Mathematical Simulation on Self-tuning Fuzzy Controller for Small Cylindrical Object Navigating near Free-surface

Shao Zhiyu\textsuperscript{a}    Fang Dongyang\textsuperscript{b}     Feng Shunshanc

\textsuperscript{a,c}State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, China
\textsuperscript{b}School of Mechatronical Engineering, Beijing Institute of Technology, Beijing 100081, China

Abstract

Based on the adaptive fuzzy control theory, a self-regulating fuzzy controller is designed for a small cylindrical object navigating near free-surface to minimize wave disturbance and to keep the object move in the desired depth. First, the near free-surface dynamics model of the cylindrical object is presented with the first and second order wave forces. Second, math simulation is introduced to testify the validity of the control method. The results obtained by a series of mathematical simulations demonstrate that the self-tuning fuzzy depth controller performs well in stabilizing the near-surface navigating object and in keeping it in the expected depth during the free-surface wave disturbance.

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1. Introduction

A kind of small cylindrical object navigating near free-surface is needed in some civil or martial uses. One of the primary challenges confronted during the design of its control system is to overcome the big wave disturbances suffered by the near-surface navigating object. The wave forces and moments can induce oscillatory motion of the object, which might cause the motion of the object to be unstable.

* Corresponding author. Tel.: +8610 68911579; fax: +8610 68912032.
\textit{E-mail address:} shaozhiyu@bit.edu.cn.
Consequently, it is necessary to find an efficient depth control method to reduce the wave disturbance and to keep the object navigate in the desired depth.

PID controllers are most widely used in industrial control systems. But parameters in a classic PID controller are fixed, which makes it inefficient in conditions of external disturbances such as waves or currents. Fuzzy control has been successfully used in the control of underwater vehicle which operates in strict and tough conditions. Study in article [1] shows that fuzzy control method can be used to compensate parametrical uncertainties of the mathematic model of some kind of underwater vehicle and can prevent viscous environmental influences. In article [2] a new self-regulating fuzzy control rule is applied to design a trajectory control system for an underwater vehicle with high nonlinearity. Simulation results show that the trajectory control system has nice dynamic properties and strong adaptability to changes in initial conditions and system parameters. According to article [3], fuzzy motion controller can be used to enhance the stability and precision of the underwater vehicle.

In this paper, a new control method using self-tuning fuzzy control rule is presented to design an efficient and robust depth controller for a kind of small cylindrical near-surface navigating object, and the validity of the self-tuning fuzzy control method is verified by the mathematical simulation results.

2. Mathematical Model of the Cylindrical Near-surface Navigating Object

Two coordinate reference frames are used in defining the motions of the 6-DOF cylindrical near-surface navigating object: the body-fixed reference frame \( X_BY_BZ_B \) and the earth-fixed (inertial) reference frame \( X_EY_EZ_E \). The origin of the body-fixed frame is at the center of the buoyancy of the object and the origin of the earth-fixed frame is at the center of buoyancy of the object at time \( t=0 \). For frame \( X_BY_BZ_B \), \( X_B \) axis points toward the head of the object, \( Y_B \) axis points toward the starboard side, and the \( Z_B \) axis points downward in accordance with the right-hand rule. For frame \( X_EY_EZ_E \), \( X_E \) and \( Y_E \) axes are directed toward the north and the east direction respectively, while \( Z_E \) axis points downward in accordance with the right-hand rule.

When designing the depth control system, what we mainly concern is the vertical motion of the cylindrical object that moves close to the free-surface. The mathematical model of the vertical motion of the underwater object is described through Newton laws of linear and angular momentum.

3. Wave spectrum and force

The wave spectrum which is normally used in the study of the influence on near-surface underwater object is the standard Pierson-Moskowitz spectrum, which is written as

\[
S(\omega) = A\omega^3 \exp(-B\omega^2)
\]

(1)

With \( A = 8.1 \times 10^{-3} \text{g}^{-2}, \ B = 3.11/Hs^2 \). \( S(\omega) \) denotes the wave spectrum density, \( \omega \) is the wave frequency, \( Hs \) is the significant wave height.

The spectrum should be modified when the water is flowing. The wave frequency \( \omega \) in equation (2) should be replaced by the encounter frequency \( \omega_e \),

\[
\omega_e = \omega - \frac{\omega U^2}{g} \cos(\mu)
\]

(2)

Where \( U \) is the velocity of the underwater object, \( g = 9.81 \text{m/s}^2 \), and \( \mu \) is the wave incidence angle in radians. The wave incidence angle is the angle between the movement direction of the wave and the velocity of the moving object. \( \mu = 180^\circ \) means that the movement direction of the wave is coincident with
the velocity of the moving object, which is theoretically the most difficult navigation condition for the navigating object to keep its depths. The controller will be designed under this condition.

According to article [4], the wave effects on a submerged object can be split mathematically into first and second order force. The component of the first order force is oscillated in high frequency and its amplitude is proportional to the wave amplitude. The amplitude of the second order force is proportional to the square of the wave amplitude. The second order force is minor compared to the first order force, and it has the effect to drag the underwater object onto the surface. When the underwater object approaches the water surface these section forces increase exponentially and produce a destabilizing effect on the already stable system.

As given in article [5], the instantaneous vertical forces of the waves acting on the underwater object $Z_{wave}$ can be expressed as

$$Z_{wave} = Z_1(t) + Z_2(t)$$

$$Z_1(t) = \sum_{i=1}^{N} C_{Zi} \sqrt{\rho} \left( 1 - \frac{1}{4} \sin^2 \mu (1 - 0.02 U \cos \mu) \times (F_{ui} \sin w_i t) \right)$$

$$Z_2(t) = -\sum_{i=1}^{N} \sum_{j=1}^{N} (F_{ui} F_{uj} \sin w_i t \sin w_j t) \times \frac{3 + \sin^2 \mu}{10m^2 \rho} C_{Zi} \frac{\rho}{U} (1 - 0.04 U \cos \mu)$$

Where $Z_1(t)$ and $Z_2(t)$ are the first and second order wave forces respectively in the vertical plane, $C_{Z1}$, $C_{Z2}$ are hydrodynamic coefficients respectively. Similarly, the instantaneous pitch moment disturbance $M_{wave}$ can be expressed as

$$M_{wave}(t) = M_1(t) + M_2(t)$$

$$M_1(t) = -\sum_{i=1}^{N} C_{Mi} L V \cos(\mu) \times (1 - 0.02 U \cos(\mu) F_{ui} \cos(w_i t))$$

$$M_2 = -C_{M2} L O Z_2(t)$$

Where $M_1(t)$ and $M_2(t)$ are the first and second order wave pitch moment disturbances respectively. $L$ is the overall length of the underwater object. $C_{M1}$, $C_{M2}$ are hydrodynamic coefficients. For this design, we have $C_{Z1}=1.58$, $C_{Z2}=0.1$, $C_{M1}=0.85$, $C_{M2}=0.05$. $\theta$ is the pitch angle, $\rho$ is the water density, $\nabla$ denotes the volume of the object. $F_{li}$ is given by

$$F_{li} = -a_i \omega_i^2 \exp(\omega_i h(t)/g)$$

Where $a_i = (2 S(\omega_i) \delta\omega)^{1/2}$. $\omega_i$ can be obtained by equation (3), in which substitute $\omega_i$ for $\omega_i$ and substitute $\omega$ for $\omega_1$, where $\omega_i = i \cdot \delta\omega$, $i = 1, 2, 3, ..., N$. $\delta\omega$ is the width of the computing bands into which the frequency range of interest of the spectrum $S(\omega)$ is divided to calculate the wave force and moment.

4. Fuzzy Depth Controller Design

The fuzzy depth control system of the cylindrical object navigating near free-surface is shown in figure 1. The pitch angle $\theta$ is selected as the inner loop feedback signal to enhance the dynamic properties of the control system.
The fuzzy depth controller presented in fig. 1 is designed using a new control method applying self-tuning fuzzy control rules, which could help to overcome defects such as steady-error and flutter phenomenon. The structure of the fuzzy controller is shown in fig. 2.

Where $e = K_e e$, $\dot{E} = K_e e \dot{c}$, $\dot{E} = \dot{a} E + (1 - \dot{a}) \dot{E}$. $K_e$, $K_c$ are scaling gains and $K_u$, $K_i$ are proportion and integration coefficients. In this design example, the depth error signal $e$ and the change in error signal $\dot{e}$ have the same membership function for linguistic input variables shown in fig. 3(a). $\dot{a}$ is the on-line searching adjusting factor which serves to change the fuzzy rules and therefore to change the output of the fuzzy depth controller according to the two input variables $e$ and $\dot{e}$. The membership function of $\dot{a}$ is shown in fig. 3(b).
The rationale for the choices for the rule bases is, for example, when there is a big positive change-in-error, then the output of the controller will be weighted heavier on $ec$ than $e$ (a small $\tilde{\alpha}$) and decreases the error rapidly. As the change-in-error decreases, the output of the controller will be weighted heavier on $e$ than $ec$ (a big $\tilde{\alpha}$) to avoid overshoot. The other part of table 1 can be explained similarly.

5. Simulation Results

Some mathematical simulations have been made using Matlab/Simulink to prove the validity of the designed fuzzy depth controller. The simulations are based on the model of the small cylindrical near-surface navigating object. The simulation time is 100 seconds, with a simulation step of 0.01 second. Before simulation, an off-line optimization for $K_c$, $K_{ec}$, $K_u$ and $K_i$ has been made according to integral-of-time-multiplied absolute-error (ITAE) criterion as described in article [6].

The depth curves of the near-surface object which is under fuzzy depth control and navigating at different sea state 2 ($H_s=1$) and 4 ($H_s=2$) with 180° incidence angle are shown in fig. 4. The simulation results of PID depth controller are also given in fig. 4 for comparison.

![Fig. 4. curves of depth error of the near-surface object under different sea states](image)

From the results of the simulation, we can observe that the designed fuzzy depth controller can successfully keep the near-surface object navigate at the depth of 3m under the two different sea state levels with maximum steady state error of less than 0.05m. The fuzzy depth controller shows a strong ability to reject the wave disturbance and can satisfy the needs for an efficient and robust depth control for the cylindrical near-surface navigating object, while the performance of the PID depth controller is not as good as the fuzzy one in preventing the wave disturbance. The maximum depth error of the near-surface navigating object with PID depth controller is about 0.3m at the sea state 4, which does not meet the performance requirements.

6. Conclusions

In this paper a new control method applying self-tuning fuzzy control rules is presented in the depth control of the cylindrical near-surface navigating object, which helps to eliminate the steady-error and the flutter phenomenon existed in PID controller and conventional fuzzy controller. The results of the
mathematical simulation show that the self-tuning fuzzy depth control method can be successfully applied to reduce the wave disturbance and to maintain the cylindrical near-surface object navigate at the expected depth.

References


