Dynamics Analysis of a Small Training oat ant Its Optimal Control

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Abstract: This paper describes dynamics analysis of a small training boat and a new type of ship s autopilot not only to keep her course but also to reduce her roll motion. Firstly, statistical analysis through multi-variate auto regressive model is carried out using the real data collected from the sea trial on an actual small training boat *Sazanami* after the navigational system of the boat was upgraded. It is shown that the roll motion is strongly influenced by the rudder motion and it is suggested that there is a possibility of reducing the roll motion by controlling the rudder order properly. Based on this observation, a new type of ship s autopilot that takes the roll motion into account is designed using the muti-variate modern control theory. Lastly, digital simulations by white noise are carried out in order to evaluate the proposed system and a typical result is demonstrated. As results of simulations, the proposed autopilot had good performance compared with the original data.

Keywords: autopilot, rudder roll stabilize, statistical analysis, noise contribution, auto regressive model, AIC, optimal control

1. INTRODUCTION

A ship is equipped with an autopilot system to keep ship s course constant. However, when operating in heavy seas, since the course fluctuates considerably because of the roll motion caused by disturbances, it must be helped very much to have a comfortable navigation if fluctuations of both of the course and the roll can be reduced at a time by controlling the rudder. There are few cases of the analysis of the relation between a course-keeping system and the roll motion quantitatively on a small boat [1]. Firstly, the navigational system was upgraded and the experiment was carried out so that a random white noise signal was added to the rudder order signal to identify system dynamics. In order to analyze experimental data, a Multi-variate Auto Regressive (MAR) model was fitted to the recorded data using the minimum AIC estimate procedure [2,3]. From the estimated MAR model, useful tools for the statistical analysis, such as a power spectrum, a noise contribution and so on, can be obtained. As a result of the analysis, it was made clear that fluctuations of the roll was strongly influenced by rudder. Secondly, a new controller was designed, based on the information obtained from the analysis. This is a new type of autopilot which orders a control signal to the steering gear taking the roll motion into consideration. The new autopilot was designed using a modern control theory under a quadratic performance function with various weighting coefficients. Digital simulations were executed to evaluate the designed controller in order to make certain that a new type of autopilot functioned as designed. As results of simulations the new system had good performance compared with the original data.

2. EXPERIMENTAL S STEM

2.1 Training oat

Toyama National College of Maritime Technology (TNCMT) possesses some training ships. One of them, on which students of the Nautical Science Department practice on-board training, is named *Sazanami* in Photo.1. Table 1 shows principal dimensions of *Sazanami*.

Photo.1 Overview of training boat *Sazanami*

Table 1 Principal dimensions of *Sazanami*

Length	16 m
Breadth	4.10 m
Depth	1.22 m
Gross Tonnage	15 tons
Service speed	20.5 Knots
Propeller	FPP
Complement	Crew 2, Prof. 3, Students 20 Total 25

It is effectively used for the practice of ship handling, however, the characteristics of this boat can not be analyzed quantitatively because it was not equipped with a system to record navigational data. Moreover, it was impossible to control the steering gear from an external signal.

2.2 External unit and sensors

In order to solve above problems, the navigational system of *Sazanami* was upgraded. Photo.2 shows an external unit to utilize the ship s own steering system.

Photo.2 External unit for steering control

One of two control modes, the her own steering and the external CPU order, can easily selected by switching the mode selector. And to record ship s motion data such as rolling and pitching, it was equipped with Fiber Optical Gyro (FOG) as shown Photo.3.

Photo.3 Fiber Optical Gyro (FOG)

As a result, to record not only the data required for developing of a course keeping system but also ship s motion data and to control the steering gear by the order signal of an external computer also was realized.

3. STATISTICAL ANAL SIS OF S IP S D NAMICS

3.1 Identification

Before designing a new type of autopilot, in this section, properties of the ship s dynamics are examined from statistical point of view using the sea trial s data on *Sazanami*. The data are composed of rudder angle (RUD), yawing (AW) and roll rate (ROLL).

Fig.1 shows the corresponding responses of the AW and the time histories of the ROLL, when random ordered signal through the steering gear is added to the RUD.

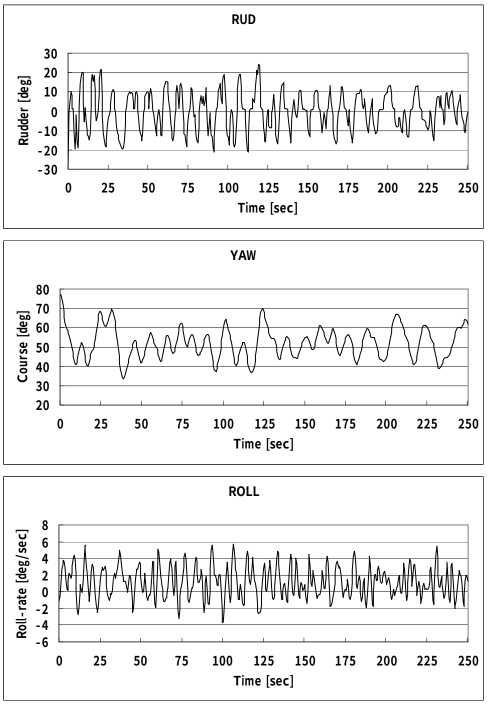

Fig.1 Time histories by random steering

The data length were 500 points sampled at 0.5 sec. In order to analyze these data, multi-variate AR model [2,3]

$$(n) = \sum_{m=1}^{M} A(m) \quad (n-m) + U(n), \qquad (1)$$

is fitted to the real data, using the minimum AIC estimate (MAICE) method [2]. Where (n) is a stationary state vector composed of the RUD, AW, and ROLL and U(n) denotes a white noise vector.

3.2 Statistical Analysis

It is necessary to analyze an influence of the RUD on the ROLL in order to design a new type of autopilot which takes account of the ROLL as shown in Fig.2.

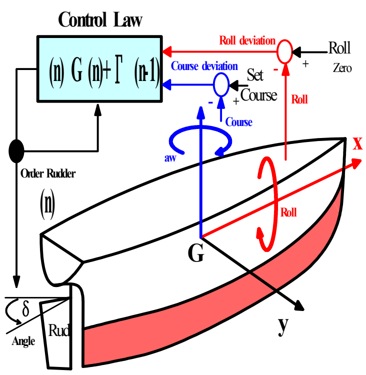

Fig.2 Concept of aw-Roll control by Rudder

In this case, it is useful to analyze using a power spectrum, a noise contribution and an impulse response. These are calculated from the estimated AR model [3,4].

The power spectrums of these three data are shown in Fig.3. Fig.4 shows the relative noise contributions.

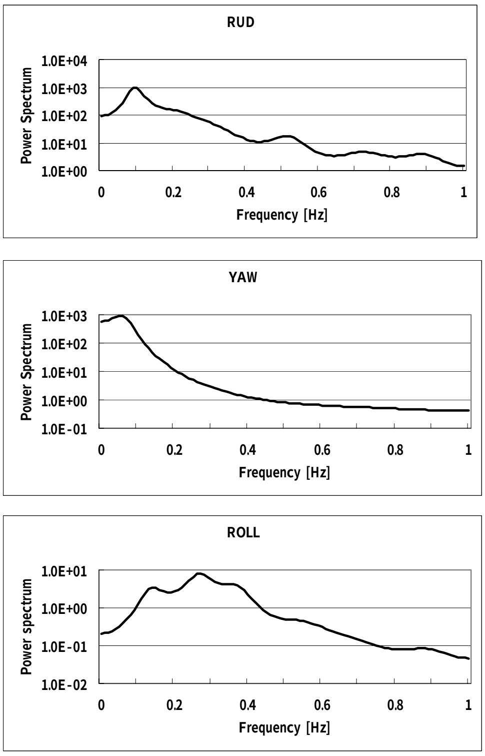

Fig.3 Power spectrum of RUD, AW and ROLL

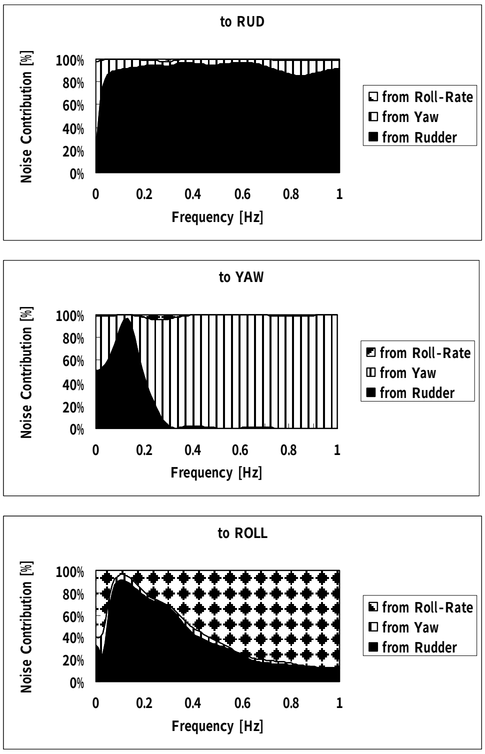

Fig.4 Noise Contribution to RUD, AW and ROLL

From Fig.3[RUD] and Fig.4[ROLL], around the frequency giving the peak of the spectrum of the RUD, the noise contribution of the RUD to the ROLL is very large. Fig.5 shows the impulse response from the RUD to the AW and to the ROLL.

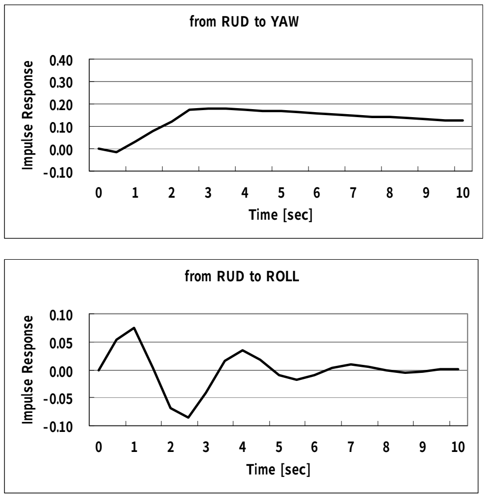

Fig.5 Impulse response from RUD to AW and ROLL

Observed the shape of Fig.5[AW], it is found that AW-RUD system has an integrator and it is seen in Fig.5[ROLL] that the ship lists to her inward direction at the first stage when the rudder is steered, the heel changes to the outward one at the next stage.

It is found that the rudder can control the roll motion.

4. AR MODEL FOR CONTROLLING

4.1 AR Controller

The model which is used for the proposed autopilot is a control type of multi-variate AR model [3]

$$(n) = \sum_{m=1}^{M} A(m) \quad (n-m) + \sum_{m=1}^{M} B(m) \quad (n-m) + U(n), \quad (2)$$

where (n) denotes a state vector whose components are the AW and ROLL and (n) denotes a control vector whose one, ordered rudder signal to steering gear.

In order to discuss in the framework of the modern control theory, the AR model is transformed to a state space representation as follows,

$$Z(n) = \Phi Z(n-1) + \Gamma \quad (n-1) + \quad (n)$$
$$(n) = HZ(n) \qquad (3)$$

Using this state space representation, an optimal controller

$$(n) = GZ(n)\,, \qquad (4)$$

under a quadratic performance function J_p

$$J_p = E\left[\sum_{n=1}^{p}\left\{ \quad (n)^t Q \quad (n) + \quad (n-1)^t R \quad (n-1)\right\}\right], \qquad (5)$$

is designed, where G denotes the optimal stationary gains, Q and R are appropriate weighting matrices to the state vector and the control one respectively [3].

4.2 Digital Simulations

In order to evaluate the proposed autopilot, digital simulations were carried out by adding a white noise to the estimated control type of AR model as follows,

$$Z(n) = \Phi Z(n-1) + \Gamma \quad (n-1) + \quad (n) \\ (n) = GZ(n) \qquad , \qquad (6)$$

where W(n) denotes white noise with appropriate variance which is the same value as the innovation covariance of the model (2) and (n) follows the optimal control law (4).

Fig.6 demonstrates the typical results of the simulations.

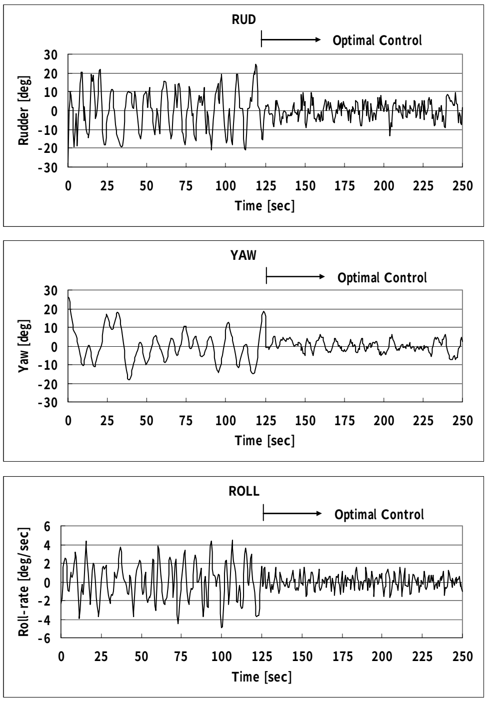

Fig.6 Results of simulations of the proposed autopilot using a white noise

The left half of Fig.6 shows time histories of the original data. And the right half of the figure demonstrates the results of simulations through the new autopilot considering the ROLL. It can be observed that the fluctuations of the ROLL through the proposed autopilot are smaller than that through the original data. Moreover, the motions of the AW through the proposed autopilot are also smaller than the original one.

Table 2 shows the results of the comparison of variances.

Table 2 Results of simulations

	Original Data	Optimal Control
Rudder [deg^2]	85.53	17.76
aw [deg^2]	72.39	9.44
Roll-rate [(deg/s)^2]	1.47	0.55

It is found that the proposed autopilot succeeds to reduce the variance of the fluctuations of the ROLL to about 1/3 by about 1/5 of the RUD.

5. CONCLUSIONS

In the first of this paper, the authors tried to identify a MAR to the ship s dynamics using the sea trial s data by an actual small training boat *Sazanami*. Using input-output data of the system, power spectrums, noise contributions and impulse responses were obtained through the estimated MAR model. As a result, characteristics of the system was found.

In the last half, a new type of autopilot taking into account of the roll information was designed using the modern multi-variate control theory. Lastly, digital simulations were carried out to evaluate the proposed autopilot. As results of simulations, a new type of autopilot had good performance compared with the original data.

ACKNOWLEDGMENTS

In the full-scale experiments to record navigational data, we received their large helpful supports from Capt. H.Kosugi and the crew of *Sazanami*. We express our heartfelt gratitude to them.

This research was supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Scientific Research (C)(2), No.16560705, 2004.

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