Synchro-control of Twin-rudder with Cloud Model

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Abstract: In ships having two rudders, an angle error exists if there is a difference in structural and electrical parameters in two steering gear systems. Such an error also results in reduced efficiency of ship maneuverability during navigation. For the sake of reducing the angle error, a synchro-ballistic control approach based on cloud model is proposed in this paper. First, the mechanism model of steering gear system is introduced. Second, the structure of synchro-control system of twin-rudder is proposed based on the master-slave control strategy. Third, synchro-ballistic controller based on cloud model is designed to solve the nonlinearity and uncertainty of system. Finally, the designed controller is tested via simulation under two different situations. The simulated results demonstrate that this method is simple and has stronger robustness against the variation of states and parameters of plants. Hence, the validity and reliability of the method is proved for synchro-control of two rudders, which is a significant engineering application.

Keywords: Ship steering, steering gear, twin-rudder, synchro-ballistic, cloud model.

1 Introduction

In ships having two rudders, both rudders should be synchronized when the ship moves. One reliable method to achieve synchronized motion is that, the two tillers, which are connected by a pole, move together with one servo system, but it can be only used in the situation when the range between two rudders is short, the power of servo system is small, and the difference of load is little. Now, the most rudder systems consist of two tillers that are steered by two servo systems separately. The two rudders are asynchronous because of the differences of structural parameters and electrical parameters in two servo systems. The efficiency of rudder and ship maneuverability are reduced because of the asynchronous twin-rudder[1].

The rudder servo system is a highly nonlinear, multi time-varying parameters system, subjected to the saturation characteristics of pump and amplifier, the dead zone characteristics of servo valve, hysteresis characteristics of torque motor, unknown loads, nonlinear friction, etc. The conventional controllers could perform poorly because nonlinearities and uncertainties in the system are not properly compensated, so different control techniques that can overcome some of the above mentioned problems have been investigated, such as adaptive fuzzy sliding-mode control, adaptive single-neuron PID control, etc.[2, 3].

The cloud model was first proposed as a model of the uncertain transition between a linguistic term and a qualitative concept based on fuzzy mathematics and probability statistics, and it provides a simple and effective way to deal with the two uncertainties in the world: randomness and fuzziness[4]. In the past few years, cloud model is well applied in control systems, such as inverted pendulum control system[5, 6], flexible-link manipulators control system[7], boiler temperature control system[8], ship course-keeping control system[9], and truck backing up control system[10]. Those works demonstrated that the controller based on cloud model is easy and has better performance and good application in solving the nonlinear and uncertain problems.

2 Model of steering gear

This paper aims at the electro-hydraulic servo system, which consists of amplifier, torque motor, differential hydraulic cylinder, three-way valves, variable pump with slanting axial piston, rudder actuator, and feedback machinery[11, 12]. The models of main section are given as follows.

2.1 Torque motor

Torque motor can be equated to inertia, so the mathematical model can be expressed as

$$\frac{T(s)}{Er(s)} = \frac{K_m}{s^2 + \frac{2\xi}{\omega_n} s + \frac{1}{\omega_n}}$$

where $T$ is the torque of motor, and $Er$ is the rudder angle error signal.

2.2 Three-way servo valve

Servo valve can be approximated by second order system, so the mathematical model can be expressed as

$$\frac{X_1(s)}{F_v(s)} = \frac{K_v}{s^2 + \frac{2\xi}{\omega_n} s + \frac{1}{\omega_n}}$$

where $X_1$ is the driving force of torque motor, $R_0$ is the range between the center of valve core and the center of rotor shaft in torque motor, and $K_0$ is the proportional gain of feedback lever.
2.3 Differential hydraulic cylinder

Hydraulic cylinder can be approximated by third-order system, so the mathematical model without load can be expressed as

$$\frac{Y_1(s)}{X_v(s)} = \frac{K_{h1}}{s^3 + \omega_{h1}^2 s^2 + 2\nu_{h1} \omega_{h1} s + 1}$$  (3)

where $Y_1$ is the displacement of piston, and $X_v$ is the opening of valve port.

2.4 Variable pump with slanting axial piston

The flow equation of variable pump can be defined by the following equation:

$$Q = D_p n = K n \tan \beta$$  (4)

where $\beta$ is the inclination of slanting plate, and $Q$ is the flow of variable pump.

2.5 Rudder actuator

Hydraulic rudder actuator with fork type can be approximated by third-order system, so the mathematical model without load can be expressed as

$$\frac{Y_2(s)}{Q(s)} = \frac{K_{h2}}{s^3 + \omega_{h2}^2 s^2 + 2\nu_{h2} \omega_{h2} s + 1}$$  (5)

$$\delta = \arctan \frac{Y_2}{R}$$  (6)

where $Y_2$ is the displacement of ram in hydraulic cylinder of rudder actuator, $\delta$ is the rudder angle, and $R$ is the range between the center of rudder stock and the center of ram.

The gain of amplifier can be denoted by $K_0$. Fig. 1 shows the nonlinear model of steering gear system (The values of parameters in model are given in the Appendix).

3 Cloud model

3.1 Cloud theory

Cloud is defined as follows, suppose that $U = \{x\}$ is the qualitative universe of discourse, and $\tilde{A}$ is a linguistic term associated with $U$. If the quantitative value $x$ is one of the random values of $\tilde{A}$ belongs to $U$ and the certainty degree $\mu_{\tilde{A}}(s)$ of $x$ to $\tilde{A}$ is a random number with stable tendency, then the distribution of $x$ in the universe of discourse $U$ is called a cloud model[14], and $x$ is a cloud drop.

Assuming that $f(E_1, E_2)$ is a random function that has one-dimensional normal distribution, $E_1$ is expected value, and $E_2$ is standard deviation, the following equations are given:

$$x_i = f(E_{x}, E_{n})$$  (7)

$$P_i = f(E_{n}, H_{e})$$  (8)

$$\mu_i = \exp\left[\frac{1}{2} \left(\frac{x_i - E_{x}}{P_i}\right)^2\right].$$  (9)

One-dimensional normal cloud model is made up of data drop$(x_i, \mu_i)$, which satisfy (7) − (9). drop$(x_i, \mu_i)$ are named as one-dimensional drop[13]. $E_x$, $E_n$, and $H_e$ are digital characteristics of cloud model and named with expected value, entropy, hyper entropy, respectively, denoted by $(E_x, E_n, H_e)$.

Expected value $(E_x)$ is the value that represents qualitative concept of discourse. It is the center point of qualitative concept.

Entropy $(E_n)$ is the tolerance of the concept coverage. It represents the range of values that could be accepted by qualitative concept in the universe of discourse, namely, the extent of fuzziness.

Hyper entropy $(H_e)$ can be considered as the entropy of $(E_n)$. It reflects the randomness of samples of a qualitative concept and reveals the relation between fuzziness and randomness. Fig. 2 shows an example of three numerical characteristics of cloud model.

Fig. 1 Scheme of steering gear system