Anti-Rolling System for Ships with Self-Powered Active Control*

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The authors propose a self-powered active control system that realizes active vibration control using energy regenerated by an energy regenerative damper and does not require external energy. In this study, self-powered active control is applied to an anti-rolling system for ships. The motor is required to act as an energy regenerative damper and an actuator, since the anti-rolling system is composed of one motor. The new control scheme that realizes self-powered active control with a single motor is proposed. Through numerical simulations and experiments using a basic model, the performance of the proposed system is examined. The results indicate that self-powered active control can be achieved in the anti-rolling system.

Key Words: Ship, Vibration Control, Dynamic Absorber, Vibration Control Device, Active Control, Energy Regeneration

1. Introduction

Suppression of rolling motion of a research vessel is important because the rolling motion prevents the crew to carry out research activities in off-shore areas. To meet this demand, a mass damper with pendulum suspension mechanism, has been developed and installed in a ship. This damper reduces the rolling motion of the ship by the movement of a mass controlled by an electric motor. This damper is called an anti-rolling system for ships. To examine its suppression performance, sea experiments were carried out. The results showed that rolling motion of the ship with the anti-rolling system was reduced compared with that of the ship without the anti-rolling system⁽¹⁾.

The authors have proposed a self-powered active vibration control system^{(2),(3)}. This system produces control force using regenerated vibration energy and requires no external energy. In this paper, the authors propose the application of self-powered active control to the anti-rolling system for ships. The proposed system can operate the anti-rolling system without energy supply. Previous self-powered active control systems^{(2),(3)} have two actuators: one actuator produces control force while the other actuator regenerates vibration energy. However, the anti-rolling system proposed here contains only one motor. To realize self-powered active control in the anti-rolling system, the motor is required to produce control force while regenerating vibration energy.

The authors propose a control scheme to enable the self-powered active control with a single motor and examine its feasibility through numerical simulation using specifications of a real ship and experiments on a basic model.

2. Ship with Anti-Rolling System

2.1 Model of the ship

Figure 1 shows the model of the ship with the anti-rolling system. The anti-rolling system has a pendulum mechanism and contains a spring element, a damping element, and an actuator. The state equations are shown in Eqs. (1) to (5), where ϕ , z_d , f and T are roll angle of the ship, stroke of the moving mass, output of actuator and moment of the wave

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Fig. 1 Anti-rolling system for ships

force, respectively. The moment of the wave force is called wave-exciting moment. The parameters used in Eqs. (1) - (5) are explained in Table 1.

$$\dot{X} = A \cdot X + B_1 \cdot T + B_2 \cdot f \quad (1)$$

$$X = [\phi \quad z_d \quad \dot{\phi} \quad \dot{z}_d]^T \quad (2)$$

$$A = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ -\omega_s^2 & \frac{m_d}{m_s \kappa^2} (g + \omega_d^2 l) \\ \omega_s^2 l + g & -\left[\left(1 + \frac{m_d l^2}{m_s \kappa^2} \right) \omega_d^2 + \frac{m_d g l}{m_s \kappa^2} \right] \\ 1 & 0 \\ 0 & 1 \\ -2\omega_s \zeta_s & \frac{m_d l}{m_s \kappa^2} 2\zeta_d \omega_d \\ 2l\zeta_s \omega_s & -2\zeta_d \omega_d \left(1 + \frac{m_d l^2}{m_s \kappa^2} \right) \end{bmatrix} \quad (3)$$

$$B_1 = \begin{bmatrix} 0 & 0 & \frac{1}{m_s \kappa^2} & -\frac{l}{m_s \kappa^2} \end{bmatrix}^T \quad (4)$$

$$B_2 = \begin{bmatrix} 0 & 0 & -\frac{l}{m_s \kappa^2} & \frac{1}{m_d} + \frac{l^2}{m_s \kappa^2} \end{bmatrix}^T \quad (5)$$

2.2 Design of active controller

The active controller is designed from the linear quadratic optimal control theory. Performance index, J , is determined as follows. The controlled values are roll of the ship and stroke of the anti-rolling system. In the anti-rolling system, the stroke of the moving mass is limited; therefore, the stroke of the moving mass, z_d , should be controlled.

$$J = \int_0^\infty (10^{15} \cdot \phi^2 + 4.8 \times 10^{11} \cdot z_d^2 + f^2) dt \quad (6)$$

2.3 Wave-exciting moment

We simulate the performance of the anti-rolling system when the ship is at sea of seastate 5. Seastate 5 describes the condition of sea in which the wave height is from 2.5 to 4.0 m. Power spectral density of the wave-exciting moment is shown in Fig. 2. The majority of frequencies of the wave-exciting moment is around the natural frequency of roll.

2.4 Model of the actuator

In the anti-rolling system, an actuator produces force via a rack and pinion gear. To simplify a model

Table 1 Specifications of the dynamics model

Description	Symbol	Value
Mass of ship	m_s	9500 t
Mass of moving weight	m_d	100 t
Natural angular frequency of roll	ω_s	0.52 rad/s
Natural angular frequency of anti-rolling system	ω_d	0.52 rad/s
Damping ratio of roll	ζ_s	0.09
Damping ratio of anti-rolling system	ζ_d	0.2
Radius of gyration	κ	7.3 m
Distance between centers of gravity and installation place of system	l	11.7 m
Gravity	g	9.8 m/s ²

Fig. 2 Power spectral density of wave exciting moment

of electric circuits of the motor, we use a DC motor as an actuator. The following equations depict the relationships in the actuator.

$$e_i = -\varphi \cdot \dot{z}_d \quad (7)$$

$$f = \varphi \cdot i, \quad (8)$$

where e_i , $\dot{z}_d$, f and i are induced voltage, stroke velocity of the moving mass, output of the actuator and electric current of the armature, respectively. Inductance is not considered in this model. The proportionality constant, φ , is inherent to the actuator and is called the motor constant. When both terminals of the actuator are connected to each other, the actuator act as a typical viscous damper. The output of actuator is derived as

$$f = -\frac{\varphi^2}{r} \cdot \dot{z}_d, \quad (9)$$

where r is resistance of the armature. Damping coefficient of this actuator is called equivalent damping coefficient, c_{eq} , and is defined by

$$c_{eq} = \frac{\varphi^2}{r}. \quad (10)$$

3. Energy Balance Analysis

3.1 Possibility of regeneration

When the actuator is connected to the power source whose voltage is e , output of the actuator is obtained by

$$f = \frac{\varphi \cdot (e - \varphi \cdot \dot{z}_d)}{r}. \quad (11)$$

To obtain the desired force, f^* , the following voltage should be supplied:

Fig. 3 Energy consumption in frequency domain

$$e = \frac{f^* \cdot r}{\varphi} + \varphi \cdot \dot{z}_d \quad (12)$$

When output of the actuator is equivalent to the desired force, power consumption E_c is

$$\begin{aligned} E_c &= i \cdot e \\ &= \frac{f}{\varphi} \cdot \left(\frac{f \cdot r}{\varphi} + \varphi \cdot \dot{z}_d \right) \\ &= \left(\frac{f^2}{c_{eq}} + f \cdot \dot{z}_d \right). \end{aligned} \quad (13)$$

When we define γ as

$$\gamma = \frac{f}{-c_{eq} \cdot \dot{z}_d}, \quad (14)$$

power consumption is expressed as

$$E_c = c_{eq} \cdot \dot{z}_d^2 \cdot \gamma \cdot (\gamma - 1). \quad (15)$$

We call γ a mode variable. It is found that power consumption assumes to take a negative value when

$$0 < \gamma < 1. \quad (16)$$

3.2 Average power consumption

The average power consumption $\bar{E}_c$ is obtained as

$$\bar{E}_c = \lim_{\tau \rightarrow \infty} \frac{1}{\tau} \int_0^\tau \left(\frac{1}{c_{eq}} f^2 + f \cdot \dot{z}_d \right). \quad (17)$$

When power spectral density of disturbance, response gain from disturbance to control input, that from disturbance to stroke velocity, phase angle of control input, and that of stroke velocity are symbolized by P_0 , G_f , $G_{\dot{z}_d}$, Φ_f and $\Phi_{\dot{z}_d}$, respectively, the average power consumption is derived as

$$\bar{E}_c = \frac{1}{\pi} \int_0^\infty \varepsilon(\omega) d\omega, \quad (18)$$

where

$$\begin{aligned} \varepsilon(\omega) &= \left(\frac{1}{c_{eq}} G_f^2(\omega) + G_f(\omega) \cdot G_{\dot{z}_d}(\omega) \right. \\ &\quad \left. \cdot \cos(\Phi_f(\omega) - \Phi_{\dot{z}_d}(\omega)) \right) \cdot P_0(\omega). \end{aligned} \quad (19)$$

3.3 Energy balance

Figure 3 shows power consumption $\varepsilon(\omega)$ when equivalent damping coefficients of the actuator are 45 kN/m/s and 225 kN/m/s, respectively. Power spectral density $P_0(\omega)$ is the same as that shown in Fig. 2. It is found that the power consumption when $c_{eqa} = 225$ kN/m/s becomes negative in the wide frequency range, while the consumption when $c_{eqa} = 45$ kN/m/s becomes positive. Figure 4 indicates the average

Fig. 4 Average power consumption

power consumption $\bar{E}_c$. The horizontal axis and the vertical axis represent equivalent damping coefficient and the average power consumption, respectively. The average power consumption becomes smaller as the equivalent damping coefficient becomes larger. The former becomes less than zero when the latter is greater than 60 N/m/s. This indicates that the motor whose equivalent damping coefficient is greater than 60 N/m/s regenerates more energy than it consumes. This regenerated energy results from the energy of wave.

4. Self-Powered Active Control

4.1 Model of the system

In energy balance analysis, it is assumed that the voltage of the power source can be controlled continuously. However, voltage of a practical power source such as a battery or a condenser cannot be controlled continuously. In this paper, we explain the control scheme when the condenser is utilized as an accumulator. The circuit of the actuator includes relay switches and a variable resistor controlled by the computer. The relay switches change the direction of electric current and the variable resistor controls the amount of electric current.

4.2 Control method

The present control methods are explained for the following three modes:

1. $0 < \gamma < 1$
2. $1 \leq \gamma$
3. $\gamma \leq 0$

In the mode 1, the power consumption becomes negative. This mode is called an energy regeneration mode. The actuator can produce the desired control force with energy regeneration. When the condenser voltage is e and the resistance of the variable resistor is r_{var} , output of the actuator is obtained as follows:

$$\begin{cases} f = \varphi \cdot \frac{(\sigma \cdot e - \varphi \cdot \dot{z}_d)}{r + r_{var}} \\ r_{var} = \left| \frac{\varphi}{f^*} (\sigma \cdot e - \varphi \cdot \dot{z}_d) \right| - r, \end{cases} \quad (20)$$

where

$$\begin{cases} \sigma = 1 (\dot{z}_d \geq 0) \\ \sigma = -1 (\dot{z}_d < 0). \end{cases} \quad (21)$$

However when the amount of induced voltage is lower than the condenser voltage, the regenerated energy cannot be transferred to the condenser. Then, the actuator stops energy regeneration and acts as a typical viscous damper. The damping coefficient is changed by the variable resistor. The output of the actuator is shown as follows:

$$\begin{cases} f = \frac{-\varphi^2 \cdot \dot{z}_d}{r + r_{\text{var}}} \\ r_{\text{var}} = \left| \frac{-\varphi^2}{f^*} \dot{z}_d \right| - r \end{cases} \quad (22)$$

In mode 2, the actuator encourages damping force using the energy accumulated in the condenser. This mode is called brake mode. Equation (23) shows output of the actuator in this mode:

$$\begin{cases} f = \varphi \frac{(-\sigma \cdot e - \varphi \cdot \dot{z}_d)}{r + r_{\text{var}}} \\ r_{\text{var}} = \left| \frac{\varphi}{f^*} (-\sigma \cdot e - \varphi \cdot \dot{z}_d) \right| - r \end{cases} \quad (23)$$

However, when

$$\left| \frac{\varphi}{f^*} (-\sigma \cdot e - \varphi \cdot \dot{z}_d) \right| - r < 0, \quad (24)$$

the resistance of the resistor is required to be less than zero. The resistor cannot take a negative value; therefore, the resistance is assigned to be zero. In this situation, the actuator cannot generate the desired force.

In mode 3, the actuator accelerates the mass using the stored energy. This mode is called the drive mode. Output of the actuator is shown in the following equation:

$$\begin{cases} f = \varphi \cdot \frac{\sigma \cdot e - \varphi \cdot \dot{z}_d}{r + r_{\text{var}}} \\ r_{\text{var}} = \left| \frac{\varphi}{f^*} (\sigma \cdot e - \varphi \cdot \dot{z}_d) \right| - r \quad (\text{when } r_{\text{var}} \geq 0). \\ r_{\text{var}} = 0 \quad (\text{when } r_{\text{var}} < 0) \end{cases} \quad (25)$$

When the condenser voltage is lower than the induced voltage, the induced current flows into the condenser. To prevent this backflow, the condenser is insulated from the actuator. In this mode, output of the actuator becomes zero. It cannot follow the desired force. Figure 5 presents the electric circuits corresponding to each mode when $\dot{z}_d \geq 0$.

4.3 Procedure of control

The flow-chart of self-powered active control is shown in Fig. 6. At first, the controller calculates the desired control input from the state variables. Then, it determines the mode and value of the resistor from condenser voltage and stroke velocity. Relay switches change the circuit and the actuator produces control force.

Fig. 5 Electric circuits of the actuator

Fig. 6 Flowchart of self-powered active control

5. Numerical Simulations

5.1 Conditions of simulation

Numerical simulations of the ship with the anti-rolling system were carried out. The data of the wave-exciting moment shown in Fig. 2 are utilized. Simulation time is 1200 seconds. The capacity of the condenser is 1.0 F and its initial voltage is 0 V.

5.2 Control input

Figure 7 presents the actuator force and its desired force from 0 seconds to 300 seconds. At first, the actuator force could not follow the desired force because sufficient energy was not accumulated in the condenser. However, after 150 seconds, the actuator force followed the desired force. This figure indicates that the system reaches active control only with the regenerated energy.

5.3 Condenser voltage

Figure 8 shows the condenser voltage. It reaches around 1500 V at 1200 seconds with fluctuation. In the regeneration mode, it increases, while in the brake or the drive mode, it decreases. This movement generates the fluctuation.

5.4 Roll of ship

Transmissibilities of roll to the wave-exciting moment are shown in Fig. 9. The line with squares represents the system with self-powered active

Fig. 7 Output of the actuator compared with its desired force

Fig. 8 Condenser voltage

Fig. 9 Transmissibility of roll to wave exciting force

control and line with triangles represents the system without control. The transmissibilities were obtained from the ratio of the square root of the power spectral density of roll to that of the wave-exciting moment. The system without control indicates the condition under which the moving mass is fixed to the ship. It is found that the ship with self-powered active control has better performance than that without control.

6. Experiments on Basic Model

6.1 Experimental setup

To confirm the performance of self-powered active vibration control, experiments on the basic model were carried out. The configuration and a photograph of the experimental setup are shown in Figs. 10 and 11, respectively. The main mass was connected to the base by leaf springs. The base was

Fig. 10 Configuration of the experimental setup

Fig. 11 Schematic view of the experimental setup

shaken in the horizontal direction by an electric vibrator. A dynamic damper was located on the main mass. The moving mass of the dynamic damper contained a DC motor that generated control force through rack and pinion gears. State equations are shown in Eqs. (26) to (31). Relative displacement of the main mass to the base and that of the moving mass to the main mass are represented by z_s and z_d , respectively:

$$\dot{X} = A \cdot X + B_1 \cdot \ddot{x}_0 + B_2 \cdot f \quad (26)$$

$$X = [z_s \ z_d \ \dot{z}_s \ \dot{z}_d]^T \quad (27)$$

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\omega_s^2 & \mu \cdot \omega_d^2 & -2 \cdot \omega_s^2 \cdot \zeta_s & 0 \\ \omega_s^2 & -\omega_d^2 \cdot (1 + \mu) & 2 \cdot \omega_s^2 \cdot \zeta_s & -2 \cdot \mu \cdot \omega_d \cdot \zeta_d \\ & & & -2 \cdot \omega_d \cdot \zeta_d \cdot (1 + \mu) \end{bmatrix} \quad (28)$$

$$B_1 = [0 \ 0 \ -1 \ 0]^T \quad (29)$$

$$B_2 = \begin{bmatrix} 0 & 0 & -\frac{1}{m_s} & \frac{1}{m_d} \cdot (1 + \mu) \end{bmatrix}^T, \quad (30)$$

where

Fig. 12 Variable resistor

$$\mu = \frac{m_d}{m_s} \quad (31)$$

Values of the state variables were estimated by the observer from values measured by a tachogenerator of the motor and an accelerometer attached to the main mass. The variable resistor used in experiments is shown in Fig. 12. In this resistor, 15 fixed resistors were connected in series and there were short-cut circuits in parallel to each resistor. These short-cut circuits were switched by relay switches. By controlling the relay switches, the resistor could change its value. It could take 15 values; 0.0, 3.1, 5.1, 8.1, 13.4, 18.1, 28.2, 38.5, 48.9, 59.6, 79.1, 89.4, 145.9, 236.2, and 330.2 Ω . Furthermore, by switching off all the relay switches, it could insulate the circuit. The values of the parameters of experimental devices are shown in Table 2. The equivalent damping coefficient of the motor is 10.3 N/m/s and the natural frequency of the main system and that of the dynamic damper system are 5.0 Hz. Values of these parameters do not correspond to the specifications of the ship with the anti-rolling system.

6.2 Design of controller

The active controller is designed on the basis of the linear quadratic optimal control theory. Performance index, J , is determined as follows:

$$J = \int_0^\infty (1.2 \cdot \ddot{x}^2 + 1.5 \times 10^5 \cdot z_d^2 + f^2) dt. \quad (32)$$

Acceleration of the main mass and stroke of the dynamic damper are controlled values. The acceleration of the main mass is given by

$$\ddot{x} = -2 \cdot \omega_s \cdot \zeta_s \cdot \dot{z}_s - \omega_s^2 \cdot z_s + \mu \cdot (2 \cdot \omega_d \cdot \zeta_d \cdot \dot{z}_d + \omega_d^2 \cdot z_d) - \frac{1}{m_s} \cdot f. \quad (33)$$

6.3 Disturbance

The vibrator generated vibration for 20 seconds and the system started self-powered active control at 5 seconds after the excitation began. Power spectral density of base acceleration is presented in Fig. 13. Similar to the simulations, the majority of the frequencies of the disturbance is around the natural frequency of the main system.

6.4 Energy balance analysis

Power consumption of the experimental system is obtained from Eqs. (18) and (19). Figure 14 shows the energy consumption in the frequency domain, that is, $\varepsilon(\omega)$. The energy consumption becomes less than zero in the range around the natural frequency. Average power consumption is obtained from the integration

Table 2 Specifications of experimental setup

Description	Symbol	Value
Main mass	m_s	5.75 kg
Mass of moving weight	m_d	0.62 kg
Natural angular frequency of main system	ω_s	31.4 rad
Natural angular frequency of dynamic damper	ω_d	31.4 rad
Damping ratio of main system	ζ_s	0.01
Damping ratio of dynamic damper	ζ_d	0.21
Motor constant	ϕ	11 V/m/s (= N/A)
Inside resistance	r	11.8 Ω
Capacity of condenser	c	0.08 F

Fig. 13 Power spectral density of base acceleration (Experiments)

Fig. 14 Energy consumption in frequency domain (Experiments)

of $\varepsilon(\omega)$ with respect to ω . It is to be -18.6 mW.

6.5 Motor output

Output of the motor and its desired value from 0 to 5 seconds are presented in Fig. 15. Motor output is estimated from the electric current of the motor. The output approximately followed its desired value. The slight difference between the output and its desired value is due to the shortage of accumulated energy and the modeling error of experimental devices.

6.6 Energy flow

Figure 16 shows energy transferred to the condenser. Negative value means power charged to the condenser and positive value represents power discharged. The total amount of energy supplied to the actuator and transferred to the condenser was 62.7 mJ

Fig. 15 Output of the motor compared with its desired force (Experiments)

Fig. 16 Time history of consumed and regenerated power (Experiments)

and 243.8 mJ, respectively.

6.7 Condenser voltage

Figure 17 indicates voltage of the condenser. Initial voltage was 0 V and reached 2.06 V at 15 seconds. The energy accumulated in the condenser, E_{store} , is obtained by

$$E_{\text{store}} = \frac{1}{2} \cdot c \cdot e^2, \quad (34)$$

where c is the capacity of the condenser. From this equation, it is found that the total amount of accumulated energy is 169.7 mJ. The difference between energy transferred to the condenser and that supplied to the actuator appeared as the energy accumulated in the condenser, although some error exists.

6.8 Acceleration of main mass

Transmissibilities of the system with self-powered active control and that of the system without control are compared in Fig. 18. In the system without control, the moving mass is fixed to the main mass. This figure indicates that the proposed system has better suppression performance than that without control.

7. Conclusion

The following conclusions are obtained:

Fig. 17 Condenser voltage (Experiments)

Fig. 18 Frequency response of acceleration of the main mass to that of the base (Experiments)

1) Self-powered active control can be applied to the anti-rolling system for ships.

2) A new control scheme to achieve self-powered active control with a single motor is proposed.

3) Numerical simulations using specifications of the practical ship and experiments using the basic model are carried out. It is found that the proposed system is superior to the system without control in isolation performance.

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