TOWARDS A UNIFIED 6 DOF MANOEUVRING MODEL IN RANDOM SEAS

Z. AYAZ, D. VASSALOS[*1], K. J. SPYROU[*2] & A. MATSUDA[*3]
*1 University of Strathclyde, 48 Colville Building, North Portland Street, Glasgow, G1 1XN
zafer.ayaz@na-me.ac.uk, d.vassalos@na-me.ac.uk
*2 National Technical University of Athens, Department of Naval Architecture and Marine Engineering, 9 Iroon Polytechniou, Zogrophou, Athens 15773, Greece
spyrou@deslab.ntua.gr
*3 National Research Institute of Fisheries Engineering, Ebidai, Hasaki, 314-0421, JAPAN
amtsuda@fra.affrc.go.jp

SUMMARY

This paper presents a research study addressing the development of an improved coupled non-linear 6-DOF model with frequency dependent coefficients, incorporating memory effects in random waves with a new axis system that allows straightforward combination between seakeeping and manoeuvring models whilst accounting for extreme motions. In order to provide feedback for the development of a numerical model, following theoretical work, extensive captive and free running model experiments were carried out at the National Research Institute of Fisheries Engineering (NRIFE), Japan for 712 tonnes Japanese Purse Seiner which operates in the East China Sea and for which extensive seakeeping and manoeuvring data has been collated as part of ITTC Benchmark tests.

NOMENCLATURE

a	Wave height (metre)
g	Gravity acceleration
T_φ	Roll period
δ	Rudder angle
λ	Wave length
ϕ	Heel angle
χ	Heading angle
ω, ωe	Wave frequency, frequency of encounter

1. INTRODUCTION

Current methodologies often calculate vertical motions tracing the vertical static equilibrium position of a ship. This allows the mathematical model to be reduced to 4 degrees-of-freedom. However, extreme pitch and heave motions can drastically change the instantaneous wetted surface. Furthermore, since the frequency of encounter in following seas is quite low, it is currently quite common to use “zero-frequency” constant hydrodynamic coefficients, as it is done in calm-water manoeuvring calculations. However, wave effects associated with the unsteady motion of the hull at the free surface and vortices which are shed from the oscillating hull, especially when a ship has very large heading angle, indicates that the convolution terms (representing the so-called “memory effects”) may not necessarily be negligible. Also, even though dangerous conditions that occur in astern random seas are relatively well known in a deterministic environment, there is scope for improving understanding also for such mechanisms in irregular waves. The essentials of this model were outlined in [*Ayaz et al. (2001)*].

To this end, the model experiments programme proceeded as follows: captive model experiments were carried out in order to observe the manoeuvring and course-keeping behaviour of the vessel in large vertical motions while considering the coupling between vertical and horizontal motions and the effect of frequency. The experiments carried out for different speeds, heading angles, sinkage, trim angles and, for some cases different wave steepness. Wave forces and moments in 6 DOF and position of the ship on the wave have been recorded. In the second stage of experimental studies, free running model experiments were carried out. The aim was to obtain experimental evidence about the possible dangerous situations such as parametric rolling and broaching-to in narrow- and broad-banded random seas. Therefore, model experiments were carried out for different heading angles and Froude numbers using ITTC and JONSWAP spectra. The extremity of the conditions investigated in NRIFE was defined according to the limits of the model basin.

Within the above framework the paper presents descriptions of the numerical model and model experiments, particulars of the model, test matrix, instrumentation and all other details regarding the experimental programme. These are followed by presentation of model run simulations on the basis of which conclusions are drawn and recommendations made.

2. NUMERICAL MODEL

Traditionally in both manoeuvring and seakeeping, hydrodynamic and inertial forces are formulated in terms of general body axes that rotate and translate with the ship. The Horizontal Body Axes, which are closely related to, but not a special case of General Body Axes, is quite a common system and it has been used in many other studies of ship manoeuvring that include roll (Chislett, 1990, Eda, 1978, and Son *et al*, 1981). Chislett (1990) also explained the use of this system for both seakeeping and manoeuvring in 4 degrees-of-freedom. Hamamoto *et al.* (1993, 1992a, b, 1994) presented the application of the system in studies of manoeuvring motion of ships in waves especially for the study of capsizing motion and the dynamic stability of ships in following and quartering seas.

In deriving the basic equations of motion, normally three different coordinate systems are used as shown in Figure 1. The first is an Earth fixed system, defined by $0-\xi\eta\zeta$.

The second is a general body axes which is fixed in the ship with the origin G being located at the centre of gravity of the ship defined by G-xyz. The third is the Horizontal body axes fixed in the ship with the origin at G and defined by G-x'y'z'.

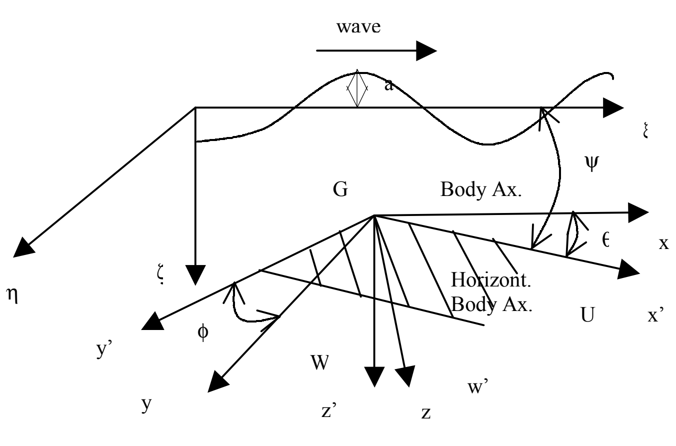


Figure 1 Systems of coordinates

Let us consider a ship moving with forward speed in waves. Newton's law of dynamics describes the equations of motion for a ship having six degrees of freedom and under the action of certain external forces. It can be formulated for translations and rotations in vector form as follows.

$$m\,(\dot{V}_G + \omega \times V_G) = X_F$$

$$\dot{H}_G + \omega \times H_G = X_M$$

Equation 1

where m is the mass of a ship, H_G the momentum about the centre of gravity, ω the angular velocity, V_G the linear velocity, X_F the external force vector and X_M the moment vector.

The terms on the right hand side of equation (1) are the external forces acting on the hull and they can be divided into hydrostatic and hydrodynamic components.

In order to describe the situation of the ship in the earth fixed axes, it is normal to use a transformation of equation (1) in terms of Eulerian angles ϕ,θ,ψ which are defined as the rotations about the body fixed axes (See Figure 1).

Instead of the general system of equations, a simpler system is used where only one rotation about the absolutely vertical axis is considered and this is called here the horizontal body axes, G-x'y'z' in Figure 1.

In order to derive the equations of motion in a practical form some approximations are necessary. Firstly, because of symmetry and because the origin is located at the centre of gravity, it is assumed that $I_{yz}=0$, $I_{xy}=0$, $I_{xz}=0$ and in the horizontal system $I_{yy} \cong I_{zz}$. However, in order to simplify these equations the following expressions are used. Substituting P for $\dot{\Phi}$, Q for $\dot{\Theta}$ and R for $\dot{\Psi}$ the equations of motion become

$$\begin{aligned} m(\dot{U} - VR) &= X' \\ m(\dot{V} + UR) &= Y' \\ m\dot{W} &= Z' + mg \end{aligned}$$

Equation 2

$$K' = (I_{yy} - I_{xx})[\sin 2\theta\,(QP + \frac{1}{2}\dot{R}) + \cos 2\theta\, QR]$$
$$+ (I_{xx}\cos^2\theta + I_{yy}\sin^2\theta)\,\dot{P} - I_{yy}RQ$$
$$M' = (I_{yy} - I_{xx})[\sin 2\theta(\frac{1}{2}R^2)]$$
$$+ (I_{xx}\cos^2\theta + \sin^2\theta)RP + I_{yy}\dot{Q}$$
$$N' = (I_{xx} - I_{zz})[\sin 2\theta\,(QR - \frac{1}{2}\dot{P}) - \cos 2\theta\, QP]$$
$$+ (I_{xx}\sin^2\theta + I_{zz}\cos^2\theta)\dot{R}$$

Equation 3

where, X', Y', Z', K', M', N' are surge, sway, heave, roll, pitch, yaw external forces and moments.

The above equations contain 12 variables. However, because of the nonlinearity of moment equations, those equations need to be solved by using some numerical method. The aforementioned variables are defined as follows:

$$\text{Variables} = (x', y', z', U, V, W, P, Q, R, \varphi, \theta, \psi, \delta, \xi)$$

Equation 4

In this study, external forces consist of wave forces, manoeuvring (hull) forces, rudder and propeller forces since they represent the most important components of the excitation. Details of the external forces and the essentials of the numerical model were given in [Ayaz et al. (2001)].

3. CAPTIVE MODEL EXPERIMENTS

The experiments was carried out in the seakeeping and manoeuvring basin named “Marin Dynamics Basin” of the National Research Institutes of Fisheries Engineering, Japan. The basin is 60 m long, 25 m wide and 3.2m deep. It has an X-Y towing carriage consisting of main sub carriages: the main carriage runs in longitudinal direction of the basin and the sub carriage on the main carriage runs in the transverse direction of the basin. The maximum velocities of the main and sub carriages are 3m/s and 1.5 m/s respectively. The basin equips an 80-segmented wave maker. The carriages and wave maker were controlled by the digital feedback system. Captive model tests, instrumentation and all other details as follows;

For these tests 2 m length (1/17.25 scale) model is used. This vessel has been tested as part of series of the benchmark tests commissioned by the ITTC Specialist Group on Stability. Test matrix and principal particulars of the model are given in Table 1 and 2. The model was equipped with rudder but without propeller and bilge keels.

H/λ	Fn	χ (deg)			Sinkage (m)			θ (deg)			ϕ (deg)	
		0	45	60	-0.2	0	0.2	-1.43	0	1.43	0	10
1/25	0.2	√				√			√		√	
	0.3	√		√		√			√		√	√
	0.4	√				√			√		√	
1/20	0.3	√	√	√	√	√	√	√	√	√	√	√
	0.4	√	√		√	√	√	√	√	√	√	√
1/15	0.3	√	√		√	√	√		√		√	
	0.4	√	√		√	√	√		√		√	

Table 1 Test matrix for λ/L=1.5, nominal GM

Parameter	Vessel	Model(1/17.5)
L_{BP}	34.50 m	2 m
B	7.60 m	0.441 m
D	3.07 m	0.178 m
d_f	2.50 m	0.145 m
d_a	2.80 m	0.162 m
C_b	0.597	0.597
Δ	425.18 t	81.08 Kg
LCG	-1.31 m	-0.076 m
KG	3.36 m	0.195 m
GM	1.0 m	0.058 m
T_φ	7.4 sec	1.9 sec

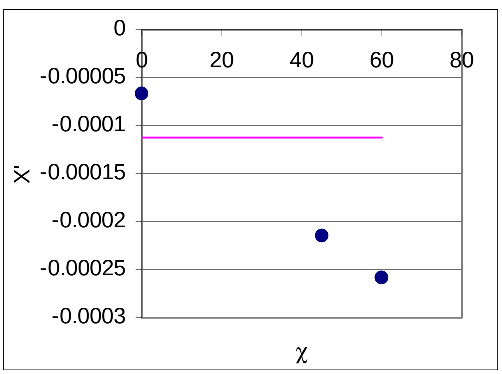
Table 2 Principal particulars of vessel and model

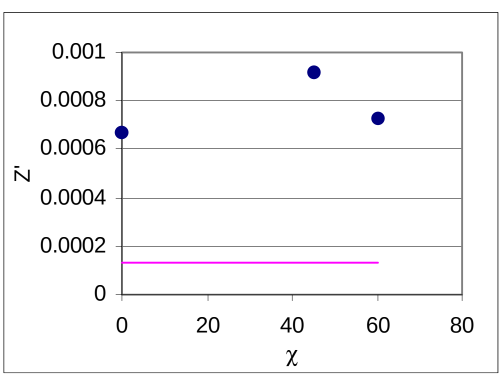
The model, which is fixed in all 6DOF, was fitted with a turning table on the sub carriage. Previously, the model is weighted and balanced with 6 components loadcell on displacement. The 6 DOF forces and moments (surge, sway, heave forces, roll, pitch and yaw moments) detected by a dynamometer, which is placed on loadcell. The centre of yaw moment is longitudinal centre of buoyancy, L.C.B., and that of the roll moment above still water surface, OG. The centres of heave and pitch are defined from the centre of X-Y axes on loadcell. A servo-needle wave probe was also fitted with the sub carriage. Based on the coordinate systems shown in Figure (1), the sign convention as follows. The positive surge force acts towards bow, the positive sway force acts starboard, the positive yaw moment induces the starboard turn, the positive roll moment results in downward movement of the starboard side and positive wave elevation indicates downwards. The positive heave force indicates towards up and the positive pitch moment aft downwards.

The relative position of centre of ship gravity to a wave trough behind the ship is non-dimensionalized with wavelength. This non-dimensional value, ξ_G/λ, of 0.0 indicates that the ship situates on wave trough; that of 0.5 indicates that the ship centre situates on the down slope of the wave. The value between 0.5 and 1.0 indicates that the ship centre situates on the down slope of the wave.

The experimental procedure is as follows. First, the wave maker generated a regular wave train propagating in the longitudinal direction of the basin. Next, combining movements of two carriages, the model was towed with a certain angle from the wave direction. Since the centre line of model had been adjusted to this towing direction, the model runs with a specified heading angle from waves but no drift angle.

Herein, non-dimensional mean value results of wave induced vertical forces and moments with respect to heading angle and wave steepness for sinkage and trim were presented in Figures 2 and 3.





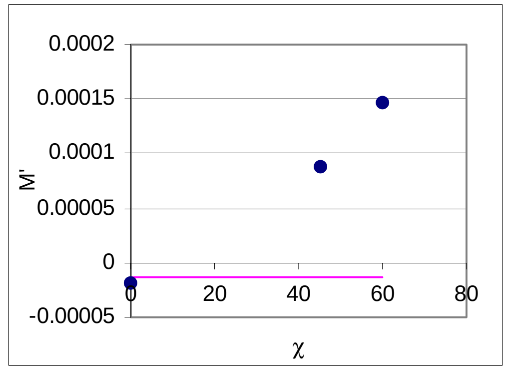
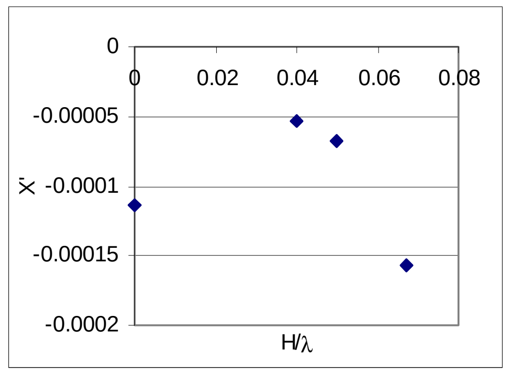
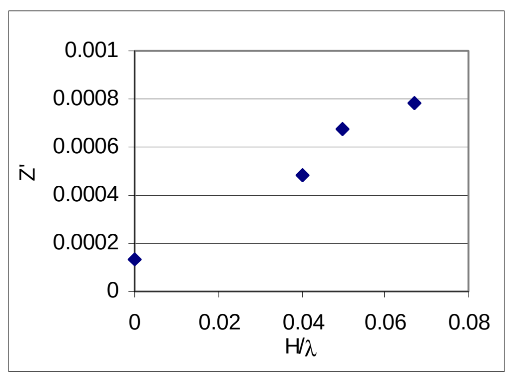


Figure 2. Wave induced forces and moments with respect to Heading angle (deg) for $H/\lambda=1/20$, Fn=0.3 and $\lambda/L=1.5$ (Line indicates the calm water mean value)





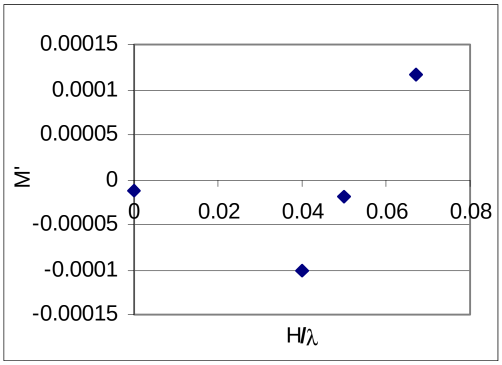


Figure 3. Wave induced forces and moments with respect to wave steepness for χ=0°, Fn=0.3 and λ/L=1.5

4. IMPULSE RESPONSE FUNCTIONS

When a body performs an irregular motion around its mean position, it is appropriate to express the hydrodynamic force acting on the body in the time domain. Following the work by Cummins (1963) and others, the radiation force in the time domain is written as:

$$F_{ij} = -a_{ij}(\infty)\dot{V}_j - \int_0^{\infty}\!\!\int K_{ij}(t)V_j(t-\tau)d\tau$$
$$i, j = 1,2,3,4,5,6$$

Equation 5

The retardation (Kernel) function of equation (5) (K_{ij}) is the real part of Fourier transform of the frequency domain damping function. In addition, the retardation can be described in terms of damping as

$$K_{ij}(t) = \frac{2}{\pi}\int_0^{\infty} B_{ij}(\omega)\cos\omega t\, d\omega$$

Equation 6

where B_{ij} is damping coefficients. These equations are standard relations in linear system theory. The impulse response function (K_{ij}) will be solved from added mass and damping data and the convolution integral (5) then evaluated for each term in the equations of motion at each time step during the simulation.

4.1. NUMERICAL SOLUTIONS OF KERNEL FUNCTIONS

To solve the Kernel functions, use is made of the Discrete Fourier transforms (DFT). The DFT is particularly suitable for describing phenomena related to a discrete time series. It can be developed from the Fourier transform of the continuing waveform samples of which are taken to form the time series. Hence, the retardation (Kernel) function for any number of sample values is written as

$$K_{ij}(t) = \sum_{n}^{N-1} B(\omega)\cos(\omega t)d\omega$$
$$0 \le n \le N-1$$

Equation 7

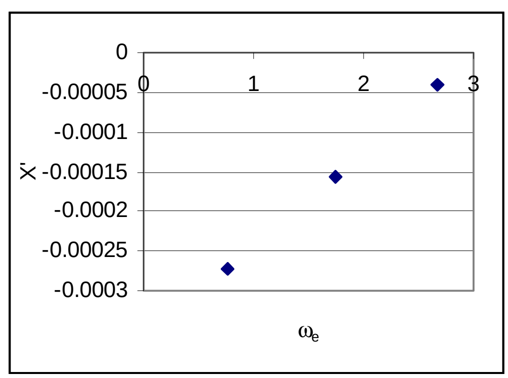
Where $B(\omega)$ is damping coefficient and $d\omega$ is frequency range. Note that the ωt expression can be written by means of general physical description as

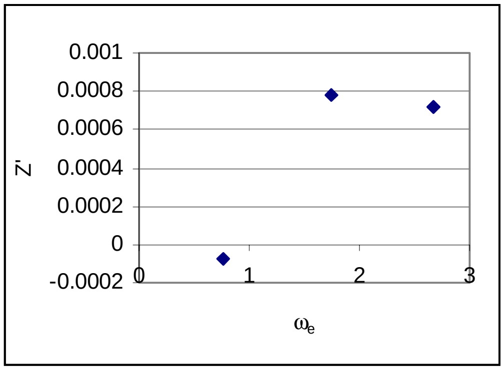
$$\omega\, t = \frac{2}{N}\pi\, n\, t(n)$$

Equation 8

where t(N) indicates the each time step.

As mentioned above, first-order convolution terms (so called "memory effects") are being incorporated that would improve the prediction of the behaviour of the vessel in non-zero frequencies of encounter. In order to see the effects, the mean values of vertical forces and moment have been plotted with respect to the frequency of encounter in Figure 4.





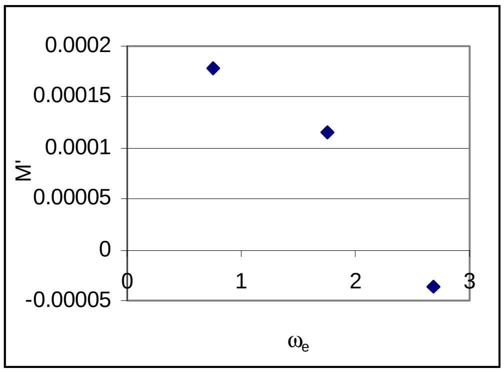


Figure 4. Vertical forces and moment with respect to the frequency of encounter for (λ/L=1.5, H/λ=1/15,ψ=0°)

5. FREE RUNNING TESTS IN RANDOM WAVES

From the free running tests point of view, the priority was to have a healthy wave spectrum to lay foundations to the numerical models in the effort of determining the boundaries of capsize. The model was run for different speeds and heading angles in both ITTC and JONSWAP wave spectrums.

For these tests 2.3 m length (1/15 scale) model is used. Its principal particulars are given in Table 2. The model was equipped with rudder, propeller and bilge keels. Model was run for two different heading angles (-5 and 45 degrees) in 3 different frequencies (3.66, 4.23, 5.18) at two different speeds (Fn=0.3 and Fn=0.4) in both ITTC and JONSWAP spectrums. Here, the some results for ITTC and JONSWAP spectrums were presented. (Figures 7-8)

Parameter	Vessel	Model (1/15)
L_{BP}	34.50 m	2.3 m
B	7.60 m	0.507 m
D	3.07 m	0.205 m
d_f	2.50 m	0.166 m
d_a	2.80 m	0.186 m
C_b	0.597	0.597
Δ	425.18 t	125.6 Kg
LCG	-1.31 m	-0.087 m
KG	3.36 m	0.224 m
GM	1.0 m	0.0667m
T_φ	7.4 sec	1.9 sec

Table 3

6. CONCLUSIONS

An improved numerical method is presented to identify dangerous situations in following and quartering seas with ships advancing in waves. In order to provide feedback in modification of the numerical program, the experiments were carried out with two main focuses. In captive model test, it was seen that the vertical motions of the model have linear characteristics in different heading angles and wave steepness despite sinkage and trim. Comparisons between the mean value of vertical forces and moment and calm water results indicate that there is a significant wave effect which might justify the relying on 6 DOF mathematical models. Also, the similar pattern has been found with respect to frequency of encounter. However it should be restated that the extremity of the conditions investigated in NRIFE was defined according to the limits of the model vessel. Therefore, the aim of “extreme conditions ” may not be reached and the some model runs seem to be remained in boundaries of linear conditions.

Currently, the incorporation of the impulse response functions and random wave motions are undertaken, as the early numerical studies indicate, that might prove more insights into 6 DOF mathematical models and effect of frequencies in regular and random waves.

7. ACKNOWLEDGMENTS

Authors would like to thank to National Institute of Fisheries Engineering of Japan for providing the model basin and equipments for experiments. Also, they would like to thank to staff at NRIFE and Dr. N. Umeda of Osaka

University for their help and contributions. It will be much appreciated.

8. REFERENCES

Ayaz, Z, Spyrou, K.J. and Vassalos, D. (2001) “An Improved Numerical Model for the Study of Controlled Ship Motions in Extreme Following and Quartering Seas”, *IFAC Conference on Control Applications in Marine Systems*, Glasgow, UK, 2001

Chislett, M.S (1990) “The Addition of A Hell-Roll Servo Mechanism to the DMI Horizontal Planar Motion Mechanism” *International Conference on Marine Simulation and Ship Manoeuvrability*, Tokyo, Japan, pp. 349-359

Cummins, W.E. (1962) “The Impulse Response Function and Ship Motions”, *Schiffstechnik*, pp. 101-109

Eda, H. (1978) “A Digital Simulation Study of Steering Control with Effects of Roll Motions” *Proceedings of 5th Ship Control Systems Symposium*, Annapolis

Hamamoto, M. and Kim, Y (1993) “A New Coordinate System and the Equations Describing Manoeuvring Motion of a Ship in Waves” *Journal of the Society of Naval Architectures of Japan*, **173**

Hamamoto, M. and Kim, Y. (1992a) “Study on Ship Motions and Capsizing in Following Waves (Final Report)” *Proceedings of Journal of Naval Architects*, Japan

Hamamoto, M. and Saito, K. (1992b), “Time Domain Analysis of Ship Motions in Following Waves”, *11th. Australasian Fluid Mechanics Conference*, University of Tasmania, Hobart, Australia, pp. 355-358

Hamamoto, M. Fujino, M and Kim, Y.S (1994) “Dynamic Stability of A Ship in Ouartering Seas” *Proceedings of Stabitility’94*, Melbourne, Florida, USA

Son, K.H and Nomoto, K. (1981) “On the Coupled Motion of Steering and Rolling of a High Speed Container Ship” *Proceedings of Journal of Naval Architects*, Japan, **150**, pp. 73-83

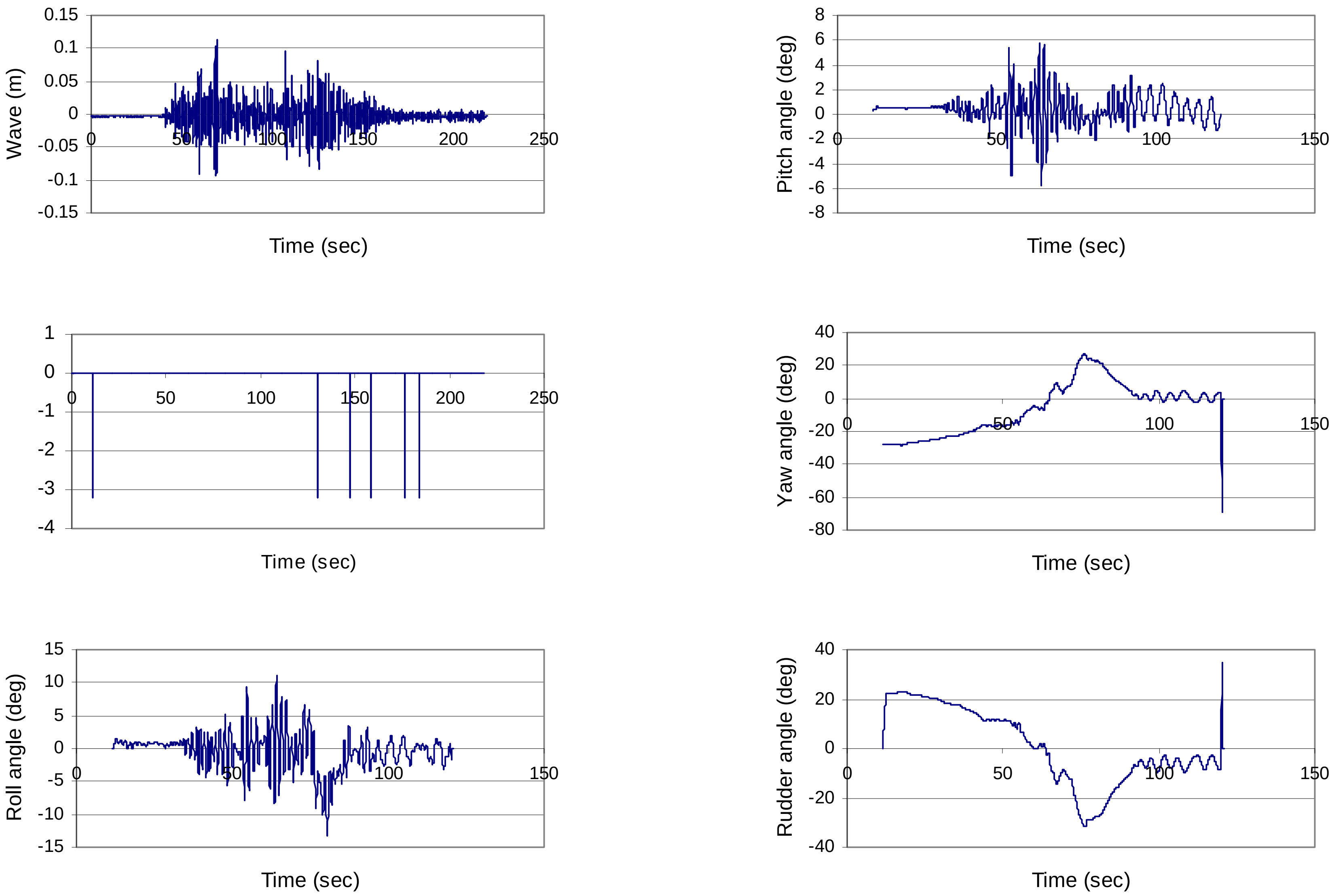


Figure 5 JONSWAP, χ=-5 degrees, Fn=0.3, H/λ=1/20

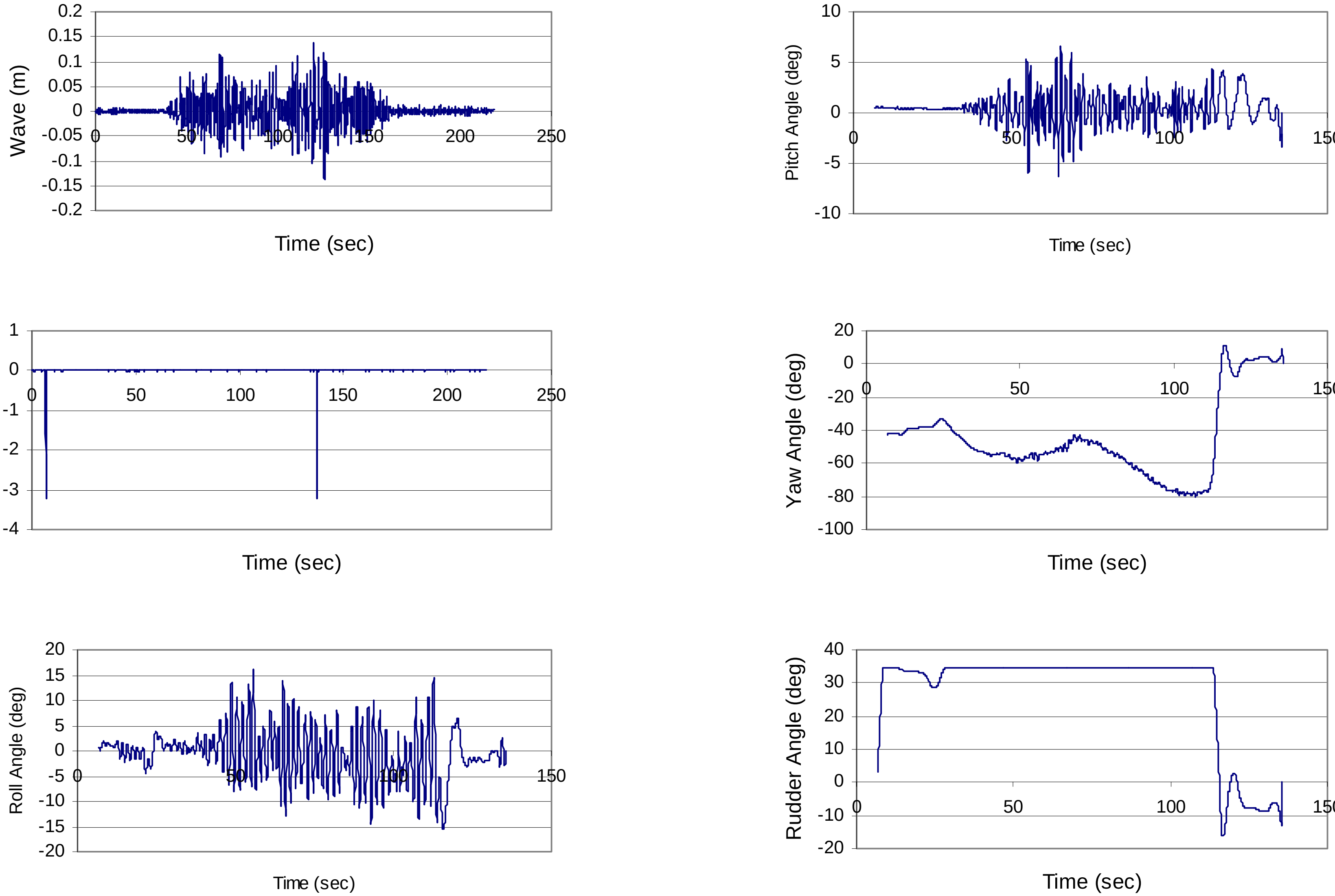


Figure 6 JONSWAP, χ=-5 (deg), Fn=0.3, H/λ=1/20