INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH & DEVELOPMENT

ISSN: 2278 – 0211 (Online)

A Study On The Effectiveness Of Active Fin Roll-Stabilizers Through Numerical Simulation

Debabrata Sen,
Professor, Department of Ocean Engineering and Naval Architecture, Indian Institute of Technology Kharagpur, India.
Jai Ram Saripilli,
Assistant surveyor, at Indian Register of Shipping, Mumbai, India

Abstract:

The effectiveness of a given fin on the roll motion of a given naval platform over a range of speed, heading, loading conditions are studied. The roll motions of the hull are determined based on both coupled sway-roll-yaw equations and uncoupled roll equations, and it is found that roll predictions can be significantly different from these two sets of equations suggesting a strong coupling between particularly sway and roll. The effect of the active fins given by a generic control equation where the fin angle depends on roll angle, roll velocity as well as roll acceleration is added within the equation of motion to determine the roll with the controls working. Results of the numerically simulated roll over different frequency and speed ranges for different control parameters for the chosen hull show that at higher speeds the roll can be reduced by as much as a factor of 6, while at lower speeds, this factor is somewhat low, of the order of 3.

1.Introduction

Active fin roll stabilizer devices are fitted in many classes of ships, in particular in naval ships, for keeping roll motions within acceptable limits. However since this devices are generally more expensive compared to passive roll-control devices, it is essential that their effectiveness in controlling roll is first established. The effectiveness of any roll control device in controlling motion depends on the motion characteristics of the given hull which in turn depends on ship speed and heading, the wave environment or sea condition, and the additional roll-damping that the device produces. For an active fin roll–stabilizer, although primarily the device produces an additional roll damping, it can also change the systems inertia and restoring characteristics depending on the control strategy used. Clearly for a given control parameters, the effectiveness will vary over the range of parameters such as wave-frequency, speed and heading. In designing the control parameters of the device, it is necessary to see that the device does not unnecessarily move when its effectiveness in controlling roll is very small and/or the absolute values of roll of the hull itself are low, eg. in high–frequency waves.

2.Ship Motion Computations

Ship motions are computed using a complete 6 degrees of freedom (dof) forward speed ship-motion code based upon the Salvesen-Faltinsen-Tuck version of the strip theory, popularly referred to as the STF version (Salvesen *et. al.* 1970). The 6dof equation of motion of a ship undergoing oscillatory motion under the action of regular incident waves is given by:

$$\sum_{k=1}^{6}\left[-\omega_e^2\left(M_{jk}+A_{jk}\right)+i\omega_e B_{jk}+C_{jk}\right]\bar{\eta}_k = F_j^{EX}$$
$$= F_j^I + F_j^D \; ; j = 1,2,\ldots,6 \qquad (1)$$

where $\bar{\eta}_k$ are the complex amplitude of the displacements in the kth mode of motion, A_{ij}, B_{ij}, C_{ij} are respectively added mass, damping and restoring force coefficients, F_i is force where the superscript EX, I, D means exciting, incident and diffraction respectively. ω_e is frequency of encounter given by:

$$\omega_e = \left|\omega - \frac{\omega^2}{g} U \cos\mu\right| \qquad (2)$$

Here μ is wave heading angle, defined as the angle between the direction of wave propagation and forward speed (or +ve $x$axis), ω is absolute wave frequency and U is the forward speed of the ship. Thus μ = 0, 45,90, 135 and 180 deg. mean respectively following, stern-quartering, beam, bow-quartering and head waves.

$$\eta_j(t) = \Re\{\bar{\eta}_j e^{i\omega_e t}\} = |\bar{\eta}_j| \cos(\omega_e t + \beta_j) \ ;$$
$$\bar{\eta}_j = \Re\{\bar{\eta}_j e^{i\omega_e t}\} \qquad (3)$$

where $\bar{\eta}_j$ is the absolute amplitude of the motion displacement in j^{th} mode, β_j is phase angle, and $\Re(\,)$ means the real part of the quantity in parenthesis is to be taken. Subscripts $j = 1,2,3,4,5,6$ refer to the six modes of motions surge, sway, heave, roll, pitch and yaw respectively. Thus $\eta_j, j = 1,2,..,6$ are respectively surge, sway, heave, roll, pitch and yaw motions displacements.

For a ship that is symmetric about its centreplane, the 6dof eqns. (1) gets decoupled into two sets of 3dof equations, one for surge-heave-pitch and the other for sway-roll-yaw. The coupled sway-yaw-roll equations are:

$$(M + A_{22})\ddot{\eta}_2 + B_{22}\dot{\eta}_2 + A_{24}\ddot{\eta}_4 + B_{24}\dot{\eta}_4 + A_{26}\ddot{\eta}_6 + B_{26}\dot{\eta}_6 = F_2^{EX} e^{i\omega_e t}$$
$$A_{42}\ddot{\eta}_2 + B_{42}\dot{\eta}_2 + (I_{44} + A_{44})\ddot{\eta}_4 + B_{44}\dot{\eta}_4 + C_{44}\eta_4 + A_{46}\ddot{\eta}_6 + B_{46}\dot{\eta}_6 = F_4^{EX} e^{i\omega_e t}$$
$$A_{62}\ddot{\eta}_2 + B_{62}\dot{\eta}_2 + A_{64}\ddot{\eta}_4 + B_{64}\dot{\eta}_4 + (I_{66} + A_{66})\ddot{\eta}_6 + B_{66}\dot{\eta}_6 = F_6^{EX} e^{i\omega_e t} \qquad (4)$$

According the strip-theory, the added mass and damping can be expressed as integration of the 2D sectional values with some correction for the forward speed effect. The complete expression can be found in (Lewis 1989)

The degenerated form of sdof roll eqn. is easily recovered from (4) :

$$(I_{44} + A_{44})\ddot{\eta}_4 + (B_{44} + B_{44}^*)\dot{\eta}_4 + C_{44}\eta_4 = F_4^{EX} e^{i\omega_e t} \qquad (5)$$

where the roll viscous damping B_{44}^{*} has been added. This is to be also added to roll damping in (4). In the present work, the latest component based method of computing this term as given in ITTC2011 has been used.

Computations here are performed for a naval ship, the details of which cannot be given for confidentiality reasons.However, the approximate dimensions of the vessel are: length 135: m, length/ breadth:8.5, length/draft: 28 displacement : 5000t. This means, the vessel has a C_B of about 0.50, indicating that it is a fine hull form.

Sample results for roll RAO computed based on both coupled equations and sdof roll equation are shown in fig. 1. It can be seen that there can be significant difference in the computed roll, suggesting that for this hull there is a significant roll-sway coupling effect.

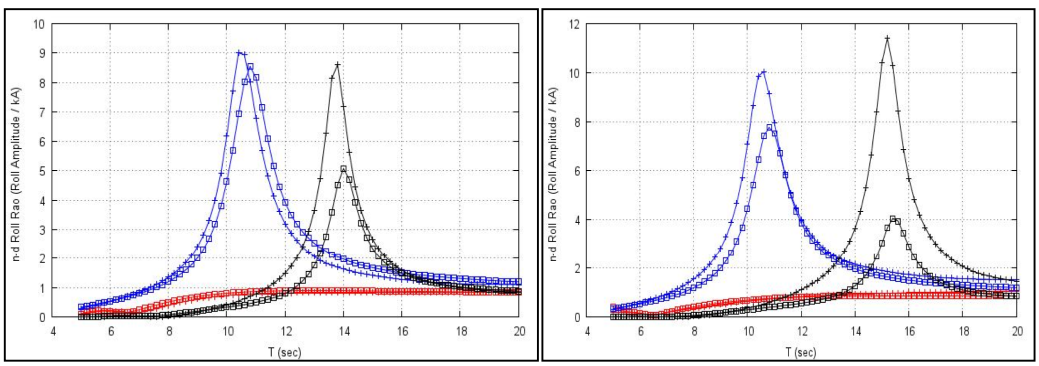

Figure 1: Non-dimensional roll RAO for the different hulls (Headings: red-45 deg; blue-90deg; black-135deg.) (+ symbol: calculation with 6dof motion, square symbol: calculation for sdof roll)

3.Fin Characteristics

In order to determine the stabilization effect of the fin, it is essential to first determine the lift produced by the fin. Lift and drag of the fin are dependent on its geometric parameters. The present fin is of rectangular platform with chord (c) and span (s) ratio of 1/1.4. The fin is flap-type with the flap-length (l_f) 25% of the chord length, $l_f/c = 1/4$. The foils are symmetrical NACA00xx sections where xx represents the percentage of thickness to chord. The flap angle β is not fixed but varies with the angle of attack α.

The CFD calculations for the lift and drag for this fin is carried out using a commercial CFD solver CFX. This is a RANSE based CFD solver and uses a vertex-centred based scheme. A standard $k - \varepsilon$ turbulence model is used. The boundary conditions used are: inlet velocity at the inlet boundary, pressure condition at the outlet boundary, free-slip wall boundary conditions at the top, bottom and the two sides of the fluid domain, and a no-slip smooth wall condition on the surface of the foil. These are the standard conditions for CFD solution of a problem of the type at hand. Calculations are performed for both 18 knots and 30 knots as inlet velocity.

Calculations are performed by treating the root section as a free-end (i.e. for an isolated fin not attached to the hull) as well as by taking the root section attached to a hull plate. It is well known that for the former case, the flow can go over the edge and causes a reduction in the achievable lift. Results for the lift coefficient C_L are displayed in fig. 2. Here C_L is defined as $C_L = L/0.5\rho AU^2$ where $A = s \times c$ is the plan area of the fin, L is the lift force on the fin. In both cases, the two velocities are found to produce almost identical results. As expected, for the latter case, the lift coefficient C_L value is considerably higher, of the order of 40% more compared to the previous case. The following values for the lift-slope are obtained:

- when root section is free:

$$(\partial C_L/\partial \alpha)_{\alpha=0} = 0.066$$

- when root section is attached to a plate:

$$(\partial C_L/\partial \alpha)_{\alpha=0} = 0.094$$

Subsequently a study of literature on the experimental and other reported values of this parameter for similarly configured fin shows that the second value may be overly high while the first value is low. After a thorough study and comparison with such results, the finally adopted value for the loft slope is: $(\partial C_L/\partial \alpha)_{\alpha=0} = 0.08$

4.Roll With Active Fin Stabilzation

Fin roll stabilizers control roll motion by producing a counter (stabilizing) roll moment to the hull. Fig. 3 illustrates the fin action. The principle of operation is to vary the angle of the fin α which is the angle describing the pitch motion of the foil. The actual or effective angle of attack α_e, which is the angle the flow makes to the fin, is a modification of α due to the roll motion of the hull to which the fin is attached. The local roll-induced flow velocity together with the forward velocity of the ship produces an angle of incidence or flow angle α_{fl}. The effective angle of attack α_e arises from a combination of α and α_{fl}. As shown in fig 3, α_{fl} is given by (see Perez 2005) :

$$\alpha_{fl} = \tan^{-1}\left(\frac{V_{roll}}{U}\right) = \tan^{-1}\left(\frac{r_f\dot{\varphi}}{U}\right) \qquad (6)$$

and the effective angle of attack is:

$$\alpha_e = -\alpha_{fl} - \alpha \qquad (7)$$

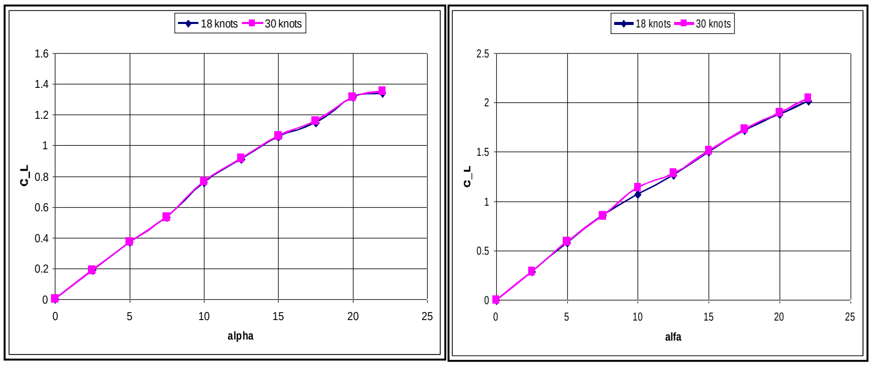

Figure 2: C_L against α; top: root section is free, bottom: root section is attached to the hull-plate

Here r_f is the roll-moment arm of the fin-induced force (see fig. 3), V_{roll} is the roll-induced velocity of the fin, U is forward speed of the ship and φ is the roll angle. In fig 3, V_{fl} is the total flow velocity to the fin, and the other symbols are self explanatory. The above equations are written following the right-handed Cartesian coordinate system based on which the ship motions have been defined. Thus a positive angle of attack will produce a positive roll moment produced by the fin (indicated in the figure as τ_{fins}. This means, according to eqn. (7), a negative value of $(\alpha_{fl} + \alpha)$ will produce a positive roll moment. When the hull rolls clockwise or with positive φ (with starboard side going down), the fin angle α should be negative for the starboard side fin (i.e. nose-up) to produce a counter-clockwise or negative fin-moment. The port side fin should move in the opposite direction to produce the same clockwise moment.

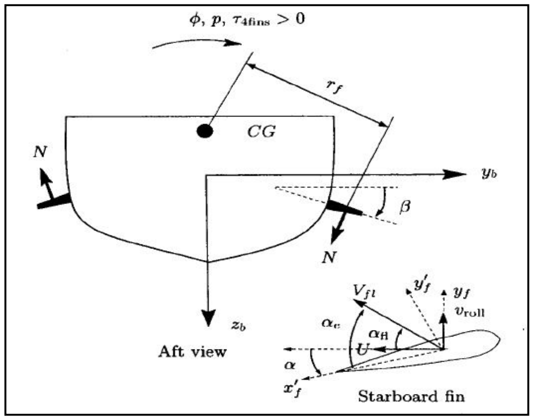

Figure 3: Fin details (from Perez 2005)

In order to determine the effect of the fin-induced roll moment, this moment is to be added to the right-hand side of the equations of motion along with wave-exciting roll moment $F_4^{EX}e^{i\omega_e t}$ in (6). By writing τ_{fins} as $F_{4fin}^{EX}e^{i\omega_e t}$ to be consistent with the nomenclature used in studying the equations of motion, the coupled sway-roll-yaw equation (4) now gets modified as:

$$(M + A_{22})\ddot{\eta}_2 + B_{22}\dot{\eta}_2 + A_{24}\ddot{\eta}_4 + B_{24}\dot{\eta}_4 + A_{26}\ddot{\eta}_6 + B_{26}\dot{\eta}_6 = F_2^{EX}e^{i\omega_e t}$$

$$A_{42}\ddot{\eta}_2 + B_{42}\dot{\eta}_2 + (I_{44} + A_{44})\ddot{\eta}_4 + B_{44}\dot{\eta}_4 + C_{44}\eta_4 + A_{46}\ddot{\eta}_6 + B_{46}\dot{\eta}_6 = F_4^{EX}e^{i\omega_e t} + F_{4fin}^{EX}e^{i\omega_e t}$$

$$A_{62}\ddot{\eta}_2 + B_{62}\dot{\eta}_2 + A_{64}\ddot{\eta}_4 + B_{64}\dot{\eta}_4 + (I_{66} + A_{66})\ddot{\eta}_6 + B_{66}\dot{\eta}_6 = F_6^{EX}e^{i\omega_e t} \quad (8)$$

Similarly, the single degree roll equation (5) is modified to:

$$(I_{44} + A_{44})\ddot{\eta}_4 + (B_{44} + B_{44}^*)\dot{\eta}_4 + C_{44}\eta_4 = F_4^{EX}e^{i\omega_e t} + F_{4fin}^{EX}e^{i\omega_e t} \quad (9)$$

If N is the normal or lift force produced by the fin, the total roll moment produced by a pair of fins can be approximated as (Perez 2005):

$$\tau_{fin} = F_{4fin}^{EX}e^{i\omega_e t} \approx 2Nr_f \quad (10)$$

N is given by:

$$N = \frac{1}{2}\rho\, V_{fl}^2\, A_f \frac{\partial C_L}{\partial \alpha_e}\bigg|_{\alpha_e=0} \qquad (11)$$

where A_f is the fin area. Thus,

$$\tau_{fin} = F_{4fin}^{EX} e^{i\omega_e t} \;\approx N = \rho\, r_f\, V_{fl}^2\, A_f \frac{\partial C_L}{\partial \alpha_e}\bigg|_{\alpha_e=0} \qquad (12)$$

V_{fl} can be approximated as the forward speed U of the vessel. Also, α_{fl} defined in (7) can be approximated as:

$$\alpha_{fl} = \tan^{-1}\left(\frac{V_{roll}}{U}\right) = \tan^{-1}\left(\frac{r_f\dot{\varphi}}{U}\right) \approx \frac{r_f\dot{\varphi}}{U} \qquad (13)$$

Thus we get

$$\tau_{fin} = F_{4fin}^{EX} e^{i\omega_e t} = 2K_a\left(-\frac{r_f}{U}\dot{\varphi} - \alpha\right) \qquad (14)$$

where

$$K_a \approx \frac{1}{2}\rho\, V_{fl}^2\, A_f \frac{\partial C_L}{\partial \alpha_e}\bigg|_{\alpha_e=0} \qquad (15)$$

For active roll control of the hull, the fin angle α needs to be changed in proportion to the roll displacement, velocity and acceleration following some control law. Let α be defined in the most general case as:

$$\alpha = K_1\varphi + K_2\dot{\varphi} + K_3\ddot{\varphi} \qquad (16)$$

where K_1, K_2, K_3 are the controller gain functions.

Inserting the above, the modified equations (8) and (9) now read as:

Coupled sway-roll-yaw equation:

$$(M + A_{22})\ddot{\eta}_2 + B_{22}\dot{\eta}_2 + A_{24}\ddot{\eta}_4 + B_{24}\dot{\eta}_4 + A_{26}\ddot{\eta}_6 + B_{26}\dot{\eta}_6 = F_2^{EX} e^{i\omega_e t}$$

$$A_{42}\ddot{\eta}_2 + B_{42}\dot{\eta}_2 + (I_{44}+A_{44})\ddot{\eta}_4 + \left[B_{44} + B_{44}^{*} + 2K_a\left(\frac{r_f}{U} + K_2\right)\right]\dot{\eta}_4 + (C_{44} + 2K_aK_1)\eta_4 + A_{46}\ddot{\eta}_6 + B_{46}\dot{\eta}_6 = F_4^{EX}e^{i\omega_e t}$$

$$A_{62}\ddot{\eta}_2 + B_{62}\dot{\eta}_2 + A_{64}\ddot{\eta}_4 + B_{64}\dot{\eta}_4 + (I_{66}+A_{66})\ddot{\eta}_6 + B_{66}\dot{\eta}_6 = F_6^{EX}e^{i\omega_e t} \tag{17}$$

Single-degree roll equation:

$$(I_{44} + A_{44} + 2K_aK_3)\ddot{\eta}_4 + \left[B_{44} + B_{44}^{*} + 2K_a\left(\frac{r_f}{U} + K_2\right)\right]\dot{\eta}_4 + (C_{44} + 2K_aK_1)\eta_4 = F_4^{EX}e^{i\omega_e t} \tag{18}$$

In terms of the amplitude, the fin angle is:

$$\alpha = \Re\{\bar{\alpha}e^{i\omega_e t}\} = |\bar{\alpha}|\cos(\omega_e t + \beta_\alpha);\ |\bar{\alpha}| = \Re\{|\bar{\alpha}|e^{\beta_\alpha}\} \tag{19}$$

where α and $|\alpha|$ are the complex and absolute amplitudes of the fin angle.

From (19), the relationship between fin and roll angles are:

$$\begin{aligned}\alpha = \Re\{\bar{\alpha}e^{i\omega_e t}\} &= \Re\{|\bar{\alpha}|e^{i\omega_e t + \beta_\alpha}\}\\ &= K_1\varphi + K_2\dot{\varphi} + K_3\ddot{\varphi}\\ &= \Re\{K_1\bar{\eta}_4 + i\omega_e K_2\bar{\eta}_4 - \omega_e^2K_3\bar{\eta}_4\}\\ &= \Re\{[(K_1 - \omega_e^2K_3) + i\omega_e K_2]|\bar{\eta}_4|e^{i\beta_4}\}\end{aligned} \tag{20}$$

This gives:

$$\frac{|\bar{\alpha}|}{|\bar{\eta}_4|} = \sqrt{[(K_1 - \omega_e^2K_3)^2 + (\omega_e K_2)^2]}$$

$$\beta_\alpha - \beta_4 = \tan^{-1}\left\{\frac{\omega_e K_2}{K_1 - \omega_e^2K_3}\right\} \tag{21}$$

Here note that $\beta_\alpha - \beta_4$ represents the phase angle by which the fin angle leads the roll angle.

The spectrum for fin angle is easily obtained in the same way as the roll spectrum, as:

$$S_\alpha(\omega_e) = \left[\frac{|\bar{\alpha}|(\omega_e)}{A}\right]^2 S_\zeta(\omega_e)$$
$$= \left[\frac{|\bar{\alpha}|(\omega_e)}{|\bar{\eta}_4|(\omega_e)}\right]^2 \left[\frac{|\bar{\eta}_4|(\omega_e)}{A}\right]^2 S_\zeta(\omega_e)$$
$$= \left[\frac{|\bar{\alpha}|(\omega_e)}{|\bar{\eta}_4|(\omega_e)}\right]^2 [roll\, RAO(\omega_e)]^2 S_\zeta(\omega_e) \tag{22}$$

The rms and 1/3rd significant amplitude of the fin angle can be obtained in the same way as for the roll angle, from the area under the fin-angle spectrum:

$$|\bar{\alpha}|_{rms} = \sqrt{m_0^\alpha}\,;\ \ |\bar{\alpha}|_{1/3} = 2\sqrt{m_0^\alpha} \tag{23}$$

$$m_0^\alpha = \int_0^\infty S_\alpha(\omega_e)d\omega_e$$
$$= \int_0^\infty \left[\frac{|\bar{\alpha}|(\omega_e)}{A}\right]^2 S_\zeta(\omega_e)d\omega_e$$
$$= \int_0^\infty \left[\frac{|\bar{\alpha}|(\omega_e)}{A}\right]^2 S_\zeta(\omega)d\omega \tag{24}$$

Similarly, the time simulation of the fin angle (maintaining a correct phase relation with roll) is given by:

$$\alpha(t) = \sum_1^N \left|\bar{\alpha}_j\left(\omega_{e_j}\right)\right| \cos(\omega_{e_t} t + \beta_\alpha + \beta_\zeta)$$
$$= \sum_1^N fin\, RAO\left(\omega_{e_j}\right) A_j\left(\omega_{e_j}\right) \cos\left(\omega_{e_j} t + \beta_\alpha + \beta_\zeta\right) \tag{25}$$

where

$$fin\, RAO = \frac{|\bar{\alpha}|}{A}$$

4.1.Control Gain Functions

It is clear from the above that the effectiveness of the fin controller will depend on the controller gin functions K_1, K_2, K_3. When $K_1 = K_3 = 0$, the controller will depend on roll velocity only, and the fin angle will lead roll displacement by 90 deg. (see. eqn. 21 which will give $\beta_\alpha - \beta_4 = \pi/2$). For non-zero values of K_1, K_3, the phase lead of fin angle to roll will be different. The values of K_1, K_2, K_3 that produces a stabilizing moment directly opposing the wave excitation moment, according to Connoly's simplified theory (Connoly 1969) is:

$$\frac{K_1}{K_2} = \omega_\varphi^2 \; ; \; \frac{K_2}{K_3} = 2n\omega_\varphi \qquad (26)$$

Since K_2 should never be zero, K_1 and K_3 expressed in terms of K_2 become:

$$K_1 = \left(\frac{\pi}{nT_\varphi}\right) K_2; \quad K_3 = \left(\frac{T_\varphi}{4n\pi}\right) K_2 \qquad (27)$$

where $T_\varphi = 2\pi/\omega_\varphi$ is the undamped roll natural period.

For the present hull T_φ lies between 10-11 sec. If the damping ratio n is assumed to be around 0.1, then according to this simplified principle, for oppose control we get K_1 about 2.4 to 3.2 times K_2 and K_3 about 7 to 8 times K_2.

4.1.Simulation Results

While computations can be performed for any conditions and values of gain functions, here the results presented are determined for the following six sets of gain functions:

- I : $K_1 = 0;\ K_2 = 2;\ K_3 = 0$
- II: $K_1 = 0;\ K_2 = 4;\ K_3 = 0$
- III: $K_1 = 0;\ K_2 = 6;\ K_3 = 0$
- IV: $K_1 = 0;\ K_2 = 8;\ K_3 = 0$
- V: $K_1 = 6;\ K_2 = 2;\ K_3 = 16$
- VI: $K_1 = 12;\ K_2 = 4;\ K_3 = 32$

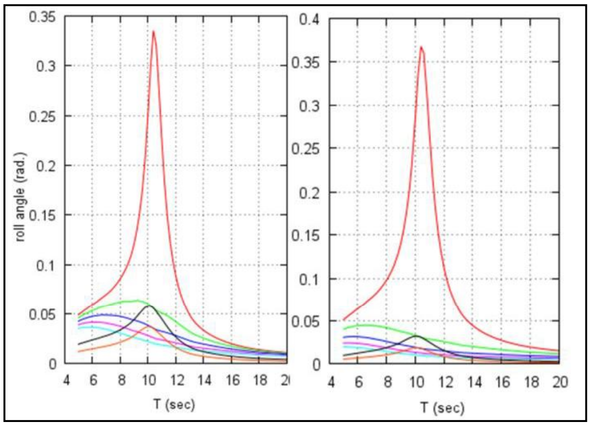

Figure 4

Fig.4 Unstabilized and stabilized roll angles for the case of beam waves, $H_{1/3} = 6$ m. The red line represents the unstabilized roll. The other 6 plots represents the 6 cases of for fin control actions I to VI. The gradually changing green to orange lines represents cases I to VI in that order. Left: 18 knots, Right: 30 knots.

Since largest roll occurs in beam waves for this hull, here the plots are shown only for the beam sea. Fig.4 shows the RAO results for both speeds 18 and 30 knots. Figs. 5 and 6 shows the time-history of roll and fin angles for the two speeds of 18 and 30 knots.

5.Observations And Concluding Remarks

From a study of the simulated results for the critcal case of rolling in beam waves (in which the rolling is very large) and in irregular waves of 6m. significant wave height, it is seen that the reduction in roll can be as low as 1/6th the unstabilized roll. At lower speed however, this factor is somewhat lower at 1/3rd reduction in roll. For the case of 135 deg. heading (bow quartering waves), although the RAO's are quite large, the unstabilized roll values are quite small compared to the beam wave case. This is because, here the large roll RAO occurs at higher periods which is outside the range of the peak of the spectrum resulting in overall low roll. On the other hand, in beam waves, the natural period is in the vicinity of the peak of the wave spectrum which explains why the rolling in beam waves for this particular hull is very high. Reduction through fin action here is also very high. Here however the case of $K_1 = K_3 = 0$ with low value of K_2 is somewhat less effective than having some non-zero values of K_1 and K_3. For the stern following waves case of $\mu = 45$deg., although the RAO is quite small and no resonance peak is observed, the unstabilized roll values are fairly large (larger or comparable to the case of bow-quartering wave case). This is because in the strern quartering case the encounter frequencies shift towards lower end (i.e. the ship encounters waves of effectively larger length). This gives rise to a so-called `hydostatic-dominated' roll. In this hydrostic-moment dominated roll, the vessel essentially follows the wave slope, producing a fairly large roll (note however that although roll is comparable to the bow-quartering case, it is still much smaller then the beam wave case). The effectiveness of the purely velocity-based controller (i.e. $K_1 = K_3 = 0$) is less effective here compared to some non-zero values of these gain functions. Indeed, the two case of bow and stern quartering waves, showing greater effectivenss of a control gain function with non-zero K_1 and K_3 is quite as expected. Note that K_1 introduces a `static stiffness', K_2 introduces a damping and K_3 introduces an additional inertia moment (see eqns. 17,18). The motions at higher frequencies are dominated by inertia-moment, at lower frequencies by the hydrostatic moment and near resonance by the damping moment. In stern-quarteting waves, the RAO shifts towards lower frequencies and in bow quartering waves it shifts towards higher frequencies. This explains why for reducing roll the static-moment producing term K_1 will have a stronger influence in stern-quartering waves while the inertia-moment producing term K_3 will have a stronger influence on bow-quartering waves.

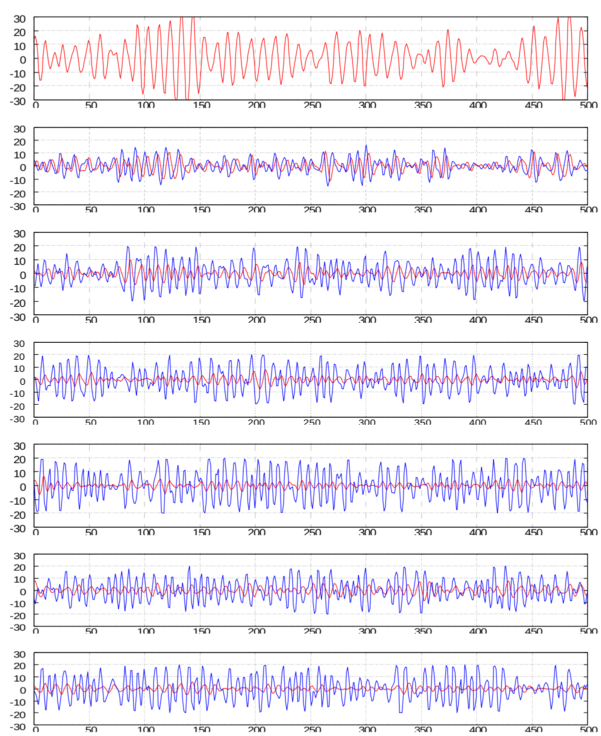

Figure 5

Fig.5 Time plots for unstabilised roll (top), and the stabilized roll (red) and fin angle (blue) for the 6 cases (top to bottom: case I to case VI), for 18 knots speed. All values are in deg., and all scales are same for comparative purpose.

It is also seen that in general a greater reduction in roll is always associated with larger fin actions, as expected. However, the reduction in roll is not linear with increase in fin action, and attempts to reduce roll more than say 1/4th may not be beneficial in the sense that the incremental fin action for a corrresponding incremental reduction in roll becomes larger.

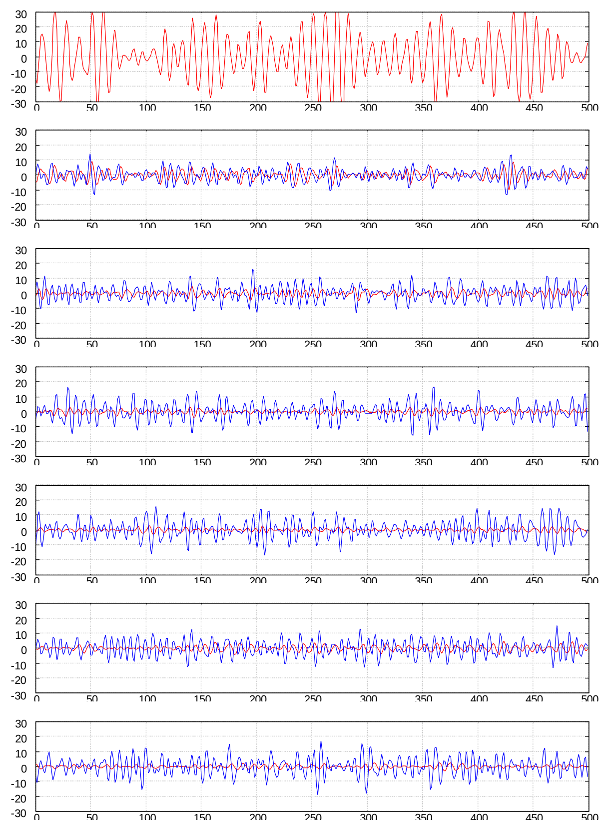

Figure 6

Fig.6 Time plots for unstabilised roll (top), and the stabilized roll (red) and fin angle (blue) for the 6 cases (top to bottom: case I to case VI), for 30 knots speed. All values are in deg., and all scales are same for comparative purpose.

6.Reference

1. Recommended Procedures : Numerical Estimation of Roll Damping, ITTC 2011.
2. Connoly, J.E.,`Rolling and its stabilization by active fins', RINA Transactions, 1969.
3. Lewis, E.V., 'Principles of Naval Architecture, Vol. III. Motions in Waves and Controllability', SNAME Publications, 1989.
4. Perez, T., 'Ship Motion Control: Course Keeping and roll Stabilization Using Rudder and Fins', Springer, 2005.
5. Salvesen, N., Tuck, E.O., and Faltinsen, O.M., `Ship motions and sea loads', SNAME Transactions, pp. 250-279, 1970.