Fin Effect on Pitch Motion and the Avoidance of Initiation of Parametric Roll

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***Abstract*— Container ships are prone to move at a greater speed compared to that of other merchant ships. The slenderness of the hull of container vessel is for better speed, but it leads to unfavorable motions especially while rolling. Such a slender hull when get twisted due to relative wave positions both port and starboard sides cause torsion and warping on the hull. The pitch and roll are related and sometimes the vessel might be forced to parametric roll condition which is very dangerous. A fin attached to the ship hull proves to be more efficient in controlling the ship motions particularly pitch. The fin is fitted at a lowest possible location of the hull surface and it is at the bow part of the ship. Computer simulation is done using proved software package ANSYS AQWA and the results are compared. Simulation is done for both regular and irregular sea and the effect of fin on ship motion is studied. The fin proves to be less effective at higher frequency range in controlling the ship motion. Although the ultimate aim in this paper is to avoid the situation leading to parametric roll, immediate attention is to modify pitch performance of the moving ship. Such situations of ship motion combined with the slender hull deformation cause the failure of lashing arrangements leading to cargo stack disorder and imbalance.**

Keywords—* *Parametric roll, Pitch control, fin systems, lashing arrangements

I. INTRODUCTION (*Heading 1*)

The effects of fixed bow anti-pitching fins on the seakeeping characteristics of ship are analyzed using proven software program. The present paper gives the results of analysis done in ANSYS AQWA which shows the effects of various fin configurations on the pitch and heave, speed loss, phase angles and vertical accelerations of a container ship in regular head seas. The test conditions included a speed range corresponding to Froude numbers from 0 to 0.22, and a range of wave lengths corresponding to wave length-ship length ratios from 0.75 to 1.51. In general, the results indicate that fixed bow fins produce maximum pitch reductions for ship-speed and wave-length combinations that correspond to near synchronous conditions. For the particular container ship of this investigation, maximum pitch reductions up to 37 per cent were obtained with fins of total plan area equal to 3.17 per cent of the water plane area and aspect ratio equal to 1.37.

A specific mode of operation called parametric rolling is very dangerous and many container ships with stream lined hull are prone to this. The head sea parametric roll is a recently identified phenomenon directly connected to very large containerships. Large roll angles more than 45 degree are likely to occur. Various authors show up different angles and claims up to 40 degree roll angle both sides. This large roll angle varies from ship to ship and sensitive to safety based on their righting arm curve versus angle of heel, sea states etc. When the natural period of the roll is nearly twice the wave encounter period, resulting in two pitch cycles per roll, there is chance of inception of such parametric roll. In other words, parametric roll occurs when natural roll period is between 1.8 to 2.1 times the pitch periods. Here, there is likely chance of ship to pitch with the incoming waves in a head sea. The parametric roll can occur for the streamlined hull and due to its low damping for roll and the ship may be forced to parametric roll. The wave heights exceeding critical values can also excite parametric roll and it is true in view of the large flare in the fore and aft of ship hull. The parametric roll can occur from within the loaded hull and due to its inherent property and the ship may be forced to parametric roll. It is the duty of the designer to avoid any unfavorable motions which will throw off cargo including containers into the seas as mentioned by Shin et al. (2004) [12]. William France et al. (2001) made an investigation of head-sea parametric rolling and its influence on container lashing systems. The author added parametric roll occurs in phase with pitch and on container ship it impart high load on the containers and to their securing system. The author also added that post panamax container ships are particularly prone to parametric roll [19]. Surendran et al. (2007) focused on the fin effect on roll motion and the fin was activated using PID controllers [14]. Surendran et al. (2006) proposed a mathematical model to

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predict the beginning of the parametric roll. The authors adapted an algebraic expression based on Duffings method to propose the solution for parametric roll initiation [15]. Surendran et al. (2007) studied the feasibility to control roll motion using active fins. The author found the effect of ship speed on the angle of attack required for the fin to stabilize the ship [13]. Surendran et al. (2006) studied the control of ship roll motion by active fins using fuzzy logic. The author activated the fin by electro-hydraulic mechanism based on the in-built intelligence using fuzzy logic control algorithm [16]. Giles et al. (2009) described the avoidance of parametric roll in head sea. The author studied the effect of bilge keel to reduce the roll motion induced by parametric roll [6]. Roberto et al. (2011) investigated on early detection of parametric roll resonance on container ship. The author stated parametric roll resonance on ships is a nonlinear phenomenon. When the waves encountered at twice the natural roll frequency could bring the vessel dynamics into a bifurcation mode and lead to extreme values of roll [10].

Abkowitz (1959) proposed that fins operated most effectively and have much less effect at higher and lower frequencies. It was stated that the loss of speed due to fin was not excessive in calm water and fixed fin could even be designed resulting a decreased resistance for a certain speed [1]. Stefun (1959) conducted experimental investigation on anti-pitching fins. Heave and pitch motions for different aspect ratio and angle were studied and the possibility of speed reduction in waves also explored [5]. Becket et al. (1959) stated that bow fins experienced ventilation and cavitation's which led to excessive vibration when bubbles collapsed on the fin and the hull [3]. Ochi (1961) focused on ships fitted with bow and stern fins. The author reported there was an increase in resistance of stern fins of two to three times that of bow fins. With bow a 10% reduction in pitch was achieved [8]. As already mentioned, Rameswar Bhattacharyya (1978) worked out pitch motion reduction using fins fitted to underwater hull. The fin was fixed as low as possible to the ship's bow, as the emergence of fin caused serious operational problem. Slamming like forces are possible during the emergence of the fin and this must be considered in the structural design. The fin used for pitch stabilization was a hydrofoil section cantilevered to the hull surface in the bow of the ship. The fin is designed in such a way that the area of the fin is roughly 4.6% of the area of the load water line [9]. Kaplan et al. (1984) studied the problem of pitch stabilization to commercial and military craft with stern and bow fin. The stern fins are less effective than the bow fin even when it is active [7]. Bassho et al. (1985) described a methodology to choose fin size and location to reduce both heave and pitch motion. However pitch is usually the main concern and heave is rarely targeted for reduction [4]. Avis (1991) studied the use of anti-pitching fin to reduce the added resistance of a yacht in waves. The author proposed mathematical model to predict the effect of anti-pitching fin on ship motion and added resistance. The author validated his results with experimental investigation which shows 22 percent reduction in pitch, 15 percent reduction in heave and 40 percent reduction in added resistance [2]. Tsong et al. (1999) investigated the effectiveness of the activated fins on reducing the pitch motion. They used a closed loop control system to activate the fin and added that a favorable pitch response can be achieved only in the linear region [18]. Ritsuo et al. (2001) did an evaluation method of passenger comfort and its application to a ship with anti-pitching fins. The author studied the effect of anti-pitching fins on ship motion from the view of passenger comfort. The author designed the most effective area of the anti-pitching fin to control the ship motion for passenger comfort [11]. Tristan et al. (2008) show that the effectiveness of ship fin stabilizers can severely deteriorate due to dynamic stall. Dynamic stall can lead to complete loss of control action depending upon how much the fin exceeds the threshold angle [17].

A new system fitted to the underwater part of hull is to be evaluated in so many angles. The overall size, here the breadth wise parameter of the fins should not project out of the prismatic frame size of the ship. As the hull is narrower at the bulbous bow region, the fin fitted with required span might be within the breadth of the vessel. The bulb interacts with the bow, and an optimum size is determined giving weight age to the better fuel consumption or higher speed. The fin was designed for both fixed and varying fin angle. The optimum fin dimensions are finalized based on operating speed of ship, ships breadth, incoming wave slope and restoring effect of ship.

II. GOVERNING EQUATION

A. *Mathematical modeling of fin moment*

The simplest anti-pitching imaginable is the hydrofoil section. This anti-pitching consists of a pair of hydrofoil section attached to the hull surface at the bow part of the ship. The fins should be as low as possible to avoid emergence out of water. The lift produced by the anti-pitching fins can be used to explain the basic principle pitch damping.

The idea is to reduce the pitch motion of the ship water therein gives the most beneficial effect on the heave and roll motion of the rest of the ship. To do this, the strategy is to make the vertical orbital velocity around the fin surface to the maximum and the ship should move at its maximum forward speed so that the stabilizing moment generated by the fin reduces the excitation moment by the wave. The ship profile with the anti-pitching fin is shown in figure 1

At zero fin angle an angle of attack "α_f" is induced on the fin which depends on the Heave velocity($\dot{z}$), Pitch angular velocity ($\dot{\theta}$), Pitch angle (θ), Ship speed (V_s), Vertical orbital velocity of the wave particle at the fin (υ). The various components of angle of attack are shown in figure 2.

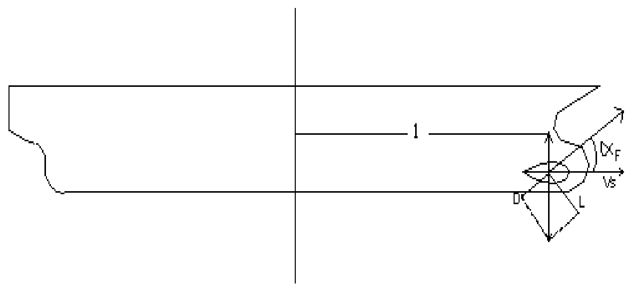

Fig. 1.Ship profile with anti-pitching fin-no fin angle

The angle of attack "α_f" is given by

$$\alpha_f = \theta + \frac{-\dot{z}-\dot{\theta}l+\upsilon}{V_s} \quad (1)$$

For small pitch angular velocity

$\dot{\theta} = q$

The angle of attack for small pitch angular velocity is given by

$$\alpha_f = \tan^{-1}\left(\frac{ql}{V_s}\right) \quad (2)$$

The angle of attack at the fin with fin angle (φ) is denoted by (α)

$$\alpha = \alpha_f + \varphi \quad (3)$$

Where

α_f is the angle of attack at zero degree fin angle

φ is the fin angle

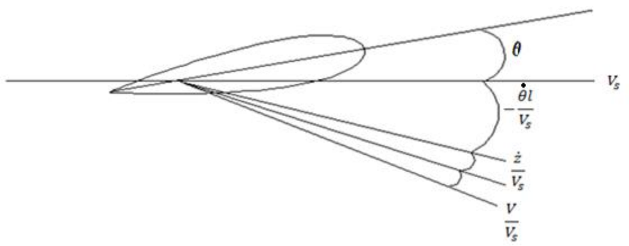

Fig. 2, Components of angle of attack on the fin

angles should be in radians and the angle of attack is then changed to degrees to enter the curve for lift coefficient versus angle of attack. The lift force on the fin is given by

$$L_f = \frac{1}{2}\rho V_s^2 A C_L(\alpha) \quad (4)$$

Where A is the area of the fin and $C_L(\alpha)$ is the lift coefficient at an angle α

The lift produced by angular velocity on the fin is expressed by

$$L_f = \left(\frac{\partial C_L}{\partial \alpha}\right)\alpha_f \frac{1}{2}\rho A\left[V_s^2 + (ql)^2\right] \quad (5)$$

The drag on the fin is expressed as

$$D_f = C_D \frac{1}{2}\rho A\left[V_s^2 + (ql)^2\right] \quad (6)$$

The fin moment (M_f) is given as the product of the vertical component of the lift force and the distance from the center of the fin to the CG of the ship (l).

$$M_f = -L_f l\cos\alpha - D_f l\sin\alpha \quad (7)$$

The moment component due to the vertical distance between the axis and the fin is neglected because of small force component and small moment arm. The most significant part of the fin angle of attack is due to pitch angular velocity $(\dot{\theta})$ and if the lift coefficient versus the angle of attack curve is linear then $\frac{\partial C_L}{\partial \alpha}$ is constant, therefore the equation of lift force becomes

$$L_f = (\alpha_f + \varphi)\frac{\partial C_L}{\partial \alpha}\frac{1}{2}\rho V_s^2 A$$

$$L_f = \left(\theta + \frac{-\dot{z}-\dot{\theta}l+\upsilon}{V_s} + \varphi\right)\frac{\partial C_L}{\partial \alpha}\frac{1}{2}\rho V_s^2 A \quad (8)$$

Where φ is the fin angle

The major component of this force is

$$-\dot{\theta}\left[\frac{l}{V_s}\frac{\partial C_L}{\partial \alpha}\frac{1}{2}\rho V_s^2 A\right]$$

This is a constant times $\dot{\theta}$ and acts in the same way as the term "b$\dot{\theta}$" in the pitch equation of motion and can be considered as an extra damping. Therefore the effect of the fin is mainly to increase the damping forces, which are considerable significant in resonant condition. Substituting the lift force and the drag force the moment equation becomes

$$M_f = -\frac{1}{2}\rho A l V_s^2\left[1 + \left(\frac{ql}{V_s}\right)^2\right]^{1/2} \times \left[\left(\frac{\partial C_L}{\partial \alpha}\right)\tan^{-1}\left(\frac{ql}{V_s}\right) + C_D\left(\frac{ql}{V_s}\right)\right] \quad (9)$$

If we are expressing the square root term in binomial expansion and the inverse tangent is expressed in power series

$$M_f = -\frac{1}{2}\rho A l V_s^2\left\{\left(\frac{\partial C_L}{\partial \alpha}\right)\left[\left(\frac{ql}{V_s}\right) + \frac{1}{6}\left(\frac{ql}{V_s}\right)^3 - \frac{11}{120}\left(\frac{ql}{V_s}\right)^5\right] + C_D\left[\frac{ql}{V_s} + \frac{1}{2}\left(\frac{ql}{V_s}\right)^3 - \frac{11}{8}\left(\frac{ql}{V_s}\right)^5\right]\right\} \quad (10)$$

The damping coefficient due to the fin is given by

$$M_f = b_f\frac{d\theta}{dt} \quad (11)$$

or

$$b_f = \left(\frac{\partial M_f}{\partial \theta}\right)_{\theta \doteq 0} = -\frac{1}{2}\rho A V_s l^2\left[\left(\frac{\partial C_L}{\partial \alpha}\right) + C_D\right]$$

For small fin angle the drag forces induced by the fin will small therefore the equation can be reduced to

$$b_f = \left(\frac{\partial M_f}{\partial \theta}\right)_{\theta \doteq 0} = -\frac{1}{2}\rho A V_s l^2\left(\frac{\partial C_L}{\partial \alpha}\right) \quad (12)$$

The value of $\frac{\partial C_L}{\partial \alpha}$ depends on the aspect ratio of the hydrofoil section. The mass of the fin can be neglected in the motion calculation, but the added mass is taken into account. The fin added mass is added to the overall added mass for heave motion, the fin added mass times l^2 is added to the virtual mass moment of inertia of the ship.

III. VESSEL PARTICULARS

A post-panamax containership of length 313.64 m, breath 36.64 m, depth 24.1 m, and draft 14.5 m is taken for study, the vessel particulars are shown in table 2 and the body plan of the ship is shown in figure 3.

The vessel is modeled using a computer package program.

The service speed of 25 knots is taken for analysis. A trend is observed to operate such vessel around 20 knots, here higher speeds are considered for academic interest to control pitch motion.

Table 2. Vessel and Model Particulars.

Particulars	Full Scale
LBP	313.64 m
B	36.64 m
Depth	24.1
Draught	14.5 m
Displacement in Tonnes	103292 ton
L/B	8.56
B/T	2.53
C_b	0.622
K_{yy}/L_{pp}	0.27

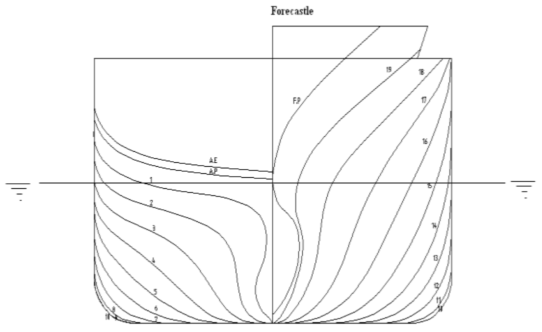

Fig. 3, Body plan of the ship.

IV. FIN DESIGN AND ANALYSIS

A suitable fin of hydrofoil section is section is selected for anti-pitching fin. Three sets of aspects ratios are taken for study and the same has been tested for efficiency. The span of the fin is selected in such a way that the fin does not project out of the ship's hull region. The fin aspects ratio is shown in table 3.

Table 3. Fin particulars.

Span (m)	Chord (m)	Aspect Ratio
8	15.9	0.50
10	15.9	0.63
12	15.9	0.75

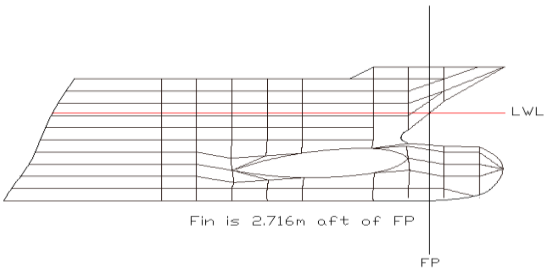

Fig. 4, Profile of bow part with the fin

The fin is fitted as closed to the hull surface to form an integral part of the ship so as to avoid cross flow and to generate a three dimensional flow around the hull surface and doubles the aspect ratio of the fin as shown in figure 4. This will increase the effectiveness of the fin. The fin encounters with waves with a forward velocity in addition to this the water particle velocity will also act on the fin. Figure 5 shows the plan of the fin fitted on the hull for a combination of aspect ratio.

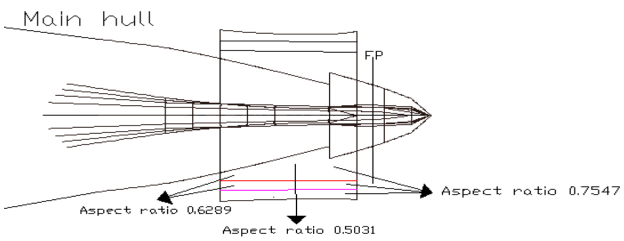

Fig. 5, Plan view of bow part of the ship with fin

V. COMPUTER SIMULATION FOR FIN ACTION

Rameswar Bhattacharyya (1978) relied upon equilibrium stabilization to control the pitch motion of the ship. The effectiveness of the stabilization depends upon the fin location, the fin angle and the fin aspect ratio. A computer model is prepared using ANSYS AQWA WORK BENCH module. It is shown in figure 6. The fin is given various tilt angle and the values of pitch angle obtained from simulation using actual ship size as shown in figure 7. Incoming regular wave of 1m to 5m wave amplitude is considered. Result shows that a fin angle of five degree is giving a maximum reduction in pitch motion. It is also found that any angle greater than five degree is less effective. At five degree fin angle the lift force generated by the fin is predominant to control the pitch motion and at the same way the drag force has lesser influence on the ship hull. Since the drag force is less the resistance offered by the fin to the ship motion should also be less. This can be justified by calculating the resistance of the ship with and without fin. The meshing details are given in table 4.

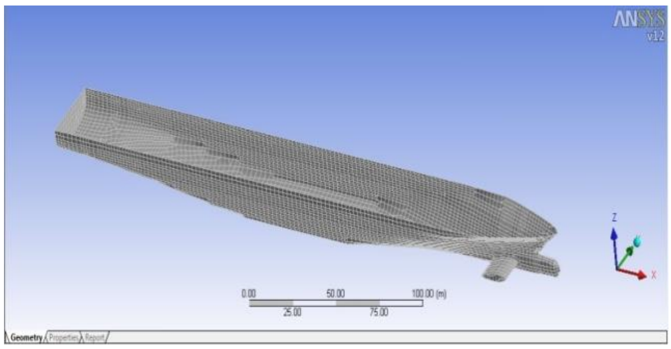

Fig. 6 Meshed model in ANSYS AQWA of actual ship

Table 4: Meshing details of container ship with fin and without fin

Sl.no	Mesh details	Without fin	With fin
1	No.of Nodes	5312	6091
2	No.of Elements	5251	6043
3	Defeaturing tolerence	2	2
4	Max element size	5	5
5	Meshing type	Program control	Program control

VI. RESULT AND DISCUSSION

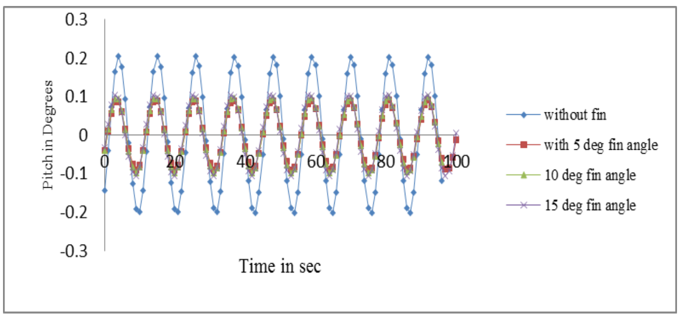

Fig. 7, Effect of anti-pitching fins for wave amplitude 1 m and period 10 seconds

Figure 7 is for head sea aspect ratio of 0. 75. The simulation shows at 5 degree fin angle the fin effect is more predominant hence 5 degree fin angle is taken into account for further study. A tilt of 5 degree found to be effective. The matrix of parameters considered for the simulation is shown in table 5. The fin is found to be more effective at higher ship speed and proves to be effective in the frequency range of 10 to 12 seconds wave period and numerical simulation are done in these frequency ranges for wave amplitude of 2 to 4 meters.

Table 5. Conditions and parameters for ship simulation.

Ship Speed (Knots)	5, 10, 15, 20, 25
Fin aspect ratio 1	0.75, 0.63, 0.5
Draft (meters)	14.5
Fin Angle (Degrees)	5, 10,15
Without fin	1
Wave period (sec)	10, 10.5,11,11.5,12
Wave amplitude (meters)	2, 3, 4

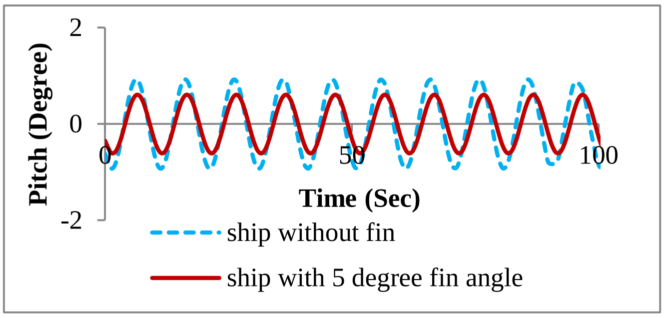

Fig. 8, Pitch for 2m wave amplitude and wave period 10 seconds

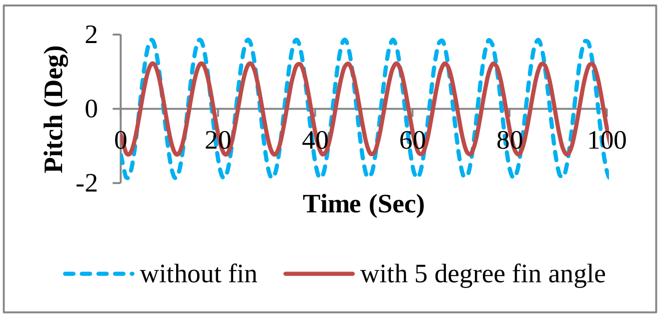

Fig. 9, Pitch for 3m wave amplitude and wave period 10 seconds

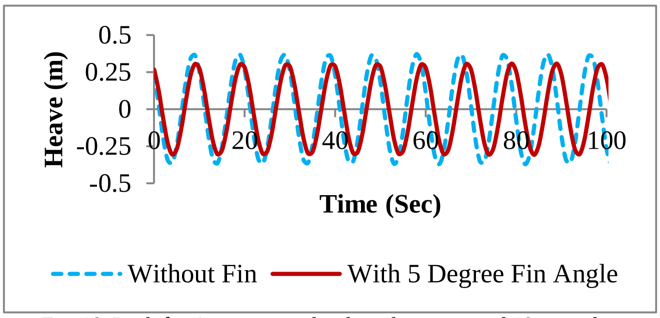

Fig. 10, Pitch for 4m wave amplitude and wave period 10 seconds

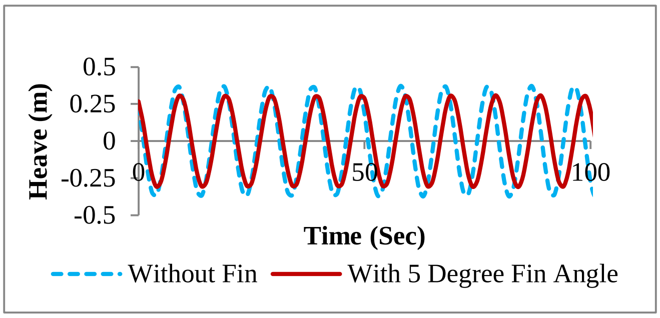

Fig. 11, Heave for 5m wave amplitude and wave period 10 seconds

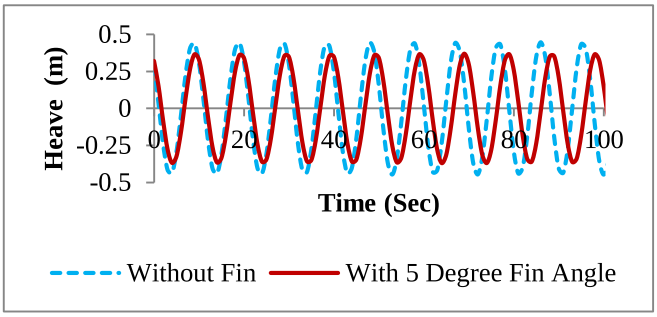

Fig. 12, Heave for 6m wave amplitude and wave period 10 seconds

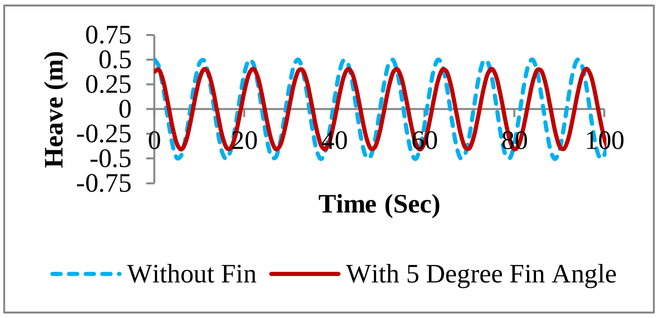

Fig. 13, Heave for 5m wave amplitude and wave period 10.5 seconds

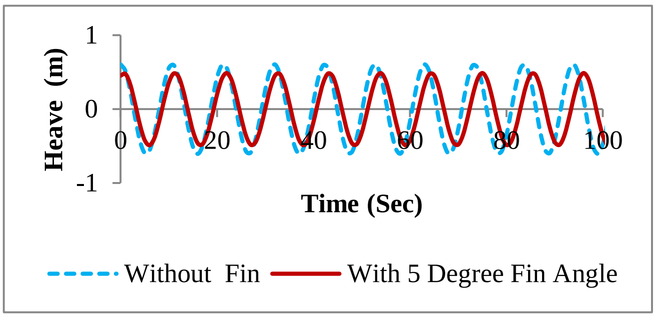

Fig. 14, Heave for 6m wave amplitude and wave period 10.5 seconds

Numerical study on ship motion in regular sea is carried out for various speeds and amplitudes in head sea condition. Wave amplitudes of 2m for 10 seconds wave period the anti-pitching fin gives a reduction of 39.4%, for a speed of 25 Knots and it is shown in figure 8. Figure 9 shows for a 3m wave amplitude, 10 seconds wave period, 25knots ship speed head on condition, the reduction in pitch is 38.6%. Figure 10 shows the pitch response with 35.3% reduction in pitch, in head sea at 25 knots and wave amplitude of 4m. Figure 11-14 shows the time domain heaves response of the ship with and without ship for wave amplitudes of 5 and 6 meters, wave period 10 and 10.5 seconds. The result shows there is reduction in heave amplitude over particular range of frequency and within this wave period the anti-pitching fin is efficient in controlling the ship motion.

The RAO of the ship with and without fin at various speeds is shown in figures 15-17.

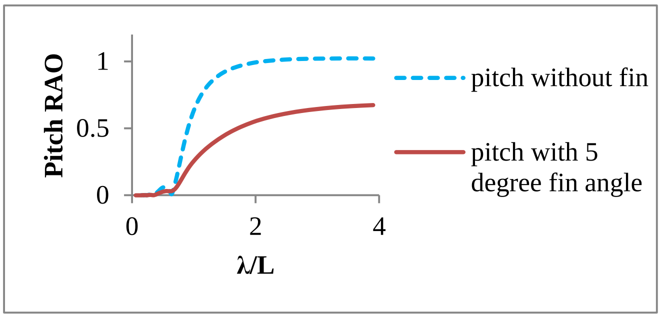

Fig.15, Pitch RAO at 20 knots in head sea

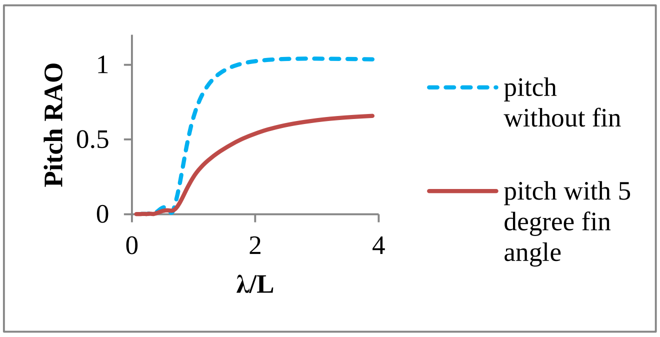

Fig.16, Pitch RAO at 25 knots in head sea

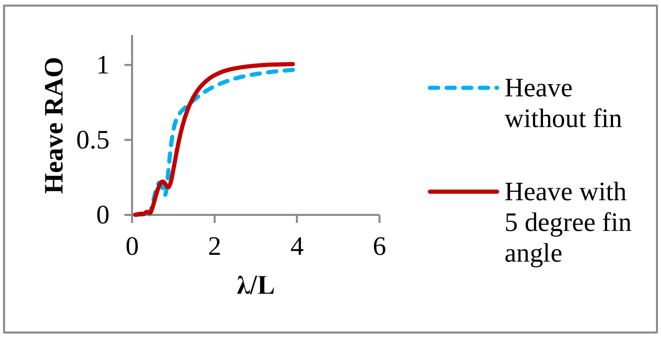

Fig.17, Heave RAO at 25 knots in head sea

Time domain response of the ship with and without fin at 25 knots in irregular sea is shown in figure 18, 19, 20, for sea state 5, 6, 7. Response spectrum at various sea states for various speeds using P-M spectrum is shown. The effectiveness of 5 Deg turn of fin angle is very well understood from the figures.

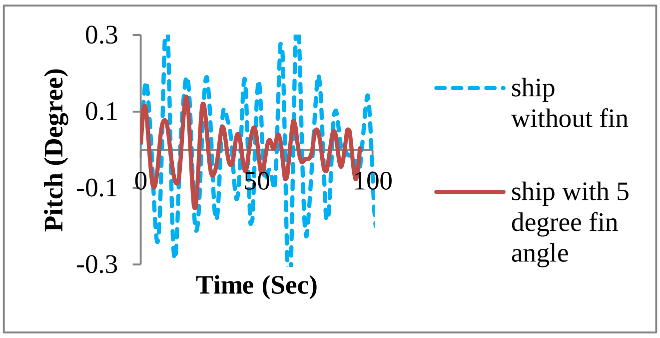

Fig. 18, Pitch for Sea state 5 without fin and with 5 degree fin angle at 25 knots head sea

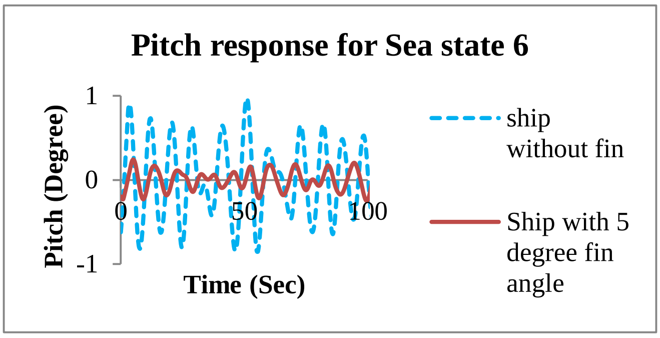

Fig. 19, Pitch for Sea state 6 without fin and with 5 degree fin angle at 25 knots head sea

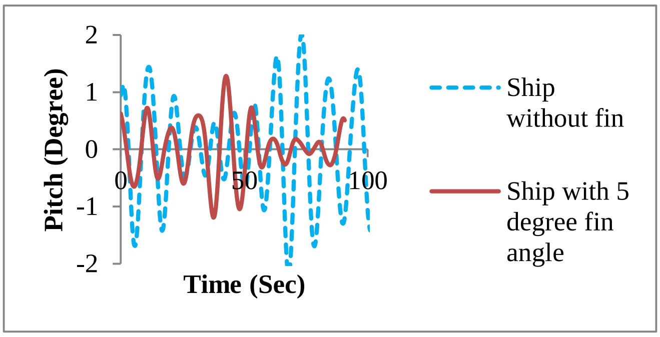

Fig. 20, Pitch for Sea state 7 without fin and with 5 degree fin angle at 25 knots head sea.

A number of simulations are done for irregular sea. The prevailing sea state is responsible for the motions of the vessel. The moving ship will encounter more number of waves in a head on condition. The fins are in fixed condition at that particular angle. The behaviour of ship in irregular sea will give maximum motion parameters as the ship encounters rough sea. The ship may have to encounter different sea states and the study on the motion behaviour of the ship is very important. Based on the ship response in the irregular sea the fin can be used effectively in open sea to control the motion parameters. Although, initially the fin system was designed and fabricated for controlling the fin position on a continuous basis during the tow, later it was decided to limit the continuous motion by fixing the fin angle to a fixed value matching a particular sea state model.

The figure 18 shows the pitch of the ship with and without fin at sea state 5 in head sea condition. The ship with fin angle of 5 degree is giving average pitch reduction 40.3%.Figure 19 shows the pitch response for sea state 6 in head sea condition. The fin is giving average pitch reduction of 28% in sea state 6. Figure 20 shows the pitch response of ship fitted with fin and without fin. The fin is giving an average pitch reduction of 37% in sea state 7.

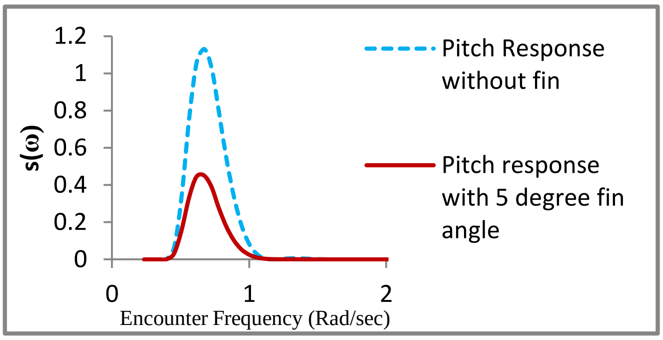

Fig. 21, Pitch response spectrum with and without fin for sea state 5 in head sea and ship speed 5 knots

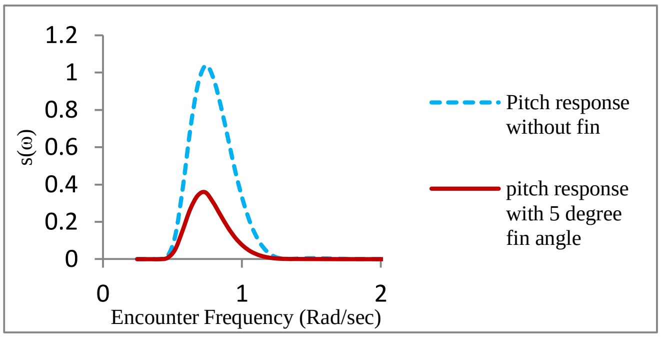

Fig. 22, Pitch response spectrum with and without fin sea state 5 in head sea and 10 knots

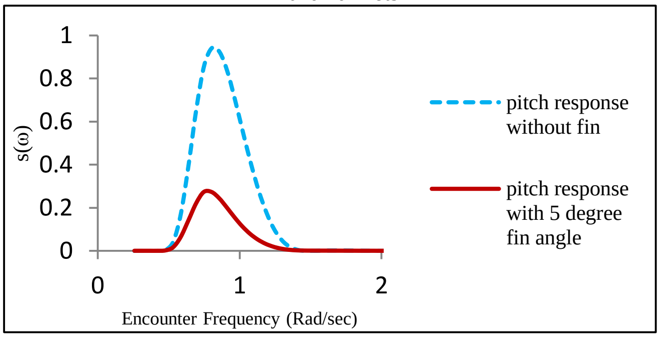

Fig. 23, Pitch response spectrum with and without fin for sea state 5 in head sea and ship speed 15 knots

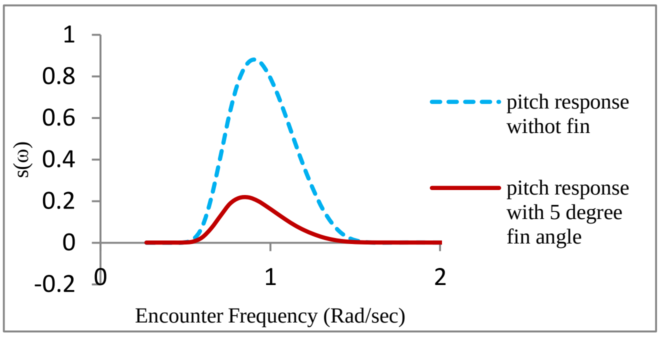

Fig. 24, Pitch response spectrum with and without fin for sea state 5 in head sea and ship speed 20 knots

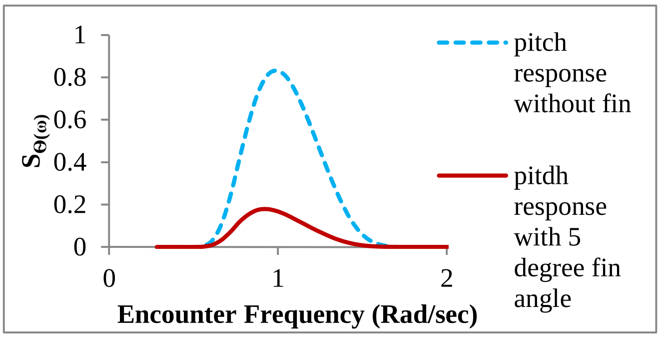

Fig. 25, Pitch response spectrum with and without fin for sea state 5 in head sea and ship speed 5 knots

Figure 21-25 shows the response spectrum for sea state 5 in head sea condition for ship with and without fin at 25 knots. The average pitch value at 25 knots is 0.811 degree for ship without fin in sea state 5 and for ship with fin is 0.366 degree.

VII. CONCLUSION

The fixed bow fin system in waves serves as damper for pitch and even in heave motion. The results show the fixed fin is more effective in a frequency range of 9 to 11 sec wave period. In irregular seaway activated fin system may more effective. By controlling the pitch motion the frequency of pitch motion is changed there by the initiation of parametric roll can be avoided in the region of resonance. For a cruising speed of 25 knots, the area under the pitch spectral curve is one fifth the area under the curve of the case of without fin. It save a lots of money for the owner and also provide safety to the crew members. There is 43% of pitch reduction in terms of the RMS value.

Table 5 Response spectrum characteristics for sea state 5 for ship with and without fin at various speed

Parameters	5 knots		10 knots		15 knots		20 knots		25 knots	
	Without fin	With fin	Without fin	With fin	Without fin	With fin	Without fin	With fin	Without fin	With fin
m_0 (Deg^2)	0.34	0.135	0.369	0.118	0.391	0.104	0.411	0.094	0.425	0.086
m_2 (Deg^2-sec^2)	0.177	0.065	0.238	0.0718	0.310	0.076	0.391	0.082	0.473	0.088
m_4 (Deg^2-sec^4)	0.103	0.0362	0.177	0.0500	0.283	0.065	0.425	0.082	0.601	0.103
Correction factor (ε^2)	0.128	0.118	0.13	0.130	0.129	0.135	0.126	0.135	0.121	0.131
Average pitch amplitude (degree)	0.732	0.457	0.755	0.427	0.777	0.401	0.797	0.380	0.811	0.366
Mean of one-third highest pitch amplitude	1.169	0.73	1.2	0.683	1.241	0.641	1.272	0.608	1.294	0.584
Mean of one-tenth highest pitch amplitude	1.14	0.92	1.53	0.869	1.579	0.816	1.618	0.773	1.647	0.743
Mean of one-hundredth highest pitch amplitude	1.95	1.21	2.01	1.139	2.070	1.070	2.121	1.014	2.159	0.974

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