slider device cannot adjust its own parameters with the change of sea state and the poor control efficiency. The simulation results show that the improved PID controller based on PSO algorithm will adjust its own parameters with the change of sea
state, and the effect of rocking reduction in different sea states has been relatively improved, which verifies the better robustness and applicability of the improved controller.

References
[1] Liang, Y.H., Jin, H.Z., and Liang, L.H. (2008) Fuzzy-PID controlled lift feedback fin stabilizer. J. Journal of Marine Science and Application., 7(2): 127-134.
[2] Li, H.L., Sun, M.X., and Luan, T.T. (2017) Design Fuzzy Input-Based Adaptive Sliding Mode Control for Vessel Lift-Feedback Fin Stabilizers with Shock and Vibration of Waves. J. Shock and Vibration., 2017:1-13.
[3] Luo, W., Hu, B., and Li, T. (2017) Neural network based fin control for ship roll stabilization with guaranteed robustness. J. Neurocomputing., 230:210-218.
[4] Ghassemi, H., Dadmarzi, F.H., and Ghadimi, P. (2010) Neural network-PID controller for roll fin stabilizer. J. Polish Maritime Research., 17(2): 23-28.
[5] Li, R., Li, T., and Bai W. (2016) an Adaptive Neural Network Approach for Ship Roll Stabilization via Fin Control. J. Neurocomputing., 173(3): 953-957.
[6] Yin, J.C., Zou, Z.J., and Xu, F. (2013) On-line prediction of ship roll motion during maneuvering using sequential learning RBF neural networks. J. Ocean Engineering., 61:139-147.
[7] Ren, R.Y., Zou, Z.J., and Wang, X.G. (2014) A two-time scale control law based on singular perturbations used in rudder roll stabilization of ships. J. Ocean Engineering., 88:488-498.
[8] Wang, L.L., Pan, H.J., and Li, X. (2015) Active Disturbance Rejection Fuzzy Controller for Roll Stabilization of Autonomous Underwater Vehicle under Wave Disturbance. J. Discrete Dynamics in Nature and Society., 2015:1-10.
[9] Brodtkorb, A.H., Nielsen, U.D., and Asgeir, J. Sørensen. (2017) Sea state estimation using vessel response in dynamic positioning. J. Applied Ocean Research., 70:76-86.
[10] Liu S, Papanikolaou A. Prediction of parametric rolling of ships in single frequency regular and triple frequency group waves[J]. Ocean Engineering, 2016, 120:274-280.