Brodogradnja/Shipbuilding/Open access Volume 67 Number 4, 2016

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http://dx.doi.org/10.21278/brod67407 ISSN 0007-215X
eISSN 1845-5859

LMI - BASED H_2 AND H_∞ STATE - FEEDBACK CONTROLLER DESIGN FOR FIN STABILIZER OF NONLINEAR ROLL MOTION OF A FISHING BOAT

UDC 629.5.017.22:629.053:629.5.025.22
Original scientific paper

Summary

This paper presents the analyses of nonlinear roll responses of a fishing boat in waves. In addition to roll damping nonlinearity, the nonlinear roll restoring which has seventh order equation has been taken into consideration to accurate control application. To overcome nonlinearity and the effects of uncertainties, LMI (Linear Matrix Inequality) - based H_2 and H_∞ State - Feedback Control are applied for the fin roll stabilizer of a fishing boat. The fin characteristics are calculated by Star CCM+ package software. Finally, utilising the studies presented to illustrate the feasibility and efficiency of the H_2 and H_∞ control methods, the results of the simulations are demonstrated the performance of fin roll stabilizer.

Key words: *H_2 and H_∞ control; linear matrix inequality; fin roll stabilizer.*

1. Introduction

Although significant advances have been made in fishing boats, fishing still remains a highly dangerous operation. While a fishing boat sailing through waves, a large rolling motion and capsizing may occur due to both resonance and inadequate potential energy. The operation of fishing boats can be improved by reducing the roll motion in roll stabilizer. The benefits of a stabilization device are clear: an increase in personnel safety, higher individual productivity and extended operating for fishing boats. In the literature, there are a number of roll stabilizer system applications such as rudder roll stabilizer [1]; u-tube [2]; fin roll stabilizers [3]; [4] and an integrated fin and rudder roll stabilization [5], [6] etc.

A rudder stabilizer achieves roll reduction through rudder deflection. Hence, the performance of a rudder roll stabilizer decreases at low speeds. Lauvdal and Fossen [7] used to design a stable controller for roll damping and course keeping using sliding mode control. angles. A nonlinear backstepping controller is developed to provide global exponential stability of roll motion.

Alarcin and Gulez [8] described the use of a neural network controller for roll stabilization of a fishing boat using the rudder to control roll and yaw motions.

Roll reduction can also be achieved by using u-tanks in the range of 20-70% (RMS). Holden et al. [9] carried out active u-tank stabilizer using Lyapunov theory for large roll If possible, the paper should be written on an even number of pages. Extra space between paragraphs, figures and tables should not be gained by inserting blank paragraphs. If in doubt, place and number the figures at the end of the paper and put captions at desired positions in the text.

Alternatively, the fin can be used to provide an active dynamic stabilization to roll motions. Galeazzi et al. [10] analyzed the stability of the nonlinear system by using Lyapunov methods and studied fin stabilizers to stabilize the roll resonance condition.

Guan and Zhang [11], who proposed backstepping-based controller for ship roll motion, controlled the nonlinear fin roll stabilizer by ignoring the high order nonlinear terms. Ghassemi et al. [12] expressed active fin stabilizers are effective devices to reduce the roll motion of a ship agaiinst wave movements. Therefore, he used PID and Neural Network combination to control attack angle. Karakaş et al. [13] designed a controller based upon Lyapunov's Direct Method to decrease roll motion. Kose [14] modelled with mechanical and electrical dynamics using a general back stepping method. Su [15] used genetic algorithm to fin controller for adjust the angle of attack.

A number of problems related to ship roll motion are investigated by many researchers. In these applications, ([16], [17], [18], [19]) different nonlinear models of roll motion have been used. Taylan [20] studied a nonlinear roll motion model and solution of this model through Krylov-Bogoliubov asymptotic method on a time line. To overcome undesirable problems, it was presented the model predictive control by Liu et al. [21]

In this paper, the problem of a nonlinear roll motion of fishing boat is considered. Section 2 deals with the fin roll stabilizer system based on nonlinear restoring moment and damping effect. Section 3 deals with the fin lifting force caused by the rotation and angle of attack. Section 4 describes designing LMI - based H_2 and H_∞ State - Feedback controller. Section 5 and 6 discusses results and conclusion

2. The Nonlinear Model for Roll Motion

In the cause of simplify to using mathematical model of ship motions, some significant suppositions are made in modelling a fishing boat rolling motion, ignoring all other degrees of freedom of ships, xz-plane symmetry, rigid body and homogenous mass distribution. Considering these simplifications, ship rolling behavior was represented by Taylan [22] the following nonlinear expression,

$$(I+\delta I)\ddot{\phi}+B_L\dot{\phi}+B_N\dot{\phi}|\dot{\phi}|+\Delta(C_1\phi+C_3\phi^3+C_5\phi^5+C_7\phi^7)= \omega_e^2\alpha_m I\cos(\omega_e t)+M_F \tag{1}$$

Where $\phi,\dot{\phi},\ddot{\phi}$ are angle, angular velocity and angular acceleration of roll motion respectively, the mass moment of inertia is shown I and the added mass moment of inertia is shown δI. B_L and B_N are roll damping coefficients, C_1, C_3, C_5 and C_7 are determined by restoring force coefficients and Δ is the weight displacement of the ship, ω_e is wave encountering frequency, α_m is the maximum wave slope, M_F is the control moment of active fins. Dividing the equation (1) throughout by $(I+\delta I)$,

$$\ddot{\phi} + b_l\dot{\phi} + b_n\dot{\phi}\,|\,\dot{\phi}\,| + \Delta(c_1\phi + c_3\phi^3 + c_5\phi^5 + c_7\phi^7) = \frac{\omega_e^2\,\alpha_m\,I\cos(\omega_e t)}{(I+\delta I)} + \frac{M_F}{(I+\delta I)} \tag{2}$$

$$\ddot{\phi} + b_l\dot{\phi} + b_n\dot{\phi}\,|\,\dot{\phi}\,| + \Delta(c_1\phi + c_3\phi^3 + c_5\phi^5 + c_7\phi^7) = \lambda_e\omega_e^2\,\alpha_m\cos(\omega_e t) - b_2\alpha_f - b_3\dot{\phi} \tag{3}$$

Where,

$$b_l = \frac{B_L}{(I+\delta I)} \tag{4}$$

$$b_n = \frac{B_N}{(I+\delta I)} \tag{5}$$

$$b_2 = \frac{\rho V^2 A_F C_L l_F}{(I+\delta I)} \tag{6}$$

$$b_3 = \frac{\rho V A_F C_L l_F{}^2}{(I+\delta I)} \tag{7}$$

Inertia moment originates owing to the ship’s reaction to a motion and is proportional to the acceleration of motion. Added inertia moment means a reaction of sea water to the ship motion.

These Inertia values can be expressed depending on weight displacement of ship (Δ), breadth (B) and the vertical distance of the center of gravity (KG), [23]

$$(I+\delta I)) = \frac{\Delta}{12g}(B^2 + 4KG^2) \tag{8}$$

The nonlinear roll damping coefficients for ship types are calculated by theoretical and semi-empirical methods considering lift effect, bilge keel, skin friction and free surface effect, [11]. A non-dimensional damping coefficient is shown as follows.

$$B_L = \frac{2a\sqrt{(I+\delta I)\Delta GM}}{\pi} \tag{9}$$

$$B_N = \frac{3}{4}d(I+\delta I) \tag{10}$$

These coefficients, given a and d in Table 1, are directly related to a linear damping coefficients B_L and a non-linear damping coefficient B_N.

Table 1. The non-dimensional damping coefficients for three different types of the ship, [11].

Type of the ship	a	d
Fishing ship	0.1	0.0140

When a ship travels through waves, the hydrostatic properties and the restoring moment vary due to the varying surface elevations. For rolling motion, the restoring moment can be approximated by the polynomial.

$$M(\phi) = c_1\phi + c_3\phi^3 + c_5\phi^5 + c_7\phi^7 + ... \quad (11)$$

Where $c_1 > 0$, $c_3 < 0$, $c_5 > 0$ and $c_7 \leq 0$ for a damaged vessel but $c_7 = 0$ for an intact vessel. The roll restoring moment coefficients are defined as follows:

$$C_1 = \frac{d(GZ)}{d\phi} = GM \quad (12)$$

$$C_3 = \frac{4}{\phi_V^4}(3A_{\phi V} - GM\phi_V^2) \quad (13)$$

$$C_5 = -\frac{3}{\phi_V^6}(4A_{\phi V} - GM\phi_V^2) \quad (14)$$

Angle of vanishing stability ϕ_v and area under the *GZ* curve $A_{\phi v}$, dynamic characteristics of the *GZ* curve such as metacentric height *GM.* Based on the above-mentioned coefficients, numerical calculations were carried out for a fishing boat, whose body plan is given Fig. 1.

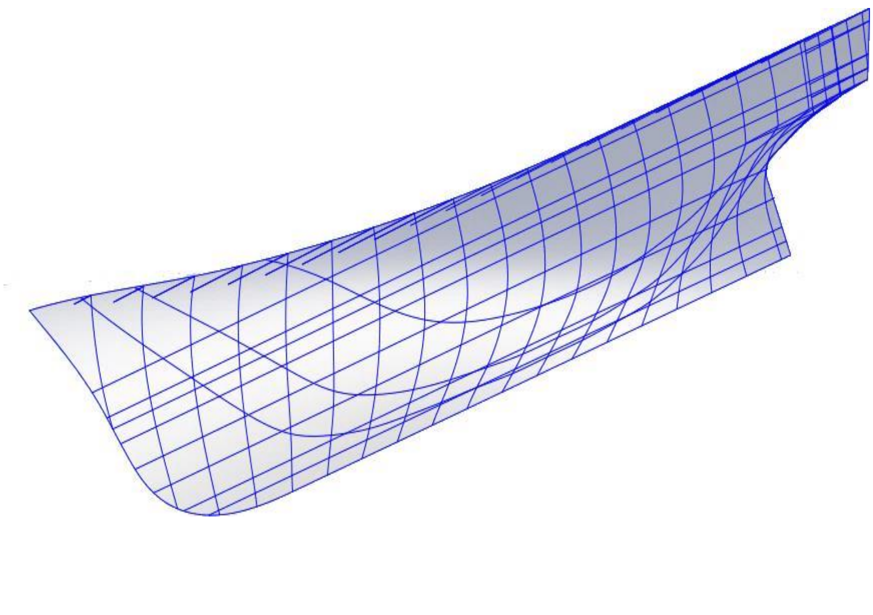

Figure 1. Body plan of the fishing boat

The right arm curve is a graphical representation of the fishing boat's stability on Fig. 2. This figure shows that the linear manner depends on the nature of restoring moment and angle of attack. The area under the curve represents the fishing boat's ability to counter the capsizing moments acting on the boat.

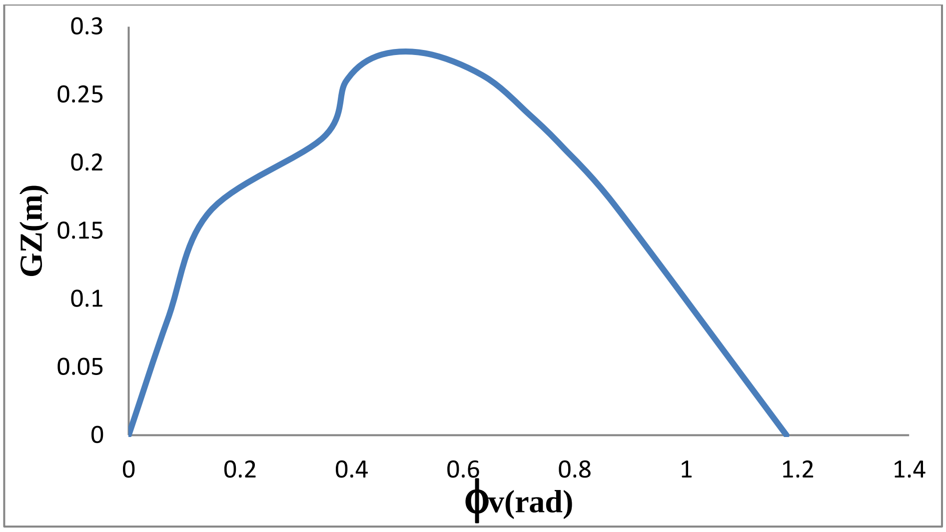

Figure 2. Righting arm curve of fishing boat

It is expressed the wave moment to consist of the encounter frequency as; [3]

$$M_w = \omega_e^2 \alpha_m I \cos(\omega_e t) \tag{15}$$

$$\omega_e = \omega_w - \frac{\omega_w^2}{g} V \cos(\mu_w) \tag{16}$$

M_w is the wave moment, ω_e is the encounter frequency of the wave, ω_w is the wave frequency, α_m is the maximum wave slope, μ_w is the wave encounter angle of the ship. It can be envisaged that the wave excitation will depend not only on amplitude and frequency of the waves but also on encountered angle and speed.

3. Roll Fin Actuator

The motion of a ship can be affected by fin actuators that impart forces and moments. Actuators play a very important role in the control system structure. When the roll fin stabilizers attack to the fluid, it can be seen that the surface of fins lifting force caused by the rotation and angle of attack. The lift force and the lift in non-dimensional form are as in the following form, [3]

$$L = \frac{1}{2} \rho V^2 A_F C_L \tag{17}$$

$$C_L = \frac{L}{0.5 \rho V^2 A_F} \tag{18}$$

Where L is the lifting force (N), ρ is the density of fluid (t/m^3), A_F is the fins area (m^2), C_L is the lift coefficient of the fin, V is the ship speed (m/s).

It is required to select the fin stabilizer having larger roll reduction performance with the smallest area. The area can be calculated by the following equation, [30]

$$A_F = \frac{\Delta \overline{GM} \sin \theta_{wsc}}{\rho C_L V^2 l_F} \tag{19}$$

Where θ_{wsc} is the wave slope capacity. General formula of fin roll moment is expressed as the following equation: [11]

$$M_F = -\rho V^2 A_F C_L \alpha \tag{20}$$

$$\alpha = \alpha_f + a' \tag{21}$$

$$a' = \frac{\dot{\phi} l_F}{V} \tag{22}$$

$$\dot{\alpha}_f = t_2 u_f - t_1 \alpha_f \tag{23}$$

$$t_1 = \pi \frac{finrate}{\max \ finangle} \tag{24}$$

$$t_1 = t_2 \tag{25}$$

$$M_F = -\rho V^2 A_F C_L \left(\alpha_f + \frac{\dot{\phi} l_F}{V} \right) l_F \tag{26}$$

Where M_F, fin roll stabilizer moment; l_F, distance from the center of the fin to the mass center of the ship; α is the total fin angle of attack, and it includes the virtual fin angle α_f and the oblique flow fin angle a'; $\dot{\alpha}_f$ express actuator dynamics.

A control system changes the mechanical angle of the fins, α_f, according to the ship roll angle ϕ and roll rate $\dot{\phi}$. A positive angle of attack is produce a positive roll moment produced by the fin. Lift of the fin is dependent on its geometric parameters. The fin stabilizer geometry is chosen as NACA 0015 foil section for calculations. The flow analyses are performed by using a commercial computational fluid dynamics (CFD) software based on finite volume method . A result for the lift coefficient is displayed in the figure 3.

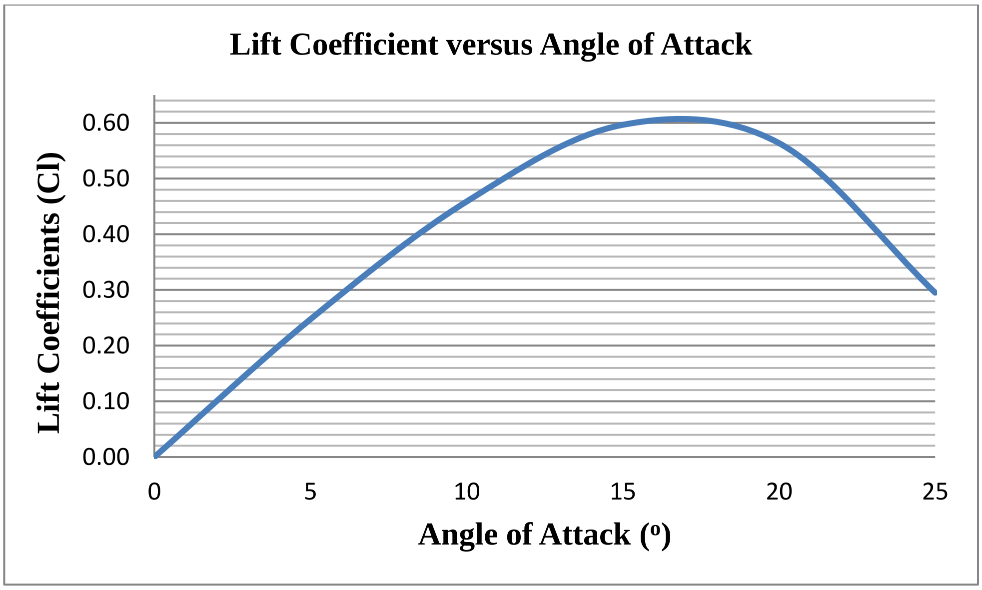

Figure 3. Lift coefficient – Angle of attack (AoA) graph

Figure 3 shows the correlation between the lift coefficient and the angle of attack. The flow is considered as steady, incompressible and fully turbulent. The numerical flow analyses are performed at different angles of attack. The fin stabilizer reaches the maximum lift coefficient at the angle of 17^o. H_2 and H_∞ State Feedback Controllers for the roll motion are modeled for the case which the fin creates the maximum lift.

4. LMI Based State - Feedback H_2 and H_∞ Controller Design

H_∞ control depends upon minimizing the infinitive norm of transfer function matrix which is written from controlled output to disturbance input in order to avoiding the disturbance input to affect the system. Thus, H_∞ control is very convenient control algorithm for the structural systems which are under effect of disturbance inputs.In other words, H_∞ control design is mostly related to frequency domain performance and does not assure good transient behaviors for the closed-loop system. H_2 control provides more practical performance on system transient behaviors. In this study to obtain desired frequency and transient response performance, H_∞ and H_2 controller are applied for control problem by the use of LMIs.

Doyle et al. derived simple state-space formulas for all controllers solving the following standard H_∞ problem and Francis examined mathematics of H_∞ control problem. [24,25]. Yazıcı and Güçlü designed LMI based state - feedback mixed H_2 / H_∞ controller for seismic excited structural system. [26].

Let us consider a nominal linear time invariant system revealed by;

$$\begin{aligned}\dot{x} &= Ax + B_1 w + B_2 u\\ z_1 &= C_1 x + D_{11} w + D_{12} u\\ z_2 &= C_2 x + D_{21} w + D_{22} u\end{aligned} \tag{27}$$

where $x \in \Re^n$ is the state vector. $u \in \Re^{m_u}$ is the control input, $w \in \Re^{m_w}$ is the disturbance input, $z_1, z_2 \in \Re^p$ is the controlled output vector. Suppose that the control input is linear function of the state, i.e., $u = Kx$ where $K \in \Re^{m_u \times n}$ is the state feedback gain. The closed-loop system is considered by

$$\begin{aligned}\dot{x} &= (A + B_2 K)x + B_1 w\\ z_1 &= (C_1 + D_{12} K)x + D_{11} w\\ z_2 &= (C_2 + D_{22} K)x + D_{21} w\end{aligned} \tag{28}$$

The state-space matrices and vectors of the closed-loop system are expressed as below.

$$A = \begin{bmatrix} 0 & 1 & 0 \\ c_1 & -b_l - b_3 & -b_2 \\ 0 & 0 & -t_1 \end{bmatrix}$$

$$B_1 = \begin{bmatrix} 0 & \lambda_e \omega_e^2 \alpha_m & 0 \end{bmatrix}^T$$

$$B_2 = \begin{bmatrix} 0 & 0 & t_2 \end{bmatrix}^T$$

$$C_1 = C_1 = I_{3x3}$$

$$D_{11} = D_{12} = D_{21} = D_{22} = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}^T$$

Assume T_{Z_1W} and T_{Z_2W} symbolize the closed-loop transfer functions, respectively from disturbance (w) to measurements (z_1 and z_2). Find a state-feedback control law u = Kx such that minimizes $\|T_{Z_2W}\|_2$ subject to $\|T_{Z_1W}\|_\infty < \gamma$ [27]. In order to determine a state-feedback control law, H_2 and H_∞ designed objectives have been severally obtained by LMIs. The Bounded Real Lemma plays a central role to obtain the H_∞ constraint. There exists a quadratic Lypunov function $V(x) = x^T P x$ P >0 , γ > 0, such that for all t . If we assume the initial conditions are zero, the Hamiltonian of the system (28) becomes.[26]

$$\dot{V} + z_1^T z_1 - \gamma^2 w^T w < 0 \tag{29}$$

and this Hamiltonian must be negative definite for all x and w. The following equation can be gained by subrogating the Equation (28) into Equation (29).

$$[(A + B_2K)x + B_1w]^T Px + x^T P[(A + B_2K)x + B_1w] + [(C_1 + D_{12}K)x + D_{11}w]^T [(C_1 + D_{12}K)x + D_{11}w] - \gamma^2 w^T w < 0 \tag{30}$$

Arranging the inequality (30) the following matrix inequality can be revealed as

$$\begin{bmatrix} [(A + B_2K)]^T P + P(A + B_2K) + (C_1 + D_{12}K)^T (C_1 + D_{12}K) & PB_1(C_1 + D_{12}K)^T D_{11} \\ B_1^T P + D_{11}^T (C_1 + D_{12}K) & -\gamma^2 I + D_{11}^T D_{11} \end{bmatrix} < 0 \tag{31}$$

The inequality (31) takes the latest form using the Schur complement. Suppose P and R symmetric matrices. The condition,

$$\begin{bmatrix} P & S \\ S^T & R \end{bmatrix} > 0 \tag{32}$$

is equal to

$$P > 0, P - SR^{-1}S^T > 0 \tag{33}$$

Pre- and post multiplying (31) by P^{-1} and using the Schur complement, inequality (34) can be expressed,

$$\begin{aligned} &P^{-1}(A + B_2K)^T Px + (A + B_2K)P^{-1} + P^{-1}(C_1 + D_{12}K)^T (C_1 + D_{12}K)P^{-1} \\ &- (B_1 + P^{-1}(C_1 + D_{12}K)^T D_{11})(-\gamma^2 I + D_{11}^T D_{11})^{-1}(B_1^T + D_{11}^T(C_1 + D_{12}K)P^{-1}) < 0 \end{aligned} \tag{34}$$

Using the variable change $X_\infty = P^{-1}$ the following LMI's can be obtained.

$$\begin{bmatrix} ((A + B_2K)X_\infty + X_\infty(A + B_2K)^T X_\infty + X_\infty(C_1 + D_{12}K)^T (C_1 + D_{12}K)X_\infty) & B_1 + X_\infty(C_1 + D_{12}K)^T D_{11} \\ B_1^T + D_{11}^T(C_1 + D_{12}K)X_\infty & -\gamma^2 I + D_{11}^T D_{11} \end{bmatrix} < 0 \tag{35}$$

$$\begin{bmatrix} ((A + B_2K)X_\infty + X_\infty(A + B_2K)^T X_\infty & B_1 \\ B_1^T & -\gamma I \end{bmatrix} + \frac{1}{\gamma}\begin{bmatrix} X_\infty(C_1 + D_{12}K)^T \\ D_{11}^T \end{bmatrix}\begin{bmatrix} (C_1 + D_{12}K)X_\infty & D_{11} \end{bmatrix} < 0 \tag{36}$$

Using the Schur complement over again, the following inequality can be revealed as H_∞ constraint of the closed-loop system (3) for $X_\infty > 0$,

$$\begin{bmatrix} A + B_2K)X_\infty + X_\infty(A + B_2K)^T & B_1 & X_\infty(C_1 + D_{12}K)^T \\ B_1^T & -\gamma I & D_{11}^T \\ (C_1 + D_{12}K)X_\infty & D_{11} & -\gamma I \end{bmatrix} < 0 \tag{37}$$

The optimal H_2 controller can be expressed by researching the minimum η which satisfies the above mentioned LMIs for $X_2 = X_2^T$ and $Q = Q_2^T$ Note that the H_2 norm of $\|T_{Z_2 W}\|_2^2$ is finite if and only if $D_{21} = 0$.

$$(A + B_2K)X_2 + X_2(A + B_2K)^T + B_1B_1^T < 0 \tag{38}$$

$$\begin{bmatrix} Q & (C_2 + D_{22}K)X_2 \\ X_2(C_2 + D_{22}K)^T & X_2 \end{bmatrix} > 0 \tag{39}$$

$$\text{Trace}(Q) < \eta \tag{40}$$

After finding a solution of this control problem, the state- feedback control matrixes for the closed-loop system is obtained as

$$K_2 = [-0.3434 \quad 0.6385 \quad -0.1064]$$

$$K_\infty = [-1.6642 \quad 2.8792 \quad -0.4833]$$

All the simulations and computations are done using Matlab with Simulink. For the solution of the resulting LMIs, Yalmip parser and Sedumi solver are used [28].

5. Simulation

The nonlinear roll model of the dynamic characteristics of the fishing boat and the model of the fin stabilizer particulars are shown in Table 2. The simulations were performed using the fishing boat model given in ref. [29].

Table 2. The fishing boat and the fin particulars

Principal Particulars	Symbol	Parameter
Length between perpendiculars	L_{bp}	*20 m*
Breadth	B	*5.714 m*
Depth	D	*3.2 m*
Draught	T	*2.285 m*
Displacement	∇	*105.76* m^3
Metacentric height	GM	*0.8 m*
Vertical center of gravity	KG	*2.35 m*
Block coefficient	C_B	*0.405*
Service speed	V	*12 kn*
Fins area	A_F	*2.81* m^2
Fins lift coefficient	C_L	*0.6*
Vanishing angle of stability	ϕ_v	68^0

First, the nonlinear roll motion of the fishing boat was considered. Then, by adding fin roll stabilizer, active system was formed. After designing H_∞ and H_2 controller, the roll angle and the roll rate were calculated.

The simulated time solutions of nonlinear roll motion controlled with LMI - based H_2 and H_∞ State Feedback control methods and of the uncontrolled nonlinear roll motion were illustrated in Figure 4 - 9, respectively. The disturbance was accepted as a sinusoidal wave form. To show effectiveness of the H_2 and H_∞ control methods, the nonlinear simulation results were compared with uncontrolled system. As can be seen from the figures, H_∞ State Feedback controller results achieved better performance.

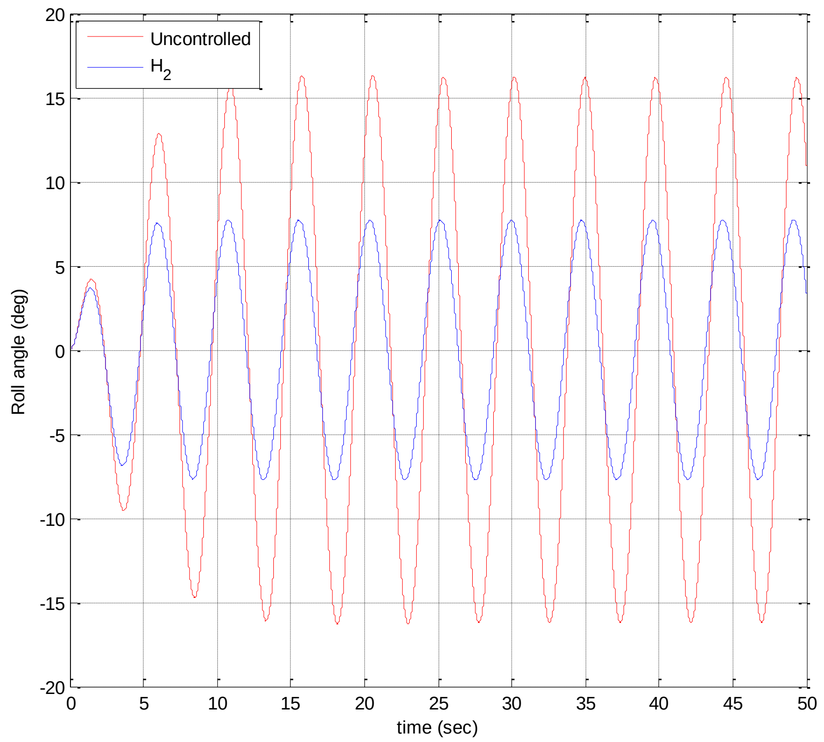

Figure 4. Comparison of roll angle response

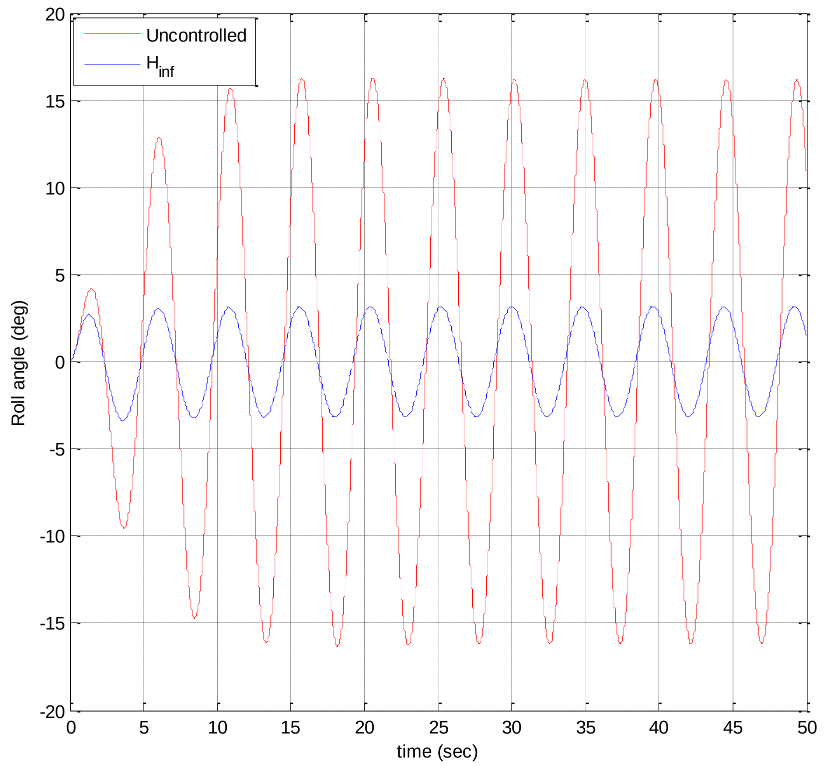

Figure 5. Comparison of roll angle response

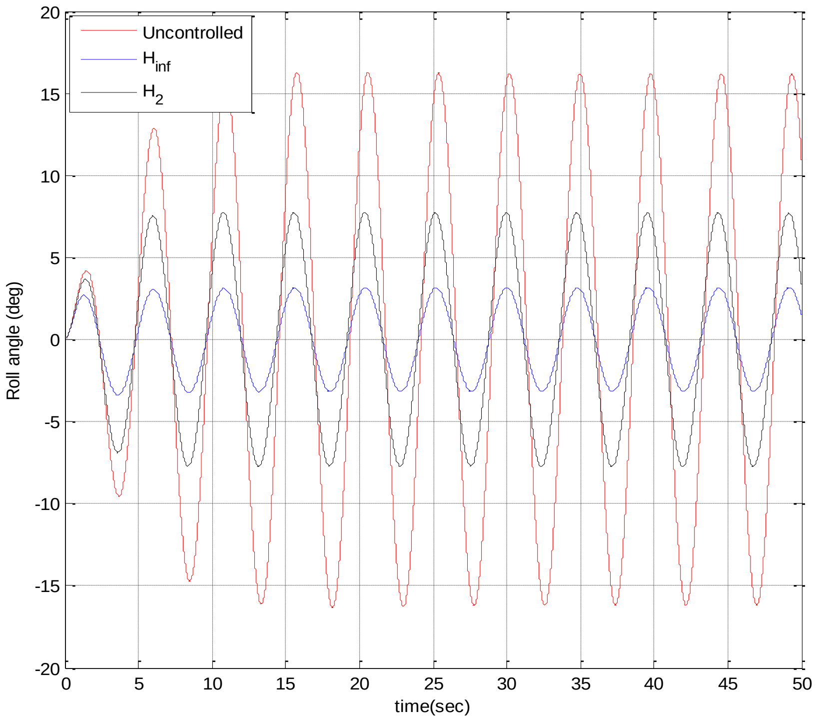

Figure 6. Comparison of roll angle response

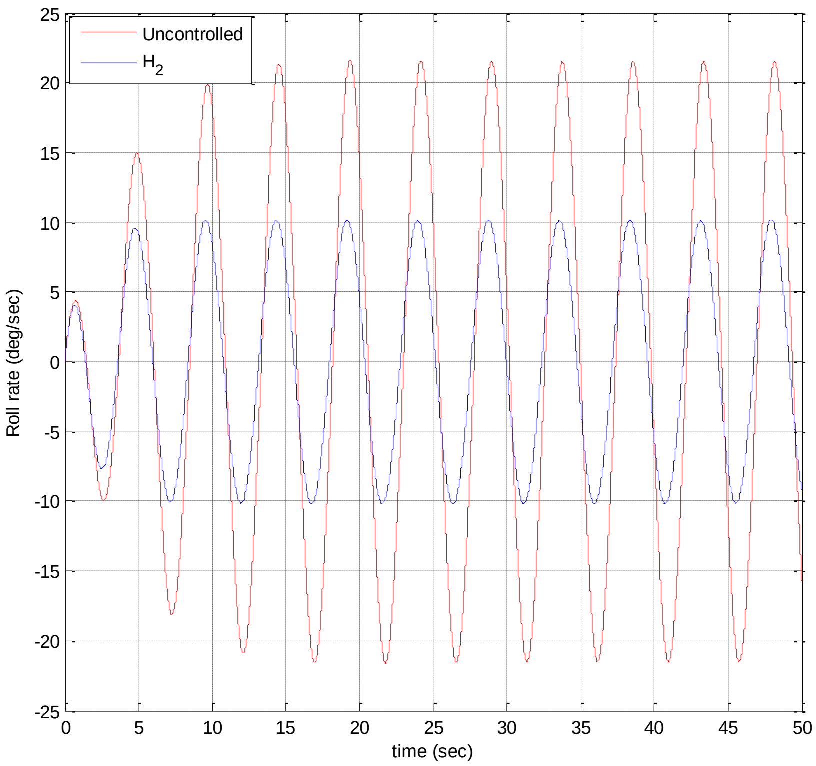

Figure 7. Comparison of roll angular velocity response

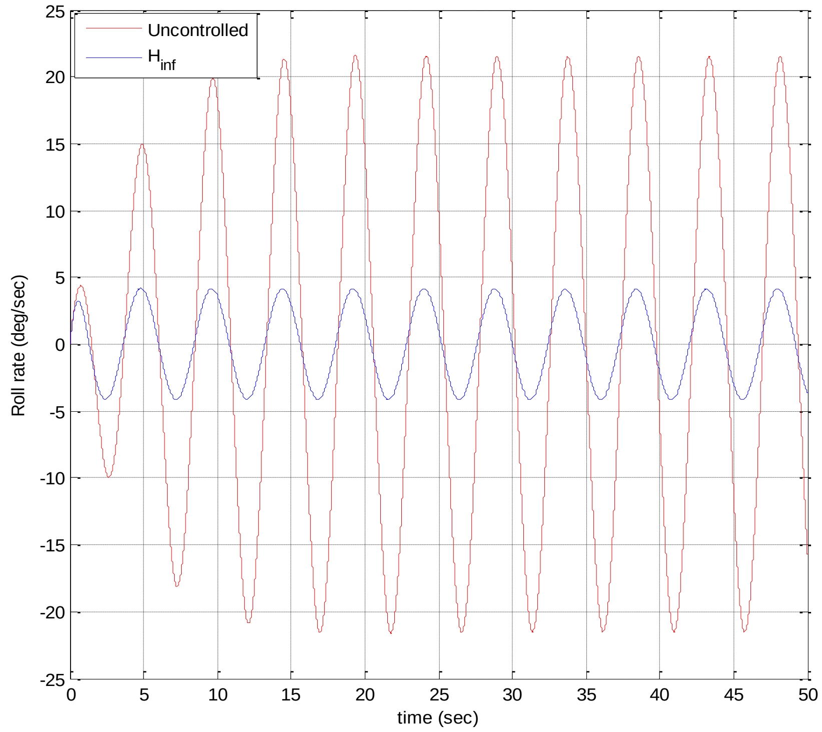

Figure 8. Comparison of roll angular velocity response

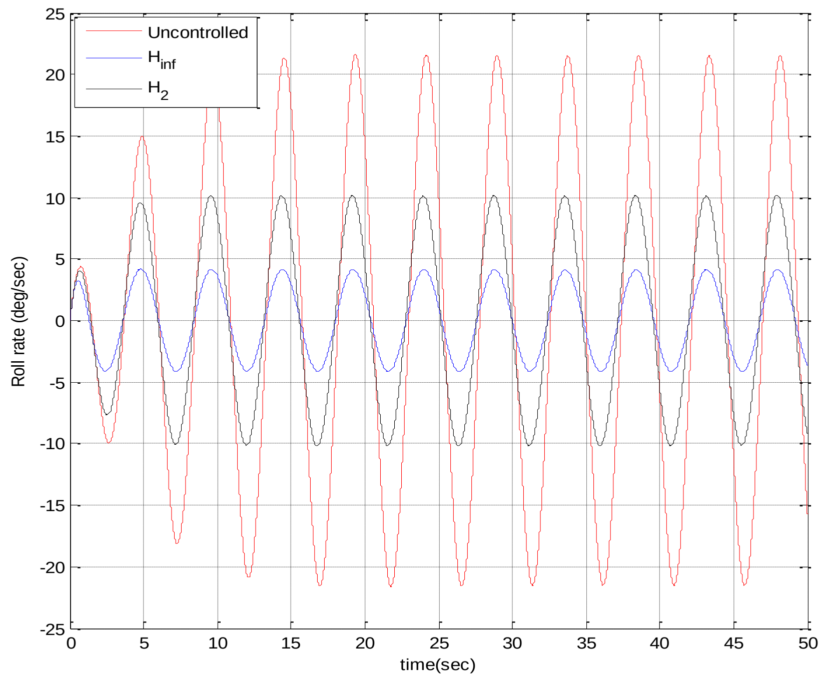

Figure 9. Comparison of roll angular velocity response

It is clear from the above that the effectiveness of the fin controller will depend on the H_∞ and H_2 controller performance. It is also seen that in general a greater reduction in roll is always associated with larger fin actions. Figure 10 shows the frequency responses of the roll motion for both controlled and uncontrolled cases. Since the system has one degree of freedom, there is a resonance frequency points at 1.31 Hz. When the response plots of the roll motion with uncontrolled and controlled cases are compared, good improvement of the resonance values is observed with the proposed controllers.

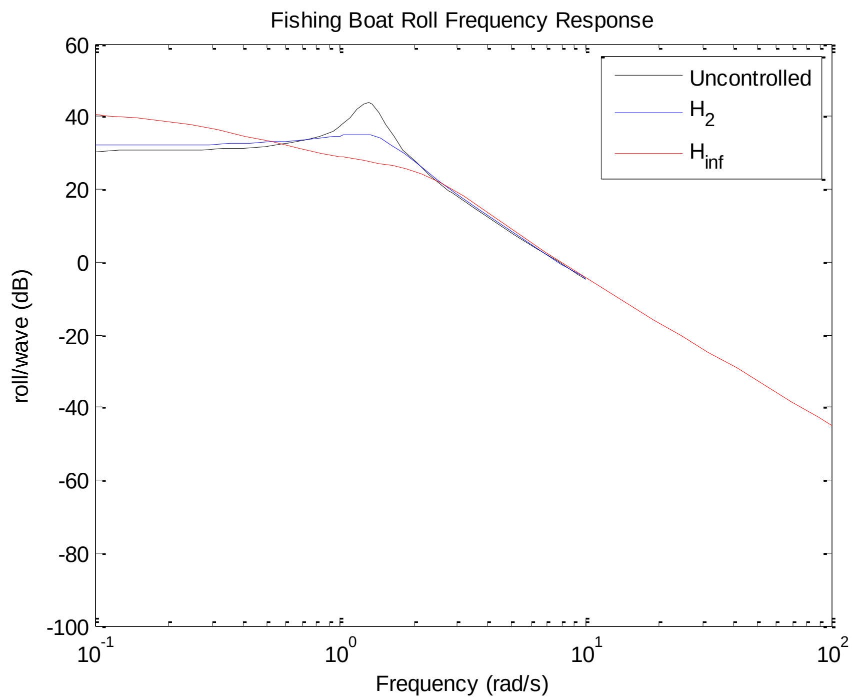

Figure 10. Frequency responses of the roll motion

6. Conclusions

In this study, nonlinear roll motion of a fishing boat, which will be capable of operating in the Black Sea and the Mediterranean Sea, was controlled by fin stabilizer system. The Computational Fluid Dynamics (CFD) calculations for the lift are carried out using Star CCM + software. A random sea is assumed for the input to cause roll. The H_∞ and H_2 controller algorithm for a fishing boat have been designed and simulation results have been presented. The control problem was formulated that considered the angles of both fins as control commands. Regarding the rolling motion as the H_∞ and H_2 control variable, it is shown that the fin roll stabilizer performance is the effective roll stabilized by H_∞ and H_2 control methods. As can be seen in the simulation results, H_∞ controller is achieved better performance by comparison with H_2 controller concerning roll reduction.

REFERENCES

[1] Blanke, M., Christensen, A., 1993. Rudder roll damping autopilot robustness to sway-yaw-roll couplings. In. Proc. of 10th SCSS, 93-119, Ottowa, Canada.

[2] Moaleji, R., Greig, A.R., 2007. On the development of ship anti-roll tanks. Ocean Engineering, 34: 103-121. http://dx.doi.org/10.1016/j.oceaneng.2005.12.013.

[3] Surendran, S., Lee, S.K., Kim, S.Y., 2007. Studies on an algorithm to control the roll motion using active fins. Ocean Engineering, 34: 542–551. http://dx.doi.org/10.1016/j.oceaneng.2006.01.008.

[4] Perez, T., Goodwin, G.C., 2008. Constrained predictive control of ship fin stabilizers to prevent dynamic stall. Control Engineering Practice, 16: 482–494. http://dx.doi.org/10.1016/j.conengprac.2006.02.016.

[5] Fang, M.C., Lin, Y.H., Wang, B.J., 2012. Applying the pd controller on the roll reduction and track keeping for the ship advancing in waves. Ocean Engineering, 54: 13-25. http://dx.doi.org/10.1016/j.oceaneng.2012.07.006.

[6] Koshkouei, A.J., Lukas, N., 2012. Stabilisation of ship roll motion via switched controllers. Ocean Engineering, 49: 66-75. http://dx.doi.org/10.1016/j.oceaneng.2012.04.002.

[7] Lauvdal, T., Fossen, T., 1997. Nonlinear rudder-roll damping of non-minimum phase ships using sliding mode control. In. Proc. of the European control conference, Brussel, Belgium.

[8] Alarcin, F., Gulez, K., 2007. Rudder roll stabilization for fishing vessel using neural network approach. Ocean Engineering, 34-13: 1811-1817.

[9] Holden, C., Galzeazzi, R., Fossen, T.I., Perez, T., 2009. Stabilization of parametric roll rezonance with active u-tanks via lyapunov control design. Proceedings of the European Control Conference, 4889-4894, Hungary.

[10] Galeazzi, R., Christian, H., Mogens, B., Fossen, T.I., 2009. Stabilisation of parametric roll resonance by combined speed and fin stabiliser control. Proceedings of the European Control Conference, 4895-4900, Budapest, Hungary,

[11] Guan, W., Zhang, X.K., 2010. Concise robust fin roll stabilizer design based on integrator backstepping. IEEE:1-10. http://dx.doi.org/10.1109/isscaa.2010.5632500.

[12] Ghassemi, H., Dadmarzi, F.H., Ghadimi, P., Ommani, B., 2010. Neural network-pid controller for roll fin stabilizer. Polish Maritime Research, 17: 23-28. http://dx.doi.org/10.2478/v10012-010-0014-3.

[13] Karakas, Ş.C., Uçer, E., Pesman, E., 2012. Control design of fin roll stabilization in beam seas based on lyapunov's direct method. Polish Maritime Research, 2 (73), 19: 25-30.

[14] Kose, S., 2007. Nonlinear control of variable speed wind turbines. Msc Thesis, GYTE.

[15] Su, K.H., 2011. Active fin for ship stabilization system using heuristic genetic optimization. Proc IMech E, Part I: J Systems and Control Engineering, 226(5): 665-677. http://dx.doi.org/10.1177/0959651811427003.

[16] Dalzell, J.F., 1978. A note on the form of ship roll damping. Journal of Ship Research, 22.

[17] Alarçin, F., Demirel, H., Su, M. E., & Yurtseven, A. (2014). Conventional PID and Modified PID Controller Design for Roll Fin Electro-Hydraulic Actuator. Acta Polytechnica Hungarica, 11(3).

[18] Chakrabarti, S., 2001. Empirical calculations of roll damping for ships and barges. Ocean Engineering, 28(7): 915-932. http://dx.doi.org/10.1016/S0029-8018(00)00036-6.

[19] Bullian, G., 2005. Nonlinear parametric rolling in regular waves- a general procedure for the analytical approximation of the GZ curve and its use in time domain simulations. Ocean Engineering, 32: 309-330. http://dx.doi.org/10.1016/j.oceaneng.2004.08.008.

[20] Taylan, M., 1999. Solution of the nonlinear roll model by a generalized asymptotic method. Ocean Engineering, 26: 1169-1181. http://dx.doi.org/10.1016/S0029-8018(98)00064-X.

[21] Liu, J., Allen, R., Yi, H., 2010. Ship motion stabilizing control using a combination of model predictive control and an adaptive input disturbances predictor. Proc IMech E, Part I: J Systems and Control Engineering, 225: 591-602. http://dx.doi.org/10.1177/2041304110394569.

[22] Taylan, M., 2000. The effect of nonlinear damping and restoring in ship rolling. Ocean Engineering, 27: 921-932. http://dx.doi.org/10.1016/S0029-8018(99)00026-8.

[23] Surendran, S., Venkata, R., Reddy, R., 2002. Roll dynamics of a ro-ro ship, International ship building progress, 49-4: 301-320.

[24] J.C. Doyle, K. Glover, P.P. Khargonekar, B.A. Francis, “State-space solutions to standart H_2 and H_∞ control problems”, IEEE Transactions on Automatic Control, Vol. 34, No. 8, pp. 831-847, 1996. http://dx.doi.org/10.1109/9.29425.

[25] B.A. Francis, “A course in H∞ control theory”, Lecture Notes in Control and Information Sciences 88, Edited by M. Thoma and A. Wyner, Springer-Verlag, 1987. http://dx.doi.org/10.1007/bfb0007371.

[26] Yazici, H., & Güçlü, R. (2011). Active vibration control of seismic excited structural system using LMI-based mixed H2/H∞ state feedback controller. Turkish Journal of Electrical Engineering & Computer Sciences, 19(6), 839-849

[27] K. Nonami, S. Sivrioglu, “Active vibration control using LMI-based mixed H_2/H_∞ state and output-feedback control with nonlinearity”, Proc. of the 35th IEEE Conference on Decision and Control (CDC), pp. 161-166, Kobe, 1996. http://dx.doi.org/10.1109/CDC.1996.574282.

[28] J. Lfberg, “Yalmip: a toolbox for modeling and optimization in MATLAB”, Proceedings of the CACSD Conference,Taipei, Taiwan, 2004. http://dx.doi.org/10.1109/cacsd.2004.1393890.

[29] Aydin, M., Akyildiz, H., 2005. Assessment of the intact stability characteristics of the fishing boats suitable for turkish water. ITU publications, 4.

[30] Kawazoe, T., Nishikido, S., & Wada, Y. (1994). Effect of fin area and control methods on reduction of roll motion with fin stabilizers. Bulletin of the MESJ,22(1), 25-32

Submitted: 27.12.2015.

Accepted: 23.09.2016.

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