Design of Internal Model Controller for Ship Dynamic Positioning Based on Inverse Algorithm

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Abstract
Aiming at the problems of multivariable coupling, nonlinearity and delay in ship motion, this paper proposes an internal model controller design for ship dynamic positioning based on the inverse algorithm. The simulation results show that compared with the traditional PID, the internal model control has the characteristics of strong robustness, high positioning accuracy and green control.

Keywords
dynamic positioning, internal model, Kalman Filter, stability.

1. Introduction

In view of the complexity of the real motion of the ship on the sea, the motion model of the ship system is decomposed into high-frequency motion and low-frequency motion, in which the low-frequency motion is caused by wind, current, second-order waves, thrusters, etc., while the high-frequency motion is caused by first-order waves[1]. The high-frequency motion of the ship will not cause the change of the average position of the ship, but only periodic oscillation [2]. In order to avoid unnecessary energy waste and thruster wear, high-frequency motion is not controlled [3]. In this paper, a dynamic positioning controller based on internal model control algorithm and inverse system principle is designed for a 2.8m ship model with two channel thrusters and two rotary thrusters. Compared with the classical PID control algorithm, the simulation results show that the controller with double closed-loop internal model control algorithm has good response performance and is suitable for engineering use.

2. Mathematical model of ship dynamic positioning

According to [4], the low-frequency motion equation of ship dynamic positioning can be expressed as

$$M\dot{V} + DV = \tau + R^T(\varphi)b + E_v w_v \tag{1}$$

Where: τ is the control force and moment; M is the inertia matrix (including hydrodynamic added mass), which meeting the positive definite requirements; D is the damping matrix, R(φ) is the transformation matrix, b is unmodeled external disturbance forces such as wind, wave and current, which can be described by the first-order markov deviation model [4]:

$$\dot{b} = -T_b^{-1}b + E_b w_b \tag{2}$$

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Where: T_b is a three-dimensional diagonal matrix containing time constants; $w_b \in R^3$ is a zero mean Gaussian white noise and $E_b \in R^3$ is a three dimensional diagonal matrix indicating the amplitude range of environmental forces. M, D is defined as follows:

$$M = \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 \\ 0 & m - Y_{\dot{v}} & mx_G - Y_{\dot{r}} \\ 0 & mx_G - Y_{\dot{v}} & I_Z - N_{\dot{r}} \end{bmatrix}, \quad D = \begin{bmatrix} -X_u & 0 & 0 \\ 0 & -Y_v & -Y_r \\ 0 & -N_v & -N_r \end{bmatrix}, \quad R(\varphi) = \begin{bmatrix} \cos\varphi & -\sin\varphi & 0 \\ \sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Where: $X_{\dot{u}}, Y_{\dot{v}}, Y_{\dot{r}}, N_{\dot{v}}, N_{\dot{r}}$ refers to the added mass coefficient of hydrodynamic force caused by acceleration, X_u, Y_v, Y_r, N_v, N_r represents the hydrodynamic linear damping coefficient.

3. DESIGN OF INTERNAL MODEL CONTROLLER

Before the dynamic positioning control system is applied in the actual environment, the simulation test must be carried out in the simulated environment. The purpose of the simulation is to verify whether the control method used by the ship in the simulated bad environment can meet the requirements of engineering control. When some control performance does not meet the requirements, adjust the controller parameters or structure to make the whole control system more perfect.

Matlab simulation software is an open system, which can carry out matrix calculation, numerical analysis and scientific data visualization in an easy to use windows environment. Matlab simulation software supports the analysis of single input and single output systems and multiple input and multiple output systems, as well as the analysis and simulation of discrete systems and continuous systems. In Matlab / Simulink environment, many control algorithms can be simulated and verified, such as classical PID control algorithm and other intelligent control algorithms. This paper mainly carries out the simulation verification of dynamic positioning control for the commonly used ship dynamic positioning control algorithms, such as PID control algorithm and internal model control algorithm, and analyzes the advantages and disadvantages of the algorithm [5].

3.1. Simulation of Classical PID Controller

The longitudinal motion of a 2.8m experimental ship in the key laboratory of ocean engineering of Guangdong university of technology is studied. During the simulation, the surge motion part of the low-frequency model structure proposed by Fossen of Norway is selected as the MATLAB simulation model of this paper [6]. The model selected for control is

$$(m - X_{\dot{u}}) \cdot \dot{u} - X_u \cdot u \cdot |u| = F_u \tag{3}$$

Where $m - X_{\dot{u}} = 223.7$, $X_u = -46.4$.

Classical PID control method is adopted, and PID control is adopted for speed loop and position loop. The Simulink simulation structure diagram of the position ring is as Fig.1 shown.

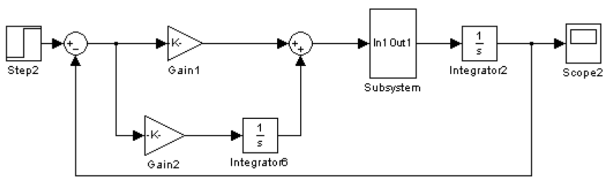

Fig.1 Response of double-loop PID

The subsystem is the speed loop subsystem, and the speed loop also adopts the same PID control structure. The given position signal is 2, and the response result of the PID control system to the position signal is shown in Fig.2.

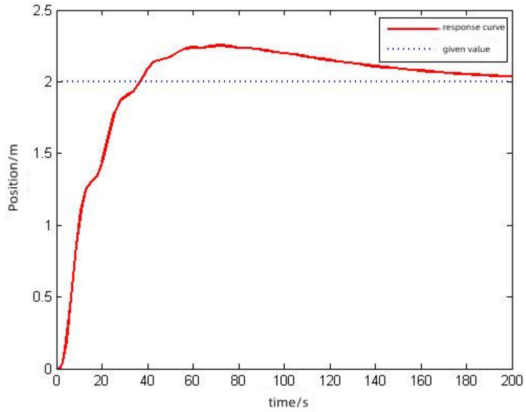

Fig.2 Response of double-loop PID

It can be seen from Fig.2 that the system cannot track and respond effectively and quickly when the double loop PID control is applied to the ship model. The control system has a huge overshoot. In the actual ship dynamic positioning, this control method is time-consuming and labor-consuming.

3.2. Design of Ship Dynamic Positioning Controller Based on Inverse System Theory and Internal Model Control Algorithm

In practical industrial control applications, most of the controlled objects are not linear models with single input and single output, but nonlinear models with multiple input and multiple output and mutual coupling. Especially for complex systems such as ship dynamic positioning, decoupling control is required during internal model control, which increases the complexity of internal model control.

The inverse system method is a kind of decoupling control method which deals with nonlinear model by feedback linearization. Internal model control (IMC) is applied to the pseudo linear system. The internal model control based on inverse system method has clear structure and simple algorithm.

Based on the inverse system theory, the α order inverse system of the original system is constructed to perform internal model control on the new system composed of the original system and the α order inverse system. The system structure diagram is as follows:

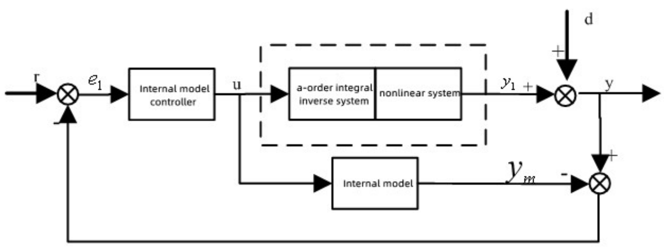

Fig.3 Internal model control under the pseudo-linear system

The structure diagram of internal model control under pseudo linear system is shown as Fig.3, in which r is the system input, d is the system disturbance, y is the control system output, and y_m is the internal model output. The new system constructed by the inverse system and the original system has a simple model, and the internal model controller design is easy and convenient, which solves the problem of constructing the inverse model of the original nonlinear system.

(1) Basic Theory of the Inverse System Principle

As a new control method, the inverse system theory has established a relatively complete design theory for general nonlinear systems in recent years. The inverse system method has no special requirements for the form of equations, so it has extensive research significance. The essence of inverse system method is to use feedback linearization to realize decoupling linearization of nonlinear, multivariable and strongly coupled systems. In this method, the nonlinear, multivariable and strongly coupled system is linearized in the global by state feedback to realize decoupling. Inverse system theory does not need to introduce problems into differential geometry and other fields, so it does not require a deep mathematical theoretical basis, which is very suitable for engineering applications.

The basic idea of inverse system theory is to generate an α order integral inverse system for the original system by using the mathematical model of the controlled object and the feedback method. The inverse system refers to the system that realizes the transformation from the output of the original system to the input. For the system with known and relatively accurate model, the α order inverse system of the original system can be obtained by mathematical derivation method, and the new system composed of the α order inverse system and the original system is pseudo linear system. Finally, various design methods and theories of linear systems are used to complete the synthesis of pseudo linear systems [7].

For a continuous nonlinear or linear system Σ, assuming that the input is u, the output is y, and the initial state is x_0, note that the operator describing the mapping relationship of the system is θ: $u \to y$, that is

$$y = u \cdot \theta \tag{4}$$

Construct another continuous nonlinear or linear system Π, assuming that the input is η and the output is u_d, the mapping operator of the system is $\overline{\theta} : \eta \to u_d$, if $\eta = y^{\partial}$, that is, η is α order derivative of y. If the operator $\overline{\theta}$ satisfies:

$$\theta \cdot \overline{\theta} \cdot \eta = \theta \cdot \overline{\theta} \cdot y^{\partial} = \theta \cdot u_d = \eta \tag{5}$$

Then the system Π is the α order inverse system of the system Σ. $\alpha = 0$ is a special case of α order inverse system, which is the unit inverse system.

The composite new system composed of the original system and its inverse system is called pseudo linear system, which composed of $\theta \cdot \overline{\theta}$. The relationship between input and output of the new composite system is linear, showing an identity mapping relationship, but the internal structure of the composite system may also be nonlinear and coupled. Only when the mapping operator θ of the original system itself is linear, the internal structure of the new composite system can be linear. Obviously, the new system composed of the inverse system and the original system can be controlled according to the general linear control method, and the whole control becomes relatively simple and clear [8]. The composition and structural composition of pseudo linear systems can be represented by the Fig.4.

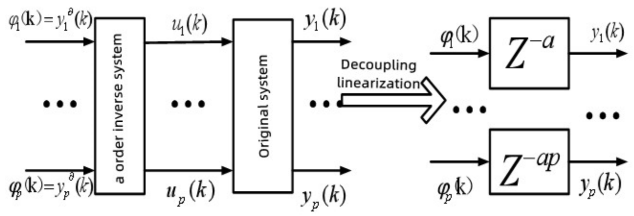

Fig.4 Based on the α–integral inverse system decoupling linearization and α–integral pseudo-linear system

(2) Controller Design

The dynamic positioning control system of a ship at sea includes two parts, one is to control the speed of the ship, and the other is to control the position of the ship. In the design of this paper, the internal model control method is used to control these two parts, forming a double closed-loop internal model control system, that is, the inner loop is the speed loop control system, and the outer loop is the position loop control system. At the same time, for the ship model, the principle of inverse system is adopted to decouple and linearize the coupled and nonlinear ship model [5].

Regardless of the coordinate conversion in the actual motion control of the ship, the structure diagram of the ship control system based on the inverse system and internal model control algorithm is shown in Fig.5:

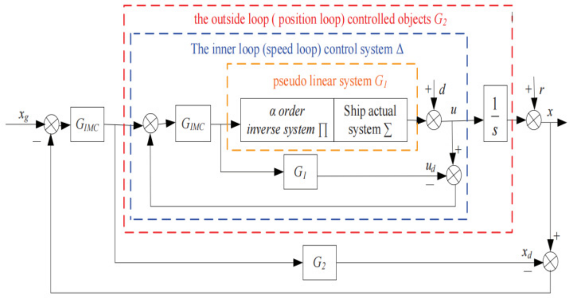

Fig.5 The structure of ship control system based on the inverse system and IMC

Where: G_1 is the pseudo linear system, which is the controlled object of the inner loop (speed loop) control system; Δ is the inner loop (speed loop) control system; $\widehat{G}_1$ is the pseudo linear system model; G_2 is the outer loop (position loop) controlled object; $\widehat{G}_2$ is the reference model of the controlled object of the outer loop (position loop) [5].

(3) Simulation analysis

According to the actual ship model, control the surge, sway and yaw of the ship. The set values of surge, sway and yaw are 3m, 2m and 2 rad respectively. The system response is shown as Fig.6.

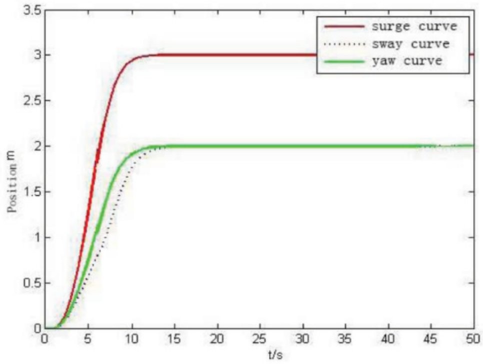

Fig.6 Response of dynamic positioning controller based on inverse system and IMC

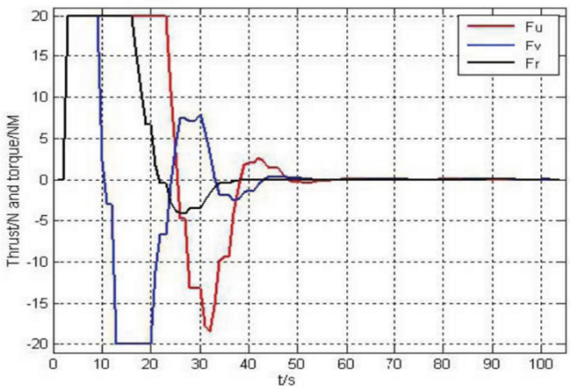

Fig.7 The force of controller

It can be seen from the simulation results in Fig.6 and Fig.7 that the simulation effect of the ship dynamic positioning controller based on the inverse system principle and internal model control algorithm proposed in this paper is good. The ship has no overshoot and error in response, stable dynamic performance and fast response. At the same time, considering the limitation of propeller thrust capacity and the imprecision of ship model in actual conditions, the ship dynamic positioning controller can still work with maximum efficiency and no deviation in response. The simulation results show the effectiveness and availability of the ship dynamic positioning controller based on the inverse system principle and internal model control algorithm.

4. CONCLUSION AND PROSPECT

For nonlinear ships, this paper proposes an inverse system control algorithm based on the internal model algorithm, the simulation results show that compared with the formation of classical PID control, the ship direction dynamic positioning controller based on the inverse system theory and internal model control algorithm has better dynamic characteristics and faster response speed, with less overshoot and strong anti-interference ability, it is suitable for engineering practice.

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