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Safety of a High Speed Passenger Ferry in Damaged Condition

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Abstract: This study describes the development of a time domain simulation to assess the dynamic behaviour of a locally designed passenger ferry in damaged and beam sea condition. The ship is a high-speed passenger ferry that has a peculiar design of high L/B ratio of more than 10. This means that it can be categorised as a slender body ship. The slender body of the ship with long compartments is very sensitive to damage stability and rolling in beam waves. The mathematical modelling for motions in beam waves has taken into consideration the progressive flooding as well as effect of water accumulation. Damage stability experiment has been done to validate the simulation results. The experiment was conducted using image processing technique. Experimental results have been found to be quite close to simulation results. Parametric investigation is carried out to identify the effect of a number of key parameters on damage stability assessment. These include the wave height and loading condition of the ship. The results of parametric investigation are presented and discussed.

Key words: High speed passenger ferry, slender body, progressive flooding, damage stability, mathematical modeling

INTRODUCTION

The safety of any ship is of paramount importance to ship designers and operators and to the regulatory bodies. For passenger ships, the consideration of safety is a complex matter as it has to be coupled with a number of conflicting factors such as the ship's mission, performance, comfort, appearance, cost and profit. The type of vessel and function influence its safety standard. Vessels built for a specific duty such as research or defense has safety as their prime concern, while for commercial vehicles it is the economic viability (Turan, 1993).

The safety standard of commercial vehicles at times conflicts with their economic viability and their operational efficiency. A compromise has to be achieved between safety and economic viability. The main concern is changes on design and regulations, results in extra cost or low operational efficiency. It is obvious that this conflict increases the potential risk of ship loses. Due to the complexity, total safety is very difficult to achieve. Therefore, improvements on the safety of ships must be practical but at the same time must offer a substantial improved standard.

A most significant problem of commercial vehicles safety is the potential accumulation of floodwater on the deck spaces in case of damage. The gradual accumulation of water strongly depends on the dynamic phenomena, especially when the ship is moving in a seaway and affects the ship's motions and the flooding mechanism, with the possible loss of stability or capsize in particular conditions are met (Papanikolaou and Spanos, 2002).

Since, the dynamic behaviour of the damaged vessel and the progression of the floodwater through the damaged vessel in a random seaway are ever changing, rendering the dynamic system highly non-linear, the technique used, of necessity, is time simulation (Vassalos *et al*., 2000). The numerical experiment considered assumes a stationary vessel beam on to the oncoming waves with progressive flooding taking place through the damage opening which could be of any shape, longitudinal and transverse extent and in any location throughout the vessel. His results showed the following effect on the survivability is damaged freeboard, subdivision, transient flooding, GM and other residual stability parameters.

An experimental research on a model of a car ferry, with bow openings in calm sea and regular head waves at

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different advance speed has been carried out by Shimizu *et al*. (2000). However, the values of water on deck in the experiments are for a model that is prevented from heeling or rolling. Testing of models representing damaged vessels exposed to rough seas has become a very important tool for investigating of problems in the field of damage stability (Schindler, 2000). An additional amount of water trapped on the Ro-Ro deck cause an increase in the mean heel of the Ro-Ro ferry. Survivability after damage can also be assessed by a Capsizing Probability considering also the effect of water shipped into the damaged region and the fluctuation restoring ability of the vessel in waves (Kambisseri and Ikeda, 2000). They revealed that severity of damage is measured by the size of damage opening while required safety depends on the value lost if the vessel sinks. A safer vessel will be the one that can survive a larger damage opening, anywhere over its hull. In impact damage, size of damage opening will be influenced by the strength of structure at the region of impact.

Another experimental and theoretical research to determine survivability of damaged Ro-Ro passenger vessels in irregular seaway were carried out (Chang and Blume, 2000). The simulation combines non-linear equations for roll and surge motions with a linear treatment of heave, pitch, sway and yaw using strip method. Transverse bulkheads are found to be a better alternative than longitudinal subdivisions with respect to survivability. However, their simulation model is capable of predicting the limit of damaged metacentric heights between safe and unsafe with respect to capsizing.

Damage stability experiments with partially flooded compartment were carried out in the early (De Kat, 2000). Experiments were conducted with a tanker model in low steepness Beam waves with different amounts of fluid inside the vessel. Meanwhile for comparison purposes, a non-linear time domain model which is capable of simulating the large amplitude motion response of an intact and damaged vessel in waves and wind. The mathematical model includes six degree-of freedom but neglects sloshing. His theoretical and experimental results showed that predicted heave motions in beam seas compare very well with measurements.

The damage that might occur to any compartment of a vessel can cause the loss of its cargo, crew and the vessel itself. Compartment damage can cause the vessel to sink, trim, heel, reduction of GM and GZ or combination of two or more of them, which could eventually lead to capsize. Therefore, it is incumbent to the designer to provide all necessary documentation to the classification society or other related/concerned authorities to prove that the vessel still has adequate minimum buoyancy and stability. Unlike intact stability, where the concern over transverse stability always outweigh the longitudinal stability, during the damage situation, both transverse and longitudinal stability need to be assessed. This is due to high possibility of forward or aft end compartment being flooded which results of excessive trim and if the damage is unsymmetrical, it also can cause the vessel to heel.

The damage stability assessment for large vessel is not adequate for small vessel. The main reason is due to the smaller reserve buoyancy and the length of compartment is relatively smaller as compared to large vessel. This reason leads the small vessel to be more sensitive to damage. As a result, a small vessel can capsize in the damaged situation even it has satisfied the damage stability criteria requirement (Samian and Maimun, 2000).

The aim of this research is to concentrate on the assessment of damage stability of small vessel. Time domain simulation approach is used to examine the vessel motions during and after flooding in order to understand the physical problems behind the capsizing phenomena. By using the results of the analysis, an approach for more realistic residual and intermediate damage stability criteria can be developed. For such an investigation the most important thing has to be studied is motion. It is common knowledge that Roll motion, which is the most important motion for the dynamic stability of vessels is normally taken into consideration when researching the capsizing especially for beam seas. The rolling motion become bigger due to asymmetry leads the vessel to heel and capsize rapidly. Parametric studies are conducted using the developed damage stability simulation program for small vessel.

It should be noted that the present study does not attempt to develop a new damage stability criteria for small vessel, but this study is to develop a methodology for assessing damage stability of small vessel using Time Domain Simulation. However, with the developed methodology for assessing damage stability of small vessel, it is believed to be very useful reference for future development of damage stability criteria.

MATHEMATICAL MODELLING

This study started in 2006 and emphased on the using of Time Domain Simulation to investigate the damage stability of small vessels in Beam Seas. Present damage stability assessment of small vessels is concerned with only residual static stability represented by residual GM, GZ and extent of damage. Frequently, small vessels can capsize or loose stability even though their stability

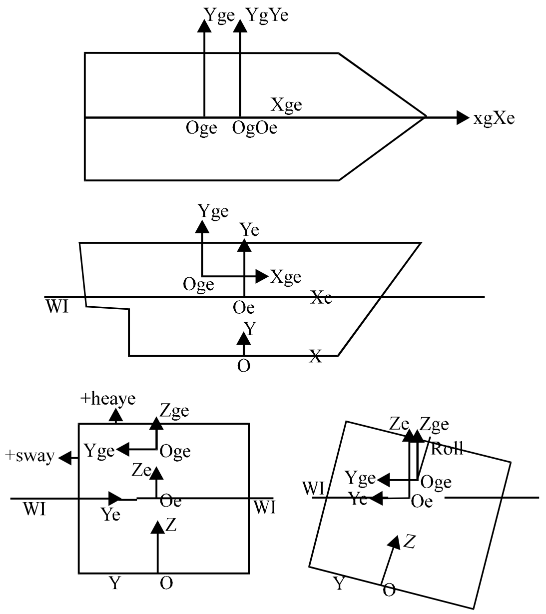

Fig. 1: Co-ordinate systems

parameters meet intact stability criteria. This proves that the small vessels could capsize in the damage situation even it has satisfied the damage stability criteria. Research carried out shows that the environmental parameters which create dynamic excitations are very dominant for any vessel and suggests that the damage stability of vessels should be considered as a dynamic problem instead of a static one.

For ease of approaching the modelling of a complex problem, such a dynamic behaviour of a damaged vessel in a realistic environment, the mathematical modelling is structured on the basis of the main contributing effects, namely hydrodynamic effect, hydrostatic effect, water flooding effect and vessel motions.

Co-ordinate system: There are three co-ordinate system are used in this research. The first is the ship co-ordinate system (O, X, Y, Z), which is used to define the ship's hull and is located at the keel level of the centre plane amidships.

The second co-ordinate system (O_ϵ, X_ϵ, Y_ϵ, Z_ϵ), the earth co-ordinate system, is used to calculate the underwater volume and parameters related to it. O_ϵ, X_ϵ, Y_ϵ, Z_ϵ is located at the calm water level of the centre plane amidships as shown in Fig. 1. When there is no heel or trim, the wave co-ordinate system has the same directions as those for the ship co-ordinate system.

The third co-ordinate system (O_{ge}, X_{ge}, Y_{ge}, Z_{ge}) is located at the centre of gravity G and the directions are parallel to the earth system. The third co-ordinate system is used to measure ship motions. Since, it is assumed that the ship rotates around the centre of gravity, all rotational motions, excitation and restoring moments are calculated with reference to it.

Motion: Since, only beam sea is considered in this research, the following non-linear coupled system of equations are four degrees of freedom; sway, heave, roll and pitch motions. The equations of motions for sway, heave, roll and pitch motions of the damaged ship are as follows:

$$\begin{aligned}&(M+A_{22})\dot{v}+(B_{22})v+(A_{23})\dot{w}+(B_{23})w+(A_{24})\\&\dot{p}+(B_{24})p+(A_{25})\dot{q}+(B_{25})q+(A_{26})r=F_{2-wave}\end{aligned} \tag{1}$$

$$\begin{aligned}&(M+A_{33})\dot{w}+(B_{33})w+C_{33}(t,z,\theta,\phi)+(A_{32})\dot{v}+(B_{32})\\&v+(A_{34})\dot{p}+(B_{34})p+(A_{35})\dot{q}+(B_{35})q=F_{3-wave}+F_{3-wod}\end{aligned} \tag{2}$$

$$\begin{aligned}&(I_{xx}+A_{44})\dot{p}+(B_{44})p+C_{44}(t,z,\theta,\phi)+(A_{42})\dot{v}+(B_{42})v+(A_{42})\\&\dot{w}+(B_{43})w+(A_{45})\dot{q}+(B_{45})q+(A_{46})\dot{r}+(B_{46})r=M_{4-wave}\end{aligned} \tag{3}$$

$$\begin{aligned}&(Iyy+A55)\dot{q}+(B55)q+C55(t,z,\theta,\phi)+(A52)\dot{v}+(B52)\\&v+(A53)\dot{w}+(B53)w+(A54)\dot{p}+(B54)p=M_{5-wave}+M_{5-wod}\end{aligned} \tag{4}$$

The solution of these equations in the time domain is carried out by using ordinary differential equation (ODE45 routines in MATLAB), based on the RUNGE-KUTTA method.

Hydrodynamic forces: Within the context of linear wave theory, the hydrodynamic oscillatory forces of a ship in waves can be represented by the linear summation of the wave excitation forces, F_W, due to wave motion and radiation forces, F_R, due to the ship's motion response. The regular wave is used to represent wave excitation forces.

The wave excitation forces can be separated into two: the Froude-Krylov forces and the diffraction forces (Faltinsen, 2005). Motion induced hydrodynamic forces (radiation) are assumed to consist of two components which are in phase with the acceleration and velocity of oscillations, the added mass and damping terms, respectively. In evaluating the above mentioned forces, the strip theory was utilized in combination with the two-dimensional wave source distribution technique known as frank-close-fit method (Frank, 1967).

The total force of the fluid motion, generated by regular waves with the stationary ship undergoing small amplitude oscillation, can be described as follows:

$$F=F_{FK}+F_D+F_R \tag{5}$$

Restoring forces and moment: These forces and moment are hydrostatic in nature with a tendency to bring the ship back to its original position after a disturbance and are related to the underwater volume of the ship. They are calculated by integrating the hydrostatic pressure up to the relative free surface (Salvensen *et al.*, 1970).

Since, only beam waves are considered in this study and the inclusion of the wave profile in the restoring calculation is not well established, hence it may lead to some inconsistency and inaccuracy, in order to include the non-linear restoring forces and moments, which result from the large amplitude motions, restoring terms are calculated instantaneously up to the calm water by taking into account the instantaneous heave, roll and pitch motions. The non-linear restoring is calculated as shown:

$$C_{32}(t, z, \theta, \phi) = g[\Delta(t, z, \theta, \phi) - \Delta(t_0)] \tag{6}$$

$$C_{44}(t, z, \theta, \phi) = g\Delta(t, z, \theta, \phi)[TCG - TCB(t, z, \theta, \phi)] \tag{7}$$

$$C_{55}(t, z, \theta, \phi) = g\Delta(t, z, \theta, \phi)[LCG - LCB(t, z, \theta, \phi)] \tag{8}$$

TIME DOMAIN SIMULATION

Damage and flooding are continuous phenomena which may lead to different results depending on the parameters used. Investigating the behaviour of ships in different conditions would certainly help to provide a better understanding of the capsizing phenomenon and to develop a realistic damage stability assessment procedure. In order to take into account non-linearities, change in excitation forces, progressive flooding and responses of ship in time, there is a need to adopt time simulation modelling (Turan, 1993).

The time simulation process starts from the beginning of flooding when the initial condition of the ship is known. At each time step, different parameters such as the amount of water inflow, heel, displacement and excitation forces and response amplitude of the ship's motions can be examined in detail. This process continues until either capsizing occurs or the total time allowed for simulation is used up.

Simple expression for time domain simulation is illustrated below (example for heave):

$$\dot{w} = \left(\frac{1}{(M_{33} + A_{33})}\right)[F_{3wave} + F_{3wod} - [B_{33}w + RES_3\ (t, z, \theta, \phi) \\ + A_{22}\dot{v} + B_{32}v + A_{34}\dot{p} + B_{34}p]] \tag{9}$$

$$z(t) = \iint_t \dot{w}(t) \tag{10}$$

The solution of these equations in the time domain is carried out by using ordinary differential equation (ODE45 routines in MATLAB), based on the RUNGE-KUTTA method.

MODELING THE DAMAGE SCENARIOS

In modelling the damage scenarios, added weight method is used. Water is added to the compartment which is assumed to be flooded. Using the intact hydrostatic values of the ship sinkage, heel and trim can be calculated for each time step when extra water is added. This method is suitable in modelling the intermediate stages of flooding as well as the flooding of compartments above the waterline.

The entrapped water on deck poses stability problems and contributes substantially to capsizing, especially on a large deck like that found on Roll on-Roll off ships. The accumulated water will induce both static and dynamic effects (Adee and Coglayan 1982). The static effect of the water is dominant; the effect of water accumulation is included in the time simulation by taking into account the instantaneous amount of water on deck, roll angle and trim. The formulation of the effect of water on deck is thus taken into account as follows:

Instantaneous amount of water on the deck:

$$W_d(t) = W_d(t - \Delta t) + W_d(\Delta t) \tag{11}$$

Instantaneous static force to sink the ship:

$$F_s(t) = gW_d(t) \tag{12}$$

It is assumed that the ship rotates around the inertial centre of gravity and hence the instantaneous static heeling moment becomes:

$$Mt_R(t, \phi, \theta) = gW_d(t)[TCG - tcg(t, \phi, \theta) \tag{13}$$

Instantaneous trim moment:

$$Mt_T(t, \phi, \theta) = gW_d(t)[LCG - lcg(t, \phi, \theta) \tag{14}$$

These forces and moments are included in the equations of motion, following appropriate transformations.

Modelling the water ingress: The modelling of water ingress is based on the relative position of the water level (wave elevation) and damage location. This instantaneous relative position is calculated by taking into account the

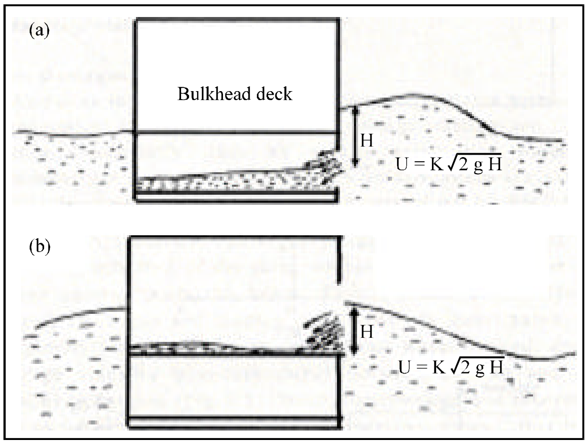

Fig. 2: Modelling of water ingress, (a) flow for a damage below the waterline and (b) flow over a deck above the waterline

instantaneous wave elevation and ship motions. Bearing in mind these problems, the emphasis here is placed upon the hydrostatic effect including wave height, edge effect and location of damage. Formulations for different damage conditions are given as follows:

Flow for a damage below the waterline: The water ingress model for this condition is based on the empirical formula developed for the steady water flow through an orifice and static pressure head is calculated by using Bernoulli's equation is shown in Fig. 2a:

$$U = K\sqrt{2gH} \tag{15}$$

and flow rate:

$$Q = U\ A_{ap} \tag{16}$$

Flow above the water surface: For this condition, the static pressure head is calculated by considering the water elevation but by using the formulation developed for flow rate over a notch or weir, which is the most suitable for the modelling of this problem (Fig. 2b). Flow rate:

$$Q = U\ A_{ap} \tag{17}$$

$$U = K\sqrt{gH} \tag{18}$$

The K-value (flow coefficient or discharge coefficient) changes depending on the shape of the damaged area, while at the same time it may also be affected by the thickness and the roughness of the hole edges. Walshaw and Jobson notes that in civil engineering applications, K is generally taken between 0.40 and 0.58 (Walshaw and Jobson, 1979).

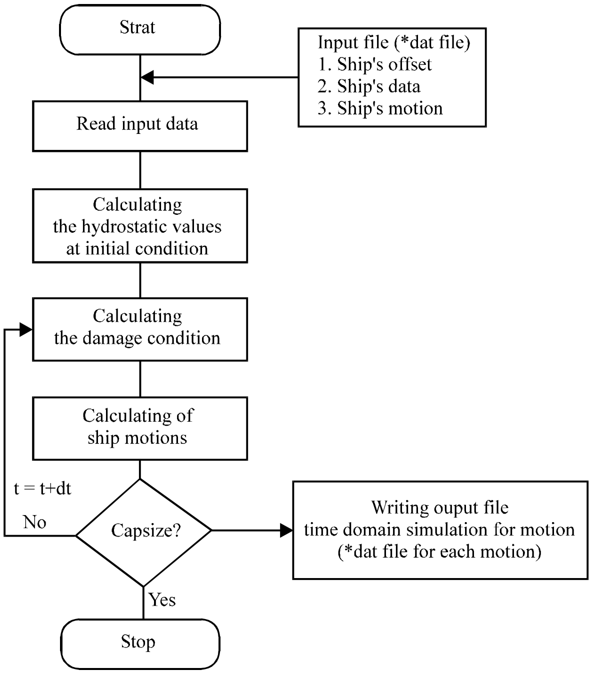

Fig. 3: Flow chart of the MATLAB program

MATLAB PROGRAM

The MATLAB program is used to investigate ship's dynamic behaviour based on real time simulation approach. The program required three input files; ship's offset, ship's data and ship's motion in order to run the simulation successfully. Assessment consists of regular waves in beam sea condition.

Progressive flooding is included in the assessment together with time dependent water ingress. Water ingress can be modeled either by entering the fixed water flow per time unit or using the relation between instantaneous water elevation and the location of the damage. Results are obtained in time domain for different parameters such as ship motions, amount of water flooding etc. The flow chart of the program is shown in Fig. 3.

DAMAGE STABILITY EXPERIMENT AND VALIDATIONS

Model preparation: For the experiment, a scaled model of a 31.5 m long Sarawak Fast Ferry was chosen. The length

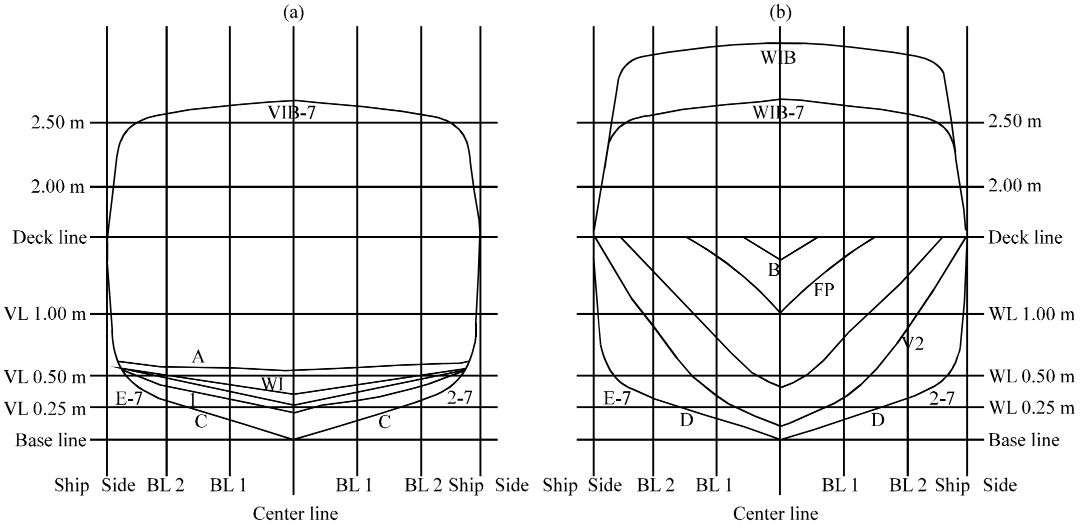

Fig. 4: Body plan of the high-speed passenger ferry, (a) after part and (b) fore part

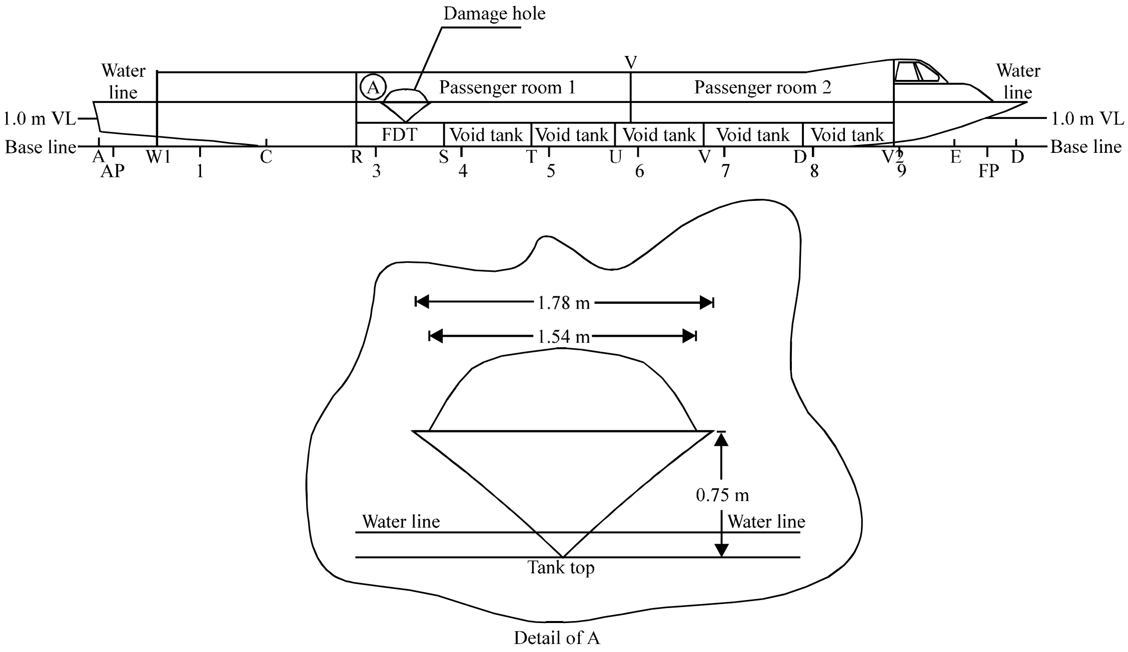

Fig. 5: Location and detail of damage hole

of 1:10 scale model is 3.15 m and 59.6543 kg weight. Details of the high-speed passenger ferry body plan are given in Fig. 4a and b.

Before experiments were conducted, the model was properly ballasted to the appropriate loading conditions. The model was first ballasted to the required displacement and balanced in water to the appropriate draught. To get real condition of damage ship, the damage hole with particular size was made on the hull. Detail size and shape of the damage hole is given in Fig. 5. This condition is used to conduct the experiment of ship motions.

Experimental set-up for damage stability test: The experiment was conducted in the Towing Tank of Marine Technology Laboratory, having dimensions of 120 m× 4 m×2.5 m. The equipments required for this test are two CCD cameras, two NI IMAQ card and LabView program. The arrangement of the experiment set-up includes the position of cameras and markers are shown in Fig. 6.

Two CCD cameras were connected to NI IMAQ card to capture the images and the LabView program was used to record the images. Two set of markers were attached to the model. These markers are used to help the program

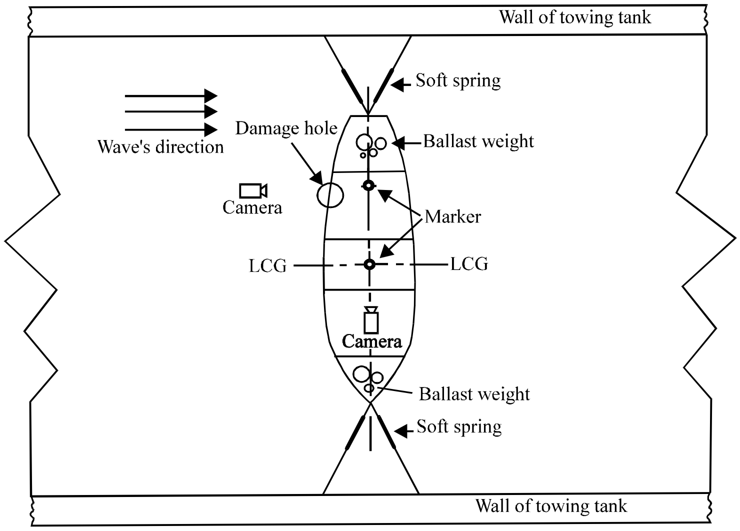

Fig. 6: Arrangement set-up of beam seas test and position of camera

Table 1: Test conditions for damage stability experiment

	Wave characteristics			
Run	Period (T) (sec)	Frequency (ω) (rad sec^{-1})	Wave height (m)	Wave length (Lw)
WH = 0.1 m	1.4204	4.4235	0.01	3.15
WH = 0.2 m	1.4204	4.4235	0.02	3.15
WH = 0.3 m	1.4204	4.4235	0.03	3.15
Calm water	Calm water			

that can easily track the motion of damage ship. First marker was used to measure the rolling and heaving motion so put on the LCG of model and the second marker was used to measure the pitching motion and correction for first marker. The number of frames per sec^{-1} also an important parameter for image processing, in this case the value chosen was 5 frames sec^{-1}.

Damage stability experiment condition: In the experiment, the model is subjected to beam sea condition with regular wave in zero forward speed at various wave lengths. A suitable wave height 0.01, 0.02 and 0.03 m corresponding to the model freeboard was used in the experiment. The KG of ballasted model for this experiment is 0.12 m. The wave periods used in the experiments is 0.704 sec. Table 1 show the test conditions for each run of the experiments, the values shown are all in model scale.

Damage stability experiment analysis: After the sequence of images (video) already captured and recorded using LabView, then the images were analysed using vision assistant program. This program has capabilities to manipulate and process the image and then to track the moving of the markers to obtain the motion of damage ship. The co-ordinate position of moving marker in time step can be track using pattern matching (Fig. 7).

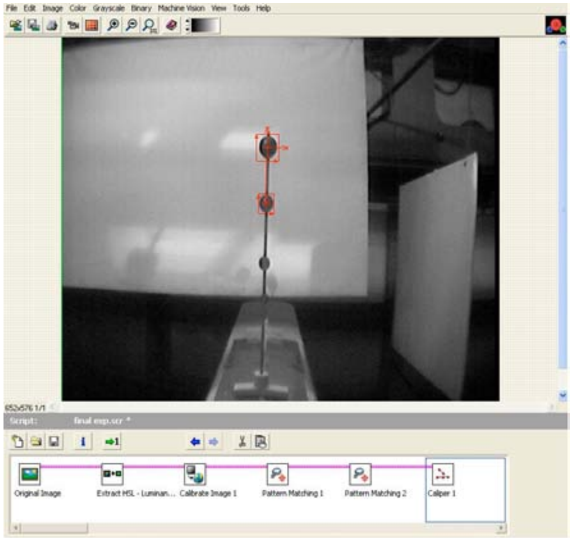

Fig. 7: Pattern matching tracked the co-ordinate of marker

Damage stability experiment results: The results of this experiment are used to validate the simulation results. The comparison between the simulation and experimental results shows that time to capsize is found to be quite similar. The comparisons have been made for calm water and in waves. The wave height considered for comparison are 0.1, 0.2 and 0.3 m and the wave length and ship length ratio is taken as $\lambda_w / L = 1$. It is to be noted that only beam waves are considered and KG is taken 1.2 m. Figure 8-10 show that the agreement are very good between the simulation results of heave motion and experimental ones on vessel's damage behavior at wave height 0.1, 0.2 and 0.3 m, respectively. Figure 11-13 show the comparison

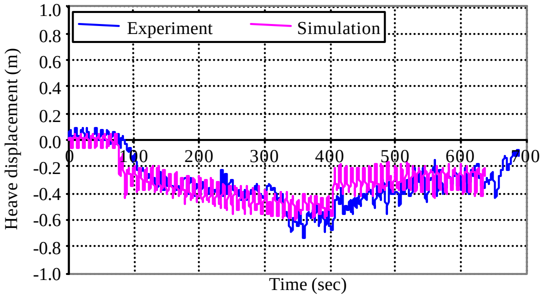

Fig. 8: Heave motion (damage stability at wave height = 0.1 m): comparison of experiment and simulation

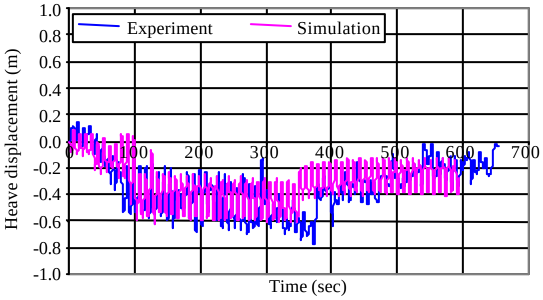

Fig. 9: Heave motion (damage stability at wave height = 0.2 m): comparison of experiment and simulation

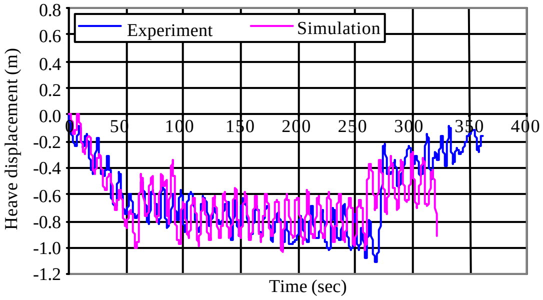

Fig. 10: Heave motion (damage stability at wave height = 0.3 m): comparison of experiment and simulation

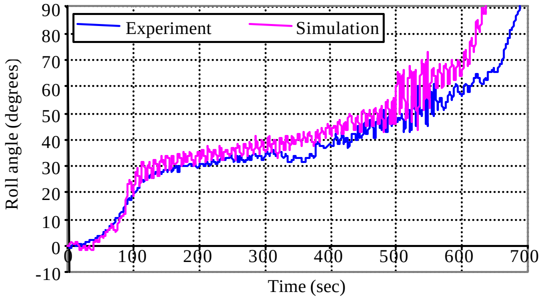

Fig. 11: Roll motion (damage stability at wave height = 0.1 m): comparison of experiment and simulation

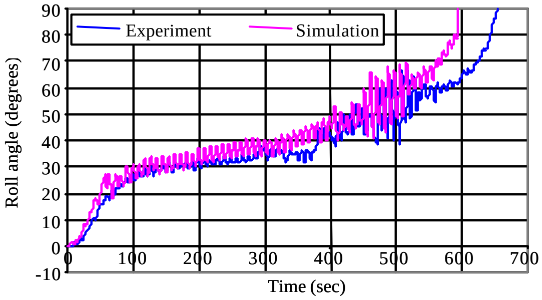

Fig. 12: Roll motion (damage stability at wave height = 0.2 m): comparison of experiment and simulation

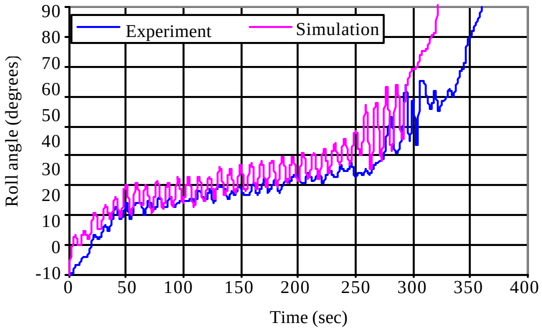

Fig. 13: Roll motion (damage stability at wave height = 0.3 m): comparison of experiment and simulation

between the simulation results and experimental ones of the roll motion on vessel's damage behavior at wave height 0.1, 0.2 and 0.3 m, respectively and indicate that this simulation program can be used to predict the large amplitude of motion and damage stability sequence of a ship operating in beam seas. The roll motion varies a little between the experiment and simulation near to the capsize time. Figure 14-16 also show the comparison between the simulation results and experimental ones of the pitch motion on vessel's damage behavior at wave height 0.1, 0.2 and 0.3 m, respectively. The comparison is not same but the period is quite similar. Comparisons have also been made for calm water condition, the heave motion is shown in Fig. 17, the roll motion in Fig. 18 and the pitch motion in Fig. 19 and it is seen that in general very good agreement is found between the simulation and experimental results that gives confidence to assess the dynamic stability of damage ship utilising the simulation program. Qualitatively, the present mathematical models

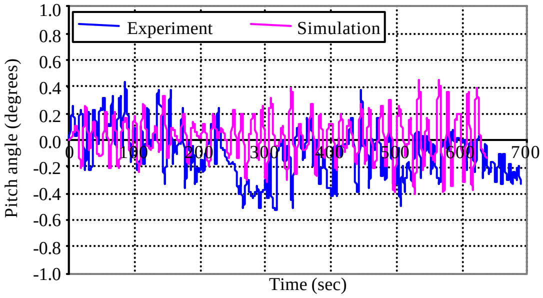

Fig. 14: Pitch motion (damage stability at wave height = 0.1 m): comparison of experiment and simulation

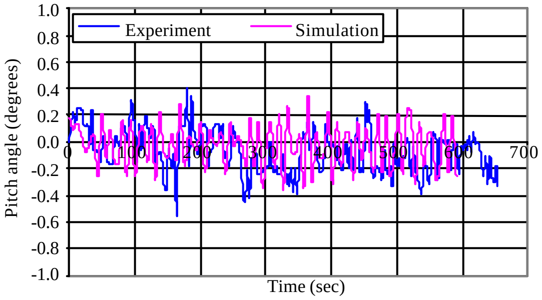

Fig. 15: Pitch motion (damage stability at wave height = 0.2 m): comparison of experiment and simulation

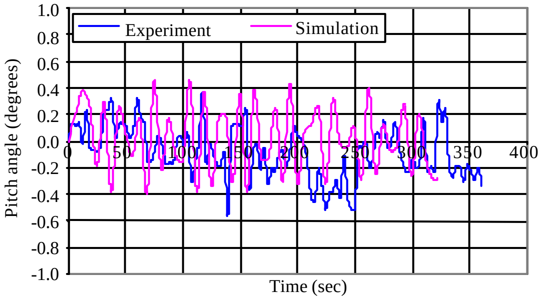

Fig. 16: Pitch motion (damage stability at wave height = 0.3 m): comparison of experiment and simulation

successfully simulate the damage stability assessment due to parametric excitation and large amplitude motion.

PARAMETRIC INVESTIGATION

A parametric investigation is carried out to find general trends and the effects of changes of parameters on the behaviour of the ship in damage condition.

The developed software allows for both irregular and regular waves in assessing a ship's dynamic behaviour.

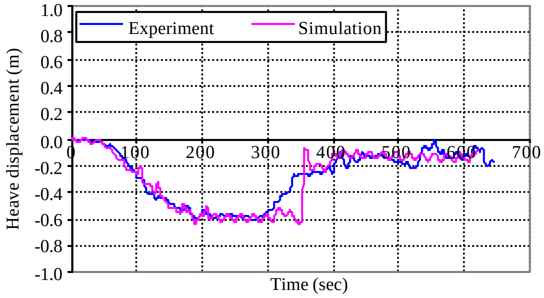

Fig. 17: Heave motion (damage stability at calm water): comparison of experiment and simulation

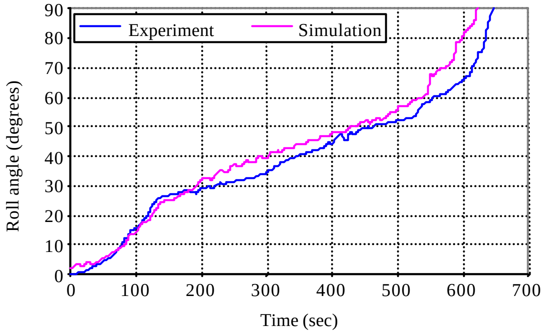

Fig. 18: Roll motion (damage stability at calm water): comparison of experiment and simulation

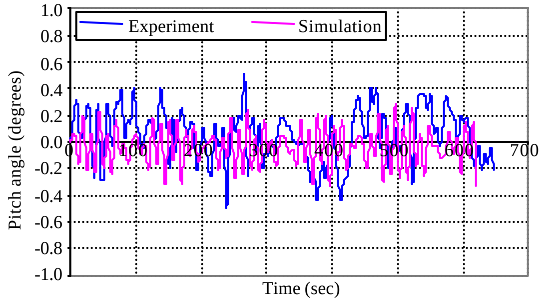

Fig. 19: Pitch motion (Damage stability at calm water): comparison of experiment and simulation

In this study, only regular waves were considered in the parametric investigation. Consideration of regular waves allows better control in studying the effect of various parameters whilst saving substantially in computational time.

As the ship is operating in riverine areas only small wave height (up to 0.3 m) is considered in the simulation. The critical wave chosen is the wave having its exciting frequency coinciding with the roll natural frequency of

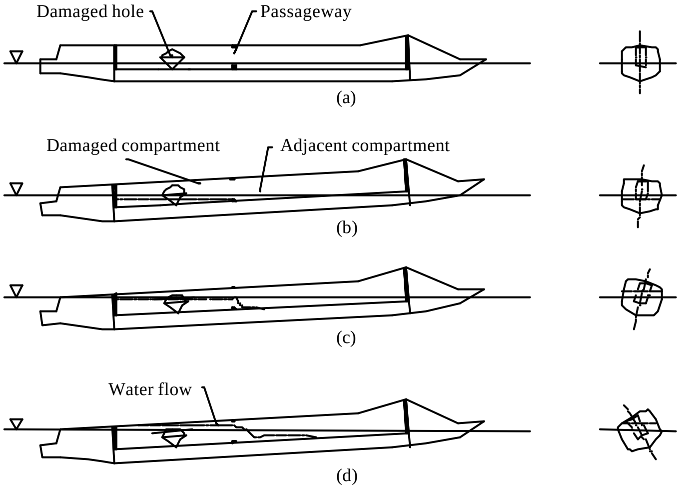

Fig. 20: Damage scenario with continuous flooding

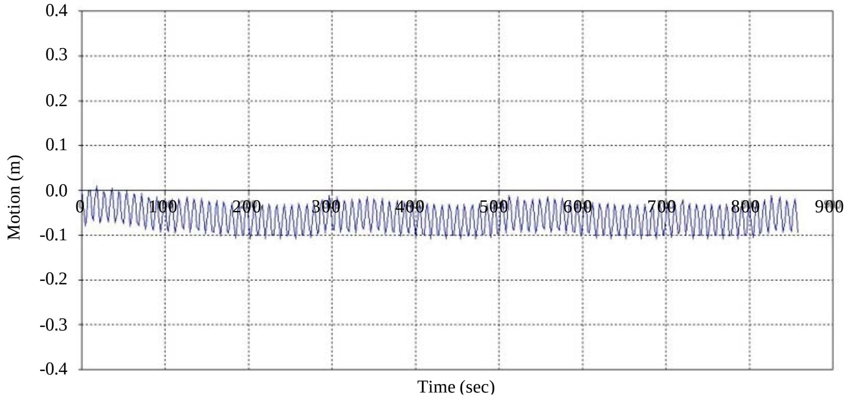

Fig. 21: Time histories of ship sway motion during progressive flooding, KG = 1.1 m, WH = 0.1 m

ship. This was found to be of wave length 31.5 m. For beam sea condition the wave direction is 90 degrees. Considering the importance of loading condition of the ship, different KG's are used in the simulation. KG's are varied between 1.1, 1.2 and 1.3 m. The simulation results for KG 1.2 m and for various wave heights have given in Fig. 8-19 and hence are not repeated. Meanwhile, water ingress which depends on the wave height is applied in the simulation. Continuous flooding occurs between the adjacent compartments. Continuous flooding which occur between damaged compartment and adjacent compartment through a passageway is assumed in this study (Fig. 20a-d). The flow concern is regarded as flow over a rectangular weir. Damage hole is assumed that the ship is collided with another ship. The location of damage and the size of damage hole is shown in Fig. 5 as mentioned before, the flow coefficient (K) is in the region of 0.20-0.45, respectively based on the shape of the area, thickness and roughness of the hole edges (Turan, 1993). In this research, the flow rate which depends on static pressure head is low due to the ship operating area at mild environmental conditions (small wave height), the suitable value of flow coefficient (K) is 0.35.

In the simulation, only the main deck which is passenger deck is assumed to be flooded. The main deck has two compartments which are connected through a passageway. It is assumed that water ingress occurs on one of the compartment due to collision which is located at the aft of the ship. Water will flow from the damaged compartment to the adjacent compartment through a passageway similar to flow over a weir.

In Fig. 21, it is seen that while water starts to enter the ship drifted a little and this is because of roll. The differences in motions are shown with the different

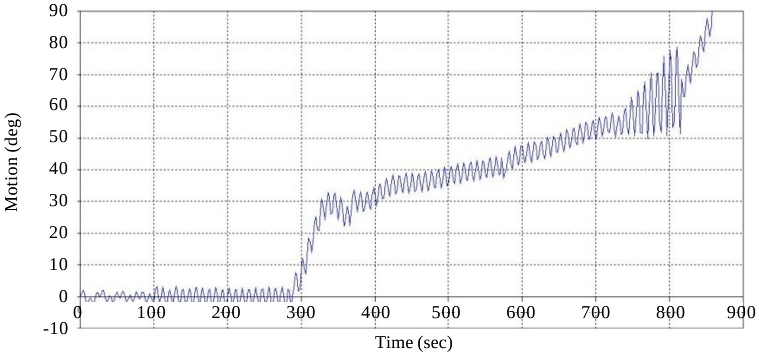

Fig. 22: Time histories of ship roll motion during progressive flooding, KG = 1.1 m, WH = 0.1 m

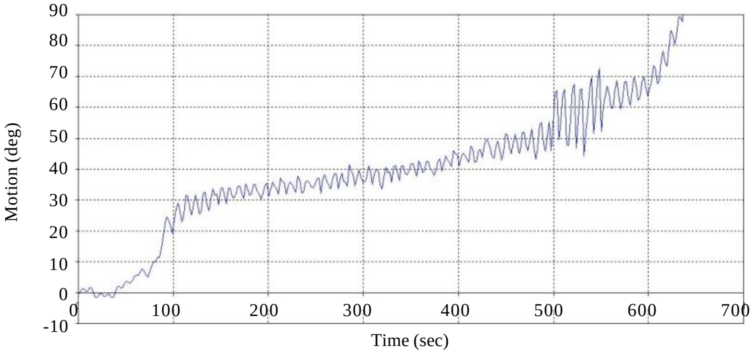

Fig. 23: Time histories of ship roll motion during progressive flooding KG = 1.2 m, WH = 0.1 m

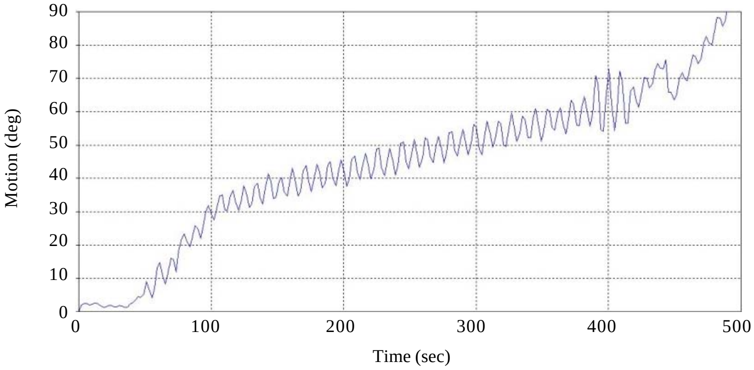

Fig. 24: Time histories of ship roll motion during progressive flooding KG = 1.3 m, WH = 0.1 m

KG and wave height values. The roll motions at wave height of 0.1 m are shown in Fig. 22-24; for KG = 1.1 m, KG = 1.2 m and KG = 1.3 m, respectively. Meanwhile the roll motions at wave height of 0.2 m are shown in Fig. 25 and 26; for KG = 1.1 m and KG = 1.3 m, respectively. The roll motions at wave height of 0.3 m are shown in Fig. 27-29; for KG = 1.1 m, KG = 1.2 m and KG = 1.3 m, respectively.

Generally, it is seen that as the water enters the compartment, sinkage is observed and the effect of water sloshing or piling and waves will result in the rolling motions. The heave motions at wave height of 0.1 m are shown in Fig. 30-32; for KG = 1.1 m, KG = 1.2 m and KG = 1.3 m, respectively. Meanwhile, the heave motions at wave height of 0.2 m are shown in Fig. 33 and 34; for KG = 1.1 m and KG = 1.3 m, respectively. The heave

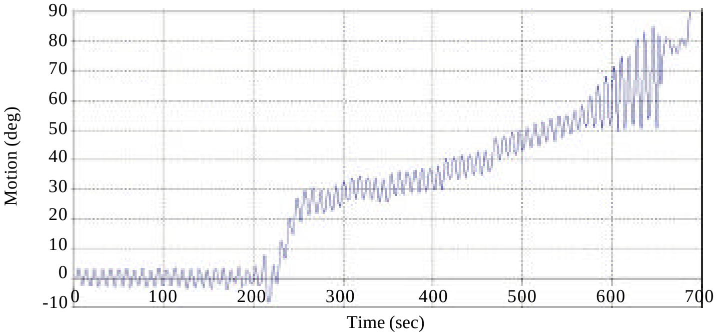

Fig. 25: Time histories of ship roll motions during progressive flooding KG = 1.1 m, WH = 0.2 m

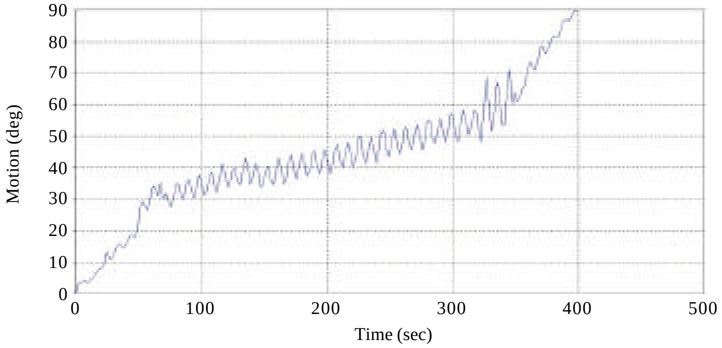

Fig. 26: Time histories of ship roll motion during progressive flooding KG = 1.3 m, WH = 0.2 m

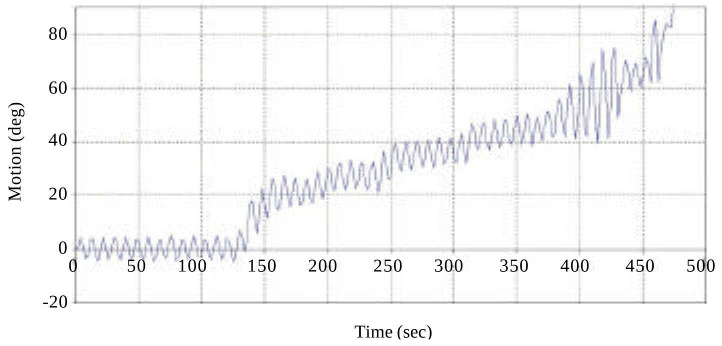

Fig. 27: Time histories of ship roll motion during progressive flooding KG = 1.1 m, WH = 0.3 m

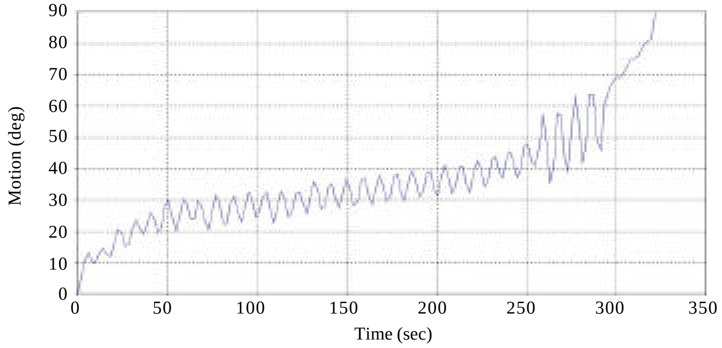

Fig. 28: Time histories of ship roll motion during progressive flooding KG = 1.2 m, WH = 0.3 m

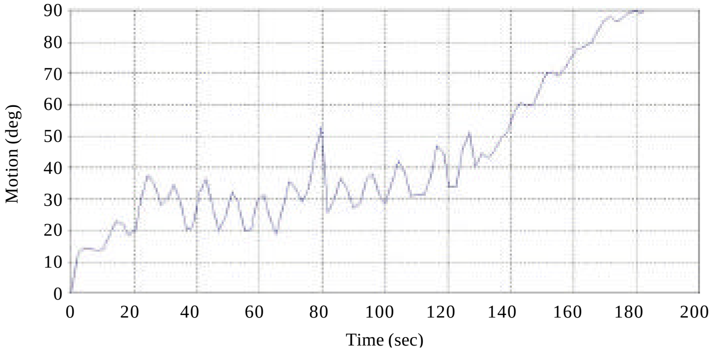

Fig. 29: Time histories of ship roll motion during progressive flooding KG = 1.3 m, WH = 0.3 m

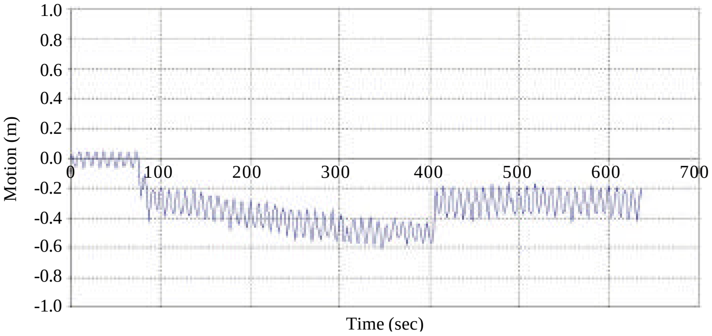

Fig. 30: Time histories of ship heave motion during progressive flooding, KG = 1.1 m, WH = 0.1 m

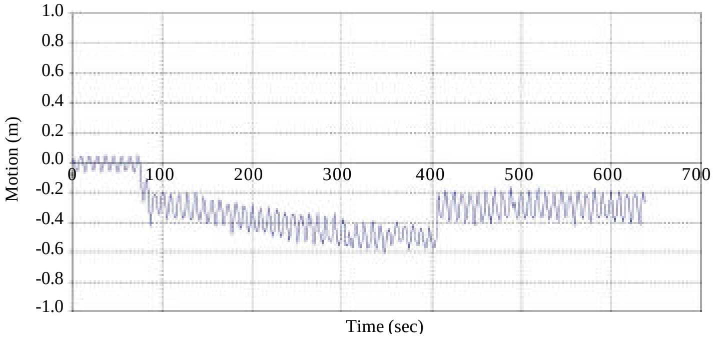

Fig. 31: Time histories of ship heave motion during progressive flooding KG = 1.2 m, WH = 0.1 m

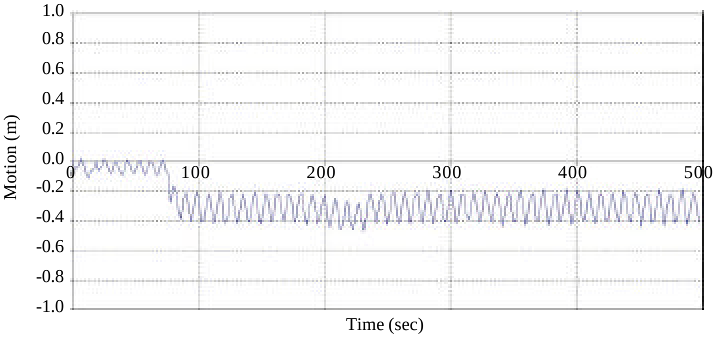

Fig. 32: Time histories of ship heave motion during progressive flooding KG = 1.3 m, WH = 0.1 m

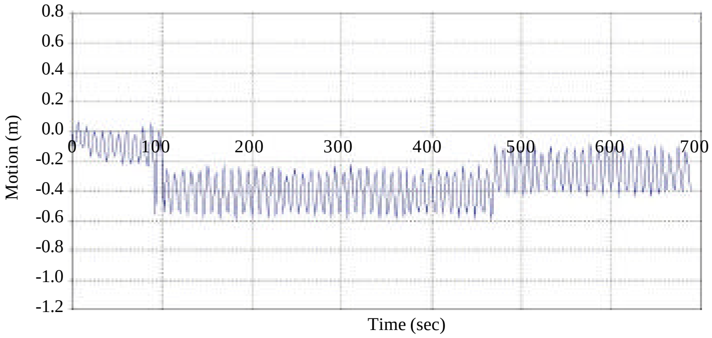

Fig. 33: Time histories of ship heave motions during progressive flooding KG = 1.1 m, WH = 0.2 m

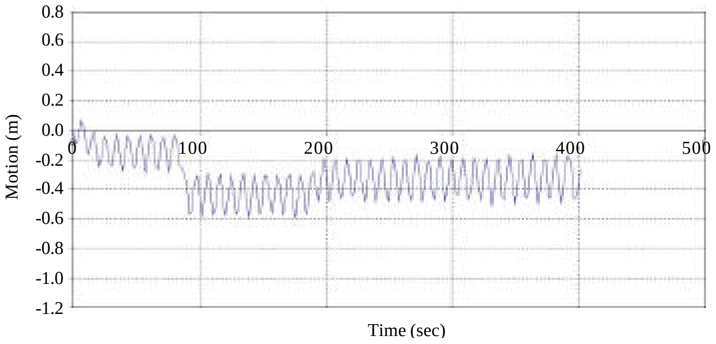

Fig. 34: Time histories of ship heave motion during progressive flooding KG = 1.3 m, WH = 0.2 m

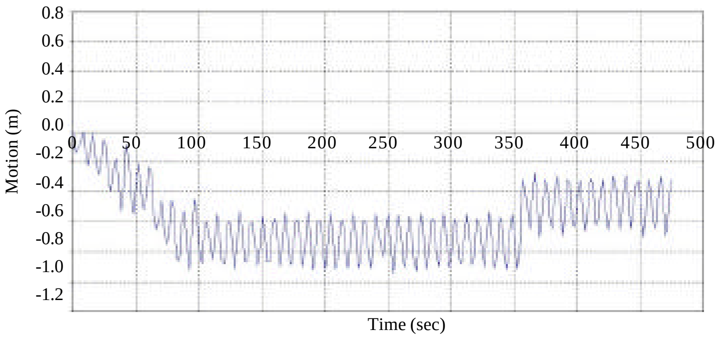

Fig. 35: Time histories of ship heave motion during progressive flooding KG = 1.1 m, WH = 0.3 m

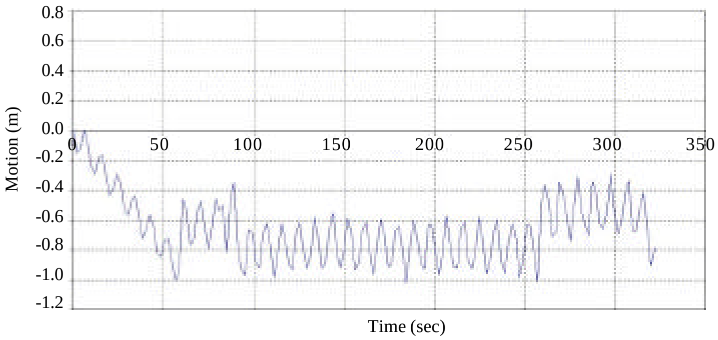

Fig. 36: Time histories of ship heave motion during progressive flooding KG = 1.2 m, WH = 0.3 m

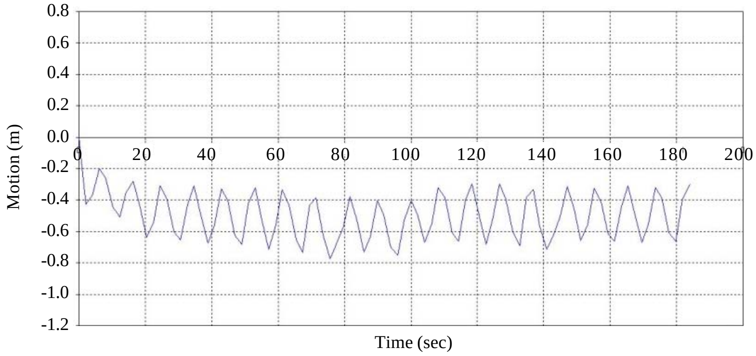

Fig. 37: Time histories of ship heave motion during progressive flooding KG = 1.3 m, WH = 0.3 m

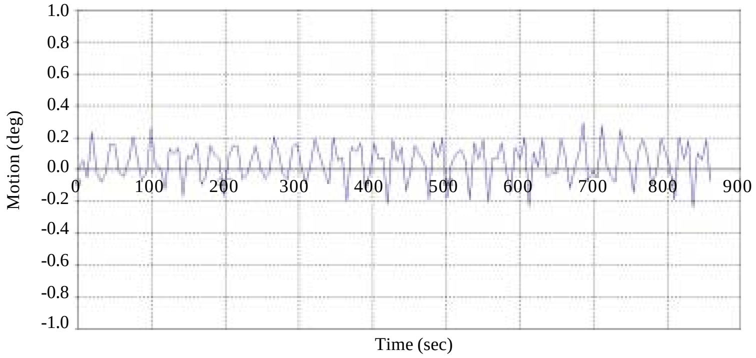

Fig. 38: Time histories of ship pitch motion during progressive flooding, KG = m, WH = 0.1 m

motions at wave height of 0.3 m are shown in Fig. 35-37; for KG = 1.1 m, KG = 1.2 m and KG = 1.3 m, respectively. Lastly, the pitch motions at wave height of 0.1 m is shown in Fig. 38; for KG = 1.1 m. From the results, it can be easily seen that safer conditions can be achieved with lowering the KG and wave height.

Generally, as wave height increases, the static heel effect becomes less important and oscillations due to excitation become more dominant. On the other hand, as wave height increases, the ship's ability to survive in large waves decreases. Heave motion increases with increasing wave height as can be seen from Fig. 30-37. The static heel does not seem to be affecting the heave motion significantly. Typically the sway and pitch (Fig. 21 and 38) are small and the maximum amplitude of the oscillation is depending on wave height. The sway motion changes if there is a big static heel or a big roll motion due to the change in underwater geometry.

From the roll simulation results for various conditions, it is seen that the vessel capsized in all conditions within the simulated period but if a short period of 300 sec (5 min) are taken as evacuation period then from the above simulated results the vessel safe and unsafe conditions can be determined.

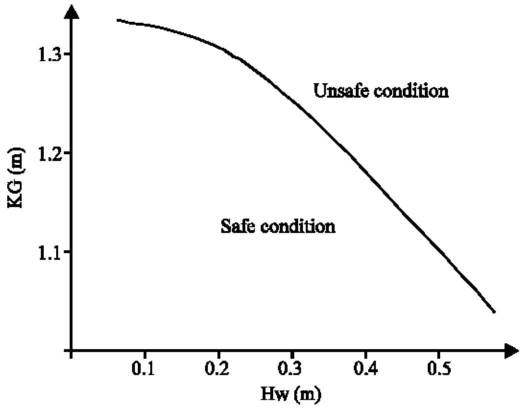

Fig. 39: Safe and unsafe condition of the sarawak fast ferry

The safe condition is assumed when the time to capsize is reached within short period of 300 sec (5 min) 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, Fig. 39 shows safe/unsafe conditions through a plot of KG against wave height. From Fig. 39, it is seen that the vessel is safe for KG = 1.3 m in a wave height of 0.2 m only for KG = 1.1 m, the vessel can sustain till 0.5 m wave heights.

DISCUSSION

The study is made for a specific hull. Thus, not possible to compare with other research and hence the simulation results are compared with experimental results. In this study, time domain simulation program developed at UTM and benchmarked by ITTC (Umeda, 2002) is used to evaluate the dynamic stability and seakeeping performance for a vessel. From the comparison between the numerical and experimental results, good agreement is obtained.

CONCLUSIONS

The present study successfully shows that the Time Domain Simulation program are suitable for investigating the stability of a damaged vessel and can predict the high-speed passenger ferry's behavior including continuous flooding with sufficient accuracy. From the above discussions the following conclusions can be made:

- The comparison between the simulation and experimental results gives confidence to assess the dynamic stability of damage vessel by utilizing the developed Time Domain Simulation program
- Wave height and loading conditions are the main parameters that influence the vessel's stability in damage condition. As wave height and KG increase, the dynamic effect of waves on the damaged vessel increases significantly and the possibility of capsizing becomes more significant
- The critical KG for Sarawak Fast Ferry was found to be 1.3 m, in this condition the vessel only can survive with wave height until 0.2 m. The safe KG was found to be 1.1 m, in this condition the vessel can survive with wave height 0.5 m

NOMENCLATURE

Aop	:	Area of the damaged hole or opening
DC	:	Distance between the centre of volume of the flooded water and the centre of rotation
H	:	The head between the water level and the center of damage hole
K	:	Flow coefficient
M_f	:	Mass of flooded water
$Mt_R(t,\phi,\theta)$	:	Instantaneous static heeling moment due to water on deck
$Mt_T(t,\phi,\theta)$	:	Instantaneous static trimming moment due to water on deck
LCB (t, z, θ, ϕ)	:	Longitudinal centre of buoyancy of the ship
LCG	:	Longitudinal centre of gravity of the ship
$lcg(t,\phi,\theta)$	:	Longitudinal centre of gravity of water on deck
Sf(t)	:	Instantaneous static sinkage force due to water on deck
TCB (t, z, θ, ϕ)	:	Transverse centre of buoyancy of the ship
TCG	:	Transverse centre of gravity of the ship
$tcg(t,\phi,\theta)$	:	Transverse centre of gravity of water on deck
U	:	Velocity of the water
Wd(t)	:	Instantaneous amount of water on deck
$\Delta\ (t, z, \theta, \phi)$	:	Instantaneous displacement
$\Delta\ (t_0)$	:	Initial displacement at time $t = t_0$
ADW(t)	:	Instantaneous amount of water on deck
A_{ij}	:	Added mass
A_{op}	:	Area of the damaged hole or opening
B_{ij}	:	Damping coefficient
C_{ij}	:	Restoring for ce
$F_{i\ wave}$, $M_{i\ wave}$	:	Wave excitation force and moment
$F_{i\ wod}$, $M_{i\ wod}$	:	Excitation force and moments due to water on deck
F_D	:	The diffracted wave force representing the disturbance of the incoming wave diffracted by the section
F_R	:	The radiation force representing the motion induced disturbance of the initially calm water
F_{FK}	:	The Froude-Krylov force representing the incoming waves.
g	:	Gravitational acceleration
I_{xx}	:	Mass of moment inertial of roll respectively
i, j	:	Mode of motion (2 = sway, 3 = heave,4 = roll)
M	:	Mass of ship
p	:	Roll rate respectively
$\dot{p}$	:	Roll acceleration respectively
t	:	Total time for simulation (from t = 1 to t = tn+1)
v, w	:	Sway velocity, heave velocity respectively
$\dot{v}, \dot{w}$	:	Sway acceleration, heave acceleration, respectively

y, z : Sway displacement, heave displacement respectively
$\Delta (t, z, \theta, \phi)$: Instantaneous displacement
$\Delta (t_0)$: Initial displacement at time $t = t_0$
θ : Instantaneous trim
ϕ : Roll angle respectively

REFERENCES

Adee, B.H. and I. Caglayan, 1982. The effect of free water on deck on the motions and stability of ships. Proceedings of 2nd International Conference on Stability of Ship and Ocean Vehicles, October 1982, Tokyo, Japan, pp: 243-253.

Chang, B.C. and P. Blume, 2000. Survivability of Damaged Ro-Ro Passenger Vessels. Vol. 1, Elsevier Science Ltd., London pp: 237-248.

De Kat, J.O., 2000. Dynamics of a Ship with Partially Flooded Compartment. Vol. 1, Elsevier Science Ltd., London, pp: 249-263.

Faltinsen, O.M., 2005. Hydrodynamics of High-speed Marine Vehicles. Cambridge University Press, Cambridge, Canada.

Frank, W., 1967. Oscillation of Cylinders in or Below the Free Surface of Deep Fluids. NSRDC., Washington.

Kambisseri, R. and Y. Ikeda, 2000. About Safety Assessment of Damaged Ships. Vol. 1, Elsevier Science Ltd., London, pp: 225-236.

Papanikolaou, A. and D. Spanos, 2002. On the probability of capsizing in transient flooding conditions. Proceeding of the 2002 Stability Workshop, Oct. 13-16, Webb Institute, pp: 1-10.

Salvensen, N., V. Tuck and O. Faltinsen, 1970. Ship motions and sea loads. Trans. Soc. Naval Architects Mar. Eng., 7: 250-287.

Samian, Y. and A. Maimun, 2001. Static and dynamic stability assessment of small craft. Seminar on Ship Design, Model Testing and Sea Trial Activities. Skudai, Johor, June 13-14.

Schindler, M., 2000. Damage Stability Tests with Models of Ro-Ro Ferries-A Cost Effective Method for Upgrading and Designing Ro-Ro Ferries. Vol. 1, Elsevier Science Ltd., London, pp: 213-224.

Shimizu, N., R. Kambisserri and Y. Ikeda, 2000. An Experiment Research on Flooding into the Car Deck of a Ro-Ro Ferry through Damaged Bow Door. Vol. 1, Elsevier, London, pp: 199-212.

Turan, O., 1993. Dynamic stability assessment of damaged passenger ship using a time simulation approach. Ph.D. Thesis, University of Strathclyde.

Umeda, N., 2002. Benchmarking testing for intact stability, specialist committee on prediction of extreme ship motions and capsizing. Proceedings 23rd International Towing Tank Conference, Venice, Italy.

Vassalos, D., L. Letizia and O. Turan, 2000. Modeling the Accumulation of Water on the Vehicle Deck of a Damaged Ro-Ro Vessel and Proposal of Survival Vol. 1, Elsevier, London, pp: 315-337.

Walshaw, A.C. and D.A. Jobson, 1979. Mechanics of Fluid. Longman Group Ltd., London.