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## RESEARCH ARTICLE

# Control of ship roll and yaw angles during turning motion

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**ARTICLE INFO**

**ABSTRACT**

The aim of this paper is to determine factors that are exposed ships to assorted hydrodynamic forces originating from internal and external influences. The adverse effect of rolling caused by turning motion should be reduced with anti-rolling systems, to ensure safe navigation. If this effect is not eliminated, it may prevent the ship from keeping its course safely. In this study, fin stabilizer system the computational analysis of the roll motion formed by the turning motion and wave effect is included in fin stabilizer system. The rudder motion that allows the ship to have the desired maneuvering angle; calculations of the fin system, which decreases the excessive roll moment, and the roll motion caused by these two effects are examined using MATLAB software. The analysis period has been determined as 300 seconds, which is the time to reach the desired turning angle of the ship. Linear quadratic tracking (LQT) algorithm has been used to solve partially unknown continuous time problems such as roll motion in this study.

**Nomenclature**

| | | | | |
|---|---|---|---|---|
| $u_0$ | Surge velocity | N | Rigid-body Coriolis/centripetal matrix |
| $v$ | Sway velocity | $\tau$ | Control vector |
| $w$ | Heave rate | $w_e$ | Wave encounter frequency |
| $p$ | Roll rate | $x_g$ | x- position the center of gravity |
| $q$ | Pitch rate | $y_g$ | y- position the center of gravity |
| $r$ | Yaw velocity | $z_g$ | z- position the center of gravity |
| $\emptyset$ | Roll angle | $N_i$ | Linear damping coefficient |
| $\theta$ | Pitch angle | $N_{\dot{i}}$ | Hydrodynamic added mass |
| $\psi$ | Yaw angle | $Y_i$ | Force |
| $e$ | East position | $K_i$ | Moment |
| M | Added mass matrix | | |

## Introduction

It is estimated that around 90% of the world trade volume is achieved by sea transportation. The volume of the ship fleet increases in parallel with this expansion (Lu et al., 2017). It is a common concern that ships are always strived to navigate at a certain speed to minimize spending time and fuel consumption. Various studies are carried out to remove the obstacles that arise while increasing energy efficiency (Lihua et al., 2018). One of the issues to be considered about safe navigation is the control of roll movement. Therefore, roll motion during the

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course is prominent in terms of the quality of navigation. Nonlinear mathematical models based on solid mechanics theory are used to estimate the roll movements of the ships with high accuracy (Hou et al., 2018). The hydrodynamic motion occurring on ships are damped by three different physical features in general; wave separation, vortexes on appendages and viscous friction on the wetted hull (Belenky et al., 2012).

The problem of energy optimization is one of the striking subjects that most of the researchers working on ships in recent years. As a result of the ship being exposed to severe rolling movements, the propulsive force and forwarding speed will decrease, and eventually some of the energy will be lost. Therefore, in this study, the roll angle reduction is taken into consideration to improve safety and energy efficiency during the cruise period. In past studies viscous and wave, resistance decreases when the vessel has a certain rolling angle range. In addition to ensuring safety at sea, increasing thrust and reducing fuel consumption can also lead to cost savings. (Yu et al., 2015). Under the influence of risen energy prices, the International Maritime Organization introduced the EEDI (Energy Efficiency Design Index), which required improved energy efficiency and emission reductions (GHG-WG, 2009). IMO has developed intact stability criteria on such fundamental principles as metacentric height (GM) and righting lever (GZ) in 1993. Then, the International Code on Intact Stability (IS Code), which entered into force on July 1, 2010, has been adopted in 2008. The mandatory requirements and recommended provisions relating to stability significantly influence the ship design parameters and overall ship safety (IMO, 2019). Considering the criteria of efficiency and legal necessities, it can be said that there are numerous related studies on this issue (Liu & Jin, 2013).

As a result of excessive roll motion, seafarers on the ship, vessel construction and transported load are adversely affected. Due to this reason, many studies have been conducted to damp the roll motion by utilizing such stabilization systems as anti-rolling tanks, bilge keels, rudders, gyro or fin stabilizers (Perez & Blanke, 2012). These systems have different characteristics since each of them has an individual triggering factor. For instance, the excessing of 10 knots, fin stabilizers are proper to damp the roll motion. The retractable fin stabilizers are hydrodynamically the most preferable way to ensure anti-rolling moment. On the contrary, as the pitching moment is relatively high than the rolling moment of a ship, a fin stabilizer is not able to handle trim angle (Kim & Kim, 2011).

There are several studies in the literature on the modelling and simulation of the rolling motion of a ship. Particularly, the roll motion problem has been presented a four-dimensional path integration approach in random beam seas (Chai et al.,

2015). Falzarano et al. (2015) examined roll damping methods and summarized the viscous roll damping prediction model in the most complex and less understood roll motion from the degree of freedom of the ship.

Irkal et al. (2016) assert that using a bilge keel is the first thing for reducing roll movements of a ship-shaped floating body when excessive heeling moments come to be a problem. Roll damping predictions both with and without a bilge keel have been demonstrated by Computational Fluid Dynamics (CFD) method and the results of CFD have been verified with a wave flume experiment (Irkal et al., 2016). Wassermann et al. (2016) have been tried to compare the advantages and disadvantages of three techniques on rolling such decay of motion, harmonic excited motion and harmonic forced motion. Chai et al. (2016) have been investigated the dynamic stability of a ship by probabilistic methods for random seas since nonlinear rolling movement is a serious threat to shipping stability. Markov diffusion theory has been applied to come out with the stochastic features of rolling motion originated from random sea wave loads. Hou & Zou (2016) have been predicted rolling fluctuations of a floating structure at an irregular sea state, it highly depends on accurate estimation of unknown damping and restoring moment coefficients in nonlinear roll motion equations. The coefficients of roll motion equations of a floating body have been suggested by using Support Vector Regression (SVR) method and random reduction technique. The roll damping coefficients have calculated with a method based on the three-dimensional CFD approach and compared with the experiment results in the study of Zhou et al. (2015). Overcoming the resistance and the yaw deviation, which needs running energy and appendage resistance due to the fin/rudder stabilization system, the total energy consumption has been analyzed by Yu et al. (2015). For this purpose, to achieve the roll reduction, the multi-objective genetic algorithm (MOGA) method based on the self-organizing PID controller has been utilized for the optimization of performance. Ship speed is significantly reduced due to the additional resistance caused by wave motion. The use of actuators to control the rudder of the ship can retrieve this speed loss. Liu et al. (2016) have been exerted a combined system using the sway–yaw motion and the roll dynamics to the reduction of loss speed.

The idea of using fin as a stabilization device consists of the dynamic ship model and fin hydrodynamic theory. The roll moment is observed in the turning process until the vessel reach desired yaw angle. In this study, it is examined that how the fin stabilizers are able to degrade the roll motion of a container ship, which is under the influence of turning in a random beam sea. In cases where the self-restoring moment acting on the hull is insufficient; the fin stabilizer is subsequently activated to

restrict the heeling angle at an acceptable range. The ship has been modelled with one fin at each side of the hull. The attack angle values of each fin are equal during the maneuver period, but their directions must be reversed to achieve a worthwhile restoring moment. For this reason, in this research, instead of using two equal restoring moments with opposite directions, magnitudes of each moment have been acted on the desired direction. The interaction of yaw, rudder and roll angles are modelled in the MATLAB environment. The restoring moment provided by the fin stabilizer is counteracted by the rolling moment in the vessel body in the absence of the fin.

The remainder of this study is organized as the linear mathematical model of the case ship, random sea state and stabilizer system description. The specifications of the vessel and selected fin stabilizer system are introduced in part 2 and the parameters of the study have been determined here. Part 3 details the results of modelled system, together with simulation statistics. The final part consists of some inferences and is derived from the recommendations.

## Materials and Methods

A ship moves at sea with 6 degrees of freedom. The planar motions are defined as surge, sway and heave which are formed by external effects. The remaining three motions are rotational movements in the x, y and z axes and are expressed as roll, pitch and yaw respectively in Figure 1.
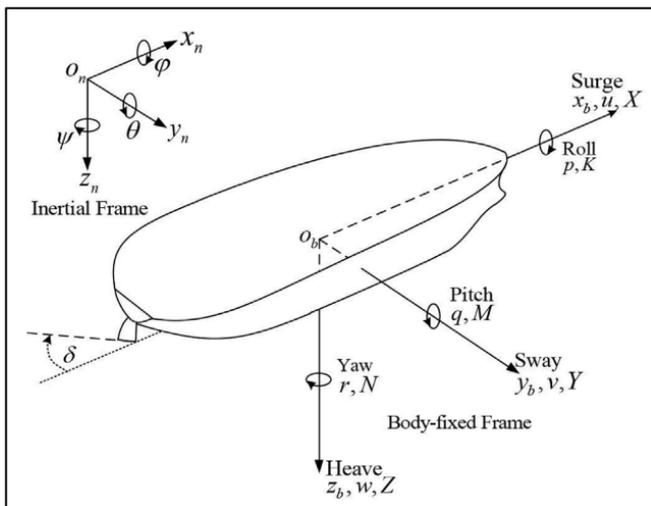


**Figure 1.** 6-DOF ship motion (Huang et al., 2018)

It is well known that roll motion has a direct and negative impact on ship stability as scrutinized in previous studies. The main research subject of this study is to reduce this destructive effect with the help of auxiliary equipment which is known as a fin stabilizer. In this part, the roll motion of a container ship during its maneuver period is examined and the damping of the excessive roll movements of the ship are caused by waves is provided by the fin stabilization mechanism (Huang et al.,

2018). In this study, the disturbance effect that causes dynamic movements is accepted as the wave force and the wind force is ignored.

### *Mathematical Model of Nondimensional Maneuvering and Autopilot*

The electronic control systems added on ships by the developing technology should have sufficient capacity to ensure safe and secure operations. One of these applications, auto-pilot design of the ships is conducted by such methods as PID-control, LQ design techniques, feedback linearization and backstopping designs. The purpose of each method is to be able to predict the course dynamics easily with high accuracy and to make accurate responses. In case the illustration of differences of ship dynamics, experimental and real ship body results are used together (Le et al., 2004).

The variables such as u velocity used in the calculations as the compound $u = \sqrt{u_0{}^2 + v^2}$ of sway and surge velocities of a vessel need to be normalized in the autopilot system design equations. This study aims to examine the motion at a set turning maneuver of a container ship for 3-DOF (Fossen, 2011).

Nonlinear control systems are used to solve problems that arise in various fields of science and technology. In the maritime transportation areas, it is utilized to determine the course and position of a ship. Due to the nonlinear equation's linearization process is applied to complex problems. In ship motions, linearization of nonlinear equations is solved by one of the controllers called the MIMO (Multi-Input Multi-Output) model which is an adaptive control approach (Bańka et al., 2013).

The linearization of the ship speed equation which is shown in equation 1 is carried out with the assumption that the external factors do not affect the motion of the ship in the direction of surge and heave, but only affect sway direction. The Linear Model of Van Amerongen and Van Cappelle MIMO model is described below:

$$M\dot{v} + N(u_0)V + G\eta = \tau \qquad (1)$$

where $u_0$=constant, $V = [v, p, r]^T$ and $\eta = [e, \phi, \psi]^T$ are the states of the ship, and $\tau$ is the control vector of the system (Perez et al., 2006).

$$M = \begin{bmatrix} m - Y_{\dot{v}} & -mz_g - Y_{\dot{p}} & mx_g - Y_{\dot{r}} \\ -mz_g - K_{\dot{v}} & I_x - K_{\dot{p}} & (-I_{xz} - N_{\dot{p}}) = 0 \\ mx_g - N_{\dot{v}} & (-I_{xz} - N_{\dot{p}}) = 0 & I_z - N_{\dot{r}} \end{bmatrix} \qquad (2)$$

When port and starboard of a ship to be regarded as symmetrical weight distribution, $I_{xy}=I_{yz}=0$ and $y_g=0$ equations are obtained. For this reason, it is compatible to choose the origin of the ship $r_g = [x_g, 0, z_g]^T$ so $I_{xz}=0$ with corresponding added inertia $K_{\dot{r}} = N_{\dot{p}} = 0$ (Blanke & Christensen, 1993).

$N(u_0)$ is generated by the linearization with the acceptance of symmetrical weight distribution and $V = [u_o, 0, 0]^T$ (Bańka et al., 2015).

$$N = \begin{bmatrix} -Y_v & -Y_p & mu_0 - Y_r \\ -K_v & -K_p & -mz_g u_0 - K_r \\ -N_v & -N_p & mx_g u_0 - N_r \end{bmatrix} \qquad (3)$$

The restoring forces and moments for a ship as a part of equation 1 are seen below:

$$G = diag\{ 0, W\overline{GM_T}, 0\} \qquad (4)$$

where, $W = mg$ is the weight of displaced water and $\overline{GM_T}$ is the transverse metacentre height (Perez et al., 2006):

The linear state-space model is described as $x = [v, p, r, \phi, \psi]$T matrix. The elements of A and B matrices are below:

$$\dot{x} = \overbrace{\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & 0 \\ a_{21} & a_{22} & a_{23} & a_{24} & 0 \\ a_{31} & a_{32} & a_{33} & a_{34} & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix}}^{A} . x + \overbrace{\begin{bmatrix} b_{11} & b_{12} & ... & b_{1r} \\ b_{21} & b_{22} & ... & b_{2r} \\ b_{31} & b_{32} & & b_{3r} \\ 0 & 0 & ... & 0 \\ 0 & 0 & & 0 \end{bmatrix}}^{B} . u \qquad (5)$$

where, the elements $a_{ij}$ are found from equation 6:

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} = -M^{-1}N(u_0); \begin{bmatrix} * & a_{14} & * \\ * & a_{24} & * \\ * & a_{34} & * \end{bmatrix} = -M^{-1}G \quad (6)$$

The elements of B matrix $b_{ij}$ are found from $B = M^{-1}TK$. K is the diagonal matrix of force coefficients (Fraga & Liu, 2012). The main objective is controlling the course of the ship $\psi = \psi_d = constant$ and damping the roll motion ($p_d = \phi_d = 0$). As a result of the control of the vessel route, the natural frequency $\omega_{roll}$ and damping ratio $\zeta_{roll}$ are increased and thus the damping takes place. Besides, it is impossible to damp the roll $\phi$ and the heading $\psi$ angle to a zero value with the help of a single rudder. Motion can be observed by performing a steady-state analysis of the compiled system. The output to be controlled is determined as follows:

$$y = [p, r, \phi, \psi]^T, \ y_d = [0, 0, 0, \psi_d]^T \qquad (7)$$

For $y = C.x$, $C$ is expressed as (Li et al., 2018):

$$C = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad (8)$$

In Continuous-Time (CT) system problems, the Linear Quadratic Tracking (LQT) system and its common solution should be determined. For the solution of these problems, there is an assumption that the reference trajectory is asymptotically stable. When the reference trajectory goes to zero, the time goes to infinity. The linear Continuous-Time system is defined as:

$$\dot{x} = Ax + Bu \qquad (9)$$

$$y = Cx \qquad (10)$$

where x ∈ R$_n$×1 is a measurable system state vector, y ∈ R$_p$×1 is the system output, u ∈ R$_m$×1 is the control input, A ∈ R$_n$×n gives the drift dynamics of the system, B ∈ R$_n$×m is the input matrix and C ∈ R$_p$×n is the output matrix (Modares & Lewis, 2014).

With $x = [v, p, r, \phi, \psi]^T$ and $\phi = c_{roll}^T x$, $\psi = c_{yaw}^T x$, the solution to the LQT problem is given below (Huang et al., 2017):

$$u = G_1 x + G_2 y_d \qquad (11)$$

where,

$$G_1 = -R^{-1}B^T P_{\infty} \qquad (12)$$

$$G_2 = -R^{-1}B^T (A + BG_1)^{-T} C^T Q \qquad (13)$$

Due to the variety of environmental conditions, ship movements cannot be expected to have the same amplitude and acceleration, so the reduction of the freedom degrees makes it easier to obtain a proper solution (Lozowicki, 2001).

The physical and the mathematical model components of the ship movement with one degree of freedom are based on the following assumptions (Zhang & Zou, 2011):

- The ship is symmetrical towards the port and starboard parts,

- All other degrees of freedom are neglected,

- The ship is accepted as a rigid body.

The above-defined model has been implemented on the container vessel to be able to design the mathematical model of ship movements easily. Under these constraints, the nonlinear state of the roll motion is expressed in equation 14.

$$(I+J)\ddot{\phi} + B_1\dot{\phi} + B_2\dot{\phi}|\dot{\phi}| + B_3\dot{\phi}^3 + \Delta(c_1\phi + c_3\phi^3 + c_5\phi^5 + c_7\phi^7) = \omega_e^2\alpha_m I\cos(\omega_e t) - M_f \qquad (14)$$

The mass moment of the inertia for roll motion is shown as I and the added mass moment of inertia for rolling is implied by J. $B_1$, $B_2$ and $B_3$ are roll damping coefficients, and $c_1$, $c_3$, $c_5$ and $c_7$ are expressed as coefficients for restoring force. Angle, angular velocity and angular acceleration of roll motion is represented as $\phi, \dot{\phi}, \ddot{\phi}$ respectively. $\Delta$ is the weight of the ship, wave encountering frequency is indicated by $\omega_e$, $\alpha_m$ corresponds to the maximum wave slope, and $M_f$ is for the fin control moment (Alarçin et al., 2014).

The ship's motion is mostly affected by the wave state. For the determination of the hydrodynamic forces on board, it is necessary to know that the wave characteristic. Equation 15 refers to the wave spectrum equation. $\chi$ is the angle of approach of the waves to the ship, $w_e$ is the encounter frequency and $\omega$ is the wave frequency.

$$w_e = w - \frac{w^2 U}{g}\cos\chi \quad (15)$$

In Figure 2, $U_0$ implies the speed of the vessel and the generic wave model affecting the ship body is also shown. The used speed of the vessel is $U_0 = 7.3$ m/s, and the approaching wave angle $\chi=90^o$ (beam seas) in this analysis (Naik & Ross, 2017).
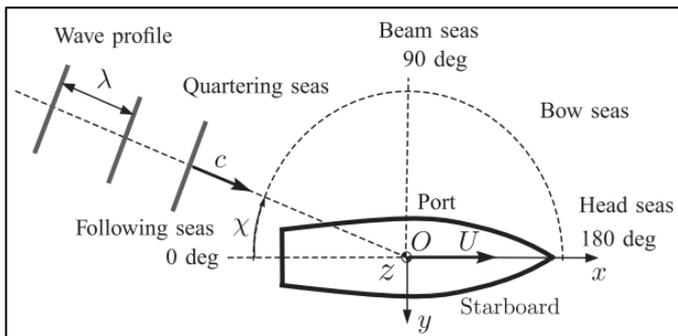


**Figure 2.** Wave demonstration

In this study, the dynamic behavior of roll motion, rudder and fin have been investigated under the wave effect for the turning trajectory. The fin stabilizer has 5-degree steps and the rudder has a 1-degree step with the purpose of damping the roll motion caused by the turning of the ship and correction of the course. The reason for separated steps is that these control systems consist of mechanical-electronic equipment and need continuous energy usage on the circuit. The control of the rudder and the fin is monitored by the LQT system. When it comes to the insufficient righting moment condition of the rudder, the fin stabilizer is activated with 5-degrees attack angles.

## Ship Specifications

The ship model S-175, which is a container ship, is used in this study because of the possibility of finding experimental data and analyzing them in mathematical environment (Son & Nomoto, 1981). The main dimensions of the container ship and stabilizer system specifications are demonstrated in Table 1. The vessel has been modelled as a single-propeller and with a single rudder. To achieve the minimized roll motion, each side of the ship has been equipped with an identical fin.

The body plan of the ship, whose roll motions are examined, is shown in Figure 3.

Typically, the GZ curve is a comparison criterion to analyze for a ship stability is depending on the heel angle. When the ship has a positive GZ value, it tends to restore itself with the righting moment arm when hydrodynamically stimulated by any destabilizing force. Thus, the analysis of GZ-φ curve is an initial and essential step for a ship designer. When a capsize situation occurs due to the degree of freedom of nonlinear hydrodynamic forces, this analysis is halted (Naik & Ross, 2017). The GZ-φ curve of the case ship is indicated in Figure 4.
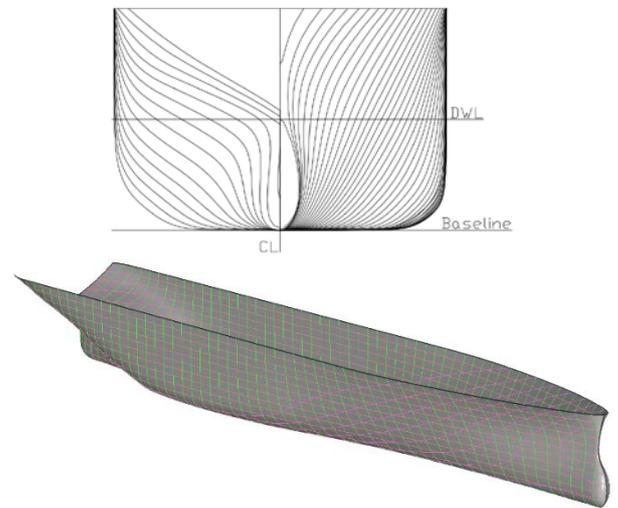


**Figure 3.** Cross sections (upper figure) and hull surface (lower figure) of the container ship

A fin is a similar construction with a rudder that is positioned usually perpendicular to the hull surface around the bilge. Nowadays, fins are widely used in oil tankers, warships, container ships, ferries and passenger ships. As shown in Figure 5, the fin geometry is positioned in the fluid material at a certain angle of attack. This positioning brings about the lifting force (L) to be formed on the wing (Demirel, 2013).

**Table 1.** Ship specifications

| Main particular of ship | | Fin stabilizer system | | Rudder specifications | |
|---|---|---|---|---|---|
| Length (m) | 175 | Foil Section | NACA 0015 | Rudder area (m$^2$) | 33.03 |
| Displacement (ton) | 21752 | Chord length (m) | 1.5 | Max rudder angle (deg) | 30 |
| Draft (m) | 8.5 | Span (m) | 6.5 | Rudder rate (deg/s) | 2 |
| Beam | 25.4 | Area (m$^2$) | 1.4625 | Quantity | 1 |
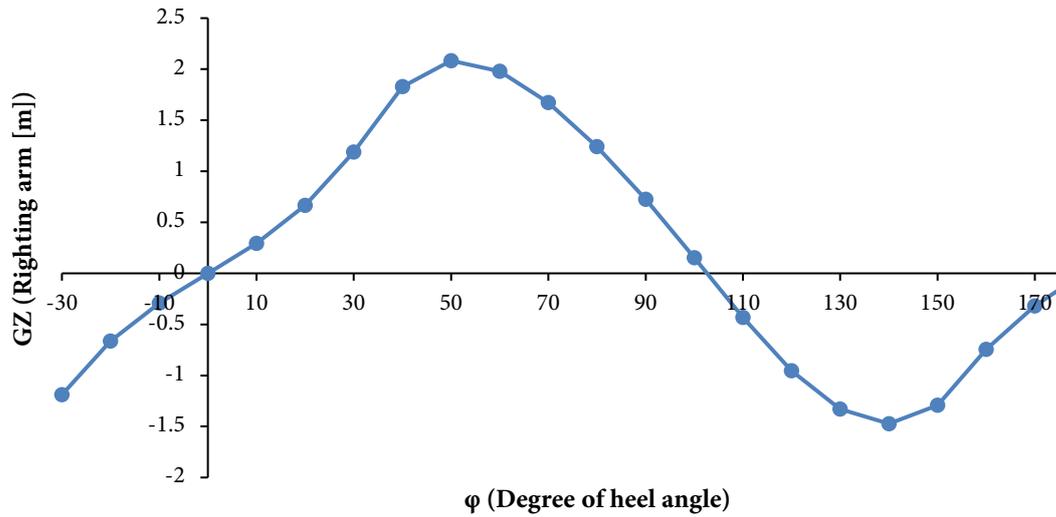


**Figure 4.** GZ-φ curve for the container ship
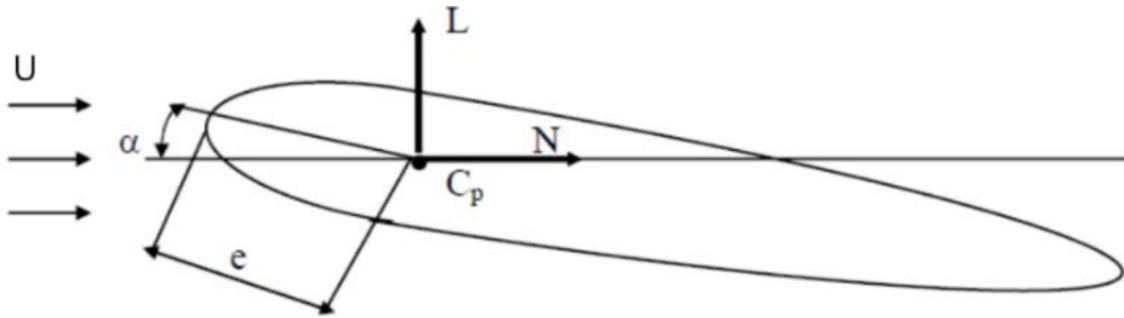


**Figure 5.** Fin geometry and forces
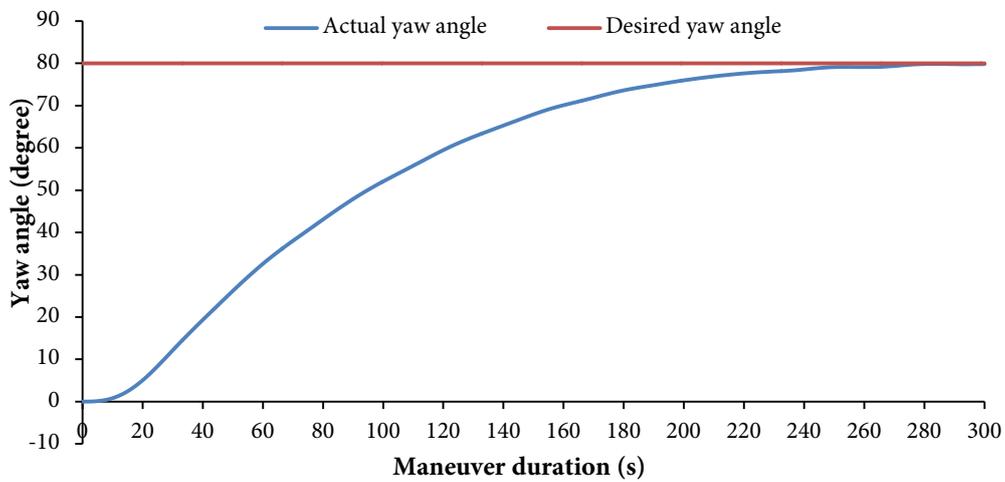


**Figure 6.** The changing of yaw angle during ship maneuver
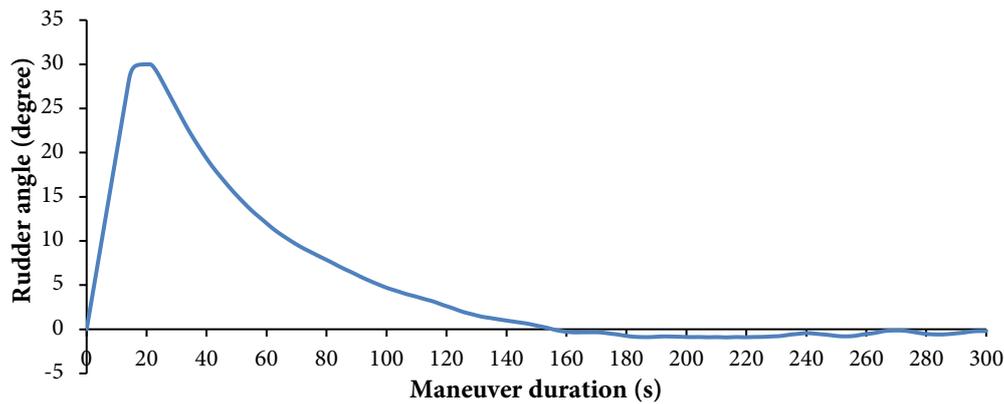
**Figure 7.** The changing of rudder angle during ship maneuver
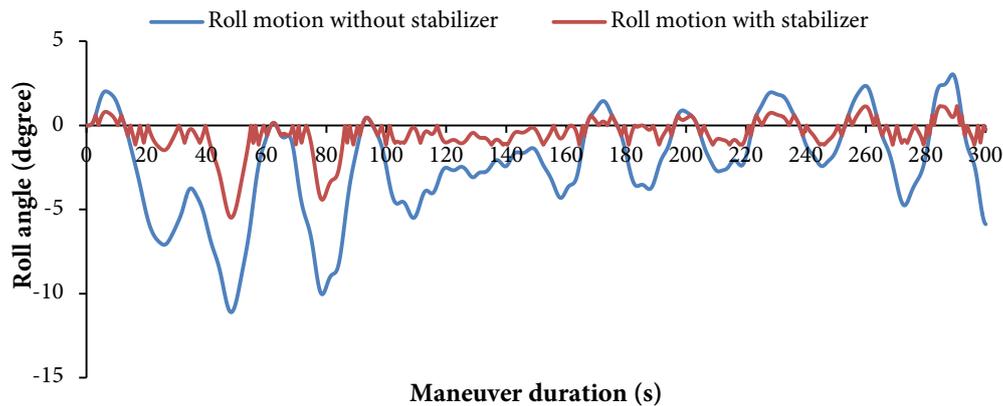


**Figure 8.** The changing of roll angle during ship maneuver

## Results and Discussion

The movement and characteristics of the hull under the sea effect of the ships are related to the hydrodynamics, dynamics and forces. According to the Abkowitz (1969) method, hydrodynamic forces and moments acting on ship body are the unknown nonlinear functions of location, speed and acceleration in six degrees of freedom. Taylor series expansions are used in the calculations of hydrodynamic forces, but the high-order hydrodynamic coefficients are neglected in this expansion (Lihua et al., 2018).

Fin stabilizer has been used to dampen the effect of the forces and moments above mentioned. The geometric characteristics of the fin are shown in Table 1 above. The Mf fin in the equation 14 is the moment of control. In this study, fin lifting forces were calculated for 1025 kg/m³ sea water density and 14 knot ship speed (Arslan, 2018). In the present study, the fin-stabilizer has been placed symmetrically on both sides of the vessel. The hydrofoil form with a low aspect ratio composes the shape of fins. The hydrodynamic behaviors on the fins can be neglected. In other words, except for the ship's roll motion, the fin systems have no hydrodynamic effect on the ship (Ghassemi et al., 2010).

The mathematical model used in the simulation was performed for the equation and boundary conditions described above. The yaw motion of the case ship to change course has been examined for 300 seconds. The reason that the time is limited to 300 seconds is that the vessel has reached the desired yaw angle of 80 degrees as shown in Figure 6. The motions after that point are about the environmental disturbances to divert the course of the ship. This new emerged problem is out of the scope of this study.

The yaw angle of the vessel for the desired maneuvering angle is modelled depending on time in the graph. The vessel is expected to rotate at 80 degrees for variable rudder angle values. As a result of the mathematical model about 240-250 s desired rotation has occurred.

For the ship to perform the action shown in Figure 6, the rudder must be controlled throughout the maneuver. In addition to asking the ship to provide the movement that will change the course, it is also expected to be a solution to the problem of roll damping. In the first stage, the equipment assigned to do this task is the rudder. The movement of the rudder along the 300-seconds route changing period is shown in Figure 7.

The rudder used for the desired maneuvering angle has a maximum rotation angle of 30 degrees in port and starboard

directions. This feature varies from ship to ship and is in the maximum range of 30-35 degrees. The rudder of the vessel is constantly kept under the control to obtain desired maneuvering angle. In the beginning of the maneuver, it has been assumed that the ship does not have any deviation of its forward direction and that the rudder angle has 0 degree. The rudder angle reaches its maximum value in the 20th second after the maneuvering has been started and then it moves in the opposite direction after that point to about 160th second.

Figure 8 shows the change of the roll angle of the ship during the maneuver period is seen in the problem created by the ignoring of the effects of the wave except for turning direction. In Figure 8, two graphs are given together to be able to compare the roll angles obtained by without and with using a fin stabilizer.

In Figure 8, the higher amplitude drawing consists of two separate effects of the rudder. The first is that it provides the desired rotation angle, and the other is that the roll angle occurring during this rotation is minimal under the current conditions. Since the roll motion in the current conditions could not be reduced sufficiently by the rudder, the mitigation effect of the fin control system to the roll motion has been shown with decreased amplitude graph.

## Conclusion

In this study, it has been investigated the hydrodynamic forces, which is affected by wave, and the rising of roll motion during turning motion is controlled by fin and rudder interaction using LQT controller. To get an easier solution under wave effect turning motion, 6-DOF ship motion has been reduced to 3-DOF. As a result of the assumption that the wave is approaching perpendicularly to the ship hull, these three neglected movements are heave, pitch and surge. However, while the ship has a constant forward speed, it is indicated by the formulas when the speed component deviates with the effect of the wave while turning. Also, in motion equations, that deviated speed has been considered. Under the specified boundary conditions, the following findings have been obtained from the results of the roll motion, rudder motion and yaw angle of the maneuvering vessel:

- Yaw angle simulation results show that desired turning motion has been got by a smooth course,

- The first 10 seconds of the turning motion have elapsed for reaction of inertia, for this reason the changing of yaw angle has a slight difference with initial condition,

- It has been seen that the rudder has been rotated by the maximum angle to the turning direction to overcome this inertia. Then, in order to ensure smooth change in the yaw angle, the rudder has been slightly rotated on the reverse direction,

- Maximum values of the roll angle are reduced to about half by the rudder and fin controller system also both motions have similar roll characteristics. This shows that LQT controller can be a practical choice for ship control systems.

Different controller systems should be applied to get an efficient ship operation as well as to conduct comfortable and safe ship operations during maneuver period. In future studies, this model can be developed and the applicability of alternative control systems to irregular.

## Compliance With Ethical Standards

### Authors' Contributions

BG: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Software, Writing - review & editing,
KB: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Software, Writing - review & editing,

### Conflict of Interest

The authors declare that there is no conflict of interest.

### Ethical Approval

For this type of study, formal consent is not required.

### References

Abkowitz, M. A. (1969). *Stability and motion control of ocean vehicles: Orgainzation, development, and initial notes of a course of instruction in the subject*. Cambridge M. I. T. Press.

Alarçin, F., Demirel, H., Ertugrul Su, M., & Yurtseven, A. (2014). Modified pid control design for roll fin actuator of nonlinear modelling of the fishing boat. *Polish Maritime Research, 21*, 3–8. https://doi.org/10.2478/pomr-2014-0001.

Arslan, M. S. (2018). Design of an optimal controller for the roll stabilization of surface ships with active fins. *Journal of ETA Maritime Science, 6*, 291–305. https://doi.org/10.5505/jems.2018.50570.

Bańka, S., Brasel, M., Dworak, P., & Jaroszewski, K. (2015). A comparative and experimental study on gradient and genetic optimization algorithms for parameter identification of linear MIMO models of a drilling vessel. International *Journal of Applied Mathematics and Computer Science, 25*, 877–893. https://doi.org/10.1515/amcs-2015-0063

Bańka, S., Dworak, P., & Brasel, M. (2013). Linear multi-controller structure for control of a nonlinear MIMO model of a drill ship. *IFAC Proceedings Volumes*, *46*, 557–562. https://doi.org/10.3182/20130708-3-CN-2036.00046

Belenky, V., Weems, K. M., Bassler, C. C., Dipper, M. J., Campbell, B. L., & Spyrou, K. J. (2012). Approaches to rare events in stochastic dynamics of ships. *Probabilistic Engineering Mechanics*, *28*, 30–38. https://doi.org/10.1016/J.PROBENGMECH.2011.08.020

Blanke, M., & Christensen, A. C. (1993). Rudder-roll damping autopilot robustness to sway-yaw-roll couplings. *Proceedings of the 10th Ship Control Systems Symposium*, Canada, pp. 31.

Chai, W., Naess, A., & Leira, B. J. (2016). Stochastic nonlinear ship rolling in random beam seas by the path integration method. *Probabilistic Engineering Mechanics*, *44*, 43–52. https://doi.org/10.1016/J.PROBENGMECH.2015.10.002

Chai, W., Naess, A., & Leira, B. J. (2015). Stochastic dynamic analysis and reliability of a vessel rolling in random beam seas. *Journal of Ship Research, 59*, 113–131. https://doi.org/10.5957/josr.59.2.140059

Demirel, H. (2013). *Bir balıkçı teknesinin yalpa hareketinin dinamik analizi ve kontrolü* [Dynamic analysis and control of the fishing boat's roll motion]. [M.Sc. Thesis. Yildiz Technical University].

Falzarano, J., Somayajula, A., & Seah, R. (2015). An overview of the prediction methods for roll damping of ships. *Ocean Systems Engineering*, *5*, 55–76. https://doi.org/10.12989/ose.2015.5.2.055

Fossen, T. I. (2011). *Handbook of marine craft hydrodynamics and motion control*. Wiley.

Fraga, R., & Liu, S. (2012). Shaping the ship yaw response by the state-space feedback gain. *Advanced Materials Research*, *566*, 515–524. https://doi.org/10.4028/www.scientific.net/amr.566.515

Ghassemi, H., Dadmarzi, F., Ghadimi, P., & Ommani, B. (2010). Neural network-PID controller for roll fin stabilizer. *Polish Maritime Research*, *17*, 23–28. https://doi.org/10.2478/v10012-010-0014-3

GHG-WG. (2009). Progress report on the work relating to fW coefficient in the energy efficiency design index (EEDI). Intersessional Meeting of the Greenhouse Gas Working Group 2nd session Agenda item 2.

Hou, X. –R., & Zou, Z. -J. (2016). Parameter identification of nonlinear roll motion equation for floating structures in irregular waves. *Applied Ocean Research, 55*, 66–75. https://doi.org/10.1016/J.APOR.2015.11.007

Hou, X. –R., Zou, Z. –J., & Liu, C. (2018). Nonparametric identification of nonlinear ship roll motion by using the motion response in irregular waves. *Applied Ocean Research, 73*, 88–99. https://doi.org/10.1016/J.APOR.2018.02.004

Huang, L., Han, Y., Duan, W., Zheng, Y., & Ma, S. (2018). Ship pitch-roll stabilization by active fins using a controller based on onboard hydrodynamic prediction. *Ocean Engineering, 164*, 212–27. https://doi.org/10.1016/J.OCEANENG.2018.06.014

Huang, Z., Zhuo, Y., & Li, T. (2017). Optimal tracking control of the ship course system with partially-unknown dynamics. *ICCSS 2017 - 2017 International Conference on Information, Cybernetics, and Computational Social Systems*, *0*, 31–635. https://doi.org/10.1109/ICCSS.2017.8091491

IMO. (2019). Stability and Subdivision. Retrieved on Month Day, Year, from www.Imo.org/En/OurWork/Safety/StabilityAndSubdivision/Pages/DefaultAspx 2019

Irkal, M. A. R., Nallayarasu, S., & Bhattacharyya, S. K. (2016). CFD approach to roll damping of ship with bilge keel with experimental validation. *Applied Ocean Research, 55*, 1–17. https://doi.org/10.1016/j.apor.2015.11.008

Kim, J. H., & Kim, Y. H. (2011). Motion control of a cruise ship by using active stabilizing fins. *Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment, 225*, 311–324. https://doi.org/10.1177/1475090211421268

Le, M. –D., Nguyen, S. –H., & Nguyen, L. -A. (2004). Study on a new and effective fuzzy PID ship autopilot. *Artificial Life and Robotics*, *8*, 197–201. https://doi.org/10.1007/s10015-004-0313-9

Li, Q., Liu, J., Fu, J., Zhou, X., & Liao, C. (2018). Comparative study on the pumping losses between continuous variable valve lift (CVVL) engine and variable valve timing (VVT) engine. *Applied Thermal Engineering*, *137*, 710–720. https://doi.org/10.1016/J.APPLTHERMALENG.2018.04.017

Lihua, L., Peng, Z., Songtao, Z., Ming, J., & Jia, Y. (2018). Simulation analysis of fin stabilizer on ship roll control during turning motion. *Ocean Engineering, 164*, 733–748. https://doi.org/10.1016/J.OCEANENG.2018.07.015

Liu, Z., & Jin, H. (2013). Extended radiated energy method and its application to a ship roll stabilisation control system. *Ocean Engineering, 72*, 25–30. https://doi.org/10.1016/J.OCEANENG.2013.06.009

Liu, Z., Jin, H., Grimble, M. J., & Katebi, R. (2016). Ship forward speed loss minimization using nonlinear course keeping and roll motion controllers. *Ocean Engineering, 113*, 201–207. https://doi.org/10.1016/J.OCEANENG.2015.11.010

Lozowicki, D. L. T. (2001). On a ship track-keeping controller with roll damping capability. *IFAC Proceedings Volumes, 34*, 191–196. https://doi.org/.1037//0033-2909.I26.1.78

Lu, L. F., Sasa, K., Sasaki, W., Terada, D., Kano, T., & Mizojiri, T. (2017). Rough wave simulation and validation using onboard ship motion data in the Southern Hemisphere to enhance ship weather routing. *Ocean Engineering, 144*, 61–77. https://doi.org/10.1016/j.oceaneng.2017.08.037

Modares, H., & Lewis, F. L. (2014). Linear quadratic tracking control of partially-unknown continuous-time systems using reinforcement learning. *IEEE Transactions on Automatic Control, 59*, 3051–3056. https://doi.org/10.1109/TAC.2014.2317301.

Naik, S., & Ross, S. D. (2017). Geometry of escaping dynamics in nonlinear ship motion. *Communications in Nonlinear Science and Numerical Simulation, 47*, 48–70. https://doi.org/10.1016/J.CNSNS.2016.10.021

Perez, T., & Blanke, M. (2012). Ship roll damping control. *Annual Reviews in Control, 36*, 129–147. https://doi.org/10.1016/j.arcontrol.2012.03.010

Perez, T., Smogelif, N., Fossenf, T. I., & Sørensen, A. J. (2006). An overview of the marine systems simulator (MSS): A simulink® toolbox for marine control systems. *Modeling, Identification and Control, 27*, 259–275. https://doi.org/10.4173/mic.2006.4.4

Son, K., & Nomoto, K. (1981). On the coupled motion of steering and rolling of a high-speed container ship. *Journal of the Society of Naval Architects of Japan, 150*, 232-244. https://doi.org/10.2534/jjasnaoe1968.1981.150_232

Wassermann, S., Feder, D. –F., & Abdel-Maksoud, M. (2016). Estimation of ship roll damping—A comparison of the decay and the harmonic excited roll motion technique for a post panamax container ship. *Ocean Engineering, 120*, 371–382. https://doi.org/10.1016/J.OCEANENG.2016.02.009

Yu, L., Liu, S., Liu, F., & Wang, H. (2014). Energy optimization of the fin/rudder roll stabilization system based on the multi-objective genetic algorithm (MOGA). *Journal of Marine Science and Application, 14*, 202–207. https://doi.org/10.1007/s11804-015-1292-z

Zhang, X. G., & Zou, Z. J. (2011). Identification of Abkowitz model for ship manoeuvring motion using ε-support vector regression. *Journal of Hydrodynamics, 23*, 353–360. https://doi.org/10.1016/S1001-6058(10)60123-0

Zhou, Y., Ma, N., Shi, X., & Zhang, C. (2015). Direct calculation method of roll damping based on three-dimensional CFD approach. *Journal of Hydrodynamics, 27*, 176–186. https://doi.org/10.1016/S1001-6058(15)60470-X