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A Study on an Anti-Rolling System Design of a Ship with the Flaps

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Roll stabilization systems for ships are employed to increase comfort for passengers, maintain full working capabilities for members of the crew and prevent cargo damage. In this paper, we have investigated the usefulness of active stabilizing system to reduce ship rolling under disturbances, using varied reaction of the flaps. In the proposed anti-rolling system for a ship, the flaps as the actuator are installed on the stern to reject rolling motion induced by disturbances such as wave. The action induced by flaps depends on power of disturbances and can take the ship balance. Especially, in this study we define the system parameters under the given system structure and design the controller to evaluate the usefulness of the proposed system.

Key Words : Ship Rolling, Flap, Anti-Rolling System, Stern, Wave, Disturbance

1. Introduction

In ship operation, the consequence of roll motion can seriously degrade the performance of mechanical and personnel effectiveness. Many studies for the roll stabilization system design have been performed and good results have been achieved, where the stabilizing fins, tanks, rudders are used (Kim, 2002 ; Koike, 1994, 1995 ; Mibasi, 1989 ; Otaka, 1993 ; Tanida, 1988, 1994 ; Yamaguchi and Shinkai, 1991). But, there exist many weak points, for examples, increasing of navigation resistance, ship control performance degradation and increasing of system complexity. To get rid of these problems, in this study we incorporate the flaps as the actuator to reduce rolling motion induced by disturbance such as wave. The actions induced by flaps which depending on power of disturbances can take the ship balance.

This type of anti-rolling system is a new one and it can be easily applicable to real world. So, in this study, we investigate usefulness of the proposed roll motion control system and evaluate system performance through simulation and experimental studies.

2. Modeling

In this study, the controlled system, the small vessel which was made by ourselves (Length :0.75m, Breadth :0.30m), is considered as illustrated in Fig. 1 and 2. In this test model, for the sake of simplicity, let us describe roll-moment equation for surface ship as follows :

$$I\ddot{\theta}+R\dot{\theta}+W\overline{GM}\sin\theta=T-T_F \qquad (1)$$

where,

I : total inertia moment of the ship
θ : roll angle
R : damping coefficient
W : displacement of the ship
$\overline{GM}$: longitudinal metacentric height
T : moment induced by disturbance like wave
T_F : moment generated by anti-rolling flap

Especially, the moment T_F which is induced by the flaps to cope with the disturbance is represented as follows :

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$$\begin{aligned} T_F &= F_y \cdot r \\ &= \frac{1}{2}\rho V^2 A \frac{dC_y}{d\alpha_F}\alpha_F r \end{aligned} \tag{2}$$

where,

F_y : lift force or stabilizing force
ρ : fluid density
V : ship speed
C_y : lift coefficient
A : flap area
α_F : flap angle
r : distance of the flap to the center line of the gravity of the ship

In the control system considered in this study, the flaps are activated by motor and other devices as illustrated in Fig. 2. As a matter of convenience, we describe the actuator system as following equation :

$$I_F\ddot{\alpha}_F + R_F\dot{\alpha}_F + K_F\alpha_F = K_m v \tag{3}$$

where,

I_F : total inertia moment of actuator
R_F : damping coefficient of the actuator
K_F : stiffness
K_m : torque constant of motor
v : motor input voltage

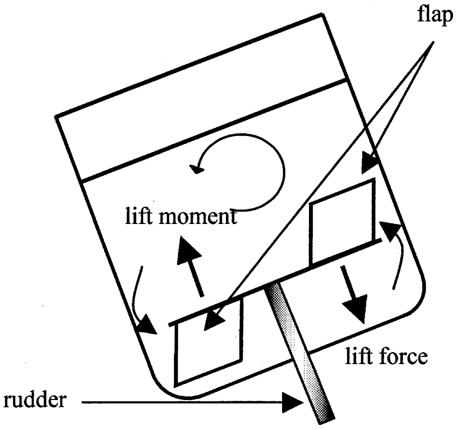


Fig. 1 An anti-rolling system with flaps

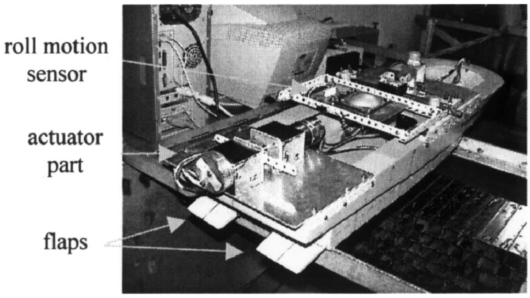


Fig. 2 Control system apparatus for experiment

3. Parameter Estimation

Parameter estimation from free rolling motion

There exist many parameters in Eqs. (1), (2) and (3), and it is too difficult to determine them exactly. Therefore, in this study, we estimate the parameters using experiment and simulation techniques.

At first, we estimate the unknown parameters which are given in Eq. (1) from the free rolling motion of the controlled ship. For this, we rewrite Eq. (1) as following :

$$I\ddot{\theta} + R\dot{\theta} + W\overline{GM}\,\theta = 0 \tag{4}$$

and

$$\begin{aligned} \ddot{\theta} &= -I^{-1}W\overline{GM}\,\theta - I^{-1}R\dot{\theta} \\ &= -\alpha W\theta - \beta\dot{\theta} \end{aligned} \tag{5}$$

where

$$\alpha = I^{-1}\overline{GM},\ \beta = I^{-1}R \tag{6}$$

Then, we rewrite Eq. (5) as

$$\begin{aligned} &\ddot{\theta} + 2\zeta\omega_n\dot{\theta} + \omega_n^2\theta = 0 \\ &\omega_n = (\alpha W)^{1/2},\ \zeta = \beta/2(\alpha W)^{1/2} \end{aligned} \tag{7}$$

From these relations, we can see that the unknown parameters are estimated using the free rolling motion of the ship shown in Fig. 3. For example, in Fig. 3, if we consider the vibration period λ and damping ratio ρ, following relations are obtained using Eq. (7).

$$\lambda = 2\pi/(1-\zeta^2)^{1/2}\omega_n,\ \rho = \exp(-2\pi\zeta/(1-\zeta^2)^{1/2}) \tag{8}$$

From these relations, the unknown parameters αW and are β determined as follows :

$$\alpha W = [4\pi^2 + (\ln\rho)^2]/\lambda^2,\ \beta = 2(-\ln\rho)/\lambda \tag{9}$$

Using this result, other unknown parameters may be calculated also.

In this study, from the Fig. 3, the period and damping ratio are calculated as following :

$$\lambda = 1.1600,\ \rho = 0.810 \tag{10}$$

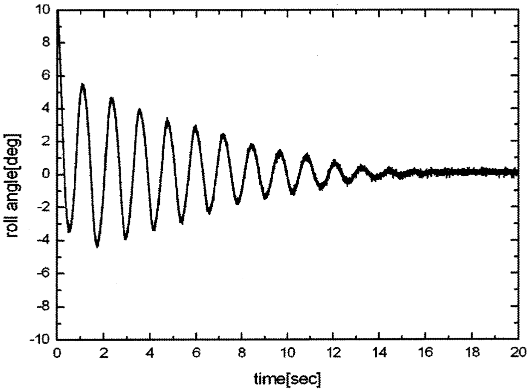


Fig. 3 Free rolling motion of the controlled ship

Therefore we have

$$\alpha=10.4890,\ \beta=0.3633 \tag{11}$$

And, the moment of inertia and metercenteric height are obtained using the above result and estimation method as follows:

$$I=1.5\times10^{-3}[\mathrm{kgm}^2],\ \overline{GM}=1.25\times10^{-3}[\mathrm{m}] \tag{12}$$

Using these results, we introduce the comparison study. Fig. 4 shows the simulation (dotted line) and experimental (solid line) results. From this figure, it is clear that the estimated parameters are useful and persuadable to analyze the dynamics of controlled system.

Parameter estimation from spectral analysis

In Eq. (1), several parameters are defined using the estimation method except the parameters described in Eq. (2). We may try to estimate them using the relation between the flap angle and roll motion which is induced by activating the flaps in the various frequencies (0.02454~3.1459 [rad/sec]). If we assume that the disturbance input $T=0$, then Eq. (1) may be rewritten as following:

$$\begin{aligned} I\ddot{\theta}+R\dot{\theta}+W\overline{GM}\theta&=-T_F\\ &=-\frac{1}{2}\rho V^2 A\frac{dC_y}{d\alpha_F}r\alpha_F\\ &=-K_\alpha\alpha_F \end{aligned} \tag{13}$$

$$K_\alpha=\frac{1}{2}\rho V^2 A\frac{dC_y}{d\alpha_F}r$$

If the ship speed is constant, it may be assumed that the parameter K_α is constant.

Therefore, it is clear that if we analyze the roll motion responses activated by flaps, the unknown parameter K_α may be estimated.

Figure 5 shows the rolling motion induced by the flap movement as shown in Fig. 6, when the

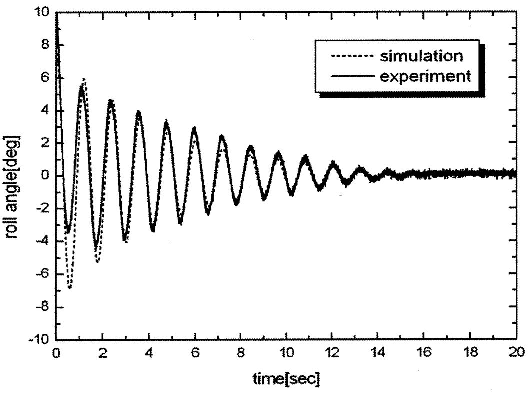


Fig. 4 Rolling motions of the open-loop systems

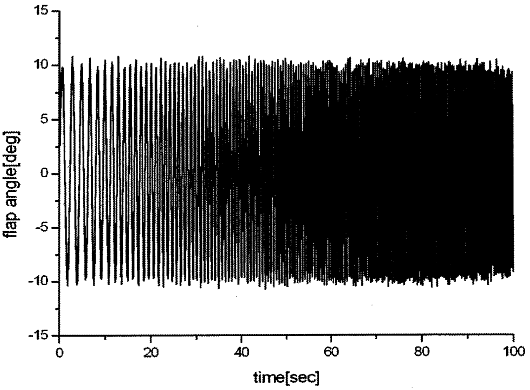


Fig. 5 Flap angle transition pattern (0.004~0.5Hz)

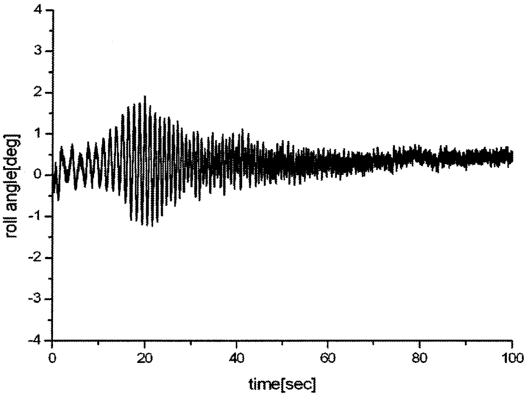


Fig. 6 Roll-motion responses to the flap movement given in Fig. 5

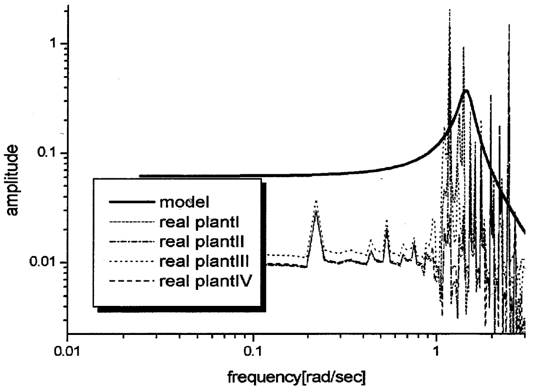


Fig. 7 Frequency responses of a model and real plants

ship speed is 0.248[m/s]. Same works were performed for several times in the various ship speeds. From the spectral analysis, we calculate frequency responses of the real plants such that a model is obtained as shown in Fig. 7.

From the experimental results as shown in Fig. 7, the defined parameter in the Eq. (13) is calculated as following:

$$K_\alpha = 0.1301 \tag{14}$$

Parameter estimation of actuator system

We try to identify the unknown parameters appeared in the actuator system which is made up motor and flaps. For this, we rewrite Eq. (3) as follows:

$$\ddot{\alpha}_F = \frac{R_F}{I_F}\dot{\alpha}_F - \frac{K_F}{I_F}\alpha_F + \frac{K_m}{I_F}v \tag{15}$$

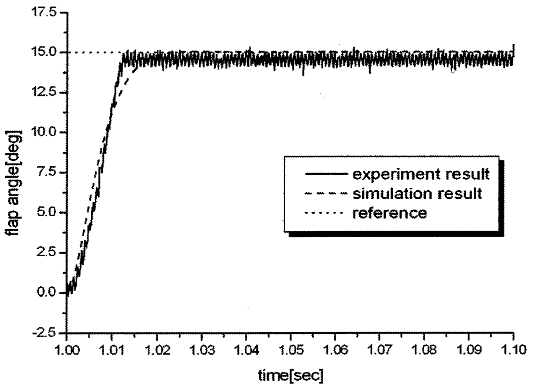


Fig. 8 Step responses of real plant and model

The uncertain parameters are estimated using the step responses obtained from experiment and simulation as shown in Fig. 8. From this, the estimated parameters are given as follows:

$$\frac{R_F}{I_F} = 19.55,\ \frac{K_F}{I_F} = 0.001,\ \frac{K_m}{I_F} = 145.00 \tag{16}$$

4. Controller Design

To obtain a basic understanding of the proposed anti-rolling system with flaps, we design a controller based on robust control theory.

If we use the parameter estimation results which are illustrated in previews section, then the overall control system representation is given as follows:

$$\begin{aligned} \dot{x} &= Ax + B_w w + Bu \\ y &= Cx + Du \end{aligned} \tag{17}$$

where, the state $x = [\dot{\theta}\ \theta\ \dot{\alpha}_F\ \alpha_F]^T$, w denotes disturbance input, T and u is the voltage input to the motor.

And,

$$A = \begin{bmatrix} -R/I & -W\overline{GM}/I & 0 & -K_F/I \\ 1 & 0 & 0 & 0 \\ 0 & 0 & -R_F/I_F & -K_F/I_F \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

$$B_w = \begin{bmatrix} 1/I \\ 0 \\ 0 \\ 0 \end{bmatrix},\ B = \begin{bmatrix} 0 \\ 0 \\ -K_m/I_F \\ 0 \end{bmatrix} \tag{18}$$

$$C = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},\ D = [0\ 0]$$

Using these relationships, the controller is calculated as following based on the robust control theory (H_∞ control),

$$\begin{aligned} \dot{x}_c &= A_c x_c + B_c y \\ u &= C_c x_c + D_c y \end{aligned} \tag{19}$$

where,

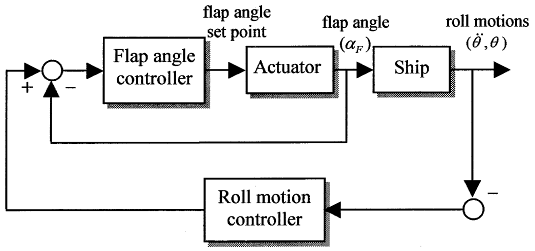


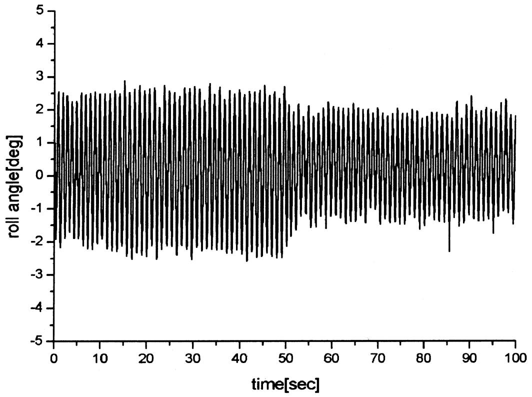
Fig. 9 Schematic diagram of the control system

$$
\begin{aligned}
A_c &= \begin{bmatrix} -0.0197 & 0.0529 & 0.7761 & 1.7169 \\ -0.0703 & -0.3847 & -0.2006 & -0.3247 \\ -0.0578 & -0.1500 & -0.5587 & -0.1038 \\ 1.0134 & 6.0507 & -2.0574 & -0.0799 \end{bmatrix} \\
B_c &= \begin{bmatrix} -0.0499 & -0.1341 \\ -0.3197 & -0.1814 \\ 0.1014 & -0.6632 \\ 6.6819 & -0.2277 \end{bmatrix} \\
C_c &= [0.1520 \quad 1.0013 \quad 6.0268 \quad 12.0675] \\
D_c &= [0 \quad 0]
\end{aligned}
\tag{20}
$$

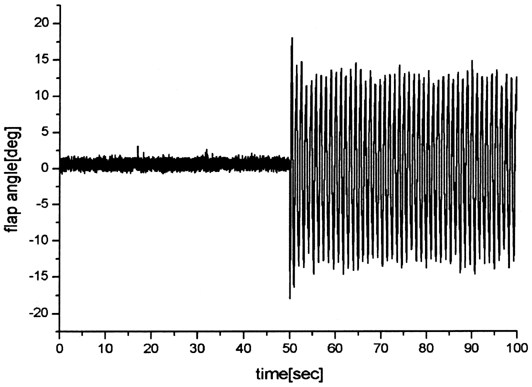
5. Experiments

Let us explain about composition of experiment for the anti-rolling system as illustrated in Fig. 2, where the flaps are incorporated to suppress the ship roll motion induced by disturbance such as wave. If the rolling motion is induced by disturbance, then the dynamics of flaps is controlled by motor based on control algorithm to suppress the ship rolling.

For our experiment, we synthesize control system as illustrated in Fig. 9 using the controller given in Eq. (19). In our experimental apparatus as illustrated in Fig. 2, a moving mass is installed on the upper deck of the model ship to activate roll-motion as disturbance. We introduce the experiment results as shown in Fig. 10~Fig. 12. In each figure, the (a) denote roll-motions activated by moving mass and suppressed by flaps, and the (b) illustrate behavior of flaps which activate the disturbance rejection power. The experiments were performed for several times in the various ship speeds.



(a) Roll-motion



(b) Behavior of flap

Fig. 10 Disturbance rejection experiment (control action is activated at 50[sec], when the ship speed is 0.447[m/sec])

In this study, we have evaluated the control performance(reduction rate) using following equation(Fossen, 1995):

$$\text{Reduction}(\%) = 100 \times \frac{\text{OP} - \text{CLP}}{\text{OP}} \tag{21}$$

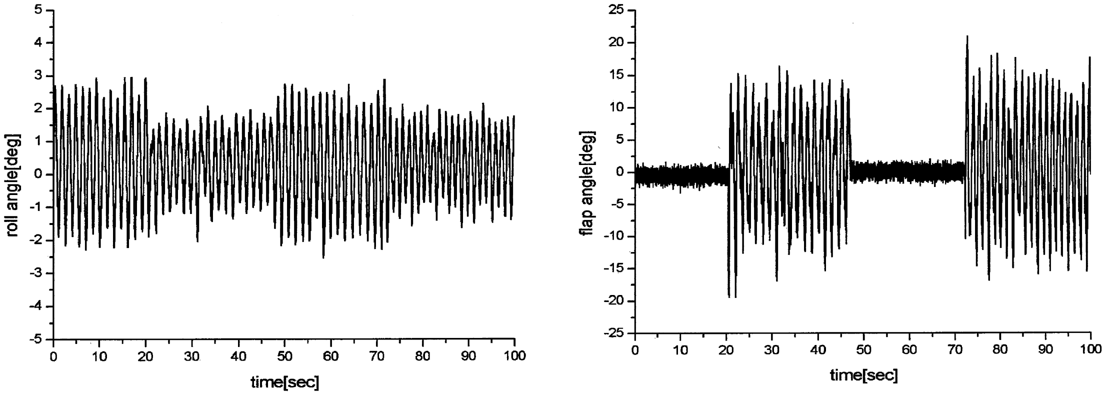
where, CLP and OP are defined as following, respectively :

CLP : =the standard deviation of the closed-loop system(controlled case)

OP : =the standard deviation of the open-loop system(uncontrolled case).

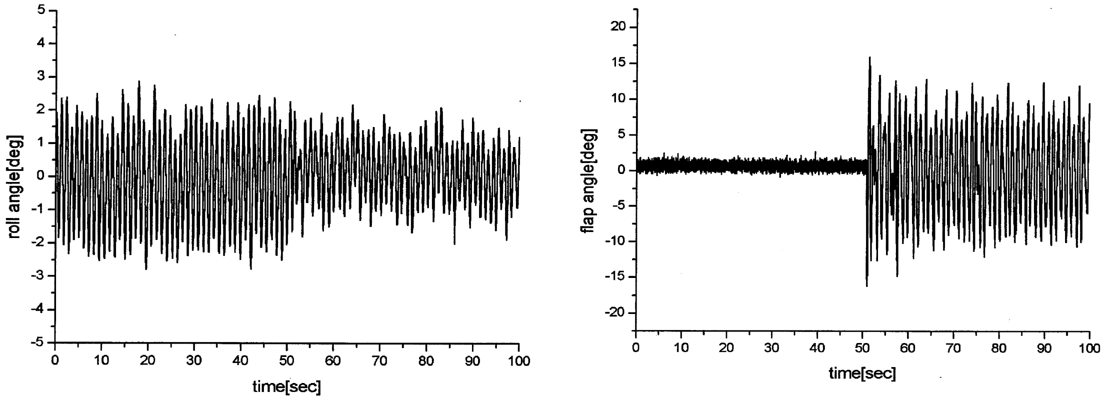
Using the Eq. (21), the reduction rate was calculated and about 40~55% reduction effect was obtained over the varying ship speed.

From this result, it is clear that if we use the proposed control system to design anti-rolling system, we can suppress the rolling motion induced by the disturbance and achieve desirable control objectives.



(a) Roll-motion (b) Behavior of flap

Fig. 11 Disturbance rejection experiment (control action is activated at 20[sec] and 70[sec], when the ship speed is 0.518[m/sec])



(a) Roll-motion (b) Behavior of flap

Fig. 12 Disturbance rejection experiment (control action is activated at 50[sec], when the ship speed is 0.552[m/sec])

6. Concluding remarks

In this study, we have investigated the usefulness of active stabilizing system to reduce ship rolling under disturbances, using the reaction of the flaps. The parameters incorporated in the control system have been identified through experiments and simulations. In the proposed anti-rolling system for the ship, the flaps as the actuator are installed on the stern to reject rolling motion. The action induced by flaps depended on the power of disturbances can take the ship balance. Especially, in this study, we designed the controller to evaluate the performance of the proposed system. It is verified that more effective control system construction can be available from the experiment results and efficient system construction as well as control performance elevation is possible. In this study, a basic approach has been performed to design an anti-rolling system where a simple type of flap has been used to activate the control power. Therefore, it is necessary that we introduce and design the various types of flaps and actuator system to improve the control performance.

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