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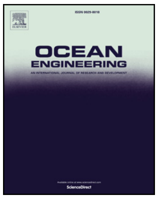

Ship pitch-roll stabilization by active fins using a controller based on onboard hydrodynamic prediction

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ABSTRACT

The reduction of roll and pitch motions is important to improve the safety and operability of a ship. A pitch-roll stabilization (PRS) control approach for a ship with two pairs of active fins is proposed. In this approach, the key part is the onboard forecasting of the ship's hydrodynamic forces. According to the proposed approach, a PRS controller was developed by integrating a short-term predictor, a force estimator and a fin angle allocator. The PRS controller outputs the optimal attack angles for the active fins by inputting the collected ship's motion time series. First, the short-term predictor serves to predict the future motions of the ship. Second, the predicted ship motions are used in the force estimator to estimate the external hydrodynamic forces. Finally, the predicted hydrodynamic forces, regarded as the expected stabilizing forces, are further employed to evaluate the optimal effective attack angles for the fins' actuator. The active fins are actuated based on the specified optimal effective attack angles. To evaluate the performance of the proposed PRS control approach, numerical simulations and experimental tests under various sea states were investigated. Both the numerical and experimental results suggest that the proposed control approach provided a satisfactory reduction of the pitch and roll motions simultaneously.

1. Introduction

Ships experience large pitch and roll motions when sailing in severe sea states. These motions lead to negative effects for maritime operations or traveling by ships in terms of safety and efficiency. The vertical accelerations caused by the pitch and roll motions make a sensory conflict that leads to seasickness. The seasickness greatly affects the comfort of the passengers and decreases the crew's ability to work. In addition, large roll motions may result in cargo damage and even cause the ship to capsize. Moreover, pitch motions resonating with the waves produce a dangerous condition for a parametric roll motion, which leads to the ship's loss of stability. Therefore, research on the reduction of the roll and pitch has been extensively conducted over the past several decades.

Anti-rolling is the first choice for improving the sea-keeping performance of a ship. Many passive and active controlled devices have been designed to reduce the roll motion. The bilge keel was the first effort in anti-rolling (William Froude, 1865). Later, water tanks were studied for the roll control (Frahm, 1911). Active methods have been attempted to further improve the roll control efficiency. Schlick (1904) invented a roll control device using the gyroscopic effects of large rotating wheels. The active gyrostabilizer system was also used in the ride control of marine vehicles (Townsend et al., 2007). Moving weights provide another feasible anti-rolling method (Treakle et al., 2000). In addition, active and passive fins have been widely investigated, where the active fins have demonstrated satisfactory performance in anti-rolling (as seen in Perez and Blanke, 2012).

In addition to roll control, anti-pitching is the second choice to improve the safety and operability of a ship. Comparatively, anti-pitching is still not as efficient for the practical purposes of anti-rolling because the pitch moment is much larger than the roll moment. Early works on pitch reduction started from passive methods. However, the latter research studies indicate the superior performance of active methods over passive methods in anti-pitching.

Fixed fins stabilizers were the most widely used passive methods to reduce pitch motion, and both bow and stern fins have been explored to prevent pitch motion. Experimental results (Abkowitz, 1959; Pournaras, 1956) have consistently shown that considerable reductions in pitch and slamming were obtained. However, bow-fixed fins lead to severe vibrations and speed loss. The deficiency was confirmed by the sea trials results (Wallace, 1955; Ochi, 1962). The bow-fixed fins induced vibrations that could be alleviated by moving the fin aft of Station 3; however, the control efficiency would be greatly reduced (Ochi, 1962). Stefun (1962) found that tip fences and deep submergence are helpful in reducing vibrations. A fixed strut-mounted hydrofoil below the bow of a yacht was also investigated (Avis, 1991), where the pitch

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and added wave resistance were found to be reduced by up to 20%. However, the total resistance was approximately 25% higher under certain encounter frequencies. Studies have shown that passive methods were effective in pitch control; however, they increase the ship's resistance and cause vibrations.

Active methods, such as a rudder or active fins, have been shown to be another possible solution for pitch control. Anti-pitching, using a pi rudder, was studied by Kaplan (1981). The pitch and bow accelerations were reduced by 30% and 50%, respectively. However, the controller design was more complex, as pitch periods have a wider range (Kaplan and Clark, 1984). Canted rudders produce both horizontal and vertical lift, in which the horizontal lift is used to control the steering, while the vertical lift controls the pitch. Kaplan and Clark (1984) investigated canted rudders mathematically by using the warfare vessel USS Oliver Hazard Perry (FFG 7). The pitch was reduced 30% when the FFG 7 was operating at sea state 6 at 20 knots. Active fins provide another relatively efficient way for anti-pitching. Pitch reductions through active fins actuated by various controller schemes, such as the proportional integral derivative (PID) (Wu et al., 1999), neural network and fuzzy-logic (Liut, 1999; Liut et al., 2001), were studied.

For practical purposes, the joint pitch-roll stabilization is the most expected method for improving the safety, comfort and operability of ships. However, studies on joint pitch-roll control have rarely been reported. Kim and Kim (2011) studied ship pitch-roll control by using two pairs of stabilizing fins. Controllers that were designed based on the PID and linear quadratic Gaussian (LQG) algorithms were compared. Numerical simulations of anti-pitching, anti-rolling and pitch-roll control on a cruise ship were carried out. Considerable reduction of the roll motion was obtained by using the PID or LQG algorithms. The roll and pitch motions were stabilized simultaneously by using two pairs of fins actuated by an LQG controller. Kim and Kim (2014) analyzed passenger comfort quantitatively based on the motion sickness dose value (MSDV) index. The roll-pitch stabilization, using two pairs of active fins, has been applied to improve passenger comfort.

Among various stabilizers, active fins function as the most effective stabilizer when the forward speed is higher than 10–15 knots (Perez, 2005). Large parts of modern ships are equipped with active fins for ship motion control. The efficiency of a ship's motions controlled by active fins mainly depends on the controller design. Wu et al. (1999) employed a PID controller for pitch reduction and verified the controller by experiments. Controllers using a variable structure (Yang and Jiang, 2004) and a linear quadratic regulator (Lee et al., 2011) have been employed for anti-rolling. To overcome the nonlinearity in controlling active fins, nonlinear approaches were used in designing the controllers. Liut (1999, Liut et al. 2001) developed controllers based on neural networks and fuzzy logic methods. Further, a model predictive controller was also applied to prevent the nonlinear effects of fins (Perez, 2005; Perez and Goodwin, 2008).

In recent years, advanced methods have been proposed for the active fin controller design. Fang et al. (2010) developed a self-tuning neural network PID controller for an anti-rolling fins stabilizer. The simulation results indicate that the proposed controller is suitable for controlling the gains acquisition. However, the controller can increase the resistance and heading error. Kaplan and Clark (1984) designed a Lyapunov's direct method based on a controller for anti-rolling and reducing the erosion of safe basins for ships. This controller successfully reduced the erosion percentage of safe basins and the roll amplitudes. For low ship speeds, however, the roll amplitudes exceeded a certain value. A genetic algorithm based on a PID controller for a fin stabilizer has been studied for roll reduction (Liut et al., 2001). The uncertain fin-roll dynamic was stabilized by using a sliding mode controller (Moradi and Malekizade, 2013). Hinostroza et al. (2015) developed a robust fin controller based on an L2 gain design to reduce the roll motion of surface ships. Liut et al. (2001) designed a sliding mode controller for both steering and roll reduction.

However, compared with the research on anti-rolling and anti-pitching, the research on pitch-roll control has rarely been reported. An adaptive estimation of the hydrodynamic forces for a pitch-roll stabilization (PRS) controller design has not been clearly solved. In the present research, a predictive approach was developed to reduce the pitch-roll motions. The predictive control approach estimates the hydrodynamic forces online based on the real-time predicted ship motions. Whereas an adaptive AR Model (Autoregressive Model) is employed to forecast the ship's motions in real-time, a PRS controller is designed to actuate two pairs of active fins. Numerical and experimental investigations were conducted to demonstrate the feasibility and to analyze the control efficiency of the proposed method.

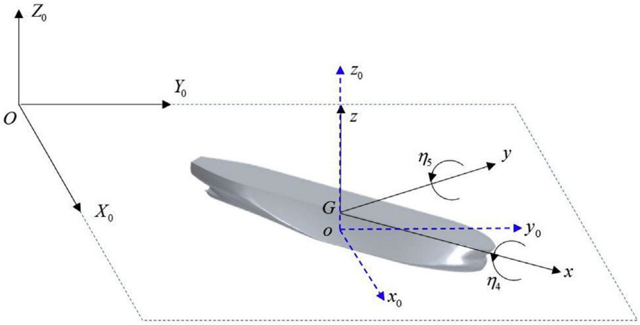

Fig. 1. Coordinate systems for ship roll-pitch-heave dynamic modeling.

This paper is organized as follows: Section 2 presents the mathematical model of a ship's dynamics, Section 3 presents the details of the controller design, Section 4 provides the experimental methodology, Section 5 discusses both the numerical and experimental results, and Section 6 presents the study's conclusions.

2. Mathematical model of ship dynamics

This section describes a mathematical model for ship roll-pitch-heave dynamics. Fig. 1 illustrates the heave, roll, pitch motions and coordinate systems for dynamic modeling. The ship motions of pitch, heave and roll are represented as η_5, η_3 and η_4, respectively.

The inertial coordinate system, O-$X_0Y_0Z_0$, fixed on the calm water surface, is used to model the wave. Ship hydrodynamics are described using the body-fixed coordinate system, G-*xyz*. This system originates at the ship's center of gravity and moves with the ship. The horizontal body coordinate system, o-$x_0y_0z_0$, is employed to describe the hydrodynamic boundary value problem. It is fixed on the calm water surface; however, it translates with the ship along the forward direction.

2.1. 3-DOF ship motions dynamic model

This subsection presents the formulations for a three degrees-of-freedom (DOF) ship dynamic model. For practical purpose, potential theories are mostly used in ship hydrodynamic modeling in the ship motion control problem. Eqs. (1)–(3) formulate the roll, heave and pitch motions in the time domain by using the impulsive response function (Cummins, 1962; Liut, 1999):

$$(I_{xx} + \mu_{44})\ddot{\eta}_4 + b_{44}\dot{\eta}_4 + \int_0^t K_{44}(t-\tau)\dot{\eta}_4 d\tau + c_{44}\eta_4 - F_4^v = F_4 \tag{1}$$

$$\begin{aligned}(M + \mu_{33})\ddot{\eta}_3 + b_{33}\dot{\eta}_3 + \int_0^t K_{33}(t-\tau)\dot{\eta}_3 d\tau + c_{33}\eta_3 + \mu_{35}\ddot{\eta}_5 + b_{35}\dot{\eta}_5 \\ + \int_0^t K_{35}(t-\tau)\dot{\eta}_5 d\tau + c_{35}\eta_3 = F_3\end{aligned} \tag{2}$$

$$\begin{aligned}(I_{yy} + \mu_{55})\ddot{\eta}_5 + b_{55}\dot{\eta}_5 + \int_0^t K_{55}(t-\tau)\dot{\eta}_5 d\tau + c_{55}\eta_5 + \mu_{53}\ddot{\eta}_3 + b_{53}\dot{\eta}_3 \\ + \int_0^t K_{53}(t-\tau)\dot{\eta}_3 d\tau + c_{53}\eta_5 = F_5\end{aligned} \tag{3}$$

where M is the ship mass; F_j is the j-th mode hydrodynamic force, and