NUMERICAL INVESTIGATION OF SHIP'S UNCOUPLED ROLL, HEAVE AND PITCH MOTION IN IRREGULAR SEA

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Abstract— The mathematical modeling of uncoupled motions of a ship is described in this paper. The dynamics of ships in extreme waves include strong nonlinearities, transient effects, and some additional physical phenomena, which may lead to a ship capsize. It is quite often that roll motion is treated as a single degree-of-freedom (DOF) dynamic problem, whereas heave and pitch are solved in a coupled two degree of freedom system. The analysis and investigation of resonance due to ship motion in wave is important with respect to the vessels stability in the beginning of design stages. In this paper, a mathematical model has been developed with the aim to describe the behavior of uncoupled pitch, heave motion and roll motions of a ship when the influences of irregular waves are dominant. There will be a great effort if the prediction instrument has been validated to a great extent by model experiments for a ship in irregular waves. Time-domain simulations are performed for ship at different encounter frequencies. The dynamic effect in wave and parametric resonance are investigated using analytical treatment to obtain roll, pitch and heave motions. In the future the experimental studies demonstrate that the motion of ship in wave acting on the concept ship is a tug.

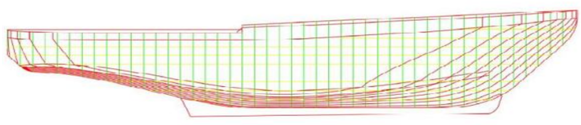
Keywords—Uncoupled Motion, Roll Amplitude, Irregular Sea Wave, Dynamic Stability and Capsizing Probability.

I. INTRODUCTION

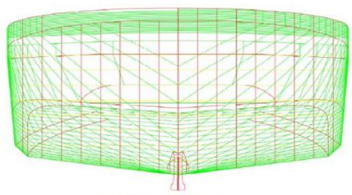
The dynamic identification of ship behavior in extreme waves can be achieved, if for any set of environmental conditions, the composition of externally exerted forces and the corresponding ship response are fully identified. The development of deeper understanding about the dynamics of ship motion and the factors that affect ship stability should be of crucial importance for the maritime community. The primary objective of this research is the modeling of the uncoupled and coupled motion in waves and the development of a reliable procedure for the assessment of stability of intact ships. Roll motion is the most important phenomenon for ship, coupled with a few others, which may lead to capsizing. An accurate assessment of ship motions under waves is considered as an important aspect in ship design. However, it is most difficult parameter to estimate because of its complex nature.. The coupling motions of heave, pitch and roll have been discovered from both experimental observations and theoretical simulations. In the analysis of ship motion in wave and the interaction between ship and fluid, neither model testing nor pure theoretical modelling alone could
provide a reliable prediction of strongly non-linear and transient phenomena involved in ship capsizing. Numerical simulations and model testing are complementary and feed each other. There are several different efforts on motion of ship or floating body in wave research and analysis. S. Grochowalski(2000) carry out experimental investigation of ship dynamics in extreme waves. His significant work is a combination of computer simulations with model experiments is investigating transient and strongly nonlinear phenomena of ship behavior in extreme waves. A study on capsizing phenomena of a ship in waves was presented by S. Y. Hong (1994). Simulation models have been developed to investigate the role of nonlinearity of righting moment in waves, and focus on the accurate estimation of righting moment in waves. Marcelo A.S. Neves(2009) emphasized that a coupled non-linear mathematical model of parametric resonance of ships in head seas. A derivative mathematical model was introduced, in which the heave, roll and pitch motions and wave passage effects were described with coupling terms up to the third order. Leo Dostal(2013) reported on Stochastic averaging of roll-pitch and roll-heave motion in random seas. The approximate probability density can be used in the design process of a ship to optimize its stability. Wave characteristics are the most important parameter in roll motion equation. But it is the most difficult parameter to estimate because of its complex nature. There are several different efforts on roll motion of ship or floating body research and analysis [7]. The works of roll motion of floating body or naval vessels were presented by Himeno (1981) analyzed many aspects of roll damping by conducting a series of model experiments towards better understanding of roll damping [12]. Jianbo Hua and Wei-Hui Wang (2001) the parametrically excited roll motion of a RoRo-ship in irregular following waves [11]. In their analysis the nonlinear parametric excitation is approached by a Volterra system and Monte-Carlo simulations are used to analyze the two most probable roll modes of a RoRo-ship due to the parametric excitation. In the recent past, a considerable amount of research has been carried out to obtain roll motions in time domain and also in frequency domain by applying various solution techniques [2]. So far, the knowledge and contributions about the motion of naval vessel on the effect of irregular following waves have widely been achieved. However, there might be a need to deeper understanding of the ship response to the sea wave at a

local level. Therefore, in the present study, a mathematical model of roll motion for single degree of freedom is constructed for obtaining the behavior of Tug boat in regular wave assuming the system is linear.

II. SELECTION OF THE SPECIFIC SHIP



(a)Half-breadth or Waterline Plan of Tug



(b) Body Plan

Figure (1) Line Drawing of 1000 HP Twin Screw Tug Boat

The numerical analysis was carried out to find the behaviour of the vessels response in wave. This helps in optimizing the vessel design from the view of vessel safety. For this purpose, it was decided to select one vessel and carry out a dynamic stability analysis for a number of different conditions. The 1000 HP screw Tug was chosen. The basic parameter of the Tug is shown below including GM metacentric height, LCB longitudinal center of buoyancy and LCF Longitudinal center of floatation

Table 1. Hydrodynamics Characteristics of Tug [5]

Particulars	Unit	Value
Length between Perpendicular, Lpp	m	29
Breath, B	m	8
Draught, T	m	5.5
Draft, t	m	2.643
Volume, V	m3	222.04
Displacement, Δ	tons	227.10
GM	m	1.093
LCF	m	12.078
LCB	m	13.688

The vessel is chosen for analysis has a length to breadth ratio approximately 3.6. Because of the length to breadth ratio is large, she is very sensitive toward motion in wave and may capsize quickly when encountering a moderate height beam waves. The hull form of a studied Tug is shown in Fig.1. The main particulars are shown in table 1.

Ship motions are described as an object with respect to six degrees of freedom in translation and rotation as figure 1. It is included includes surge, sway and heave and the rotation movement includes roll (heel), pitch (trim) and yaw. In the actual operation condition, ship motions have a complicated relationship. However, ship motions can be split into two categories. The first category consists of pitch, heave and roll influenced by sea waves and the second category consists of surge, sway and yaw produced by propeller force, rudder, current and wind.

III. MATHEMATICAL FORMULATION

The developed mathematical model can be used as a tool of an assessment methodology of ship stability. Ship motions in waves are often described with a six degrees-of-freedom model as three-dimensional motions of a rigid body. When establishing the ship motion equations, Newton's Second Law of Motion may be used as a basic. In general, a ship's equations of motion might appear as

$$(M)\ddot{\eta} = \sum F \qquad (1)$$

where, M is the mass of the ship, $\ddot{\eta}$ is the acceleration of the ship, for $n = \frac{b}{2i^2}$, and $\sum F$ is the sum of all applied forces from waves. The task now is t o identify the forces on the ship.
The equation for the roll angle, η4:

$$\frac{d^2\eta_4}{dt^2} + 2n\frac{d\eta_4}{dt} + \omega_{n4}^2\eta_4 = \frac{2\pi\xi_0}{\lambda}\sin(\omega_\omega t - \pi/2) \qquad (2)$$

For small angles and with the definition of the radius of gyration, i, the linear equation of rolling in beam seas becomes, As an approximation the roll inertia can be described as the total vessel mass times the square of an ideal distance called radius of gyration. This can be estimated by carrying out rolling experiments. It is also customary that, the radius of gyration for roll (im) is expressed as a percentage of the vessel's breadth i.e.

$$i_m = C\,B \qquad (3)$$

The coefficient for radius gyration (C) value is almost constant for a great variety of vessel types: values: large cargo and passenger vessels, 0.85; small cargo and passenger vessels, 0.77; tugs, 0.76; wide barges, 0.79.
The equation of the uncoupled heave motion has been developed as shown below. The assumptions are required to get that the wavelength is large compared to the dimensions of the water plane. This analogy holds only for the form of the governing equations.

$$(m + A_{33})\ddot{\eta}_3 + b\dot{\eta}_3 + \rho g A_w \eta_3 = \rho g A_w \zeta_0 \cos\omega_E t \qquad (4)$$

Equations for uncoupled pitch motion can

$$\frac{d^2\eta_5}{dt^2} + \frac{g\,\overline{GM}}{i_{55}^2}\eta_5 - \frac{g\,\overline{GM}}{i_{55}^2}\gamma\sin\frac{2\pi t}{T_E} = 0 \qquad (5)$$

where i55 is the radius of inertia of the ship mass about the Oy-axis, γ is the maximum pitch amplitude, and TE is the period of encounter.

$$\omega_E = \frac{2\pi}{T_E} \qquad (6)$$

These systems of second order non-linear equation given above are solved in the time domain using the Runge-Kutta Fourth Order numerical integration techniques. RK4 can solve most of ODE with better numerical stability of equations and any others ODE solvers are not utilized in this paper. In order to solve a non-linear second order (or higher order) ordinary differential equation system, a system of ordinary differential equations has to be written in first form. In order to solve the above equations a number of boundary conditions which is equal to the number of equations in the system are also required. These initial values are the initial displacements and velocities of the ship motions. Matlab has seven ODE solvers available for different numerical schemes. The Runge–Kutta fifth order one-step solver (Matlab ODE45), the Adams-Bashforth-Moulton multistep solver (Matlab ODE113), and the ODE solver based on the numerical, backward differentiation formulas (Matlab ODE15s), and the delay differential equation solver (dde23) were used to compute the best time domain solution and are tested for the above criteria.

IV. RESULTS AND DISCUSSION

After driving all the governing equations for every motion of the vessel and obtaining all the derivative coefficients of equations for a given hull, numerical simulations for the motions may be performed. Results are given below for a 1000 HP Twin Screw Tug. Figures 2 to 11 shows that the simulations of heave, roll and pitch motions as the ship motion in wave.

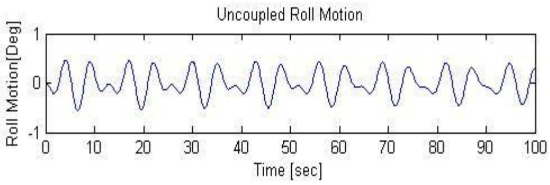


Figure (2) Roll Motion with time

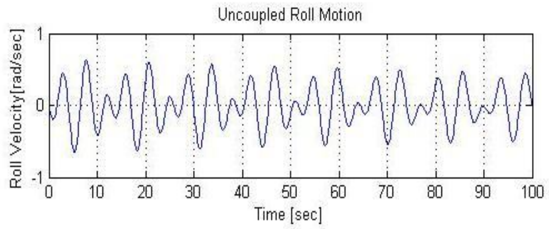


Figure (3) Roll Velocity with time

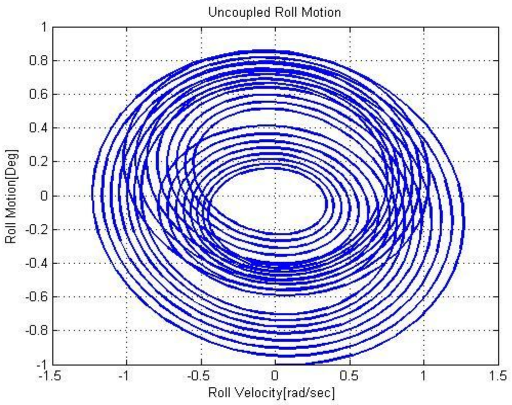


Figure (4) Roll motion with roll velocity

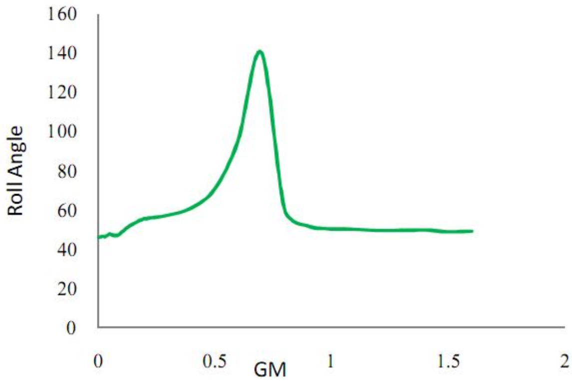


Figure (5) GM variation roll motion

From Figure 2 to 5, the safe and comfort conditions of the vessel in roll motion are determined. Since roll motion has a large influence on ship motion and rolling motion that leads to capsize even on small wave height. The safe condition is assumed when the time to capsize is reached within short period of 100 seconds (5 minutes) or less. Safe and unsafe conditions are determined by varying either the KG or wave height and observing the capsizing developed with respect to time. Based on these observations, Figure above are shown safe / unsafe conditions through a plot of KG against wave height.

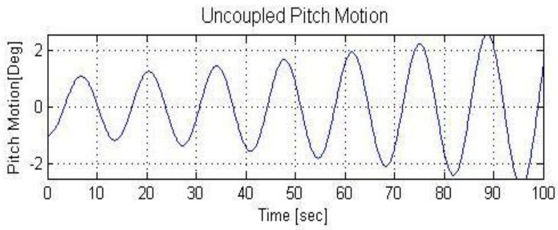


Figure (6) Pitch Angular velocity with time

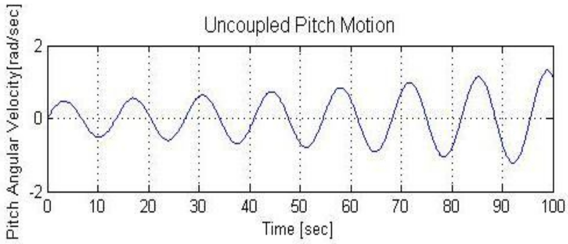


Figure (7) Pitch angle with time

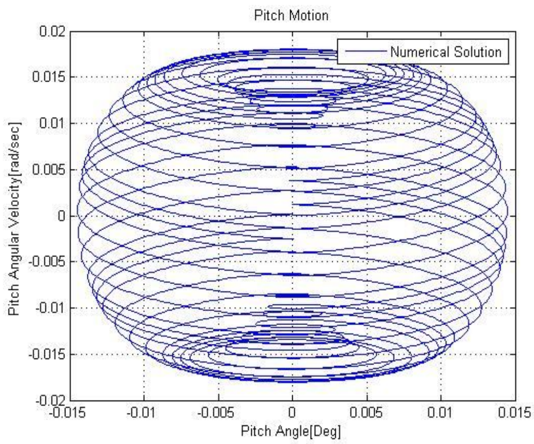


Figure (8) Pitch Velocity with time

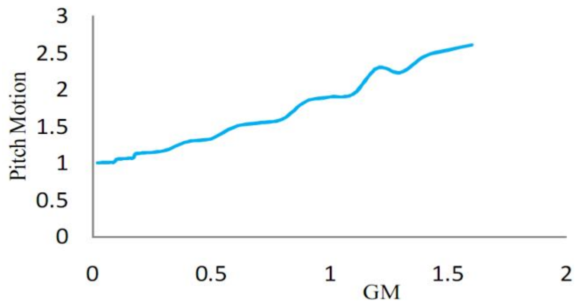


Figure (9) GM variation in pitch motion

The behavior of ship in pitching motion can be expressed in the figure (6), (7), (8) and (9). Compared to the plots where the roll motion occurred, the pitching have been increased these plots show totally different behavior. And also with change of the pitch angle, the increase in GM can be seen as shown in figure (9).

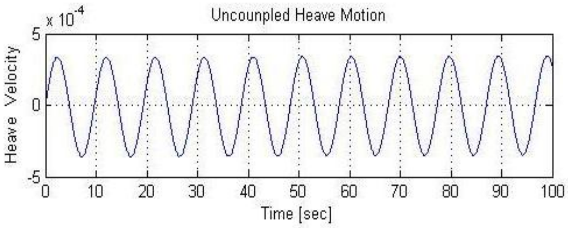


Figure (10) Heave velocity with time

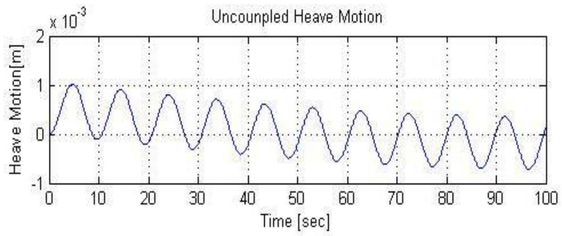


Figure (11) Heave Motion in time

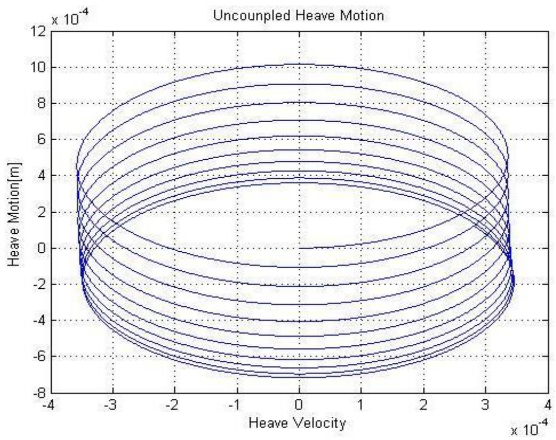


Figure (12) Heave Motion in time

The ship in heaving motion can be expressed in the figure (10), (11) and (12). The condition of ship in heave motion can be seen that it response fewer and decreasing heaving motion with the time as it may be affected on the speed of the ship when they are passing through the heavy sea condition.

The differences in motions are shown with the different KG and wave height values. From the results, it can be easily seen that safer conditions can be achieved with lowering the GM and wave height.

CONCLUSIONS

A time domain simulation, which is able to take into account the non-linear effect between the motions is utilised to solve the problem of stability of vessel in dynamic condition. Since the study is concentrated on the situation when amplitude of wave and ship motions in irregular seas, it also need accurate computation of ship response becomes important. The results obtained from the derivative mathematical model were for the roll, pitch and heave motions and wave effects. They are obtained by solving in the time domain using the Runge-Kutta Fourth Order numerical integration method. The numerical result of the studied ship shows that the parametric excitation has to be taken into account for the assessment of the ship motion behavior. From the numerical simulation results, the conditions of ship in dynamic behavior mainly depend on roll motion compared to heave and pitch. And there can be determined capsizing probability of the vessel.
It is highly recommended that the analysis of dynamic and motion of ship in wave can be optimized by using numerical and simulation tools. But it should be considered and checked more carefully with experimental methods. Dynamic condition and motions in coupled will be performed as a part of the future work with collaboration in Workbench CFX.

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NOMENCLATURE

Aij Added-mass coefficients
Aw Water plane area of the ship
B Breath of ship

b Damping coefficients
C Constant for variety of vessel types
Fj Exciting force/moment
G CG position of floating body
$\overline{GM}$ Metacentric height
ijk Moment of inertia
LCB Longitudinal center of buoyancy
LCF Longitudinal center of floatation
Lpp Length between perpendicular
Mjk Mass matrix for floating body
g Gravitational acceleration
T Draught of the ship
t Time variable
V Volume of the ship
Δ Displaced volume of ship
γ The maximum pitch amplitude
η, $\dot{\eta}$, $\ddot{\eta}$ Non-dimensional displacement, velocity and acceleration
J Displacements (j = 1, 2 . . . 6 refer to surge, sway, heave, roll, pitch, and respectively)
ω_w The wave angular frequency
ω_E Encountering wave frequency for a floating body
ρ Density of water
ζ Damping factor

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