Simulation comparisons by three strategies of control on Ships’ fin stabilizer control system

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Abstract. Reducing the ship rolling motion is an important subject of the ship motion control. And the fin stabilizer is one of the most effective ship stabilizers, which plays an important role in improving the ship seaworthiness, giving a longer life for the ship, ensuring the equipments on the ship working better and making the ship members feel comfortable, advance battle effectiveness of the naval ship. Since the ship rolling motion has the characters of the nonlinearity and randomicity. The building of the mathematic model is difficult. Therefore, the method, that the exact mathematic model is not needed priorly, will be suitable for the control system. In the strict sense, the PID and MFLAC are in accord with these characters. Simulations are given for the fin stabilizer’s control system with three different control methods: Proportion Integration Differentiation (PID), Model-Free Learning Adaptive Control (MFLAC) and the improved MFLAC based on Multi-Innovation (MI-MFLAC). The principles of the three methods are introduced and the advantages and disadvantages of the three methods are represented. The satisfied control effects are achieved with the latter two control strategies.

1. Introduction

The ship sailing in seaway usually endures large motions and large accelerations due to waves, which may lead to seasickness, disturbance of the ship operation, stability loss, etc. Among the six degree motions the rolling is the most important influence factor. And fin stabilizer is one of the most effective ship-stabilized equipment. [1]As the computer technology and intellective control theory have developed quickly in recent years, a series of studies have been done to design some effective and intelligent fin stabilizer in order to improve the control effect of the fin stabilizer system. The fin stabilizer's control system consists of four modules: the characters of random sea wave, the characters of linear model of ship roll motion, the theory of steady of ship roll motion and the equipment for it, and the control system of fin stabilizer and the style of control. [2] Each of modules has the necessity of its existence. The control method is the emphasis point of the paper.

In recent years, the control methods of ships’ fin stabilizer system include: PID control, [1, 12] the fuzzy control, [1, 4] BP artificial neural network control, [2] robust control [3] etc. The scholars applied kinds of methods to the ships’ fin stabilization control system and certain good quality researches are achieved. However the traditional control strategies even the simulation models with the intelligent algorithms require an accurate mathematic model. These belong to model-based methods. The nonlinearity and randomicity of ships’ rolling performance make restrict requirements on the application of all the above methods. The MFLAC method was generated in this background, in which I/O data is the only needed data, the complex model is simplified reasonably. In this paper, the PID control, the MFLAC and the MI-MFLAC methods are applied separately to ships’ fin stabilizer. Based on the principles of every method the simulation studies are carried out and comparisons are
made to distinguish the superiorities and inferiorities of all the three methods. Results were shown that the MFLAC and MI-MFLAC are suitable for the ships’ fin stabilization control system. Especially when the system changes, the MFLAC and MI-MFLAC have better performance compared with PID method. In addition, the MI-MFLAC has better control effect than MFLAC.

2. Fin stabilizer control system

When the ships are sailing in the sea, the wave motions make the ship generate the rolling motion. The use for fin stabilizer control system is to reduce the rolling. The principle of ships’ fin stabilization is that the ship roll angular speed signals are detected by the rate gyroscope, through the controller handling the signals then the signals are passed to electro-hydraulic servo actuator system, which drives the fin to rotate an angle. At this time the fin by means of water flow generates a lift force. Normally, there is a pair of fins equipped with the port and starboard. When the fin is working the rotate angle has the character that they are equal in numbers and opposite in directions. Then the stable moment which is opposite with wave moment is generated. The aim of reducing roll then will be achieved.

Based on the theory of random sea wave, the constitution of the random sea wave in terms of its spectrum was discussed. The simulation problem of slope of wave surface was solved and carried out by programming. Based on the character of ship roll motion, a linear model of ship roll motion by a certain ship parameters is built, and then a curve of ship roll motion in opened loop and the infection of certain slope of wave surface are achieved. [4] The wave slope angle is the input data, the system model used in the simulation chooses the Chinese fishery administration vessel 32, the standard of fin named NJ5 was chosen in the simulation, the module of ship and follow-up system etc. are all described as transfer functions. The structure of the fin stabilizer’s system is described as below. [1]

Fig 1. The structure of the ships’ fin stabilizer’s system

2.1. Wave slope angle

According to the wave theory, the idea of wave slope angle simulation is that discretizing the random wave during the period of simulation frequency band, then determining the wave slope angle of harmonic wave under various particular frequencies, then defining the initial phase position of the wave slope angle of harmonic wave, then superimposing the wave slope angle of harmonic wave on the principle of superposition. After the above calculations the random wave slope angles may be simulated. The math simulation model is described as below.

\[
\phi(t) = \sum_{i=1}^{N} \phi_i(t) = \sum_{i=1}^{N} \left( \sqrt{2S_{\phi}(\omega_i)} \Delta \omega \cos(\omega_i t + \epsilon_i) \right)
\]

Where \(\Delta \omega\) is the increment of frequency; \(S_{\phi}(\omega)\) is the energy spectrum density of the wave slope angle; \(S(\omega)\) can choose the appropriate formalizations of the random wave spectrum based on the simulation requirement; \(g\) is the acceleration of gravity; \(\epsilon_i\) is the initial phase position, which will be chosen from the range of \(0 \sim 2\pi\); \(t\) is the simulation time.

The impact from speed and heading of the ship to the wave can be described as the exchange of the ship frequency under the wave effect, which is defined as encounter frequency, noted as \(\omega_e\).
\[ \omega_v = \omega - \frac{\omega^2}{g} V \cos \beta \]  

(2)

Where \( V \) is the speed of ship, \( \beta \) is the wave direction angles.

To avoiding calculation overflow of the computer, finally, the wave slope angle is described as below.

\[
a_v(t) = \left\{ \sum_{i=1}^{\infty} (\sqrt{2S_i(\omega_i)\Delta \omega \cos(\omega_i t + \xi_i)}) \right\} \sin \beta
\]  

(3)

When the ship and wave parameter are chosen, the wave slope angle will be simulated quickly.

2.2. Ship

According to the theory of Conolly, the ship linear rolling can be describes as.

\[
(\Delta I_x + \bar{I}_x)\ddot{\phi} + 2N\dot{\phi} + Dh\phi = -Dh\alpha_v
\]  

(4)

Where \( \Delta I_x \) is roll moment of inertia, \( \bar{I}_x \) is coefficient of roll damping, \( N \) is the displacement of ship, \( \alpha_v \) is the metacentric height of ship, \( \phi \) is roll angle, \( \alpha \) is the effective wave slope.

After Laplace transform of the above equation, the transfer function of ship on the effective wave inclination under zero initial conditions is achieved, which is described as.

\[
G_v(s) = \frac{\phi(s)}{\alpha_v(s)} = \frac{1}{T_v^2s^2 + 2T_v\zeta_v s + 1}
\]  

(5)

Where \( T_v = \sqrt{\frac{\Delta I_x + \bar{I}_x}{Dh}} \) is the inherent rolling period of the ship, \( \zeta_v = \sqrt{\frac{N}{Dh(\Delta I_x + \bar{I}_x)}} \) is the coefficients of the dimensionless damping of the ship.

When the ship is chosen and the wave slope angle is simulated, the rolling response will be achieved.

2.3. The rate gyroscope

In the ships' fin stabilizer's system the measuring element is the rate gyroscope which can measure the ships' roll angular velocity and export as the voltage signal. The translation function can be described as second-order shock element.

2.4. The preamplifier

The function of the preamplifier is increase the roll angular velocity. It can be replaced as a proportionality factor.

2.5. The speed regulation

According to the hydrodynamics theory the moment generated by the fins is in direct proportion to the square of the ships' speed. To strengthen the stable of the fin, the max fin angle must be adjusted according to the different speeds of the ship.

2.6. The wave grad regulation

In view of the ships' severe roll can reduce the efficiency of the fins. To prolong the life expectancy of the fin stabilization system, and give full play to the capacity of the fin, the wave grad regulation is important which is described as a variable with the exchange of wave scale.

2.7. The follow-up system

When the fin is rotating, the large moment is needed, so the follow-up system often is described as an electro-fluid servo system. The math model can described as a second order shock element approximately.
When the ship is chosen, the above system will be expressed clearly. [9]

In this paper the emphasis point is the control strategies implying. The control theory of the PID, the control theory of MFLAC method and the MI-MFLAC method were applied into the same system of fin stabilizer to compare the control effects.

3. Principles of the three methods

3.1. PID control method

The PID controller is the most widely used control method in industries because of its simplicity of both theory and application. It is based on information from the I/O data of the plant. The commonly used formula is described as below.

$$u(k) = u(k-1) + k_p \left[ e(k) - e(k-1) + \frac{\Delta T}{\tau} \int e(k) + \frac{\Delta T}{\tau^2} [e(k) - 2e(k-1) + e(k-2)] \right]$$

(6)

Where $e(k)$, $u(k)$ are the inputs and outputs of the system, $k_p$ is the proportion factor, $\tau$ is the integration factor, and $\Delta T$ is the step of simulation time. Through the formula above, we can know that the PID method only uses I/O data of the plant.

3.2. MFLAC method

Defining with the development of computer science, the control systems become more and more complex. In the ship fin stabilizer’s system because of the nonlinearity and randomicity of the ship motion and the tradition model-based control strategies require accurate mathematic model, and only achieve a good performance model, and only achieve a good performance under a certain sea situation. Under this background the MFLAC was first proposed by Hou Zhongsheng in 1993, the basic idea is to use a new concept named pseudo gradient to substitute the dynamic linear time-varying model for the real nonlinear system, and utilize the I/O data to estimate the pseudo gradient online. The MFLAC method works by cycling of the online control and online identification. So far the MFLAC has been successfully applied in the field of oil refining, chemical engineering, electrical powering, city transportation control, etc. [6, 7, 10] Consider the following discrete-time nonlinear system:

$$y(k+1) = f(y(k), y(k-n_1), u(k), \ldots, u(k-n_s))$$

(7)

Where $y(k)$, $u(k)$ are the input and the output of system, $u(k) \in \mathbb{R}^r$ or $u(k) \in \mathbb{R}^p$, and $n_1$, $n_s$ stands for the system order.

With some assumptions the pseudo partial derivative (pseudo gradient) identification algorithm and control algorithm can be described as below.

$$\dot{\phi}(k) = \dot{\phi}(k-1) + \frac{\eta_0 u(k-1)}{\mu} \left[ k_y y(k) - \dot{\phi}(k-1) \right]$$

$$\dot{\phi}(k) = \dot{\phi}(1), \quad \forall T \dot{\phi}(k) \leq \varepsilon \quad \text{or} \quad \|u(k) - 1\| \leq \varepsilon$$

$$u(k) = u(k-1) + \frac{\rho_\lambda}{\lambda + \|\phi(k)\|} \times \phi(k) \{ y_0 - y(k) \}$$

(8)

Where $\phi(k)$ is the pseudo gradient, $\lambda$, $\rho_\lambda \in (0, 2)$, $\mu$, $\lambda$ are weighted factors, $\varepsilon$ is a sufficiently small value, and $\phi(1)$ is the initial value of $\phi(k)$.

The MFLAC method procedure based on the former I/O data. The procedure will be carried out repeatedly until the system output $y(k+1)$ is sufficiently close to the given ideal output $y_s$. When the appropriate data to the parameters is given, the satisfied result was achieved.
3.3. MI-MFLAC method

The pseudo gradient in MFLAC only utilizes the current set of data; however, the last set of data that are not used may carry useful information. Based on above ideas, the improvement of the MFLAC based on multi-innovation was proposed by Qin Pinle. [8] Compared with the MFLAC, the convergence rate of the pseudo gradient and the control law of MI-MFLAC were improved. The convergence of the MI-MFLAC method was proved in the reference and the tracking performance was verified. [8, 11] After the improvement, the pseudo gradient identification algorithm and control algorithm can be described as below.

\[
\hat{\theta}(k) = \hat{\theta}(k-1) + \frac{\eta \Delta \omega(k-1)}{\mu + \| \Delta \omega(k-1) \|} \left[ \Delta y(k) - \hat{\theta}(k-1) \Delta \omega(k-1) \right] \\
(10)
\]

\[
\hat{\phi}(k) = \hat{\phi}(1), \text{ if } \text{sign}(\phi(1)) \neq \text{sign}(\hat{\phi}(k)) \\
\hat{\phi}(k) = \hat{\phi}(1), \text{ if } |\hat{\phi}(k)| \geq M \text{ or } |\hat{\phi}(k)| \leq \varepsilon
\]

\[
u(k) = \nu(k-1) + \frac{\lambda_2}{\alpha + \| \Phi(p,k) \|} \times \Phi(p,k) \left\{ Y'(p,k+1) - Y(p,k) \right\} \\
(11)
\]

Where \( Y'(p,k+1) \) is the system expected output vector with \( p \) length, \( Y(p,k) \) denotes the system real output vector with \( p \) length. The Eq. (10) and Eq. (11) constitute the multi-innovation model-free learning adaptive control.

4. Numerical simulations

To verify the effect of different control strategies, simulations results are shown as follow partly, the input data is the simulation of wave slope angle, which is shown in Fig. 2. The output data is the roll angle, the contrast data is the roll angle between the non-control system which is shown in Fig. 3 and the control system with the different control strategies which are shown below.

Fig 2. Simulation of wave slope of angle
To test the control strategies' validity, we choose the specific wave parameters. It is difficult to achieve better control effect, even the increasing rolling will be generated, which is shown in Fig.4.

Fig 3. Roll angle

Fig 4. The control effect of PID-based controller for roll stabilization

Fig 5. The control effect of MFLAC-based controller for the roll stabilization

Fig 6. The control effect of MI-MFLAC-based controller for the same system
Fig. 4 shows that the system after PID method controlling appears diverging. To the same system, the compare results between MFLAC and PID is shown in Fig. 5. The compare results between MI-MFLAC and PID is shown in Fig. 6.

As space is limited, results under varied parameters are not all shown in this paper. When the outside environment changed, such as wave length or wave height or wave period, the results with PID control method may appear the increasing rolling, the parameters must be readjusted, but to the same condition, the results with MFLAC and MI-MFLAC still are decreasing rolling without parameters adjusting. In most cases, the adjustments of parameters in the PID control method are difficult. Comparatively speaking, the MFLAC and MI-MFLAC control method are easier than the PID control method. This proves that the method MFLAC and MI-MFLAC are suitable for the varied external environment. The strong nonlinear system can be solved with these two methods and the satisfied control effects can be achieved.

In the reference paper [13] shows that MI-MFLAC method can improve the performance of MFLAC and has faster convergence rate. The effect of control is the best of the three control strategies for the same control system. To the ships’ fin stabilization system, the effective control method not only means the roll reducing, but also requires the quick convergence rate. Therefore, the implying of MI-MFLAC in ships’ fin stabilization system is reasonable in the future.

5. Conclusion and further research

In the strict sense, the three methods that mentioned in the paper are classed as the method independent of the mathematic model. In the paper, the technique of applying the Proportion Integration Differentiation (PID), Model-Free Learning Adaptive Control (MFLAC) and the improvement of MFLAC based on Multi-Innovation (MI-MFLAC) to the stabilizer fin to reduce the ship rolling motion is developed. According to a series of numerical calculations and comparisons, the results show that the methods of MFLAC and MI-MFLAC have better control effect than PID control method, especially the disturbance changed, the PID cannot best adapt to the varying of environment. Since the MFLAC and MI-MFLAC is not within the domain of model-based control strategy, the methods can meet the control requirement in situations when the system model cannot be formulated and the disturbance will change. In view of these, the MFLAC and MI-MFLAC are suitable for the fin stabilizer's control system. To be suitable for the varying control system, the intelligent algorithms should be introduced into the selecting of the control parameters. This will be the prospect work in the future.

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