Effect of Wave Kinematics on the Response of Spar Platform

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Abstract-**The exploration of hydrocarbon reservoirs in ultra deep water requires the use of innovative floating platform configurations. The hydrodynamic interaction of such platforms with ocean waves and the understanding and quantification of the nonlinear components of theses interactions have been a subject of continuing research. This paper examines these non-linear interaction components for a typical deep-draft spar platform type that is increasingly being used in the oceans now. The motion responses of the spar platform in different environmental conditions have been determined using a time-domain simulation method. The numerical method presented here can consider several nonlinearities such as free surface force integration, displaced position force calculation and nonlinearities in the equation of motion. Wave forces are calculated using Morison's equation. The effect of using different wave kinematics methods on the predicted surge, heave and pitch responses are presented and discussed.**

I. INTRODUCTION

As the offshore industry depletes hydrodynamic reservoirs below the sea bed in deep water depths (up to 1500m), it is increasingly required to develop such deposits in considerably high deeper water. The increased water depth makes the use of sea bed mounted platforms uneconomic leaving a variety of floating platform types as the viable only options for oil and gas production operations. One such option is the spar platform which is basically a very large floating vertical cylinder structure of around 200m draft and 40m or so in diameter. Such hull configurations have been shown to have several advantages over other options such as TLP and ship shape hulls. Some of these advantages include structural simplicity, low motions in moderate and extreme ocean waves because of their relatively long natural periods, good protection of riser connections to the sea bed, low cost and so on (Vardeman et al.[1]).

In recent years the realization that large spar platforms offer low cost production options in very deep water has prompted several experimental studies and numerical simulations to obtain a better understanding of their response to ocean waves. Research using numerical simulations has utilized the two traditional frequency domain and time domain approaches. One such study presented by Weggel et al. [2] uses the frequency domain technique and directly gives the statistical parameters of the spar response at relatively low computation cost. However it may be subject to large errors due to the linearization of some non-linear terms, such as the viscous term, in the equations of motion. There is evidence that this linearization probably overestimates viscous effects [3]. Most researchers prefer, therefore, to simulate spar motion in the time domain and this is the approach adopted in this paper.

Simulation of the motion of a spar buoy requires the definition of the equations of motion and the evaluation of all forces acting on it due to wind, current ocean waves and mooring lines. The conventional approach in offshore engineering is to use the linear form of the equations to describe the motions of rigid bodies. For large motions the non-linear equations of motion [4] should be used but it is only practical if the exciting forces can be calculated without evolving wave diffraction analysis.

A key element of the analysis of a spar buoy is to evaluate the forces and moments on it due to ocean waves and currents. One possibility to obtain these is to perform a numerical analysis of the fully non-linear interaction between the spar and its surrounding fluid. Although it is not impossible, this task require very powerful computer resources and is, therefore, not feasible in practice. An alternative approach is to carry out a diffraction analysis based on second order potential theory (see for example, Ran et al. [3]). The computation cost of this approach is still quite high. Also this method usually generates results in the frequency domain and thereafter a transformation is needed to obtain forces in the time domain.

Another approach, often used in offshore engineering for wave force evaluation, is based on slender body theory that requires much less computational effort and can be directly implemented in time domain analysis. In this approach, the body is assumed 'thin' and the force (and/or moment) is obtained by the sum of the force on each short segment of the slender body. The force in each segment is decomposed into two parts - an inviscid force and viscous drag force. One typical slender body wave force formulation is the well-known Morison equation, in which the first part is proportional to the relative acceleration and the second part to the product of the relative velocity.

The main purpose of this paper is to investigate the relative importance effect of the selected wave kinematics approach on the predicted spar responses. The methodology employed uses the fully non-linear equations of motion with the mooring lines replaced by springs.

II. NUMERICAL PROCEDURE

Considering the incident waves are long crested and advancing in the x-direction, a spar is approximated by a rigid body of three degree of freedom (surge, heave and pitch), it derives its static resistance from support systems (mooring lines, risers) and hydrostatic stiffness.

Two coordinate systems are employed in the analysis (see fig.1), the space fixed coordinate system oxz and two dimensional local coordinate Gζη which is fixed on the body with the origin at its center of gravity (CG). B is the center of buoyancy and F denotes fairlead.

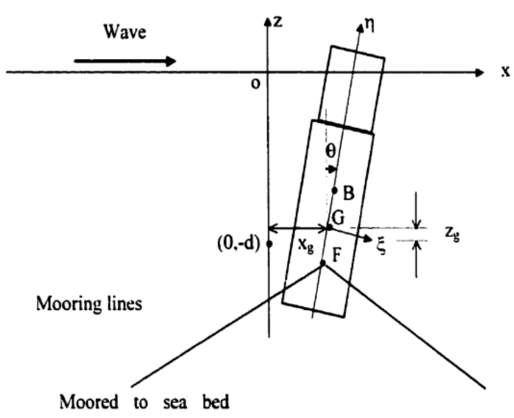

Figure.1 3-DOF Surge-heave-pitch Model of the Spar

The dynamic equations of the surge-heave-pitch motions of the spar are:

$$[M]\{\ddot{X}\}+[C]\{\dot{X}\}+[K]\{X\}=\{F(t)\} \qquad (1)$$

where:

- $\{X\}$ is the structural displacement vector with respect to the center of gravity,
- $\{\dot{X}\}$ is the structural velocity vector with respect to the center of gravity,
- $\{\ddot{X}\}$ is the structural acceleration vector with respect to the center of gravity,
- $[M]$ is a mass matrix = M^{SPAR} + $M^{Added\ Mass}$
- $[K]$ is stiffness matrix = $K^{Hydrostatic(hy)}$ + $K^{Horizental\ Spring(hz)}$,
- [C] is structural damping matrix.
- [F(t)] is the hydrodynamic force vector and is calculated using modified Morison equation.

The wave forces are decomposed into the normal force F_{EXn} and tangential force F_{EXt}

$$\begin{bmatrix} F_{EXn} \\ M_{EX} \end{bmatrix} = \int_{-d_1}^{\varsigma} \rho(1+C_m)A(n)a_n \begin{Bmatrix}1\\ n\end{Bmatrix} dn$$

$$+ \int_{-d_1}^{\varsigma} \frac{1}{2}\rho C_D D\left|V_n\right| V_n \begin{Bmatrix}1\\ n\end{Bmatrix} dn \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

where

$$a_n = \left|a-(a.\vec{\tau})\vec{\tau}\right|$$

$$V_n = \left|V - r_s - ((V-r_s).\vec{\tau})\vec{\tau}\right|$$

$$F_{EXt} = \iint \rho \frac{\partial \vartheta_1}{\partial t} + \frac{1}{2}\rho\left|\nabla\varphi_1\right|^2 n_t \partial s \ldots\ldots\ldots\ldots\ldots(3)$$

Cm is the added mass coefficient, Cd is the drag coefficient, V_n the relative normal velocity and $\vec{\tau}$ is a unit vector along the n-axis. a and V are respectively wave particle acceleration and velocity and r_s is strucure velocity.The tangential force can be determined by integrating the hydrodynamic pressure on the bottom surface. ϑ_1 is the firdt potential of incident waves.

In time domain using numerical integration technique the equation of motion can be solved, incorporating all the time dependent nonlinearities, stiffness coefficient changes due to mooring line tension with time, added mass from Morison equation, and with evaluation of wave forces at the instantaneous displaced position of the structure. At each step, the force vector is updated to take into account the change in the mooring line tension. The equation of motion is solved by an iterative procedure using unconditionally stable Newmark Beta method and this is programmed using MATLAB.

III. APPLICATION

The methodology presented above has been applied to determine the motions of a large diameter spar geometry which is being studied in the JIP. The particulars of this spar are given in Table 1. Different environmental conditions as outlined in Table 2. have been used to study the response.

IV. RESULTS AND DISCUSSION

The responses of the spar platform in regular waves have been determined first. All response results presented in this study are at the C.G. of the spar. Experimental and numerical results for this paper under similar conditions are presented by Mekha et al. [5], for platform motions measured at 55m above SWL. These experimental results can be compared with numerical results of this study, although the numerical results are not produced here. Figs. 2 and 3 show the surge and heave responses in LC1 case. These responses do not appear to be affected by the method chosen for estimating particle kinematics. Linear Airy theory, Weeler and Chakrabarti stretching formulas are giving identical results. The same trend have been seen in pitch response (Fig. 4) also. However, there is a reduction in pitch amplitude when wave kinematics are computed only up to the SWL. Figs. 5 and 6 show the surge and heave responses in the case of regular waves and current. Once again, all the three methods predict identical response. The pitch response in the presence of regular waves and uniform current is shown in Fig. 7. It is seen that Weeler and Chakrabarti stretching formulas predict reduced pitch amplitude compare to Fig. 4 which is expected. The Linear theory also predicts lower amplitude of pitch motion which indicates that free surface force integration affects pitch motion more than surge and heave responses. Considering the above mentioned differences between the experimental results and our numerical results, the results appear to be in reasonably good agreement, qualitatively as well as quantitatively, with experimental results and predictions based on different numerical models.

JONSWAP spectrum is used for wave simulation in the case of random waves LC3 because it is more versatile and represents the spectral peaks better than PM spectrum. RAO for surge, heave and pitch, in (LC3), responses are shown in figs.8, 9 and 10 respectively.

V. CONCLUSION

The nonlinear responses of a spar platform under different environmental conditions such as regular, random waves and current have been determined using a time-domain simulation model. The model can consider several non-linear effects and the complete non-linear rigid body equations of motion are solved in the time domain. Hydrodynamic forces and moments are computed using Morison equation combined with accurate prediction of wave particle kinematics and force calculations in the displaced position of the platform give reliable prediction of platform responses.

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TABLE I.

MAIN PARTICULARS OF JIP SPAR

Diameter	40.54 m
Draft	198.12 m
Mass (with entrapped water)	2.592x10^8 kg
Radius of gyration (pitch)	62.33 m
Center of gravity (from SWL)	- 105.98 m
Mooring line stiffness (0-13.7m offset)	191 KN/m
Mooring line stiffness (>13.7m offset)	406 KN/m

Table II.

ENVIRONMENTAL CONDITIONS

Case	Description
LC1	Regular waves, H=6 m, T=14s, No current.
LC2	Regular waves, H=6m, T=14s, Uniform current, 0.5 m/s.
LC3	Random waves, Hs=13m, To=14s

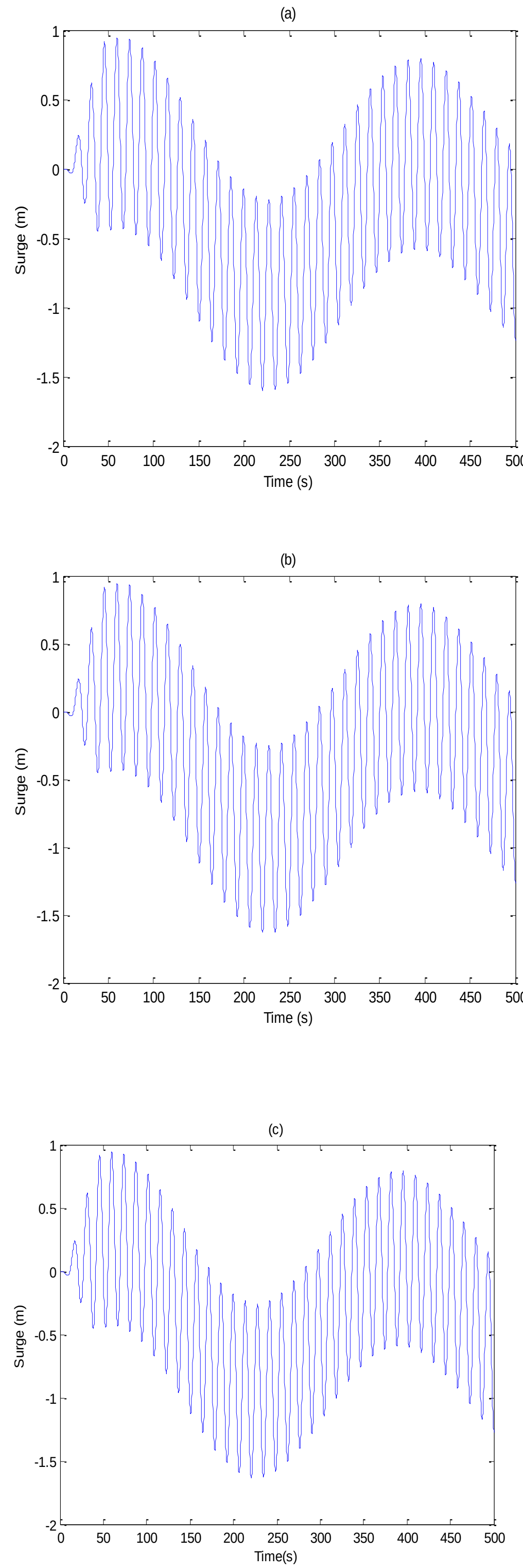

Figure 2. Surge response in regular waves (LC1)
(a)Linear Airy Wave Theory
(b)Wheeler Stretching
(c) Chakrabarti Stretching

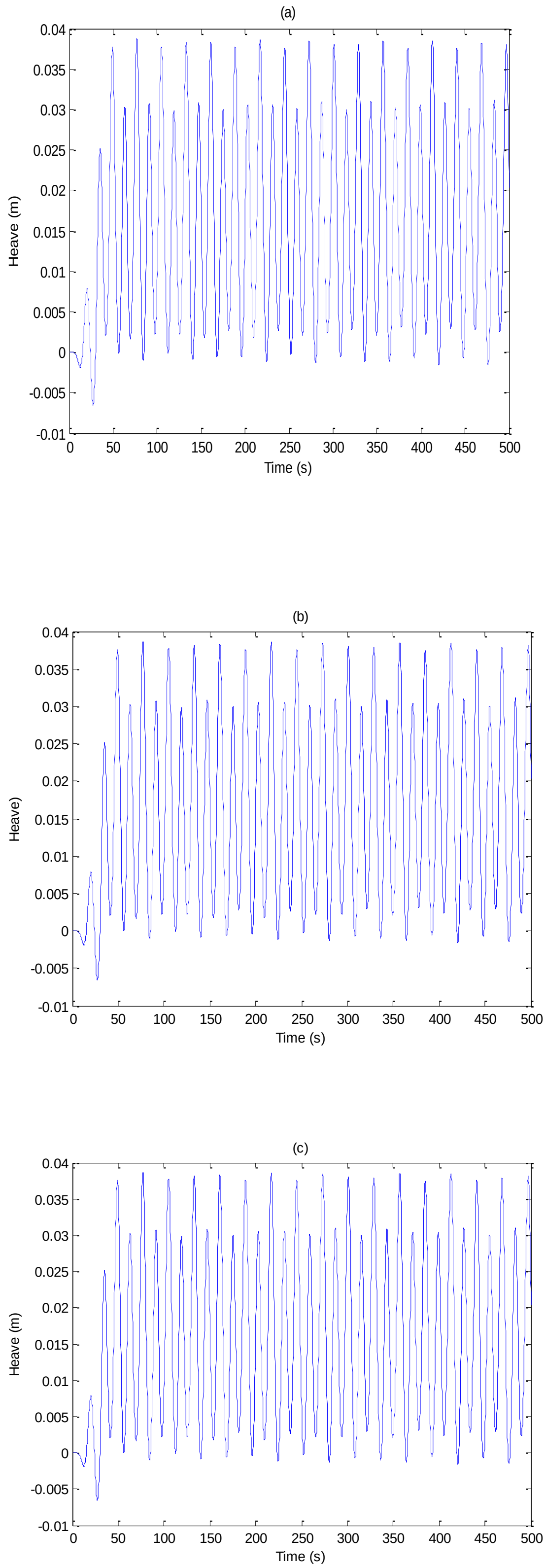

Figure. 3 Heave response in regular waves (LC1)
(a)Linear Airy Wave Theory
(b)Wheeler Stretching
(c) Chakrabarti Stretching

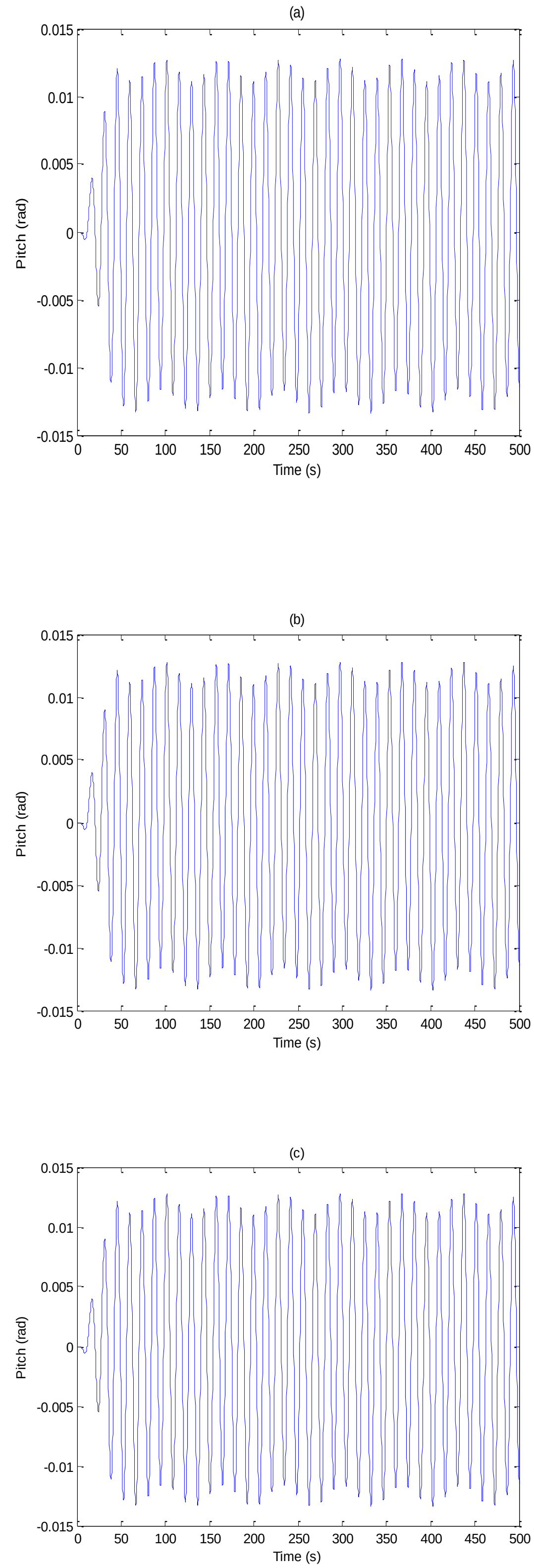

Figure. 4 Pitch response in regular waves (LC1)
(a)Linear Airy Wave Theory
(b)Wheeler Stretching
(c) Chakrabarti Stretching

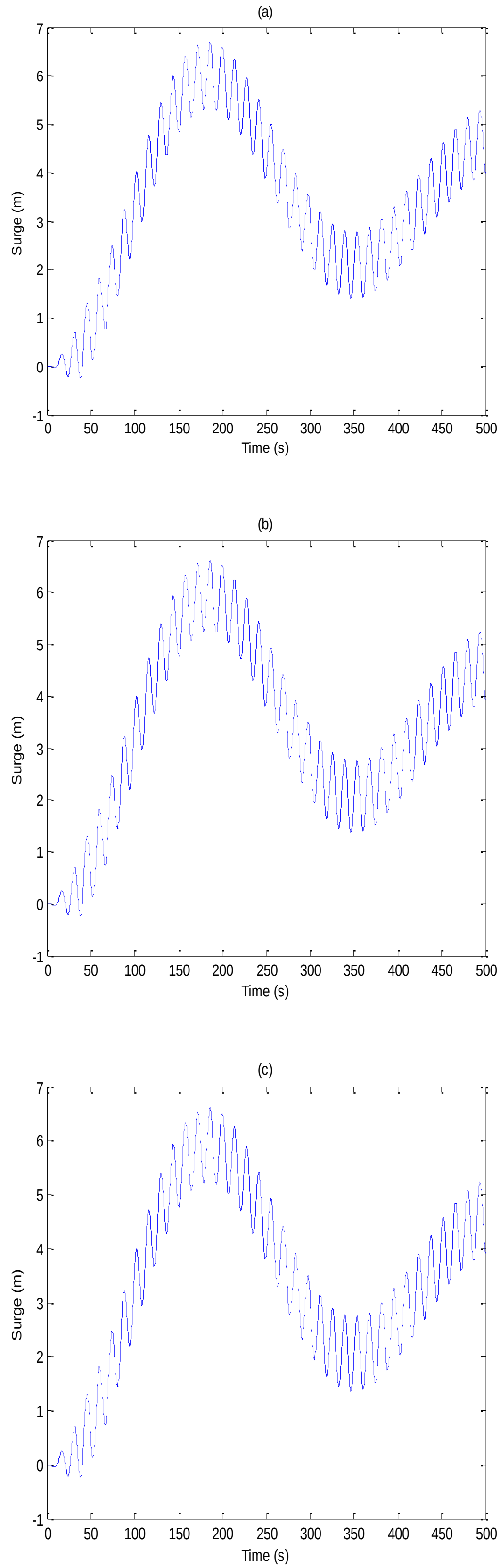

Figure. 5 Surge response in regular waves (LC2)
(a)Linear Airy Wave Theory
(b)Wheeler Stretching
(c) Chakrabarti Stretching

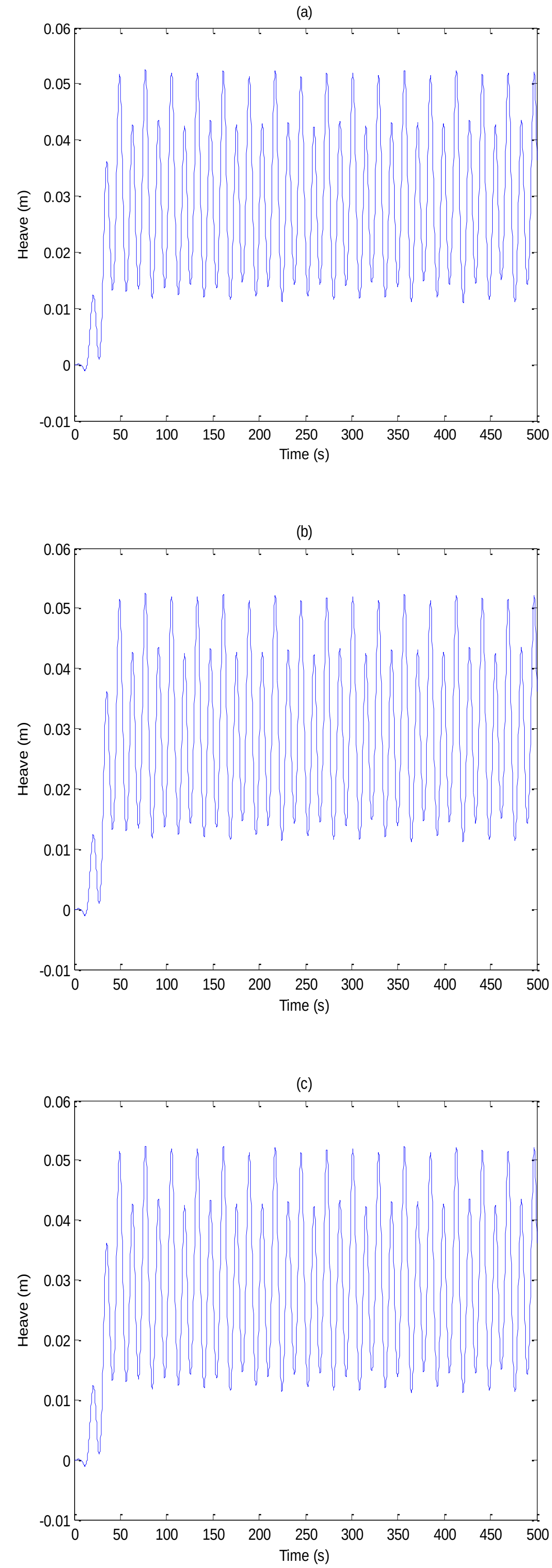

Figure. 6 Heave response in regular waves (LC2
(a)Linear Airy Wave Theory
(b)Wheeler Stretching
(c) Chakrabarti Stretching

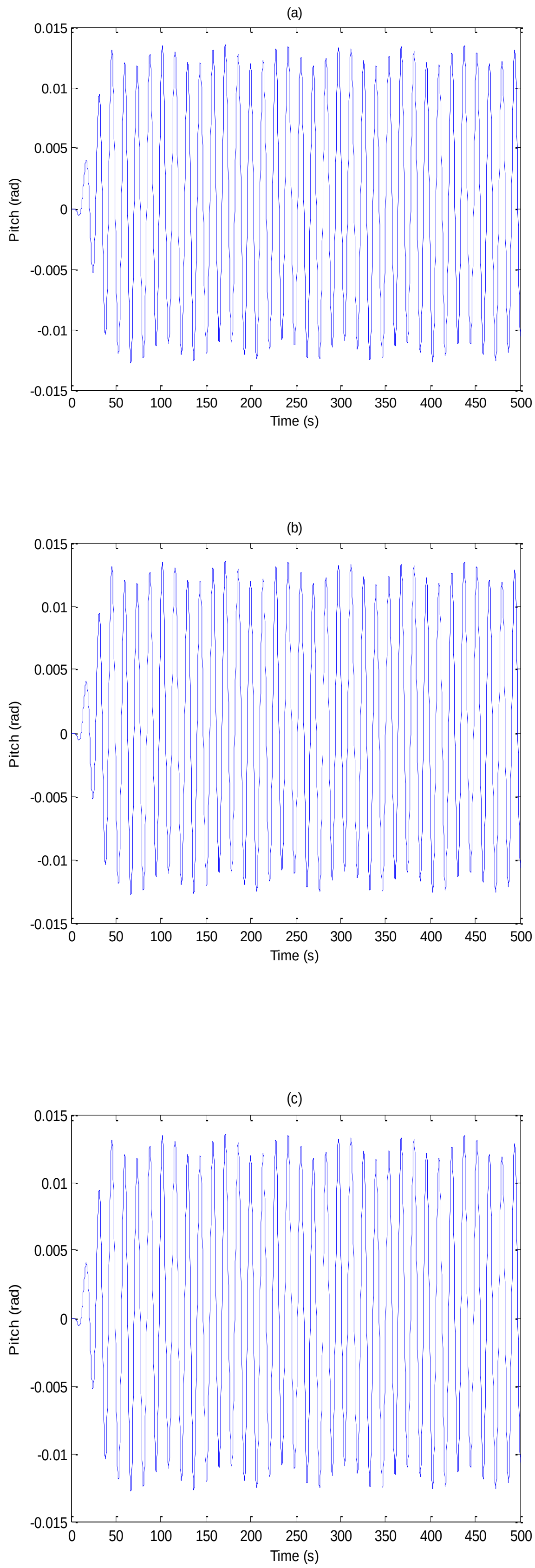

Figure. 7 Pitch response in regular waves (LC2)
a)Linear Airy Wave Theory
(b)Wheeler Stretching
(c) Chakrabarti Stretching

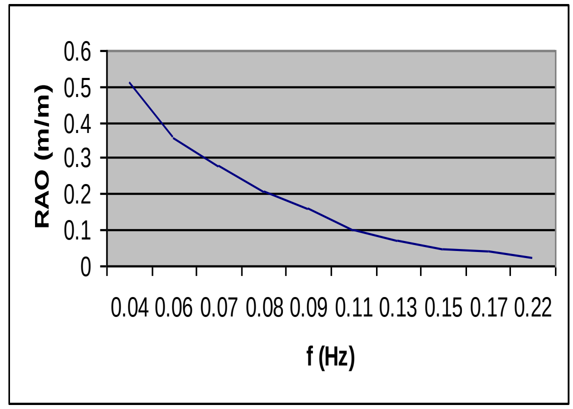

Figure. 8 RAO Surge in random waves (LC3)

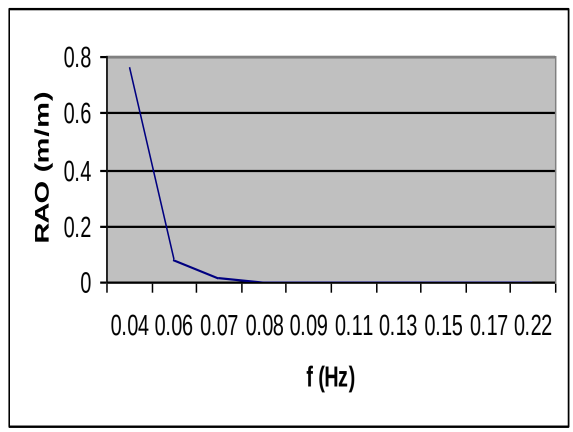

Figure. 9 RAO Heave in random waves (LC3)

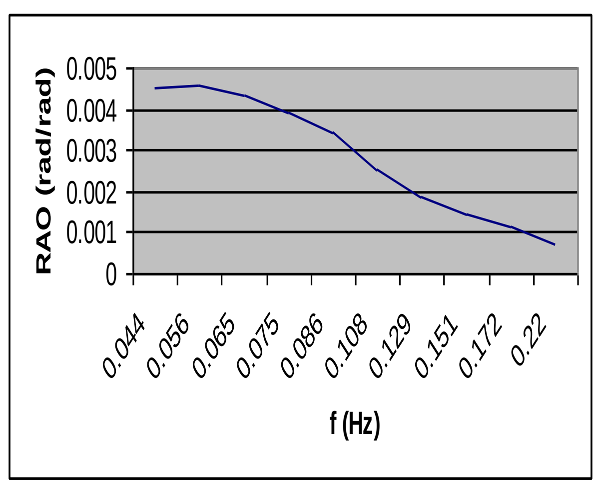

Figure.10 RAO Pitch in random waves (LC3)