Motion Simulation of a Naval Vessel with Forward Speed in a Rough Sea

The thesis is submitted to the Department of Naval Architecture and Marine Engineering, BUET, Dhaka, in partial fulfilment of the requirements for the degree of Masters of Science in Naval Architecture and Marine Engineering.

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CERTIFICATE OF RESEARCH

This is to certify that this research work has been done by the candidate and it was not submitted elsewhere for the award of degree of Masters of Science in Engineering or for any diploma.

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ABSTRACT

Solving problems of ship hydrodynamics took a lot of attention during the last few decades. In case of a floating ship, the interactiou between the body of the ship and the incoming waves is quite important for designing the structure of the ship as well as during operation of the ship at sea. The hydrodynamic coefficients and the wave exciting forces and moments acting on the body of the ship operating at rough sea have significant influence to the six degrees of motions of the ship. The forward speed of the ship will also have significant effect on those forces and moments and hence motions.

Most of the research works in this field were carried out mainly on the fuller vessels. Such work on a fine shaped vessel like naval ship is limited. So in this present research work, considerable effort has been given to develop a computer program to predict and simulate the motions of a naval ship operating in a rough sea conditions at the Bay of Bengal. The behaviour of the ship at different sea conditions were predicted and time domain simulation of motions were carried out. The motions were also simulated by using long crested waves having different wave height, different ship speed and the wave spectrum of the Bay of Beugal.

The present research work mainly focuses on the prediction and simulation of oscillations/motions of a naval ship which is presently operating in the Bangladesh territorial water and Exclusive Economic Zone.

Hydrodynamic coefficients and wave exciting forces and moments were calculated in regular waves and by utilizing these results, the six degrees of motions of the said naval ship were predicted and simulated in irregular long crested waves.

In order to verify the accuracy of the numerical code developed in the present work, results of experimental as well as practical works of the said naval vessel was not found available in the published papers/literature. However, a Series 60 vessel of block co-efficient 0.60 was selected and hydrodynamic coefficients and wave exciting forces and moments were calculated using the same program and compared with the published results and was found in good agreement.

From this research, it has been found that the ship can run smoothly up tu sea state 3 with the ship speed up to 22.8 knots if both heave and pitch motions are considered at the same time. Considering the heave and pitch effect separately, the ship can run up to sea state 5 with ship speed up to 22.8 knots, up to sea state 6 with ship speed 18.2 knots and up to sea state 7 with ship speed 11.5 knots. Beyond this limit, ship will face high surge/heave/pitch motion and the propeller tip may come out of the still water level.

The trend of the results shows that it would be safer to increase ship speed up to certain sea state which will decrease motions but beyond that limit, with the increase of sea state, it would be better to decrease ship speed.

NOMENCLATURE

Symbol	Descriptions
χ	wave heading angle from X –axis or wave attack angle
ε_i	uniformly distributed random phases.
Φ	total velocity potential
ϕ_s	steady velocity potential due to mean forward speed
ϕ_0	incident wave potential
ϕ_7	diffraction wave potential
ϕ_j	potential due to motion of body in j-th mode i.e. radiation potentials,
λ	wave length
ω_e	encountering frequency
ω	circular frequency of incident wave
ω^*	constant frequency chosen arbitrarily
$\Delta\omega$	difference between two successive circular frequency
$S(\omega)$	wave spectral density
ζ_a	incident wave amplitude
k	wave number
(ξ,η,ζ)	coordinate of a point Q on the body surface S

Symbol	Descriptions
σ	source density Q
$\partial(\chi)$	directional distribution function
ρ	mass density
∇	volume displacement
A_{wp}	water plane area
a'_{33}	non dimensional heave added mass coefficient
a'_{55}	non-dimensional pitch added mass coefficient
a_{kj}	added mass coefficient matrix of kj
B	breadth of the ship
b'_{33}	non-dimensional heave damping coefficient
b'_{55}	non-dimensional pitch damping coefficient
b_{kj}	damping coefficient matrix of kj
B_n	non linear damping coefficient matrix of kj,
C	restoring force coefficient matrix of kj,
c	wave propagation speed
F_1	surge wave exciting force
F'_1	non dimensional surge wave exciting force
F_3	heave wave exciting force
F'_3	non dimensional heave wave exciting force

Symbol	Descriptions
F_k	k-th component of wave exciting forces or moments
F_{kj}	k-th component of forces/moments arising from the j-th component of motion of the body.
F'_x	non-dimensional surge wave exciting force
F'_z	non-dimensional heave wave exciting force
F_k	wave exciting force vector in **k**-mode,
F_n	Froude number
GM_T	transverse metacentric height
GM_L	longitudinal metacentric height
$H_{\frac{1}{3}}$	significant wave height
I	mass moment of inertia
L	length of the ship
M_{kj}	inertia matrix in k- mode due to the motion in j- mode
M_2	wave exciting moment (pitch)
M	mass of the structure
M'_2	non dimensional wave exciting moment (pitch)
m_{kj}	frequency independent added mass matrix of kj
m	direction cosine related to mean forward speed
n_j	direction cosine on the surface of the body

Symbol	Descriptions
R_{kj}	retardation matrix of kj
SWH	significant wave height
$\overline{U}$	mean forward speed.
$\overline{W}$	velocity vector of the steady flow relative to the moving reference frame
X_j	vector containing three translational and three rotational oscillations about the co-ordinate axes in j- mode
$\dot{X}_j$	velocity in jth mode
$\ddot{X}_j$	acceleration in jth mode
$\overline{X}_j$	motion amplitude of the body in j-th mode,
Z_B	vertical coordinate of center of buoyancy
Z_G	vertical coordinate of center of gravity
z	wave elevation from still water level

CHAPTER 1

INTRODUCTION

1.1 General

Sea is the grazing ground where conventional marine vehicles, high-speed Merchant ships, Yachts / Passenger ships, Naval vessels etc are moving from one place to another. These vehicles are the cheapest mode of transportation for goods, equipments and passengers. Ships also serve a large variety of other purposes like naval operations, drilling, marine operations, fishing, sports and leisure activities. They are equipped with sophisticated sensors and equipments. Wave is an important phenomenon which developed in the sea and having a considerable effect on the floating structures at sea. Wave induced motions like heaving, rolling, pitching etc can hamper the movement of ship, create severe stress on the structure and may be problem from an operational point of view of fishing vessels, crane vessels, passenger ships and naval vessels. Vertical accelerations and relative vertical motions between the ship and the waves are important responses. Accelerations determine loads on cargo and equipment and are an important reason for seasickness. So the knowledge about wave induced loads and motions are important both in design of ships and its operational studies.

Bangladesh being a coastal state in the Bay of Bengal has a fairly long coast line of 710 kilometers, 70,000 square kilometers of Exclusive Economic Zone and continental shelf up to 350 nautical miles. The Bay is rich in marine resources, both living and mineral. The country's main trade routes and sea lines of communication also run through the Bay of Bengal which is the only outlet to the vast expanse of the Indian Ocean and larger world beyond.

A coastal state like Bangladesh, having more than 130 millions people and a most densely populated country in the world, is always anxious to exploit her offshore resources as we have very limited land resources. The ocean is an enormous source of energy, raw materials and food. To meet the need of our people we have to search the viable resources from the sea. So we need a big fleet of Merchant vessel, Fishing trawlers, Naval ships and vessels for offshore research, exploration and exploitation of minerals and drilling for oil and gas. All these vessels have to operate or work in the rough sea of the Bay of Bengal and obviously to face sea loads and motions due to waves.

The physical phenomenon of ship motion is not yet fully understood due to its complexity. The ship itself is a complex geometry, elastic body and from the environment around the ship i.e. sea, wind etc. which is a complete stochastic process of yet no clear statistical estimates and probability functions. Marine structures, considered as floating body, will as a matter of course require structural analyses in their design in view of their safety, reliability and economy. And the estimation of wave loads acting on such floating structures presupposes knowledge of their motions iu waves. The six degrees of motions amplitude of a ship need to know at different sea conditions and also at different ship speeds to determine the operational restrictions and also for the safety/security of ship and its men. Since the ships are generally moving with forward speed while undergoing motions in waves, the effect of forward speed should also be taken into consideration. It should thus be effective to establish a system for treating floating structures that would consistently follow the flow:

Hydrodynamic forces → Motion response → Operational restrictions.

1.2 Literature Review

Wave forces and its responses on a floating body are often calculated by two dimensional strip theory [1, 2] and slender body theory [3, 4] which are inadequate because of the over all dimensions and arbitrary shape of the body. Strip theories describe the hydrodynamic properties of each section by using Lewis forms/other particular shape which means accurate shape of the body in concern is not accounted.

Strip theory is also a low Froude Number theory [5]. It does not properly account for the interaction between the steady wave system and the oscillatory effects of ship motions. Another limitation of this theory is the assumption of linearity between response and incident wave amplitude.

As such, 3D source distribution techniques [6, 7, 8, and 9] have been developed to get more accurate results by considering the accurate shape of the vessel. The three-dimensional source method or linear source method is a most versatile technique for calculating the potential flow field in harmonic oscillation. It does not require particular restrictive assumptions on the shape of the body considered and can in principle provide exact solutions.

3-D source distribution technique have been developed enabling the calculation of the hydrodynamic forces on a body oscillating in calm water and the loading on a fixed body in waves. These theories could only be applied to bodies at a zero forward speed and not directly applicable to ships travelling with forward speed due to much more complicated general boundary condition for the speed dependent situation. This difficulty has been overcome [10, 11, 12 and 13] and the analysis and techniques have been extended to calculate the hydrodynamic coefficients of arbitrary shape bodies oscillating and translating in the calm water surface. The same theoretical models were used again to calculate the wave exciting forces and moments acting on an arbitrary shape body moving with a mean forward speed but works are very limited, notably M.Chang [10], R. B. Inglis and W. G. Price [11, 12 and 13]. These works have been carried out by taking the large size of the panels due to the limitation of the computing facility. But with the development of high speed computer, this problem has been eliminated and now a days, large number of panels having small mesh size can be used.

Panel methods are very efficient for sea-keeping calculations. But problem lies with the forward speed at which a lot of numerical and theoretical difficulties appear. Recently, using either Steepest Decent Method (Iwashita and Okhusu[14]), Super Green Function Method (Chen and Noblesse [15]) or Simpson Adaptive Method (Ba & Guilbaud[16], Nontakaew et. al[17]), progresses in the calculations of Green function have been performed. Some researcher's (Chapman[18], Yeung and Kim[19], Yamasaki and Fujino[20], Faltinsen and Zoha[21]) works on this field to solve motion problems also can be mentioned. Wehausen, J.V. & Laitone, E.V.[22] introduced a Green Function applicable for surface wave source with forward speed effect. The first order wave diffraction and radiation problems are well studied by several researchers (Zienkiewicz & Bettes[23], Pinkester, J.A. & Ortmerssen, G. Van[24]). Works on wave forces, hydrodynamic loadings and motions by

Lighthill, J.[25], Cummins, W.E.[26], Inoue, Y. and Seif, M.S.[27] etc can be referred.

Most of the above researches related to hydrodynamic forces and motion analyses were carried out on fuller vessels. But works on vessels having fine shape considering forward speed is limited. So in the present research work, a fine shaped naval ship is selected and by using 3D source distribution method, concern velocity potentials were calculated by utilizing the Green Function in regular sea. In order to obtain the motion simulation in an irregular wave, the hydrodynamic coefficients and wave exciting forces and moments were calculated in regular sea with the help of this velocity potential and utilizing the above results, time domain motion simulation of a naval ship at rough sea is carried out.

1.3 Methodology

The main objective of this research work is to predict and simulate the six degrees of motions by time domain simulation of a naval vessel operating at a rough sea of the Bay of Bengal by considering the forward speed effect.

3-D source-distribution technique was applied in this research work. A fine shaped naval vessel was selected. To utilize the 3-D source distribution method, the whole under water wetted surface area of the ship were divided into 360 panels/meshes.

The hydrodynamic coefficients and wave-exciting forces and moments with forward speed effect of the said naval ship in regular waves have been calculated by the program developed in 3-D source-distribution method. The diffraction potential was ignored for calculating total potential in regular waves due to less scattering of waves from the body of the fine shaped naval vessel and consequently hydrodynamic coefficients and wave-exciting forces and moments were calculated.

A computer program was also developed to simulate the motion in irregular waves. With this program and by utilizing the hydrodynamic coefficients and wave-exciting forces and moments obtained at regular sea, the time history of six degrees of motious were calculated by considering the effect of forward speed and rough sea condition. The wave spectrum of the Bay of Bengal was incorporated in the program. Different significant wave height and long crested waves were also considered for the motion simulation in different speeds.

Validation of the results of the hydrodynamic coefficients and wave-exciting forces and moments were carried out by a Series 60 vessel (Model Number 4210W) due to non availability of experimental or model test data for fine shaped vessel.

1.4 Organization of the Thesis

This thesis is organised in five chapters.

Chapter One (Introduction) is an overview of the present research work. It presents the general importance of this research work, literature review to describe the gradual development of the works done in this field and the methodology to show the sequence of works carried out in the present research.

Chapter Two (Theoretical Model) describes the basic concepts, technique and the theory for the evaluation of hydrodynamic coefficients, wave exciting forces and moments on a ship moving at uniform speed in regular waves. It also discusses about the coordinate system adopted, effect of forward speed, general equation for hydrodynamic coefficients, wave exciting forces and moments, boundary conditions to be satisfied and the general rule to make non-dimensional of the above mentioned forces and moments.

Chapter Three (Equation of Motion) focuses on the equation of motion, mainly on the time domain equation of motion, which is utilized to predict the time history of motion of the naval vessel in rough sea. It also expresses the Newmark-Wilson method which is used to solve the motion equation in time domain. Long and short crested wave profiles of the Bay of Bengal are presented in this chapter.

Chapter Four (Motion Simulation) presents in detail about the researches carried out on the naval ship. It discusses about the selected Naval and Series 60 vessel and their principal particulars, panelling of underwater hull surface, calculation of hydrodynamic coefficients and wave exciting forces and moments, motion simulation of the naval vessel at different sea condition with various ship speed etc. This chapter also presents the result of simulation and observations based on the basis of trend of figures which helps to get idea about operational restrictions and sustainability of the ship at rough sea.

Chapter Five (Conclusions) presents the conclusions and observations drawn based on the basis of present research work which can be a tool for the operation of the naval ship in rough sea in the Bay of Bengal or future design of fine shaped naval vessel. Recommendations for future studies in this field have also been presented in this chapter.

CHAPTER 2

THEORETICAL MODEL

2.1 General

The importance of the prediction and simulation of wave induced motions of a floating body has been discussed in the previous chapter. This chapter addresses to set up the velocity potential applicable to ships moving with constant forward speed as well as the hydrodynamic forces of a ship. Reliable prediction and clear understanding of the dynamic characteristic of a floating body is significant from the view point of reality, safety and operation of the structure. These factors are mainly governed by the accuracy of the mathematical models used to describe the hydrodynamic and motion behaviour of the floating body. As the present research work carried out mainly on a fine shaped naval vessel and the characteristic dimension of the ship is relatively small compared to the wave length and because of that reason, the structure creates less obstruction to the propagation of waves and due to fine underwater shape, the incident waves also get less scattered. Thus the diffraction potential of the incident waves will be smaller in comparison to other potentials. In this chapter, the hydrodynamic forces have been described by means of hydrodynamic co-efficient which is evaluated by 3-D source technique by using panel method which is also called Boundary Element method.

2.2 Co-ordinate system

To describe the hydrodynamic co-efficient, wave exciting forces and moments and motions of a floating body, two right-handed Cartesian co-ordinate systems, one fixed with respect to the mean position to the body (X, Y, Z) and another fixed to the space (X_0, Y_0, Z_0) have been introduced. The positive Z-axis is the vertically upward. For the fixed co-ordinate system, the positive Z-axis (OZ) passes through the centre of gravity of the body in still water condition, the origin O in the plane of the undisturbed free-surface i.e. in the calm water surface and OXY represents the calm water plane. If the body moves with a mean forward speed ($\overline{U}$), this coordinate system moves with the same speed. The body is normally assumed to have the X-Z plane as a plane of symmetry. Let the translatory displacements in the X , Y and Z directions with respect to the origin be X_1, X_2 and X_3 respectively so that X_1 is the surge, X_2 is the sway and X_3 is the heave displacement. Furthermore, let the angular displacement of the rotational motion about the X , Y and Z axis be X_4, X_5 and X_6 respectively so that X_4 is the roll, X_5 is the pitch and X_6 is the yaw angle. The coordinate system and the translatory and angular displacement conventions are shown for the case of ship in Fig: 2.01.

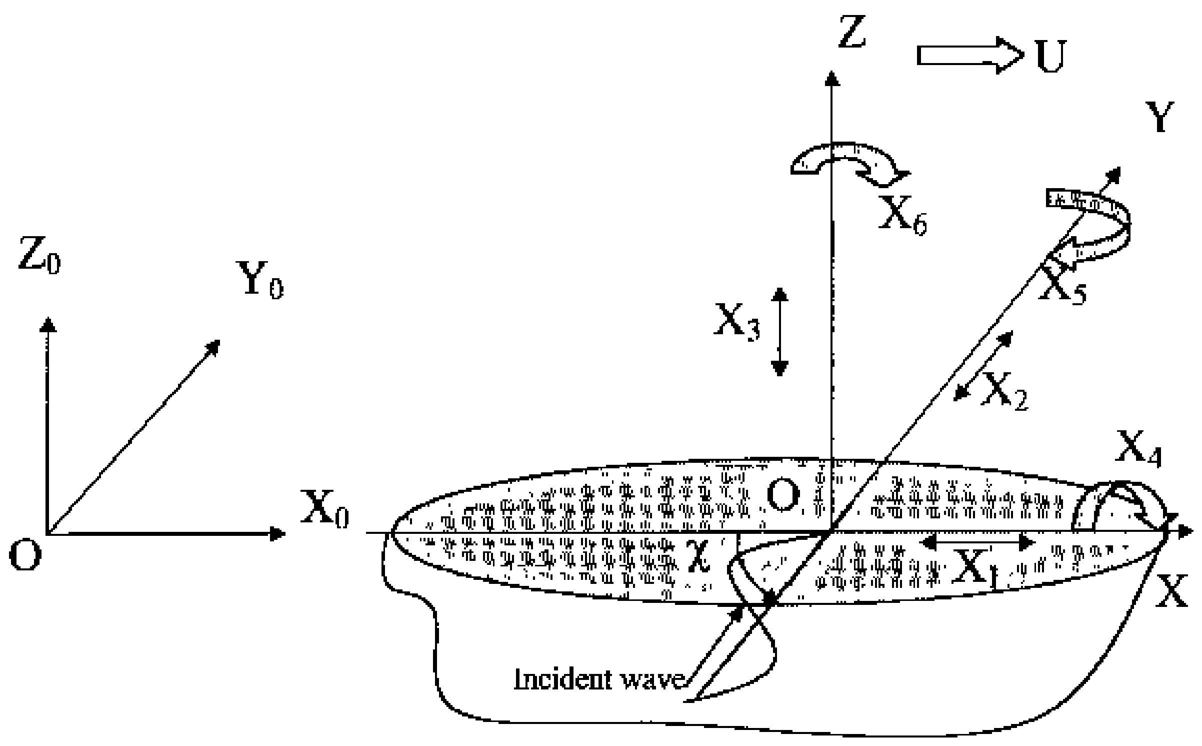


Fig:2.01 Convention for co-ordinate system

2.3 Forward speed effect

The forward speed of a floating structure will influence the added mass and damping coefficients. An important effect for a ship at forward speed is the effect of the frequency of encounter [5]. This can be explained by an idealistic situation that can be created in a ship model basin. In one end of the tank there is a wave maker that creates sinusoidal waves of period T_0. On the towing carriage, the vessel is mounted. The carriage is heading into the waves with a constant speed $\overline{U}$. The phase speed of the waves (the propagation speed of the wave profile) is $c = g/\omega$, where ω is the circular frequency. Let us concentrate on a point on the vessel and consider the time

T_e it takes for two successive wave crests to pass that point. This will obviously be less than T_0.

From Fig: 2.02, we can write

$$\overline{U}\,T_e + cT_e = \lambda \qquad (2.01)$$

Where, $\lambda = 2\pi g/\omega^2$.

This means that the circular frequency of encounter $\omega_e = 2\pi/T_e$ between the ship and the waves can be written as

$$\omega_e = \omega + \omega^2 \frac{\overline{U}}{g} \qquad (2.02)$$

The above equation is valid for head sea condition. For a general heading angle χ between the vessel and the wave propagation direction, measured in anticlockwise direction (Positive X-axis direction i.e. ship's forward speed direction is taken as positive) we can write

$$\omega_e = \omega - \omega^2 \frac{\overline{U}}{g} \cos\chi \qquad (2.03)$$

Here $\chi=0^\circ$ is following seas, $\chi=90^\circ$ is beam seas and $\chi = 180^\circ$ is head seas. We note that $\omega_e= \omega$ for beam seas and that ω_e is smaller than ω for following seas. The frequency of encounter can actually be zero which means the ship stays with the wave profile. For following seas ($\chi = 0^\circ$) this occurs when $T_0 =2\pi\frac{\overline{U}}{g}$. According to the above equation ω_e can be negative.

If this occurs we will interpret ω_e as the absolute value of the right hand side of the equation. Because the ship having forward speed will oscillate with the circular frequency of encounter and the added mass and damping coefficients have to be evaluated for ω_e.

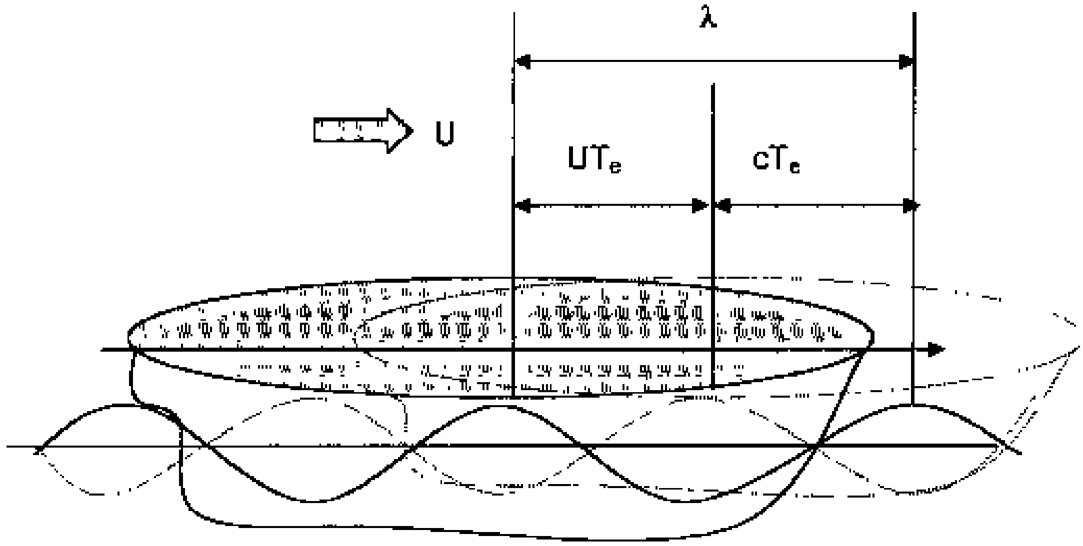


Fig:2.02 Effect of frequency of encounter when a ship is in regular head sea waves.

2.4 Governing Equations and Assumptions

To describe the hydrodynamic forces and moments on an arbitrary shaped body, a right handed coordinate system with origin O in the calm water surface, OZ vertically upward and OXY in the plane of the calm water surface is already introduced as shown in Fig: 2.01. Now let us consider the three-dimensional arbitrary shaped body travelling at constant forward speed $\overline{U}$. The amplitude of the motions as well as the incident waves are supposed to be small, while the fluid is assumed to be inviscid and irrotational. Therefore the total velocity potential [28] Φ can be written as

$$\Phi(x, y, z, t) = -\overline{U}x + \phi_s + \phi \tag{2.04}$$

where, ϕ_s = steady velocity potential due to mean forward speed of the ship and $$\phi = \phi_0 e^{-i\omega_e t} + \phi_7 e^{-i\omega_e t} + \sum_{j=1}^{6} - i\omega_e \overline{X_j}\phi_j \tag{2.05}$$

ϕ_0 =incident wave potential

ϕ_7 =diffraction wave potential

ϕ_j = potential due to motion of the body in j-th mode i.e. radiation wave potentials,

$\overline{X}_j$ = motion amplitude of the body in j-th mode,

ω_e = encountering frequency and is defined as

$$\omega_e = \omega - \frac{\omega^2 \overline{U}}{g}\cos\chi \tag{2.06}$$

ω= circular frequency of incident wave

According to the previous discussion, due to less scattering of incident waves at fine under water hull, the diffraction potential will be very very less compared to other potentials and can be neglected and ϕ_7 can be taken as zero i.e. $\phi_7 = 0$. So the velocity potential can be written as follows:

$$\phi = \phi_0 e^{-i\omega_e t} + \sum_{j=1}^{6} - i\omega_e \overline{X_j}\phi_j \tag{2.07}$$

The incident wave potential is defined as follows:

$$\phi_0 = \frac{-ig\zeta_a}{\omega}\frac{\cosh\left[k(z+h)\right]}{\cosh kh} e^{ik(x\cos\chi + y\sin\chi)} \tag{2.08}$$

where, ζ_a = incident wave amplitude,

χ = wave heading angle from X -axis

The differential equation governing the fluid motion follows from the application of the continuity equation which yields the Laplace equation. The individual potentials are the solutions of the following Laplace equation:

$$\nabla^2\phi = 0 \tag{2.09}$$

2.5 Boundary Conditions

On the mean wetted surface area S, the above linear velocity potentials must satisfy the Laplace equation and also the following boundary conditions:

(i) The steady motion potential:

$$\overline{W}.n = 0 \text{ on S} \tag{2.10}$$

where $\overline{W}.n = \overline{U}\nabla(\overline{\phi} - x)$ and $\overline{U\phi} = \phi_s$

(ii) Linearized free surface boundary condition:

$$\frac{\partial\phi}{\partial z} = \frac{\omega_e^2}{g}\phi \quad \text{at } z = 0 \tag{2.11}$$

iii) The boundary conditions on the wetted surface of the floating bodies. Due to linearization, this boundary condition may be applied on the wetted surface of the floating bodies in their equilibrium position

$$\frac{\partial\phi_0}{\partial n} + \frac{\partial\phi_7}{\partial n} = 0 \quad \text{on } S \tag{2.12}$$

For the case considered ($\phi_7 = 0$)

Therefore,

$$\frac{\partial\phi_0}{\partial n} = 0 \text{ on S} \tag{2.13}$$

$$\frac{\partial\phi_j^m}{\partial n} = i\omega_e n_j + \overline{U} m_j \quad \text{ou } S \tag{2.14}$$

In which n_j is the direction cosine on the surface of the body in the j-th mode of motion and has the following form:

$$n_1 = \cos(n,x),$$

$$n_2 = \cos(n,y),$$

$$n_3 = \cos(n,z),$$

$$n_4 = (y - y_G)n_3 - (z - z_G)n_2,$$

$$n_5 = (z - z_G)n_1 - (x - x_G)n_3,$$

$$n_6 = (x - x_G)n_2 - (y - y_G)n_1,$$

and $m_1 = m_2 = m_3 = m_4 = 0$, $m_5 = n_3$, $m_6 = -n_2$

where x_G, y_G and z_G are the co-ordinate of the centre of gravity of the body and x, y, z are the investigating point on the wetted surface of the body.

2.6 Hydrodynamic Forces and Moments

There is no analytical solution for ϕ_j. So the problem should be solved numerically. According to the 3-D source method, the potentials ϕ_j can be expressed in terms of well-known Green functions. As a resolt, boundary conditions are reduced only on wetted surface of the body. So, the wetted surfaces should be subdivided into a number of panels to transform integral equations to a system of algebraic equations to determine unknown source density over each panel. The numerical calculation of the source density and velocity potential based on Green function have been given in **Appendix-A**.

After getting the velocity potentials, the hydrodynamic pressure at any point on the body can be obtained from the linearized Bernoulli's equation and can be written as:

$$\frac{\partial \Phi}{\partial t} + \frac{1}{2}(\nabla \Phi)^2 + \frac{P}{\rho} + gz = 0 \qquad (2.15)$$

Now after putting the value of Φ in the equation (2.15), the following expression is obtained,

$$-\frac{P}{\rho} = -i\omega_e \phi + \frac{1}{2}\{\nabla(-\overline{U}x + \phi_s)\}^2 + \nabla(-\overline{U}x + \phi_s).\nabla\phi + \frac{1}{2}(\nabla\phi)^2 + gz \qquad (2.16)$$

By neglecting the higher order terms, we can write

$$P = \rho\left(\frac{\overline{U}}{2}\frac{\partial \phi_S}{\partial x} - gz\right) + \rho\left(i\omega_e \phi + \overline{U}\frac{\partial \phi}{\partial x}\right) \qquad (2.17)$$

As first part of equation (2.17) is associated with the hydrostatic and steady forces, so neglecting this part, the first order wave exciting forces or moments and oscillatory forces and moments caused by the dynamic fluid pressure acting on the body can be obtained from the following integrals:

$$F_k.e^{-i\omega_e t} = -i\rho\omega_e e^{-i\omega_e t}\int_s \left\{\phi_0 - i\frac{\overline{U}}{\omega_e}\left(\frac{\partial \phi_0}{\partial x}\right)\right\}.n_k ds \qquad (2.18)$$

$$F_{kj}.e^{i\omega_e t} = -\rho e^{-i\omega_e t}\int_s \left\{\omega_e^2 \overline{X}_j \phi_j - i\omega_e \overline{X}_j \overline{U}\frac{\partial \phi_j}{\partial x}\right\}.n_k.ds \qquad (2.19)$$

where,

F_k denotes the k-th component of wave exciting forces or moments

F_{kj} denotes the k-th component of force arising from the j-th component of motion of the body.

Moreover, it is customary to decompose the hydrodynamic forces resulting from motion of the bodies into components in phase with the acceleration and velocity of the rigid body motions. These yield the added mass and damping coefficients respectively. These coefficients can be expressed from equation as:

$$a_{kj} = -\rho.\mathrm{Re}\left[\int_s (\phi_j + \frac{\overline{U}}{\omega_e}\frac{\partial \phi_j}{\partial x}).n_k.ds\right], \tag{2.20}$$

$$b_{kj} = -\rho\omega_e.\mathrm{Re}\left[\int_s (\phi_j + \frac{\overline{U}}{\omega_e}\frac{\partial \phi_j}{\partial x}).n_k.ds\right] \tag{2.21}$$

2.7 Non-dimensionalization:

Added mass, damping co-efficient, wave exciting forces and moments can be non-dimensionalised as follows:

Added mass (heave and pitch)

$$a'_{33} = \frac{a_{33}}{\rho\nabla}, \qquad a'_{55} = \frac{a_{55}}{\frac{1}{4}\rho\nabla L^2},$$

Damping coefficients (heave and pitch)

$$b'_{33} = \frac{b_{33}}{\rho\nabla\omega_e}, \qquad b'_{55} = \frac{b_{55}}{\frac{1}{4}\rho\nabla\omega_e L^2}$$

Wave exciting forces and moments (surge, heave and pitch)

$$F'_1 = \frac{F_1}{\frac{1}{2}\rho g\zeta_a BL}, \qquad F'_3 = \frac{F_3}{\frac{1}{2}\rho g\zeta_a BL}$$

and $$M'_2 = \frac{M_2}{\frac{1}{4}\rho g\zeta_a BL^2}$$

CHAPTER 3

EQUATION OF MOTION

3.1 Equation of Motion in Time Domain

The approach to the hydrodynamics of a floating body has been discussed in the previous section based on a description of fluid and body motion in frequency domain. Such description is quite adequate provided that the system is linear and the mean position of the floating structure does not change. But as soon as the non-linear load displacement characteristics are considered, a time domain description is required.

For time domain motion analysis of a floating structure, motion equation can be derived on the basis of the equation proposed by Cummins [26]. In this method frequency dependency of hydrodynamic reaction forces is taken into account by means of convolution integral and no other assumption is required than linearity of hydrodynamic forces. The equation of motion in time domain can be written as:

$$\sum_{j=1}^{6} \left(M_{kj} + m_{kj}\right)\ddot{X}_j + \int_{-\infty}^{t} R_{kj}(t-\tau)\dot{X}_j \, d\tau + B_n\left|\dot{X}_j\right|\dot{X}_j + CX_j = F_k \qquad (3.02)$$

Where,

M_{kj} = inertia matrix of kj,

m_{kj} = frequency independent added mass matrix of kj,

R_{kj} = retardation function matrix of kj,

B_n = non linear damping coefficient matrix of kj,

C = restoring coefficient matrix of kj,

F_k = wave exciting force vector in k-mode,
The mass of the structure M and I is the mass moment of inertia.

Where,

$$[M] = \begin{bmatrix} m & 0 & 0 & 0 & 0 & 0 \\ 0 & m & 0 & 0 & 0 & 0 \\ 0 & 0 & m & 0 & 0 & 0 \\ 0 & 0 & 0 & I_{44} & -I_{45} & -I_{46} \\ 0 & 0 & 0 & -I_{54} & I_{55} & -I^{i}_{56} \\ 0 & 0 & 0 & -I_{64} & -I_{65} & I_{66} \end{bmatrix}$$

The inertia matrix for motion analysis of a floating body has the following form:

$$[M_s] = \begin{bmatrix} M & 0 & 0 & 0 & 0 & 0 \\ 0 & M & 0 & 0 & 0 & 0 \\ 0 & 0 & M & 0 & 0 & 0 \\ 0 & 0 & 0 & I_{44} & 0 & -I_{46} \\ 0 & 0 & 0 & 0 & I_{55} & 0 \\ 0 & 0 & 0 & -I_{46} & 0 & I_{66} \end{bmatrix}$$

In which:

$$I_{44} = \iiint_v \rho(y^2 + z^2)dv$$

$$I_{55} = \iiint_v \rho(z^2 + x^2)dv$$

$$I_{66} = \iiint_v \rho(x^2 + y^2)dv$$

$$I_{45} = \iiint_v \rho xydv$$

$$I_{46} = \iiint_v \rho xzdv$$

$$I_{56} = \iiint_v \rho yzdv$$

In the above expression, ρ is the mass density of the fluid.

The hydrodynamic restoring force coefficient matrix $[C]$ has the following form

$$[C] = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & c_{33} & 0 & c_{35} & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & c_{53} & 0 & c_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Where,

$$c_{33} = \rho g A_{wp}$$

$$c_{35} = c_{53} = -\rho g \iint_{A_{wp}} x ds$$

$$c_{44} = \rho g V (Z_B - Z_G) + \rho g \iint_{A_{wp}} y^2 ds = \rho g GM_T$$

$$c_{55} = \rho g V (Z_B - Z_G) + \rho g \iint_{A_{wp}} x^2 ds = \rho g GM_L$$

where. A_{wp}, Z_B and Z_G are water plane area, vertical coordinate of center of buoyancy and vertical coordinate of center of gravity of the floating body. GM_T and GM_L are transverse and longitudinal metacentric height of the ship respectively.

Components of m_{kj} and R_{kj} matrices have the following forms:

$$m_{kj} = a_{kj}(\omega^*) + \frac{1}{\omega^*}\int_0^\infty R_{kj}(t)\sin(\omega^* t)dt \qquad (3.03)$$

$$R_{kj}(t) = \frac{2}{\pi}\int_0^\infty b_{kj}(\omega)\cos(\omega t)d\omega \qquad (3.04)$$

Here a_{kj} and b_{kj} are frequency dependent added mass and damping coefficients matrices respectively (k and j take values from 1 to 6) and ω^* is the constant frequency which can be chosen arbitrarily. The advantages of describing the hydrodynamic radiation forces due to added mass and damping effects using retardation functions lies in the fact that arbitrary motions can be accommodated correctly, irrespective of the motions of the structure. Using above definition, the equation of motion showing only the linear damping term at n-th time step (t = $n\Delta t$) can be rewritten in the following form[29]:

$$\sum_{j=1}^{6}(M_{kj}+m_{kj})\ddot{X}_j+\Delta t R_{kj}(p=0)\dot{X}_j+CX_j=F_k-\sum_{p=1}^{n}R_{kj}(p)\dot{X}_j(n-p)\Delta t \tag{3.05}$$

The above equation can be solved by one of the numerical integration techniques in each time step. For the present study Newmark-Wilson method has been applied to solve the equation.

3.2 Solution of Equation of Motion in time domain

Many different methods have been developed for solving the linear dynamic equations of motion. The direct integration is a simple approach which can have considerable advantages for some problems. The basic equation is satisfied at discrete points in time, 0, Δt, $2\Delta t$, $3\Delta t$ .... t, $t+\Delta t$,....T. The solution starts from a point in time where the displacements, velocities and accelerations are known. Based on an assumption on the behaviour of the system during the next small increment of time, the displacements, velocities and accelerations at the next point in time can be evaluated. One of the most flexible step-by-step integration methods has been presented by Newmark-Wilson [30].

Newmark-Wilson method

This method is based on the following expressions for the velocity and displacement at the end of the time interval:

$$\dot{U}_{t+\Delta t} = \dot{U}_t + \Delta t(1-\delta)\ddot{U}_t + \Delta t \delta \ddot{U}_{t+\Delta t} \tag{3.06}$$

$$U_{t+\Delta t} = U_t + \Delta t \dot{U}_t + \Delta t^2 (\frac{1}{2} - \alpha)\ddot{U}_t + \Delta t^2 \alpha \ddot{U}_{t+\Delta t} \tag{3.07}$$

where α and δ are selected to produce the desired accuracy and stability. If $\delta=\frac{1}{2}$ and $\alpha = \frac{1}{6}$ the well known linear acceleration is produced, which is also a conditionally stable method. One of the most widely used methods is the constant-average-acceleration method ($\delta=\frac{1}{2}$ and $\alpha = \frac{1}{4}$) which is an unconditionally stable method without numerical damping.

This method is called 'implicit integration method' since it satisfies the equilibrium equation of motion at time $t+\Delta t$, or

$$M\ddot{U}_{t+\Delta t} + C\dot{U}_{t+\Delta t} + KU_{t+\Delta t} = F_{t+\Delta t} \tag{3.08}$$

This equation can be solved by iteration. However equation 3.06, 3.07 and 3.08 can be combined into a step-by-step algorithm which involves the solution of a set of equations at each time step form

$$K^* U_{t+\Delta t} = F^* \tag{3.09}$$

Since K^* is not a function of time it can be traingularized once at the beginning of the calculations. The computer solution time for this type of algorithm is basically proportional to the number of time steps required.
The Wilson θ method is a technique which can be used to modify the basic Newmark method in order to increase the stability limits and to add numerical damping. The θ method was first applied to the linear acceleration

method in order to improve stability and has been used to damp out high frequency oscillations which often develop in linear and non-linear step-by-step integration.The technique involves using the Newmark method to find the solution t $+\theta\Delta t$, then, based on linear acceleration, calculating the results at $t + \Delta t$ for use as initial conditions for the next time step. The Newmark-Wilson algorithm is summarized below. With $\theta=1$ the approach is the standard Newmark method. An unconditionally stable method with large damping in the higher modes is produced with $\delta=\frac{1}{2}$, $\alpha = \frac{1}{6}$ and $\theta=1.4$.

Newmark-Wilson algorithm for linear step-by-step integration

A. Initial Calculation:

1. Form stiffness matrix K, mass matrix M and damping matrix C

2. Initialize U_0, $\dot{U}_0$ and $\ddot{U}_0$

3. Specify algorithm parameters α, δ and θ

   $\delta \geq 0.50$, $\alpha \geq 0.25(0.5+\delta)^2$; $\theta \geq 1.0$

4. Calculate integration constants:

   $$\tau = \theta\Delta t \qquad a_0 = \frac{1}{\alpha\tau^2} \qquad a_1 = \frac{\delta}{\alpha\tau} \qquad a_2 = \frac{1}{\alpha\tau} \qquad a_3 = \frac{1}{2\alpha} - 1$$

   $$a_4 = \frac{\delta}{\alpha} - 1 \qquad a_5 = \frac{\tau}{2}(\delta/\alpha - 2) \qquad a_6 = \Delta t(1-\delta) \qquad a_7 = \Delta t\, \delta$$

   $$a_8 = \Delta t^2(\frac{1}{2} - \alpha) \qquad a_9 = \alpha\, \Delta t^2 \qquad \text{where, } \tau \text{ is } \Delta t$$

5. Form effective stiffness matrix $K^* = K + a_0 M + a_1 C$

6. Traingularize K^* : $K^* = LDL^T$

B. For Each Time Step

1. Calculate effective load vector at time $t + \tau$:

$$F^* = F_{t+\tau} + M(a_0 U_t + a_2 \dot{U}_t + a_3 \ddot{U}_T) + C(a_1 U_t + a_4 \dot{U}_t + a_5 \ddot{U}_t)$$

2. Solve for displacement at time t + τ :

   $$LDL^T U_{t+\tau} = F^*$$

3. Calculate accelerations, velocities and displacement at $t + \Delta t$:

   $$\ddot{U}_{t+\tau} = a_0 (U_{t+\tau} - U_t) - a_2 \dot{U}_t - a_3 \ddot{U}_t$$

   $$\ddot{U}_{t+\Delta t} = \ddot{U}_t + \frac{1}{\theta}(\ddot{U}_{t+\tau} - \ddot{U}_t)$$

   $$\dot{U}_{t+\Delta t} = \dot{U}_t + a_6 \ddot{U}_t + a_7 \ddot{U}_{t+\Delta t}$$

   $$U_{t+\Delta t} = U_t + \Delta t \dot{U}_t + a_8 \ddot{U}_t + a_9 \ddot{U}_{t+\Delta t}$$

3.3 Wave Profile used in time domain Simulation

For multidirectional irregular waves, the profile can be written as sum of component harmonic waves [29] as follows:

$$\zeta(t : x, y) = \sum_i a_i \cos(\omega_i t - k_i x \cos \chi_i - k_i y \sin \chi_i + \varepsilon_i) \qquad (3.10)$$

where a_i is the wave amplitude of a component wave of attack angle χ_i, frequency ω_i, wave nnmber k_i and ε_i is in general a uniform distributed random phases. Then the wave elevation of equation (3.10) at the centre of co-ordinates becomes:

$$\zeta(t) = \sum_i a_i \cos(\omega_i t + \varepsilon_i) \qquad (3.11)$$

$$= \mathrm{Re} \sum_i A_i e^{i\omega_i t}$$

The wave amplitude A_i can be expressed by a wave spectrum $S(\omega)$ and can be written as:

$$\frac{1}{2}A_i^2 = S(\omega)\Delta\omega \qquad (3.12)$$

Where, $\Delta\omega$ is a constant difference between successive frequencies

The approximate formula for spectral density of wave as function of circular frequency and significant wave height which could be applied for estimation of spectral density at Hiron point of The Bay of Bengal [31] are given below.

$$S(\omega) = A\omega^{-5} e^{-\frac{B}{\omega^4}} \qquad (3.13)$$

where,

$A = 0.061$ and $B = \frac{0.244}{H_{1/3}^2}$ for Hiron point.

Where, $H_{1/3}$ = Significant wave height

ω = Circular frequency in rad/sec

$S(\omega)$ = wave spectrum

A_i = Wave amplitude

$\Delta\omega = \omega_2 - \omega_1$

The wave spectrum in directional short crested waves $S(\omega,\chi)$ is defined by the following expression:

$$S(\omega,\chi) = S(\omega)\partial(\chi) \qquad (3.14)$$

Where, $S(\omega)$ is the wave spectral density of irregular long crested waves and $\partial(\chi)$ is the directional distribution function which must satisfy the following relationship:

$$\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \partial(\chi)\,d\chi = 1 \qquad (3.15)$$

Where,

χ is the wave heading angle measured with the principal incident wave or main wave.

And the modified distribution functiou [29] is defined as follows:

$$\partial(\chi) = \frac{2}{\pi}\cos^2(\chi) \tag{3.16}$$

The wave profiles found by using the wave spectrum of the Bay of Bengal (3.13) for long and short crested waves with significant wave height 1.0 and 3.0 meters are shown in Fig:3.01 to Fig: 3.06.

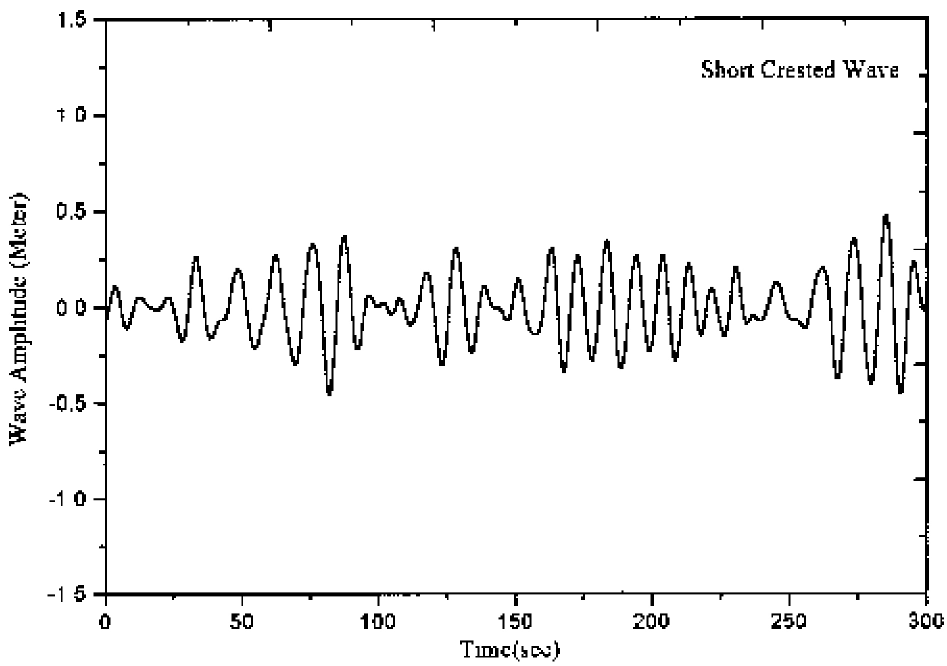


Fig 3.01 Short Crested Wave Profile of Bay of Bengal (SWH:1.0m)

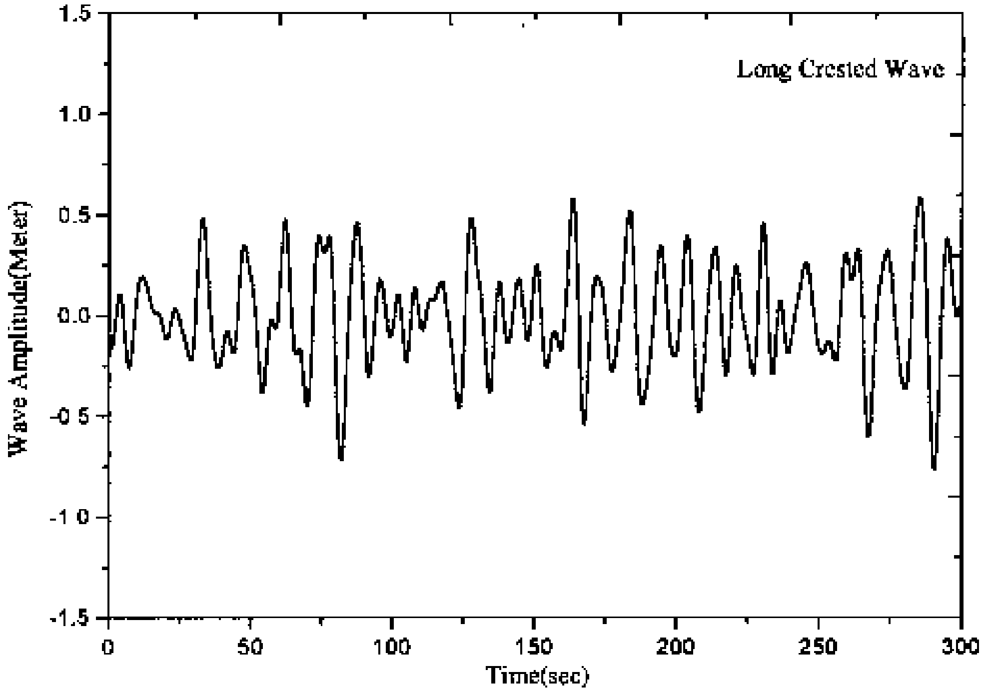


Fig:3.02 Long Crested Wave profile of Bay of Bengal (SWH 1.0m)

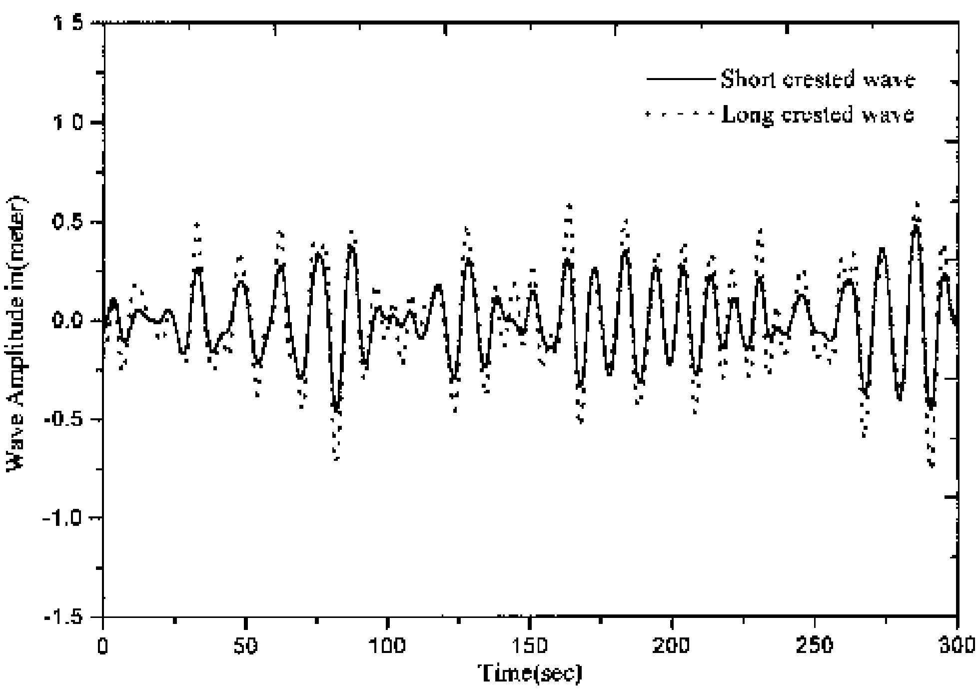
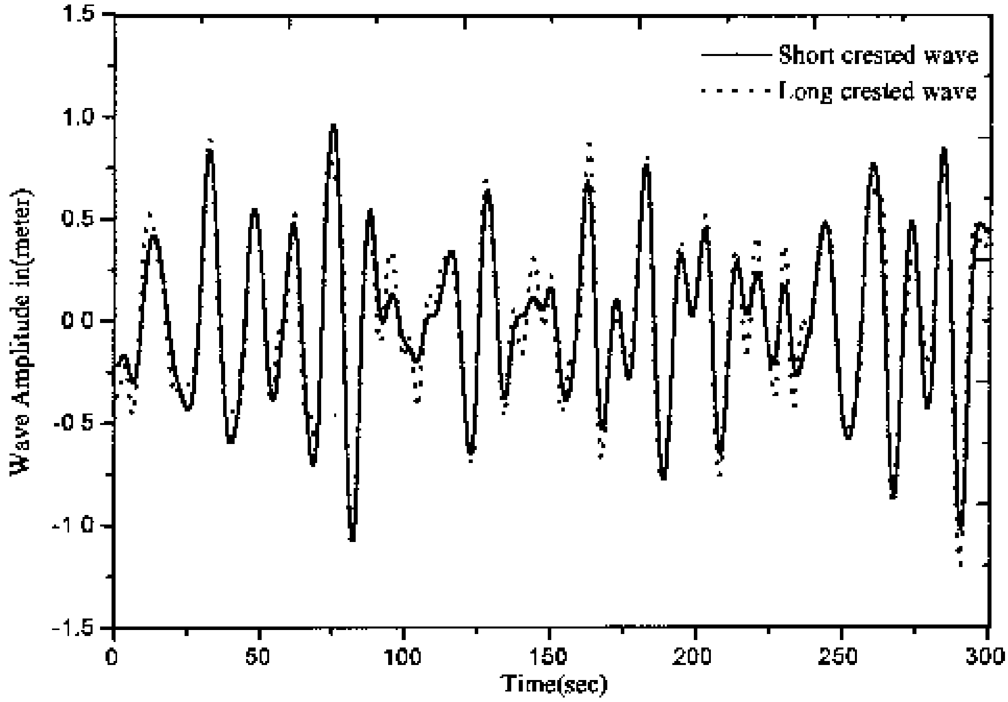
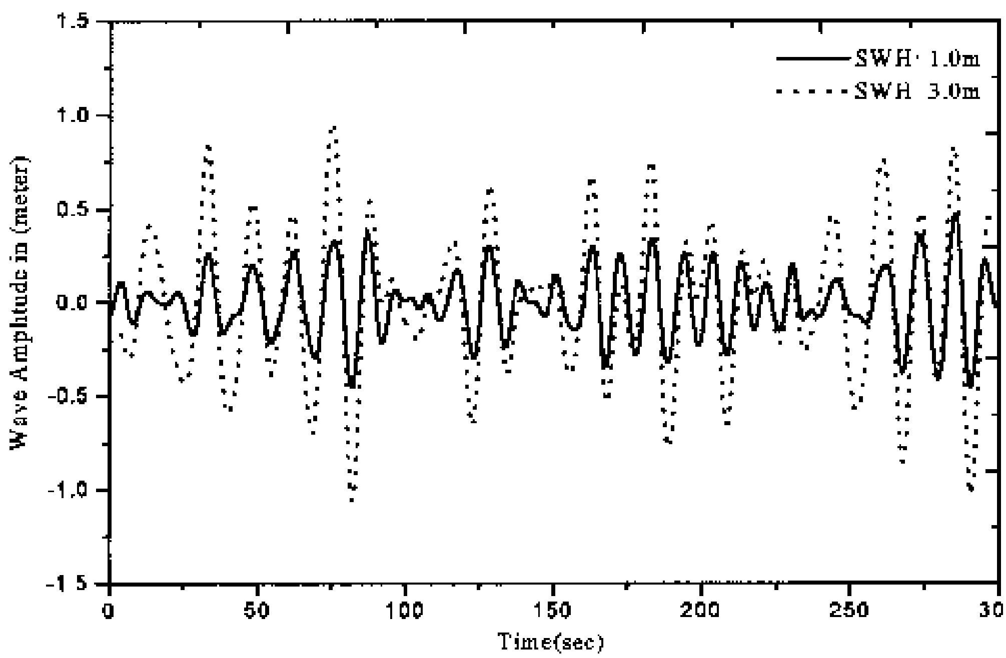


Fig: 3.03 Comparison of Wave profile of Bay of Bengal(SWH: 1.0m)



Fig' 3.04 Comparison of Wave profile of Bay of Bengal(SWH:3.0m)



Fig' 3.05 Comparison of Wave profile of Bay of Bengal(Short crested)

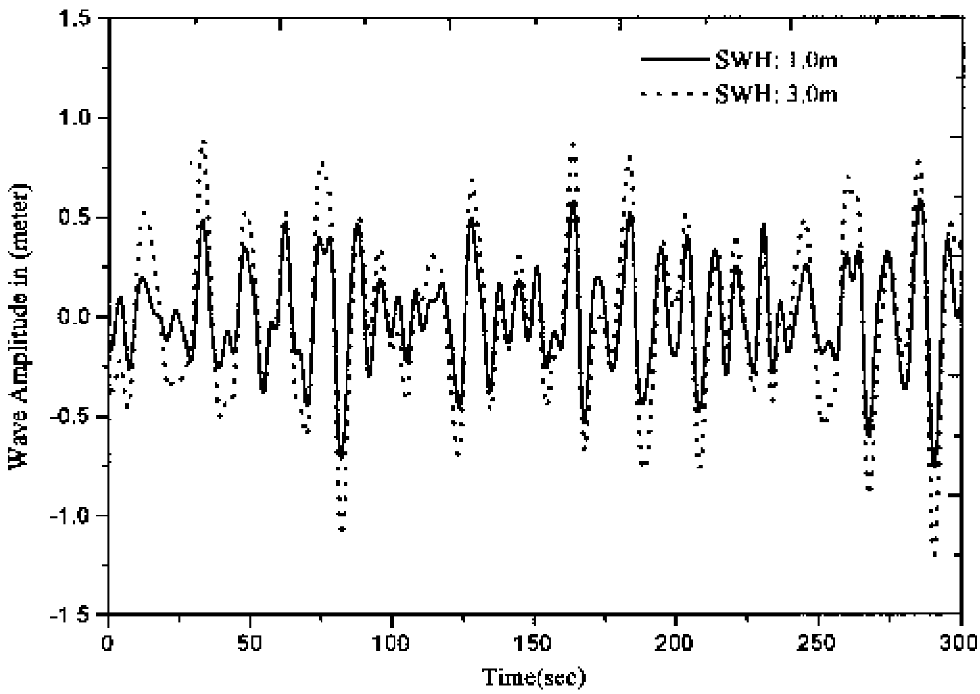


Fig: 3.06 Comparison of Wave profile of Bay of Bengal (Long crested)

3.4 Results and Discussions:

In this chapter, time domain equation of motions is shown and solved by numerical procedure using Newmark-Wilson method. The equation for irregular wave profile and the wave spectrum for the Bay of Bengal are presented. Long and short crested waves are also considered. On the basis of the above solution procedure and utilizing the long crested irregular wave profiles of the Bay of Bengal, a computer program have been developed to simulate the motions of a fine shaped fast vessel in rough sea which are discussed in the next chapter.

The wave profiles utilized in the simulation of motions in time domain are shown in figures (Fig: 3.01 to 3.06). Comparison between short and long crested wave profiles and also the profiles of different significant wave height are shown in those figures.

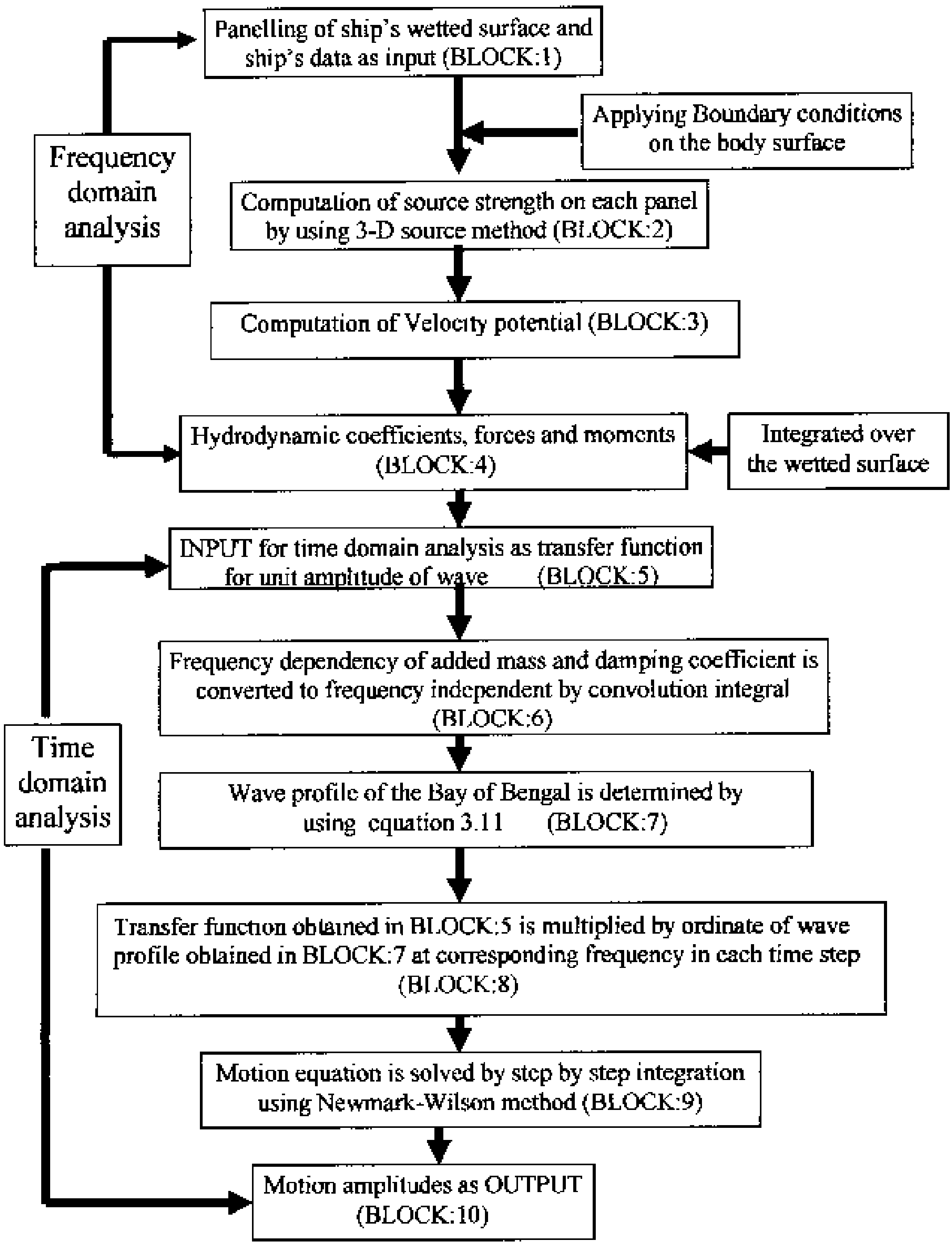
By comparing the long and short crested waves, it is observed that for both 1.0 and 3.0 meter significant wave heights (Fig:3.03 & 3.04), amplitudes are found slightly higher in case of long crested wave than short crested wave. For both the cases, wave amplitudes are increasing with the increase of significant wave height.

CHAPTER 4

MOTION SIMULATION

4.1 Development of Computer Program

A computer program developed by 3-D source method considering forward speed effect [28] has been modified for fine shaped naval vessel to calculate the hydrodynamic coefficients and wave exciting forces and moments of the ship at regular sea. Another computer program in time domain motion simulation for six degrees of motions has also been modified using Newmark-Wilson method. In this program, the hydrodynamic coefficients and wave exciting forces and moments calculated in regular head seas are utilized as transfer function for unit amplitude wave. The irregular long crested waves and the wave spectrum of the Bay of Bengal, recommended for Hiron point [31] were included in the program. The flow chart of program and motion simulation are given below:



Flow Chart for Motion Simulation

4.2 Ship Selection for Research Work

Most of the works on Motion Simulation field were carried out on relatively fuller and larger ships having slower speed. Such works on fine shaped faster and smaller vessel is uot so much. As such, an existing fine shaped naval vessel has been selected for this research work. The said naval ship is a fine shaped high speed vessel having low water plane area. The ship is an anti-submarine coastal escort and coastal surface fighting vessel. Her mission is to perform search and surveillance against enemy submarine, to accomplish escort of convoys, escort of fishing boats, picket and patrol missions along coastal areas etc. She mainly operates in the Bay of Bengal within the Bangladesh territorial water and Exclusive Economic Zone. The ship operates round the year in the Bay of Bengal by facing different sea conditions. Maximum speed of the ship is 30.5 knots and the economic/cruising speed is 18 knots. Principle particulars of the ship are given in Table: 4(a).

Length, Maximum(over all)	58.773 m
Length, at designed water line	56.000m
Breadth, max.	7.200 m
Breadth at the designed water line	6.900 m
Depth, moulded, at midship at upper deck	4.300 m
Depth, moulded, at stem	6.000 m
Depth, moulded, at stem	4.200 m
Draft, at full load displacement	2.258 m
Displacement, at full load	392.08 tons
Block coefficient	0.439
Transverse Metacentric height	0.730 m
Longitudinal Metacentric height	139.5 m
Draft up to propeller tip (one blade vertically upward)	1.10 m

Table: 4(a) Principal Particulars of the Naval Ship

4.3 Ship Selection for Validation

Practical/experimental/ model test result of Motion Simulation of a fine shaped high speed vessel was not found in the books/literatures. So for validation purpose, a Series 60 vessel was selected. The hydrodynamic coefficients and wave exciting forces and moments were calculated in regular waves for Series 60 vessel using the same program and compared with published results. The principle particulars of the selected Series 60 vessel are given in Table: 4(b).

Model Number	4210W
Length (Water Line)	124.0m
Length (Between Perpendicular)	122.0 m
Breadth	16.26 m
Draft	6.50 m
Block coefficient	0.60
Displacement	7807 tons
Water- plane coefficient	0.706

Table: 4(b) Principal Particulars of Series 60 Ship

4.4 Panelling/Meshing of Ship

There exist practical numerical tools based on three-dimensional analyses that predict linear wave-induced motions and loads on a floating body at steady forward speed. A wave spectrum is used to describe a sea state and results in an irregular sea can be obtained by linear superposition of results from regular incident waves. Panel methods are the most common techniques used to analyze the linear steady state response in regular waves. One way is to distribute sources over the mean wetted body surface. The source technique is commonly used for the calculation of wave loads and hydrodynamic co-efficient for a floating moving body in water. For numerical computation, the wetted surface of the navy ship has been subdivided in to a number of panels. Ship's draft line was divided into 9 water lines of 0.250 meter apart and the load water line was sub-divided into 20 equal stations. The whole wetted surface area was taken into consideration and the full body mesh was made. Complete wetted surface area was divided into 399 nodes and 360 panels/meshes. The full body mesh arrangement is shown in Figure: 4.01 & 4.02. Following the same procedure, wetted surface area of Series 60 vessel were divided into 325 nodes with 288 panels for full body. The full body mesh arrangement of Series 60 vessel is shown in Figure: 4.03 and Fig: 4.04.

Fig: 4.01 Full body mesh arrangement of navy ship (Top View)

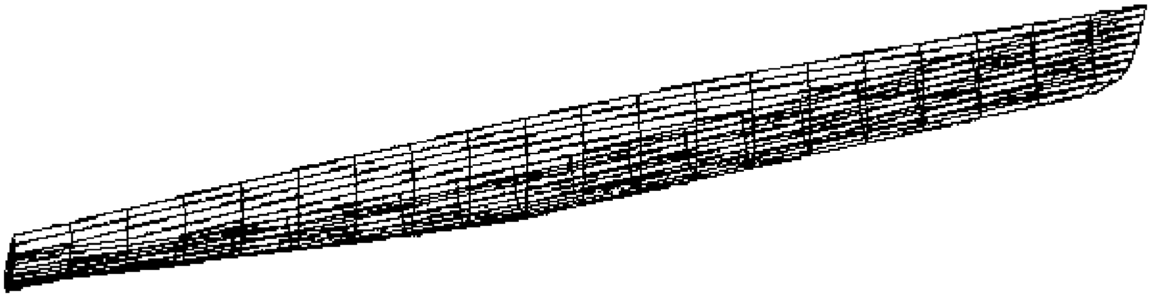


Fig: 4.02   Full body mesh arrangement of navy ship (Elevation)

Fig: 4.03 Full body mesh arrangement of Series 60 vessel (Top view)

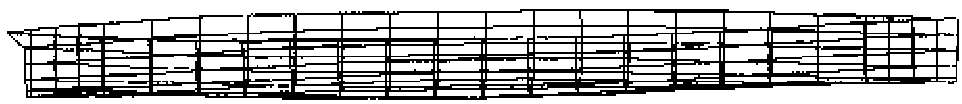


Fig: 4.04 Full body mesh arrangement of Series 60 vessel (Elevation)

4.5 Validation

The theoretical/experimental/model test result of hydrodynamic coefficients and motions in frequency/time domain for fine shaped high speed vessel with low water plane area including forward speed effect was not found available in published literatures/books. So steps have been taken to validate the developed program used to calculate the hydrodynamic coefficients and motions of the naval ship in regular wave with constant forward speed in frequency domain, with the help of a Series 60 ship (Model number: 4210W).

A set of coefficients had been experimentally determined by Garritsma [32] in 1960 for Series 60 parent forms of block coefficients C_B = 0.60, 0.70 and 0.80. Models were oscillated at various frequencies while at constant speed in calm water. The added mass (Heave) in calm water for model having block coefficient 0.60 is plotted as non-dimensional coefficient ($a'_{33} = \frac{a_{33}}{\Delta}$, where Δ is the ship mass $\frac{W}{g}$) against wave encountering frequency and compared with the computed result in head sea condition of same Series 60 vessel by 3-D source method and shown in Fig: 4.05. Although Garritsma considered the calm water condition and the computed results are for regular head sea but still there is a satisfactory agreement between the computed result and Garritsma's model test result of added mass. The discrepancy occurs due to different condition as Gerritsma obtained results in calm water.

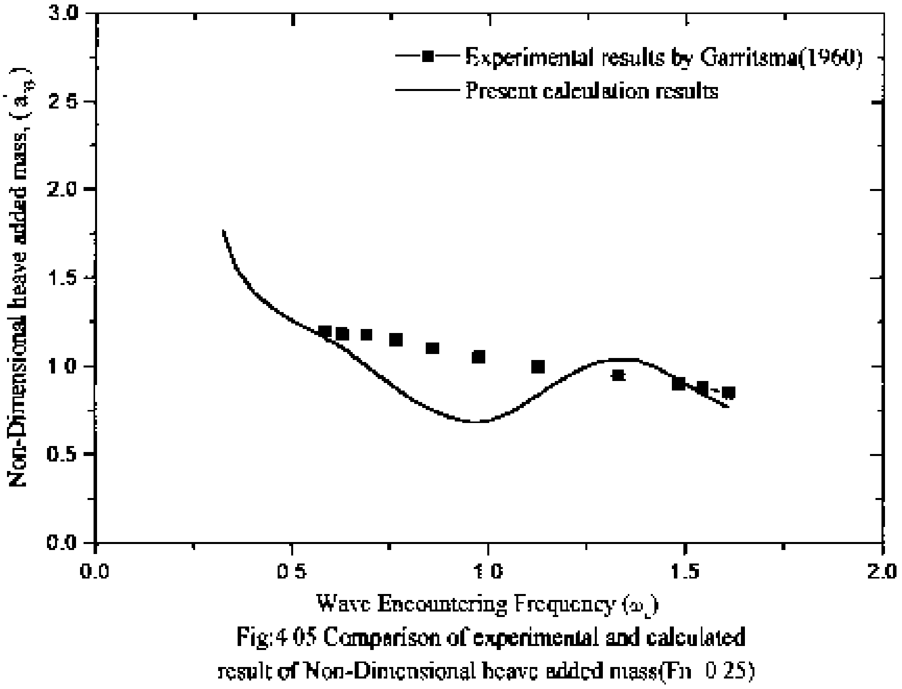


Fig:4.05 Comparison of experimental and calculated result of Non-Dimensional heave added mass(Fn 0.25)

Garritsma also experimentally investigated the pitch and heave motions with forward speed effect in head sea condition of Series 60 parent forms. The motions obtained by Garritsma [32] are plotted against different wave encountering frequency and compared with the computed motions in frequency domain in regular head sea condition of same Series 60 vessel by 3-D source method and shown in Fig: 4.06 and Fig: 4.07 respectively. By analyzing the heave and pitch motions, it is found that the agreement is very good between Garritsma's results and computed results within the range of encountering frequency 1.0 and above and have satisfactory similarity in shape and magnitude at encountering frequency below 0.90. Computed results show a sudden jump at frequency range 0.90 to 1.0 but within this range experimental results are not available but the overall shape of the curve have good agreement. This sudden jump may happen due to natural heave period of the vessel.

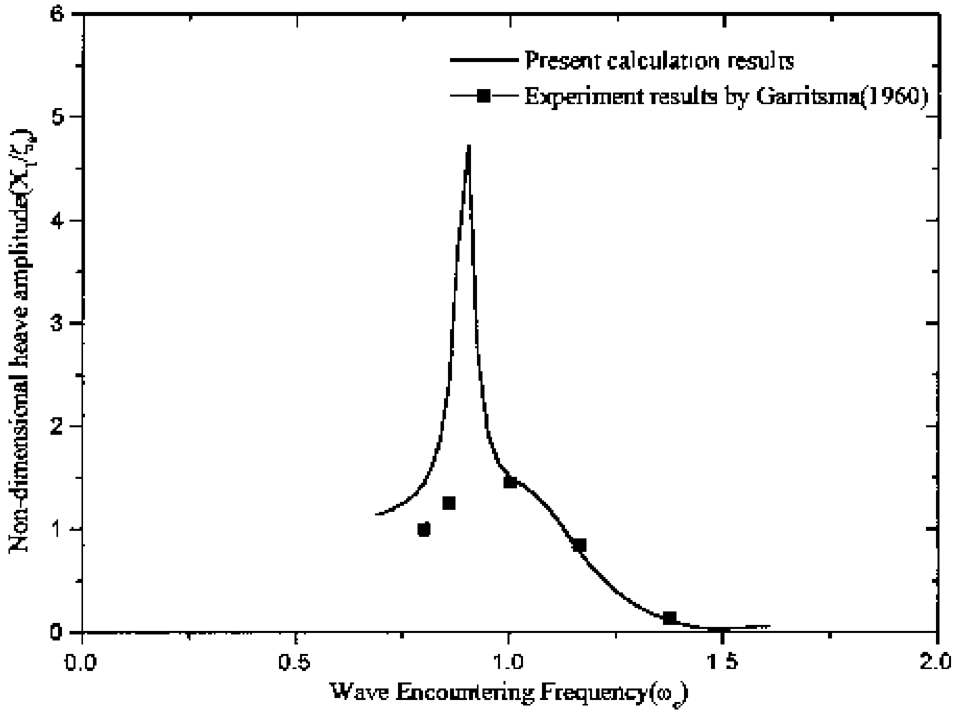


Fig:4.06 Comparison of experimental and calculated results of heave response (Fn: 0.25)

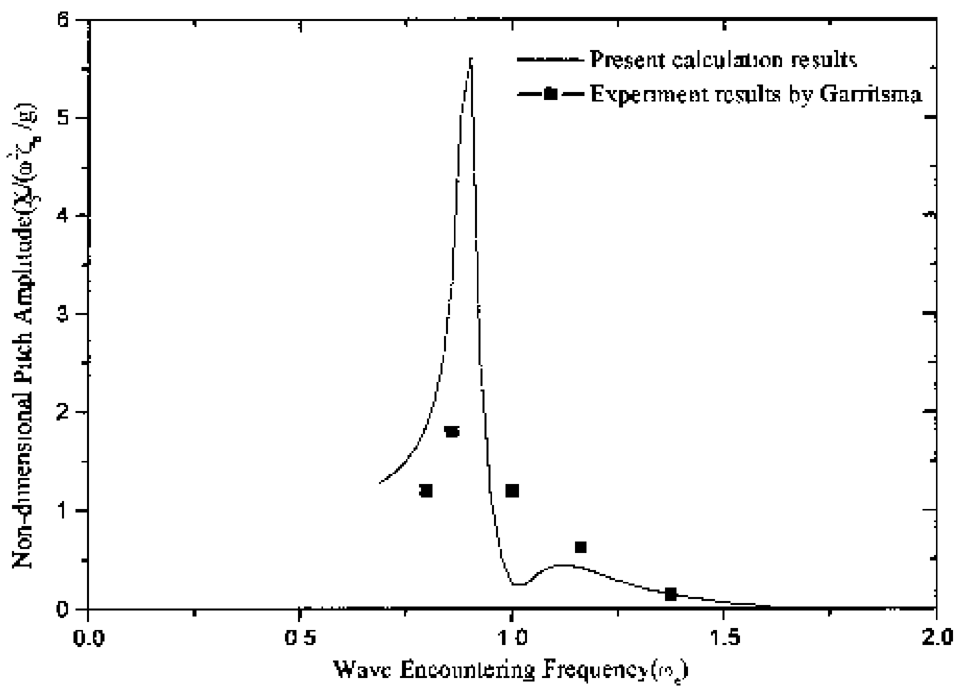


Fig:4.07 Comparison of experimental and calculated results of Pitch response (Fn:0.25)

4.6 Results of Hydrodynamic Forces and moments

For the study of a ship's behavior at rough sea i.e. to find out the time history of motions in irregular waves, the frequency dependent hydrodynamic forces and moments need to know. With the help of a program developed [28] by utilizing source distribution technique and the theory discussed in chapter two, the hydrodynamic coefficients and wave exciting forces and moments for the navy ship were calculated for head sea condition. The added mass, damping coefficients, wave exciting forces and moments etc. are calculated at Froude Numbers 0.25, 0.40 and 0.50 for wave height 1.0 meter in regular head sea. The non-dimensional form of added mass (Heave, Pitch), Damping coefficients (Heave, Pitch) and wave exciting forces/moments (Surge, Heave, Pitch) against various wave encountering frequency of the navy ship for Froude Number 0.25, 0.40 and 0.50 are plotted and shown in Fig: 4.08 to Fig: 4.14. Total 50 different frequencies ranging from time period 7.0 to 24.0 were considered.

By analyzing the figures (Fig:4.08 to 4.11), it is observed that added mass and damping coefficient are increasing suddenly at lower wave encountering frequency (ω_e in between 0.30 to 0.50) i.e. at higher wave period and with the increase of ω_e, the magnitudes are decreasing and tending towards a constant value. It is also observed that the added mass have the tendency to reduce with the increase of ship speed. The magnitude of wave exciting forces for surge in comparison with heave force is less (Fig: 4.12 & 4.13). Surge force is increasing slowly but heave force is decreasing rapidly with the increase of ω_e. Pitch moment is increasing slowly with the increase of ship speed and also with wave encountering frequency in the lower range of ω_e (Fig: 4.14).

Considering the Froude Number 0.25 (Fig:4.08 to 4.11), it can be noticed that the trend of graphs of added mass and damping coefficients are showing sudden rise and fall around encountering frequency in between 0.30 to 0.50 and maximum value found around time period 20 sec (circular frequency 0.314). The natural frequency (heave) of the navy ship is found at time period 19.16 sec (circular frequency 0.328). Probable cause of this sudden fluctuation of hydrodynamic coefficients may be due to the resonance of this wave frequency and the ships heave natural frequency.

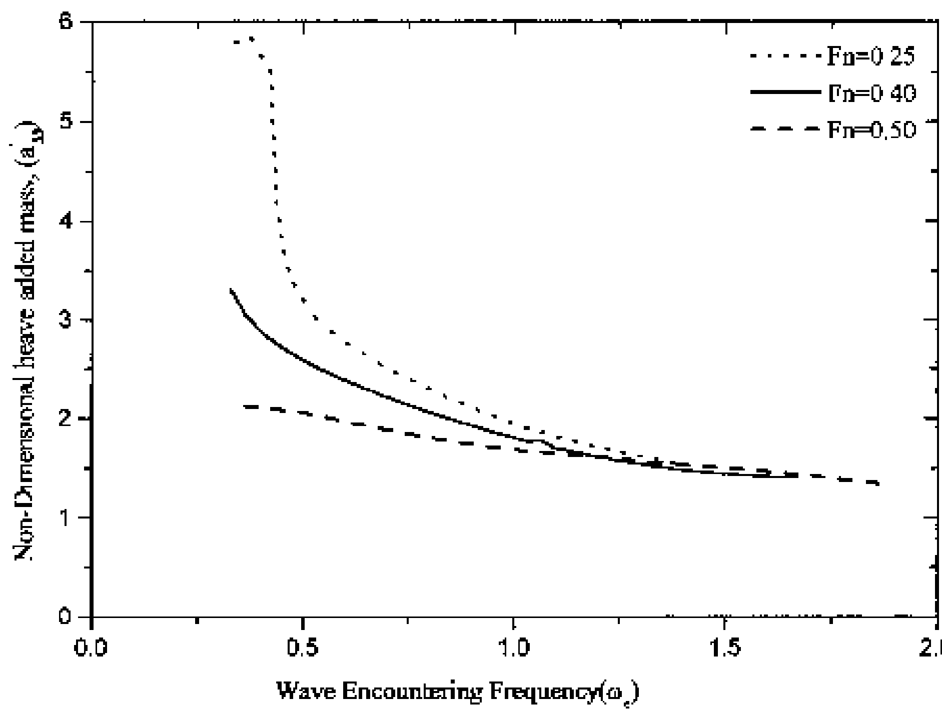


Fig 4.08 Non-Dimensional heave added mass

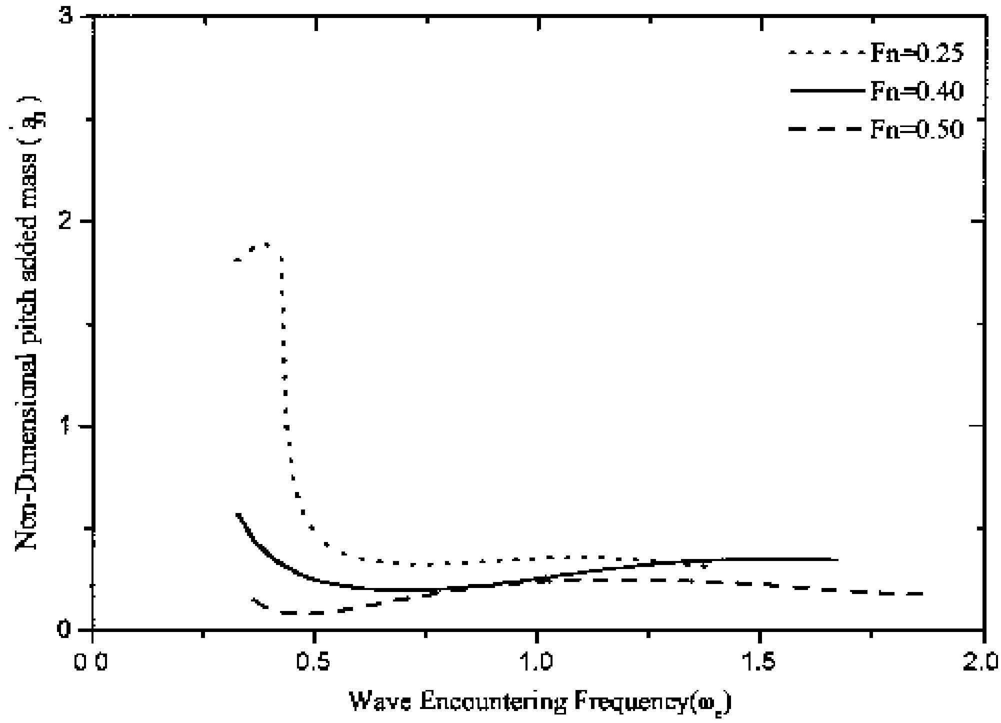


Fig: 4 09 Non-Dimensional pitch added mass

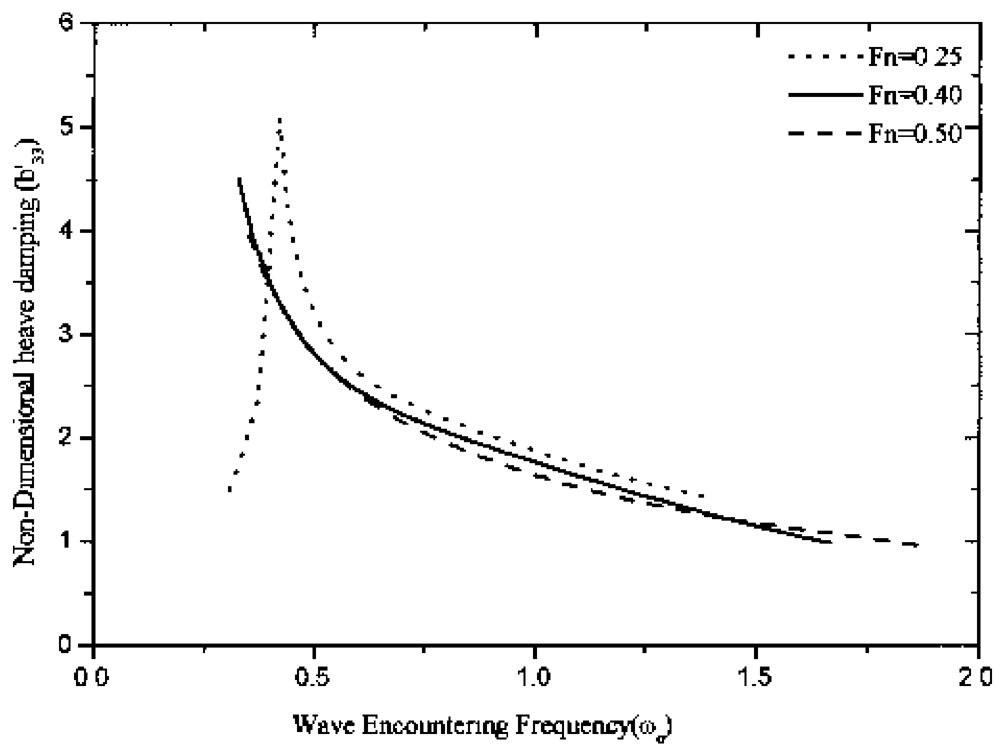


Fig 4 10 Non-Dimensional heave damping

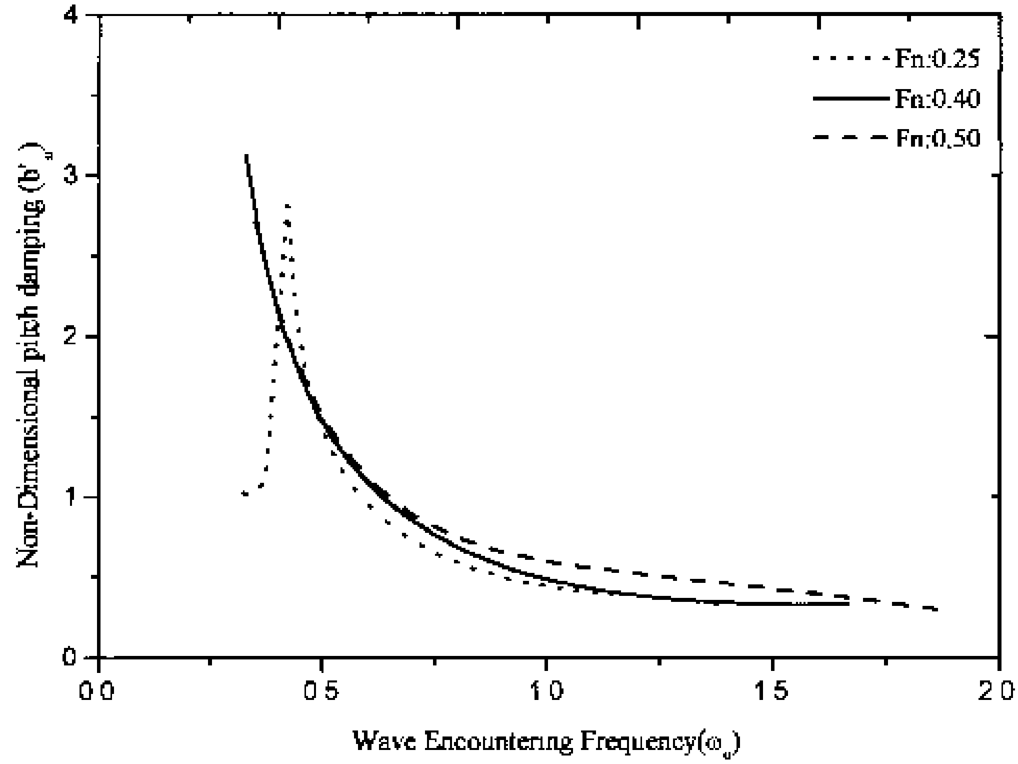


Fig: 4.11 Non-Dimensional pitch damping

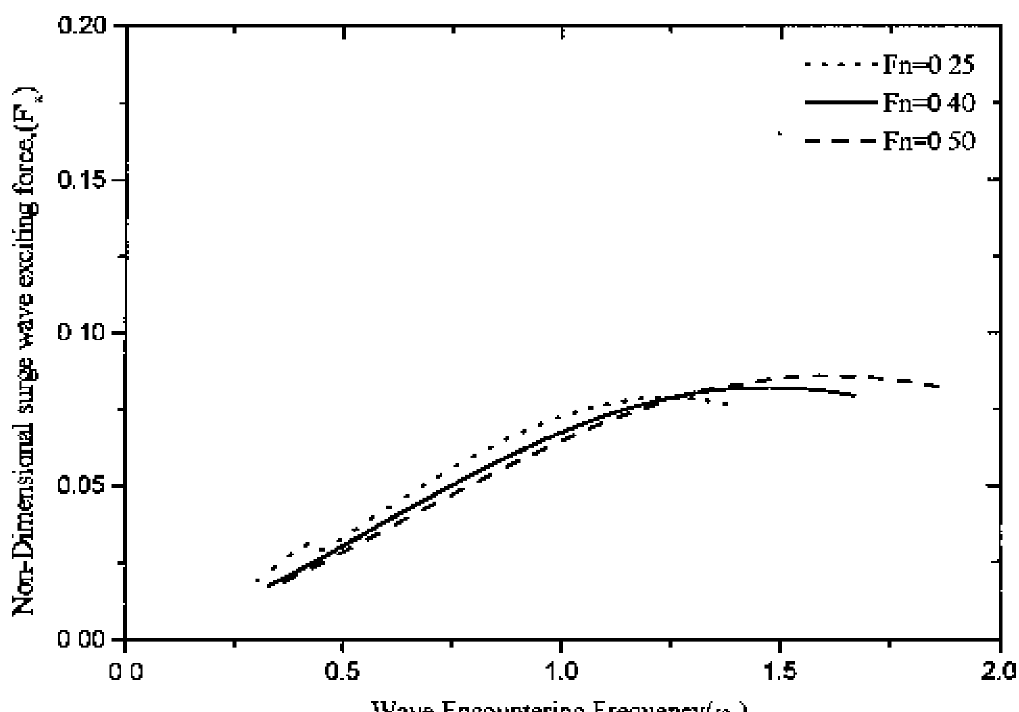


Fig. 4.12 Non-Dimensional surge wave exciting force

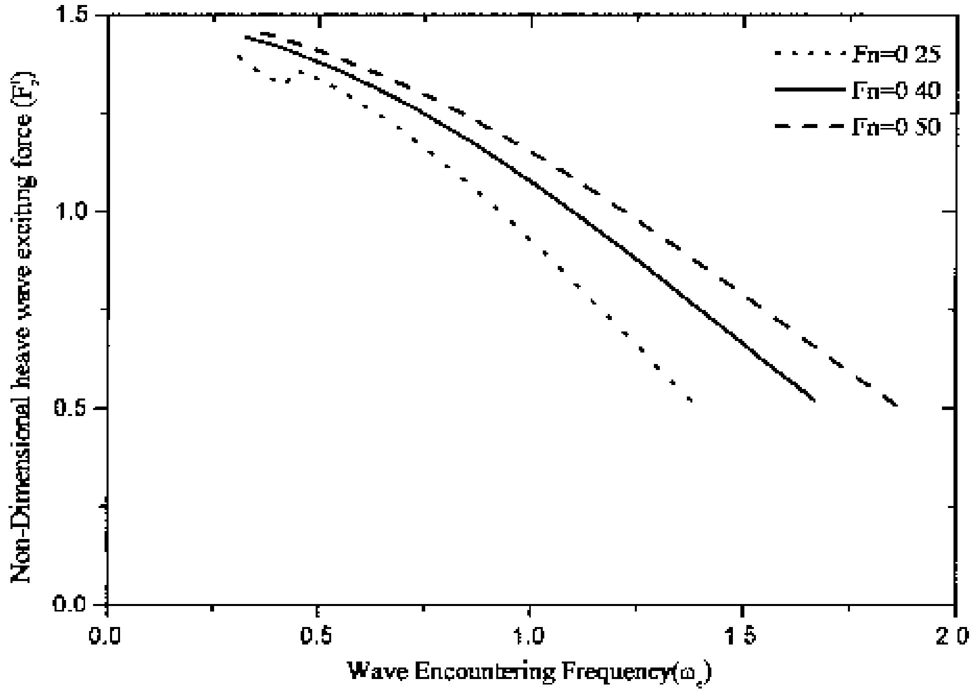
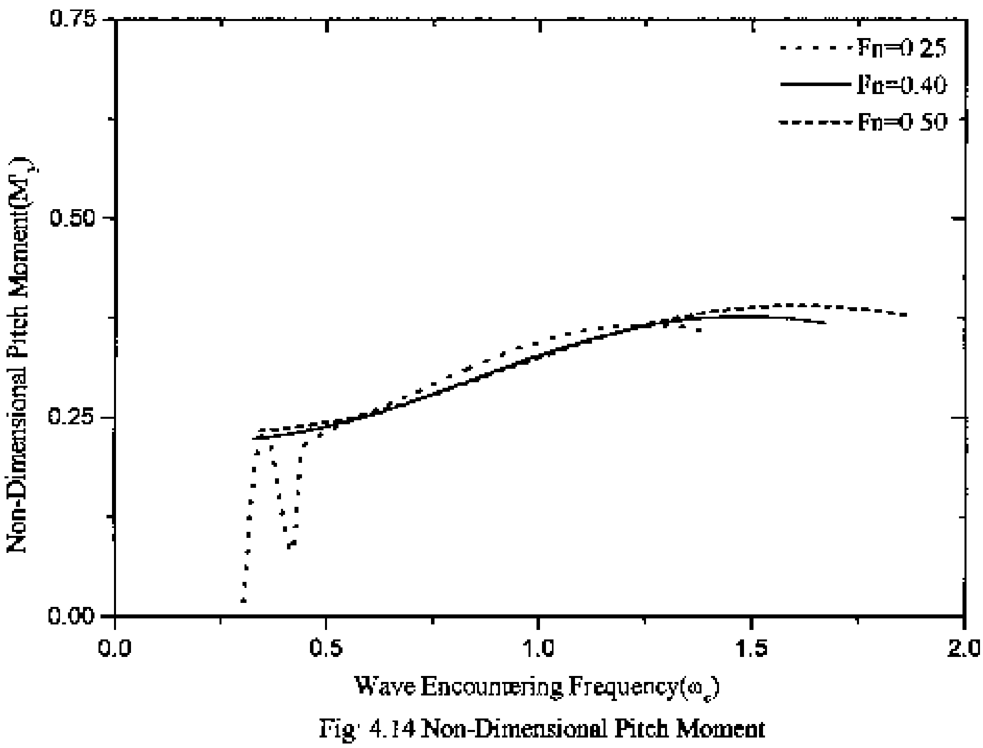


Fig 13 Non-Dimensional heave wave exciting force



Fig' 4.14 Non-Dimensional Pitch Moment

4.7 Results of Time Domain Motion Simulation at different ship speed

With the help of computer program, time domain simulations of six degrees of motions are carried out. The computed time history of motion at Froude Number 0.25, 0.40 and 0.50 with significant wave height 1.0, 3.0, 5.0, 7.0 and 9.0 m are plotted against simulated time in figures 4.15 to 4.57. From figures 4.16, 4.19 & 4.21, it is shown that at ship speed 11.5 knots (Fn: 0.25), significant wave height 3.0 m and in head sea condition, sway, roll and yaw amplitudes are found negligible. Within the simulation time, maximum surge and heave amplitudes are found 1.60 and 0.65 m respectively. From figure 4.20, it is observed that the highest pitch amplitude is 0.032 radian (1.83 degrees). This pitch will cause vertical displacement of stern/stem from load water level by 0.90 meter. Since the minimum freeboard of the ship is 2.0 m, hence all the above motions are within the sustainable range if maximum heave and pitch motion considered occurring at different time. So the ship can operate with ship speed 11.5 knots at sea state 5. Sea states are shown in **Appendix- B.**

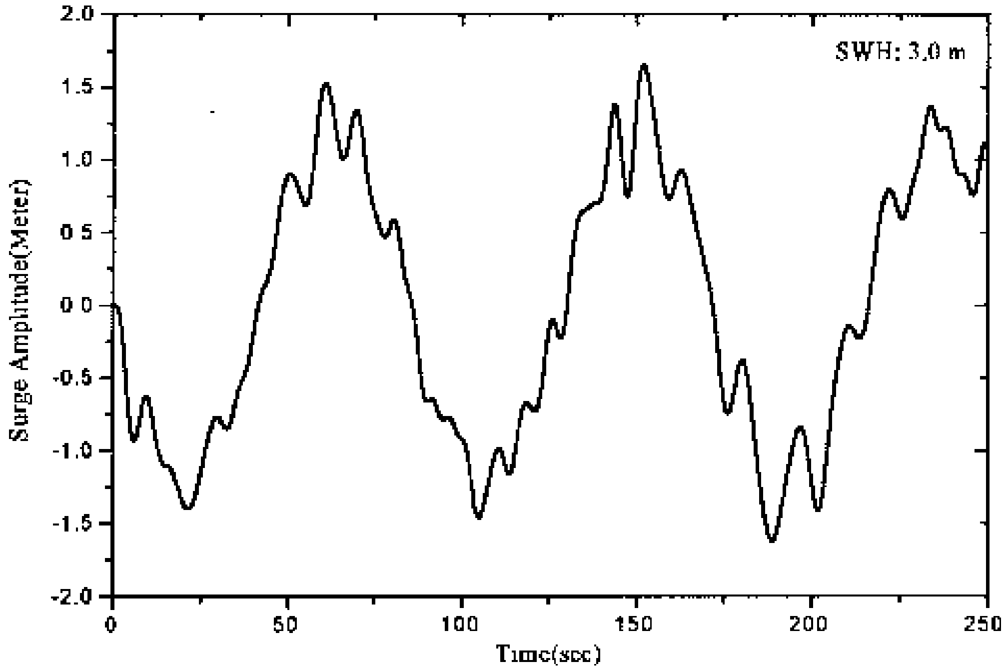


Fig. 4.15 Surge motion of navy ship in long crested irregular waves(Fn: 0.25)

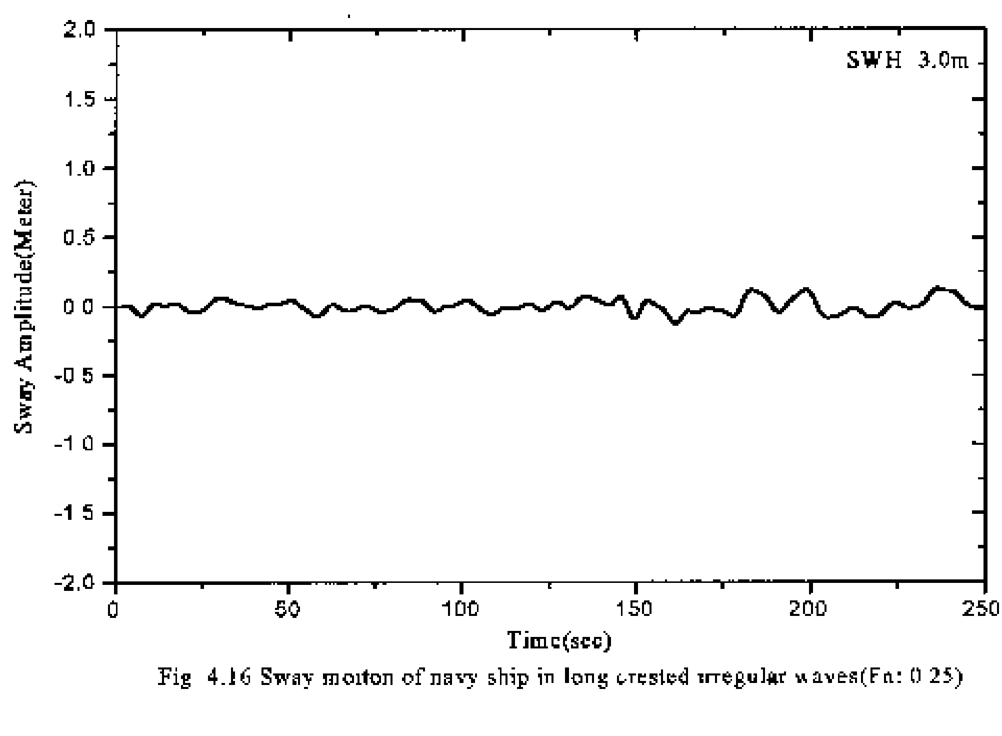


Fig. 4.16 Sway motion of navy ship in long crested irregular waves(Fn: 0.25)

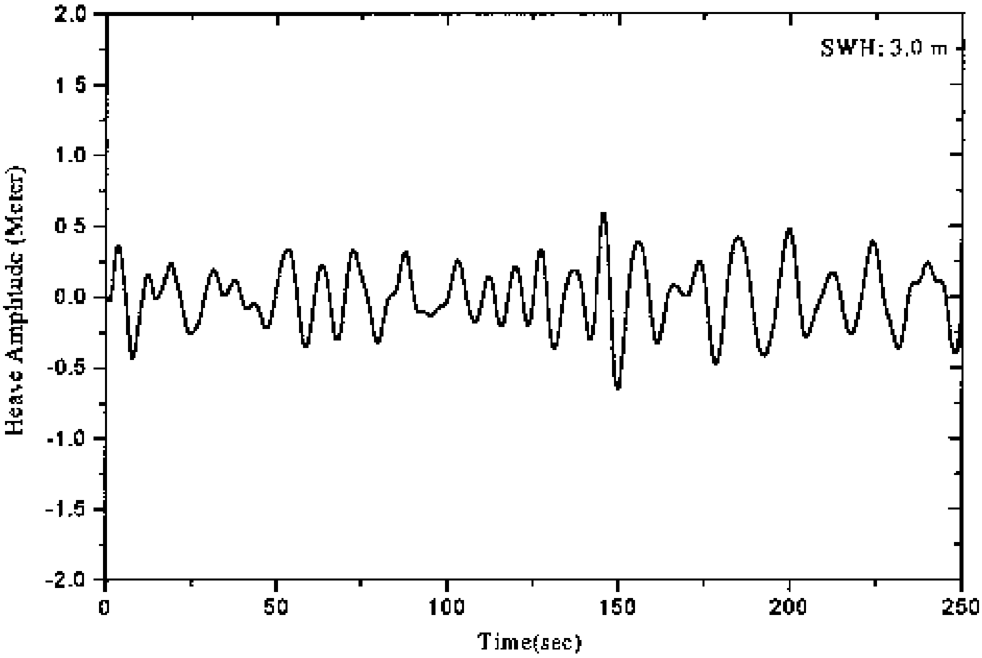


Fig: 4.17 Heave motion of navy ship in long crested irregular waves(Fn:0.25)

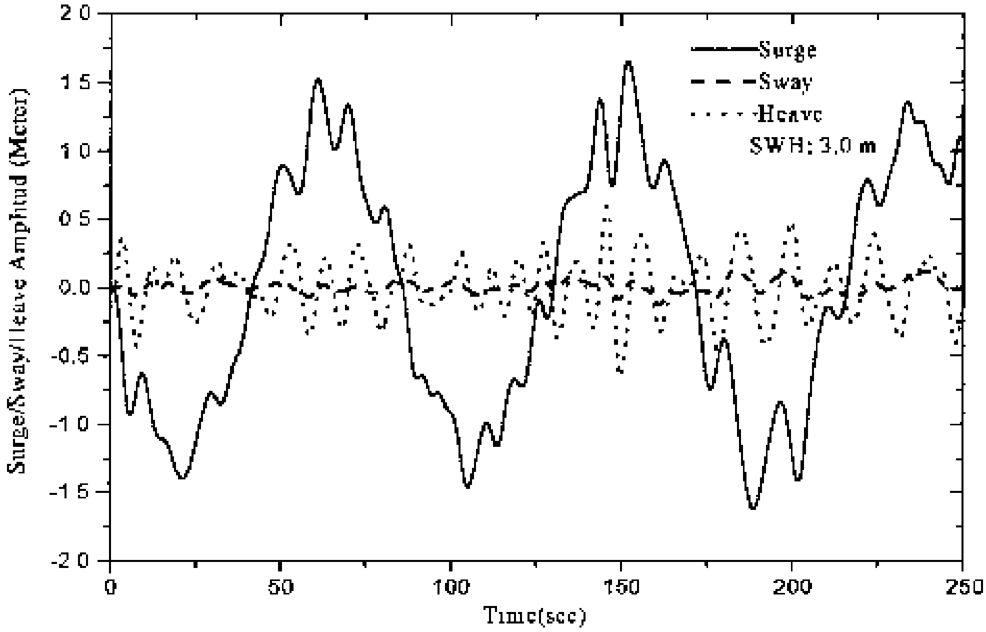


Fig: 4.18 Comparison of Surge/Sway/Heave motion of navy ship in long crested waves (Fn 0.25)

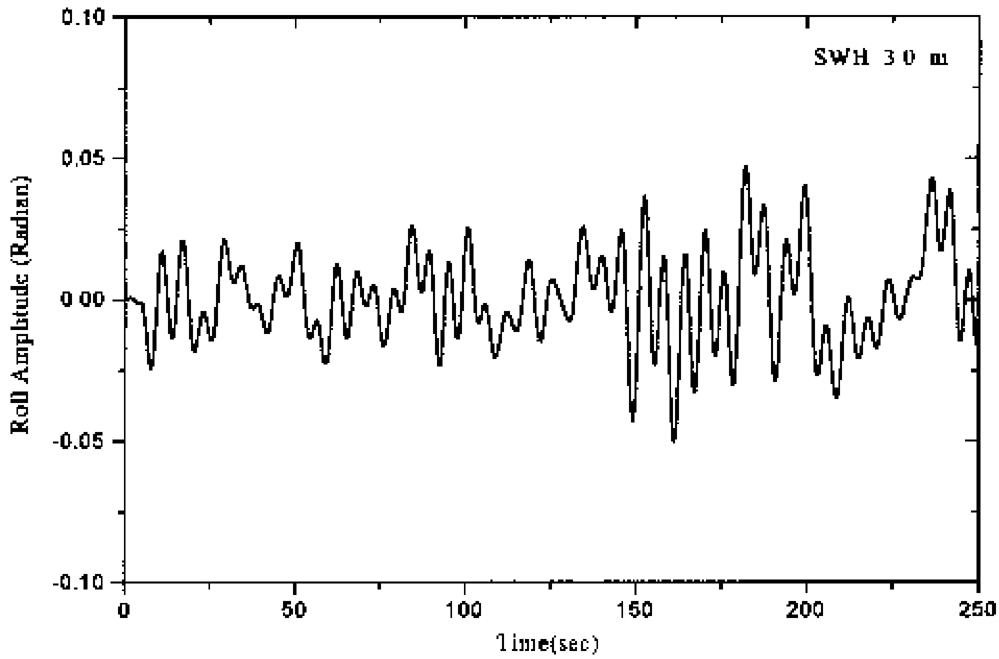


Fig 4 19 Roll motion of navy ship in long crested irregular waves(Fn: 0 25)

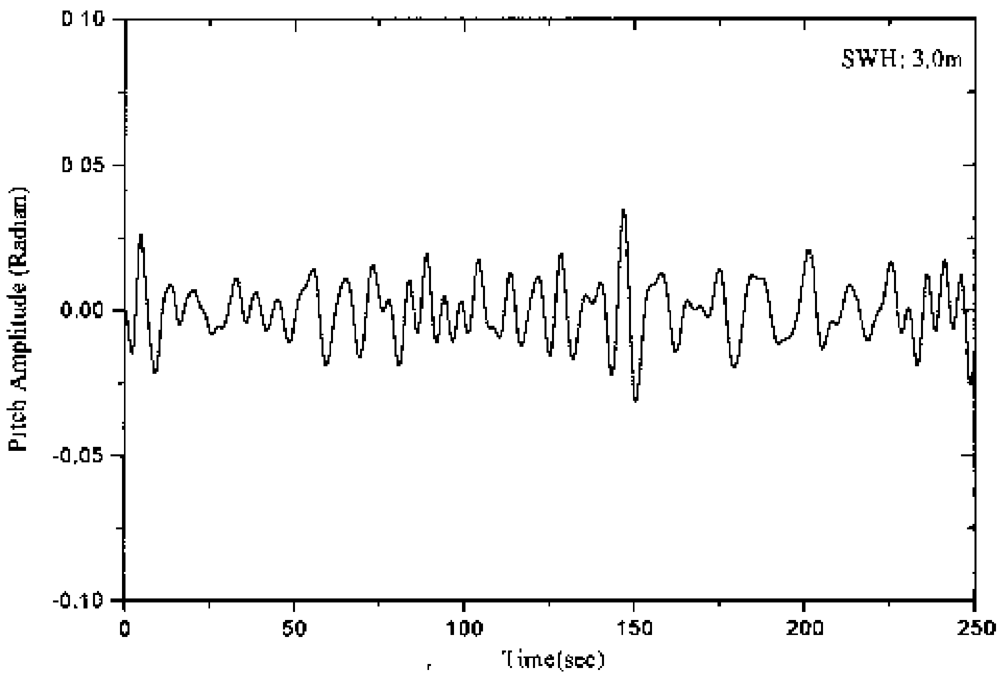


Fig 4.20 Pitch motion of navy ship in long crested irregular waves(Fn: 0 25)

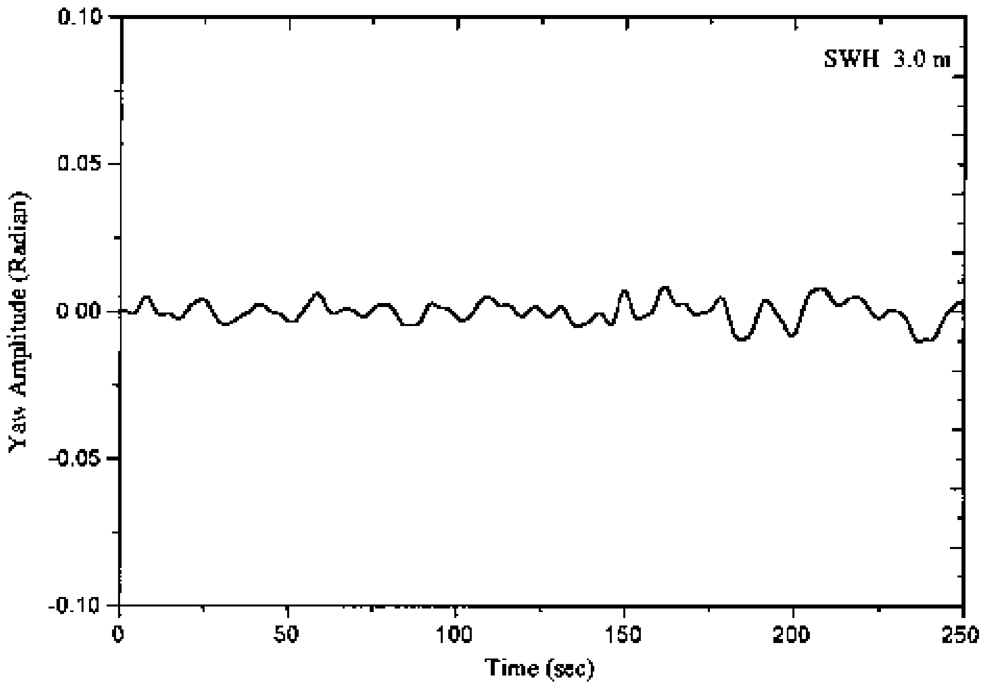


Fig 4 21 Yaw motion of navy ship in long crested irregular waves(Fn 0 25)

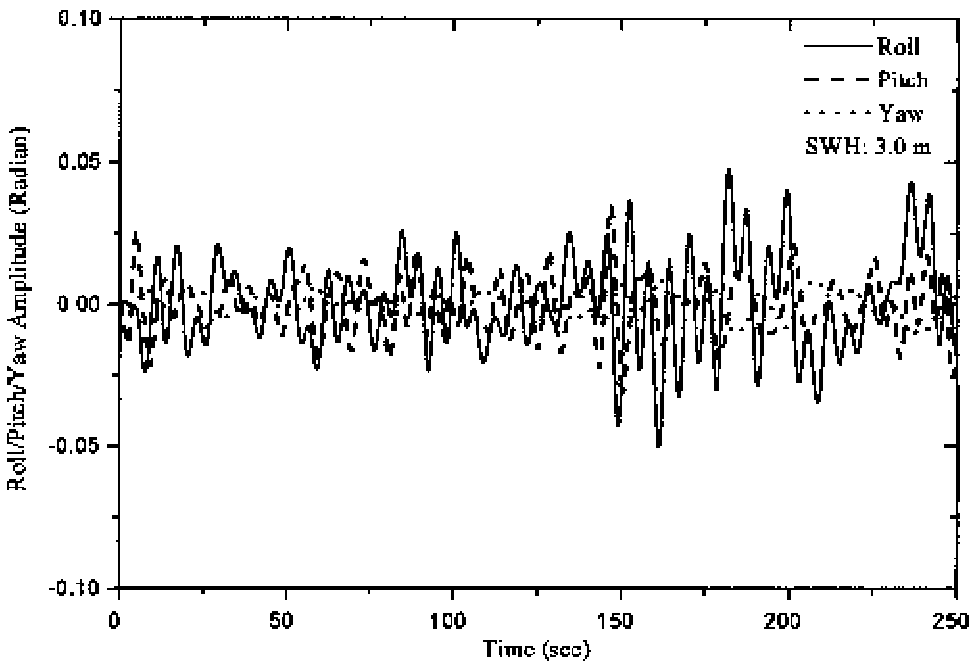


Fig. 4.22 Comparoson of Roll/PItch/Yaw motion of navy ship
in long crested irregular waves(Fn 0.25)

The time history of surge, heave and pitch motion at Froude Number 0.40 in irregular head sea with significant wave height 3.0 are shown in Fig: 4.23 to Fig: 4.26. By analyzing Fig: 4.23, 4.24 & 4.26, maximum surge, heave and pitch amplitudes are found 1.55 m, 0.525 m and 0.03 radian respectively. The maximum vertical displacement from still water level at stern/stem due to pitch motion will be 0.84 meter. The amplitudes of motions are slightly decreased with the increase of ship speed (From 11.5 to 18 2 knots) by keeping wave height and other conditions same (Fig: 4.15 to 4.26). The ship can safely run with speed 18.2 knots (Fn: 0.40) at sea state 5 and in this condition maximum heave amplitude will be 0.525 m from still water llevel and the vertical movement of stern/stem due to pitch motion will be 0.84m (Pitch 1.7 degree) if heave and pitch assumed occurring at different time. But in the case of both the motion occurring at the same time in the same direction, the ships propeller will come slightly above the still water level as propeller tip starts from 1.10 meter draft.

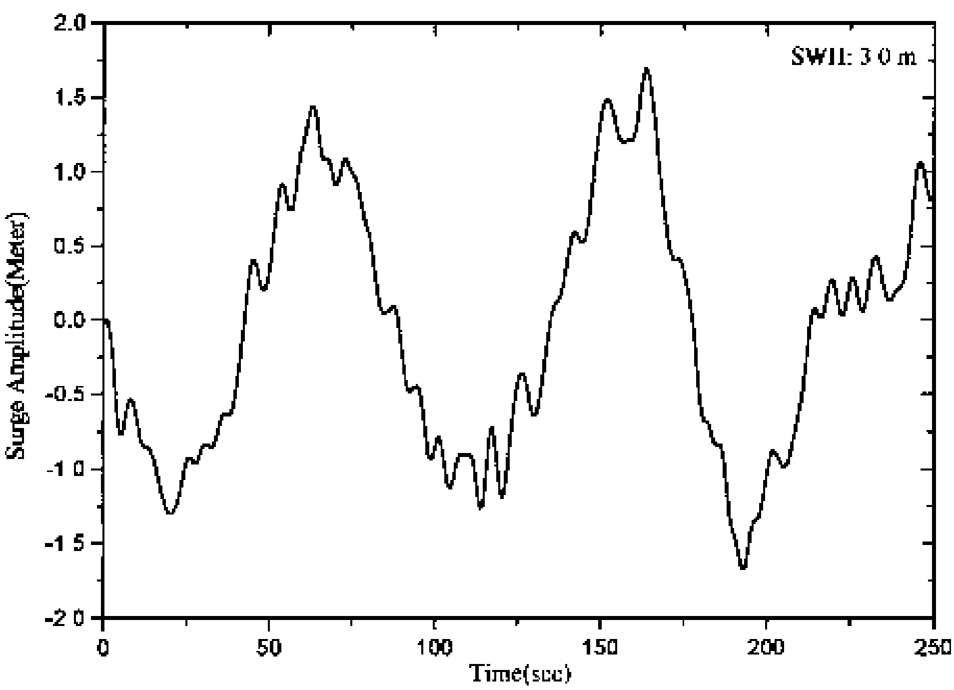


Fig 4 23 Surge motion in long crested irregular waves(Fn=0.40)

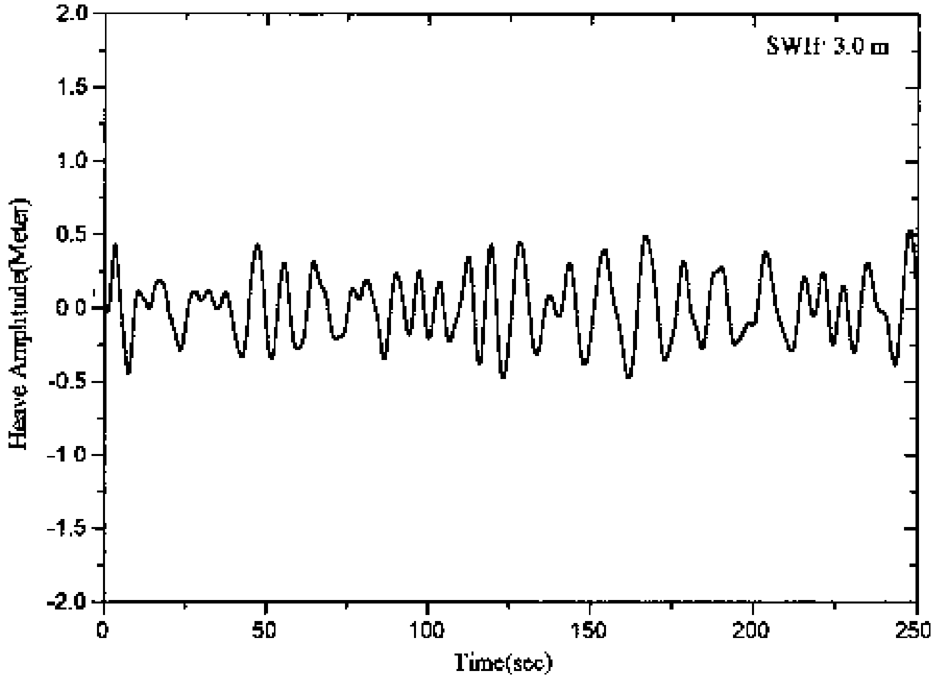


Fig. 4.24 Heave motion of navy ship in long crested irregular waves(Fn 0.40)

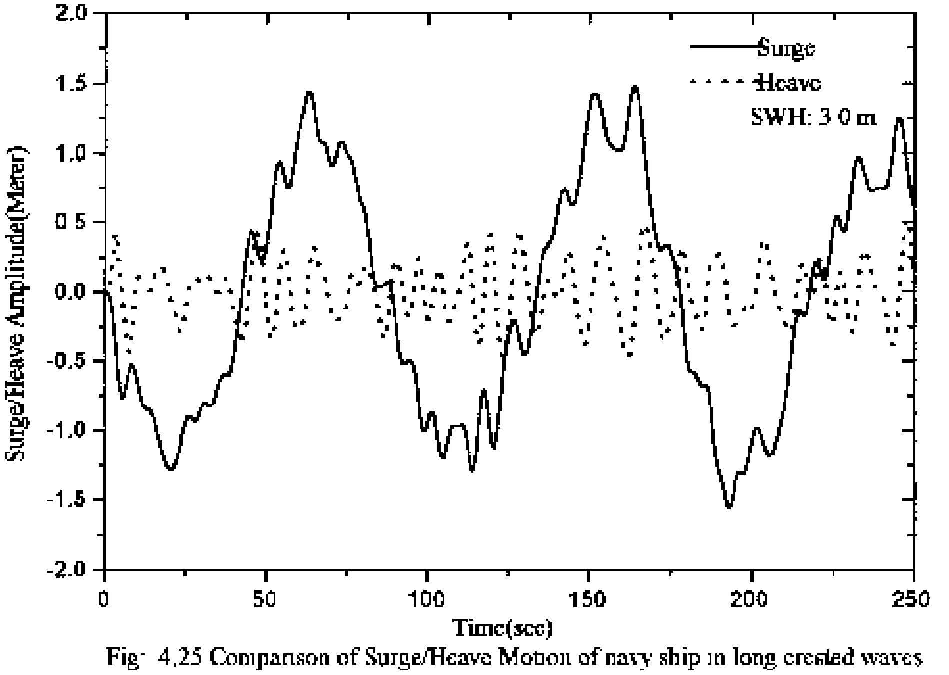


Fig. 4.25 Comparison of Surge/Heave Motion of navy ship in long crested waves (Fn: 0.40)

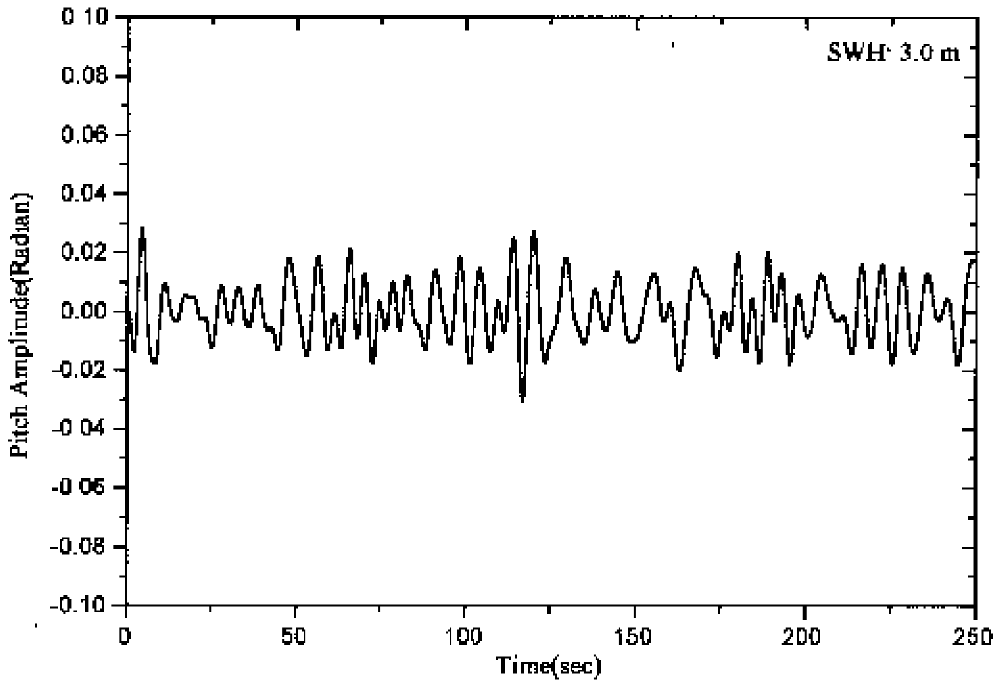


Fig:4 26 Pitch Motion of navy ship in long crested irregular waves(Fn 0 40)

The Surge, Heave and Pitch motions at Froude Number 0.50 in irregular head sea with significant wave height 3.0 are shown in Fig: 4.27 to Fig: 4.30. Maximum surge, heave and pitch amplitudes are found 1.25 m, 0.50 m and 0.027 radian respectively. The maximum vertical displacement from load water line at stern/stem due to pitch motion will be 0.75 meter. By analyzing the figures (4.15 to 4.30), it can say that amplitudes of surge, heave and pitch motions are slightly decreasing with the increase of ship speed if the wave height remains same. It is evident that the ship can operate without any problem with 22.8 knots (Fn: 0.50) speed at sea state 5 if heave and pitch assumed occurring at different time. But in the case of both the motion occurring at the same time in the same direction, the ships propeller will come slightly above the still water level.

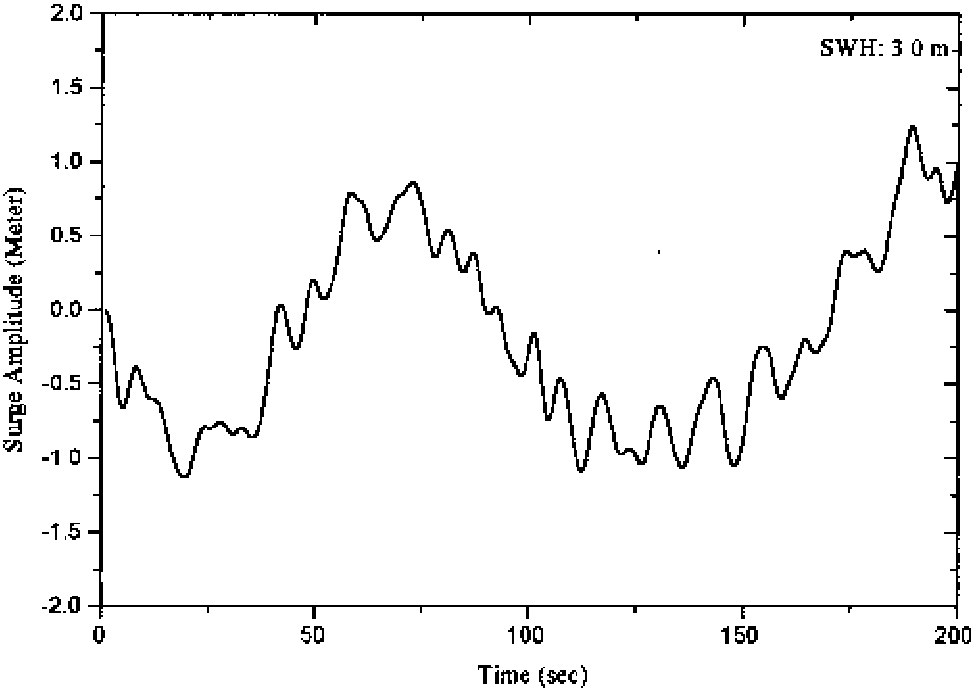


Fig 4 27 Surge motion of navy ship in irregular long crested waves(Fn: 0 50)

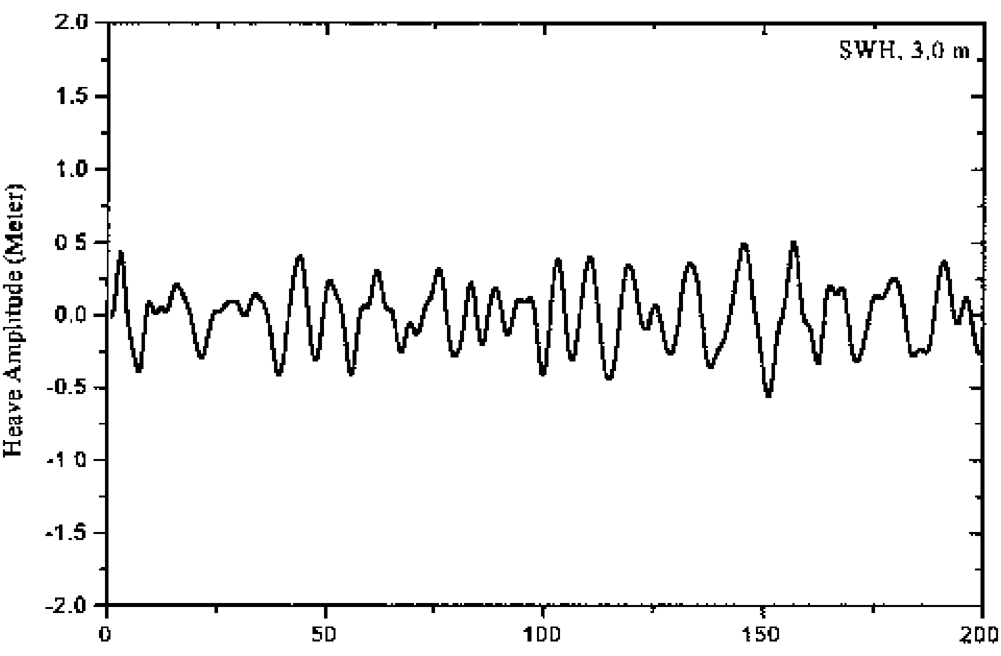


Fig 4 28 Heave motion of navy ship in irregular long crested waves(Fn 0.50)

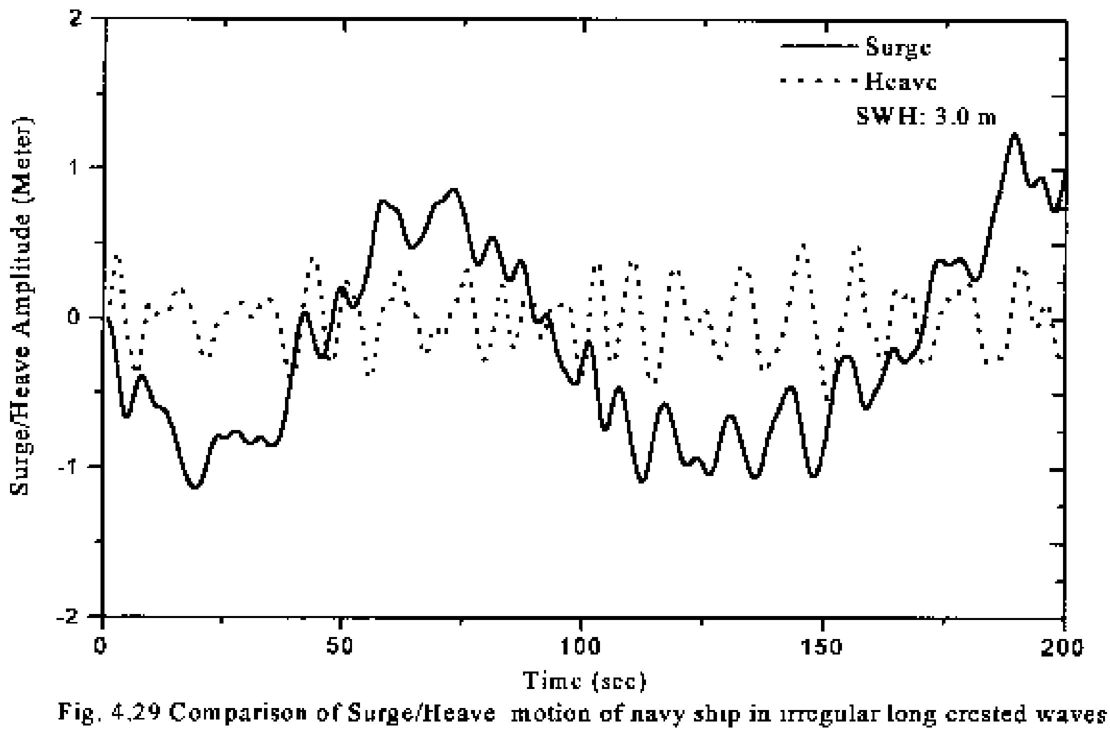


Fig. 4.29 Comparison of Surge/Heave motion of navy ship in irregular long crested waves (Fn: 0 50)

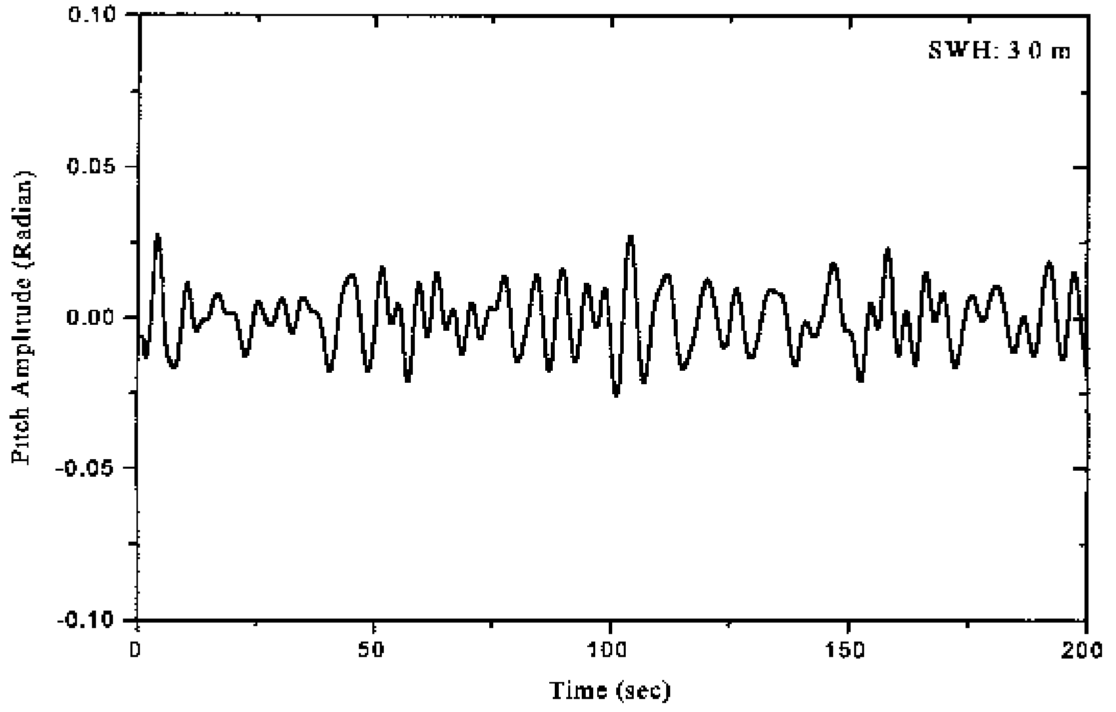


Fig: 4.30 Pitch motion of navy ship in irregular long crested waves(Fn: 0 50)

The Comparison of time domain motion amplitudes of surge, Heave and Pitch at Froude Number 0.25, 0.40 and 0.50 by keeping significant wave height constant at 1.0m, 3.0m, and 5.0m respectively are shown in Fig:4.31 to Fig:4.39. The irregular head sea conditions are considered. By observing the previous figures, it is evident that keeping the significant wave height constant at 1.0 and 3.0 m separately, the amplitude of motions have tendency to decrease with the increase of ship speed. At ship speed 18.2 knots with wave height 5.0 m (Fig: 4.37 to 4.39), the maximum surge, heave and pitch amplitudes are found 1.60 m, 1.00 m and 0.035 radian. The maximum vertical displacement from still water level at stern/stem due to pitch motion will be 0.98 meter. So the ship is supposed to sustain in motions in sea state 6 with speed 18.2 knots if maximum heave and pitch assumed occurring at different time. But in the case of both the motion occurring at the same time in the same direction, the ships propeller will start coming out of the still water level. In this condition, if speed is increased to 22.8 knots, she have to face 5.0 m surge, 1.10 m heave and 1.05 m vertical displacement of stern/stem due to pitch. In this situation, the ship will experience high surge motion.

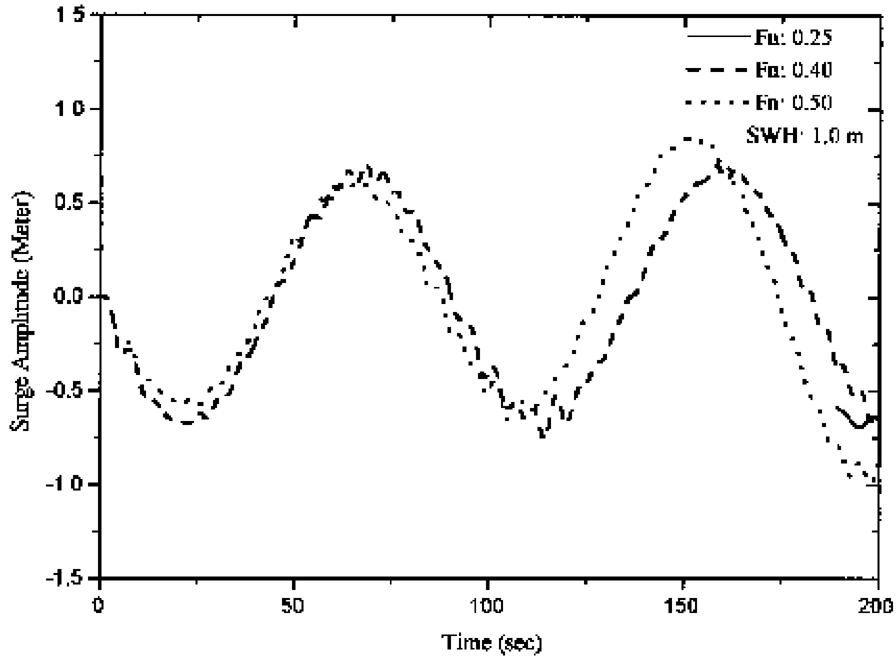


Fig 4 31 Comparison of Surge motion at various Froude number in irregular waves

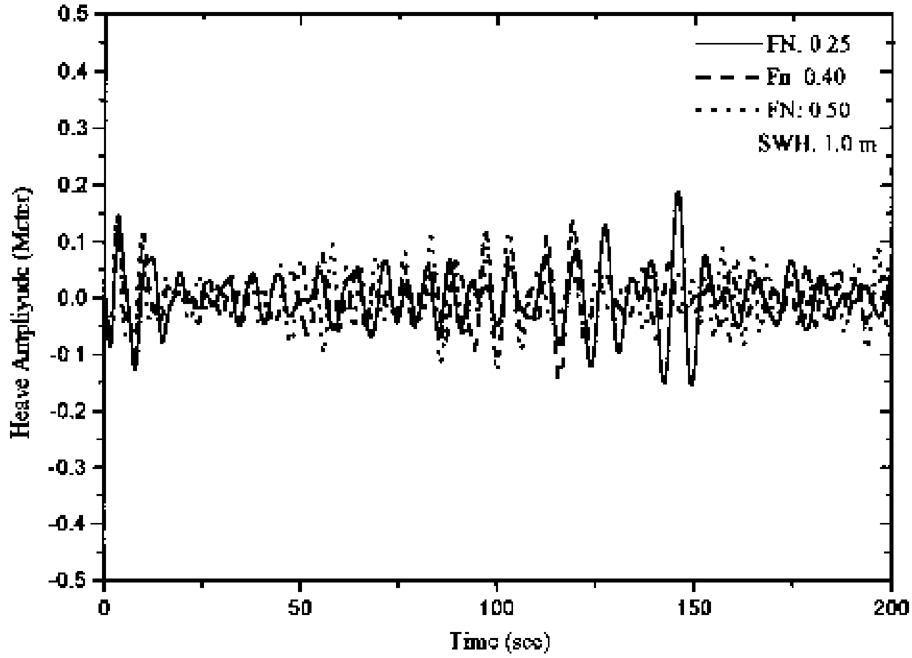


Fig: 4.32 Comparison of Heave motion at different Froude number in irregular waves

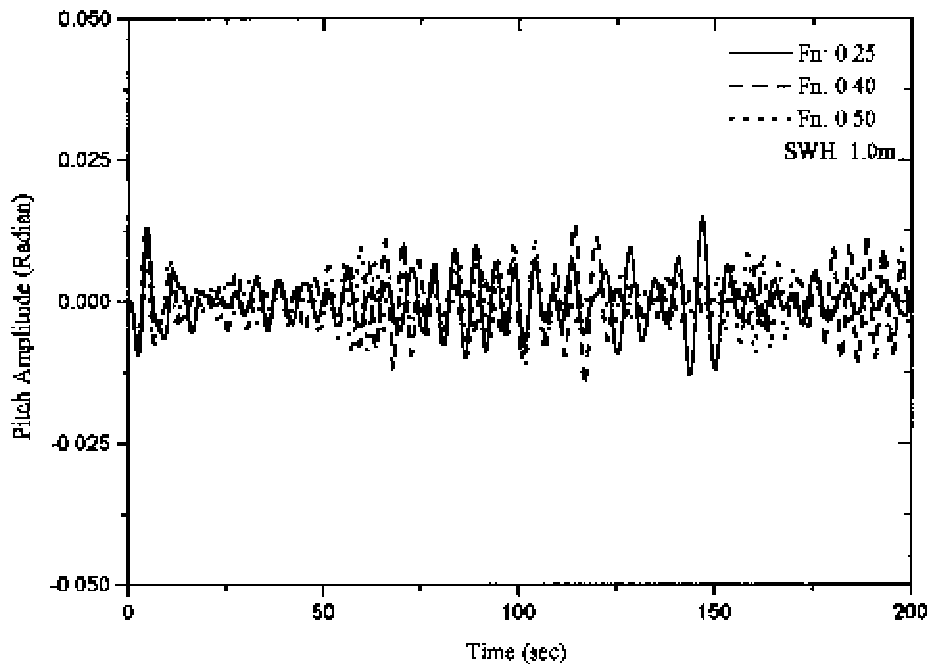


Fig. 4.33 Comparison of Pitch motion at various Froude number in irregular waves

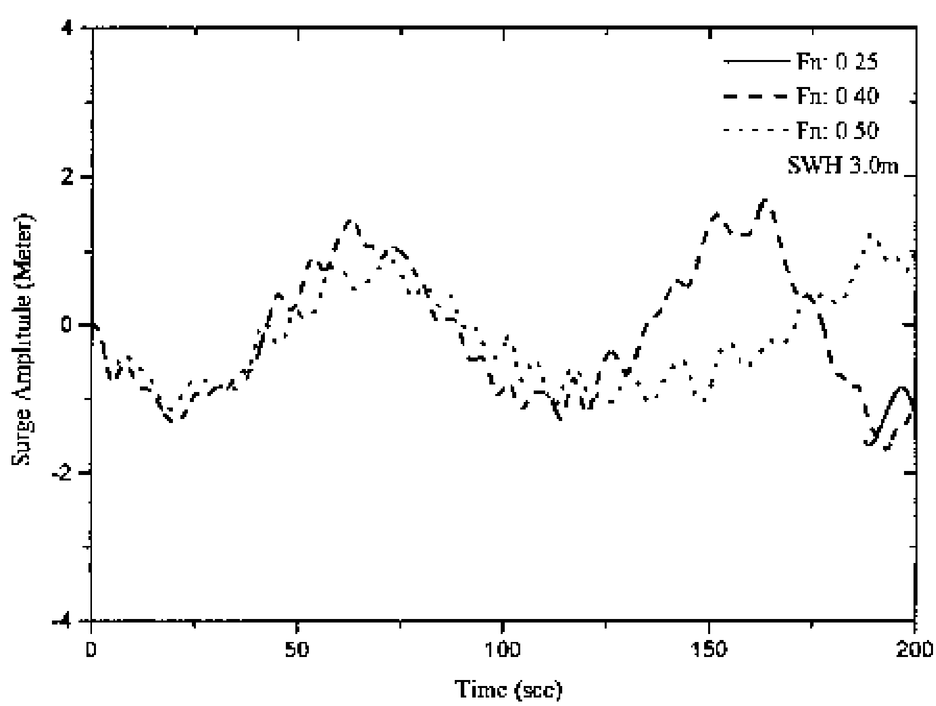


Fig 4.34 Comparison of Surge motion at various Froude number in irregular waves

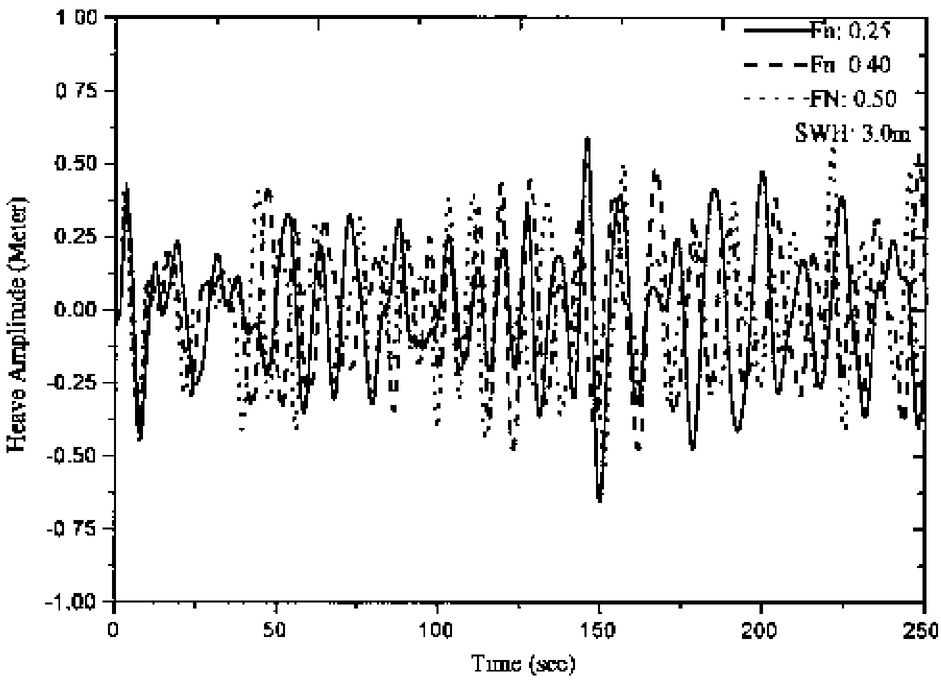


Fig 4 35 Comparison of Heave motion at different Froude number in irregular waves

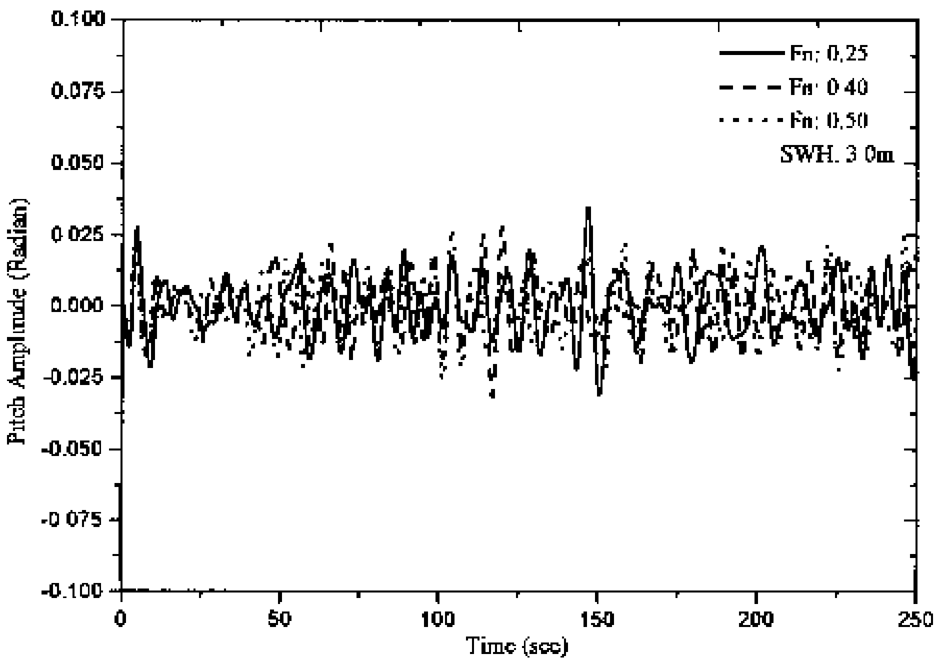


Fig. 4 36 Comparison of Pitch motion at various Froude number in irregular waves

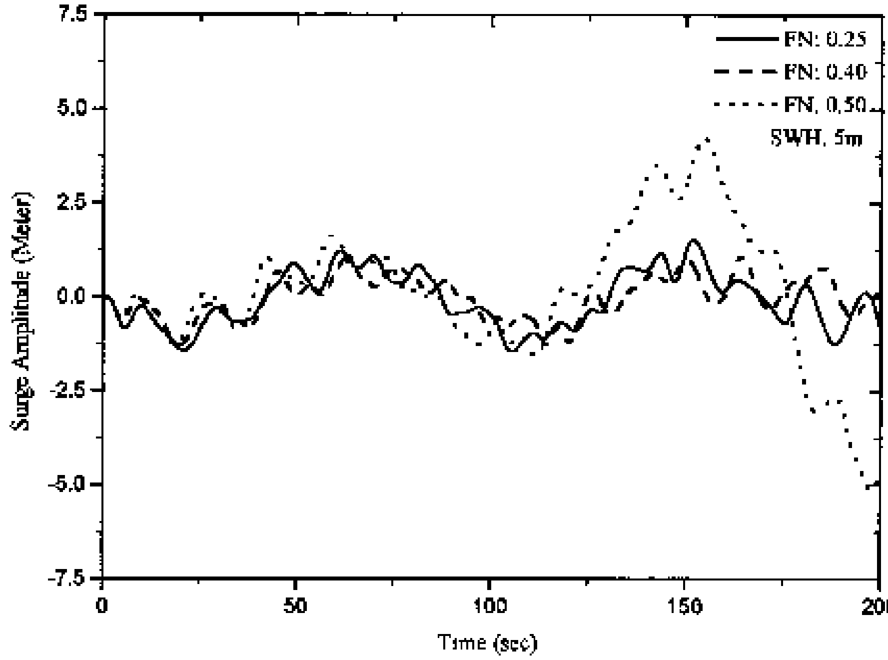


Fig: 4.37 Comparison of Surge motion at various Froude number in irregular waves

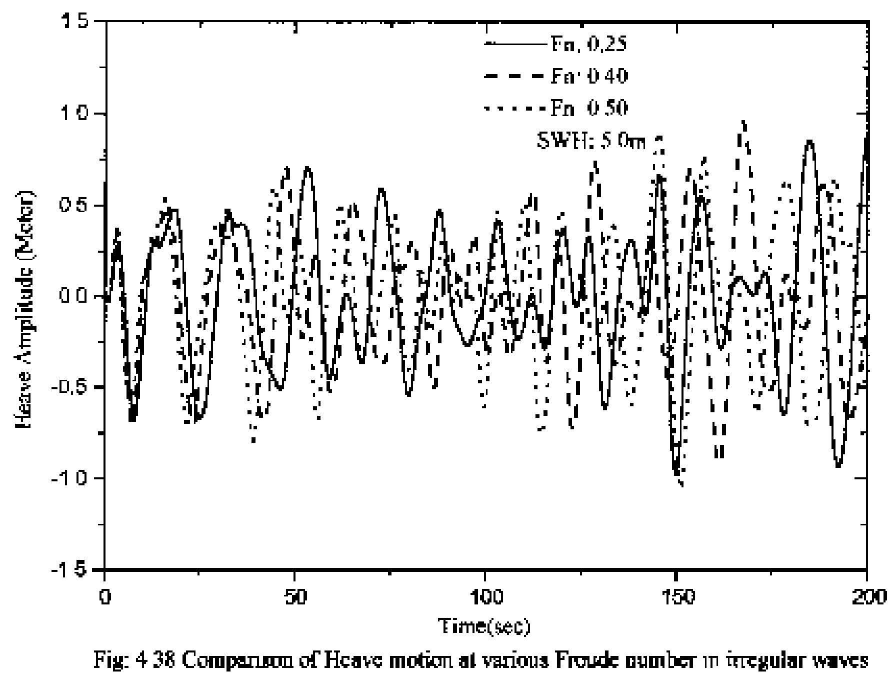


Fig: 4.38 Comparison of Heave motion at various Froude number in irregular waves

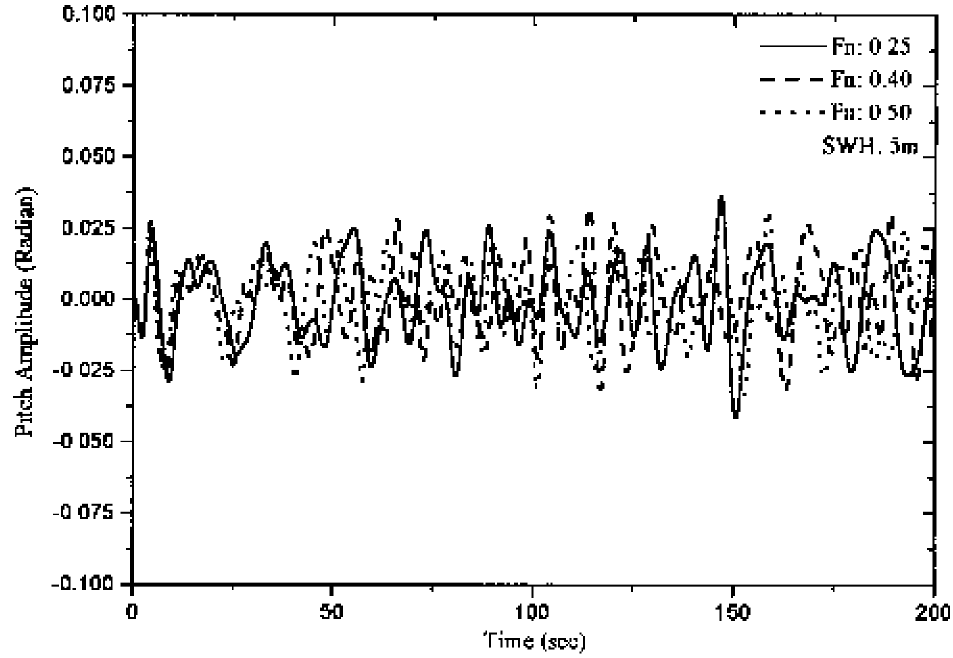


Fig 4.39 Comparison of Pitch motion at various Froude number in irregelar waves

4.8 Results of Comparison of Motion Simulation at various Significant Wave Height

The effects of waves of different significant height on motions are also compared by considering particular ship speed. Significant wave of 1.0, 3.0, 5.0, 7.0 and 9.0 meter height respectively are taken into consideration. Motions for Froude Number 0.25 are plotted in Fig: 4.40 to Fig: 4.45. For Froude Number 0.40 and 0.50, motions are shown in Fig: 4.46 to Fig: 4.51 and Fig: 4.52 to Fig: 4.57 respectively. Comparing the amplitude of motions at different wave height keeping ship speed fixed, it is clear that the amplitude of motions are increasing with the increase of wave height. But in case of wave height limited within a range (For surge 3.0m, heave 4.0m and pitch 6.0m), amplitude of motions are slightly decreasing with the increase of ship speed where as for wave height above these limit, the phenomenon is reversed i.e. amplitude of motions have increasing tendency with the increase of ship speed. It can also be mentioned that the ship at Fn:0.25 with SWH: 7.0m would face maximum surge 2.25 m, heave 1.1 m and maximum vertical displacement from load water line at stern/stem due to pitch motion (0.0375 radian) will be 1.05 meter. The ship can run with this condition if heave and pitch assumed occurring at different time. But in the case of both the motion occurring at the same time in the same direction, the ships propeller will start coming out of the still water level. For Fn: 0.25 with SWH above 7m, Fn: 0.40 with SWH above 5m and Fn: 0.50 with SWH above 5m, ships heave motion will be above 1.10m, which may bring the propeller tip out of water by individual heave and pitch action as the propeller tip starts from a depth of 1.10 m and ship will also experience high surge motion.

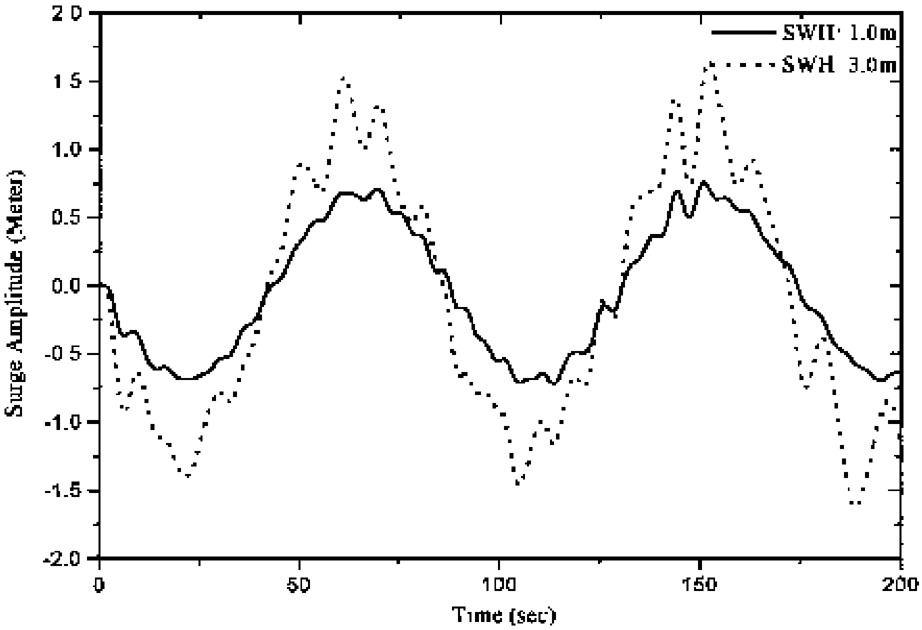


Fig: 4 40 Comparison of Surge motion at different wave height in irregular sea
(Fn. 0.25)

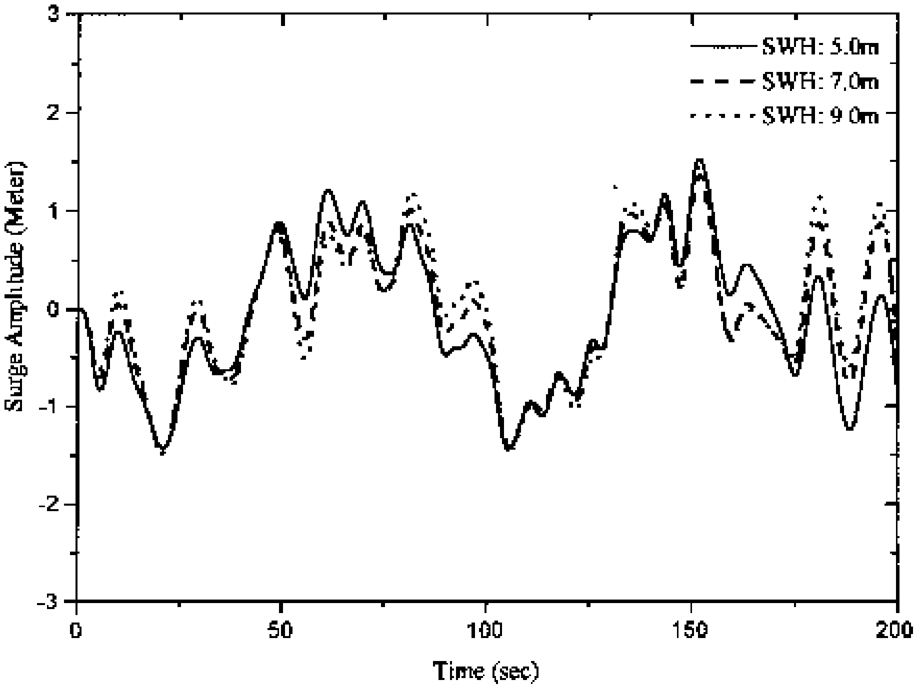


Fig: 4 41 Comparison of Surge motion at different wave height in irregular sea
(Fn 0.25)

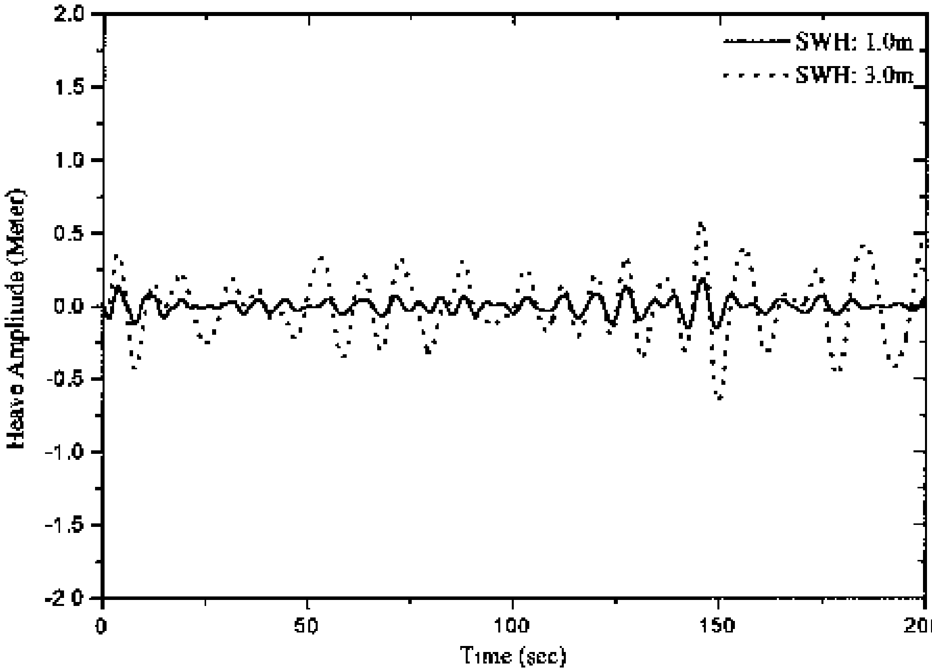


Fig: 4 42 Comparison of Heave motion at different wave height in irregular sea
(Fn 0 25)

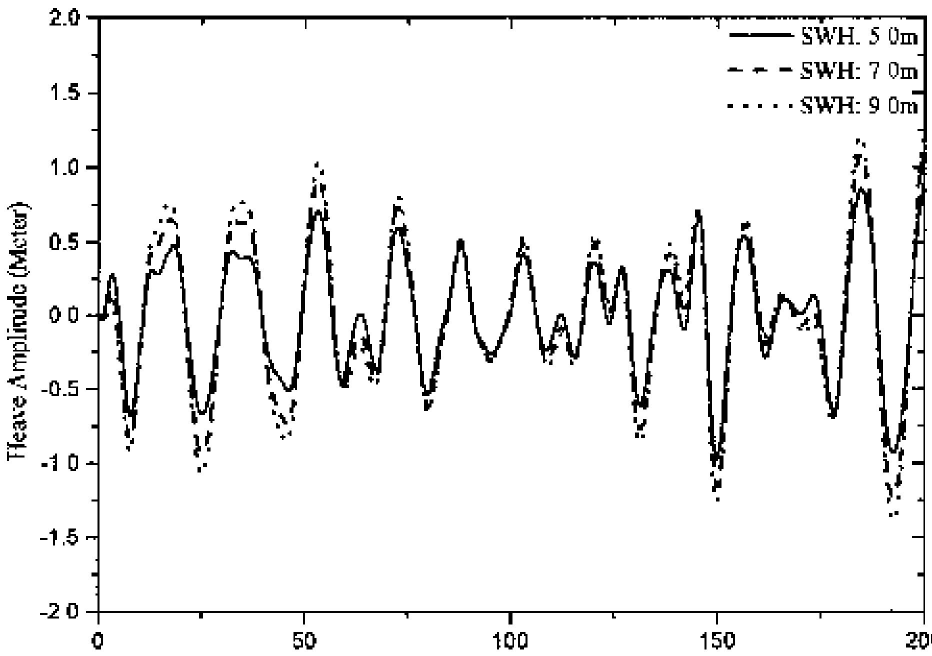


Fig 4 43 Comparison of Heave motion at different wave height in irregular sea
(Fn: 0.25)

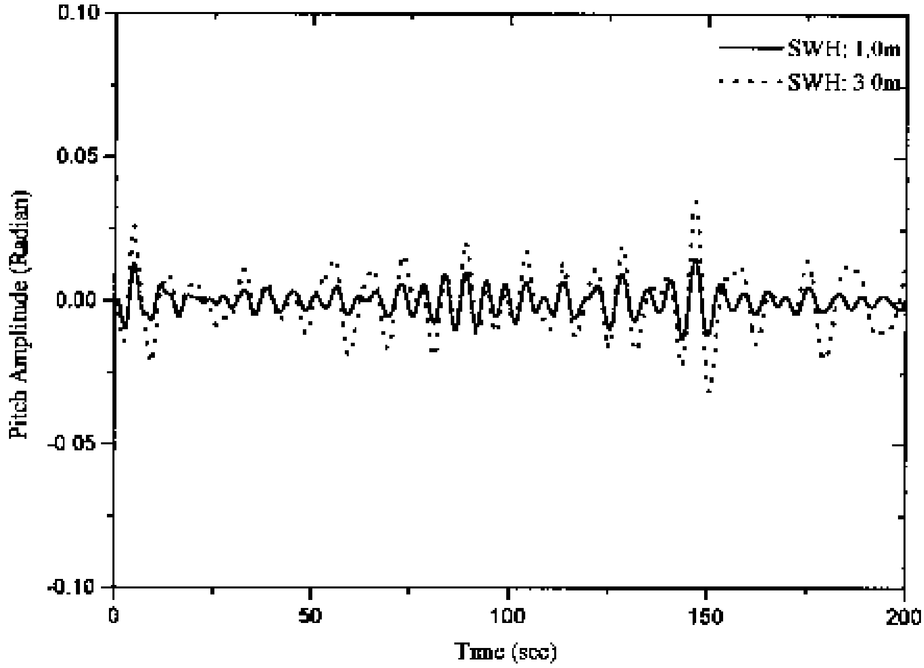


Fig: 4.44 Comparison of Pitch motion at different wave height in irregular sea (Fn: 0.25)

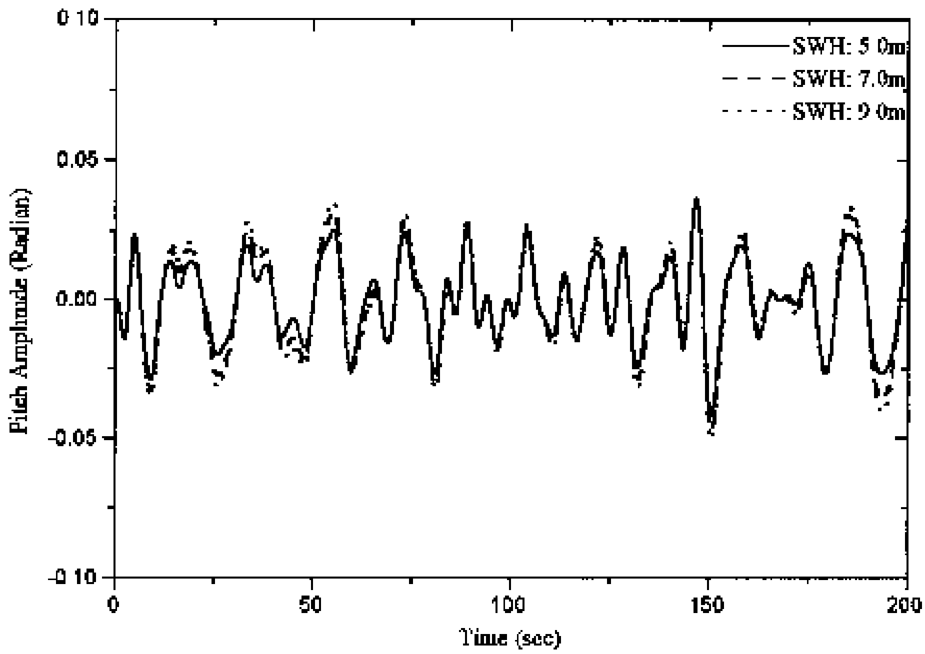


Fig: 4.45 Comparison of Pitch motion at different wave height in irregular sea (Fn: 0.25)

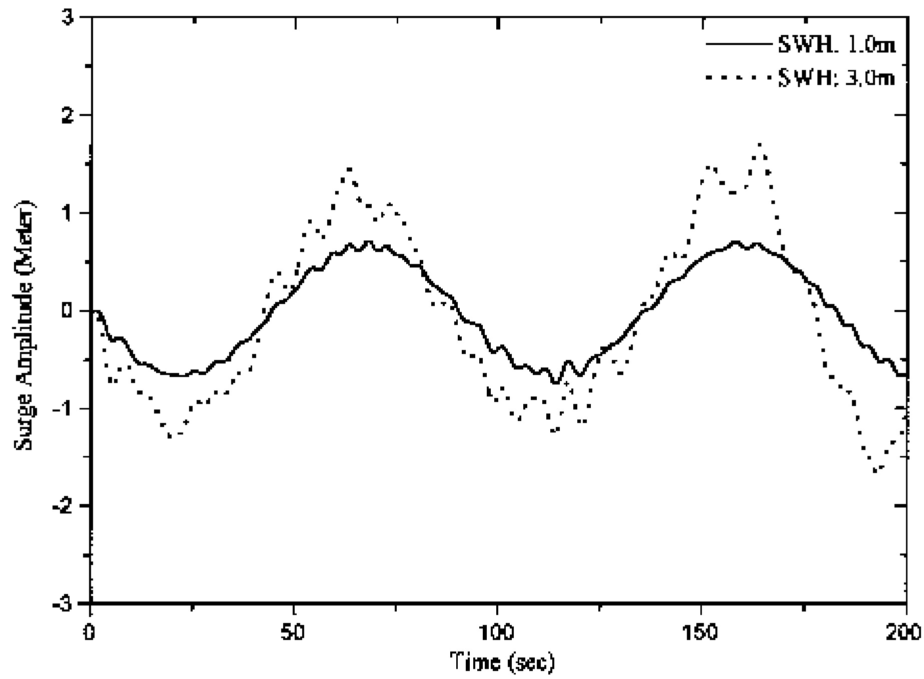


Fig 4.46 Comparison of Surge motion at different wave height in irregular sea (Fn 0.40)

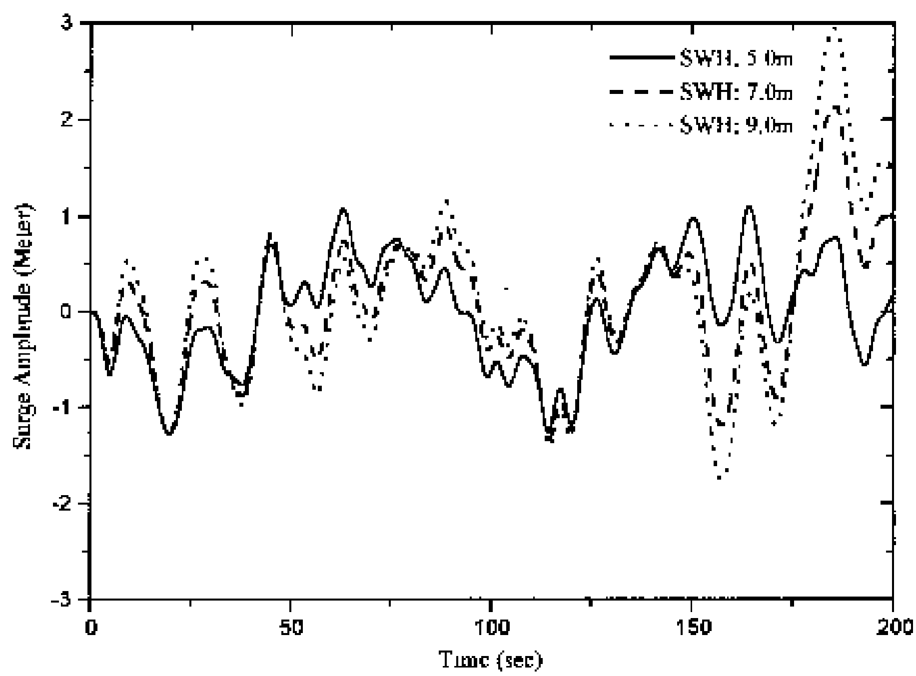


Fig. 4.47 Comparison of Surge motion at different wave height in irregular sea (Fn 0.40)

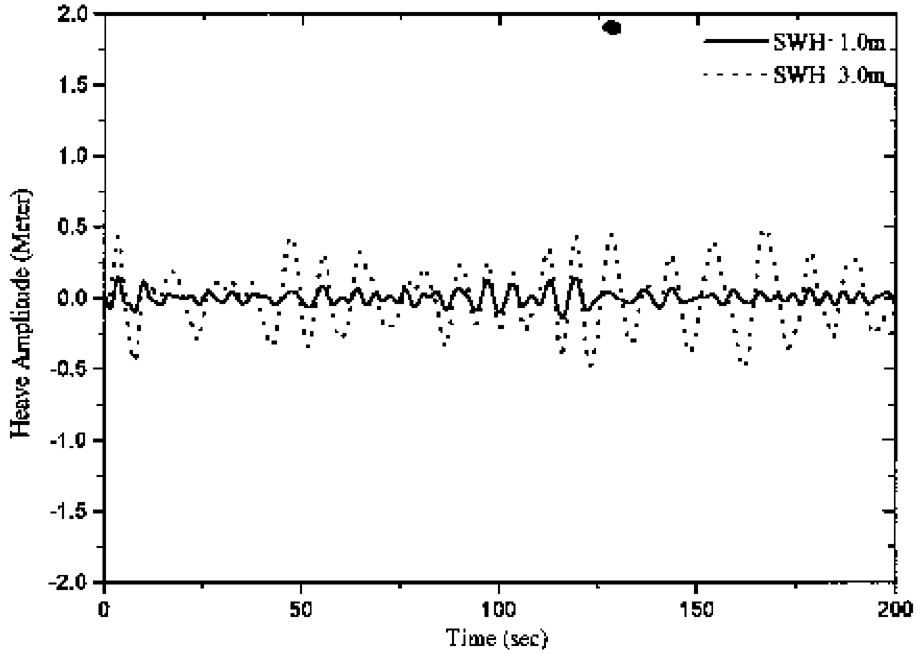


Fig: 4.48 Comparison of Heave motion at different wave height in irregular sea (Fn. 0.40)

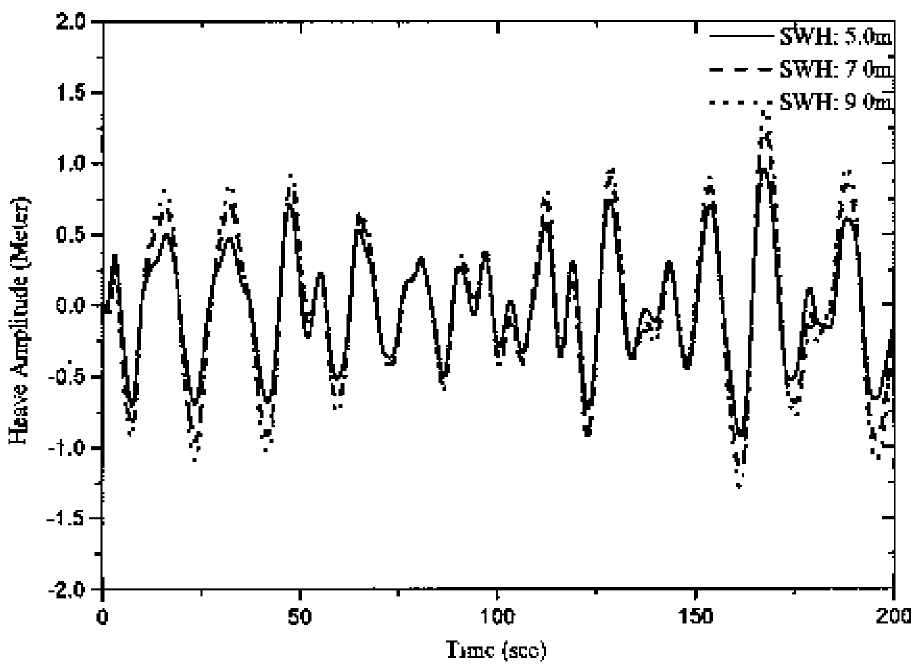


Fig: 4.49 Comparison of Heave motion at different wave height in irregular sea (Fn: 0.40)

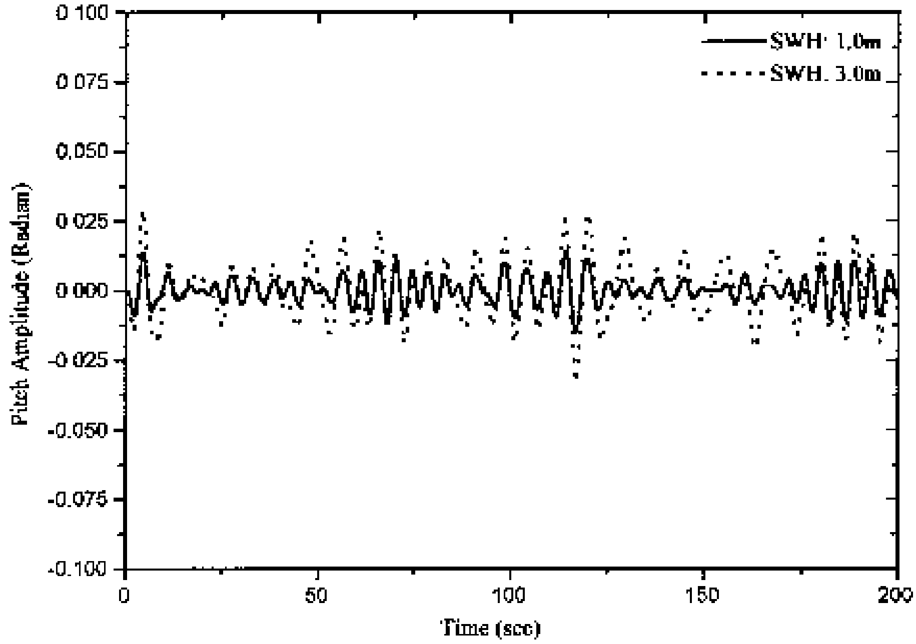


Fig 4.50 Comparison of Pitch motion at different wave height in irregular sea (Fn. 0.40)

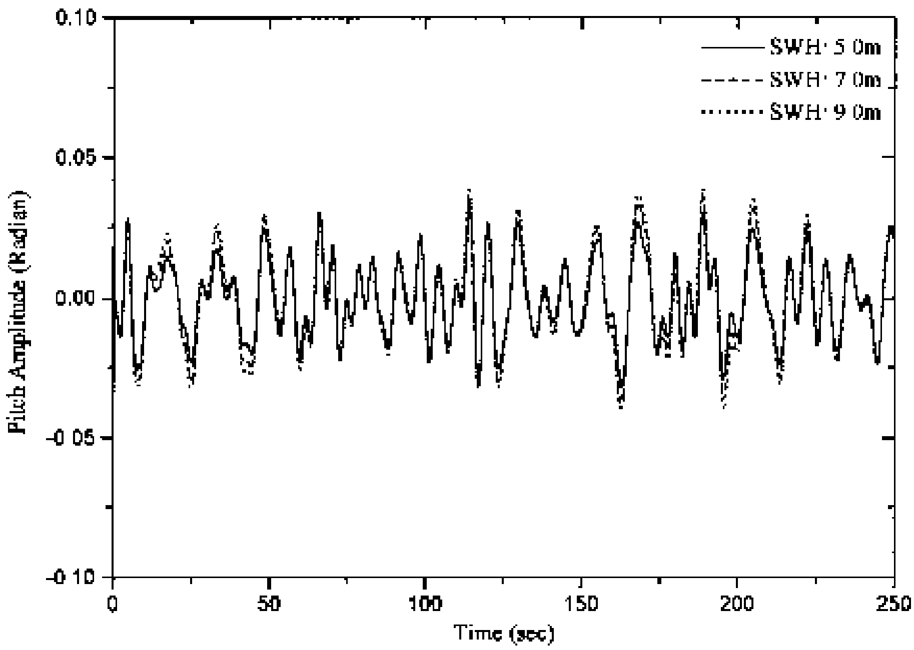


Fig. 4.51 Pitch motion at different wave height in irregular sea (Fn. 0.40)

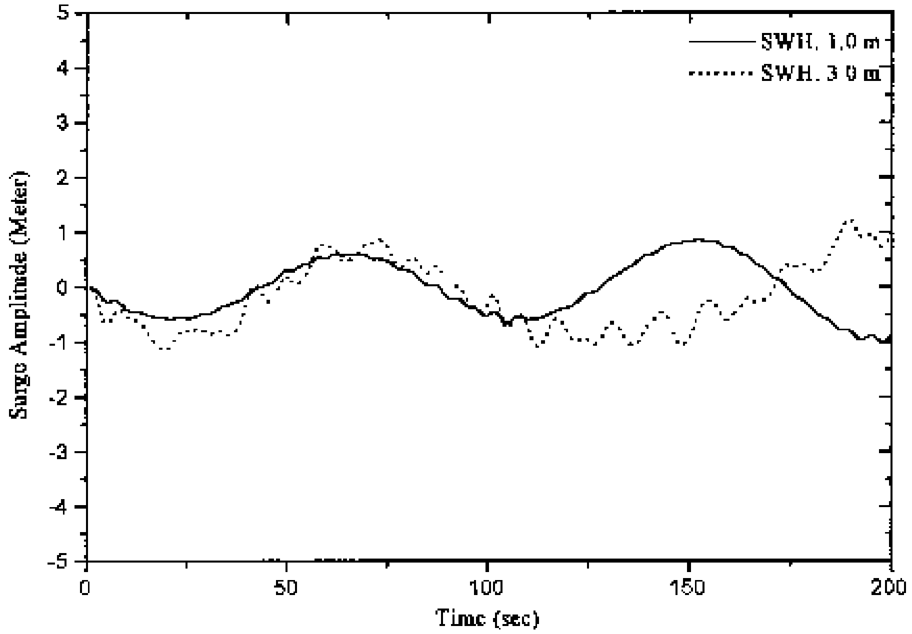


Fig: 4.52 Surge motion at different wave height in irregular sea
(Fn: 0.50)

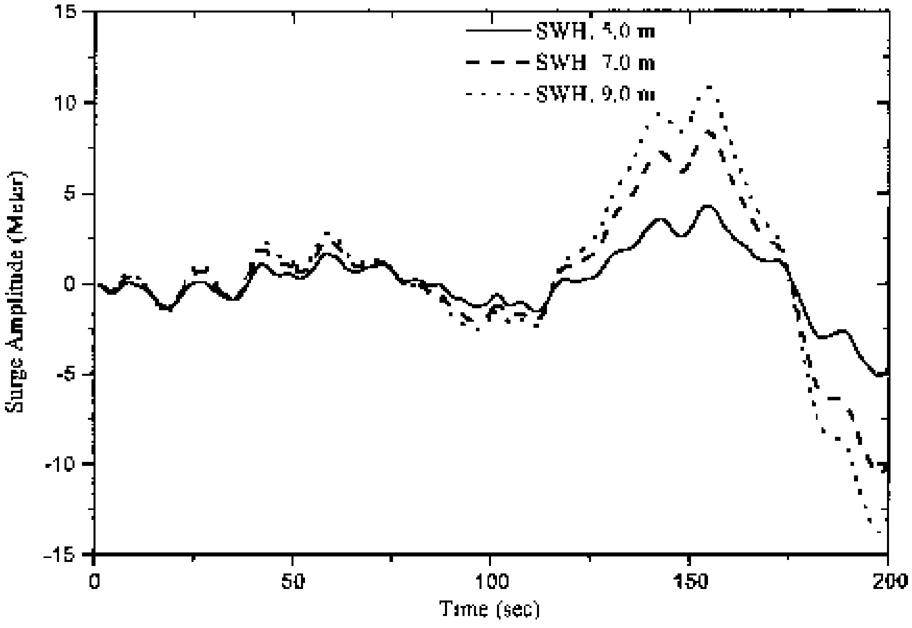


Fig: 4.53 Comparison of Surge motion at different wave height in irregular sea
(Fn: 0.50)

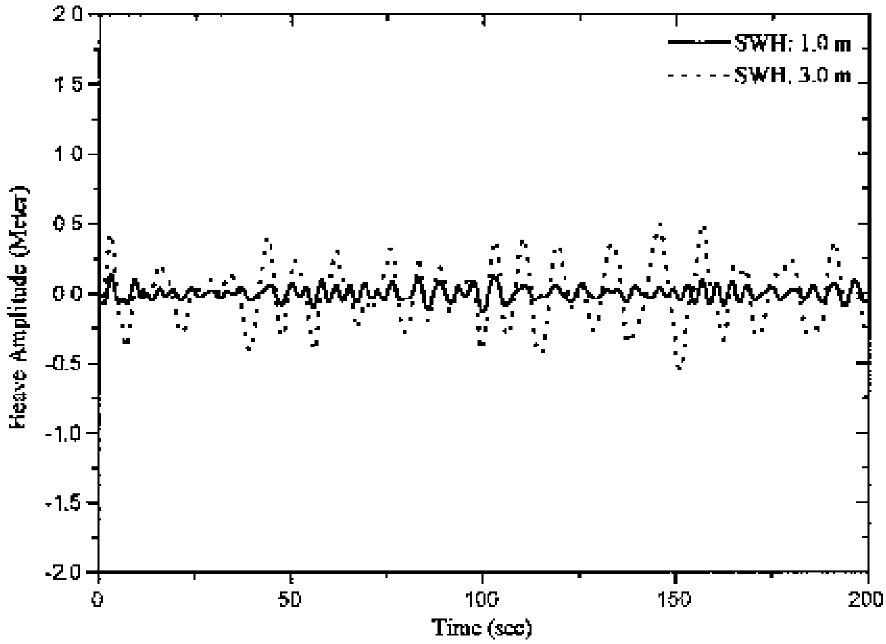


Fig. 4.54 Comparison of Heave motion at different wave height in irregular sea
(Fn: 0.50)

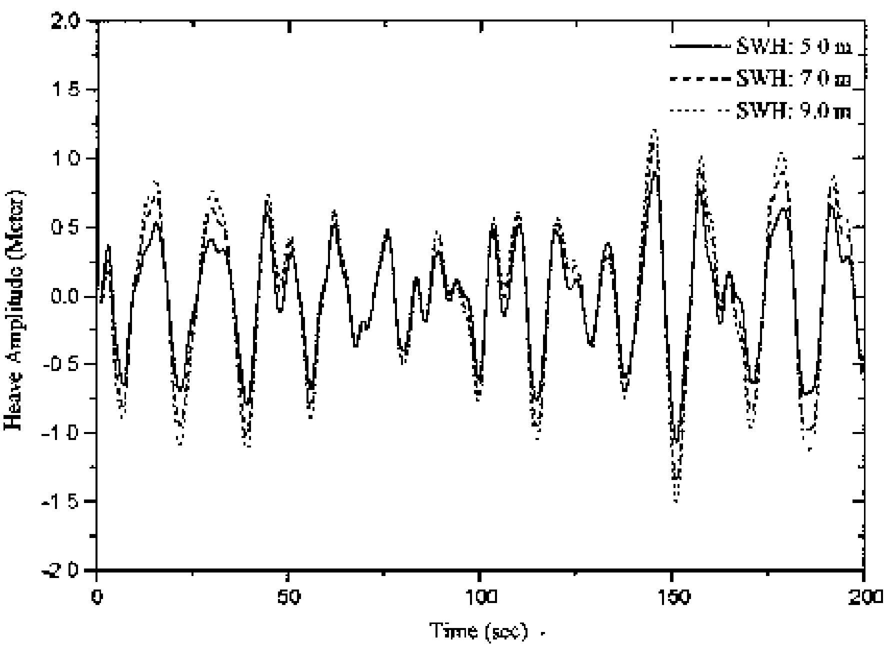


Fig: 4.55 Comparison of Heave motion at different wave height in irregular sea
(Fn: 0.50)

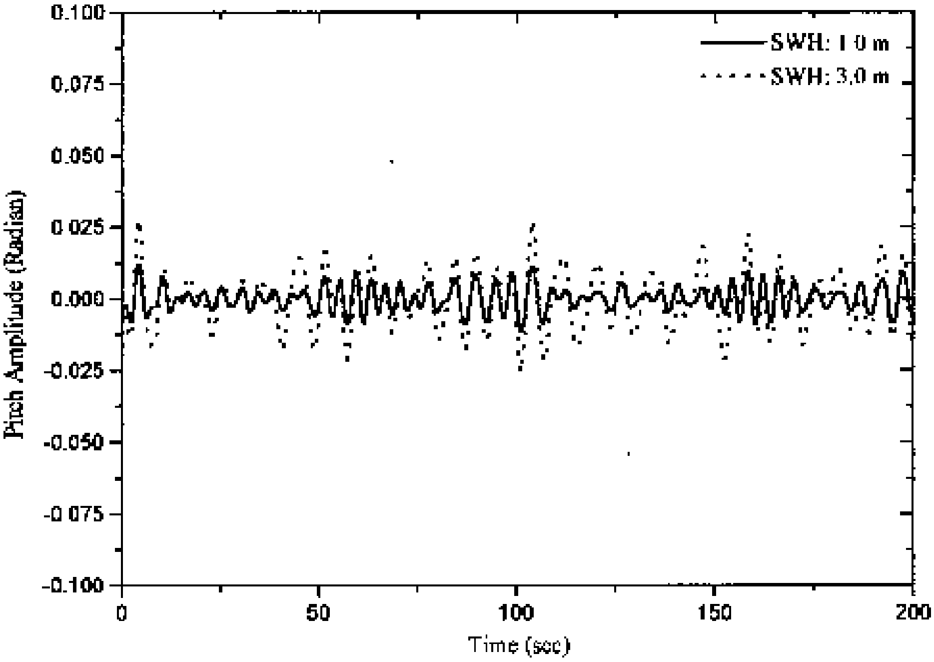


Fig: 4.56 Comparison of Pitch motion at different wave height in irregular sea
(Fn: 0.50)

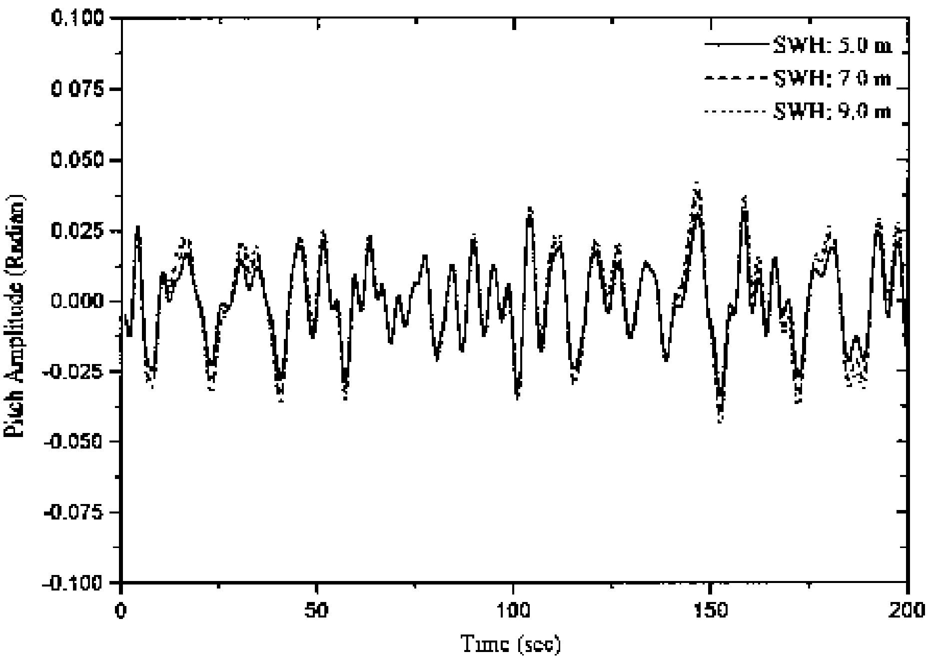


Fig: 4.57 Comparison of Pitch motion at different wave height in irregular sea
(Fn: 0.50)

4.9 Results of comparative statements of Motion Amplitudes

Within the simulated time, the comparative statements of maximum surge, heave and pitch motion at various ship speeds and significant wave height are shown in Table: 4.03 to 4.05. The maximum surge, heave and pitch amplitudes at different ship speed are plotted against different significant wave height and shown in Fig: 4.58 to 4.60. The figures indicate that amplitudes of motions are decreasing with the increase of ship speed up to a certain level of significant wave height but beyond that limit amplitudes are increasing with the increase of ship speed.

Froude Number (Fn)	SWH ($H_{1/3}$) (Meter)	Surge Amp. (Meter) Max.	Heave Amp.(z) (Meter) Max.	Pitch Amp. (θ) (Radian) Max.	Pitch Amp. ($x\theta$) at stern (Meter) Max.	$z+x\theta$ (Meter) Max.
0 25	1.0	0.75	0.18	0.014	0.392	0.572
	3.0	1.60	0.65	0.032	0.896	1.546
	5.0	1.70	0.925	0.037	1.036	1.961
	7.0	2.25	1.10	0.0375	1.05	2.150
	9.0	2.60	1.30	0.040	1.12	2.420

Table: 4.03 Surge/Heave/Pitch motion at various wave height at Froude Number 0.25

Froude Number (Fn)	SWH ($H_{1/3}$) (Meter)	Surge Amp. (Meter) Max.	Heave Amp.(z) (Meter) Max.	Pitch Amp. (θ) (Radian) Max.	Pitch Amp. ($x\theta$) at stern (Meter) Max.	$z+x\theta$ (Meter) Max.
0.40	1.0	0.70	0.140	0.0135	0.378	0.518
	3.0	1.55	0.525	0.030	0.84	1.365
	5.0	1.60	1.00	0.035	0.98	1.980
	7.0	2.20	1.22	0.037	1.036	2.256
	9.0	2.90	1.32	0.042	1.172	2.492

Table: 4.03 Surge/Heave/Pitch motion at various wave height

at Froude Number 0.40

Froude Number (Fn)	SWH ($H_{1/3}$) (Meter)	Surge Amp. (Meter) Max.	Heave Amp.(z) (Meter) Max.	Pitch Amp. (θ) (Radian) Max.	Pitch Amp. ($x\theta$) at stern (Meter) Max	$z+x\theta$ (Meter) Max.
0.5	1.0	1.00	0.10	0.012	0.336	0.436
	3.0	1.25	0.50	0.027	0.756	1.256
	5.0	5.00	1.10	0.0325	0.91	2.010
	7.0	10.50	1.22	0.042	1.176	2.396
	9.0	14.00	1.37	0.047	1.316	2.686

Table: 4.03 Surge/Heave/Pitch motion at various wave height

at Froude Number 0. 50

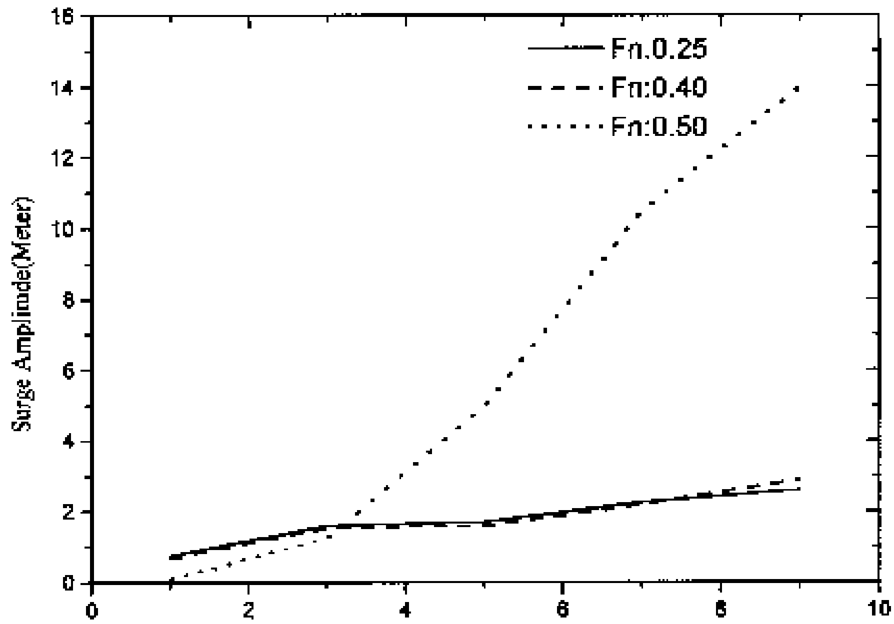


Fig 4.58 Surge motion at various SWH at different Froude number

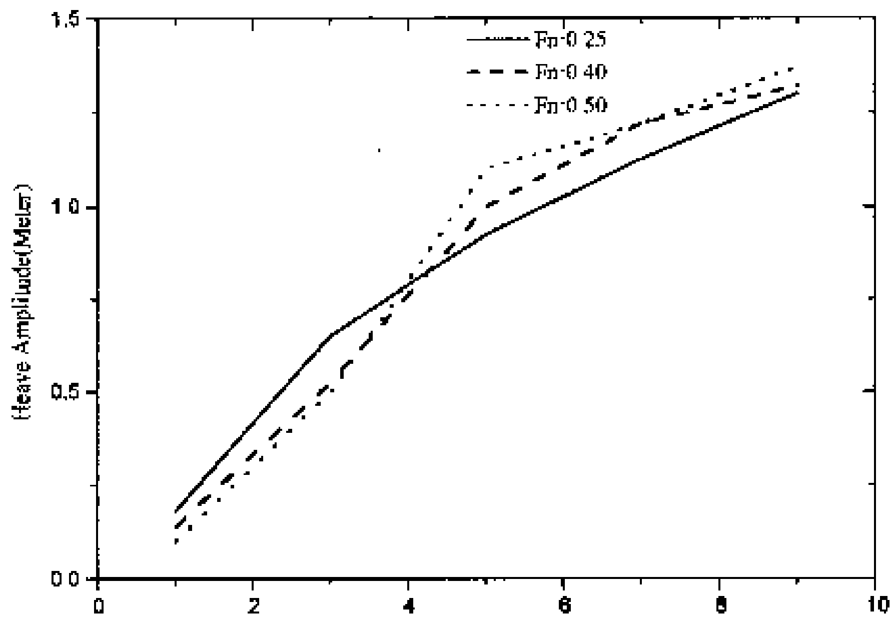


Fig:4.59 Heave motion at various SWH at different Froude number

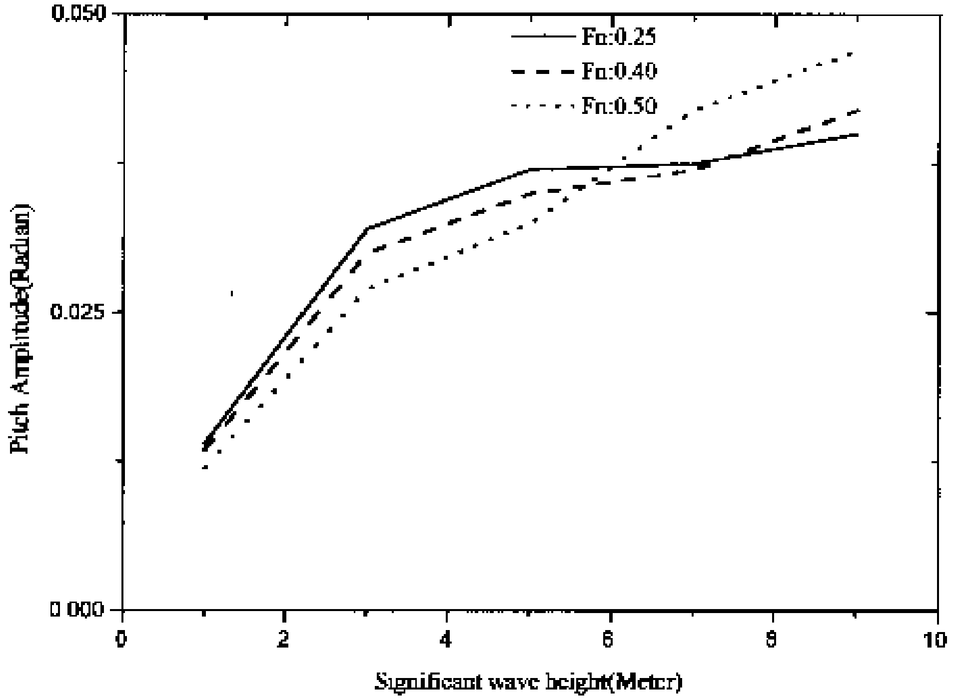


Fig 4 60 Pitch motion at various SWH at different Froude number

4.10 Results of comparative statements of vertical displacement at stern due to Heave, Pitch and Wave Amplitude

The vertical displacement at stern due to the combined effect of heave and pitch motion and wave elevation at stern are calculated and plotted in figures (Figure: 4.61 to 4.66). Their combined effects are added according to sign convention to get total vertical displacement of a point relative to wave surface at stern position which was initially on the load water line in calm water condition.

For maximum heave motion within the simulated time, it is seen from Fig: 4.61, that for Froude Number 0.25 with significant wave height 1.0 m, relative stern rise above the wave surface, considering heave, pitch and wave [a+b-(±c) = +0.189+0.223-(-0.0616), where a, b and c are defined in Fig: 4.67] is 0.474 m and for maximum pitch condition 0.515 m. From Fig: 4.62, with significant wave height 3.0 m, the corresponding values are 1.47 m and 1.554 m respectively.

Similarly, for maximum heave motion within the simulated time, it is seen from Fig: 4.63, that for Froude Number 0.40 with significant wave height 1.0 m, relative stern rise above the wave surface is 0.3713 m and for maximum pitch condition 0.5616m. From Fig: 4.64, with significant wave height 3.0 m, the corresponding values are 1.008 m and 1.1027 m. respectively.

Again, for maximum heave motion within the simulated time, it is seen from Fig: 4.65, that for Froude Number 0.50 with significant wave height 1.0 m, relative stem rise above the wave surface is 0.187 m and for maximum pitch condition 0.430m. From Fig: 4.66, with significant wave height 3.0 m, the corresponding values are 1.174 m and 1.196 m respectively.

By superimposing the three figures of heave, vertical displacement of stern due to pitch and wave elevation at stern position (Fig: 4.61 to 4.66), it is observed that maximum heave, maximum pitch and wave crest/trough are not coinciding at a point simultaneously. It may be noted that the propeller tip clearance from calm water level is 1.10 m. Considering this, it is seen from these three elevations that the ship can run smoothly with speed up to 22.8 knots (Fn: 0.50) at significant wave height 1.0m (sea state up to 3) without any propeller emergence. Above sea state 3, there is partial emergence of propeller once in the simulated time.

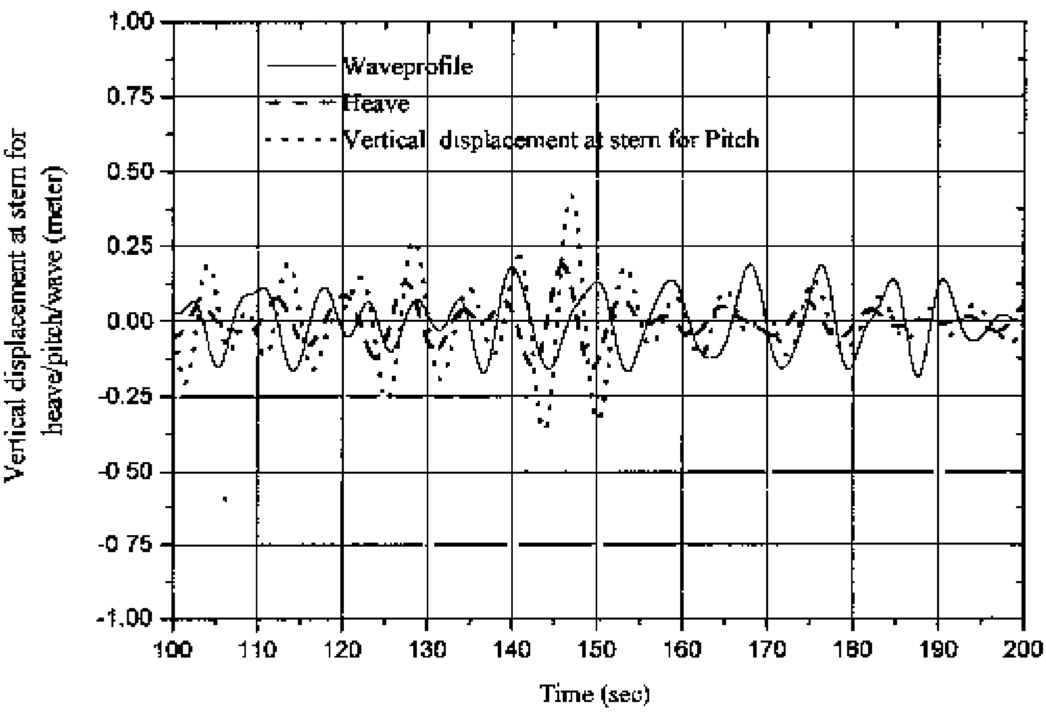


Fig:4.61 Comparison of heave motion and vertical displacement at stern due to pitch with wave elevation (Fn=0.25,SWH=1m)

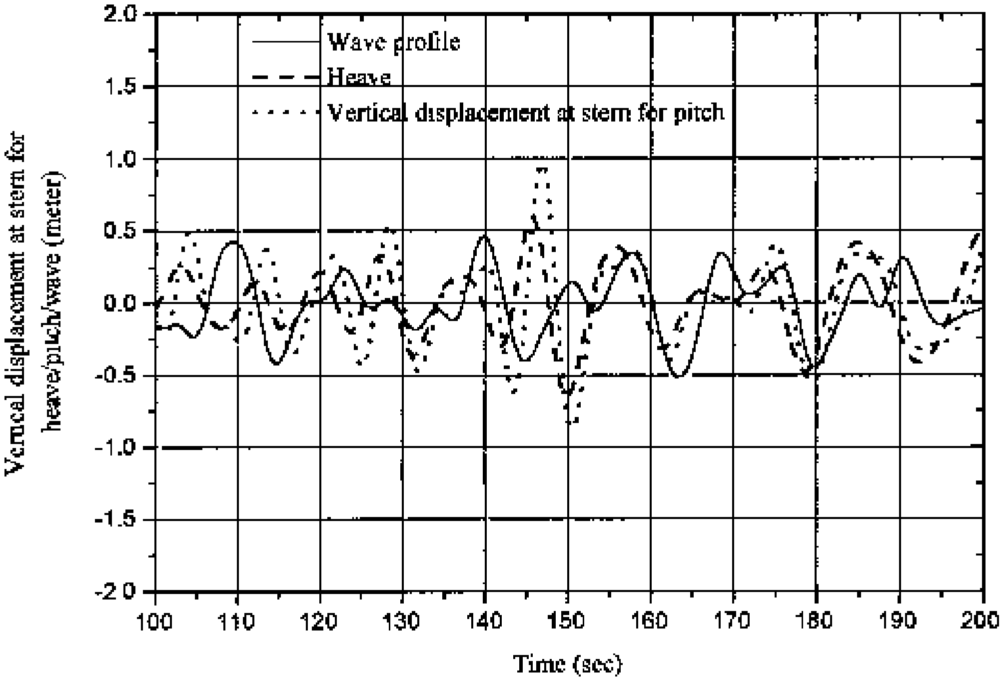


Fig 4 62 Comparison of heave motion and vertical displacement at stern due to pitch with wave elevation (Fn=0.25,SWH=3m)

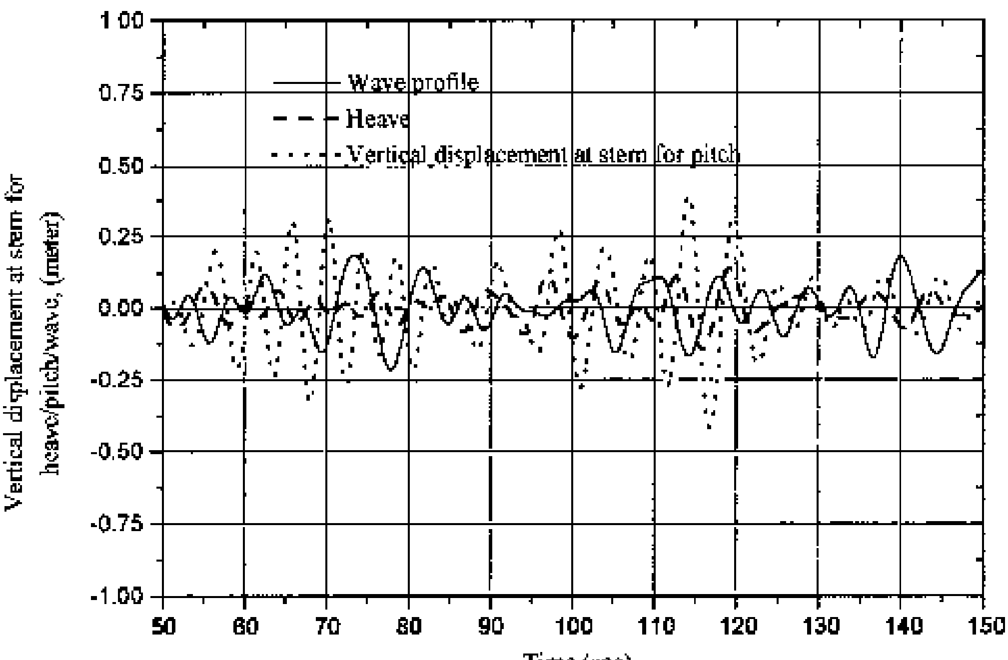


Fig:4.63 Comparison of heave motion and vertical displacement at stern due to pitch with wave elevation (Fn=0.40,SWH=1m)

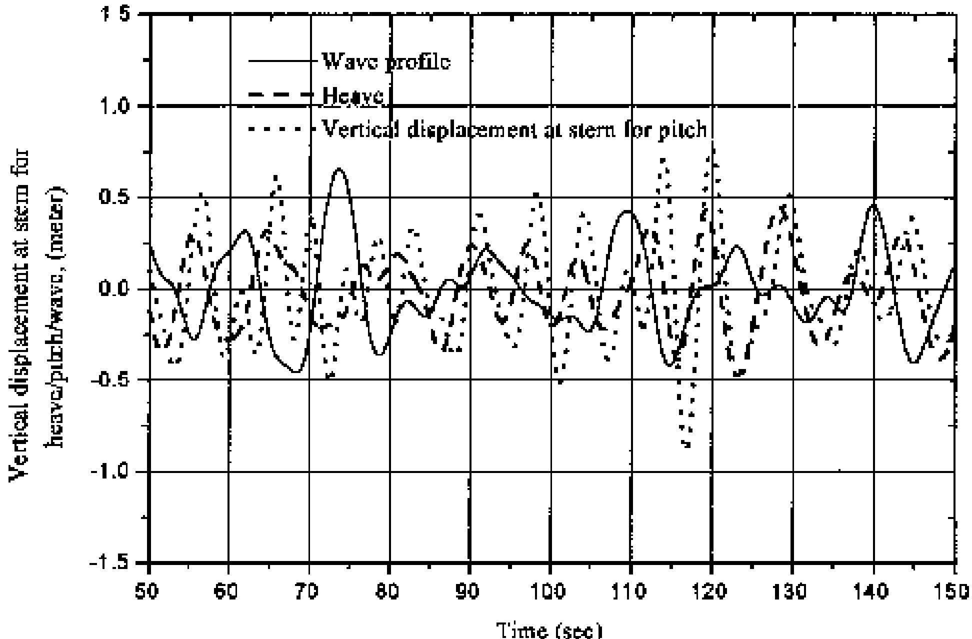


Fig:4.64 Comparison of heave motion and vertical displacement at stern due to pitch with wave elevation (Fn=0.40,SWH=3m)

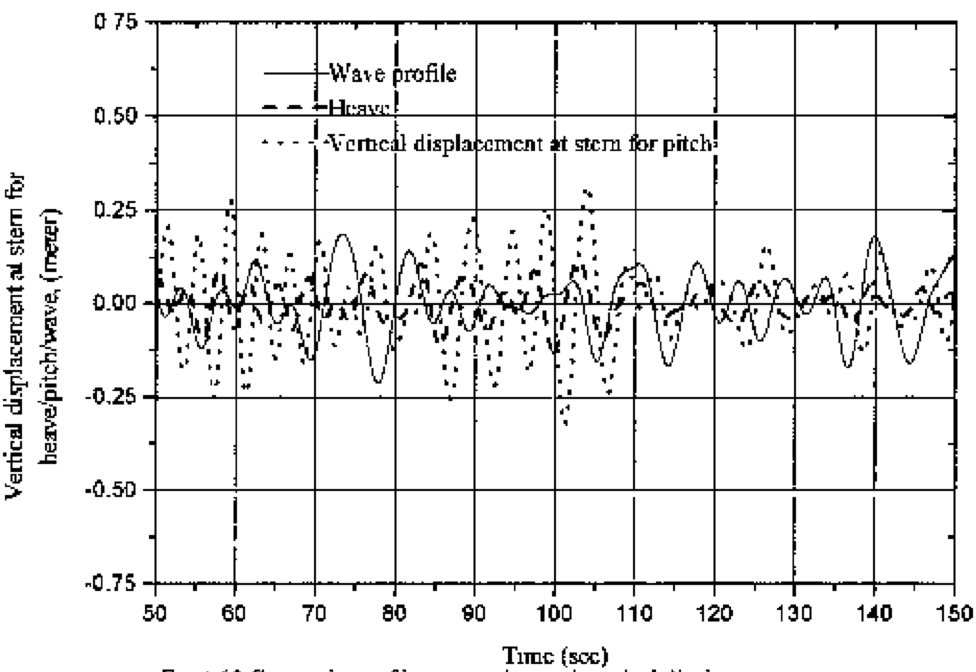


Fig:4.65 Comparison of heave motion and vertical displacement at stern due to pitch with wave elevation (Fn=0.50,SWH=1m)

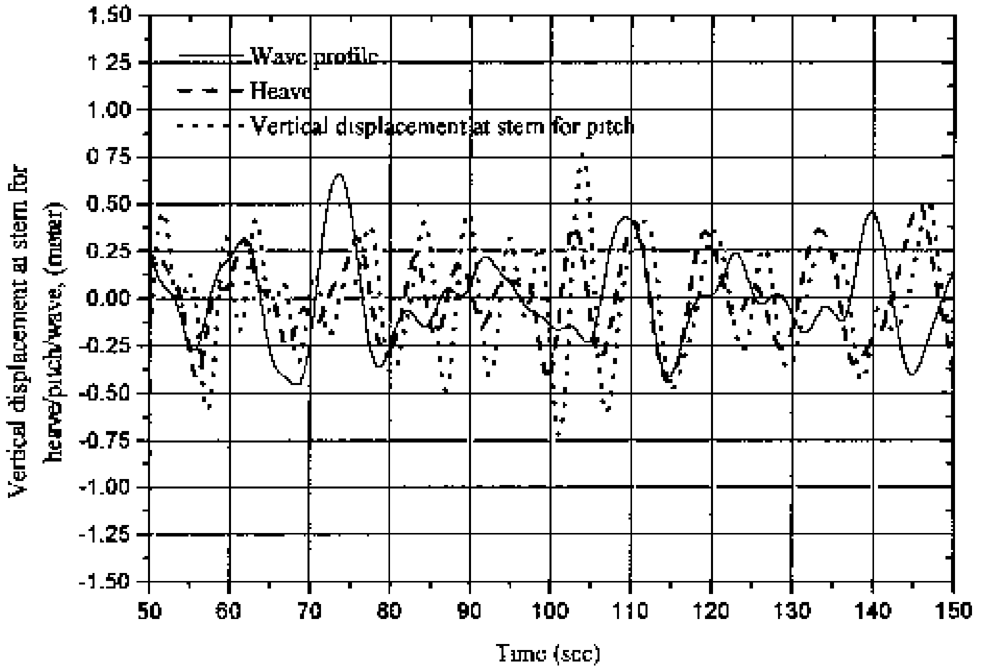


Fig:4 66 Comparison of heave motion and vertical displacement at stern due to pitch with wave elevation (Fn=0.50,SWH=3m)

a = heave amplitude
b = vertical displacement at stern due to pitch effect
c = wave elevation at stern

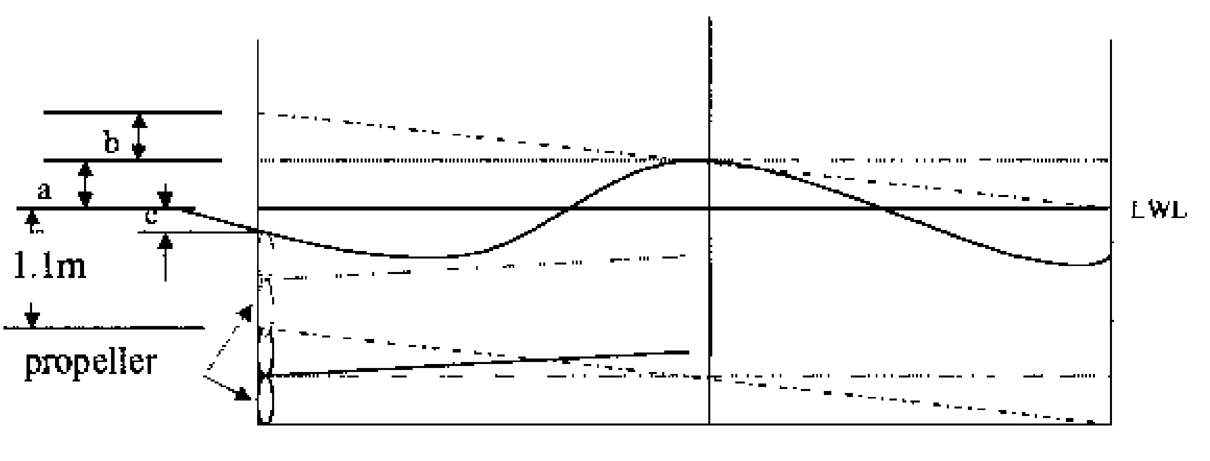


Fig: 4.67 A typical sketch for relative rise of stern above wave surface

CHAPTER 5

CONCLUSIONS

5.1 General:

An attempt has been made in this research work to predict motions of an existing fine shaped naval vessel in rough sea in the Bay of Bengal considering the forward speed effect. From the previous discussions, the following conclusions may be drawn:

The motions of the ship can be determined from the simulation result.

The ship can operate at speed 22.8 Knots at sea state up to 5, at 18.2 knots up to sea state 6 and 11.5 knots up to sea state 7 if only individual heave and pitch motion effects are considered. Beyond these limits, the ship will experience high surge, heave and pitch motions.

It is safer to increase ship speed up to sea state around 5 and decrease it with the further increase of sea state. Actions can be taken accordingly for safety and security of the ship during operation at rough sea in the Bay of Bengal.

The ship can run smoothly up to sea state 3 with ship speed up to 22.8 knots if both heave, pitch and wave elevations are considered. Beyond this range, the combined effect will start bringing the propeller tip out of water occasionally.

5.2 Recommendations for future Research:

Further scope of research work in this field can be summarized as follows:
Motions can be simulated by utilizing beam sea or other wave heading conditions and validation of the time domain motions could be done by model test or by collecting practical motion data during actual operation of the ship at Bay of Bengal which could not be carried out due to limitation of resources/facilities.

Wind and current effects can be included in the prediction of motions. On the basis of the results obtained, total sea, wind and current loads can be predicted and bending moments can also be calculated for structural design. Due to the effect of the above loads, extra power requirement for constant speed running or speed reduction during constant power running can be estimated.

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APPENDIX-A

Evaluation of Green Function and velocity Potential

The potential function at some point P(x,y,z) in the fluid region in terms of surface distribution of sources can be written as:

$$\phi_j(x,y,z) = \frac{1}{4\pi}\iint_s \sigma_j(\xi,\eta,\zeta)G(x,y,z,\xi,\eta,\zeta)ds \qquad \text{(A-1)}$$

Where, (ξ,η,ζ) denotes a point Q, on surface S and $\sigma(\xi,\eta,\zeta)$ denotes the unknown source distribution. The integral is to be carried out over complete immerged surface of the object. The Green function G (source potential) must in order of the representation in equation (A-1) to be valid, satisfy all the boundary conditions of the problem with the exception of the kinematics condition [equation 2.12, 2.13, 2.14] and have a source like behavour.

The particular expression for G appropriate to the boundary value problems posed is given in two different forms by Wehausen and Laitone [22] in 1969. One of these is the integral form and has the following forms:

$$G(x,y,z;\xi,\eta,\zeta) = \frac{1}{R_1} - \frac{1}{R_2} + \frac{2g}{\pi}\int_0^{\pi}\int_0^{\infty}\frac{h(k,\theta)}{gk-(\omega_e+\bar{U}k\cos\theta)^2}dk\,d\theta \qquad \text{(A-2)}$$

where,

$$h(k,\theta) = k.e^{k\{z_P+z_Q+i(x_P-x_Q)\cos\theta\}}.\cos\{k(y_P-y_Q)\sin\theta\}$$

$$R_j^2 = (x_P-x_Q)^2+(y_P-y_Q)^2+(z_P+(-1)^j z_Q)^2 \quad \text{for } j=1,2$$

The solution to the boundary value problem is given by equation (A-1) satisfied all the boundary conditions and since G itself satisfies these couditions. When the kinematics boundary conditions on the immersed surface is applied; the following integral equation is obtained:

$$\frac{\partial \phi_j(x,y,z)}{\partial n} = -\frac{1}{2}\sigma_j(x,y,z) + \frac{1}{4\pi}\iint_s \sigma_j(\xi,\eta,\zeta)\frac{\partial}{\partial n}G(x,y,z;\xi,\eta,\zeta)ds \qquad \text{(A-3)}$$

The first term of the above equation consider the contribution of the normal derivative of the Green function at the source location $x=\xi, y=\eta, z=\zeta$ where the Green function and its derivative are not defined and where, $\frac{\partial G}{\partial n}$ denotes the normal derivative of the Green function in the outward normal direction and (x,y,z) denotes the point on S. This derivative of G may be evaluated from

$$\frac{\partial G}{\partial n} = \nabla G.\bar{n} = \frac{\partial G}{\partial x}n_x + \frac{\partial G}{\partial y}n_y + \frac{\partial G}{\partial z}n_z, \qquad \text{(A-4)}$$

where, $\frac{\partial G}{\partial x}, \frac{\partial G}{\partial y}$ and $\frac{\partial G}{\partial z}$ are determined through a straightforward differentiation of G. The vector $\bar{n}$ represents the unit normal vector, $\bar{n} = n_x i + n_y j + n_z k$, where n_x, n_y, n_z denote the x,y,z components respectively such that $n_x^2 + n_y^2 + n_z^2 = 1$.

Numerical solution of the velocity potential

The kernel of the integral equation (A-3) $\frac{\partial G}{\partial n}$ is complex and does not permit any solution in closed form so a numerical approach should be required to solve the equation (A-3) and to do so the wetted surface of body is subdivided into a l number of quadrilateral panels of area $\Delta s_l(1........E_n)$ and identifying the node points at the centroid of each panel. The continuous formulation of the solution indicates that the equation (A-3) is to be satisfied at all points (x,y,z) on the immersed surface. In order to obtain a discretized numerical solution it is necessary to relax this requirement and apply the condition at only N control points and the location of the control points may in principle be chosen arbitrarily. However for convenience the locations of the control points have been chosen at the panel centroids. Thus in the discretization process equation (A-3) replaced by the following equation:

$$-\frac{1}{2}(\sigma_j)_l + \frac{1}{4\pi}\sum_{k=1}^{E_m} \iint_{\Delta s_k} (\sigma_j)_k \frac{\partial G}{\partial n}(l,k)ds = n_j \qquad \text{(A-5)}$$

The above equation can be written in a general format in the following form

$$[a_{lk} - I_l](\sigma_j)_k = 2(n_j)_l, [j = 1........6] \qquad \text{(A-6)}$$

where I denotes the unit matrix.

In matrix form

$$\begin{bmatrix} a_{11}-1 & a_{12} & \dots & a_{1N} \\ a_{21} & a_{22}-1 & \dots & a_{2N} \\ .. & .. & .. & .. \\ a_{N1} & \dots & \dots & a_{NN}-1 \end{bmatrix} \begin{bmatrix} \sigma_{j1} \\ .. \\ .. \\ \sigma_{jN} \end{bmatrix} = 2 \begin{bmatrix} n_{j1} \\ .. \\ .. \\ n_{jN} \end{bmatrix} \qquad \text{(A-7)}$$

Where,

$$a_{lk} = \frac{1}{2\pi}\sum_{k=1}^{E_k} \iint_{\Delta s_k} \frac{\partial G}{\partial n}(l,k)ds \qquad \text{(A-8)}$$

Now after inversion of the above matrix equation, the source density σ_j is known and the velocity potential can be find from the following expression:

$$(\phi_j)_l = \beta_{lk}(\sigma_j)_k, \qquad \text{(A-9)}$$

where,

$$\beta_{lk} = \frac{1}{4\pi}\iint_{\Delta s_k} G(j,k)ds \qquad \text{(A-10)}$$

The above equation yields the value of velocity potential at the 'l' control points. However 'l' subscript may be dropped and velocity potential can be evaluated at any point (x,y,z) in the field region.

APPENDIX- B

Table: Sea State-Significant Wave Height

Sea State	Significant Wave Height(Meter)
0	0
1	0-0.10
2	0.10-0.50
3	0.50-1.25
4	1.25-2.50
5	2.50-4.00
6	4.00-6.00
7	6.00-9.00
8	9.00-14.00
9	14.00 and above