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Hardware-In-the-Loop Simulation for Development of Fin Stabilizer†

Hyeon Kyu Yoon[1*] and Gyeong Joong Lee[2]

[1]*Department of Naval Architecture and Marine Engineering, Changwon National University, Gyeongnam 641-773, Korea*
[2]*Maritime & Ocean Engineering Research Institute, KIOST, Daejeon, 305-343, Korea*

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Abstract

A ship cruising in the ocean oscillates continuously due to wave action. In order to reduce the ship's roll, we developed a fin stabilizer as an anti-rolling device for a 500-ton-class high-speed marine vessel. During the development phase, it was necessary to set up control gains for the motion and hydraulic systems and assess the effectiveness of the anti-rolling performance on the ground. For this reason, a Target Simulator, which simulated the ship's motion, was given operator inputs such as the engine telegraph and waterjet deflection angle, and generated roll using a one-degree-of-freedom motion base. Hardware-In-the-Loop Simulation (HILS) was performed using the Target Simulator in order to confirm the various logics of the developed fin stabilizer, select initial control gains, and estimate the anti-rolling performance. In conclusion, it was confirmed that HILS was very helpful to develop the fin stabilizer because it could reduce the number of sea trial tests that were needed and could find many malfunctions in the factory a priori.

Keywords: Fin stabilizer, Hardware-In-the-Loop Simulation (HILS), Target simulator, Ship motion

1. Introduction

A ship cruising in the ocean oscillates continuously as a result of wave action. For convenience, this motion can be separated into six modes: the surge, sway, heave, roll, pitch, and yaw [1]. Among the various motion modes of a conventional displacement-type ship, roll has the greatest effect on the cargo and passenger safety and tactical operational effectiveness. For this reason, there is an increasing trend for passenger ships and warships to be equipped with anti-rolling devices to reduce such roll motion [2].

We developed a fin stabilizer as an anti-rolling device for a 500-ton-class high-speed marine vessel [3]. During the development phase, it was necessary to set up control gains for the motion and hydraulic systems and assess the effectiveness of the anti-rolling performance on the ground prior to installing it in a real ship. For this reason, a Target Simulator was developed. This Target Simulator simulates a ship's motion in waves based on operator inputs such as the engine rpm and waterjet bucket deflection angle. In addition, it displays the current fin angle values and a three-dimensional graphical representation of the ship's motion, together with the wave profile, at every time step. The fin stabilizer measures the ship's roll using inertial sensors like an accelerometer or rate gyro [4]. Therefore, a simple motion base was manufactured to generate a one-dimensional ship's roll and mount the inertial sensor. A ship's six-degree-of-freedom motion in the Target Simulator is calculated by using

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*Corresponding author. Tel.: +82-55-213-3683, Fax.: +82-55-213-3689.
E-mail address: hkyoon@changwon.ac.kr.

fully nonlinear coupled equations for the motion and wave exciting force calculated using the strip method [5][6].

Using the aforementioned Target Simulator, a Hardware-In-the-Loop Simulation (HILS) was carried out in order to confirm the various logics of the fin stabilizer, which were installed in the main control unit, select the initial control gains, and estimate the anti-rolling performance of the developed fin stabilizer. The hardware used for HILS was the total fin stabilizer system, which consists of a fin, hydraulic actuating system, motor switch box, main control unit, and bridge control panel. The software includes a ship and environmental factors such as waves, current, etc.

The results of HILS for the developed fin stabilizer confirmed that it was very helpful to develop a fin stabilizer because it could reduce the number of sea trial tests that were needed and find many malfunctions in the factory a priori.

2. Developed Fin Stabilizer

The developed fin stabilizer consists of four parts, which are the fin blade, hydraulic actuating device, main control unit, including the motor switch box, and command input devices. All of the components and the overall system are shown in Figs. 1 and 2, respectively.

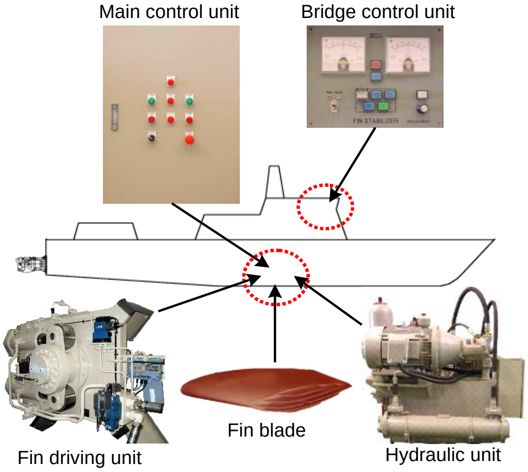


Fig. 1. Configuration of developed fin stabilizer system

Fig. 2. Overall fin stabilizer system on ground

2.1 Fin blade

The size of a fin blade has to be determined based on the objective roll reduction performance of a target ship. In addition, the detailed shape of the blade has to be designed from the fluid mechanical point of view to obtain high lift. If the target ship is a warship, the characteristics of the cavitation-borne noise have to be considered. Typical values for the fin blade shown in Fig. 1 are a 1.2 effective aspect ratio and 2.3 m^2 projected area.

2.2 Hydraulic actuating unit

The maximum lift acting on a fin blade was estimated as 7 tons, and the torque exerted on a fin stock was up to 1 ton-m. Therefore, a hydraulic system was selected as the type of actuating device, which is suitable for obtaining a large force. The hydraulic actuating unit consists of a hydraulic unit and fin driving unit, as shown in Fig. 1. The hydraulic unit includes a pump, various pressure control valves, thermometer, etc., and the fin driving unit consists of the actuating device, proportional valve, locking valve, fin angle transmitter, etc.

2.3 Main control unit

The main control unit (MCU), including the motor switch box, is the most important part. It receives most of the information from the bridge control unit and generates electrical actuating signals, which are calculated by the installed software program and operating logics. MCU consists of the hydraulic control unit, power control unit with the motor switch box hardware, motion sensor to measure the ship's roll and its rate, and ship interface unit, which is necessary to acquire an em-log pulse.

2.4 Command I/O consoles

A crew operates a fin stabilizer using command I/O consoles with MCU. There are two kinds of command I/O consoles: a bridge control unit (BCU) and remote control panel (RCP). The former is used by a crew to operate a fin stabilizer under normal conditions, and the latter is used for a developer to carry out sea trial tests, change the control gains, and monitor the operating status in the development phase.

3. Hardware-In-the-Loop Simulation

3.1 Concept

When testing the developed hardware under real-world conditions is difficult, Hardware-In-the-Loop Simulation (HILS) is used to replace the difficult part of the actual conditions with an alternative software simulation. In the case of total system HILS on the ground, a ship's motion in waves, wind, and current was simulated. HILS is widely used to develop and confirm independent components or a total hardware system.

In our case, we carried out subsystem HILS and total system HILS. Subsystem HILS was performed to develop the MCU logic, which was the most important part of the fin stabilizer system, as mentioned before. After developing the MCU, total system HILS was carried out to verify whether all of the components worked well. Fig. 3 shows the configuration of the total system HILS. When the subsystem HILS was performed, only MCU was operated, and the command fin angle was transmitted to the signal receiver installed in the Target Simulator.

3.2 Target Simulator

In order to carry out HILS, the Target Simulator was an inevitable device. The "Target" is something that will be simulated. Therefore, the Target Simulator developed in our case realizes real

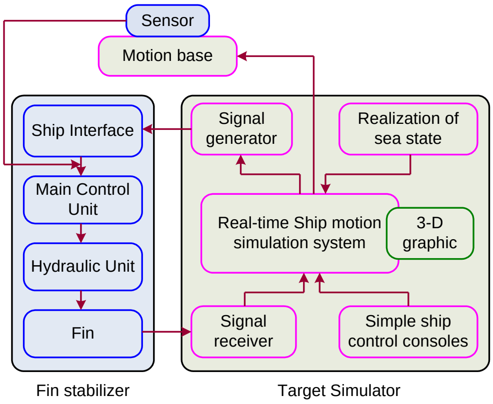
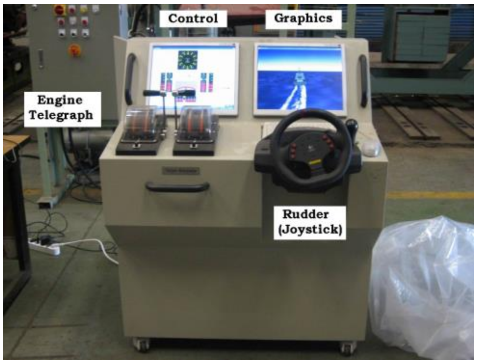
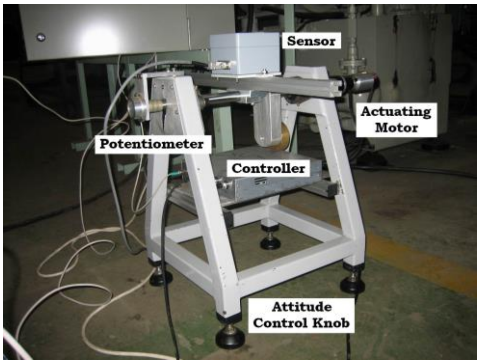


Fig. 3. Configuration of total system HILS for fin stabilizer

situations that can appear for a ship, and simulates a ship's motion under such environmental conditions. The motion base rotates with the same degree of roll and at the same roll rate as the simulated ship's motion, which can be measured using a motion sensor such as an accelerometer or rate gyro for the fin stabilizer.



(a) Main unit



(b) Motion base

Fig. 4. Target simulator

As the main unit of Target Simulator, one personal computer with two monitors calculates everything needed for the simulation, manages inputs and outputs, generates an em-log signal, and sends the input signal to the motion base. The motion base was composed of a DC servo motor. Fig. 4 shows the Target Simulator that was developed and used in the HILS.

As shown in Fig. 3, the real-time ship motion simulation system with a three-dimensional graphic display simulates the sea state, ship's motion characteristics, actuating performance of the hydraulic system (which was used only for the MCU subsystem HILS), motion response associated with the fin deflection angle, and speed and course change of a ship following the changes in the engine telegraphs and waterjet bucket angles.

In order to calculate the ship's motion, maneuvering and seakeeping coupled six-degree-of-freedom equations of motion were formulated [6]. The wave exciting force, which consists of the Froude-Krylov force and diffraction force, was calculated using the two-dimensional potential theory and strip method in order to extend the two-dimensional results into three-dimensional values. The unsteady buoyant force was calculated by the integration of the hydrostatic pressure acting on the submerged surface of a ship at every time step. Therefore, the offset of the ship was necessary for the precise calculation of buoyancy. The radiation force, which is the so-called memory effect and is composed of the added mass and wave damping, was calculated by the convolution integrals of the impulse response functions with respect to the velocities in six directions in the time domain. Such impulse response functions were obtained by Fourier transforms of the damping coefficients with respect to the frequencies [7]. The maneuvering force that acts on a ship in low-frequency motion was calculated using the hydrodynamic coefficients obtained with an empirical formula [8]. Finally, the fin control force was modeled by using the lift curve slope coefficient of the low aspect ratio wing section [8].

As shown in Fig. 4, there are two monitors in the main unit. The left one is the main control screen, where the status of every simulated variable such as the fin angle, waterjet bucket angle (which is the same as the rudder angle), ship's roll, and speed is displayed, and many control parameters for the simulation can be set. The control screen that is displayed on the left monitor is shown in Fig. 5. The right one displays the three-dimensional motion of a ship in waves with the wave profile in real-time. Various viewpoints can be set by using the joystick control attached to the right side of the main unit or the mouse, as shown in Fig. 4. The three-dimensional graphics were programmed using OpenGL Performer [9]. We could confirm the roll reduction performance conveniently using the graphic display during HILS. Fig. 6 shows a ship moving in waves during the HILS test.

Finally, there are two simplified input devices, the engine telegraph and joystick handle. The former is used for increasing or decreasing the engine rpm, and the latter is used for deflecting the waterjet bucket angle. A keyboard and mouse were included as redundant input devices.

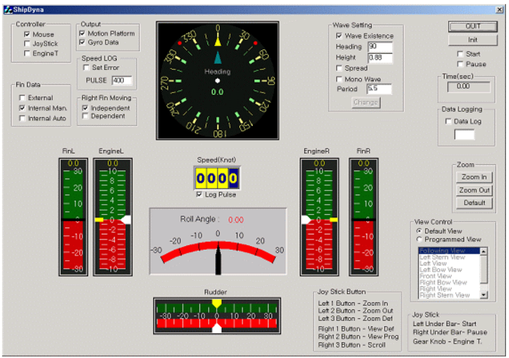


Fig. 5. Control screen in main unit of Target Simulator

Fig. 6. Three-dimensional graphic display of ship in waves and wave profile

4. Results

4.1 Resonance roll reduction ratio

The resonance roll reduction ratio [2] is widely used for the assessment of a fin stabilizer's performance. In the real world, it is very difficult to determine how much a developed fin stabilizer will reduce a ship's roll under pre-determined wave conditions, because wave conditions are stochastic, and the direction changes during a short period.

The resonance roll reduction ratio is defined as follows:

$$R(\%)=\left(1-\frac{B_0}{B_c}\right)\times 100 \qquad (1)$$

where, B_0 and B_c are the roll damping coefficients for a bare hull and fin control in the case of the resonant frequency of a ship's natural roll, respectively. Therefore, if the fin control damping coefficient, which can be interpreted as the roll reduction performance, is large, then the roll reduction ratio might be high.

In order to calculate the resonant roll reduction ratio, three kinds of tests have to be performed. The first one is to measure a ship's natural period. The second one consists of a test for measuring the roll response coefficient with respect to fin deflection, along with a free roll decay test for measuring the damping coefficient of a bare hull. The last one is a control test. The trial methods are all similar. First, a ship is excited by using the sinusoidal action of the fin stabilizer. Then, the fin deflection angle is zero or controlled following the free roll decay test or control test, respectively.

Such tests to obtain the resonant roll reduction ratio were carried out using HILS. We developed the software to calculate the roll reduction ratio using the results of tests obtained by HILS or sea trials. Figs. 7~9 show the results of three kinds of tests using HILS and the calculation of the necessary intermediate parameters. The solid and broken lines in the figures are the ship's roll and fin angle, respectively. Fig. 10 shows the final calculation results of the test for obtaining the resonant roll reduction ratio.

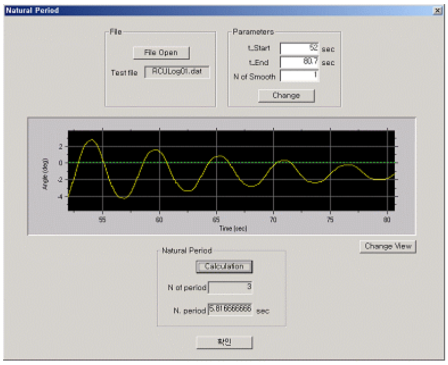


Fig. 7. Results of test for measuring ship's natural period

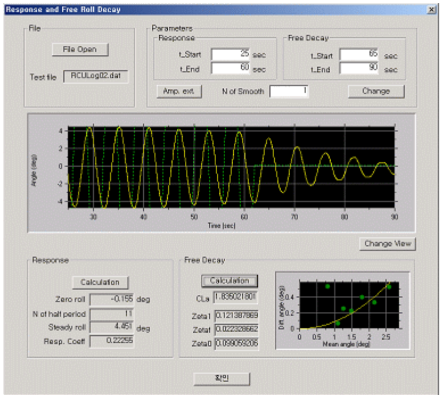


Fig. 8. Results of test for measuring response coefficient and damping coefficient of bare hull

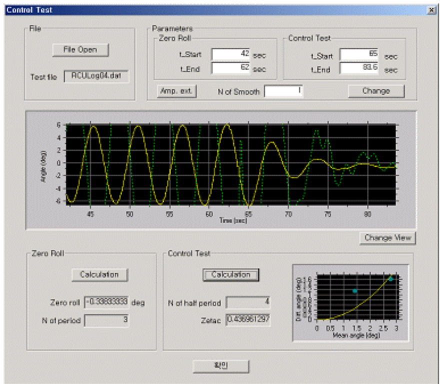


Fig. 9. Results of control test

4.2 Roll reduction test in waves

As mentioned before, while it is not easy to test a fin stabilizer under the wave conditions of a real sea trial, by using HILS, we had no problem testing it under any environmental conditions, because the wind, waves, and current could be simulated by mathematical models simply by setting the parameters in the model. Fig. 11 shows the performance test results demonstrating how the developed fin stabilizer can reduce a ship's roll.

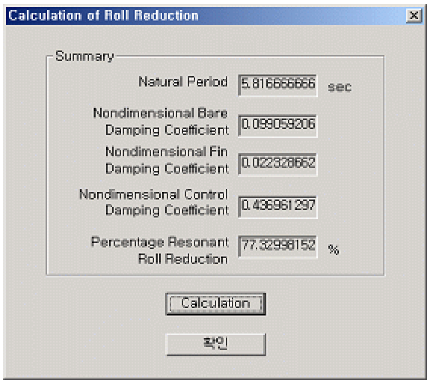


Fig. 10. Final results of test to obtain resonant roll reduction ratio

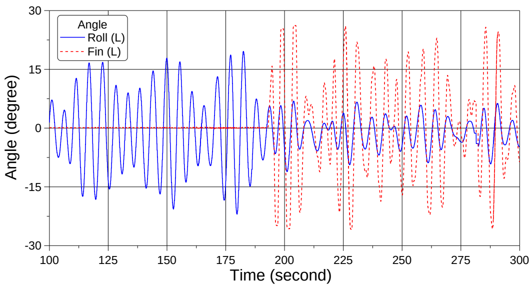


Fig. 11. Roll reduction test in irregular waves

During the HILS test, the sea state was assumed to be 5, which means the significant wave height was 3 m [8]. The ship's speed was 15 knots. In Fig. 11, the solid and broken lines are the ship's roll and fin deflection angle, respectively. In order to compare the roll stabilizing performance, the fin stabilizer did not operate until 200 s. When the fin stabilizer did not control the ship's roll, its maximum amplitude reached about 17°. However, in the case of control, it could be within about 5°, which means the roll reduction performance was about 70% in an irregular sea, which is similar to real sea conditions.

5. Conclusion

A fin stabilizer that could be installed in a 500-ton-class fast marine vessel was developed. In order to determine the control gains for the motion and hydraulic systems, develop various logics for the main control unit, and test the roll reduction performance on the ground, Hardware-In-the-Loop Simulation (HILS) was used by developing a Target Simulator, which consists of a main unit and one-dimensional roll motion base.

The main unit includes a personal computer, two LCD monitors, two engine telegraphs, a simplified rudder helm represented by a wheel joystick, pulse generator for creating an em-log signal, and spare keyboard and mouse. We could set various environmental conditions, and mathematical models simulated a ship's six-degree-of-freedom motions in waves.

HILS was carried out by using the Target Simulator and the developed fin stabilizer. At that time, the fin stabilizer operated under the same conditions as in a case where it is installed in a ship. HILS was used to manufacture the fin stabilizer during the development process. This paper described the roll reduction performance tests using HILS.

In conclusion, the HILS was thought to be very useful for developing the hardware, and it could be helpful in reducing the development costs, because it might decrease the number of sea trial tests that are needed.

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