Nonlinear Response of SemiSWATH Ship, Bow-diving, and Fin Stabilizer Effect in Following Seas

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***Abstract*--**In this research, the response of a Semi-SWATH (Small Waterplane Area) ship in following sea condition with fins stabilizer was investigated. In the waves, a ship move with periodic dynamic surge motion caused by the external sea wave force and moment. In addition, in following seas with high steep waves, the ship can surf, high pitch, bow-dive, and lead the ship in the non-linear response. A numerical simulation program in 3DOF (surge, heave and pitch) with time varying model equation was developed to study the ship responses. This study focuses on the effect of variation of wave parameter to the ship response and the effects of fins stabilizer; fixed and active. The numerical simulations were validated with model tests in towing tank. Simulations results showed that the dynamic ship response was stabilized effectively and reduced pitch angle by active fins stabilizer action.

Keywords: semiSWATH, bow-diving ,surf-riding

I. INTRODUCTION

A. Background

Ship motion in sea wave normally moves in a dynamic of periodic surging motions. In following sea waves, the ship may have some conditions such as; the ship is trapped in between the crest of waves, the ship overtakes the waves or the ship along with the wave's celerity. In a high Froude numbers, the high steepness waves can lead the ship condition to surf-ride. Even the ship can experience acceleration to the trough wave and cause the bow diving arise. The dynamic stability properties in relation to periodic type behaviour, surf-riding and bow-diving were very important because of direct relation to the safety in the sea.

One of the non-linear motions effect in following seas identified is a bow diving which it always preceded surf riding. It emerges when the buoyancy is not sufficiently restraining the surging force during her surfing. For multihull ship such as Catamaran, the slender hull shape has been experimentally confirmed that in following seas the ship tends to surf and may have a bow diving effect (I.W.Dand, 2006). Like Catamaran, semi-SWATH has a more slender shape than Catamaran, she has a fore shape hull follows the SWATH and Catamaran shape at another end. In stationary condition, the stiff force slightly low than catamaran affects the low response at fore and more tends to surf-ride and bow-dive.

As usual the SWATH design with fin stabilizer, Semi-SWATH uses fins stabilizer at fore end and at aft end used to decrease the lack of porpoising in head seas. In following seas, the fin used to decrease the probability of having surf-ride and bow-dive effect. The fins act as like wing-foil to increase the lift force and damping force in the sea waves.

Until recently, investigation of ship behaviour in following sea wave has done by few researchers in the world. A numeric analysis on surf-ride of a fishing boat was conducted by Umeda (1990). He investigated the probability of surf-riding in regular and irregular following waves, and then the research was extended by Spyrou (1995) on the ship behaviour in quartering waves and its stability in one wavelength and the possibility of surf-riding.

Recent work by Spyrou (2006) analyzed the ship behaviour in following seas based on the mathematical model of surge motion, which includes ship resistance, ship propulsion, and hull characteristics. Based on the model, he obtained the threshold of global surf-riding and the periodic of surging in high steepness following waves (Spyrou, 2010). Thereafter, the model extended to a nonlinear model of surge, heave and pitch motion include the effect of ship weight on surge motion (Spyrou, 2011). Research on the model scale was conducted by Matsuda at.al (2004). He investigated the main cause of capsizing due to bow diving in following sea waves.

Non-linear effect of the ship motions in following seas was the focus of many research conducted (Kan M,1990), even unstable effect in surf-ride can bring the ship in capsize condition. In this paper, the dynamic motion of semi-SWATH in following seas and the effects of fins stabilizer were investigated to see the ship behaviour in relation of non-linear response and bow-dive condition. The initial condition that can lead to an oscillatory motion was a regular wave and some others bow dive scenario. The scenario was focused on the emergence of bow dive and the effect of fin stabilizer on reducing the effect of non-linear response and ignores the bow dive effect.

The mathematical model of ship motion was modeled in 3DOF of nonlinear equation. However, we have very few

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studies on bow dive problem with fin stabilizer and no research done on the semi-SWATH ship.

B. Scope

This research studied the free distance of fore deck and sea wave surface, pitch and the effects of a fixed and active fin stabilizer traveling in following seas based on time-domain simulation program results. The program was validated by experimental results in towing tank, and the parametric analysis derived from the results of a series of simulation.

C. Limitation

The oscillation response of the simulated ship was provided by the regular waves in the following seas. In addition, the force effect by between hulls was not integrated. The ship hulls have a more slender shape that can reduce the generated waves.

II. MATHEMATIC MODEL

A. Ship Motion Model

In this research, the characteristics of the ship in longitudinal and vertical motion were considered as such; surge, heave and pitch motion. The motions has cross effect each other but the effect of decoupling motion in longitudinal to vertical motion is negligible because the ship has a slender form (Umeda, 1990), while the vertical motion of heave and pitch has a significant effect of decoupling (Lloyd,1989). The second order of the linear differential equations comprise of force coefficients; added mass, a_{ii}, damping, b_{ii}, stiff, c_{ii}, and external of wave force, and moment F_i, and ship weight force on slope of waves (mg.sinϕ/mg.cosϕ), the index *i* indicates ship motions were expressed in the following form;

$$\begin{aligned}
&(a_{11}+m)\ddot{x}_1+[R(u)-T(u,n)]=F_1^W-mg\sin x_5\\
&(a_{33}+m)\ddot{x}_3+b_{33}\dot{x}_3+c_{33}x_3+a_{35}\ddot{x}_5+b_{35}\dot{x}_5+c_{33}x_5\cdots\\
&\qquad=F_3+mg\cos\theta\\
&a_{53}\ddot{x}_3+b_{53}\dot{x}_3+c_{53}x_3+(a_{55}+I_{55})\ddot{x}_5+b_{55}\dot{x}_5+c_{55}x_5\cdots\\
&\qquad=F_5-x_S mg\cos\theta
\end{aligned}\tag{1}$$

The surge motion is a longitudinal motion superimposed on trust propeller, *T*, hull resistance, *R*, and harmonic incident wave force of Froude-Krylov, F_1, (Umeda N, 1990; Djatmiko, 2004) and effect of ship weight (Spyrou, 2011; Wan W et al, 2010). The model was integrated with fins stabilizer effect and derived the resistance and trust propeller into the equations (1) as follows;

$$\begin{aligned}
&(a_{11}+m)\ddot{x}_1+\left\{[3r_3c^2+2(r_2-\tau_2)c+r_1]-\tau_1 n\right\}\dot{x}\cdots\\
&+\left[3r_3c+(r_2-\tau_2)\right]\dot{x}^2+r_3\dot{x}^3=(\tau_2c^2+\tau_1cn+\tau_0n^2)\cdots\\
&-(r_1c+r_2c^2+r_3c^3)-f\sin(kx)-mg\sin x_5+F_1^{\,f}
\end{aligned}\tag{2.a}$$

$$\begin{aligned}
&(a_{33}+m+a_{33}^f+m_f)\ddot{x}_3+(b_{33}+b_f)\dot{x}_3+c_{33}x_3\cdots\\
&+(a_{35}-l(m_f+a_{33}^f)\ddot{x}_5+(b_{35}-b_f)\dot{x}_5+(c_{35}+c_{35}^f)x_5\cdots\\
&=F_3^{\,w}+F_3^{\,f}+mg\cos x_5
\end{aligned}\tag{2.b}$$

$$\begin{aligned}
&(a_{53}-l(m_f+a_{33}^f)\ddot{x}_3+(b_{53}-b_f)\dot{x}_3+c_{53}x_3+(a_{55}+I_{55}\cdots\\
&+l^2(m_f+a_{33}^f))\ddot{x}_5+(b_{55}+b_f)\dot{x}_5+(c_{55}-c_{55}^f)x_5\cdots\\
&=F_5^{\,w}+F_5^{\,f}-x_{S(G)}mg\cos x_5
\end{aligned}\tag{2.c}$$

The superscript of *w*, *f*, *p* indicates of wave, fin and propeller respectively, x_1 is the distance from a wave crest, $\dot{x}_1$ is the relative velocity of ship to the wave celerity, $\dot{x}_1=u-c$.

$$\begin{aligned}
&R(u)=r_1u+r_2u^2+r_3u^3\\
&T(u,n)=(1-t_p)\rho n^2D_P^4K_T(u;n)\\
&K_T(u;n)=K_0+K_1J(u;n)+K_2J^2(u;n)\\
&J(u;n)=\frac{u(1-w_P)}{nD_P}\\
&T(u;n)=\tau_0n^2+\tau_1un+\tau_2u^2\\
&\tau_0=\kappa_0(1-t_P)\rho D_P^4 \qquad\qquad \tau_1=\kappa_1(1-t_P)(1-w_P)\rho D_P^3\\
&\tau_2=\kappa_2(1-t_P)(1-w_P)^2\rho D_P^2
\end{aligned}$$

The model equation (2) can be simplified in arranged of state space form below;

$$\begin{aligned}
&M(t)\,\dot{x}(t)=A(t)\,x(t)+B(t)\,u(t)\\
&y(t)=C(t)\,x(t)
\end{aligned}\tag{3}$$

$$\begin{aligned}
&\dot{x}(t)=M^{-1}(t)A(t)\,x(t)+M^{-1}(t)\,B(t)\,u(t)\\
&\dot{x}(t)=A_t(t)\,x(t)+B_t(t)\,u(t)
\end{aligned}\tag{4}$$

M is the added mass matrix, *A* is a variable state matrix comprises of damping and stiff coefficients, *B* is a variable input matrix, *u* is input system, *x* is variable state vector, and *y* is vector output. Solution of the state space form (4) can be obtained as follows;

$$x(t)=e^{A_t(t-t_0)}\,x(t_0)+\int_{t_0}^{t}e^{A(t-\tau)}B_t(t)\,u(\tau)d\tau \tag{5}$$

The equation above may solve using a discrete model as follows;

$$\begin{aligned}
&x\left[(k+1)T\right]=\phi\left[(k+1)T,kT\right]x(kT)\cdots\\
&\qquad\qquad+\int_{kT}^{(k+1)T}\phi\left[(k+1)T,\tau\right]B(\tau)\,u(\tau)\,d\tau
\end{aligned}\tag{6}$$

The integration part in above equation simply calculated using a simple discrete integral as follow (Joseph S. Rosko, 1971);

$$x[(k+1)T] = \phi[(k+1)T, kT]\, x(kT) + \frac{T}{2} B_t[(k+1)T]\, u[(k+1)T] \cdots \quad (7)$$
$$+ \frac{T}{2} \phi[(k+1)T, kT]\, B_t(kT)\, u[(k+1)T]$$

and,

$$\phi[(k+1)T, kT] = e^{\int_{kT}^{(kT+1)T} A(\beta) d\beta}$$

B. *Fin Stabilizer Model*

The mathematical model of the servo control of fins stabilizer is based on the results of Van Amerongen (1982) and Van der Klught (1987). They developed the first order of mathematical model of the steering rudder machine in Laplace form with settling time τ_r as follows;

$$\frac{\alpha(s)}{\alpha_d(s)} = \frac{1}{1+\tau_r s} \quad (8)$$

The settling time τ_r obtained from the identification of servo motor system applied for fins stabilizer in seakeeping test.

C. *Fin Force and Moment*

The force and moment of fins stabilizer calculated using the basic model of wing-foil. The effective of fin depends on the angle of attack, distance of fin surface to water surface, interaction fin to fin and hull boundary layer (Lloyd, 1998; Kenevissi et al., 2003), in this simulation, this effect were calculated at each step of time simulation.

The lift force and moment of the fins were obtained as follow (Bhattacharya, 1978);

$$F_L = \tfrac{1}{2} \rho U^2 A \left(C_{L\alpha} \alpha_f + C_{L\delta} \delta\right) \quad (9)$$
$$M = F_L\, x_f$$

$$\alpha_f = \theta + \frac{-\dot{z} - \dot{\theta}\, l + \upsilon}{V_S} \quad (10)$$

$\theta, \dot{\theta}$: Pitch and rate of pitch angle (rad, rad/s)

z : heave amplitude (m)

δ : fin angle (rad)

l : distance from fin pressure centre to pitch axis (m)

υ : velocity of vertical orbital of waves (m/s)

V_S : forward velocity (m/s)

The fin stabilizer has a symmetrically streamlined section of NACA 0015. The lift and drag force has a minimum at zero angle of attack. At small angles, the lift coefficient $(dC_L / d\alpha)$ increases more or less linearly with the incidence angle. Whicker and Fehlner, 1958 have studied the variety of the lifting surfaces of low aspect ratio and derived empirical formula for lift curve slope of rectangular plan forms as a function of an aspect ratio as follows (Lloyd, 1989; Perez,2005);

$$\frac{dC_L}{d\alpha} = \frac{1.8\, \pi\, a_F}{1.8 + \sqrt{a_F^2 + 4}} \qquad rad^{-1} \quad (11)$$

lift and drag coefficients C_L and C_D were calculated as follows;

$$C_L = \frac{dC_L}{d\alpha} \alpha_f \qquad C_D = C_{D0} + \frac{C_L^2}{0.9\, \pi\, a} \quad (12)$$

C_{D0} is the minimum section drag for NACA 0015 is C_{D0}=0.0065 (Perez, T., 2005).

III. Control System

In order to control the ship motion, fin stabilizer used as an actuator to affect the ship motion by the effect of wave disturbance. In this study, the seakeeping simulation of semi-SWATH uses a mechanism of control as shown in Fig.1. The control system consists of an inner loop and outer loop controller. The inner loop controller regulates the angle of fins stabilizer based on servo system with control signal from the outer loop controller. The outer loop controller calculates the control signal proportionally to the pitch angle using fuzzy logic algorithm. The fuzzy logic concept is based on an interpretation of human skill regulating the ship motions, derived from the basic method of fuzzy logic of model of mamdani (Van Amerongen et al, 1977).

Fuzzy logic controller was proposed by Zadeh, in 1965 then, it was developed in research of ship maneuvering by Van Amerongen in 1977. The control mechanism arranged by the logic rules based on the way to control the inverted pendulum system stands on its stable position.

IV. NUMERICAL RESULT

In order to study the nonlinear of ship behaviour, a time domain simulation program was developed, performed the ship behaviour in following regular waves with fins stabilizer.

The heave and pitch coefficients of added mass and damping were calculated by the code of Maxsurf. While the added mass coefficient of surge motion obtained by surge oscillation test in towing tank at zero speed (Brien and Kuchenreuther, 1957). The surge damping coefficient derived from the resistance test. The integrated stations concerning hull geometry were carried out on the basis of 20 stations along the hull length.

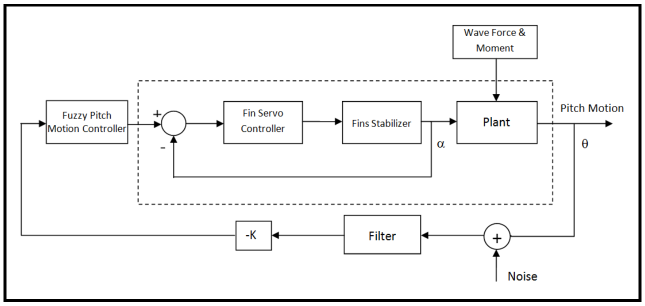

Figure 1: Diagram of Ship Seakeeping Control System

The program simulates the semi-SWATH ship with ship particulars as follows;

Table 1: Model Particulars

Length	2.311 m
Breadth	0.8 m
Draft	0.2 m
Deck high	0.36 m
Distance between hulls	0.64 m
Fin Type	NACA 0015
Bow fins	0.146 Ls fr. stem
Stern fins	0.816 Ls fr. stem

The numerical of time domain simulation program follows the diagram in Fig.2, the hydrodynamic coefficients was load into computer memory at the first iteration, then calculate the hydrostatic parameters at equilibrium condition and then stored into the memory.

A. Heave and Pitch Verification

The vertical heave and pitch motion of simulation were verified with captive model test in towing tank. The model tested in following sea wave with active fin stabilizer. Ratio of the speed of the model to wave's celerity was 1.13. The wave steepness was 0.06 and wave length to ship length ratio was 1.0. With these parameters, the model tested one and half cycle of ship motions in following wave. Wave generator runs for certain before the carriage to have a generated wave created along 2/3 of effective test length required, then the carriage runs with constant speed. The results of the simulation and experiments were shown in figure-3a,b. The solid line represents simulation results and dashed line represents test results.

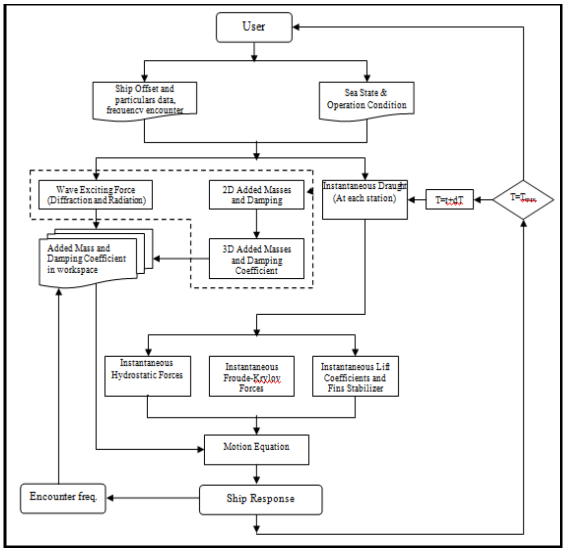

Figure 2: Diagram of numerical Simulation program

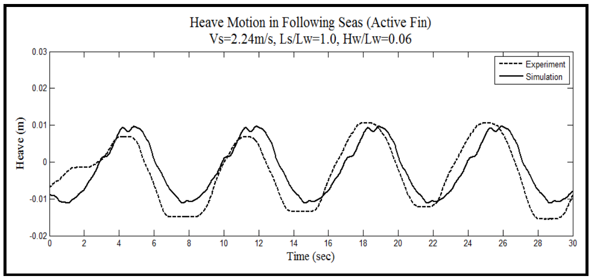

Figure 3a: Heave in following seas with active fin stabilizer.

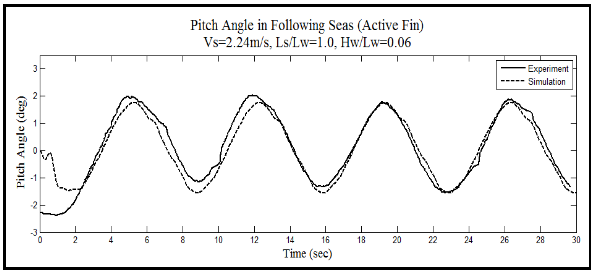

Figure 3b: Pitch in following seas with active fin stabilizer.

B. Surge Force Verification

Verification of surge motion did not compare the surge movement of a model in the test due to captive model test used, where the model was towed at a constant speed with fixed attached at an air strut (connector). Verification conducted by comparing the longitudinal oscillation force in the test and in simulation. This approach based on the assumption during the ship overtakes the sea waves in following waves that the decrease of the force measured indicates there a force affect the ship to accelerate (surfing condition) or the increase of force measured indicates there a force affect the ship to decelerate (climbing condition). Based on that assumption, the oscillation surge force was used for indirect verification of the surge motion. The surge motion was a relative ship motion to the sea wave motion (eq 2a). A correction factor of encounter frequency for simulation results was required, and the correction factor derived as follows;

$$\omega_e = \frac{2\pi\left(V_w - \left(V_s + dV_s\right)\cos\mu\right)}{L_w}$$

$$\omega_e = \frac{2\pi\left(V_w - V_s\cos\mu\right)}{L_w} - \frac{2\pi\, dV_s\cos\mu}{L_w}$$

Then the correction factor used was;

$$cor_f = 1 \pm \frac{dV_s\cos\mu}{\left(V_w - V_s\cos\mu\right)}$$

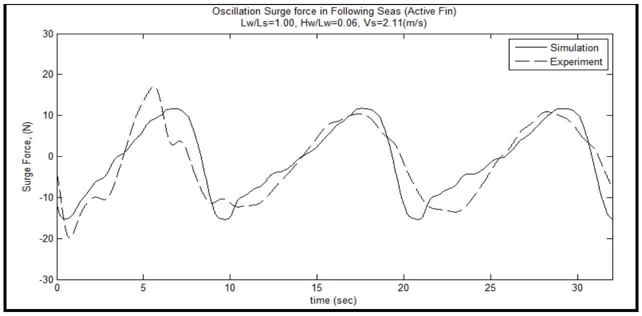

Figure 4: Oscillation force in following seas; surfing, and climbing.

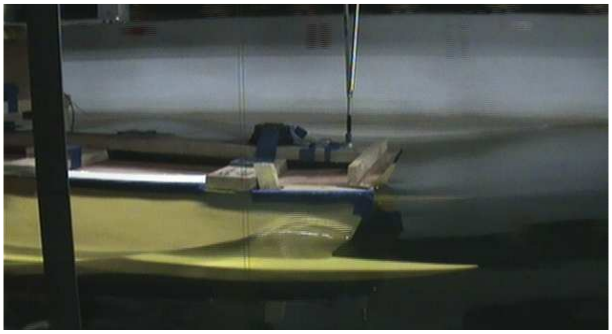

Figure 3c.: Seakeeping test in following waves conducted in towing tank of University Teknologi Malaysia (UTM).

There were changes of ship speed at climbing condition (ship climbs from trough to crest) and surfing condition (ship surfs from crest to trough). The mean of speed changes in simulation as *dVs* was the oscillating surge velocity relatively to the wave celerity.

V. SIMULATION

The ship response sailing in following seas was simulated using certain variation of parameters in relation to the ship and wave. This is to determine the extent of the influence of wave and ship parameters on the ship performance.

The ship speed used in simulation was based on the ship speed required when the ship sail in calm water. Travelling in sea waves, the ship speed tends to change by the effect of oscillating wave. The ship simulated in the ratio of ship speed and wave celerity (Vs/Vw), wave length and the ship length (Lw/Ls), and the wave steepness as a ratio of the wave high and wave length (Hw/Lw).

One of the dynamic motions in following seas was phenomena of a bow-diving. This is always preceded by the surf riding condition where the ship overtakes the waves with ship speed more than wave celerity. At the crest, the ship tends to trim and surf to the trough of sea waves with acceleration. Near the wave's trough, the bow flare begins touching the upslope wave. At the same time, the bow is lifted by its buoyancy. Since the buoyancy less to force the bow arise, the bow may tends to dive under the upslope wave and the effect of bow-diving likely happens when the wave steepness tends to increase.

In the fig.5a, b, c the ship simulated with fixed fins at fore and aft. The ratio of wavelength to ship length were Lw/Ls=1.0, 1.25 and 1.50 and the ratio of ship speed to wave celerity (Vs/Vw) were in the range of 1.1 and 1.35. In these graph show the bow-dive condition emerge at Hw/Lw=0.08.

In Fig.6a, b, c, the ship simulated with fixed fin stabilizer at bow and active fins stabilizer at aft. The fins stabilizer controls the pitch angle to as small as possible. When the pitch angle is positive or the ship on the upslope wave, the angle of stern fin stabilizer turns to positive to provide a negative moment to counter the wave pitch moment. When the angle of pitch is negative or the ship in surfing condition, the controller turns the fin to negative to provide a positive moment to counter the wave moments. In upslope wave, the ship climbs to the crest with a deceleration of speed and in down slope the ship surfs to sea trough with an acceleration of speed.

In the range of studied parameters, the bow diving was not emerge when the fins was set to active and the effect of active fin stabilizer can reduce the ship to surf and restrain to have a bow-diving effect. Furthermore, the fin stabilizer cause the ship was entrapped between the wave's crests. The active fins increase the drag force that reduces the ship speed and the pitch angle decrease. The low pitch angle decrease the effect of ship weight in relation to the longitudinal force.

In Fig.7a, b, c, the pitch response change linearly to steep waves but it changes non-linearly to the change of speed ratio Vs/Vw. The dynamic of pitch motion at Lw/Ls=1.5, Fig.7c, showed the ship pitch has a significant non-linear change. This may affected by the changes of ship encounter frequency at surf condition. While in Fig.8a, b, c showed the effect of active fins stabilizer of the change of pitch angle were not significant except at steep wave 0.08 where the pitch change twice to the change at Hw/Lw; 0.07, 0.06 and 0.05.

The ship response with Hw/Lw=0.08 shown in Fig.9, The extreme bow-dive emerge at Lw/Ls=1.25 with speed ratio Vs/Vw ≥1.15. While ship with ratio Lw/Ls=1.0, the bow-diving emerge at Vs/Vw=1.15 and Vs/Vw≥1.33, and the ship with ratio Lw/Ls=1.50 the bow-diving emerge at Vs/Vw≥1.23.

In Fig.10, shows the boundary of the ship entrapped under effect of active fins stabilizer. The ship condition above the lines showed a condition of the ship surf-riding while under the lines the ship condition entrapped.

In Fig.11a, b shows the ship response in surge, heave, and pitch motion with high dynamic motion. The ship experienced a bow-dive where at certain time, the free bow deck below the wave line. The ship overtakes the waves with high dynamic motion, high heave, and pitch amplitude.

In Fig.12a, b the ship overtakes the wave with low surge motion and with low heave and pitch amplitude. The fins stabilizer angle controlled proportionally to the pitch angle.

In Fig.13a, b the ship entrapped between the crest. The heave, pitch and surge velocity amplitude converge to stationary condition where the ship sailing along with the wave celerity. In this condition the encounter frequency is near or equal to zero.

VI. CONCLUSION

In this paper, the semi-SWATH ship was simulated in the following sea with certain variation of the ship speed, wave length, wave high, and wave steepness with passive and active fin stabilizer. From the figures of all responses the author conclude;

Active fins stabilizer provides a significant reduction effect of the bow-diving and the fin can keep the ship in a stable change of the ship response. The significant non-linear change response emerges at Lw/Ls=1.5 with both fins stabilizer was fixed.

The bow diving occurs at high wave steepness Hw/Lw=0.08 with fixed fin stabilizer. The extreme bow-diving occurs at Lw/Ls=1.25.

The effect of active fin stabilizer can provide the ship not have bow-diving condition but certain conditions the ship was entrapped in between of the crests of wave.

In the future, research, analysis of the ship behavior in following seas with irregular waves and more complex problem required to investigate the effects of parameters of the ship and waves and the fixed, and active fin stabilizer.

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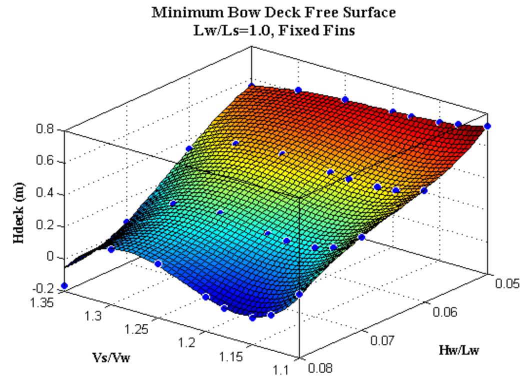

Fig.5(a): free surface of bow-deck in following seas with fixed fins stabilizer and Lw/Ls=1.00

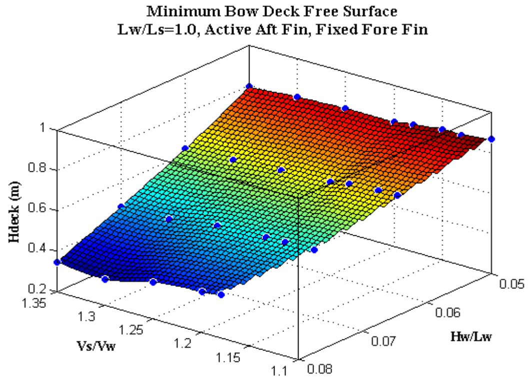

Fig.6(a): free surface of bow-deck in following seas with fixed bow fins and active stern fins stabilizer and Lw/Ls=1.00

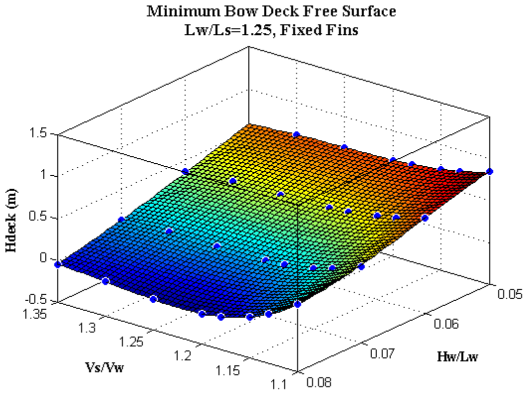

Fig.5(b): free surface of bow-deck in following seas with fixed fins stabilizer and Lw/Ls=1.25

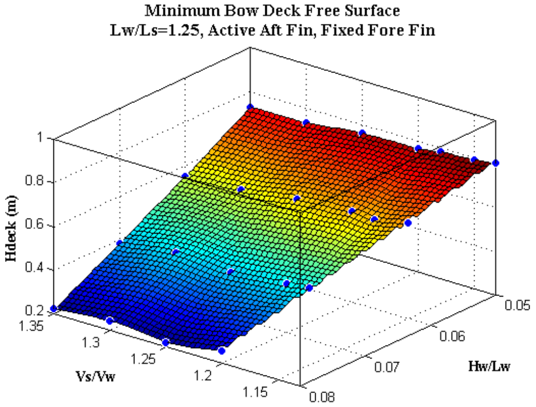

Fig.6(b): free surface of bow-deck in following seas with fixed bow fins and active stern fins stabilizer and Lw/Ls=1.25

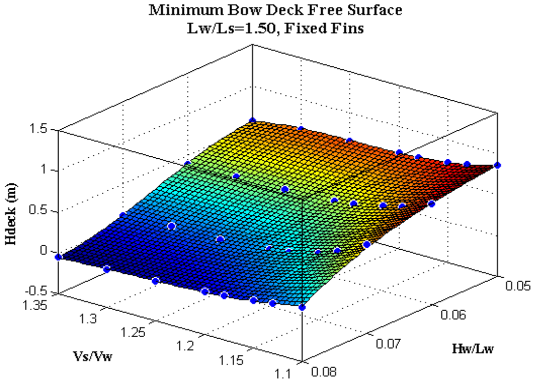

Fig.5(c): free surface of bow-deck in following seas with fixed fins stabilizer with Lw/Ls=1.50

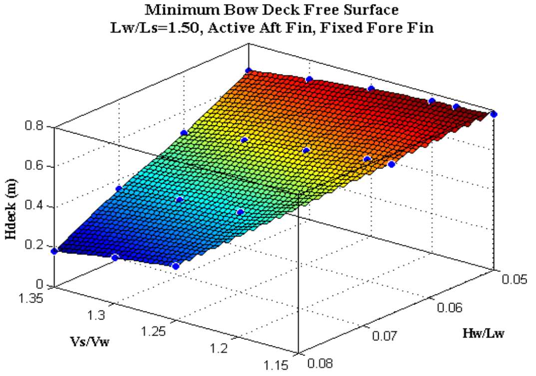

Fig.6(c): free surface of bow-deck in following seas with fixed bow fins and active stern fins stabilizer with Lw/Ls=1.50

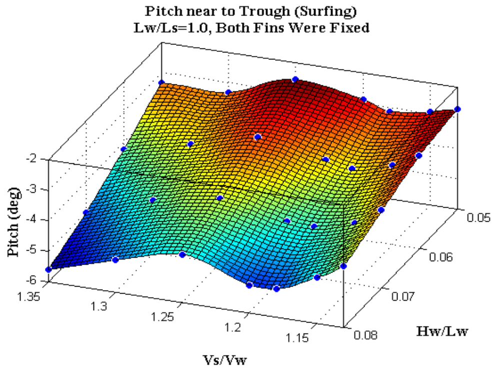

Fig.7(a): The change of pitch angle near the trough of wave in relation to steep wave (Hw/Lw) and ship speed (Vs/Vw) parameters. Both fins were set fixed with Lw/Ls=1.0

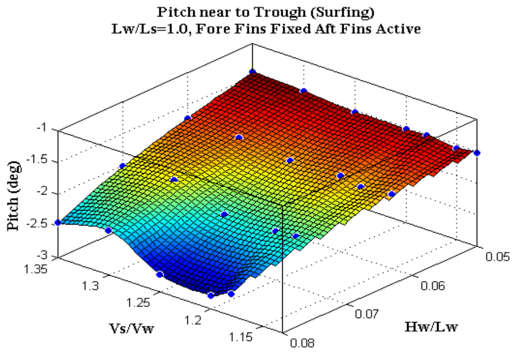

Fig.8(a): The change of pitch angle near the trough of wave in relation to steep wave (Hw/Lw) and ship speed (Vs/Vw) parameters. Bow fin was fixed, stern fin was active with Lw/Ls=1.0.

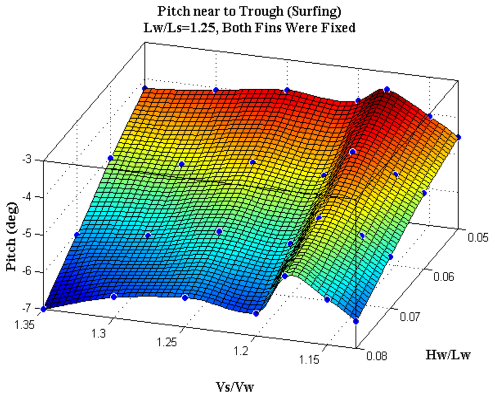

Fig.7(b): The change of pitch angle near the trough of wave in relation to steep wave (Hw/Lw) and ship speed (Vs/Vw) parameters. Both fins were set fixed with Lw/Ls=1.25

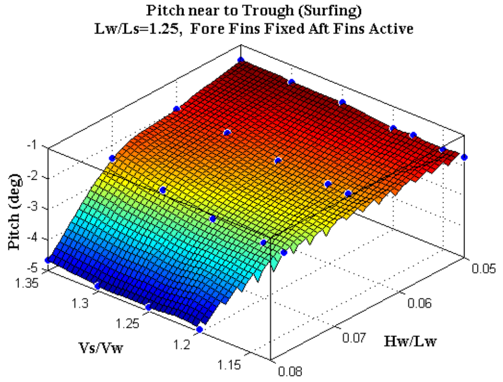

Fig.8(b): The change of pitch angle near the trough of wave in relation to steep wave (Hw/Lw) and ship speed (Vs/Vw) parameters. Bow fin was fixed, stern fin was active with Lw/Ls=1.25.

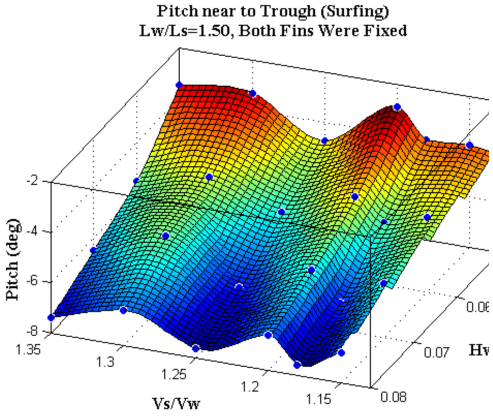

Fig.7(c): The change of pitch angle near the trough of wave in relation to steep wave (Hw/Lw) and ship speed (Vs/Vw) parameters. Both fins were set fixed with Lw/Ls=1.5

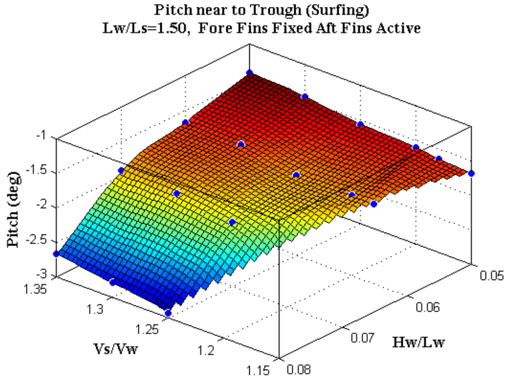

Fig.8(c): The change of pitch angle near the trough of wave in relation to steep wave (Hw/Lw) and ship speed (Vs/Vw) parameters. Bow fin was fixed, stern fin was active with Lw/Ls=1.5.

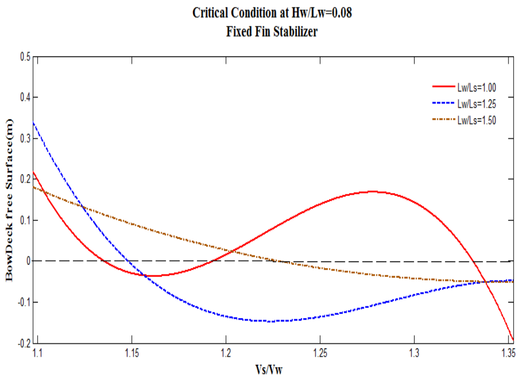

Fig.9: Bow-dive in following seas with fixed fins stabilizer at Hw/Lw=0.08 and Lw/Ls=1.00,1.25, 1.50

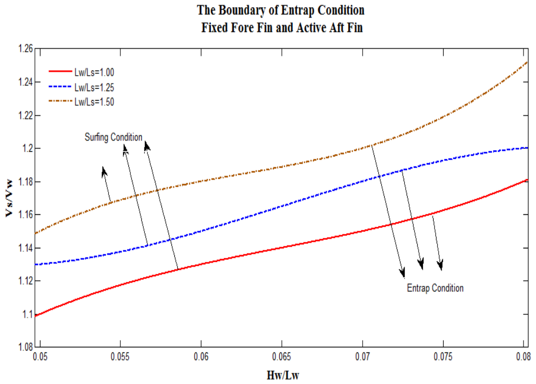

Fig.10: Entrap condition in following seas with fixed bow fins and active stern fins stabilizer, above line is surf condition, and below line is entrap condition

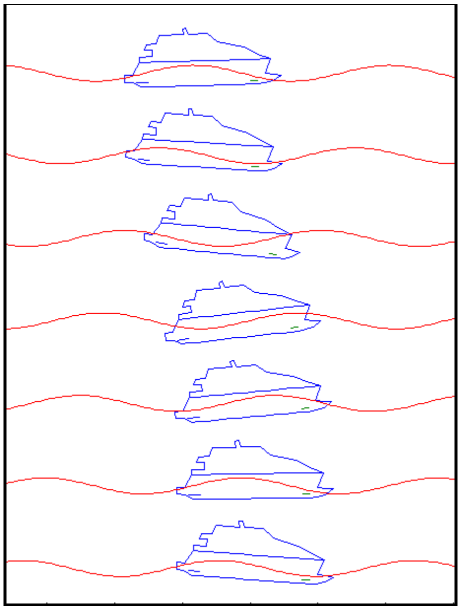

Fig 11(a): Ship response in following seas, Vs=16.3 knot, Vs/Vw=1.25, Lw/Ls=1.25 with both fins stabilizer were fixed

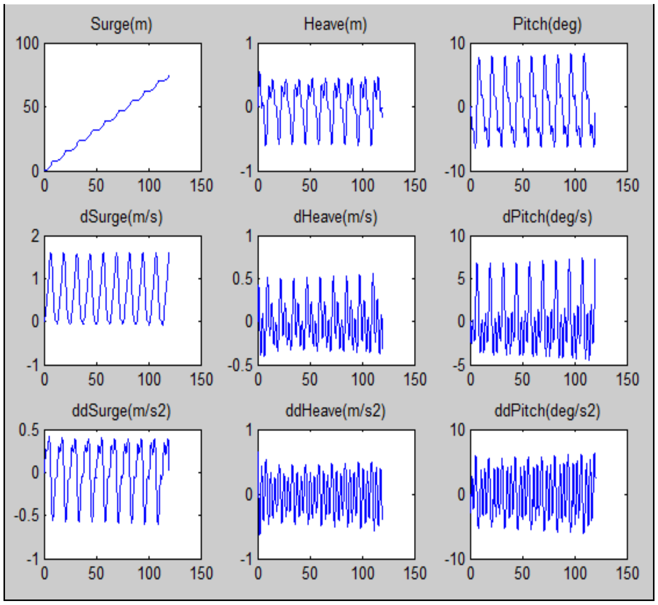

Fig 11(b): Surge, Heave and Pitch response in following seas, Vs=16.3 knot, Vs/Vw=1.25, Lw/Ls=1.25 with both fins stabilizer were fixed

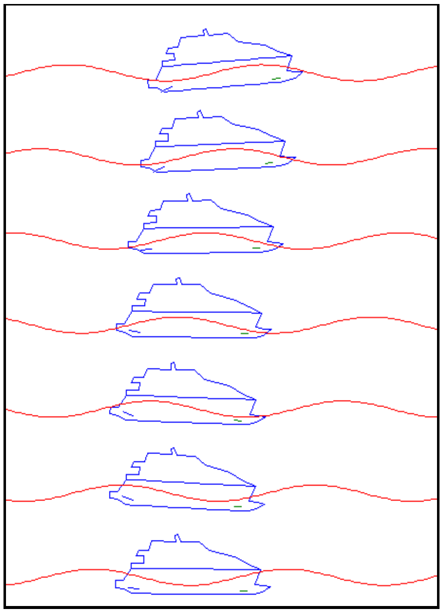

Fig 12(a): Ship response in following seas, Vs=16.3 knot, Vs/Vw=1.25, Lw/Ls=1.25 with fixed bow fin and active stern fin stabilizer

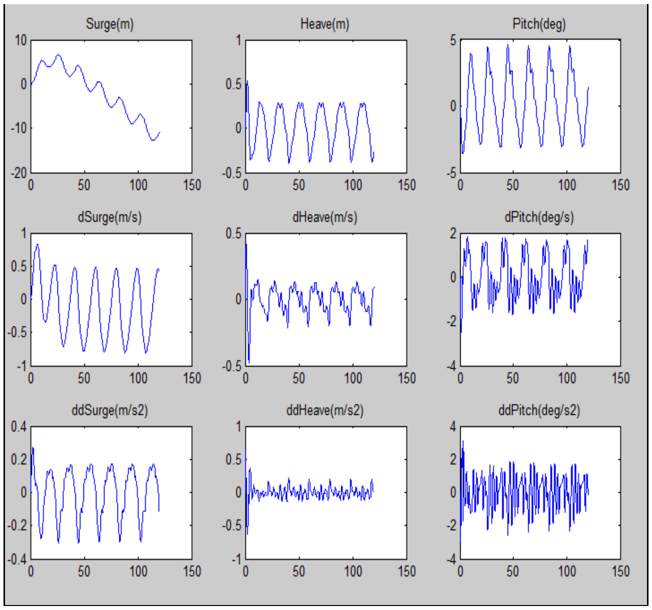

Fig 12(b): Surge, Heave and Pitch response in following seas, Vs=16.3 knot, Vs/Vw=1.25, Lw/Ls=1.25 with fixed bow fin and active stern fin stabilizer

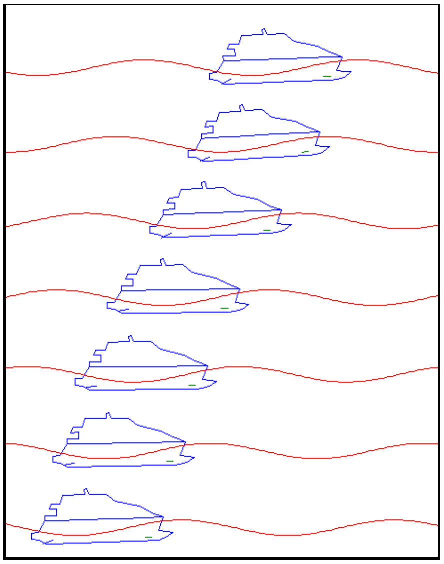

Fig 13(a): Entrapped ship in following seas, initial speed Vs=14.6 knot, Vs/Vw=1.12, Lw/Ls=1.25 with fixed bow fin and active stern fin stabilizer

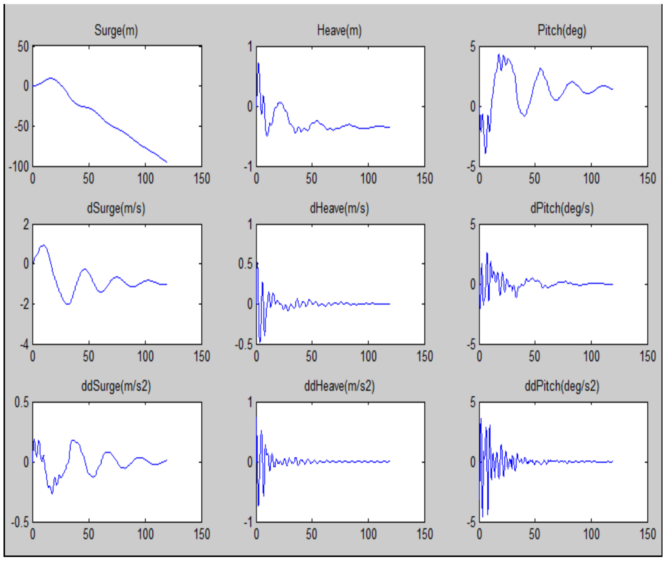

Fig 13(b): Surge, Heave and Pitch response in following seas, Vs=14.6 knot, Vs/Vw=1.12, Lw/Ls=1.25 with fixed bow fin and active stern fin stabilizer