BACKSTEPPING CONTROL OF NONLINEAR ROLL MOTION FOR A TRAWLER WITH FIN STABILIZER

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SUMMARY

A backstepping control design procedure for nonlinear fin roll control of a trawler is presented in this paper. A roll equation consisting of linear and nonlinear damping and restoring moment on the roll response is expressed. Flow analyses are carried out for a scaled model of trawler type fishing vessel including fin stabilizers on both sides of the hull. The fin stabilizer geometry is chosen as NACA 0015 foil section which is widely used in the literature. The flow analyses are performed by using a commercial computational fluid dynamics (CFD) software based on finite volume method. The flow problem is modeled in a 3-dimensional manner while the flow is considered as steady, incompressible and fully turbulent. The numerical model consists of the ship wetted surface and the fin stabilizer in order to investigate the hull-fin interaction. Non-dimensional lift coefficients of the fin stabilizer for different angles of attack are gained. Both controlled and uncontrolled roll motions are examined and simulated in time domain for the maximum lift coefficient. Backstepping controller for roll motion has given a rapid and precise result.

1. INTRODUCTION

The roll motion of ships in external sea conditions is very difficult to control due to nonlinear effects. By these reasons, roll motion control has been an attractive area for many researchers in recent years. To attenuate the roll due to the waves, fin roll stabilizer is proposed.

Dalzell (1978) developed a solution method for linear ship rolling motion using the roll extinction data obtained from free vibration experiment for the analysis. Zborowsky and Taylan (1989) examined a small vessel's roll motion stability and evaluated for resonance conditions. Fossen (1994, 2002) studied ship motion control systems and expressed solutions for linear and nonlinear models. Surendran et al. (2007) studied PID control algorithm for roll motion of a frigate using active fins and determined lift characteristics of the fins in hydrodynamic flow using CFD software ANSYS Fluent. Zhang et al. (2006) designed nonlinear backstepping robust control algorithm of ship navigation. Perez and Goodwin (2008) suggested the use of a model predictive control (MPC) for ship fin stabilizers to prevent dynamic stall. Alarcin et al. (2014a, 2014b) designed PID controller for roll fin actuator of a fishing boat. Lee at al. (2005) carried out effect of live fish tanks orientation, arrangement of baffles inside the tank for non-linear roll motion which is caused by the sloshing effects of the mass and free surface in the live fish tank. Dadras and Momeni (2009) examined the adaptive control for roll motion of a ship as a nonlinear system with five equilibrium points which faces external disturbance. The main aim is to design a durable controller under the external sinusoidal disturbances. Ghassemi et al. (2010) presented results of PID and combined neural network for roll motion control of a ship with low draught. The acquired results demonstrate good performance of the controller in decreasing roll amplitude in random seas. Therefore, this approach can be used also for any irregular sea conditions. Li et al. (2015) worked on adaptive backstepping with neural network technique for the ship roll stabilization using Lyapunov function to specify system stabilization and to determine unknown parameters of problem.

In this paper, flow around a trawler type fishing boat is investigated numerically by using a commercial CFD software. The flow is modeled in 3-dimensionally including fin stabilizers on both sides of the hull with a scale factor of 8. Wetted surface of the ship with the fins is examined in order to calculate non-dimensional lift coefficients of the fin at different angles of attack. The angle of attack giving the maximum lift force is chosen for backstepping controller design. Back stepping controller is designed for absorbing the roll motion of the trawler. The results of backstepping controller is compared with the uncontrolled condition by means of roll amplitude and roll angular velocity. It is seen that the backstepping controller performance is satisfactory.

1.1 THE MATHEMATICAL MODEL OF ROLL MOTION

In order to discretize the mathematical equation, some important assumptions are made in modelling the roll motion of the trawler model by neglecting all other degrees of freedom. After these simplifications, trawler roll motion equation can be suggested by the following nonlinear expression;

$$(I+J)\,\ddot{\varphi}+B_1\dot{\varphi}+B_2\dot{\varphi}|\dot{\varphi}|+B_3\dot{\varphi}^3+\Delta(C_1\varphi+C_3\varphi^3+C_5\varphi^5+C_7\varphi^7)=\omega_e^2\,\alpha_m\,I\cos(\omega_e t)-M_F \tag{1}$$

Angle, angular velocity and angular acceleration of roll motion are represented as $\varphi,\dot{\varphi},\ddot{\varphi}$, respectively. I and J are described by the mass moment of inertia and the added mass moment of inertia. B_1, B_2, B_3 are considered as roll damping coefficients while C_1, C_3, C_5 and C_7 are expressed as restoring force coefficients and Δ, as the weight displacement of the ship. ω_e is used for the wave encountering frequency and α_m is expressed as the maximum wave slope. Finally, M_f is the control moment of active fins.

Dividing the equation (1) throughout by $(I+J)$,

$$\ddot{\varphi}+b_1\dot{\varphi}+b_2\dot{\varphi}|\dot{\varphi}|+b_3\dot{\varphi}^3+\Delta(c_1\varphi+c_3\varphi^3+c_5\varphi^5+c_7\varphi^7)= \frac{\omega_e^2\,\alpha_m\,I\cos(\omega_e t)}{I+J}-\frac{M_F}{I+J} \tag{2}$$

These inertia values can be calculated as follow (Guan & Zhang, 2010):

$$(I+J)=\frac{\Delta}{12\,g}(B^2+4\,KG^2) \tag{3}$$

A non-dimensional damping coefficient for a trawler is expressed as follows:

$$B_1=\frac{2\,a\sqrt{(I+J)\Delta GM}}{\pi} \tag{4}$$

$$B_2=\frac{3}{4}b(I+J) \tag{5}$$

$$B_3=0.7\,B_2 \tag{6}$$

These coefficients, given a (0.1) and b (0.0140) (Guan & Zhang, 2010) are directly related to a linear damping coefficient B_1 and a non-linear damping coefficient B_2 represents quadratic drag and B_3 is cubic.

The restoring moment for roll motion can be approximated by the polynomial.

$$M(\varphi)=c_1\,\varphi+c_3\,\varphi^3+c_5\,\varphi^5+c_7\,\varphi^7+\ldots \tag{7}$$

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 expressed as follow:

$$C_1=\frac{d\,(GZ)}{d\,\varphi}=GM \tag{8}$$

$$C_3=\frac{4}{\varphi_v^4}(3\,A_{\varphi v}-GM\,\varphi_v^2) \tag{9}$$

$$C_5=-\frac{3}{\varphi_v^6}(4\,A_{\varphi v}-GM\,\varphi_v^2) \tag{10}$$

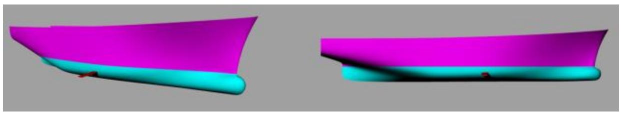

Figure 1. General CAD view of the trawler model

As can be seen from Figure 1, the fin stabilizers and the ship hull are modeled together in order to estimate the hull-fin interaction by means of lift coefficient of the fin. Main particulars of the ship and fin stabilizer are given in table 1. The fin section is taken as NACA 0015.

Table 1. Main particulars of the ship and fin stabilizer

	Model	**Ship**
Scale	1/8	1
L_{BP} (m)	5.183	41.469
B_{WL} (m)	1.320	10.561
T_M (m)	0.311	2.495
S (m^2)	6.340	405.818
Δ (t)	1.078	552.3
C_B	0.514	0.514
GM (m)	0.080	0.645
KG (m)	0.562	4.5
V_S (knot)	3.535	10
A_F (m^2)	0.075	4.8

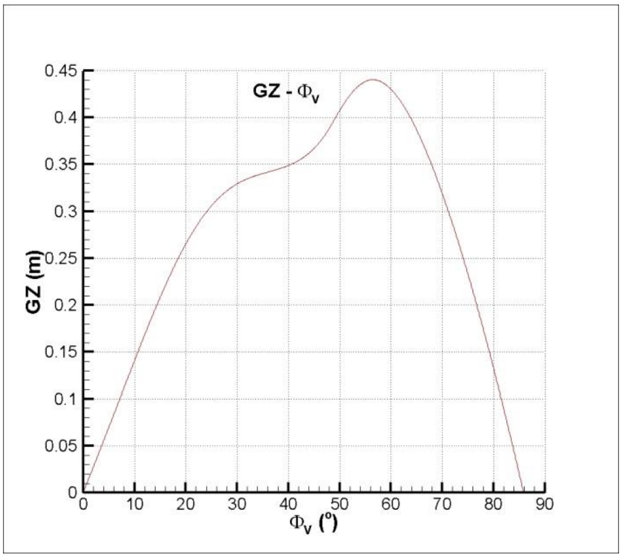

Figure 2. Restoring arm – Vanishing angle graph

Figure 2 represents the relation between GZ and Φ_V. The area under the curve given in Figure 2 is calculated as 0.4147 rad-m. while the vanishing angle is 85.9°.

2. ROLL FIN ACTUATOR

In this study, to overcome the roll due to the waves, two fin roll stabilizers are proposed. Fin stabilizer is a hull stability equipment for reduction of hull rolling by generating lift, extended to the both sides of a hull. The lift force and the lift coefficient in non-dimensional form are expressed as follow:

$$L = \frac{1}{2}\rho V^2 A_F C_L \tag{11}$$

$$C_L = \frac{L}{0.5\rho V^2 A_F} \tag{12}$$

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). Fin roll moment is expressed as below;

$$M_F = \rho V^2 A_F C_L I_F(\alpha_F + \frac{\dot{\varphi}}{v}\ I_F) \tag{13}$$

$$fs_1 = \rho V^2 A_F C_L I_F\ ,\ fs_2 = \frac{\rho V^2 A_F C_L I_F}{v}\ I_F \tag{14}$$

M_F is the fin roll stabilizer moment; I_F is the fin force arm; α_F is the angle of attack.

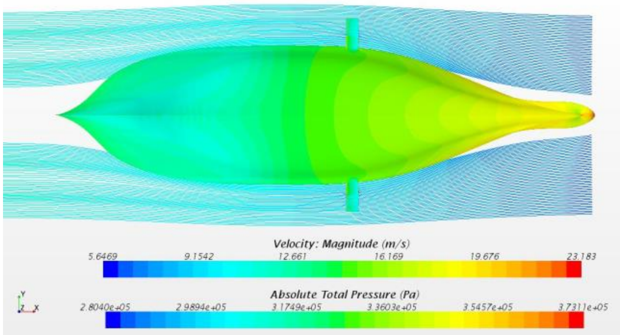

Figure 3. Pressure contour with velocity vectors along the hull and the fin stabilizer at AoA 45°

It can be seen clearly in Figure 4 that the flow around the hull with the fin stabilizer follows a smooth pathline. This is the case which gives the maximum lift force at 45°.

Figure 4 gives the correlation between the lift coefficient and the angle of attack. The numerical flow analyses are performed for the ship model with the fin stabilizers on both sides for a constant, uniform flow velocity at different angles of attack. Range of the angle changes between 0°<AoA<60°. The fin stabilizer reaches the maximum lift coefficient at the angle of 45° while the fin starts to stall just after 45°. The backstepping controller for the roll motion is modeled for the case which the fin creates the maximum lift.

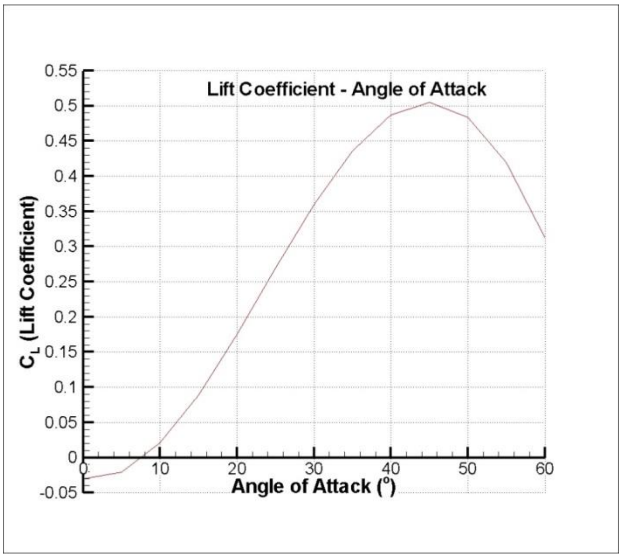

Figure 4. Lift coefficient – Angle of attack (AoA) graph

3. A BACKSTEPPING CONTROL FOR A TRAWLER

A trawler type fishing vessel is called stable when it has enough positive stability to counter the external forces generated by a fishing conditions and it will return to its upright position. Lyapunov function V_x satisfying

$$V_x > 0 \quad \text{positive definite and} \quad V(0)=0 \tag{15}$$

$$\frac{dV(\vec{x})}{dt} \le 0 \tag{16}$$

$$\mathrm{V(x)} \to \infty \quad \text{as} \quad \|\mathrm{x}\| \to \infty \tag{17}$$

Lyapunov second method can be used to test the roll stability.

$$\dot{V}(t) = \frac{dV(\vec{x})}{dt} = \tilde{N}V^T\vec{\dot{x}} \tag{18}$$

If this value is smaller than zero, non-linear roll motion can be said to be stable. Lyapunov function is obtained depending on the non-linear roll damping coefficient.

$$\dot{V}(x) = -\varphi_2^2(b_1 + b_2|\varphi_2| + b_3\varphi_2^2) < 0 \tag{19}$$

$$V(x) = \omega_0^2\frac{\varphi_1^2}{2} + c_3\frac{\varphi_1^4}{4} + c_5\frac{\varphi_1^6}{6} + \frac{\varphi_2^2}{2} \tag{20}$$

Backstepping control methods offer a systematic procedure for the construction of Lyapunov function which guarantees the stability of the roll motion. The main idea of backstepping can be demonstrated by considering a nonlinear scaler system

$$\dot{x}_1 = f_1(x_1) + g_1(x_1)x_2$$
$$\dot{x}_2 = f_2(x) + g_2(x)u_F \qquad (21)$$

One can assume that

$$g_1(x_1)\ 0 \qquad " x_1\ \hat{I}\ R$$
$$g_2(x)\ 0 \qquad " x_1\ \hat{I}\ R^2 \qquad (22)$$

This is a cascade connection of two components of which the first is an integrator in Figure. 5.

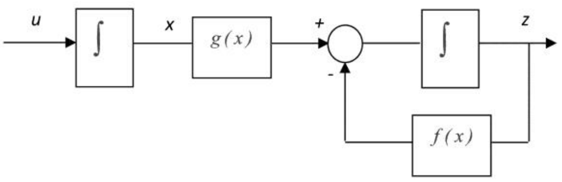

Figure 5. Backstepping initial system (Fossen & Strand, 1999)

By using state variables of equation (2), the model of the ship can be written as.

$$\ddot{\varphi} + b_1\dot{\varphi} + b_2\dot{\varphi}\,|\,\dot{\varphi}\ | + b_3\dot{\varphi}^3 + \Delta(c_1\varphi + c_3\,\varphi^3 + c_5\,\varphi^5 + c_7\,\varphi^7\ ) =$$
$$W - fs_1\,\alpha_F - fs_2\,\dot{\varphi} \qquad (23)$$

The exciter (electro-hydraulic system) dynamics of fin stabilizer system is assumed to be governed by the diagram given in Figure 6.

$$\dot{\alpha}_F + t_1\,\alpha_F = t_2\,u_F \qquad (24)$$

where α_F is the actuator output (actual fin angle), u is the input to the electro-hydraulic systems.

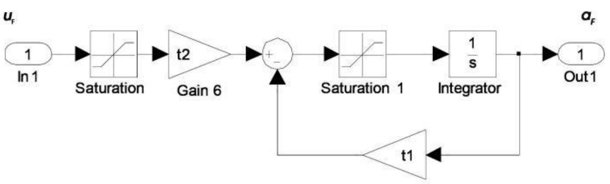

Figure 6. Block diagram of fin stabilizer system

$$\dot{\phi} = x_1\ ,\ \ \alpha_F = x_2$$

The state space model for a nonlinear roll motion and fin roll stabilizer,

$$\dot{x}_1 = -(b_1 + fs_2)\,x_1 - b_2 x_1|x_1\ | - b_3 x_1^3$$
$$-\omega_0^2\int x_1\,dt - c_3\int x_1^3\,dt - c_5\int x_1^5\,dt - c_7\int x_1^7\,dt + W - fs_1\,x_2$$
$$\dot{x}_2 = -t_1\,x_2 + t_2\,u_F \qquad (25)$$

The design of the speed controller is made by applying classical Lyapunov theory, whereas the fin stabiliser is designed by applying backstepping. There are two main steps in the backstepping controller design.

Step 1: In the first step, the control error z_1 is defined as follow:

$$z_1 = y - y_r = x_1 - y_r$$
$$z_2 = x_2 - \alpha(z_1, y_r) \qquad (26)$$

The stabilizing function is defined as α . The new state variable z_2 will not be used in the first step. The derivative of z_1 is computed as:

$$\dot{z}_1 = \Big[-(b_1 + fs_2)(z_1 + y_r) - b_2|z_1 + y_r|(z_1 + y_r) - b_3(z_1 + y_r)^3\Big]$$
$$\begin{bmatrix} -\omega_0^2\int(z_1 + y_r)\,dt - c_3\int(z_1 + y_r)^3 dt \\ -c_5\int(z_1 + y_r)^5\,dt - c_7\int(z_1 + y_r)^7\,dt - fs_1\left[z_2 + \alpha(z_1, y_r)\right] - \dot{y}_r \end{bmatrix} \qquad (27)$$

According to the back stepping procedure, the first Lyapunov function and its derivative are

$$V_1(z_1) = \frac{1}{2}z_1^2 \qquad (28)$$
$$\dot{V}_1(z_1) = z_1\,\dot{z}_1$$

Substituting

$$\dot{V}_1(z_1) = -m_1 z_1^2 + fs_1\,z_1\,z_2 \qquad (29)$$

where m_1 is a positive design parameter. The "undesired" effects of z_2 on $\dot{V}_1$ will be dealt with at the next step.

Step 2: In the second step, z_2 is presented depending on x_2 and $\alpha(z_1, y_r)$.

$$z_2 = x_2 - \alpha(z_1, y_r) \qquad (30)$$

The derivative of z_2 is computed as,

$$\dot{z}_2 = \dot{x}_2 - \dot{\alpha}(z_1, y_r) \qquad (31)$$

The augmented Lyapunov function is:

$$V_2 = V_1 + \frac{1}{2} z_2^2 \tag{32}$$

The derivative of the V_2 is computed as:

$$\dot{V}_2 = \dot{V}_1 + z_2 \dot{z}_2 \tag{33}$$

$$\dot{V}_2 = -m_1 z_1^2 - m_2 z_2^2 \leq 0 \tag{34}$$

Since $\dot{V}_1 \leq 0$, it implies that z_1 and z_2 are bounded. It is ensured that z_1 and z_2 are converged to zero as $t \to \infty$. Backstepping controller guarantees asymptotical stability of the roll motion. When implementing the control law, α is written as (see eq35),

The control action is selected as,

$$u_F = \frac{1}{t_2}\begin{bmatrix} -m_2 z_2 + fs_1 z_1 + t_1 x_2 + \dfrac{\partial \alpha}{\partial z_1}\left(-m_1 z_1 - fs_1 z_2\right) \\ + \dfrac{\partial \alpha}{\partial yr}\dot{y}_r + \dfrac{\partial \alpha}{\partial \dot{y}r}\ddot{y}_r \end{bmatrix} \tag{36}$$

The simulink diagram of the back stepping controller on the fin stabilizer system, shown in Figure 7.

4. SIMULATION

For the effective controlling of fin stabilizers, backstepping controller is preferred. Two fins placed on both sides of the vessel are controlled in a different way to overcome unsymmetrical behaviour resulting from free surface effects. A controller based on backstepping algorithm is designed to reduce roll amplitudes. It is observed from the results that the fin control system is successful to reduce the roll amplitudes to a reasonable value.

Comparisons of roll amplitude, roll angular velocity and frequency diagram of controlled and uncontrolled roll motion are shown in the following figures.

Figure 8 and Figure 9 show roll amplitude and roll velocity response both for contolled and uncontrolled condition, respectively. The backsepping controller decreases the roll motion rapidly to zero after 25 seconds.

$$\alpha(z_1, y_r) = -\frac{1}{fs_1}\begin{bmatrix} m_1 z_1 - \left(b_1 + fs_2\right)\left(z_1 + y_r\right) \\ -b_2\left|z_1 + y_r\right|\left(z_1 + y_r\right) - b_3\left(z_1 + y_r\right)^3 \end{bmatrix}$$
$$\left[-\omega_0^2 \int\left(z_1 + y_r\right)dt - c_3\int\left(z_1 + y_r\right)^3 dt - c_5\int\left(z_1 + y_r\right)^5 dt - c_7\int\left(z_1 + y_r\right)^7 dt - \dot{y}_r\right] \tag{35}$$

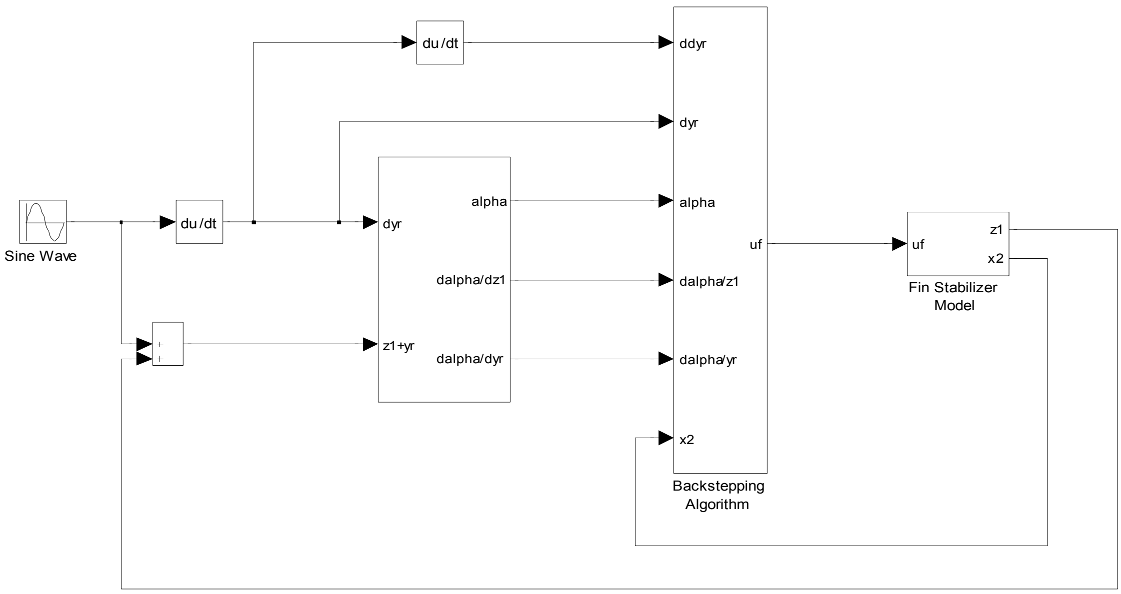

Figure 7. Backstepping controller for roll fin stabilizer simulink diagram

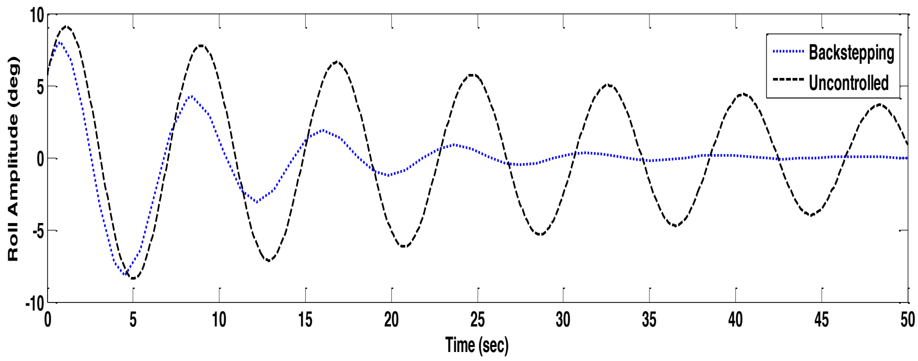

Figure 8. Roll Amplitude Response for Uncontrolled and Controlled Condition

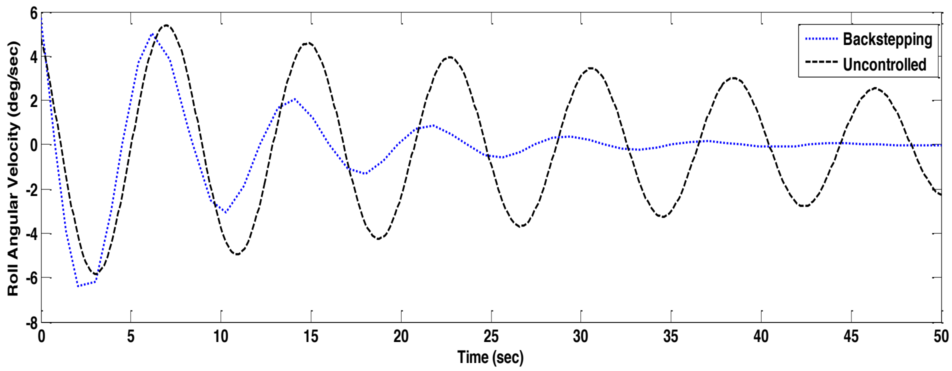

Figure 9. Roll Velocity Response for Uncontrolled and Controlled Condition

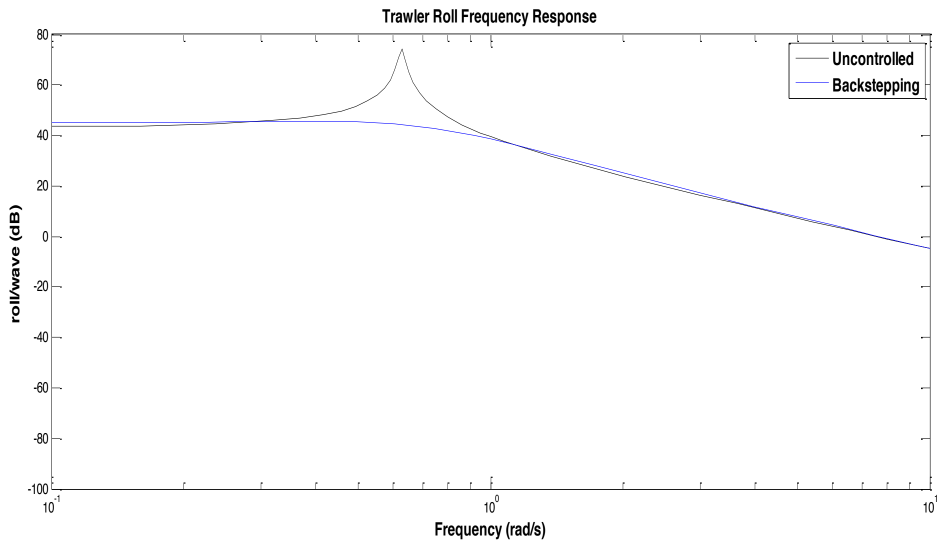

Figure 10. Frequency Simulation for Uncontrolled and Controlled Condition

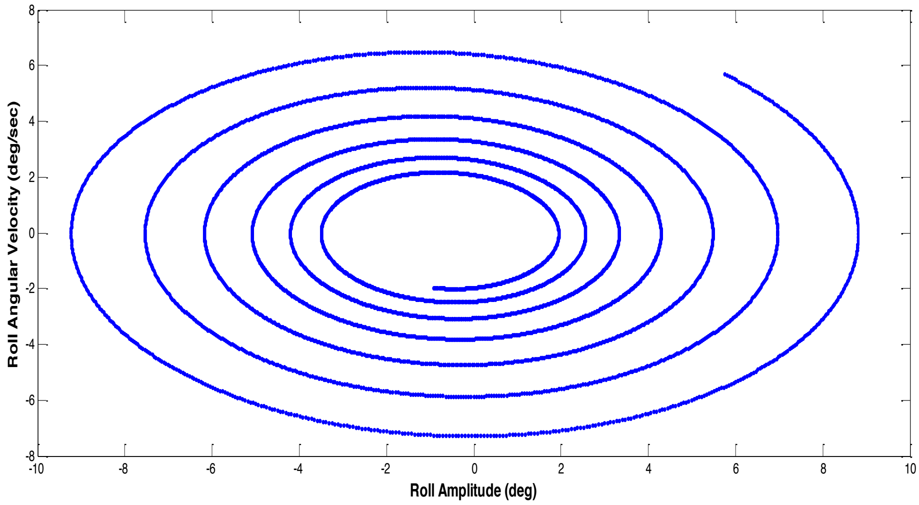

Figure 11. Phase Diagram for the Nonlinear Roll Model

Figure 10 represents the frequency simulation for both conditions while Figure 11 gives phase diagram for the non-linear roll. The frequency peak is minimized by the backstepping controller to control the roll motion. The phase diagram shows that the system is in a stable condition.

5. CONCLUSION

In the present study, in order to improve the roll stabilizer performance and to decrease undesirable roll motion, backstepping control is preffered which offers a systematic procedure to construct the Lyapunov functions and related stabilizing feedback control laws. In this manner, a numerical model is created including the ship wetted surface and the fin stabilizers on both sides of the ship. The flow around the model ship is discretized by means of a computational fluid dynamics approach. In this regard, the interaction between the ship hull and the fin stabilizers is taken into account. With this assumption, the lift coefficient of the fin at different angles of attack is calculated more precisely. The maximum lift coefficient is chosen for modeling a backstepping controller. This is accomplished with the backstepping algorithm. Regarding the rolling motion as the control variable, it is shown that the fin stabilizer is globally stabilized by backstepping control law.

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