DAMAGE STABILITY OF SMALL VESSEL

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DEDICATION

I dedicate this work of mine to:

My beloved Wife and My beloved "QueeN"
My Father, My Late Mother and My Aunty "AS"
My father and My Mother in Law
My Brother and My Sister
My Sister in Law

Whom I always remember for the help they have given me throughout my studies, emotionally, prayers, support, loves, understanding, and assistance.

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ABSTRACT

The survivability of a vessel is related to intact and damage stability requirements. However, intact ship survivability has received more attention than damage ship survivability. This study seeks to emphasise in damage stability for the reason, the safety of passenger vessels has always been the prime concern of regulatory bodies. There are various ways of assessing the damage stability such as deterministic, probabilistic and real time simulation approaches. The purpose of this study is to further develop a ship stability program using MATLAB based on real time simulation of the dynamic behaviour of the damaged vessel in wave conditions. The mathematical model comprises six degrees of freedom motions in beam seas whilst taking into consideration progressive flooding as well as water accumulation. The 'Sarawak Fast Ferry' was chosen for parametric study for the application of the developed Damage Stability Program. Damage stability experiment was carried out to validate the simulation program. The experiment was conducted using image processing technique. Experimental results have shown good correlation to the results of simulation. The result of the study also indicated that wave height and loading conditions are the main parameters influencing ship's stability in damage condition. The critical KG for Sarawak Fast Ferry was found to be 1.3 m and the vessel only can survive with wave height until 0.2 m. The safety KG was found to be 1.1 m since the vessel can survive with wave height 0.5m. On the basis of the results, suggestions are made to improve the damage survivability of the vessel.

ABSTRAK

Ketahanan suatu kapal berkait dengan syarat kestabilan bocor dan juga kestabilan tanpa bocor. Walaupun begitu, ketahanan kapal tanpa bocor lebih mendapat perhatian daripada ketahanan kapal bocor. Kajian ini memberi penekanan kepada kestabilan bocor atas sebab keselamatan penumpang yang merupakan aspek yang diberi keutamaan oleh badan penyeragaman. Terdapat beberapa kaedah untuk menilai kestabilan bocor seperti kaedah penentuan, kaedah kemungkinann dan pendekatan simulasi masa sebenar. Tujuan kajian ini adalah memperkembangkan lagi pembangunan suatu perisian kestabilan kapal berasaskan simulasi masa sebenar dengan menggunakan MATLAB bagi perlakuan dinamik kapal bocor dalam keadaan laut berombak. Model matematik yang terdiri dari pergerakan enam darjah kebebasan pada keadaan ombak dari samping kapal dengan mengambil kira bocor yang berketerusan dan keadaan semasa pengumpulan air. ‘Feri Cepat Sarawak’ dijadikan kajian kes bagi aplikasi perisian kestabilan bocor. Sebagai pengesahan kesahihan perisian tersebut, uji kaji kestabilan bocor telah dilakukan. Uji kaji ini dijalankan dengan menggunakan teknik pemprosesan imej. Keputusan uji kaji menunjukkan hasil yang sesuai dengan keputusan perisian simulasi. Keputusan dari kajian ini menunjukkan terdapat dua parameter utama yang memberi pengaruh kepada kestabilan kapal bocor iaitu ketinggian ombak dan kondisi pembebanan kapal. Keputusan memberikan KG kritikal bagi Feri Cepat Sarawak adalah 1.3 m kerana kapal hanya mampu bertahan dengan tinggi ombak sampai 0.2 m. Adapun keadaan KG yang selamat adalah 1.1 m kerana kerana kapal mampu bertahan dengan tingi ombak sampai 0.5 m. Berdasarkan keputusan tersebut, sebarang cadangan diperbuat untuk memperbaiki ketahanan bocor dari kapal tersebut.

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NOMENCLATURES

Vessel/Environment Parameters

B	:	Breadth of vessel
Cb	:	Block coefficient
C_m	:	Midship area coefficient
C_{PL}	:	Longitudinal prismatic coefficient
D	:	Depth of vessel
D_W	:	Water depth
F_{bd}	:	Freeboard of vessel
GM	:	Metacentric height
GZ	:	Righting lever
H_W	:	Wave height
T	:	Draught of vessel
KG	:	Vertical height of centre of gravity from the Keel
L	:	Length of vessel
V_S	:	Forward speed of vessel
V_W	:	Wave celerity
Δ	:	Displacement
λ_W	:	Wave length
ζ_W	:	Wave profile
γ	:	Wave number
η	:	Wave elevation

Co-ordinate Systems

oxyz	:	Vessel co-ordinate system
OeXeYeZe	:	Earth co-ordinate system
OgeXgeYgeZge	:	Co-ordinate system at the centre of gravity G and the directions are parallel to the earth system, is used to measure vessel motions.

Equations of Motion

a_n	:	Added mass
b	:	Damping moment coefficient
b_c	:	Critical damping
$F_{i\ wave}$, $M_{i\ wave}$	:	Wave excitation force and moment
$F_{i\ wod}$, $M_{i\ wod}$	:	Excitation force and moments due to water on deck
i, j	:	Mode of motion, 1 for surge, 2 for Sway, 3 for Heave, 4 for Roll, 5 for pitch and 6 for yaw
I_{ij}	:	Mass moment of inertia
I_v	:	Virtual mass moment of inertia
M	:	Mass of vessel
u, v, w	:	Velocity of linear motion : surge, sway and heave respectively
$\dot{u}$, $\dot{v}$, $\dot{w}$	:	Acceleration of linear motion : surge, sway and heave respectively
p, q, r	:	Velocity of angular motion : roll, pitch and yaw respectively
$\dot{p}$, $\dot{q}$, $\dot{r}$	:	Acceleration of angular motion : roll, pitch and yaw respectively
RES_i	:	Restoring force and moments
x,y,z	:	Displacement of linear motion : surge, sway and heave respectively
ϕ,θ,ψ	:	Angle of angular motion : roll, pitch and yaw respectively
ϕ_{max}	:	Roll response
ϕ_3	:	Roll amplitude at time t_3
ϕ_1	:	Roll amplitude at time t_1
γ	:	Damping ratio

κ : Non-dimensional damping factor

Λ : Tuning factor

μ_{ϕ} : Magnification factor

Water Ingress and Flooding

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 vessel

LCG : Longitudinal centre of gravity of the vessel

lcg(t,ϕ,θ) : 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 vessel

TCG : Transverse centre of gravity of the vessel

tcg(t,ϕ,θ) : 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 $t = t_0$

Forces and Moments

a : Maximum amplitude of the incident wave

cos(n,j) : Cosines directions

G : Pulsating source potential of unit strength at a point (ζ,η) in the strip contour

g : Gravitational acceleration

$n^{(i)}$: Direction cosines of the outward normal vector for each mode of motion

$p^{(i)}$: Hydrodynamic sectional pressure

Q_d : Unknown source strength

S : Wetted surface area of vessel

s : Wetted contour of the strip section

V_n : the normal velocity component of a point on the section contour.

ρ : Density of water

∇ : Under water volume of vessel

μ : Heading angle (0.0:following, 180:head, 90 and 270:beam seas)

ω : Frequency of excitation

ω_e : Frequency of encounter

$n^{(i)}$: Directional cosines of the outward normal vector and changes depending on the mode of motion (i)

$\phi_D(y,z)$: Sectional diffracted wave potential

$\phi_I(y,z)$: Sectional incident wave potential

Φ_{RR} : Real part of radiated velocity potential

Φ_{RI} : Imaginary part of radiated velocity potential

Φ_I : The incident wave potential (Froude-Krylov potential) representing the incoming waves

Φ_D : The diffracted wave potential representing the disturbance waves diffracted by the section

Φ_R : The radiation potential representing the motion induced disturbance of the initially calm water

Hydrodynamic Coefficients

A_{ij}	:	Hydrodynamic reaction in phase with acceleration (added mass) in the i^{th} and j^{th} direction (i,j = 1,2,…,6)
B_{ij}	:	Hydrodynamic reaction in phase with velocity (damping) in the i^{th} and j^{th} direction (i,j = 1,2,…,6)
C_{ij}	:	Hydrostatic stiffness of body in the i^{th} and j^{th} direction (i,j = 1,2,…,6)
M_i	:	Mass or mass moment of inertia of body in the i^{th} direction (i = 1,2,…,6)

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CHAPTER 1

INTRODUCTION

1.1 Background

The safety of any vessel is of paramount importance to vessel designers and operators and to the regulatory bodies. For this reason, it is mandatory requirement for the vessel designers to submit stability booklet to the regulatory bodies such as classification society and marine department before the construction begins. Stability is generally defined as the ability of the vessel to return to the upright position whenever it heels to one side either by internal or external forces.

The consideration of safety is a complex matter as it has to be considered together with a number of conflicting factors such as the vessel'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 vessel at times conflict with their economical viability and their operational efficiency. A compromise has to be achieved between safety and economic viability. The main concern changes on design and regulations, results in extra cost or low operational efficiency. It is obvious that this conflict increases the potential risk of vessels loss. Therefore, improvement in the safety of vessel must be practical but at the same time offer a substantially improved standard.

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. The 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 to develop a 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 as a reference for future development of damage stability criteria.

1.2 Research Objectives

The objectives of this research are given as follow:

i. To develop mathematical model to describe the water ingress and motions of small vessel in damaged condition.
ii. To develop a technique using Time Domain Simulation for the stability assessment of damaged vessel.
iii. To validate the output of simulation program with the experiment result.

1.3 Scopes of Research

i. The research is to modify an existing Time Domain Simulation program for damage stability.
ii. This research covers progressive flooding and method of calculation being used is added weight method.
iii. The research is limited to regular wave in Beam Sea condition and includes 6 degrees-of-freedom motions.
iv. The simulation program will be applied to the parametric study of “Sarawak Fast Ferry”
v. The experiment will be run to verify the output of the simulation program.

1.4 Research Outline

This study starts by critical review of the existing damage stability criteria. The summary of the background and basis of the existing damage stability criteria are provided. Then, it concentrates on the limitation of the existing damage stability criteria and the problem of damage vessel stability. This is followed by the use of Time Domain Simulation approach to analyze the vessel motion.

In the modelling part, a six-degrees-of-freedom mathematical model is adopted to the simulation program. The main effort of this model is based on the accurate computation of the water ingress acting on the vessel at each instant of time. Whilst, the dynamic term in the equation of motion is estimated by using the frequency independent coefficient, which can be obtained through the published literatures.

In the analysis, parametric studies are carried out to find the behaviour of the vessel in damage condition. The vessel is chosen for analysis is Sarawak Fast Ferry. In parametric studies, the boundary of safe region is determined by changing the environment and vessel design parameters. The experimental results will be used to validate the simulation output.

Finally, the safe and unsafe region determined by studying the results obtained from the parametric studies. These results are then discussed and conclusions are drawn. For future work, suggestions and steps to improve the present study are recommended.

CHAPTER 2

LITERATURE REVIEW

2.1 General

The aim of this chapter is to give an overview of the vessel survivability and the assessment method to evaluate the vessel survivability. This chapter is divided into five parts. The first part is historical background of passenger vessel's survivability. The second part is to provide a better understanding of the method to investigate ship stability. The third part is the critical review of the existing damage stability criteria and the behaviour of small vessel in dynamic situation. The fourth part discusses the stability and survivability problems. The fifth part gives the recent methods to investigate the ship response in a dynamic situation and considering the design aspect for improving vessel survivability.

2.2 Historical Background of Passenger Vessel Survivability

The idea of having damage stability requirements on an international basis goes back to the 1910's with the loss of the Titanic stimulating the process to reach agreement. However, the agreement reached at the SOLAS (Safety of Life at Sea) conference 1913, never came into effect because of World War 1. Following the war, studies of subdivision were renewed because vessel owners insisted that the 1914 Convention requirements were too penalizing. During the 1920's several informal conferences were held and a number of studies and tests were carried out.

In 1929 a full international conference on SOLAS was convened and as a result the criterion of service and factorial system of subdivision were adopted to draw distinction between vessels in the carriage of cargo and those dedicated to the carriage of passengers. In 1948, another SOLAS conference was held but since there had not been any major sea disaster between 1929 and 1948, regulatory bodies were not forced to make major changes. The capsizing of the *Andrea Doria*, built under the 1948 Convention, raised discussions on the inadequacies in practical applications of the 1948 Convention and consequently substantial changes were proposed in the 1960 SOLAS conference. Since time was insufficient to reach any agreement for major changes, it was decided to form a sub-committee to carry out a study for the new rules. In 1960, despite the raised standards, the principal regulations remained the same.

The sub-committee (SOLAS Sub-committee on stability, subdivision and load lines) started its research in 1961. Its purposes was to review the existing criteria concerning the subdivision and damage stability of passenger certified vessels and to consider the relevant part of these criteria in comparison with other possible criteria based on probabilistic studies, from the point of view of stability and feasibility of application. These new regulations on subdivision and stability for passenger vessels were drawn up to the last form in1974 and adopted as new regulations. Due to the complexity of the new subdivision requirements and the need for specific computer programs for their application, the new regulations were adopted as being equivalent to and a total alternative to the provision of part B of chapter II of the 1960 convention (IMO, 1974) and this decision remains the same to date.

With such tragedies such as the *European Gateway* and the *Herald of Free Enterprise*, strong common views expressed that the 1960 Convention, which refers to the current mandatory criteria, had to be replaced by a more realistic and updated damage stability assessment. Regulatory bodies studied the problems and, for the first time, they introduced in 1990 extensive residual stability standards, for both passenger and cargo vessels which entered into force in 29 April 1990 and is called “SOLAS ’90 standard” (IMO, 1990). The Sub-Committee on stability, subdivision and load lines, at its thirty-eighth session (March 1994), in considering that the criteria in regulation of chapter II-1 of the 1974 SOLAS Convention are adequate to prevent the rapid capsize of a vessel in moderate seas and bearing in mind that the measure of the dynamic capability of a damaged vessel to resist heeling is the area under the residual stability curve.

The limited understanding of the complex dynamic behaviour of a damaged vessel and the progression of flood water through the vessel in a random sea state has, to date, resulted in approaches for assessing the damage survivability of vessels that rely mainly on hydrostatic properties with potentially serious consequences concerning the loss of life and property whilst endangering the environment. The tragic accidents of the Herald of Free Enterprise and Estonia were the strongest indicators yet of the magnitude of the problem at hand, particularly when water enters the deck of vessels with large undivided spaces, such as Ro-Ro vessels. The vessel loss could be catastrophic as a result of rapid capsize, rendering evacuation of passengers and crew impractical, with disastrous (unacceptable) consequences.

Concerted action to address the water-on-deck problem in the wake of these led to the proposal of new stability requirements, known as the Stockholm Regional Agreement, or more commonly as SOLAS ‘90+50, pertaining to compliance of existing Ro-Ro vessels with SOLAS ‘90 requirements whilst accounting for the presence of a maximum 0.5 m height of water on the vehicle deck. In view of the uncertainties in the current state of knowledge concerning the ability of a vessel to survive damage in a given sea-state, an alternative route has been allowed which provides a non-prescriptive way of ensuring compliance and one hopes enhanced survivability, namely the “Equivalence” route, by performing model experiments in accordance with the requirements of the SOLAS regulation II-1/8.

In response to these developments, the shipping industry, slowly but steadily, appears to be favoring the model experiments route, implicitly demonstrating mistrust towards deterministic regulations which, admittedly, lack solid foundations. An attractive alternate route to tackling the water-on-deck problem in a way that allows for a systematic identification of the most cost-effective and survivability-effective solutions had been introduced by the Ship Stability Research Centre (SSRC) at the University of Strathclyde, by making use of a mathematical/numerical model, developed and validated since 1997, describing the dynamic behaviour of a damaged vessel in seaway whilst subjected to progressive flooding (Vassalos et al., 2000)

2.3 Methods of Investigating Vessel Stability

Vessel stability is very important to vessel designers, vessel operators and regulatory bodies, because it is a major design requirement and also the key factor in ensuring the safety of human life. Throughout this period, numerous studies have been carried out to evaluate the vessel stability. Generally, the vessel stability can be solved in four different methods, namely: (i) Statistical approach; (ii) Analytical approach; (iii) Experimental approach; and (iv) Time Domain Simulation approach.

2.3.1 Statistical Approach

Under the statistical approach, it is assumed that vessel stability can be determined by analyzing the vessel geometry and the weight distribution. In other words, vessel stability depends on the shape of the GZ curve in still water. In this approach, the main assumptions are (i) The buoyancy force is constant, (ii) The contribution of the kinetic energy or energy dissipation is ignored, (iii) The excitation force acting on the vessel can be neglected, and (iv) The coupling and hydrodynamic effects are ignored. Statistical approach is still the basis of many regulations proposed by the International Maritime Organisation (IMO), U.S. Coast Guard (USCG), U.S Navy etc, and Lewis (1988).

2.3.2 Analytical Approach

The analytical approach is a method using mathematical function to analyze the problem of vessel motion. This approach provides an efficient way of obtaining stability boundaries without having to solve the equations of motion. Bifurcation method (Umeda, 1999) and the use of Mathieu equation (Neves et al., 1999) to define the boundary of the parametric excitation region are the examples of the analytical approach. Unfortunately, the analytical approach involves the theories and mathematics that are difficult to understand by the designers and legislators. Moreover, the link between the mathematical stability and vessel stability has not been shown to satisfaction of the practicing vessel designers.

2.3.3 Experimental Approach

The experimental approach is the most reliable method to evaluate vessel stability. The main reason is due to the ability of experiment to show the real situation in a particular condition. As shown by Grochowalski (1989) and Yamakoshi et al. (1982), the experimental approach is very useful and could be applied to simulate the problem of vessel stability in dynamic situation. Generally, there are two types of model testing; Captive Model Test and Free Running Model Test. The difference between these testing is, captive model test is conducted in a towing tank, whilst the free running model test is conducted in open water.

The use of experimental approach in vessel stability is limited because it is very expensive and also very time consuming. As a consequence, the main purpose of experiment concentrates on checking and verifying the results obtain from theoretical analyses. For example it is very difficult to model the non-linear roll motion that is dominant by the viscosity.

2.3.4 Time Domain Simulation Approach

The aim of the Time Domain Simulation approach is to relate the vessel stability to the vessel motion. Previously, this concept was hard to be followed because it involves many complicated computation procedures. However, with the advancement of computer technology, this study becomes easier and it has attracted many researchers to follow this concept such as Paulling et al. (1975), Hamamoto and Akiyoshi (1988), de Kat and Paulling (1989) and Umeda et al. (2000). Under this concept, the equations of motions, which are made up by three translation components: surge, sway and heave, and three rotational components: roll, pitch and yaw are solved simultaneously by utilizing numerical integration procedure.

Although this approach is able to provide a faster result, but care should be taken when applying this approach. The following points must be properly considered while using this approach.

- Mathematical Modeling

Time Domain Simulation approach depends on the mathematical model and the assumptions incorporated in the analysis. Until now, many mathematical models have been developed around the world. As yet, there is no real proof to show that which type of mathematical model is the most suitable one; each model has its own advantages.

- Non-linearity

In large amplitude and capsizing situation, the equation of vessel motion is strongly dominant by many non-linearity terms. Therefore, the use of linear theory (frequency domain) is not suitable to be applied in this case. Consequently, the complicated non-linear equations of motion require the use of Time Domain Simulation approach as a tool to solve this problem.

- Hydrodynamic coefficient

The accurate prediction of the hydrodynamic coefficient such as added mass and damping is a complicated process. It is because of both the added mass and damping strongly depending on the frequency and underwater geometry. The well-known strip theory proposed by Salvesen et al. (1970) is the method frequently used to solve this problem. But, it should be noted that this theory is developed for vessel motion in small amplitude and viscous effect is neglected.

- Reliability

Since it is very difficult to cover all the effects in the equations of motions, this approach provides only some trends and solutions of vessel safety in certain conditions. Generally, performing experiment is the only proven method to evaluate the reliability of the simulation result.

- Practical application

One of the limitations of the results obtained from the theoretical approach is very hard to be understood by those without the specialised knowledge in this filed. As a result, vessel designers usually do not appreciate the physical meaning of the results. In order to avoid this problem, the results should be presented in a form, which is simple and easily understood by the user.

2.4 Review of Existing Damage Stability Criteria for Small Vessel

With the development of many new types of HSC in the 1980s and 1990s, IMO decided to adopt new international regulations dealing with the special needs of this type of vessel. In 1994, IMO adopted the International Code of Safety for High-Speed Craft (HSC Code) (resolution MSC.36 (63), which was developed following a revision of the Code of Safety of Dynamically Supported Craft (resolution A.373(X)). Also in 1994, IMO adopted a new SOLAS chapter X - Safety measures for high-speed craft, which makes the HSC Code mandatory high-speed craft built on or after 1 January 1996. The Chapter was adopted in May 1994 and entered into force on 1 January 1996.

The HSC Code applies to high-speed craft engaged on international voyages, including passenger craft which do not proceed for more than four hours at operational speed from a place of refuge when fully laden and cargo craft of 500 gross tonnage and above which do not go more than eight hours from a port of refuge. The Code requires that all passengers are provided with a seat and that no enclosed sleeping berths are provided for passengers.

The Code is intended to be a complete set of comprehensive requirements for high-speed craft, including equipment and conditions for operation and maintenance. A basic aim is to provide levels of safety which are equivalent to those contained in SOLAS and the International Convention on Load Lines, 1966. The HSC Code includes very detailed requirements such that a high-speed craft deemed to be in compliance with the Code is therefore deemed to be in complaince with SOLAS chapters I to IV and regulation V (12).

Due to rapid pace of development in the HSC sector, in December 2000, the Maritime Safety Committee adopted amendments to SOLAS chapter X to make mandatory for new ships the High-Speed Craft Code 2000. The 2000 HSC Code updates the 1994 HSC Code and will apply to all HSC built after the date of entry into force, 1 July 2002. The original Code will continue to apply to existing high-speed craft. The changes incorporated in the new Code are intended to bring it into line with amendments to SOLAS and new recommendations that have been adopted in the past four years - for example, requirements covering public address systems and helicopter pick-up areas.

Table 2.1 shows the extent of damage for small craft under HSC Code (2000) requirement. The permeability of compartment may range between 65 to 95 percent depending upon the type of compartment and the cargo inside it.

Table 2.1 : Extent of damage length

Extent of Damage	Passenger/Cargo (HSC Code)
A. Side Damage	
1. Longitudinal	0.1L or 3m + 0.03L or 11 m whichever Least
2. Transverse	0.2B or 0.05L or 5m whichever Least
3. Vertical	Full Depth
B. Bottom Damage	
1. Longitudinal	0.1L or 3m + 0.03L or 11 m whichever Least
2. Transverse	Full breadth or 7m whichever Least
3. Vertical	0.02B or 5m whichever Least

In assessing the damaged stability of small vessel, the criteria used are considered less rigorous than the large vessel, but nonetheless it takes into consideration the minimum freeboard, maximum allowable heel angle, and residual stability (Samian and Maimun, 2000). As for intact stability, the damage stability criteria also vary depending upon the purpose of the craft. For HSC code (IMO, 2000) the damage stability criteria can be summarized as in Table 2.2.

Table 2.2 : Damage stability criteria for small vessel

Damage Stability Criteria	Passenger Craft (HSC Code)
1. Damage Waterline	300 mm
2. Freeboard	Positive
3. Angle of Heel	≤ 10 deg
4. Residual Stability	
a. Range of Positive GZ	≥ 15 deg
b. Area Under GZ Curve	≥ 0.015 m
c. Maximum GZ	≥ 0.1 m
d. GM	≥ 0.05 m
e. GZ due to Heeling Moment	Heel moment/disp + 0.04 and ≥ 0.1 m

2.5 Limitation of the Existing Stability Criteria

As mention previously, the existing stability criteria are developed based on conventional approach. Although this type of stability criteria are easier to be followed, but many problems still can be found on the stability criteria. Below are the limitations that occur in the existing stability criteria.

- Lack of the sample data

The size of sample data is very important for the development of the statistical approach stability criteria. But, it is difficult to obtain lots of casualty data. As a result, this makes the statistical analysis become unsatisfactory.

- Dissimilarity occurs in the sample data

The dissimilarity of sample data is another problem making the statistical stability criteria become unsatisfactory. This problem arises due to the difficulty to collect the sample data that is similar in size, projected lateral area and the same loading condition. Not only that, but also the casualty happened on the vessel is different.

- Over-simplified the problem occurs on vessel stability

The introduction of the righting arm curve in still water is too ideal looking for the problem arises in vessel stability. In fact, the effect of wind and wave forces acting on the vessel cannot be neglected in the vessel stability. Although some criteria like IMO Weather criteria and Strathclyde criteria include the effect of wind and wave on the vessel stability, but all are taking in quasi-static situation and do not solve the problem arises in dynamic situation.

- Not suitable for new design

The design of vessel especially small vessel is continuously changed. Hence, reliance on the old criteria for the use of the new design is less reliable. Amy et al (1976) showed an example of a supply vessel. In their study, they found that the stability criteria based on conventional hull form always not possible to ensure the safety of the new design of supply vessel. For this reason, stability criteria should be continuously revised and developed based on sufficient information of the new design.

2.6 Characteristic of Small Vessels in Dynamic Situation

Stability of small vessel is considered as a complex matter compared to the large vessel. The main reason is due to the size, specific mission and design of small vessel is totally different from large vessel. In the study of Nickum (1978), he discussed the U.S. Coast Guard criteria and IMCO criteria of the seagoing vessel. He concluded that there was no problem had been found on the existing stability criteria as a guideline to evaluate vessel stability of large vessel. But, for vessel under 100m such as coastal freighters, coastal bulk carriers, fishing vessels, towing vessels, yachts and research vessels usually suffered the most part of casualties even it had satisfied the stability requirement.

Storch (1980) analyzed 22 cases of crab boat casualties in the Pacific Northwest during the years 1970 to 1974. He grouped the causes contributed to each casualty as human error, bad weather, design deficiencies, improper maintenance and stability loss. He found that human error contributed the highest cause of casualty. Although no clearly indication to point out that the main crab boat casualty was related to the problem of existing stability criteria proposed by IMCO, but he still emphasized that the stability instruction given by the regulatory body should be strictly followed by the operators to avoid casualty.

Morall (1979) conducted capsizing experiment on small fishing boat models in various sea states and made a conclusion that the IMO criteria were rather inadequate. He indicated that dependency on GM alone to define vessel stability is not enough. Then, he recommended more emphasis should be given on determining the maximum value and position of the maximum righting moment on the stability curves as well as the minimum value of the angle of vanishing stability. His findings were similar to the problem faced by many offshore supply vessels in United States, Bovet (1973). Casualty records showed that the dependency on GM alone in defining safe stability criteria has led to a number of vessels being lost.

Based on the analysis of vessel lost of small fishing vessel during 1965-1984 in north China inshore water, Huang et al (1994) found that many lost vessels are well designed to meet the requirement of the stability criteria. The finding indicated that the main reason of this problem is due to the current stability criteria are simply based on the statical equilibrium between heeling and righting moment.

Obviously, many studies showed that the existing regulations are not enough for defining safe stability of small vessel in dynamic situations (effect of wind and wave). The main reason is due to small vessel having small reserve buoyancy and more susceptible to large motions as compared to large vessel. Hence, a critical look on the stability of small vessel should be carried out. It is recommended that the new stability criteria not only cover the possible problem arising in dynamic situation but also practical to be referred by the vessel designer and operator.

2.7 Review on Stability and Survivability Problems

Being a popular subject, safety and survivability of vessels is of great interest to everyone. A considerable amount of studies on this subject have been carried out and others are still ongoing. The interest for researchers in understanding the reasons for the different problems of survivability such as capsizing and loss of stability lead some of them to focus on different factors. Some investigators focus on the effect of the environmental aspects and findings from these investigations has resulted in conclusions and solutions to some of the problems.

Pioneering damage stability experiments were carried out in the early 1970s by Bird and Browne (1973), and Middleton and Numata (1970). From the damage stability experiments carried out in Bird and Browne (1973), it can be concluded that capsizing is definitely related to environmental parameters. In this study the model used was a typical Passenger/Vehicle ferry and the experiments were carried out for different sea states, loading conditions and freeboards. Where capsizing occurred, the primary cause was considered to be the accumulation of water on the main deck due to spillage of water and roll motion. These experiments also revealed that wave height is a very significant affecting capsizing. The findings suggest that significant increases in initial stability are required in order to resist capsize, as freeboard decreases and wave height increases.

Research by W. Blocki (1986) supports the commonly held view that the probability of capsizing of a vessel increases at higher sea states and for longer periods of stay in given conditions. When the deck is flooded (especially the car deck) the static stability becomes worse due to the dramatic decrease in the water plane area. The combination of low GM and accumulation of water leads the vessel to rapid capsizing as was experienced in the Herald of Free Enterprise disaster.

Another observation is that the critical GM (metacentric height to avoid capsizing) is very sensitive to initial heel. The experiments carried out by Adee and Pantazopoulus (1986) indicated that most of the capsizing cases were related to the large static or pseudo-static heel due to trapped water on the vessel's deck. For intermediate and low metacentric height cases the presence of water on deck results in a larger roll oscillation and leads to dangerous conditions including capsizing.

The static and dynamic effect of water on deck is an important effect to be considered. It was found from experiments and confirmed by theoretical studies that the dynamic behaviour of water on deck has an adverse effect on vessel motions when the natural rolling period of the vessel is close to that of the motions of shipping water (Faltinsen, 1974). It was also claimed that the motion of water on deck sometimes works as a damping mechanism against the vessel's motion (Dillingham, 1981). This problem is highly non-linear and is difficult to model analytically. Most of the results concerning the effect of water on deck have been derived from model experiments, and the studies are mainly on small vessels such as fishing vessels and on liquid tanks of LNG vessels. Therefore, it is important to investigate the static and dynamic effects of water on the vehicle deck of ferries.

A vessel with static heel can be excited easily by a large range of sea states, as static heel changes the hydrostatic and hydrodynamic characteristics of the vessel. Kobayashi (1975) concluded from his theoretical and experimental work that heel, waves, wind and their direction are very important parameters influencing vessel motions and stability. He also claimed that the effect of heaving motion on roll motion cannot be ignored for an inclined vessel. His experimental and theoretical results showed that the roll amplitude for heeled conditions is greater than that for the upright condition, especially at around the resonant frequency.

Although theoretical methods used to calculate the hydrodynamic coefficients are well established, they cannot predict most of the non-linearities such as viscous effects and non-linear couplings. This is important for motions such as roll which is affected significantly by these non-linearities, especially when the excitation frequency is close to the natural roll frequency. Therefore, probably the best way to determine hydrodynamic coefficients is by means of model experiments. Non-linear effects which cannot be modelled theoretically can also be measured by means of experiments.

Pioneering experiments for the determination of hydrodynamic coefficients were carried out in the late 1950's and early 1960's. Vugts (1968) carried out experiments for different cross-sectional shapes, draughts and frequencies and his results have been the major reference for most researchers. However, his results are for small amplitude motions and include only two-dimensional effects. Beukelman (1984) also carried out experiments for a whole vessel in shallow waters and measured the coefficients at predefined sections. By using these experimental results he tried to improve strip theory calculation for shallow water. However all these experiments were carried out for vessels at upright conditions and for small amplitudes. As mentioned above, coefficients may change for an inclined vessel due to the new underwater volume of the vessel and hence the restoring force and moments, can change significantly.

Another study attempted to develop an analytical method for predicting the wave-excited motions of vessels with static heel due to asymmetrical flooding (Lee and Kim, 1982). This method is based on linear wave excitation formulated in the frequency domain and takes into account 5 degrees of freedom coupled motions. The hydrodynamic coefficients are obtained again by using strip theory. In order to predict the roll motion correctly around the resonant condition, viscous damping and wave drag forces are included in the mathematical model. In this study, while it was accepted that the vessel motions at an inclined condition may be non-linear, the linear method is claimed to provide most of the essential features of the motion characteristics of the vessel. Based on this method it was found that a vessel with a static heel can be excited to large roll amplitudes in the case of head waves. It was also claimed that for a vessel at neutral heel, waves coming from the opposite direction to heel could excite larger roll motion than waves coming from the heeling side. However, this model is formulated in the frequency domain and the static inclination is modelled by assuming asymmetric weight distribution. Therefore, the method cannot provide any information on water accumulation or the behaviour of a vessel during progressive flooding.

The idea of directional instability due to sway-roll-yaw coupling was one of the reasons behind capsizing as put forward by Bishop, Price and Temarel (1989). A combination of other effects (flooding, water on deck, waves, heel, trim) with forward speed can cause directional instability and may lead to rapid capsizing. Although it would not be the primary cause for capsizing or instability of a damaged vessel, it surely has a contributory effect on capsizing and must be considered in the case of forward speed.

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 by Vassalos (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_f 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 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 (Kambiseri 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 by 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 2000s by 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.

Development of mathematical model for the simulation of large amplitude vessel motions and capsize of a damaged vessel at zero speed in waves was carried out by Papanikolaou (2000). The non-linear equations of vessel motions, accounting for the effect of flooding, have been exactly formulated based on large amplitude rigid body dynamics. However, in order to simplify their solution, the mass of the flood water is assumed to be concentrated at the centre of vessel's volume occupied by the fluid. A semi-empirical water ingress/outflow model accounting for the damage opening and the effective pressure head is used for the modelling of the water flow into and out the damaged vessel compartments.

Another experimental research was carried out to determine the relation between the height of water on deck and the critical significant wave height for capsizing, and on the effect of the peak period of wave spectrum (Haraguchi and Murashige, 2000). In this experimental research, beam waves were carried out having the characteristics of Japanese vessels and waves around Japan. It concluded that when a vessel has no initial heel angle capsizing does not occur, but an initial heel angle of as small as 2 degrees put the vessel in dangerous condition for capsizing. Meanwhile, the critical significant wave height for capsizing is affected by the peak period of the wave spectrum.

Contribution of the water accumulation on the Ro-Ro vehicle deck and the characteristics of the flooding process are an important effect to be considered (Vassalos et al. 2000). Experiments were carried by using a scaled model of a typical Ro-Ro vessel. Another research attempted to relate the effect of GM_d (GM in damaged condition) on the mean heel angle and the mean water on deck in the stationary condition (Ishida et al., 2000). In this research, an experiment on the stability of a Ro-Ro passenger vessel with side damage was conducted in Beam seas. Ishida and his teams showed that when GM_d (GM on damaged conditions) gets larger, the mean water on deck also becomes larger, but the vessel is stable with smaller heel angle value.

2.8 Review on Vessel Response

In order to calculate vessel motions, there are two main approaches depending on whether a solution is sought in the frequency or the time domains.

Frequency domain analysis is a very good approach for engineering purposes when a wide range of information is required. General information on sea states, hydrodynamic coefficients or vessel responses can be obtained immediately by looking at one graph. Another advantage is that results can be obtained very quickly with short computing time. However, it is difficult to obtain explicit results especially if there are time dependent parameters, non-linearities and large amplitude motions. Today, frequency domain analysis is widely used for preliminary calculations of hydrodynamic forces (Dillingham, 1981; Bishop, 1989; Inglis and Price, 1982a; Inglis and Price, 1982b) and vessel Response Amplitude Operator (RAO). By obtaining the relevant information from these preliminary calculations, the next stage, which refers to time explicit calculations, can be carried out.

In order to obtain an exact solution, one must observe the changes in parameters and responses, and reflect these changes immediately on other parameters, as well as including the non-linearities and large amplitude motions (Turan and Vassalos, 1993). Time simulation seems the only option for modelling such detailed calculations.

The development of time simulation has been linked to computer technology. Almost 40 years ago, the majority of the studies were undertaken in the frequency domain due to the limitation on computer technology and its availability. However, as computer technology has advanced, the time simulation approach gained more ground. Today, very fast computers force most of the research activities to utilize simulation techniques.

The greatest contribution of time simulation is that non-linear effects can be included in the study. The instantaneous changes in the underwater volume of a vessel was proven to be very important on vessel motions and included in the calculations (De Kat and Paulling, 1989). Time simulation also showed that hydrostatic coupling, especially between roll and heave, is very strong (Francescutto and Armenio, 1990). This was further improved when the effects of the instantaneous wave profile were included (De Kat and Paulling, 1989).This approach which provides non-linear restoring/excitation has gained some ground for head and following waves but not for beam waves (Denise, 1982).

In order to model flooding, the best approach is the time dependent added weight method which allows the water to be added at specified time steps while the vessel motions are calculated at that instantaneous moment (Turan, 1993). The same approach can be used to investigate water accumulation.

Another very important benefit that time simulation provides is the modelling of random waves. In time simulation the vessel can experience waves which have different frequencies and heights. Of course there are still points that are not really well established such as time dependent hydrodynamic coefficients and forces. De Kat and Paulling (1989) tried to introduce time dependence on hydrodynamic coefficients so that different frequencies can be employed during the time simulation. It is quite likely that as time simulation attracts more researchers and computers become faster these problems will be solved gradually.

2.9 Considering the Design Aspects

High operational efficiency is desired by the owners of commercial vessels and is attained by neglecting some design factors which are related to vessel survivability. This, however, simply increases the potential risk of disaster. For instance, short-range ferries which have a high passenger capacity have capsized or sunk in Bangladesh and in Philippines with a large number of deaths. These ferries are designed for shallow waters, and have very low freeboard and high superstructure which reduce their seakeeping characteristics and seaworthiness. In addition, most of these boats do not meet the existing stability criteria at some operating conditions and are usually overloaded.

In the region such as North Sea, Baltic Sea, English Channel, and European Continent where the economic standards of the countries are similar, large trade volume, hence busy transportation, exists. This factor makes Passenger/Vehicle ferries very popular, therefore the ferries serving in these areas are the most advanced ferries with very high standards of service. However, despite the improved standards of service they do not have good safety standards in realistic terms and the recent ferry disaster (Herald of Free Enterprise) focused everyone's attention on the potential capsizing risk of ferries.

Car decks in ferries are not divided by any transverse bulkheads, this, of course, increases the risk of capsizing or loss in the case of flooding. Subdividing the vehicle deck transversely is probably the most reliable approach when considering safety, but the least viable when considering the initial cost, and the resulting low capacity and low efficiency. Recently, some designs which divide the vehicle deck transversely were proposed. These designs use mainly partial or full height retractable barriers. Fitting portable barriers seems a reasonable idea considering their flexibility and better economic efficiency compared to fixed barriers. Furthermore, partial bulkheads are not structurally as strong as fixed bulkheads, therefore, they may be damage very easily in the case of shifting cargo or collision. Therefore, before rushing into fitting these bulkheads without knowing the consequences, extensive investigations must be carried out by taking into account effects of different structural bulkhead designs, compartment lengths etc.

A recent trend in designs is to have a double skin below the bulkhead deck to prevent flooding against minor damages and this can be designed along the whole vessel length or part of it. This type of design is also recommended by the probabilistic approach, as long as the depth of the double skin is not less than 20 % of the beam at each side. This is a very efficient arrangement to keep flooding in the small side tanks, as long as the inner hull is not penetrated. It would cause heel only due to the asymmetric flooding of the side tanks, but, this permanent heel may cause a problem if the side structure above the bulkhead deck is damaged. Another and probably the worst problem may results following penetration of the inner skin which will flood the inner hull. Since the probabilistic approach allows vessels to have an undivided inner hull, any damage would inevitably sink the vessel.

In order to minimize sinkage and heeling of a vessel by the amount of water entering, it is logical to reduce the permeability of the flooded compartment especially below the waterline. This can be done by storing empty drums inside the wing tanks. Polythene drums or balls seem to be suitable in wing spaces because they cannot corrode and can be removed very easily (Vossnack, 1987).

As mentioned before, in order to comply with the new damage stability rules, existing ferries have to be modified to increase their residual stability. To meet these standards some vessels had to be fitted with side sponsons to increase the residual buoyancy (Llyoids, 1990). In order to create enough residual buoyancy as well as stability for new designs, the side tank arrangement above the bulkhead deck has been proposed (Llyoids, 1990) which may be more economically viable.

2.10 Concluding Remarks

The existing damage stability criteria are inadequate and do not reflect the true standard of safety since they ignore the changes in modern vessel design. The effect of waves and other external forces are neglected in the existing criteria, and reliance is based only on the reserve stability of the intact vessel. Although the probabilistic approach is more realistic compared to the deterministic approach, it is more complex and lacks experience in its application. Furthermore, it does not include the effect of waves and other external forces. Review of existing studies leads to the conclusion that external forces such as waves, wind, and accumulation of water on deck are prime causes of capsizing or loss of damaged vessels. It is also concluded that the initial permanent heel due to asymmetric flooding affects the vessel's stability considerably. Transverse bulkheads are found to be a better alternative than longitudinal subdivisions with respect to survivability. It is very clear that there is a need for a more comprehensive approach to the damage stability assessment of passenger vessels. For this reason, the damaged vessel motions, under the effect of external forces, must be investigated as a first step to help in the development of a dynamic damage stability assessment.

CHAPTER 3

RESEARCH APPROACHES

3.1 General

This chapter puts emphasis 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 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.

In addition, there are some parameters other than environmental which are found to have an affect on damage stability. These include progressive flooding, asymmetric flooding, flooding of the main vehicle deck and accumulation of water.

In order to achieve success in developing realistic damage stability for vessels, the most important step is to adopt a new approach to investigate the capsizing and damage stability for small vessels. This approach must include all the important parameters influencing dynamic damage stability in the most meaningful way. The damage scenarios must be modelled and a computational procedure must be developed.

3.2 Dynamic Analysis

In order to develop a realistic model which include the dynamic effects, it is not only a matter of including everything, but also important to incorporate and combine all these effects in the most meaningful way. For the dynamic analysis, the approach adopted and the parameters taken into account in the modelling are-

i. Time simulation approach,
ii. Motions,
iii. Forces and moments,
iv. Flooding, and
v. Water Accumulation

3.2.1 Time Domain Simulation Approach

Damage and flooding are continuous phenomena which may lead to different results depending on the parameters used. Investigating the behaviour of vessel in different conditions would certainly help to provide a better understanding of the capsizing phenomenon and to develop a realistic damage stability assessment procedure. Small vessels have smaller reserve buoyancy and the length of compartment, progressive flooding will be the serious part. In order to take into account non-linearities, changes in excitation forces, response of vessel in time, and progressive flooding is a need to adopt time simulation modelling.

Time simulation with small steps gives a very clear fact of what is happening. The time simulation process starts from the beginning of flooding when the initial condition of the vessel is known. At each time step, different parameters such as the amount of water inflow, heel, displacement, excitation force and response amplitude of the vessel's motions can be examined in detail. This process continues until either capsizing occurs or the total time allowed for simulation is used up.

3.2.2 Vessel Motions

The static and dynamic stability of a vessel depend on its heeling or rolling motion. This heel or roll angle is itself used as a criterion which is considered by intact and damage stability assessments of vessel. However, in a real environment there are others motions which effect the vessel's stability and roll motion, directly or indirectly.

The most important effect of heave motion is the non-linear coupling between roll and heave due to changes in restoring forces and moment. This occurs due to the significant changes on the instantaneous underwater volume of the vessel which becomes more vital in the case of large amplitudes.

Another effect of heave is that, it may cause water to flood in if the vessel's main deck submerges due to large heaving amplitudes. The coupling between sway and roll is well known and this may be strong enough to exacerbate the vessel's roll. Especially in a damaged condition, even a few degrees of roll amplitude due to sway may be enough to flood the areas above the waterline (Turan and Vassalos, 1993).

In the case of Beam seas, pitching is usually small and thus it can be ignored, but trim is considered to be vital for stability and its effect is taken into account. Due to the reasons explained above the equation of motion following non-linear coupled system of equations is used for the calculation of surge, sway, heave, roll, pith and yaw motions together with instantaneous sinkage and trim.

3.2.3 Forces and Moments

It is assumed that the cause of vessel motions derives from wave and wind excitation, as well as the internal conditions of the vessel and its cargo such as flooding, water accumulation on deck or shifting of cargo. The latter excitations originate of course, from wave and wind effects. In response to these excitation forces the vessel produces reaction forces such as hydrostatic (restoring) and hydrodynamic (radiation forces and wave excitation forces). The following sections explain how these parameters are determined.

- **Wave Excitation Forces**

Waves may be considered as regular or irregular, but in this research regular waves are taken into account in the investigations undertaken. In addition, although the mathematical model can handle waves from any direction, only beam waves are considered in this study. The wave excitation forces and moments can be separated into two: Firstly, the Froude-Krylov forces and moments which are caused by the undisturbed incident wave when it passes through the vessel, assuming that the vessel is not there; secondly, the diffraction forces and moments which are caused by the hydrodynamic disturbance due to the presence of the vessel. Wave excitation forces and moments are calculated by using a two dimensional method using integral equation.

- **Hydrodynamic Coefficients**

The hydrodynamic coefficients (radiation force) are very important in estimating vessel motions by theoretical and experimental methods. The theoretical method used in this research to estimate the hydrodynamic coefficients (added mass and damping) is based on two dimensional linear potential theory and thus it does not include viscous effect. The sectional added mass and damping are integrated along the vessel to obtain the total coefficients of a vessel.

In addition, the vessel is assumed to oscillate with small amplitudes to satisfy the linear theory requirements. This may affect the prediction of vessel motions, especially the roll motion significantly. The estimation of roll damping, in particular, is quite difficult because it is significantly affected by fluid viscosity. Ikeda’s semi-empirical roll damping calculation method, which includes viscous effect and has been shown to give good results for symmetric vessel and moderately large amplitudes, is used for the estimation of roll damping (Ikeda et al. 1978).

- **Restoring Forces**

In order to take into account the non-linearity in the restoring forces, which result from large amplitude motions, they are calculated instantaneously at each time step. This is accomplished by calculating the underwater volume of the vessel up to the free surface at each time step and by taking into account instantaneous roll and heave motions. Free surface in the calculations can be defined either by taking into account the calm water or the wave profile.

When the wave profile is taken into account, the resultant force is not purely the restoring force but the combination of restoring and hydrostatic wave excitation force, which is called static Froude-Krylov force (De Kat and Paulling, 1989). This force is a result of the undisturbed wave profile.

Application of restoring force together with static Froude-Krylov force is still fraught with problems, which may be due to the limitation with the mathematical modelling. Furthermore it creates inconsistency between the calculation approaches of hydrodynamic properties of vessel (i.e Wave excitation forces are calculated up to the exact free surface, but added mass and damping properties of the vessel can be calculated only up to the calm water surface).

Application of the integration of the pressure up to the exact free surface proves to be giving good results for following waves De Kat and Paulling, 1989) but seems to fail for Beam seas since the results of vessel motions appear to be overestimated. Due to the uncertainties and limitations during the analysis, the free surface is presently defined by considering the calm water level.

3.2.4 Flooding

Flooding can be defined in two ways. Firstly, by assuming that there is a constant rate of flooding at each time step and that the total amount of water can be predefined. Secondly, by taking into account the instantaneous relative water elevation at the damage location, which is probably the most realistic method. The method determines whether water floods in or not and continues until the vessel either capsizes or the predefined period for time simulation is used up.

Considering the second option of water ingress is presently used in the parametric study. The effect of water on vessel has been studied in this research. The water will flow in or out depend on the wave, its direction and height, and vessel motions on the water ingress, location and extent of damage. After the water in damaged compartment reached certain height, the water will flow in to the adjacent compartment similar to flow over a weir.

3.2.5 Water Accumulation

The entrapped water on deck poses stability problems and contributes substantially to capsizing. The effect of water can be of either static or dynamic in nature. At present the accumulation of water is included in the equations of vessel motions in a static sense, by taking into account the instantaneous amount of water on deck, roll and trim.

3.3 Computer Programming

Using the new mathematical model, a computer program based on MATLAB was developed. The solution of the mathematical model of vessel motions in time domain is carried out by using ODE's Library in MATLAB program. The damaged vessel behaviours is then simulated numerically in time domain.

3.4 Model Experiments

In the experiments, the integration of module using progressive scans CCD cameras and image processing techniques is applied to investigate the motions of model performance. The results of experiment are used to verify the simulation output. The experiments covered the following:

i. Roll decay test to determine the natural roll period and KG of the vessel.

ii. Damage stability experiment on still water to determine the flow coefficient (K) of water ingress.

iii. Damage stability experiment on dynamic situation to obtain the vessel motions.

3.5 Parametric Study

The main point of parametric study is to give a better understanding of the influence of parameter on the damage stability performance of small vessels. Beside that parametric study carried out to find the behaviour of the small vessels in damage condition. This help in optimising the small vessel design in view of vessel safety. The vessel is chosen for analysis is Sarawak Fast Ferry. The vessel has a large passenger capacity and large length to breadth ratio approximately 10. If the length to breadth ratio is large, it means that the vessel is slim with small breadth. Hence, she is very sensitive toward rolling motion and may capsize quickly if encounter a moderate height beam waves.

For the purpose of analysis, information such as lines plan, hydrostatic data and curves, and general arrangement are needed. Only regular beam waves are considered in this parametric study. The wave length was chosen to be equal to ship length and the wave direction is 90 degrees. The most important thing is verifying the output of simulation program with the result of experiment for validation.

The investigation addresses a range of parameters known or expected to play a key role, including: wave height and length, vessel motion, and loading condition. Both excitation and vessel parameters are investigated systematically over a wide range, so that the most important parameters and their limiting values can be identified. The Information obtained from the investigation, using a time domain procedure forms the basis for developing the damage stability assessment procedure.

3.6 Concluding Remarks

In order to develop a dynamic analysis for damaged ship by using time domain simulation, a procedure is followed to ensure the study can be conducted in a systematic way. The present approach attempts to incorporate all the key factors known or expected to play an important role in affecting the dynamic behaviour of a damaged ship in realistic environmental conditions. Furthermore, emphasis is placed on practical ship stability (in understanding how capsizing occurs), what cause it, which conditions are dangerous, how ship survivability can be enhanced and how it can be assessed.

CHAPTER 4

MATHEMATICAL MODEL

4.1 General

Technique of simulating ship motions in damaged situation is presented in this chapter. The theory behind the Time Domain Simulation program is explained. This involves the treatment of the forces in the program and method to solve the equations of motion.

For ease of approaching the modelling of a complex problem, such as the dynamic behaviour of a damaged vessel in a realistic environment, the mathematical modelling is structured on the basis of the main contributing effects which can be grouped as follows:

i. Hydrodynamic effects (wave excitation and hydrodynamic reaction)
ii. Hydrostatic effects (restoring forces and moment)
iii. Flooding effect (water ingress and flooding)
iv. The above effects are incorporated in the formulation of the vessel motions in the time domain, which comprises coupled sway, heave and roll.

However, first, the co-ordinate systems used in the above calculations are defined.

4.2 Co-ordinate System

In the development of the mathematical model, there are three co-ordinate systems used in this study and these together with the associated sign conventions are defined as follows:

The first is the vessel co-ordinate system (oxyz), which is used to define the vessel's hull and is located at the keel level of the center plane of amidship. In this system, x is positive forward; y is positive to starboard; and z is positive upwards.

The second co-ordinate system (OeXeYeZe), the earth co-ordinate system, is used to calculate the underwater volume and parameters related to it. OeXeYeZe is located at the calm water level of the centre plane amidships as shown in Figure 4.1(a). When there is no heel or trim, the wave co-ordinate system has the same direction as those for the vessel co-ordinate system.

The third co-ordinate system (OgeXgeYgeZge) 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 vessel motions. Since it is assumed that the vessel rotates around the centre of gravity, all rotational motions, exciting and restoring moments are calculated with reference to it (Figure 4.1(b)). Anti-clockwise roll motion, upwards heave in the z direction and starboard sway in the y direction are defined as positive motions.

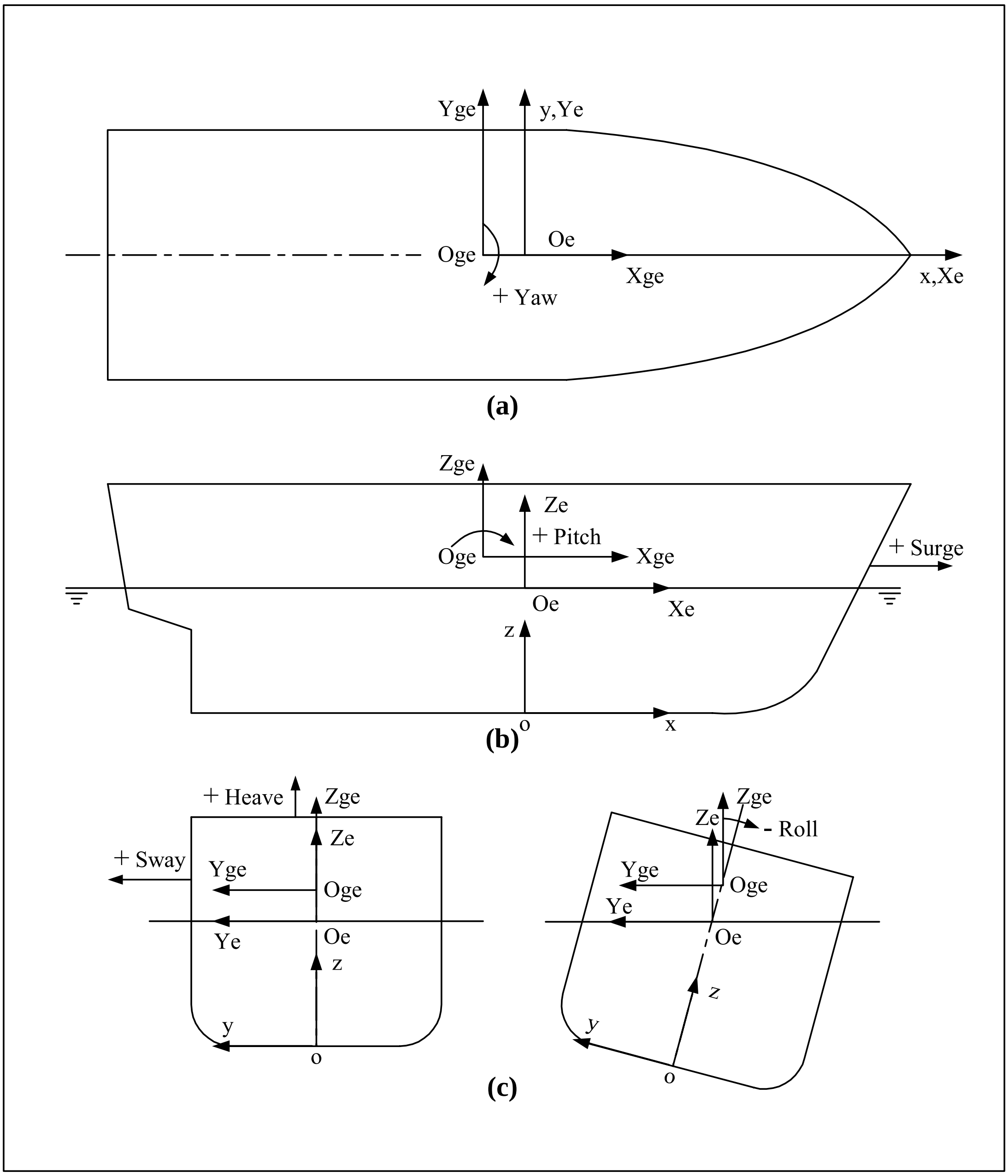


Figure 4.1 Co-ordinate system

4.3 Hydrodynamic Forces

Within the context of linear theory, the hydrodynamic oscillatory forces of a vessel 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 vessel's motion response.

Although three dimensional effects are anticipated, it is assumed that the length of the vessel is much greater than the beam and draught such that the hydrodynamic interaction in the longitudinal direction can be neglected. Under this assumption strip theory is used to formulate the above mentioned force components for a number of vessel's sections, and then integrated along the vessel length to obtain the total component force.

The wave excitation forces can be separated into two: Firstly, the Froude-Krylov forces which are caused by the undisturbed incident wave when it passes through the vessel, assuming that the vessel is not there; secondly, the diffraction forces which are caused by the hydrodynamic disturbance due to the presence of the vessel.

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.

The total velocity potential of the fluid motion, generated by regular waves with the stationary vessel section undergoing small amplitude oscillation, can be described by the time dependent potential

$$\Phi(x, y, z, t) = \Phi_I(x, y, z, t) + \Phi_D(x, y, z, t) + \Phi_R(x, y, z, t) \qquad (4.1)$$

Where, Φ_I, Φ_D and Φ_R are the incident, the diffracted and the radiated wave potentials, respectively.

In order to define the above mentioned potentials, certain boundary conditions are imposed and the problem is solved as a boundary value problem in the presence of these conditions. The solution can be separated into well known problems in association with the diffraction and radiation components which would yield the wave excitation forces and added mass/damping coefficients respectively. Definition of these boundary conditions and solution of the potentials are summarized in Appendix A for completeness.

4.3.1 Wave Excitation Forces

In this study, only the regular beam waves are considered. As mentioned above, the two dimensional source and sink method is based on sinusoidal waves. Having obtained the velocity potential for the incident and diffracted waves, the pressure distribution around a cross section can be calculated from the linearized Bernoulli equation as follows:

$$p^{(i)} = -\rho \frac{\partial \Phi}{\partial t} \tag{4.2}$$

Sectional excitation forces can be obtained by integrating the pressure as shown below:

$$f^{(i)} = \int_S p^{(i)}\, n^{(i)}\, ds \tag{4.3}$$

If these sectional forces are integrated along the vessel length the total wave excitation forces for the particular condition (frequency, wave direction, height) can be evaluated. Details of this application can be found in Appendix A.

4.3.2 Hydrodynamic Coefficients

In order to calculate motion induced forces (added mass and damping), the radiation velocity potential (Φ_R) is calculated at each section using again the Frank-Close-Fit method as in the estimation of diffraction forces. Finally, sectional added mass and damping are integrated along the vessel to obtain the corresponding coefficients for the vessel. Details are given in Appendix A.

4.3.2.1 Estimation of the Mass Moment of Inertia for Roll

A moment of inertia is the sum of all the component parts comprising vessel mass, such as machinery, structural parts, etc., each multiplied by the square of its distance from the axis about which the moment is taken. However, it is very difficult to calculate inertia in this way and it involves too much work. 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 (i_{44}) is expressed as a percentage of the vessel's breadth i.e.

$$i_{44} = C_r\ B \tag{4.4}$$

The coefficient for radius gyration (C_r) value is almost constant for a great variety of vessel types (Scheltema and Bakker 1969). For practical application the value of C_r attains the following values:

$$0.335 < C_r < 0.425 \quad \text{i.e.} \tag{4.5}$$

For large passenger vessels	$C_r = 0.425$
For warships	$C_r = 0.38 - 0.40$

Therefore, the calculations in this study the moment of inertia of the intact vessel is taken as:

$$I_{xx} = (i_{44})^2\ \Delta \tag{4.6}$$

where

$$i_{44} = 0.39\ B \tag{4.7}$$

In the case of a damaged vessel the inertia of the flooded water has to be included in the total inertia term. This can be done as shown:

$$I'_{xx} = I_{xx} + M_f \, DC^2 \qquad (4.8)$$

In this approximation, the moment of inertia of the flooded water with respect to its own axis is neglected. The roll mass moment of inertia is calculated according to the co-ordinate system, which is passing through the centre of gravity and is fixed to earth (OgeXgeYgeZge). In the case of a static heel angle, the roll mass moment of inertia will not change due to the static heel.

4.3.2.2 Vessel Mass

The mass of the vessel changes instantaneous in case of flooding and the total amount of water inflow in the damaged compartment is added to the total mass of the vessel.

4.4 Restoring Forces and Moments

These forces and moment are hydrostatic in nature with a tendency to bring the vessel back to its original position after a disturbance, and are related to the underwater volume of the vessel. These are calculated by integrating the hydrostatic pressure up to the relative free surface as shown below:

$$F(t) = \int_L \int_S p_s \; n \; ds \; dx \qquad (4.9)$$

In linear theory, the heave restoring force is represented as a function of waterplane area, while the restoring moment for roll is represented as a function of the transverse metacentric height (GM) in the static equilibrium condition (calm water). However, in a non-linear approach, these parameters are calculated by using the actual instantaneous underwater volume of the vessel and the pressure can be integrated either up to calm water level or up to the instantaneous water surface (wave position). If integration is done up to the wave surface the force is obtained, which consists not only restoring force but also static wave excitation force, is called the static Froude-Krylov force (De Kat and Paulling, 1989). The pressure and associated limits are as shown:

$$p = \rho\, g\, z \qquad ; \quad \infty < z < 0 \text{ or } \eta \tag{4.10}$$

In recent years integrating the pressure up to the instantaneous water surface has been reported to produce more realistic results when the vessel with forward speed is in following waves and wave length/vessel length ratio is around 1 (De Kat and Paulling, 1989). However, this approach does not give satisfactory results for all conditions especially in Beam waves and there is an uncertainty regarding the appropriate expression of the pressure above the calm water plane (Denise, 1982). Furthermore, Kobylinski (1990) emphasizes that in Beam Seas, as the non-linearity increases and because of incomplete definitions of some effects, the problem becomes more complex and the reliability of complex solutions becomes questionable. Some investigations regarding the effect of integration up to exact free surface indicated that in Beam Seas the response of the vessel, in the case of restoring forces, calculated up to exact free surface, is overestimated considerably compared to the experimental results, while calculation of the restoring force up to calm water produced good results compared with the experimental results.

In a fully dynamic solution an equation of motion in time domain can be written as:

$$(I_i + A_i)\, \ddot{x}_i(t) + B_i\, \dot{x}_i(t) + C_i\, x_i(t) = F_i(t) \tag{4.11}$$

Usually in this equation, added mass (A) and damping (B) coefficients are calculated in calm water and kept fixed during the simulation, while the restoring parameter, C_x, can be replaced with a non-linear restoring term which is calculated up to the calm water or the free surface instantaneously. However, calculation of restoring force up to instantaneous water surface may lead to inconsistencies and inaccurate results for some conditions unless certain non-linearities and some other effects (higher order wave excitation, non-linear coefficients) are fully taken into account. Moreover, within the limits of linear theory or other methods, inclusion of such effects even if this possible, may become very complex, difficult and unreliable (Kobylinski, 1990). Therefore, unless the same approach is used for the calculation of all relevant effects, and all non-linearities are included, it is believed that calculations must be carried out based on more established methods which provide more consistent and reliable results.

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. Thus, the non-linear restoring is calculated as shown:

$$C_{33}\,(t,z,\theta,\phi) = g \times \left[\Delta\,(t,z,\theta,\phi) - \Delta\,(t_0)\right] \tag{4.12}$$

$$C_{44}\,(t,z,\theta,\phi) = g \times \Delta\,(t,z,\theta,\phi)\left[\mathrm{TCG} - \mathrm{TCB}\;\;(t,z,\theta,\phi)\right] \tag{4.13}$$

$$C_{55}\;(t,z,\theta,\phi) = g \times \Delta\,(t,z,\theta,\phi)\left[\mathrm{LCG} - \mathrm{LCB}\;\;(t,z,\theta,\phi)\right] \tag{4.14}$$

4.5 Modelling the Damage Scenarios

In order to investigate the motions of a damaged vessel, first of all a method has to be adopted to include the effect of damaged compartments in the calculations.

There have been a number of sea accidents whereby vessels have been lost before they reached the final stage of flooding. Following recent sea accidents, the behaviour of damaged passenger vessels has become a very popular subject and as result intermediate stages of flooding have also started to receive a lot of attention.

The main aim is to analyze the motions of the damaged vessel during the intermediate stages of flooding and after the final stage of flooding in the time domain. Therefore, the method employed must be flexible enough to accommodate the following requirements:

i. Capability to define more than one damaged compartment independently at any location along the vessel and at different decks at the same time.

ii. Capability to create temporary asymmetric flooding and water transfer from one compartment to another.

iii. Capability to control and change the amount of water and flooding time in each compartment, separately.

iv. Capability to model water ingress by considering the wave elevation relative to the damage location.

v. Capability to calculate the effect of water inside each compartment, instantaneously.

4.5.1 Damage Calculation Methods

In classical naval architecture, there are two main methods to evaluate the stability of a damage vessel: lost buoyancy methods and added weight method. In this study, combination of the time dependent added weight method and accumulation of water is used.

4.5.1.1 Lost Buoyancy Method

In this method, it is assumed that the damaged compartments are opened to the sea and the vessel has lost buoyancy in these compartments. This assumption represents the final equilibrium position of the damaged vessel. Calculations can only be carried out for the final stage of flooding. Although the lost buoyancy method is suitable for the equilibrium position, intermediate stages of flooding cannot be analyzed. Moreover, the damage and flooding of the compartments above the waterline cannot be modelled by this method.

4.5.1.2 Added Weight Method

In this approach, water is added to the compartment which is assumed to be flooded. Using the intact hydrostatic values of the vessel sinkage, heel and trim can be calculated for each time step when extra water is added. This method is suitable to model the intermediate stages of flooding as well as the flooding of compartments above the waterline.

4.5.1.3 Combination of Time Dependent Added Weight Method and Accumulation of Water

The entrapped water on deck poses stability problem and contributes substantially to capsizing, especially on a large deck like that found on Roll on-Roll off vessels. The accumulated water will induce both static and dynamic effects [Adee and Caglayan (1982)]. Modelling the dynamic effect however, is very difficult from a mathematical point of view. Nowadays, this can be modelled within a certain accuracy for limited conditions with regard to boundary conditions, motion amplitude, viscosity, shape of tanks, while calculations are carried out using numerical solution techniques such as finite difference, finite elements, together with powerful computing.

The accumulation of water can be important from a dynamic point of view when the existing frequency is close to the natural frequency of water in the tank (Faltinsen, 1978). Although this is possible in smaller vessels, it is not common in the case of ferries, to meet resonant conditions, since the roll frequency in the latter is in general very low. On the other hand, progressive flooding would not allow resonant condition since the water depth changes continuously. The other effect is that water in a very large compartment may flow to the corner of the deck and create static heel. As a result, the effective breadth of the tank would be very small and water depth high. On the other hand, some experiments and a number of studies suggest that the effect of the water on deck can be represented by a pseudo-static heel angle (Caglayan, 1985).

Considering the difficulties of modelling the dynamic effect of the accumulated water and that 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,

$$W_d(t) = W_d(t - \Delta t) + W_d(\Delta t) \tag{4.15}$$

Instantaneous static force to sink the vessel,

$$F_S(t) = g\ W_d(t) \tag{4.16}$$

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

$$Mt_R(t, \phi, \theta) = g\ W_d(t)\,[TCG - tcg(t, \phi, \theta)] \tag{4.17}$$

Instantaneous trim moment,

$$Mt_T(t, \phi, \theta) = g\ W_d(t)\,[LCG - lcg(t, \phi, \theta)] \tag{4.18}$$

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

4.5.2 Modelling the Water Ingress

Water ingress is modelled in two different ways and each option serves different purposes. The two options are explained as follow:

4.5.2.1 Option 1

This option is based on predefined water flow for each damaged compartment and modelling is done as follows:

i. A maximum of three damaged compartments can be defined independently from each other. These compartments are defined according to the vessel co-ordinate system, vertically or horizontally at any location of vessel.

ii. Flooding and damage for each compartment can be specified by defining:

- The TOTAL AMOUNT OF WATER, which is expected to flow into each compartment between the initial and final stages of flooding.
- The INITIAL AMOUNT OF WATER, which is the amount already having flooded in before the time simulation starts.
- The FLOW RATE which is the amount of water flowing in to a particular compartment per unit time.
- The FLOODING TIME, which is the length of time that progressive flooding takes place.
- The STARTING TIME which controls the starting time of flooding for each compartment.

All these parameters for each compartment are defined separately and thus enabling total control on the mode of flooding. This flexibility provides the opportunity for extensive analyses over a wide range of parameters.

4.5.2.2 Option 2

This option 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 instantaneous wave elevation and vessel motions. Option 2 of water ingress provides more realistic modelling of the progressive flooding of the compartments, especially the decks above the waterline as water ingress depends on wave height and vessel motions.

As stated before, damage can occur vertically and longitudinally anywhere in the vessel. The damage opening due to collision or grounding may occur below or above the water surface or a combination of these. It has been found from theoretical studies that the flow rate of water is mainly related to the pressure head, which changes depending on the location of the hole relative to the water surface. At the same time, flow rate also related to the shape and area of the opening and empirical formula are based on these parameters as well as on the static pressure head.

The empirical formulations have generally been derived for civil engineering applications such as dam design, river flooding or canal flow. Therefore all the empirical formulations about water flow are based on calm water surface. If damage is below the water surface the existing formulation can estimate the water flow with good accuracy. However, in the case of damage at or especially above calm water surface, the existence of waves may affect the water flow considerably. At the moment empirical formula are available for the steady water flow through an opening at calm water surface such as flow over a notch or weir (Walshaw and Jobson, 1979), but there is no formulation for the water flow in a wave environment through, an opening above the calm water surface. In such cases, pressure is entirely dependent on the wave particulars such as wave height, direction and steepness. Therefore, the existing formulation which is for water flow over a notch may not give very accurate results. It has been found from damage stability experiments that water ingress is considerably affected by the wave direction (Dand, 1990), thus existing formulations may have to be correlated for this kind of problem. 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 attended as follows:

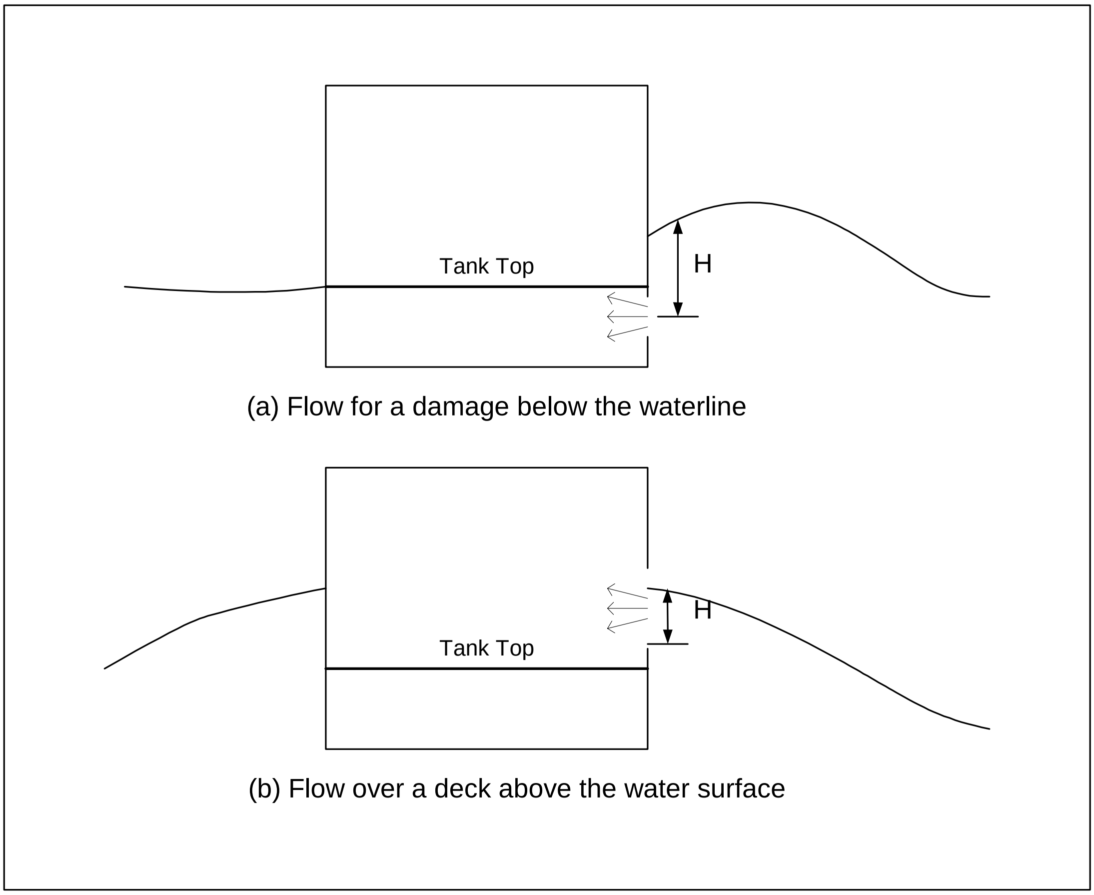


Figure 4.2 Modelling of water ingress

Flow for a damage below the waterline (Figure 4.2(a))

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,

$$U = K\sqrt{2\,g\,H} \tag{4.19}$$

Flow rate,

$$Q = U\,A_{op} \tag{4.20}$$

Flow above the water surface (Figure 4.2(b))

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.

$$U = K \sqrt{g H} \tag{4.21}$$

Flow rate calculation using equation (4.20). 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. In civil engineering applications, K is generally taken between 0.45 and 0.58 (Walshaw and Jobson, 1979). The existing empirical formula and coefficients for the water flow over a notch are approximated by using the calm surface and free discharge conditions, with these formula being based on the static pressure head. However, in the case of flooding of the compartments of a vessel above the waterline, the other effects such as wave height, direction, velocity of wave and orbital velocity of water particles, which would influence the water flow, are not included in any empirical formula. Moreover, the amount of water, which may flow out back to sea due to vessel motions is unknown and this makes the scenario more complex to model.

Since there is no relevant empirical formula for estimating the water inflow and outflow for this particular condition, the net water ingress at each time step can be approximated by using the existing formula but with an adjusted flow coefficient (K). K values for damage into and away from waves were found to be in the region of 0.2 – 0.45, respectively (Turan, 1993).

It must emphasize that these values are approximate values based on limited experiments whose objectives were different. Therefore, in order to establish an accurate estimation, specifically designed experiments for different wave directions and wave heights must be carried out.

4.6 Motions

For the analysis of vessels dynamic behaviour, the following non-linear coupled system is used for the calculation of surge, sway, heave, roll, pitch and yaw motion of the damaged vessel. Subscripts i and j (A_{ij}) show the mode of motion. i,j = 1 denotes surge motion, i,j = 2 denotes sway motion, i,j = 3 heave motion i,j = 4 roll motion, i,j = 5 denotes pitch motion and i,j = 6 denotes yaw motion. The six degrees equation of motion are:

$$(M + A_{11})\dot{u} + (B_{11})u + R_T = F_1 wave \quad (4.22)$$

$$\begin{aligned}&(M + A_{22})\dot{v} + (B_{22})v + (A_{23})\dot{w} + (B_{23})w + (A_{24})\dot{p} + (B_{24})p + (A_{25})\dot{q}\\ &+ (B_{25})q + (A_{26})\dot{r} + (B_{26})r = F_2 wave\end{aligned} \quad (4.23)$$

$$\begin{aligned}&(M + A_{33})\dot{w} + (B_{33})w + C_{33}(t,z,\theta,\phi) + (A_{32})\dot{v} + (B_{32})v + (A_{34})\dot{p} + (B_{34})p\\ &+ (A_{35})\dot{q} + (B_{35})q = F_3 wave + F_3 wod\end{aligned}$$

(4.24)

$$\begin{aligned}&(I_{xx} + A_{44})\dot{p} + (B_{44})p + C_{44}(t,z,\theta,\phi) + (A_{42})\dot{v} + (B_{42})v + (A_{43})\dot{w} + (B_{43})w\\ &+ (A_{45})\dot{q} + (B_{45})q + (A_{46})\dot{r} + (B_{46})r = M_4 wave + M_4 wod\end{aligned}$$

(4.25)

$$\begin{aligned}&(I_{yy} + A_{55})\dot{q} + (B_{55})q + C_{55}(t,z,\theta,\phi) + (A_{52})\dot{v} + (B_{52})v + (A_{53})\dot{w} + (B_{53})w\\ &+ (A_{54})\dot{p} + (B_{54})p = M_5 wave + M_5 wod\end{aligned}$$

(4.26)

$$\begin{aligned}&(I_{zz} + A_{66})\dot{r} + (B_{66})r + (A_{64})\dot{p} + (B_{64})p + (A_{65})\dot{q} + (B_{65})q + (A_{63})\dot{w}\\ &+ (B_{43})w + (A_{62})\dot{v} + (B_{62})v = M_6 wave\end{aligned} \quad (4.27)$$

The solution of these equations in the time domain is carried out by using ODE45 routines library in MATLAB program, based on the RUNGE-KUTTA method (see Appendix C).

4.7 Time Simulation Approach

To obtain the motion of the vessel in time step, the numerical investigation technique is applied to solve the equations of motion. In this study, a fourth order Runge-Kutta integration procedure is utilised. This procedure has been widely used in the solution of the differential equations. The advantage of this method is able to provide a very fast and reliable computation result. In the simulation program, this method is readily available from the MATLAB Library file.

To apply this method, the second order term occurs in the equation of motion is transformed to the first order differential equation. The procedure to apply this method is showed as follows:

Equation (4.28) is the general equation of motion.

$$a_j\ddot{x} + b_j\dot{x} + c_j x + \sum_{k\neq j}^{6} a_{jk}\ddot{x}_k - \sum_{k=1}^{6} b_{jk}\dot{x}_k + \sum_{k=1}^{6} c_{jk}x_k = F_j \tag{4.28}$$

Then, the equation of motion is rewritten in the form that needs to be integrated.

$$\ddot{x} = \left[F_j - b_j\dot{x} - c_j x - \sum_{k\neq j}^{6} a_{jk}\ddot{x}_k - \sum_{k=1}^{6} b_{jk}\dot{x}_k - \sum_{k=1}^{6} c_{jk}x_k \right] / a_j \tag{4.29}$$

To integrate the above set of equation with the numerical integration technique, the second order term is transformed to the first order term.

Let,

$$y_1 = x \tag{4.30}$$

and,

$$y_2 = \dot{x} \tag{4.31}$$

Therefore, the first order differential equation become:

$$\dot{y}_1 = y_2 \tag{4.32}$$

and,

$$\dot{y}_2 = \left[F_j - b_j \dot{x} - c_j x - \sum_{k \neq j}^{6} a_{jk} \ddot{x}_k - \sum_{k=1}^{6} b_{jk} \dot{x}_k - \sum_{k=1}^{6} c_{jk} x_k \right] / a_j \tag{4.33}$$

4.8 Concluding Remarks

A time domain simulation program, which is able to take into account the non-linear effect and the coupling between the motions is utilised to solve the problem of damage stability of vessel in dynamic condition. Since the study is concentrated on the situation after damage and large amplitude of damaged ship motions in Beam Seas, accurate computation of damage scenario becomes important. Accumulation of water flooding has a significant effect on the vessel stability.

CHAPTER 5

SIMULATION PROGRAM

5.1 General

This chapter is mainly about the particulars of the simulation program. The simulation program is used to investigate ship's dynamic behaviour based on real time simulation approach. 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 modelled either by entering the fixed water flow per unit time or using the relationship 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.

5.2 Simulation Program

The simulation program is developed with MATLAB R12® to assess the dynamic stability of damaged ship. This program is based on Time Domain Simulation and able to compute fully coupled motions up to 6 degrees of freedom, namely the surge, sway, heave, roll, pitch and yaw motion. The structure of the input files, such as the Ship Hull Form Data, Vessel Condition & Environment Data and Hydrodynamic Coefficients Data are described briefly. Detail of each input files can be seen in Appendix D.

Damage can be defined at any location of the ship and calculation can be carried out either using Lost Buoyancy or Added Weight method. Simulations can be carried out for monohull and multihull vessel. The flowchart diagram of the simulation program is shown in Figure 5.1 and detail of flow chart diagram is shown in Appendix D.

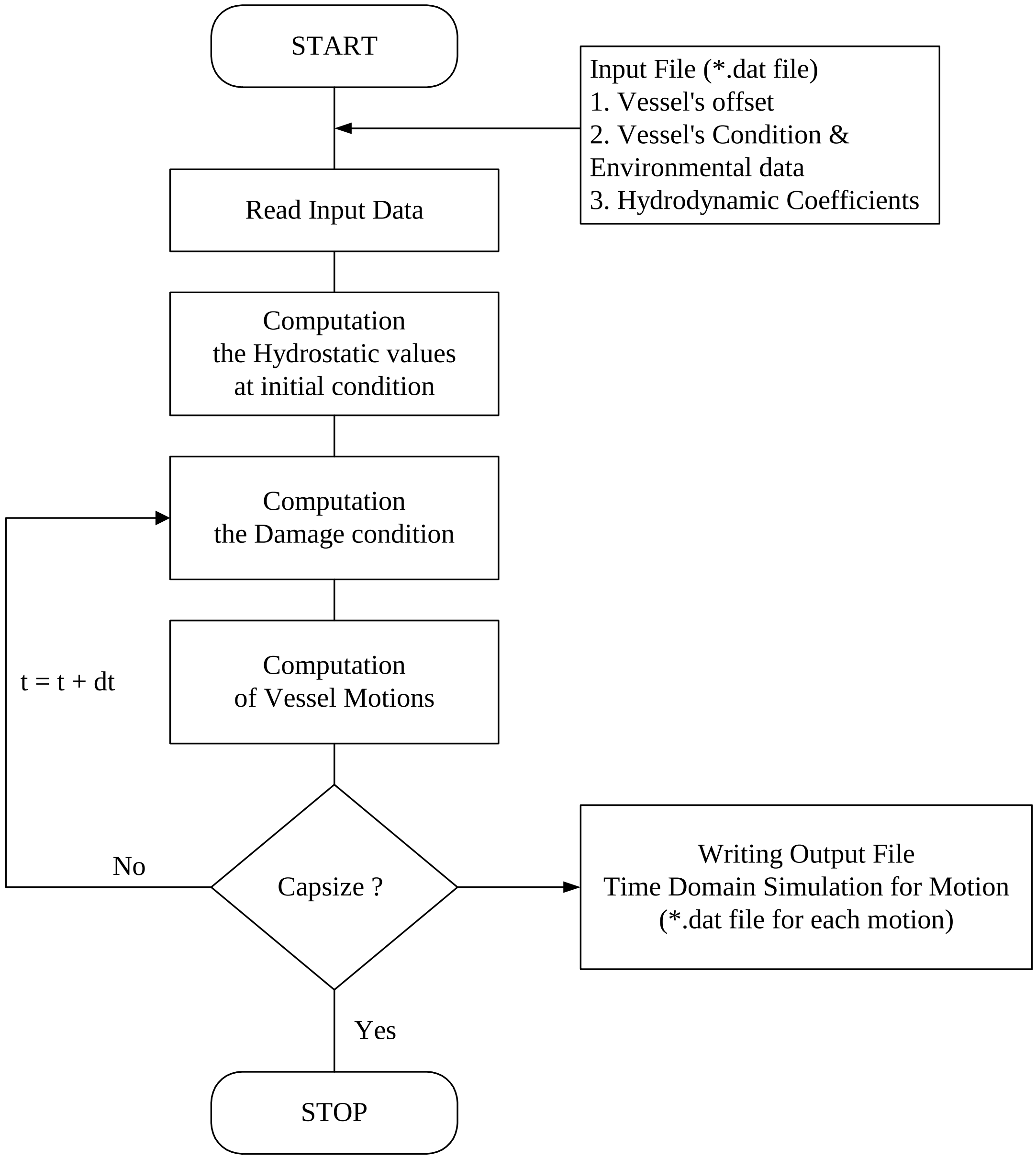


Figure 5.1 Flowchart of simulation program

5.3 Ship Hull Form Data File

This file contains the hull form definition of the ship, appendages, and damaged compartments in the form of two-dimensional sections along the ship length. This data file consists of two parts:

i. **The form data of the intact ship:** In order to prepare the intact ship data the number of the sections of the intact ship, the number of points at each section, longitudinal location of each section according to the ship coordinate system must be known and must be typed correctly in the following form.

ii. **The definition of the appendages and the damaged compartments**: The existence of the appendages and the damaged compartments must be identified by typing letter B in the first row and column, after the end of the intact ship data as shown in the ship hull form data format in Appendix D.1. In order to define the damages, the total number of damaged appendages must be known.

If Lost Buoyancy method is used, only the number of damaged appendages (NOAPPEND) value is required. Other values can be set to zero or any other integer values. For instance: 3 0 0 0 0 (assuming that NOAPPEND=3)

If the Added weight method is used, the number of the damaged compartments and damaged appendages in each compartment must be defined correctly. In this method the following expression must be obtained:

$$NOAPPEND=NODAP1+NODAP2+NODAP3 \qquad (5.1)$$

After arranging the number of damaged compartments, each damaged appendage must be defined by entering the number of the sections in the appendage (AP_NOS) and the permeability of the damaged appendage (PERM). Permeability of the damaged appendage must be minus (-) and equal to 1 or less. This is followed by the number of the points in the section (NOF), location of the section (X_INT) and the damage identification (DAM) which is 1 if damage is symmetric and 2 if damage is asymmetric. If DAM is 1 the program creates the other half of the section and if DAM is 2 the program uses the sectional data as it is given. Therefore, asymmetric damage should be defined explicitly. It should be taken into account that the first and the last points are connected in the program as a straight line; so that exact sectional area can be defined properly.

5.4 Vessel Condition and Environment Data File

Vessel condition and environment data file includes the environmental and ship parameters that can be changed depending on the required condition. In the file, there are some parameters that are not used by the time simulation program. However, stability program uses all the parameters, therefore format of the file was not changed. So that they can be used for both time simulation and stability programs. The parameters that are used by the time simulation are stated. The structure of the control file is as shown in Appendix D.3.

For the equilibrium condition before the time simulation starts, there are two values to be considered first: displacement (DISIN) and the draught (T). If calculations are to be carried out for the displacement at initial condition then correct displacement must be provided. Even if the draft is provided together with the displacement, displacement is taken as main parameter. However, if draft is used for the initial condition, the displacement (DISIN) must be set to 0.

5.5 Hydrodynamic Coefficient Data File

This input file includes all the relevant hydrodynamic coefficients, excitation force and moments for the given condition of the ship and the excitation frequency. This file also includes all the control parameters for the progressive flooding.

The file contains the control parameters for both the option 1 and 2 of the water ingress. The structure of this file is illustrated in Appendix D.2 and each parameter will be explained in the definition of the parameters part.

Although damage is based on progressive flooding, compartments may be defined as fully flooded before the time simulation starts. For option 1 of water ingress, total amount of water (TVOLUME), which is expected to be flooded the compartment in question (check) will be entered as the initial volume (VOLUMEIN). In that case initial amount of water and the total amount of water will be equal. Furthermore starting and the finishing time of the flooding of the progressive flooding must be equal and set to 1 sec. This arrangement would be provided and compartment is completely flooded before time simulation starts.

In case of option 2 of water ingress, it is dependent on the wave elevation at the damage opening and there is no control on the maximum amount of water that would flow in. Therefore to express the flooding of the damaged compartment fully before the time simulation starts, the value of total amount of water (TVOLUME) should be represented as the initial volume (VOLUMEIN). In that case initial amount of water will equal to total volume.

5.6 Concluding remarks

This chapter has described briefly about the required particulars for the simulation. The formats of the input files have been illustrated in this chapter. Samples that illustrate the structure of the file have been enclosed in the Appendix D. In order to ensure a smooth and convincing simulation, the format or the structure of the data input file should be followed strictly.

CHAPTER 6

MODEL EXPERIMENTS

6.1 General

In order to validate the results obtained from Simulation Program, an experiment was conducted to provide experimental results. There are three main parts of the experiment which will be described in this chapter. The first part will describe on roll decay test. Roll decay test is performed to determine the natural roll period and vertical centre of gravity of the model. The second part will describe on the water ingress experiment to determine the flow coefficient (K) of the water ingress. The experiment was conducted in the calm water condition with damage hole on model. The third part is related to image processing technique that is used to process images, captured by the camera during the experiment to obtain the motions of damage vessel.

6.2 Model Preparation

For the experiment, a scaled model of a 31.5 m long Sarawak Fast Ferry was chosen. The length of 1:10 scale model is 3.15 m and 59.6543 kg weight. Details of the Sarawak Fast Ferry and the model are given in Appendix E.

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. However the final adjustment of weight was done by considering the three draft marks at forward, aft and middle sections. The centre of gravity was obtained using roll decay test.

To get real condition of damage vessel, the damage hole with particular size was made on the hull of the hull. Detail size and shape of the damage hole is given in Appendix E. This condition is used to conduct the experiment of water ingress and vessel motions.

6.3 Roll Decay Test

Roll decay test is performed to determine the roll damping coefficient in calm water for a vessel. This test is also done to find the metacentric height, GM_T of the model from the natural frequency of model obtained. Roll decay test is also called roll decrement test. It consists of a free decay in the model roll motion, starting from an initial heel angle. When given an initial roll angle and released, the roll response of the vessel will be achieved from the accelerometer. Over a given time, the number of cycles of the roll motion shows the amplitude decay till the vessel or model stopped.

In this research, the determination of loading condition on board corresponds to “Sarawak Fast Ferry” model is done through this test. Firstly the experimental set up should be done including the calibration of equipment and then secondly the data obtained from experiment was analyzed.

6.3.1 Experimental Set-Up for Roll Decay Test

Before running the experiment, the equipments need proper setup. The equipment require for this test are two channel wire with the accelerometer for port side and starboard side, the ballasted model and the Data Acquisition System that need in analyzing the raw data from the test. Firstly, the channel wire from the accelerometers is fixed to the carriage. Then, it is being calibrated and the values are saved in the computer. Then, the accelerometers are attached to the model at the starboard and port side by means of double-sided tape. By checking all the channels, and configurations, the accelerometers are being zeroed.

The model is given an initial small angle of roll and the output is monitored in the computer. If the decay curve touches the x-axis during start and end of the roll motion, then, roll decay test is ready to be carried out. The model is given a roll angle that is not more than 10 degrees. The acceleration signal in time-domain will picked-up by the accelerometers and then recorded in the Data Acquisition System. This signal is processed by using the *MVR Off-line Analysis Package*.

6.3.2 Roll Decay Test Analysis

The damped natural frequency can be obtained by measuring the period from the roll decay curve being plotted in the *MVR software*. From there, frequency of the model is calculated by using logarithmic decrement equation, which is:

$$|\phi_{\max}| = \phi_0 e^{-\gamma\omega_n t} \tag{6.1}$$

From there, the ratio of two amplitudes is calculated to find the damping ratio,

$$\frac{\phi_3}{\phi_1} = e^{\frac{2\pi\gamma}{\sqrt{1-\gamma^2}}} \tag{6.2}$$

When the value of damping ratio, γ is found, then the critical damping can be found by:

$$\gamma = \frac{b}{b_c} \tag{6.3}$$

$$b_c = 2 \times I_v \times \omega_n \tag{6.4}$$

$$I_v = \Delta \times k_{xx}^{\ 2} \tag{6.5}$$

$$\omega_d = \frac{2\pi}{T_d} \tag{6.6}$$

$$\omega_d = \omega_n \sqrt{1-\gamma^2} \tag{6.7}$$

$$\mu_\phi = \frac{\phi_a}{\phi_{st}} = \frac{1}{\sqrt{(1-\Lambda^2)^2 + 4\kappa^2\Lambda^2}} \tag{6.8}$$

$$\Lambda = \frac{\omega_e}{\omega_n} \tag{6.9}$$

$$\kappa = \frac{\nu}{\omega_n} \tag{6.10}$$

$$\nu = \frac{b}{2(m+a_n)} \tag{6.11}$$

6.3.3 Roll Decay Test Results

From roll decrement curve obtained by experiment then the analysis of result is done by measuring the amplitude and the damped period per cycle. Although the unit of amplitude measured is in acceleration unit, but as the analysis done by the ration of the value, so it could be acceptable without have to transfer to displacement unit. Table 6.1 shows the summary of results of roll decay test conducted.

Table 6.1: Summary of results for roll decay test of Sarawak Fast Ferry

No	Descriptions	Sarawak Fast Ferry	Unit
1	Mass Displacement, Δ	60	tonnes
2	Radius of gyration, *kxx*	1.14738	m
3	Added mass (20%), *an*	12	tonnes
4	Virtual mass moment of inertial, *Iv*	93.6808	tonnes.m^2
5	Damped Period, (T_d)model	1.308	s
6	Damped frequency, (ω_d)model	4.804	rad/s
7	Natural Period, (*Tn*)model	1.307	s
8	Natural frequency, (ωn)model	4.806	rad/s
9	Natural Period, (*Tn*)ship	4.134	s
10	Natural frequency, (ωn)ship	1.520	rad/s
11	Natural frequency, (*fn*)ship	0.242	Hz
12	Damping moment coefficient, *b*	8.58	tonnes.m^2/s
13	Critical damping, b_c	284.74	tonnes.m^2/s
14	Damping ratio, γ	0.0172	
15	Tuning factor, Λ	1.00	
16	Decaying constant, *v*	0.0503	m^2/s
17	Non-dimensional damping factor, κ	0.0331	
18	Magnification factor ,μ_ϕ	15.117	
19	Restoring moment coefficient, *c*	216.368	Nm
20	GMt (from roll decay test)	0.373	m
21	KMt (from hydrostatic data)	1.571	m
22	KG ship	1.198	m
23	KG model	11.98	cm

6.4 Water Ingress Experiment

As stated in chapter 4, it has been found from theoretical studies that the flow rate of water is mainly related to the pressure head, which changes depending on the location of the hole relative to the water surface. At the same time, flow rate also related to the shape and area of the opening and empirical formula are based on these parameters as well as on the static pressure head.

At the moment empirical formula are available for the steady water flow through an opening at calm water surface such as flow over a notch or weir (Walshaw and Jobson, 1979), but there is no formulation for the water flow in a wave environment through, an opening above the calm water surface. In such cases, pressure is entirely dependent on the wave particulars such as wave height, direction and steepness. The existing formulation which is for water flow over a notch may not give very accurate results. Therefore this experiment was conducted to obtain the flow coefficient (K) of water ingress to validate with empirical formula.

6.4.1 Experimental Set-Up for Water Ingress

Before the experiment conducted, it needs to be set-up first. The equipment require for this test are the ballasted model, stop watch, and weights that is needed in calculating the amount of water ingress in certain time. Firstly, the damage hole on the model is covered using binding tape then the model put into the towing tank.

The damage hole on the model was opened at the time = 0 until the certain time. After the time was reached, the damage hole is covered using binding tape then the amount of water flow into the model is weighted. The time of measurement that are used to analyze the water ingress are 5 seconds, 10 seconds, 20 second, 30 seconds, 40 seconds and 60 seconds. Details of experiments set up are shown in Appendix F.

6.4.2 Water Ingress Experiment Analysis

Before calculating the flow coefficient (K), the flow rate of water ingress should be obtained first by measuring the volume of water flow into the model at time, t. The flow rate of the water ingress is calculated by using simple equation, which is:

Volume of water = weight of water / density of water (6.12)

Flow rate = volume of water ingress / time (6.13)

From each time in experiment, we can calculate the flow rate of water ingress and the using the formula by Walshaw and Jobson (1979) as stated in chapter 4, the flow coefficient (K) can be obtained. The result of this experiment can be used to validate the K coefficient based on empirical formula as flow over a notch or weir (Walshaw and Jobson, 1979).

6.4.3 Water Ingress Experiment Results

Table 6.2 below shows the summary of results of water ingress experiment conducted.

Table 6.2: Summary of results of water ingress experiment

No	Time of Measurement	Volume of Water Ingress	Velocity of Water (m/s)	Coefficient K
1	4.95 seconds	0.05 m^3	0.420875	0.346955
2	10.58 seconds	0.25 m^3	0.497809	0.355396
3	19.51 seconds	1.2 m^3	0.575907	0.335704
4	29.55 seconds	6.7 m^3	0.764264	0.345083
5	40.10 seconds	11.5 m^3	0.798912	0.34394
6	60.39 seconds	17.2 m^3	0.793431	0.34158
			Average of flow coefficient (K)	0.344777

After finishing water ingress experiment, the total amount of water in the model compartment can be measured. The flow rate of water ingress for the model can be calculated. The scale up is needed to get the flow rate of water ingress for full scale vessel. Finally using the formula for flow over the weir the flow coefficient (K) was calculated. From the Table 6.2, the average value of K is taken then input for simulation program.

6.5 Damage Stability Experiment

The Motion of damage vessel are very unique, during progressive flooding the motions can be rolling on one side and/or heaving on sinkage. Based on this condition, although the experiment was conducted in beam seas condition, the accelerometer can not be used to measure the roll motion of damage vessel. The accelerometer only can measure the rolling motion but can not measure the heeling angle of damage vessel. The new system should be developed to measure the motion of damage vessel in time step. In this case, image processing technique was used.

In this method, image processing technique will capture and record the images of damage vessel in beam sea condition in time step. Then the captured images will be analysed using image processing program analysis.

6.5.1 Experimental Set-Up for Damage Stability Test

The experiment was conducted in the towing tank of Marine Technology Laboratory, having dimensions of 120m x 4m x 2.5m. The equipment 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 Figure 6.1 and Figure 6.2. Details of experimental set up are shown in Appendix F.

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 that can easily track the motion of damage vessel. 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 second also an important parameter for image processing, in this case the value chosen was 5 frames per second.

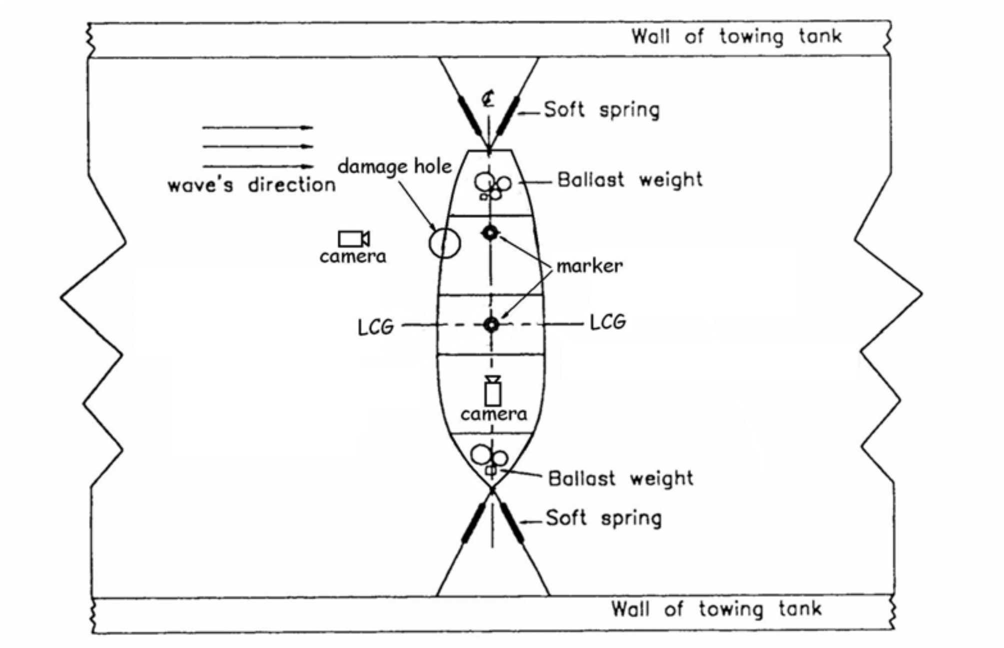


Figure 6.1 Arrangement set-up of beam seas test and position of camera

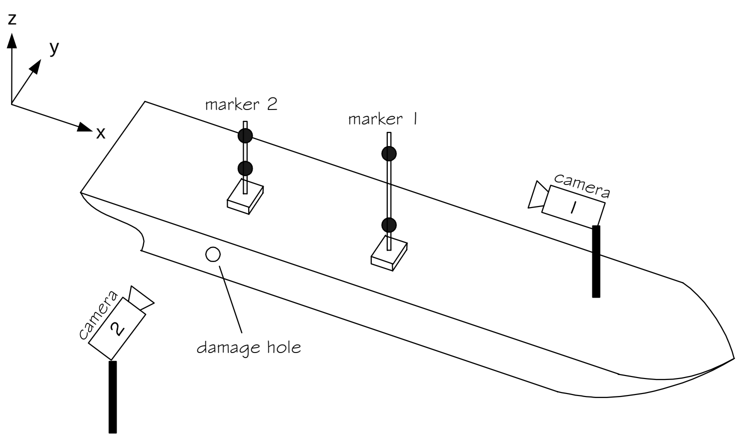


Figure 6.2 Perspective views of cameras and markers

There are two LabView programs were developed to capture images, capturing images program and read AVI file program. The front panel and block diagram of capturing images program are shown in Figure 6.3 and Figure 6.4.

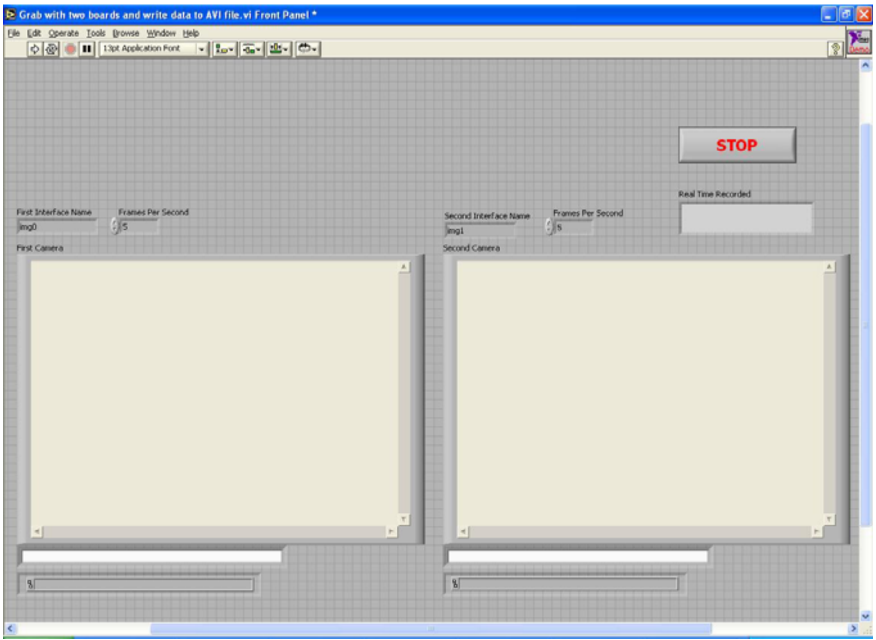


Figure 6.3 Front panel of capturing images program in LabView

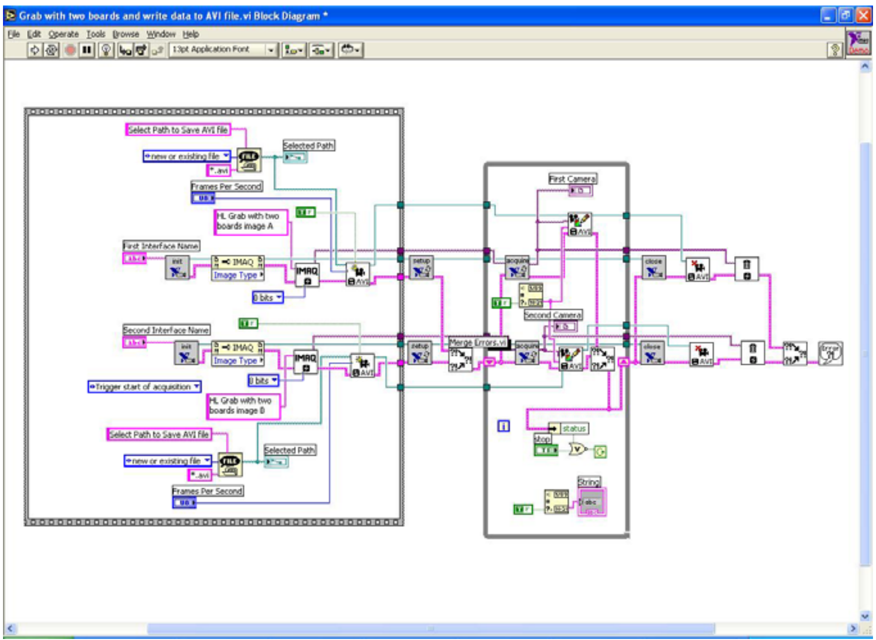


Figure 6.4 Block diagram of capturing images program in LabView

This program can capture images in real time and writes the time to each image in every frame. The writing time was used to check the position of image in time step of experiment. Read AVI file program was developed to check the number of frames per second and the position of image in time. The front panel and block diagram of this program are shown in Figure 6.5 and Figure 6.6.

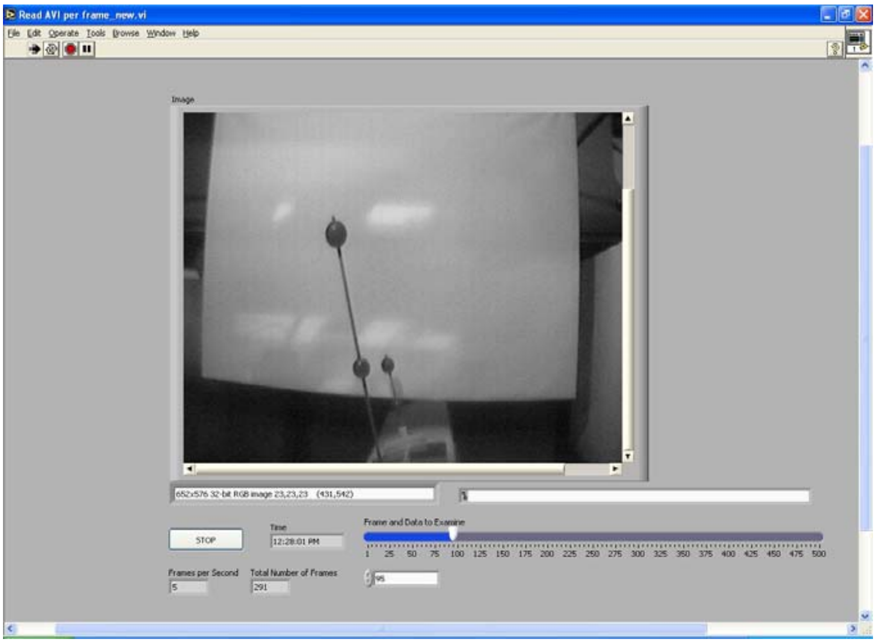


Figure 6.5 Front panel of read AVI file program in LabView

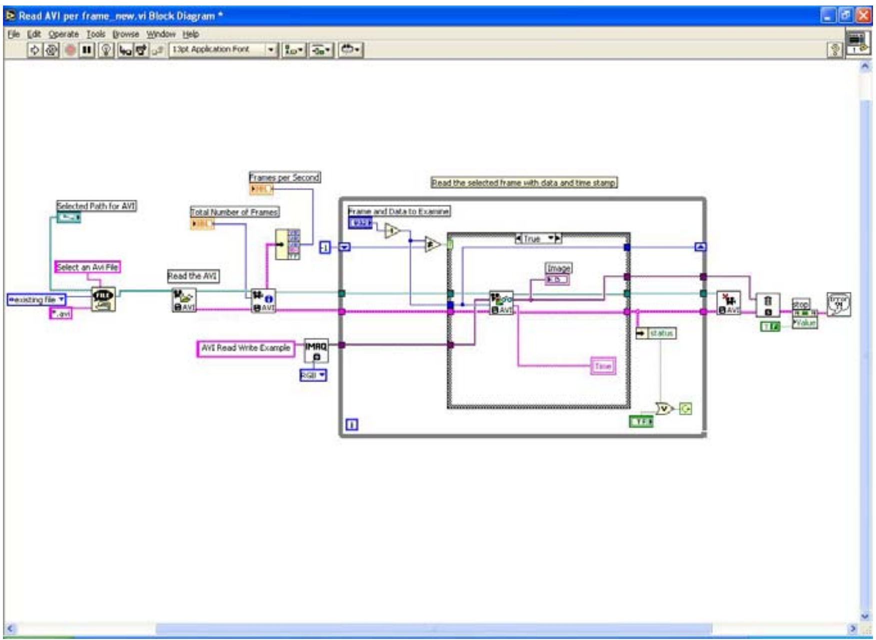


Figure 6.6 Block diagram of read AVI file program using LabView

The experiment was run in beam sea condition with the model dynamically positioned with the aid of two sets of soft spring across the breadth of the towing tank. The sets of soft springs used are to prevent the model from hitting the wall of towing tank while the model is allowed to move freely with minimum constraints. The location of the springs attached should be coincide with the roll axis which a pair at bow and another at stern. The roll axis in this experiment is assumed at the intersection of centerline of the hull and the draft waterline.

For the experiment purposes with regular waves, the waves are generated by a wave flap at the end of the towing tank of Marine Technology Laboratory, UTM which is able to generate long crested regular and random waves. The capabilities of wave generator to generate regular waves are at period range 0.5 sec to 2.5 sec with a wave height corresponding to a maximum steepness of 1/10 in a period range of 0.5 to 1.7 second. The created wave is absorbed by a wave absorber at the other end of the tank.

For each test, the wave height is measured by a wave probe via the experiment. This wave probe is located in front of the model facing the incoming waves. Before running the experiment, local calibration of a wave probe is carried out to ensure that the signals captured were correct and precisely recorded.

6.5.2 Damage Stability Experiment Condition

In the experiment, the model is subjected to beam sea condition with regular wave in zero forward speed with various wave lengths. A suitable wave height 0.01 m, 0.02 m 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 s. Table 6.3 show the test conditions for each run of the experiments, the values shown are all in model scale.

Table 6.3: Test conditions for damage stability experiment

No. of run	Wave characteristics			
	Period,T (s)	**Frequency,ω (rad/s)**	**Wave Height (m)**	**Wave length, Lw (m)**
1	1.4204	4.4235	0.01	3.15
2	1.4204	4.4235	0.02	3.15
3	1.4204	4.4235	0.03	3.15
4	0	0	0	0

6.5.3 Damage Stability Experiment Analysis

After the sequence of images (video) already captured and recorded using LabView , then the images was 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 vessel.

Since the recorded the sequence of images in AVI video file format, the quality of image is in RGB format. Beside that the NI IMAQ card is black and white quality format. Although during experiment the colour CCD camera was used, the recorded the sequence of images is in black and white quality.

There are four main parts to analysed the images using Vision Assistant program, these are:

i. Extract the AVI file into images per frame.

The sequence of images (video) was extracted into single image per frame (see Figure 6.7). Total number of single image is equal to total recorded time times to number of frames per second. In this part, the quality of images was still in RGB format. This is impossible to process the black and white image in RGB format using pattern matching. The pattern matching only can process 8-bit binary format of image. Then the second main part applied for next step of analysis.

Figure 6.7 Extracted the AVI file to single image

ii. Change the quality of image

Before the pattern matching was applied, the image quality should be changed to 8-bit binary format using HSL Luminance command. This command would change the quality of image from RGB format to 8-bit binary format. After changed the quality of image, then the image should be calibrated.

iii. Calibration of images

In this part, the pixel of the image was calibrated into the real world units. To obtain the high calibration, the unit chosen was millimeter. The origin (0,0) point of the image also defined in this calibration part. When the co-ordinate of moving marker was tracked, the coordinate was automatically in millimeter base on the position of the origin point.

iv. Track the position of the marker

This part is the final part of analysis image in Vision Assistant program. The co-ordinate position of moving marker in time step can be track using pattern matching. How to track the position of moving marker is shown in Figure 6.8.

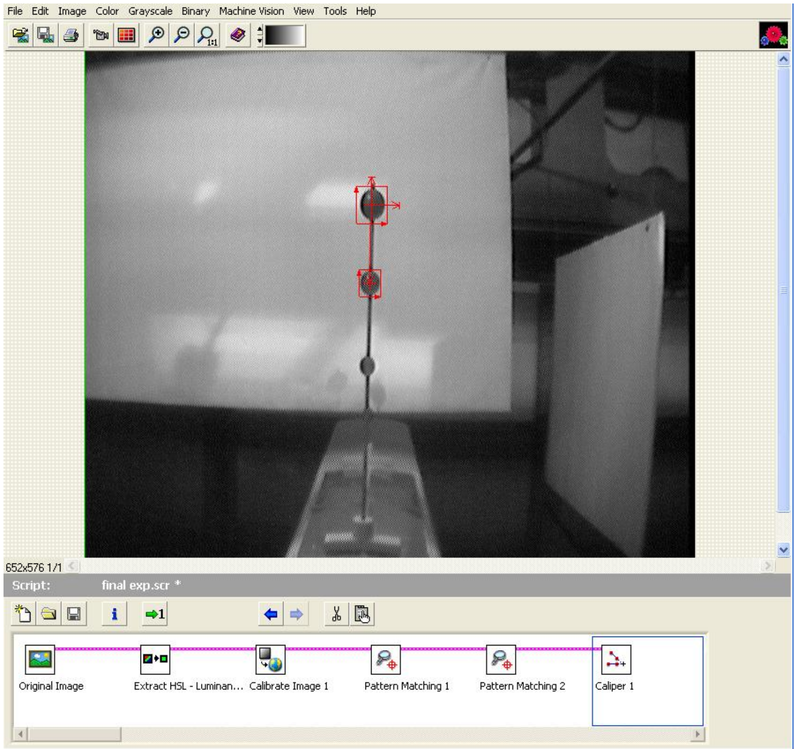


Figure 6.8 Pattern matching tracked the co-ordinate of marker

Since the size of each marker was different, it made easier for the pattern matching to tracks the co-ordinate of each marker without any mistakes. Measured co-ordinate in time step of each marker was used to calculate the heaving, rolling and pitching motion of the damage vessel. Marker 1 had co-ordinate in y and z direction and marker 2 had coordinate in x and z direction. Marker 1 was used to calculate the heaving and rolling motion and marker 2 for pitching motion.

As stated in chapter 4 that the centre motion of vessel is the same as the centre of gravity of the vessel, the calculation to obtain the motion of damage vessel from this experiment base on the moving of the centre of gravity of the vessel. It has been done for heaving, rolling and pitching motion of damage vessel from the damage stability experiment. Based on Figure 6.9 and Figure 6.10, the simple mathematical geometry formulas were used.

These are the simple formulas were used:

Rolling angle = ϕ

= $\arctan[(y_{1a} - y_{2b}) / (z_{1a} - z_{2b})]$ (6.14)

Heaving motion = Δz

= $(y_{1a} - y_{2a})$ (6.15)

= $[y_{1a} - (y_a \cos\phi)]$ (6.16)

Pitching angle = θ

= $\arctan[(x_{1c} - x_{2d}) / (z_{1c} - z_{2d})]$ (6.17)

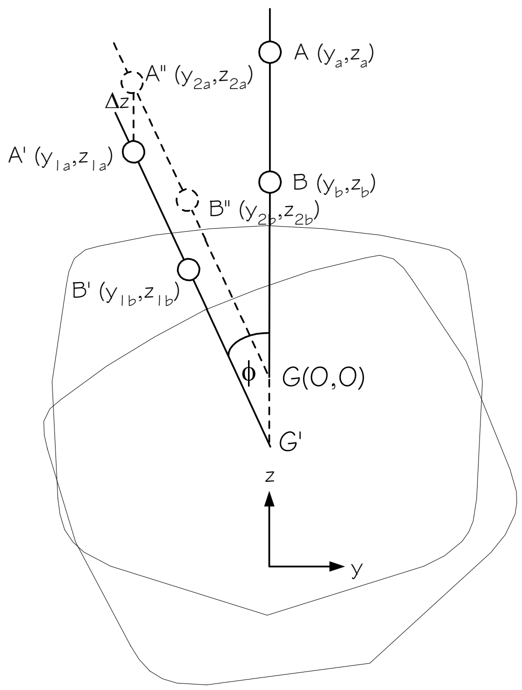


Figure 6.9 Measured co-ordinates for heaving and rolling motion.

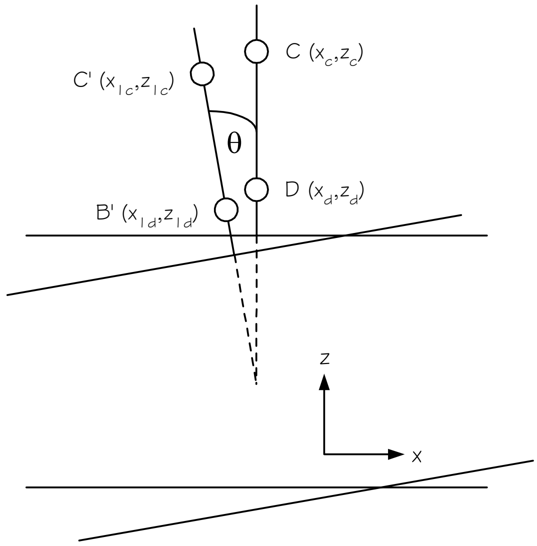


Figure 6.10 Measured co-ordinates for pitching motion

6.5.4 Damage Stability Experiment Results

The results of this experiment are heaving, rolling and pitching motion of damage vessel in time domain until the capsizing occurred. The results are used to validate the simulation program. Details of experimental results are shown in Chapter 7, validation.

6.6 Concluding Remarks

The roll decay test is an important experiment to conduct for checking the KG of ballasted model. In other hand, the roll damping of vessel can be obtained from the roll decay test. The roll decay test give the higher accuracy compare with swing frame and easier to run compare with inclining test. The image processing technique is a good tool to measure the motion of damage vessel in beam sea condition. The results of image processing experiment can be used to validate the simulation program.

CHAPTER 7

VALIDATION

7.1 General

In this chapter, a comparison is carried out between simulation results and the experimental data is carried out to validate the simulation program. Three responses are considered in the comparison, those are heave, roll and pitch motions.

7.2 Comparison of Experimental and Simulation Results

For comparison, a displacement passenger ship called Sarawak Fast Ferry has been chosen for the investigation of ship motion in dynamic situation. The ship particulars are shown in Appendix E.1. There are four cases specified in the comparison. The summary of the comparison condition is shown in Table 7.1.

For all the simulation condition, the wave length to ship length ratio is taken as $\lambda_W / L = 1$ and wave height is taking are 0.1m, 0.2 m and 0.3 m. The required hydrodynamic coefficients are calculated using the Frank-Close-Fit program developed by Voon (2001). The detail of the simulation particulars can be referred in the chapter 8.

Table 7.1: Comparison condition for Sarawak Fast Ferry

Case	Wave Condition	KG	Condition
A	Hw = 0.1 m (Beam sea)	1.2 m	Capsize
B	Hw = 0.2 m (Beam sea)	1.2 m	Capsize
C	Hw = 0.3 m (Beam sea)	1.2 m	Capsize
D	Hw = 0 (Calm Water)	1.2 m	Capsize

Figure 7.1 to 7.9 show the results of the comparison between simulation and experiment. In overall, it is found that the developed simulation program successfully predicted behaviour of damage vessel due to parametric excitation and large amplitude motion of a ship operating in beam seas condition.

For case A, B, C and D, both the simulation and experiment results show that the model capsizes in Beam Sea during damage condition.

The comparison between the simulation and experimental results shows that time to capsize for damage vessel between simulation and experiment is found to be quite similar. The comparison of the roll motion indicates 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. However, further improvement on the simulation program should be done because the rolling amplitude of the simulation is bigger as compared to the experiment.

Since the experiment using spring to hold the model, the pitch motion between simulation and experiment is not same but the period is quite similar.

Case A: Damage Stability at Wave Height = 0.1 m.

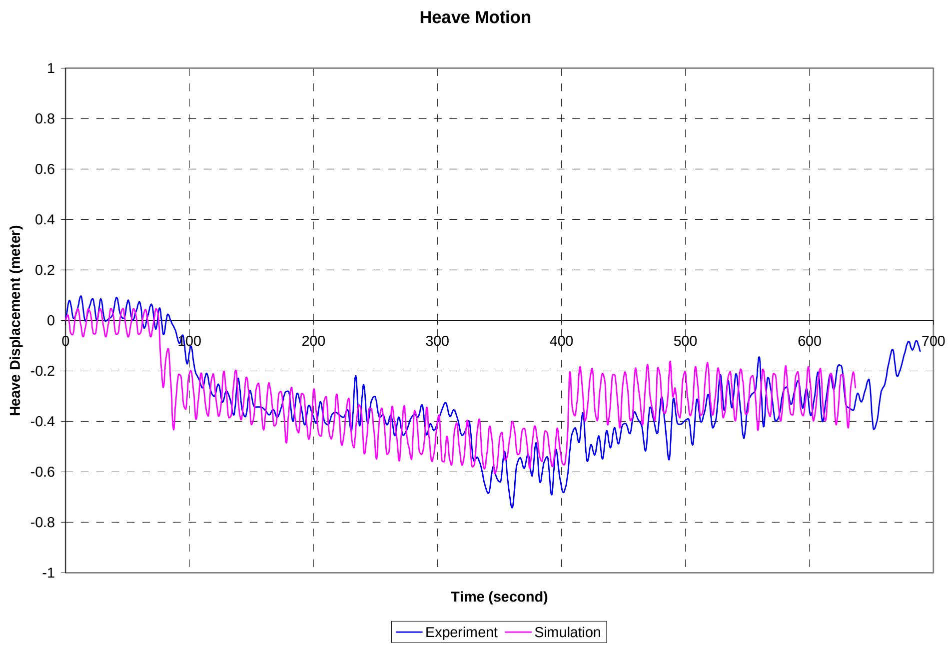


Figure 7.1: Heave motion (case A): Comparison of experiment and simulation

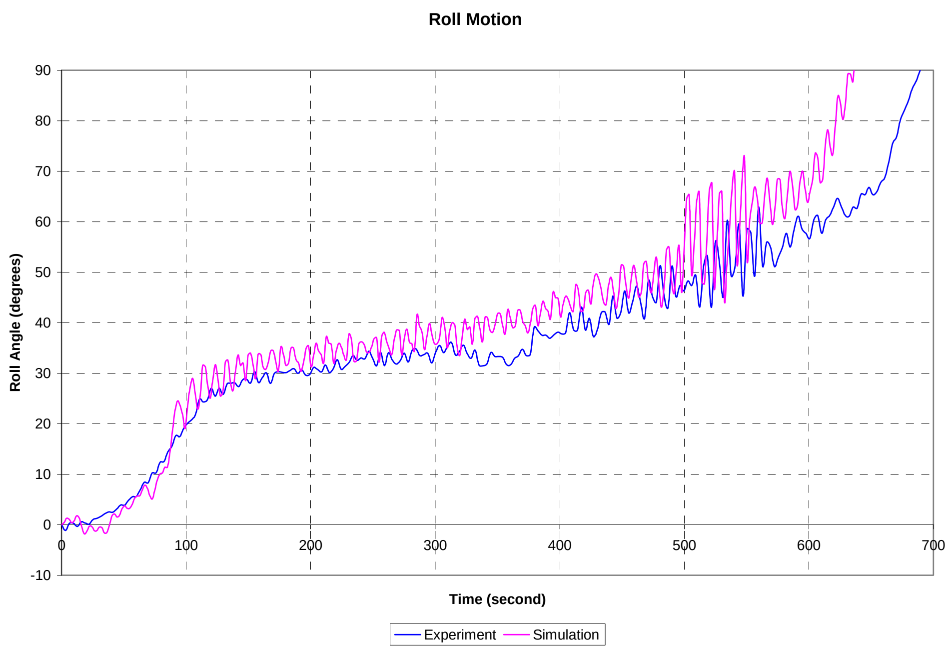


Figure 7.2: Roll motion (case A): Comparison of experiment and simulation

Figure 7.3: Pitch motion (case A): Comparison of experiment and simulation

Case B: Damage Stability at Wave Height = 0.2 m.

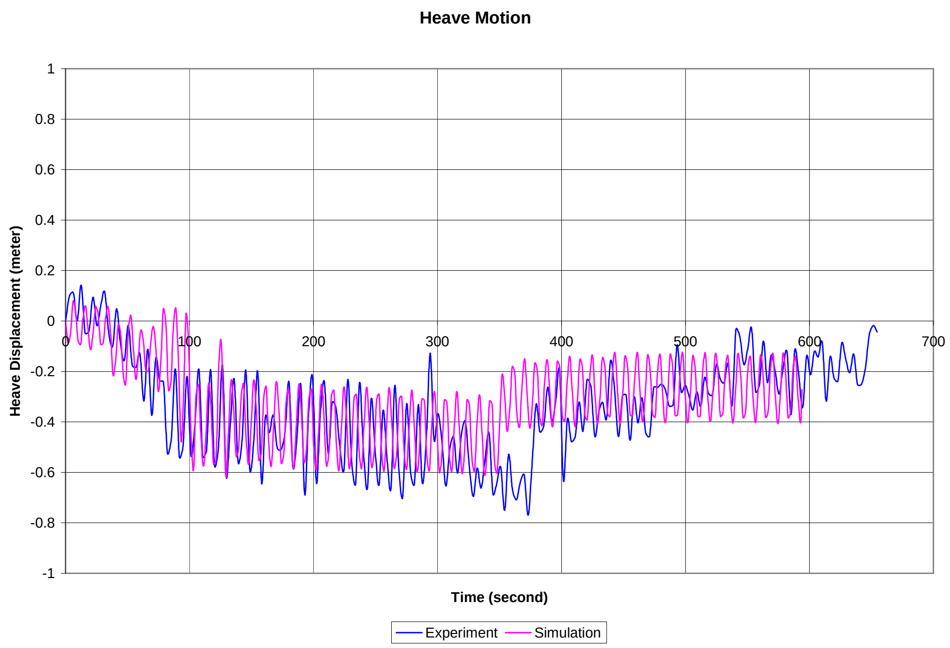


Figure 7.4: Heave motion (case B): Comparison of experiment and simulation

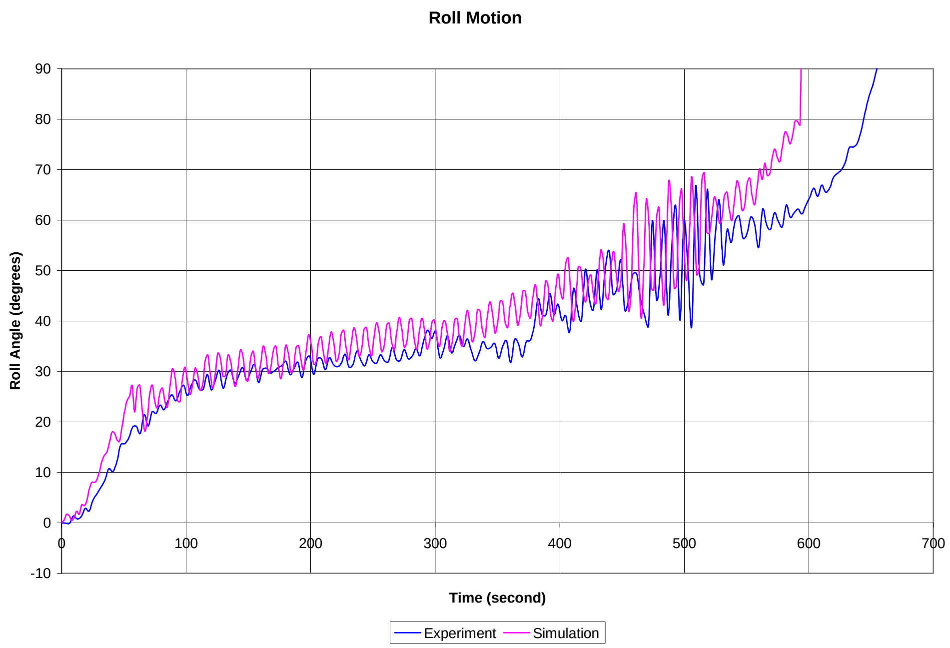


Figure 7.5: Roll motion (case B): Comparison of experiment and simulation

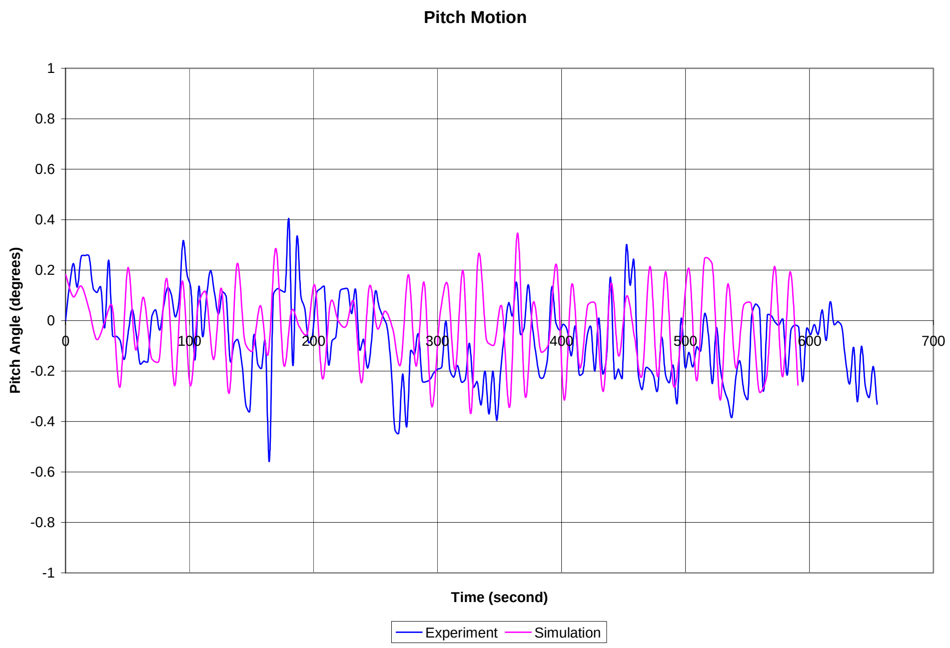


Figure 7.6: Pitch motion (case B): Comparison of experiment and simulation

Case C: Damage Stability at Wave Height = 0.2 m.

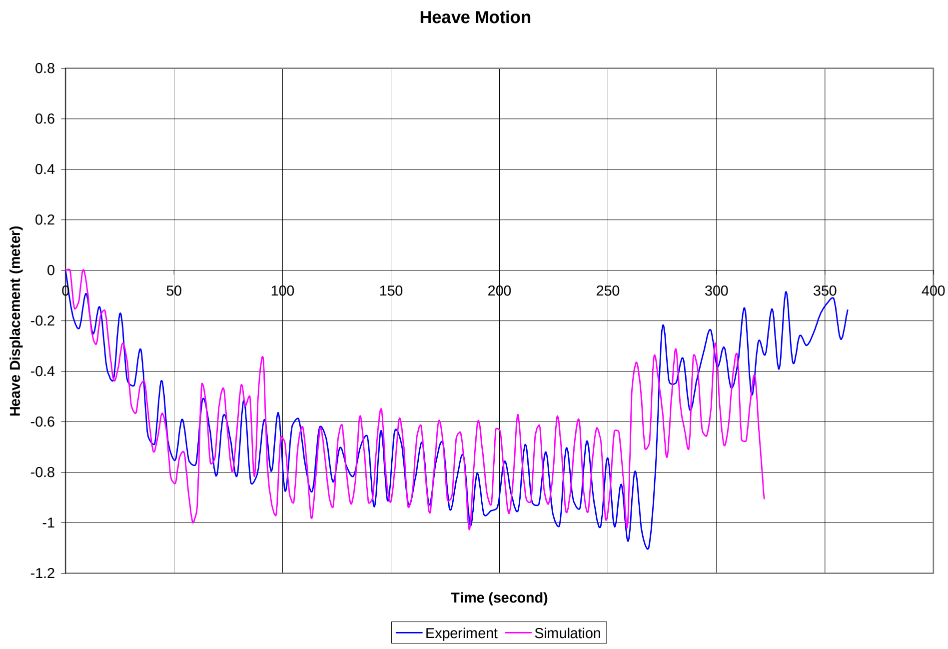


Figure 7.7: Heave motion (case C): Comparison of experiment and simulation

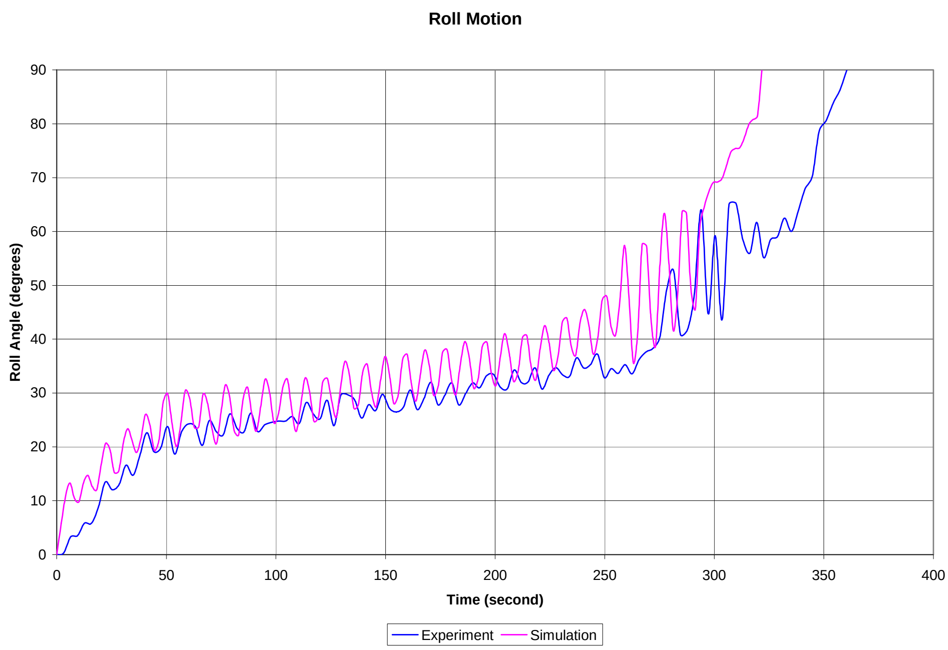


Figure 7.8: Roll motion (case C): Comparison of experiment and simulation

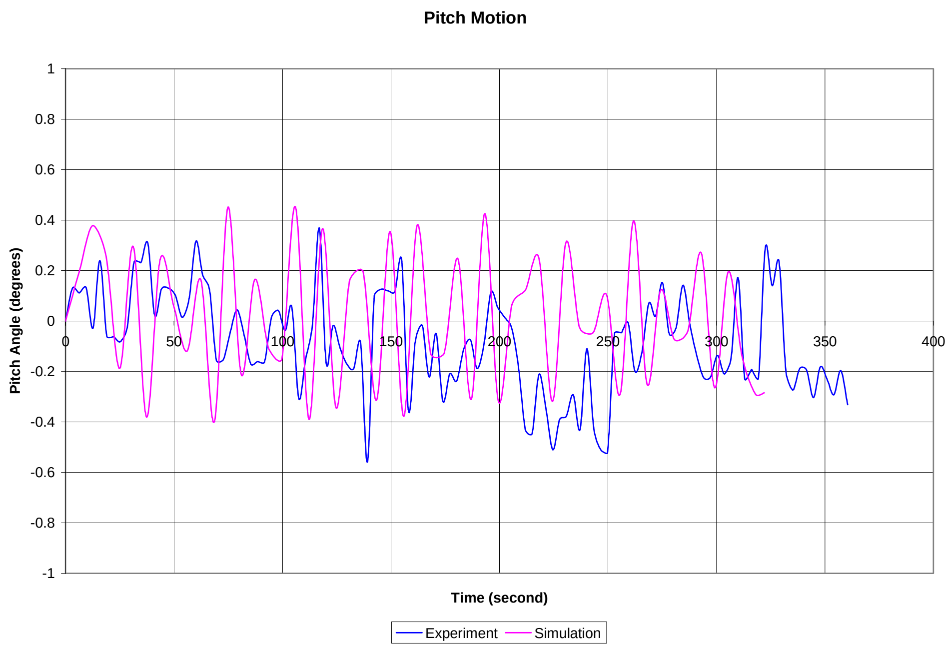


Figure 7.9: Pitch motion (case C): Comparison of experiment and simulation

Case D: Damage Stability at Calm Water

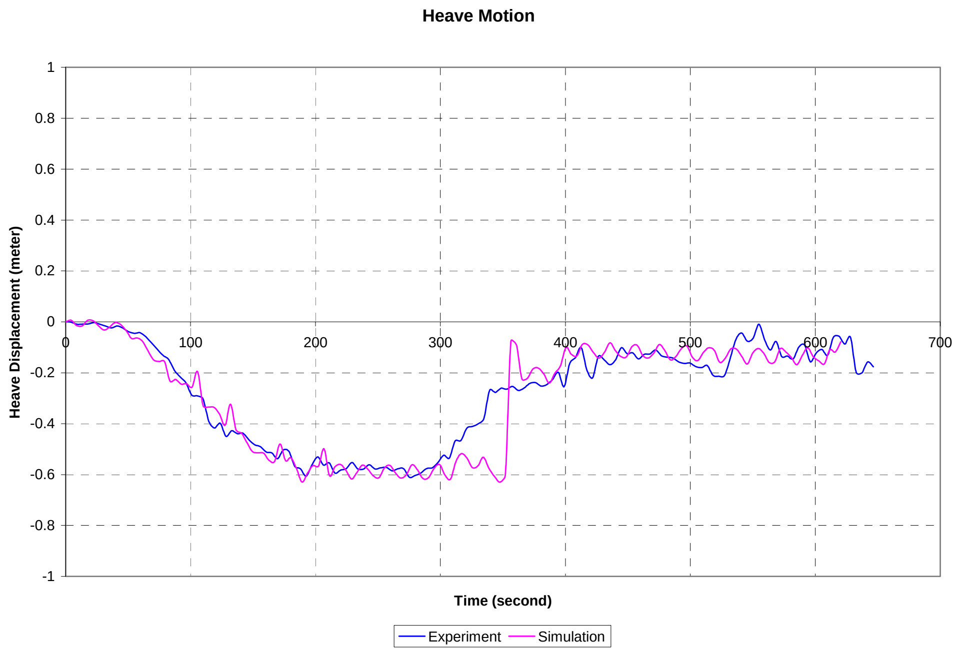


Figure 7.10: Heave motion (case D): Comparison of experiment and simulation

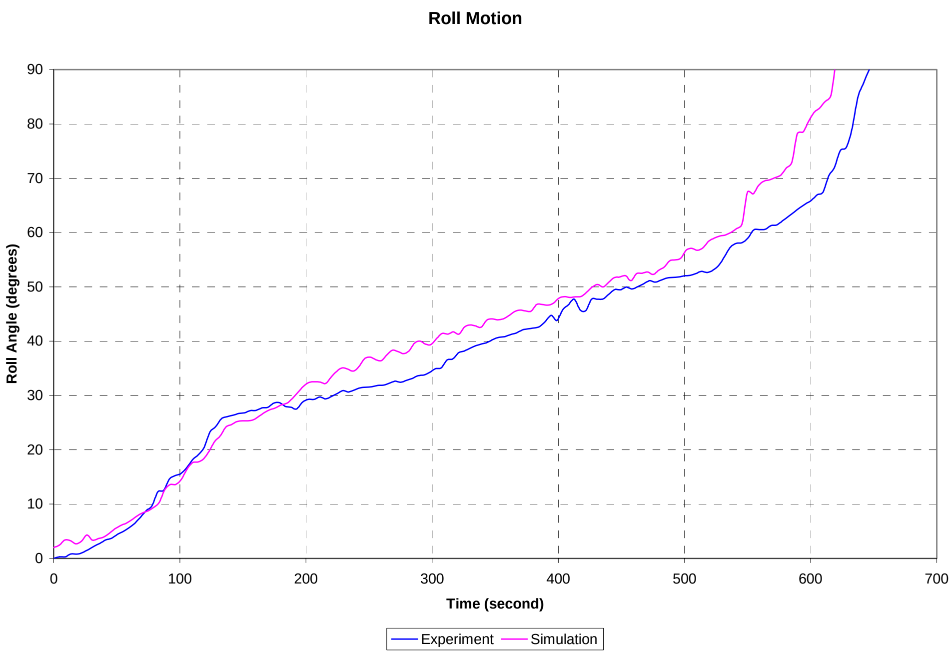


Figure 7.11: Roll motion (case D): Comparison of experiment and simulation

Figure 7.12: Pitch motion (case D): Comparison of experiment and simulation

7.3 Concluding Remarks

Generally, the comparison between simulation program and experimental results, gives confidence to assess the dynamic stability of damage vessel utilising the simulation program. Qualitatively, the present mathematical models successfully simulate the damage stability assessment due to parametric excitation and large amplitude motion.

CHAPTER 8

PARAMETRIC STUDY

8.1 General

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. Time domain simulation program is a useful tool to conduct parametric study. With the use of simulation, many different situation and complex motions can be analyzed. However, without following a strategic and systematic procedure, it can lead to endless runs of simulation. To avoid this problem, a simulation procedure is selected in the parametric study. In this chapter, the author will discuss the effect of wave height and loading condition toward the vessel being investigated. On the other hand, the worst damage scenario is considered in the parametric investigation which is assumed the main passenger deck to be flooded. Results obtained from the simulation program will be analysed and discussed.

8.2 Simulation Procedure

There are two main goals that should be achieved by the selected procedure. The first one is relating the dynamic behaviour of vessel with the environmental and vessel design parameters. The second one is optimizing the simulations by varying the aforementioned parameters near the critical situation.

To achieve the goals, the general outline of the procedure is given as follows:

- Selection of specific vessel
- Identify the important parameters
- Conditions and assumptions
- Identification of the situation after damage
- Damage Scenarios
- Dynamic Analysis
- Derive boundary curves of safe and unsafe condition by using the identified important parameters

8.3 Selection of Specific Vessel

Parametric study was carried out to find the behaviour of the small vessels in damage condition. This helps in optimizing the small 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 Sarawak Fast Ferry for the purposed of carrying passenger was chosen. The vessel is chosen for analysis because she has a large passenger capacity and large length to breadth ratio approximately 10. If the length to breadth ratio is large, it means that the ship has very slender body. Hence, she is very sensitive toward rolling motion and may capsize quickly when encountering a moderate height beam waves.

For the purpose of analysis, certain information such as lines plan, hydrostatic data and curves, and general arrangement are needed. Hull fairing has to be done in AUTOCAD before attempting to input the vessel hull form data on MATLAB. Detail drawings of the vessel are given in Appendix E.

The operating draught is 1.0 m and vertical centre of gravity (KG) is 1.2 m. Hence, longitudinal centre of gravity (LCG) is 1.19 m aft of midship based on the operating draught. The hydrostatic particulars calculated from the simulation program at the initial condition before assessing the damage stability calculation is shown in Figure 8.1.

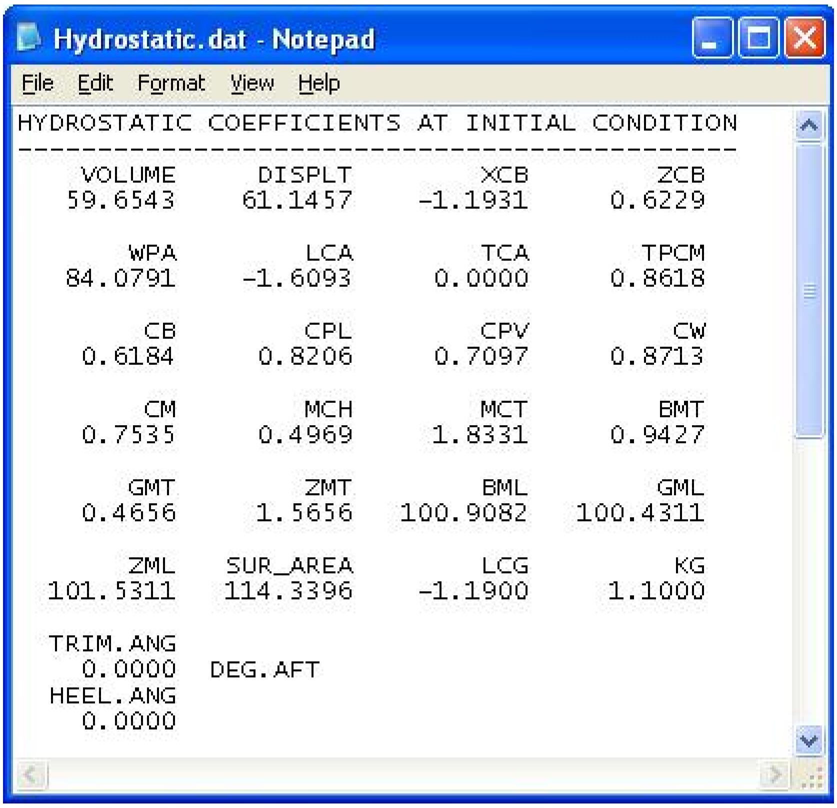


Figure 8.1: Hydrostatic coefficients at initial condition

8.4 Identification of Important Parameters

To undertake an effective parametric study, the parameters are divided into four groups as mentioned previously: (i) the environment, (ii) loading condition, and (iii) compartment length

- The environment

The wave properties are the only parameters to be considered representing the environment. Since only regular beam waves beam waves considering in this parametric study, effect of wave to the roll motions is an important parameter. The critical wave chosen is the wave having its exciting frequency coinciding with the roll natural frequency of vessel. This parameter depends on the length of the wave.

The severity of wave environment is also the main factor that can cause the vessel capsizing. The severity of the wave environment can be described by using wave height. At the same wave length, the higher the value of wave height the more severe is the wave environment.

For deep sea condition ($D_W > \frac{\lambda_W}{2}$), wave period and wave speed are obtained by using the equations (8.1) and (8.2) respectively.

$$T_W = \left(\frac{2\pi\lambda_W}{g} \right)^{1/2} \tag{8.1}$$

$$V_W = \frac{\lambda_W}{T_W} \tag{8.2}$$

where, D_W is water depth, λ_W is wave length, T_W is wave period, V_W is wave speed and g is gravitational acceleration.

- Loading condition

Loading conditions are usually described by displacement and the position of the centre of gravity. The vertical centre of gravity is selected to measure the ship stability of the offered guideline. This is because of the vertical centre of gravity is a parameter, which frequently varies and depends upon the operational condition.

The vertical centre of gravity of vessel is an importance parameter which has effect on response of vessel. It also affects the natural roll frequency of vessel. Also, it has a significant effect on the restoring moment.

- Compartment length

Since the vessel has a large passenger room, a very large area can therefore be flooded if water starts to enter. In this very large area, water can flow freely and can very easily change the balance of the ship. It is important to know the limiting compartment length on the passenger room which could restrict the dynamic motions and other harmful effects.

This limiting compartment length would depend on wave height as well as loading conditions. In order to find the critical length of the passenger room a limited parametric study should be carried out by using only design KG and a range of wave heights. This provides a good idea on allowable compartment length which can be explored further in order to achieve optimum design modifications.

8.5 Conditions and Assumptions

The common problem found in the Time Domain Simulation approach is in determining the initial condition. This is because of the simulation results are sensitive to the change of initial condition. As indicated by Hamamato et al. (1991), simulation result is strongly affected by the initial conditions such as wave height, relative velocity of ship to waves, metacentric height, initial position of ship to wave and heading angle of ship to wave. Therefore, initial conditions should clearly be identified in each run of the simulation. 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.

There is a limited wave height that can be used in simulation due to the operating area at river. Limited wave height mentioned is up to 0.3 m. Only regular beam seas is considered in this study. The wave length chosen is the wave that has equal length with the vessel and the wave direction is 90 degrees.

Considering the importance of loading condition of the ship, different KGs are used in the calculations. The values of KG varies between 1.1 m, 1.2 m and 1.3 m, thus intact GM between 0.271 m and 0.471 m.

Meanwhile water ingress which depends on the wave elevation and damage location is applied on the simulation (option 2 of water ingress). The flow rate and the total amount of water which can flood in are chosen depending on the location of the damage and the volume of the compartment. The water ingress assumption is based on the fact that water is flooding into the ship. Instantaneous and continuous flooding are considered based on damage scenarios.

Damage hole is assumed that the vessel collision with another one. The location of damage and the size of damage hole is shown in Appendix E 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 study, the flow rate which depends on static pressure head is low due to the vessel operating area at mild environmental conditions (small wave height). Based on the experiment in chapter 6, the suitable value of flow coefficient (K) is 0.35.

8.6 Identification of the Situation after Damage

The main reason of conducting parametric study is to investigate the effect of parameter on the damage vessel stability in dynamic situation. This involves the identification of the situation after damage in waves. There are four possibility situations after damage are considered for vessel in damage condition, namely sinking, parametric excitation, pure loss of stability and plunging.

Sinking conditions is caused by the addition of weight (flooding water). The progressive flooding water has caused the force of gravity to exceed the force of buoyancy. The rolling and pitching motions are found to be small but the heaving motion of the damage vessel becomes bigger and the ship goes down within a minutes.

Parametric excitation is a resonance situation. Since only beam seas considering in parametric study, the situation happens where the frequency of wave excitation coinciding with the natural frequency of roll or the frequency of water trapped moving inside compartment coinciding with the natural frequency of roll. At this situation, the result always shows that the roll amplitude increases progressively. This may endanger the vessel and the vessel rapidly capsizes after few roll cycles.

Pure loss of stability is a capsizing situation due to the loss of restoring moment. It occurs when the water flooding into the vessel, the accumulation of water trapped inside the compartment affect to the GZ (righting lever) of vessel. Reducing of GZ value makes the righting moment of damage vessel become smaller. When a small transverse force such as from the wind or wave acting on the vessel coupled with motions of water accumulation, the vessel could heeling on one side before capsize due to sudden loss of static balance.

Plunging or Loss of longitudinal stability is the situation of the trimming moment exceeds the longitudinal righting moment (TM > RM) and the ship sinks by the bow or stern. For the damage location on after and fore body of the ship, the flooding of water ingress give more effect to trim or pitching motion rather than rolling and heaving. The accumulation of water increases the trimming moment. At certain time, the trimming moment exceeds the longitudinal righting moment, the vessel start plunging.

8.7 Damage Scenarios

The reasons and consequences of the accidents may very greatly therefore, considering different types of damage would help to view the full range of possible effect on vessel conditions. Definitions must be done in a way that the most realistic and potentially most dangerous damage conditions would be examined. Defining and studying all the possible worst damage conditions can derive the necessary information taking the current precaution.

Damage scenario can be defined as a passenger room 1 and 2 are assumed to be flooded. The continuous flooding occurs between passenger room 1 and passenger room 2 through a passageway is applied in this parametric study. The flow concern is regarded as flow over a rectangular weir. This scenario is shown in Figure 8.2.

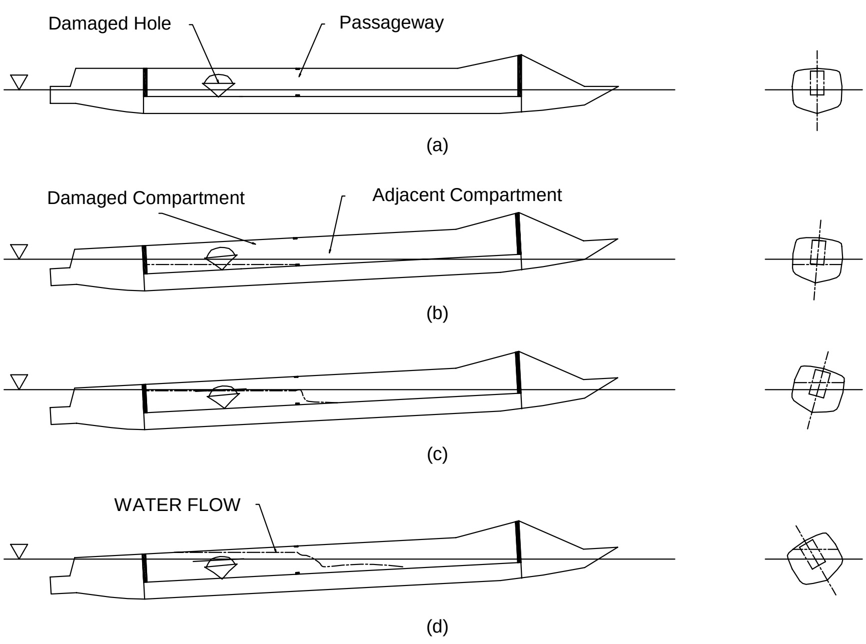


Figure 8.2 Damage scenario includes continuous flooding.

8.8 Hydrodynamic Coefficients

One of the most important input files for the simulation program is hydrodynamic coefficient data file. The main part of this file consists of hydrodynamic coefficients for six motions. These coefficients did not obtain using experiment but obtained using simulation program. The program using the Frank-Close-Fit method combined with strip theory. The program enable to obtain hydrodynamic coefficients of added mass and damping coefficient for sway, heave, roll, coupled sway-roll, pitch and yaw. For this study, the wave frequencies vary between 0.1 to 2.2 rad/s with interval 0.1 rad/s.

From the simulation results in the below then we can summarized the input file for damage stability simulation program. The summarized of hydrodynamic coefficients which are used in damage stability program are shown in Table 8.1.

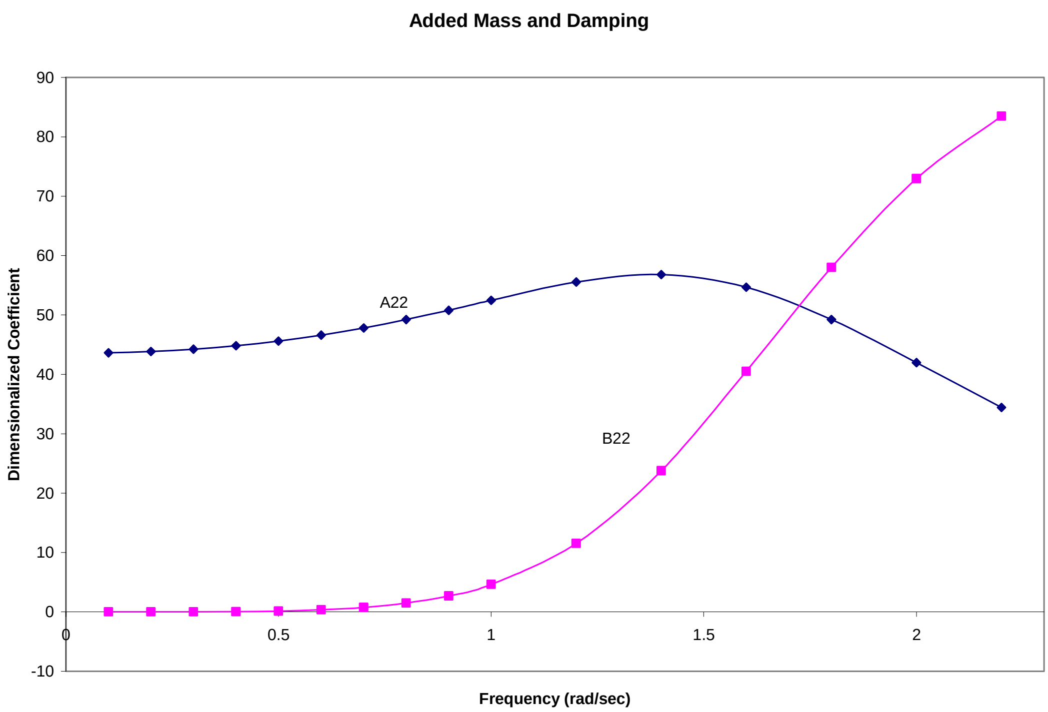


Figure 8.3 Added mass and damping coefficient for swaying versus frequency

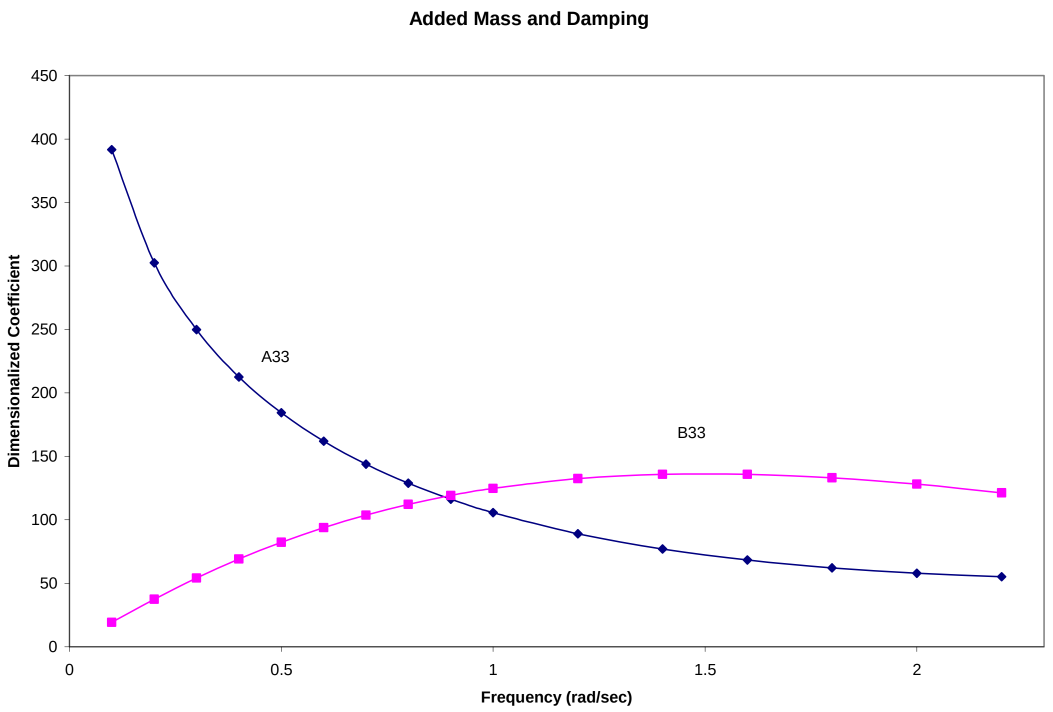


Figure 8.4 Added mass and damping coefficient for heaving versus frequency

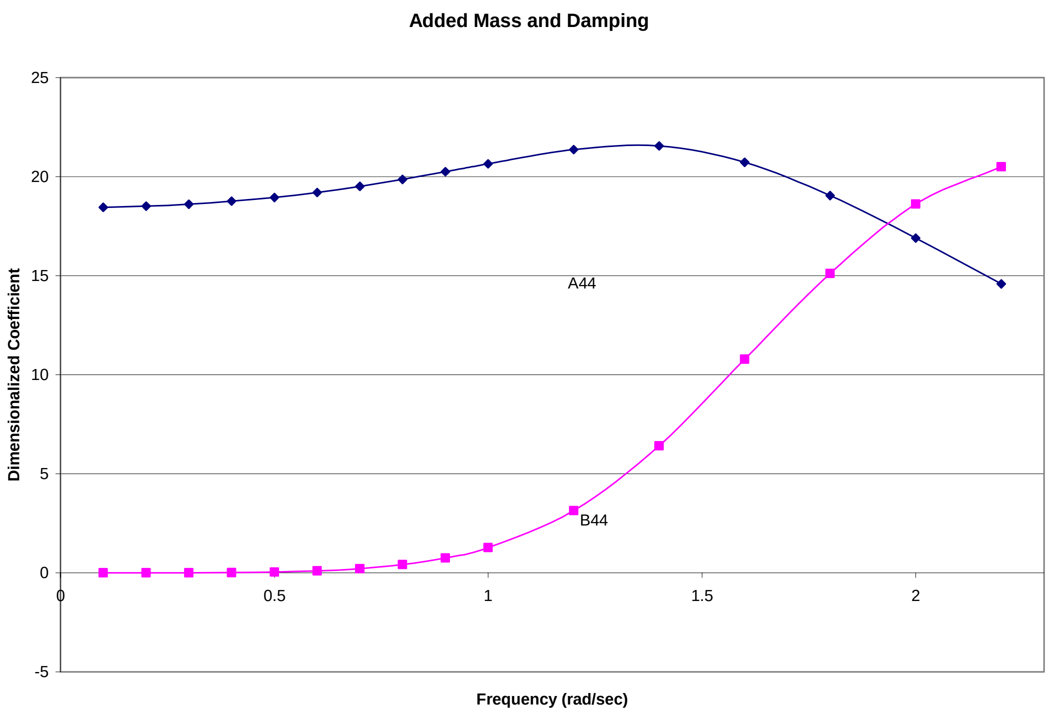


Figure 8.5 Added mass and damping coefficient for rolling versus frequency

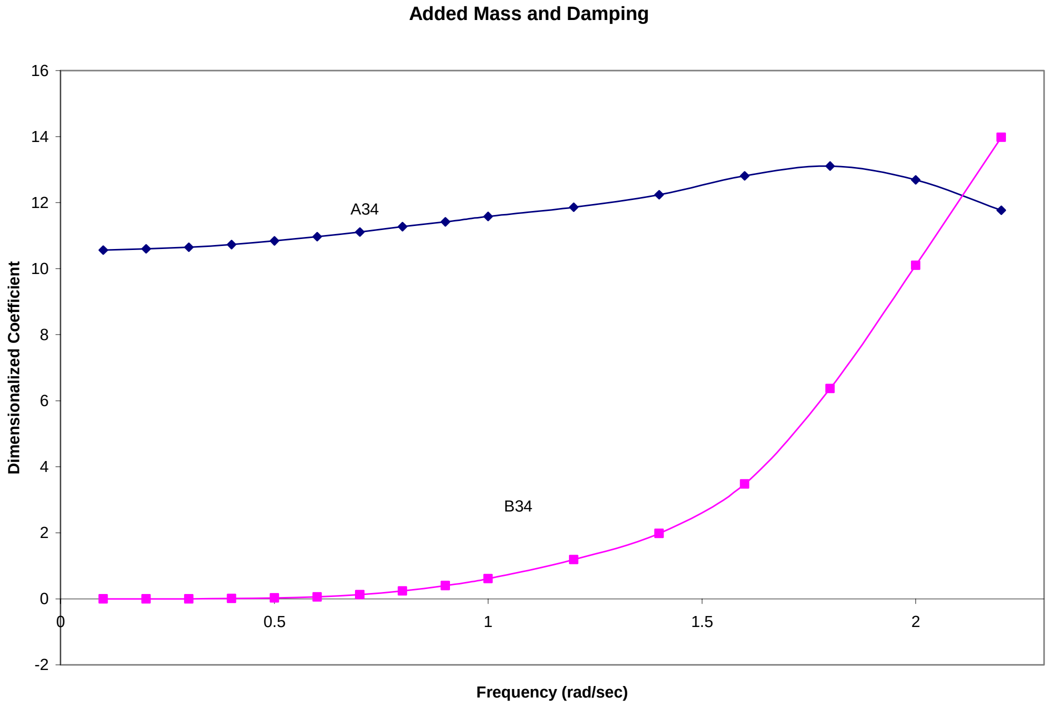


Figure 8.6 Added mass and damping coefficient for coupled sway-roll versus frequency

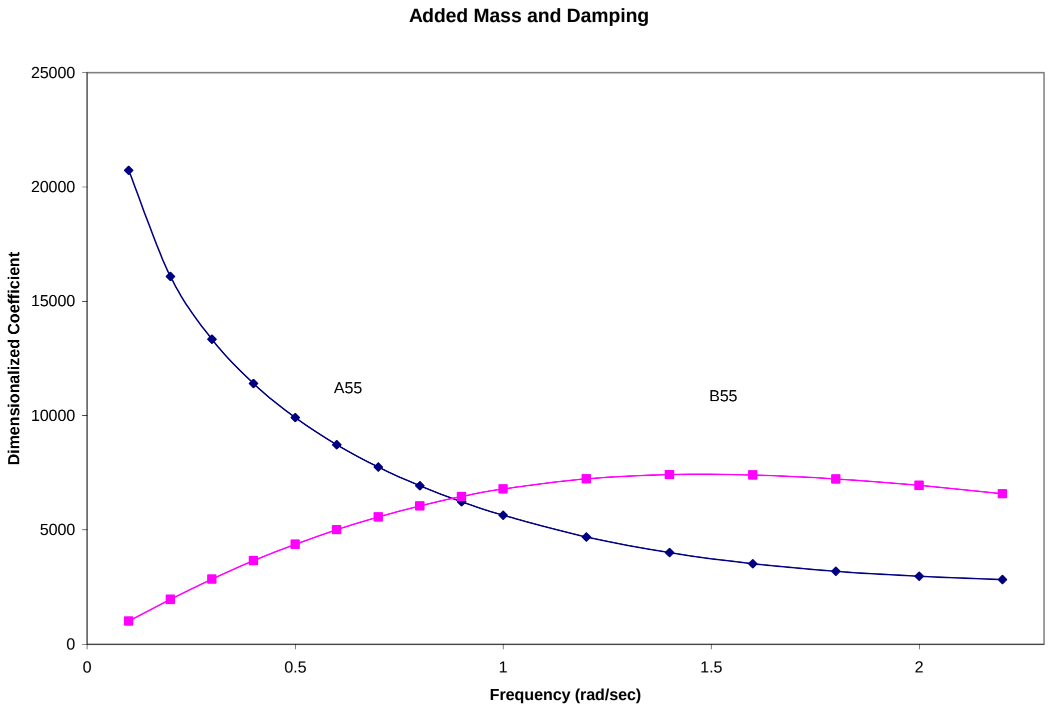


Figure 8.7 Added mass and damping coefficient for pitching versus frequency

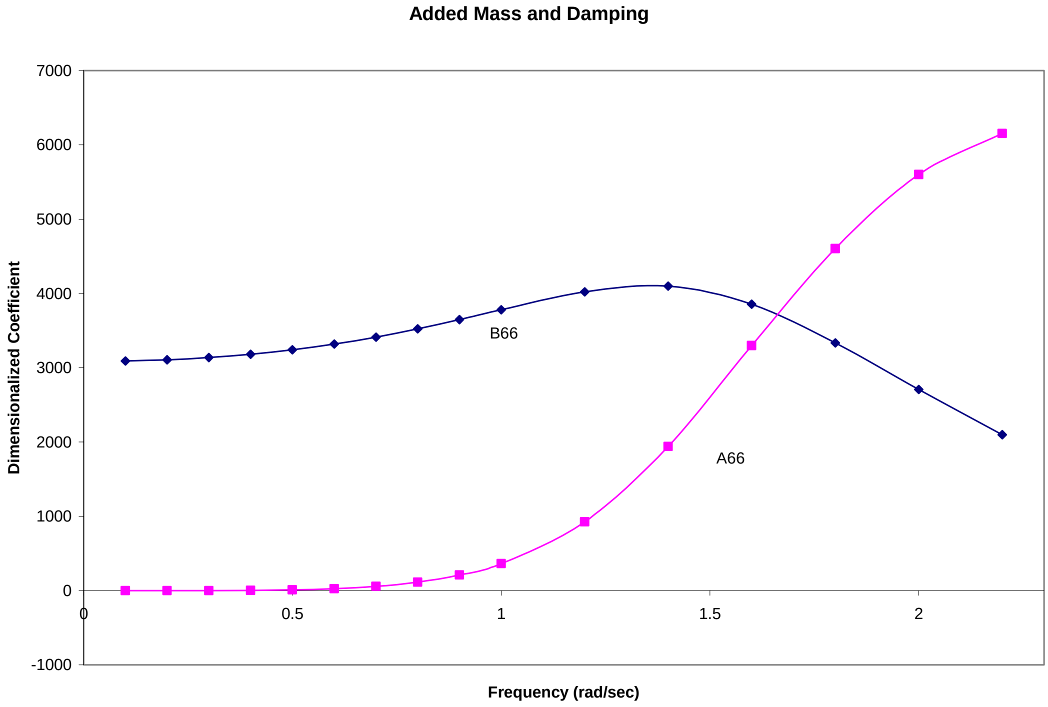


Figure 8.8: Added mass and damping coefficient for yawing versus frequency

Table 8.1: Summarized of hydrodynamic coefficients for simulation program

No	Hydrodynamic Coefficients	Interpolation	Polynomial	Average
1	A22	56.8125	56.5610	56.6868
2	B22	23.7193	24.0137	23.8665
3	A33	77.0195	75.7755	76.3975
4	B33	135.8899	137.1318	136.5109
5	A44	21.5490	21.4636	21.5063
6	B44	6.4010	6.4721	6.4366
7	A24	12.2378	12.3375	12.2876
8	B24	1.9754	1.9507	1.9631
9	A55	4010.8070	3957.9543	3984.3807
10	B55	7417.6758	7419.4006	7418.5382
11	A66	4098.8929	4069.9072	4084.4001
12	B66	1935.4385	1966.6509	1951.0447

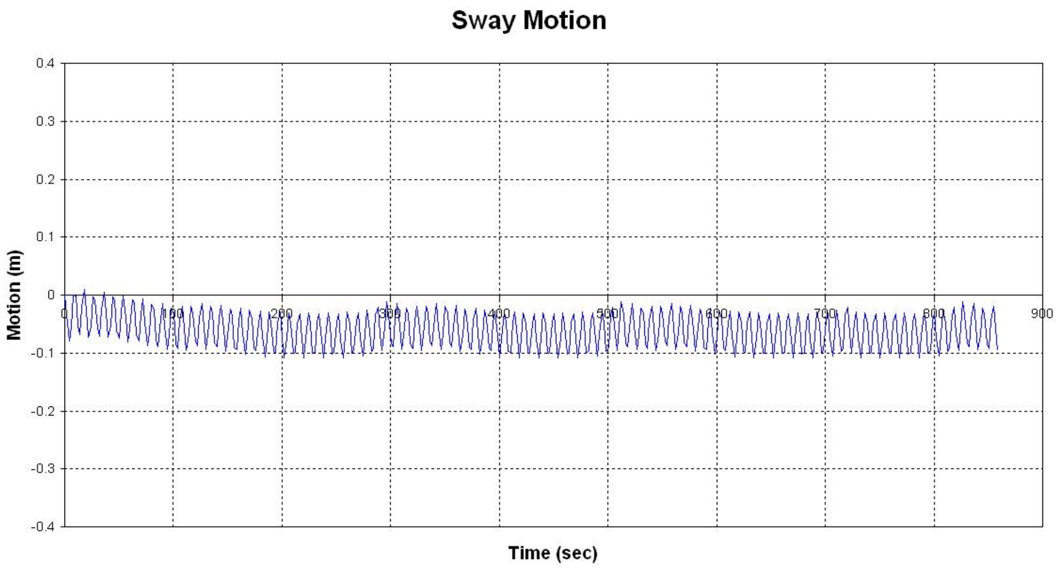
8.9 Dynamic Analysis

In this condition, 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 vessel. Water will flow from the damaged compartment to the adjacent compartment through a passageway similar to flow over a weir.

In Figures 8.9 to 8.17 shows that the simulations of sway, heave, roll and pitch motions as the water enters the compartment through the damage hole. The differences in motions are shown with the different KG and wave height values. Generally, 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. 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. The static heel does not seem to be affecting the heave motion significantly.

Typically the sway and pith 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.



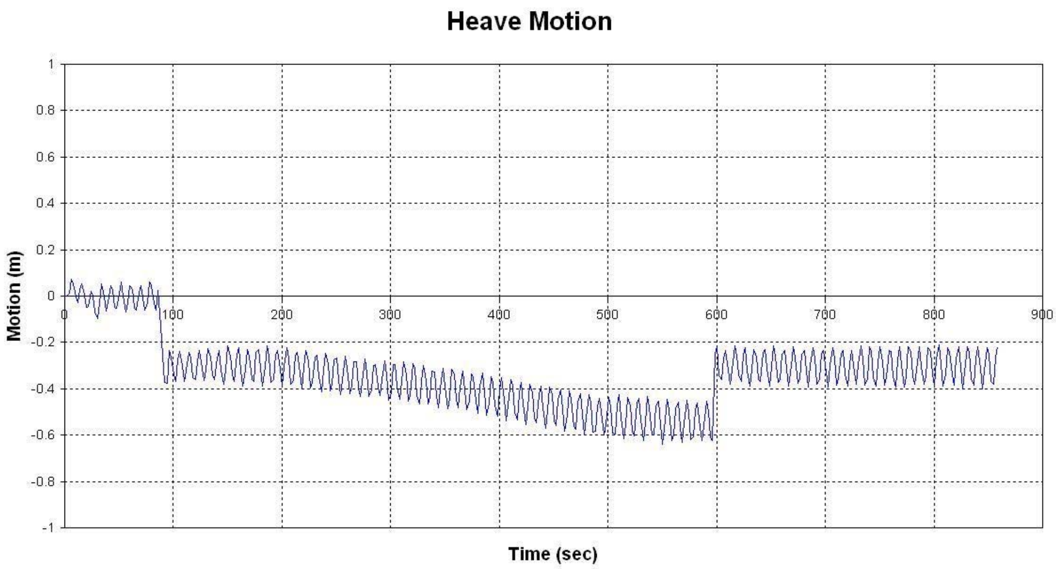
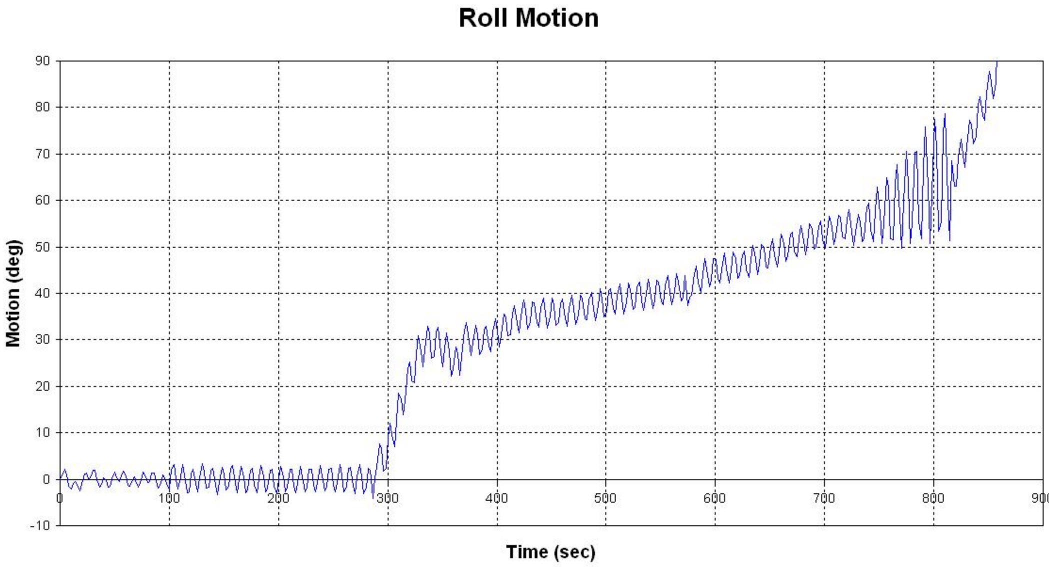


Figure 8.9a Time histories of ship motions during progressive flooding, KG = 1.1 m, WH = 0.1 m.



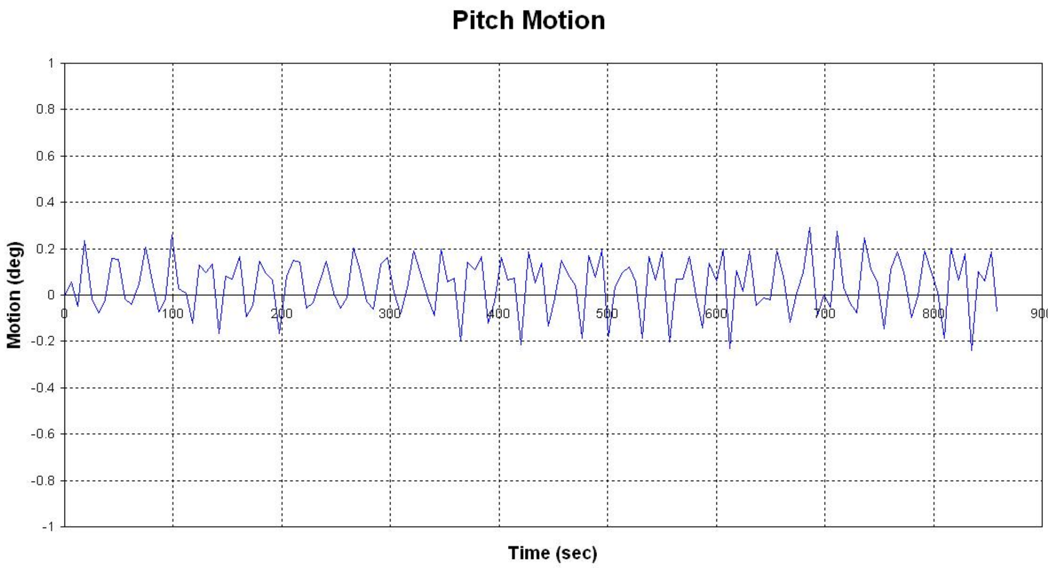
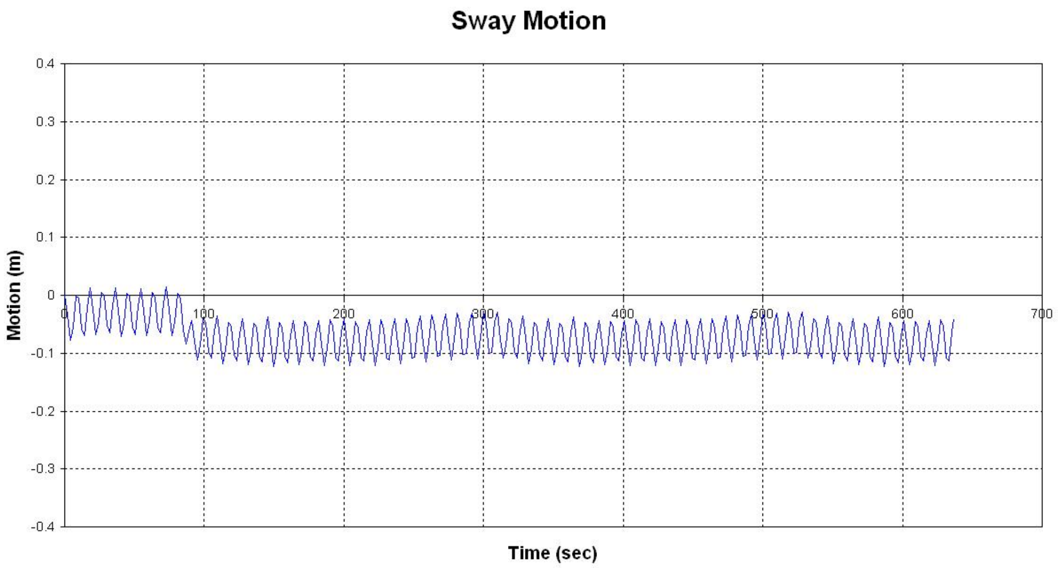


Figure 8.9b Time histories of ship motions during progressive flooding,

KG = 1.1 m, WH = 0.1 m.



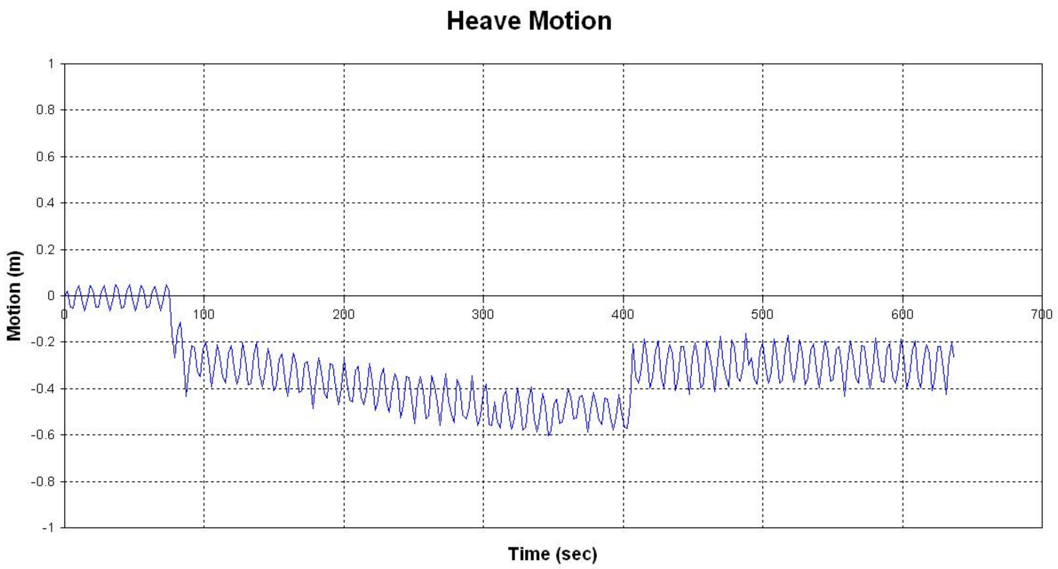
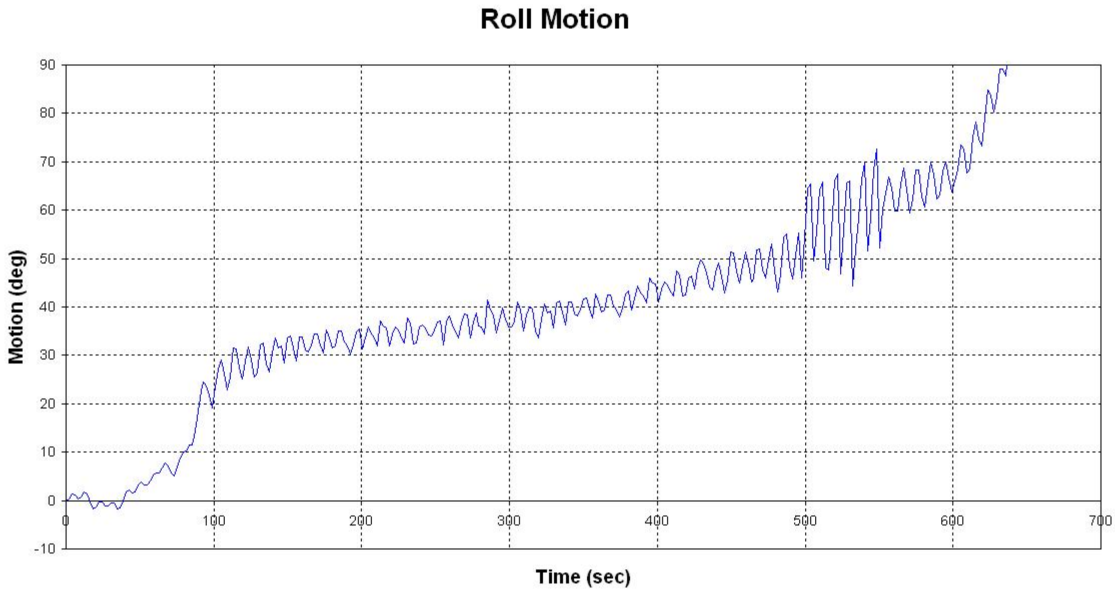


Figure 8.10a Time histories of ship motions during progressive flooding,

KG = 1.2 m, WH = 0.1 m.



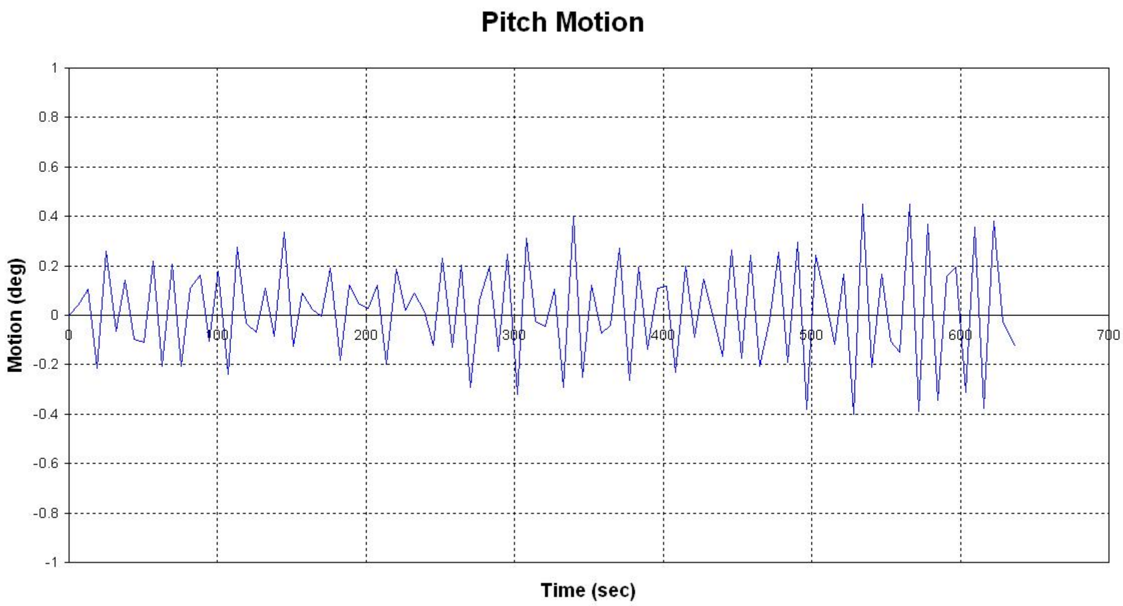


Figure 8.10b Time histories of ship motions during progressive flooding,

KG = 1.2 m, WH = 0.1 m.

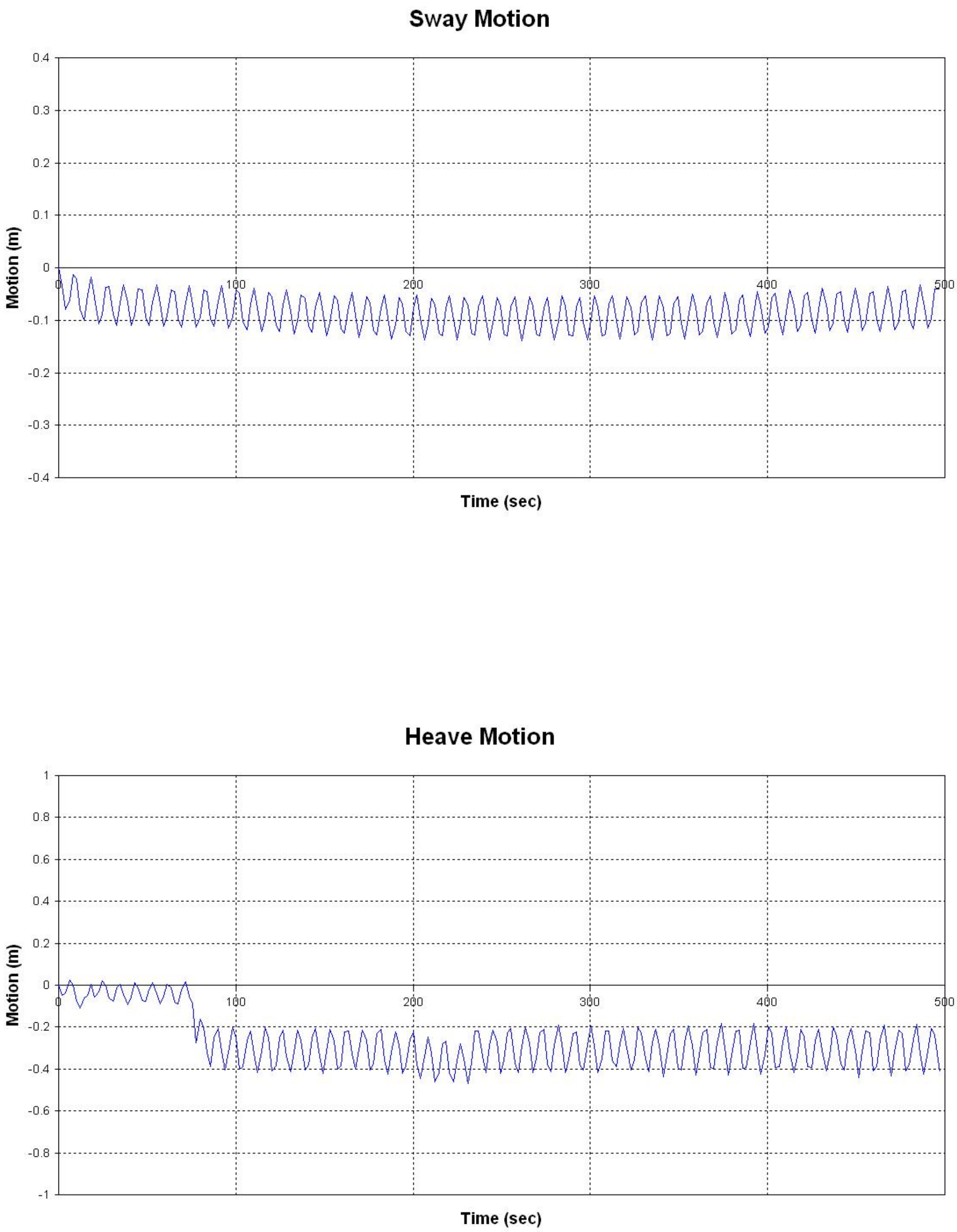
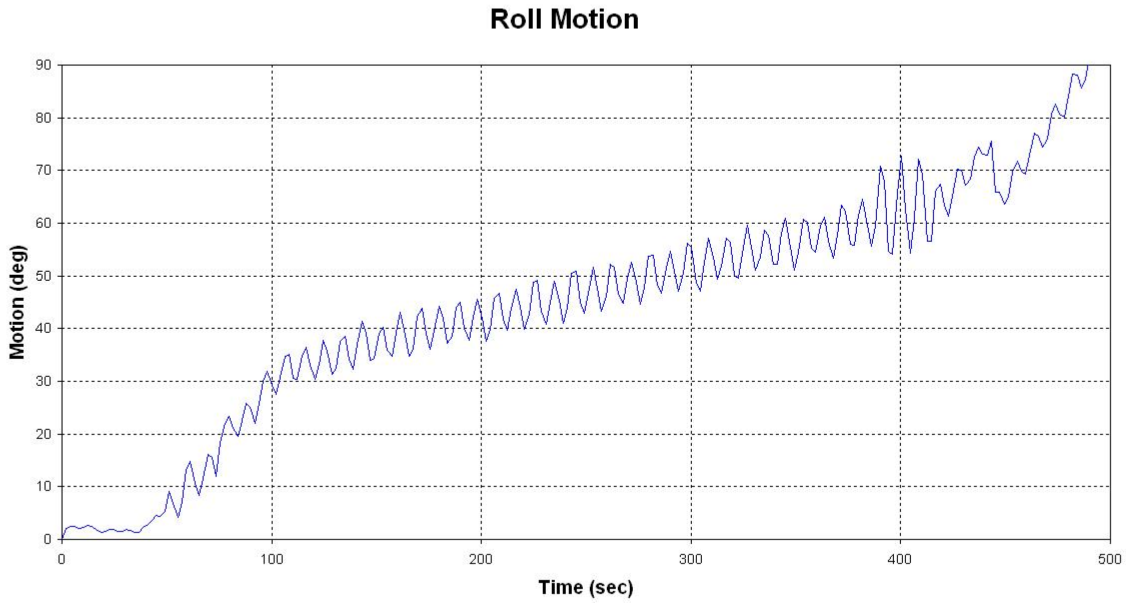


Figure 8.11a Time histories of ship motions during progressive flooding, KG = 1.3 m, WH = 0.1 m.



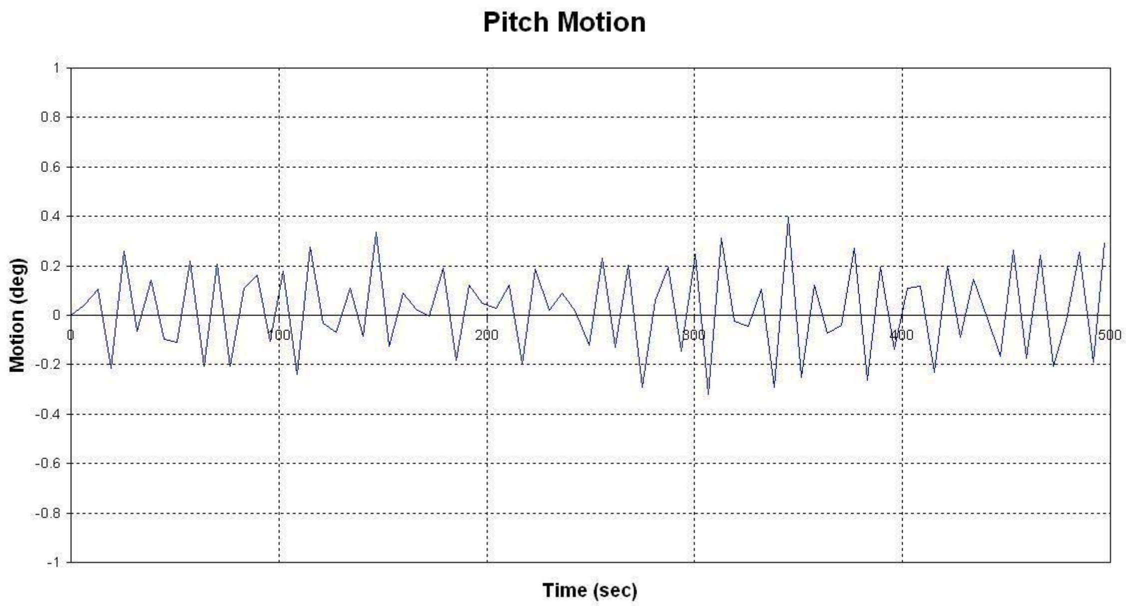
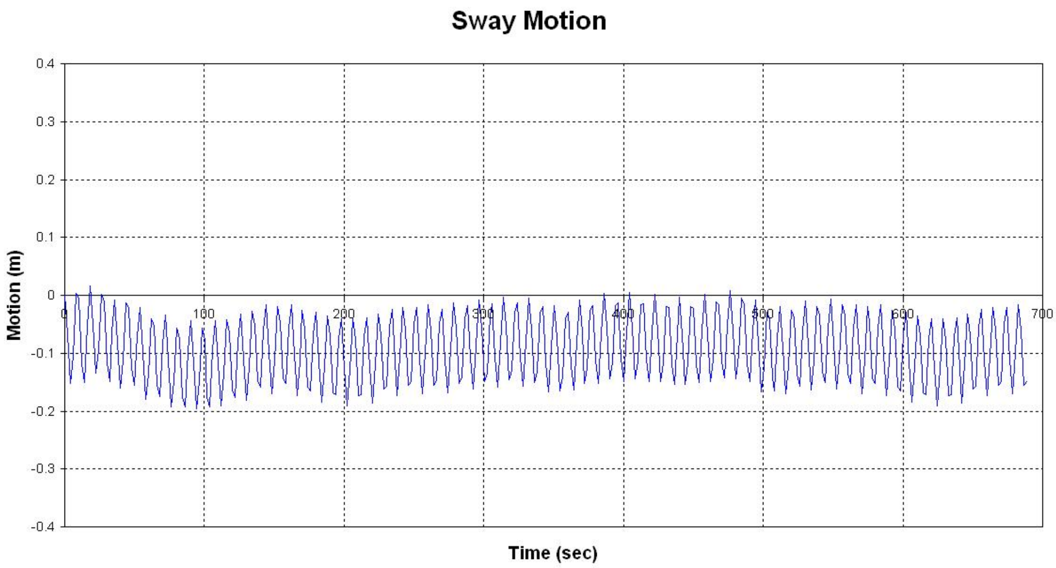


Figure 8.11b Time histories of ship motions during progressive flooding,

KG = 1.3 m, WH = 0.1 m.



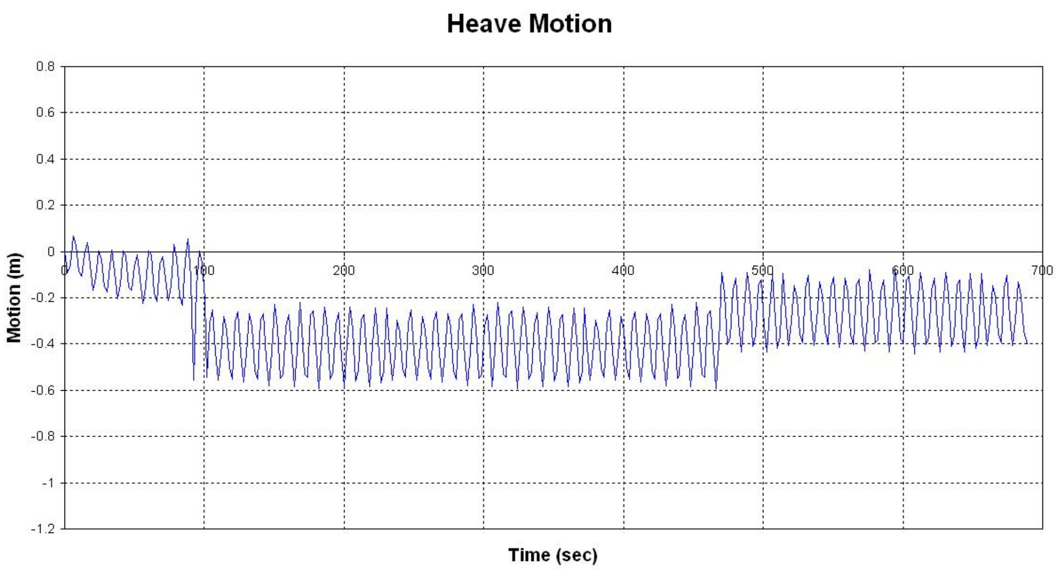
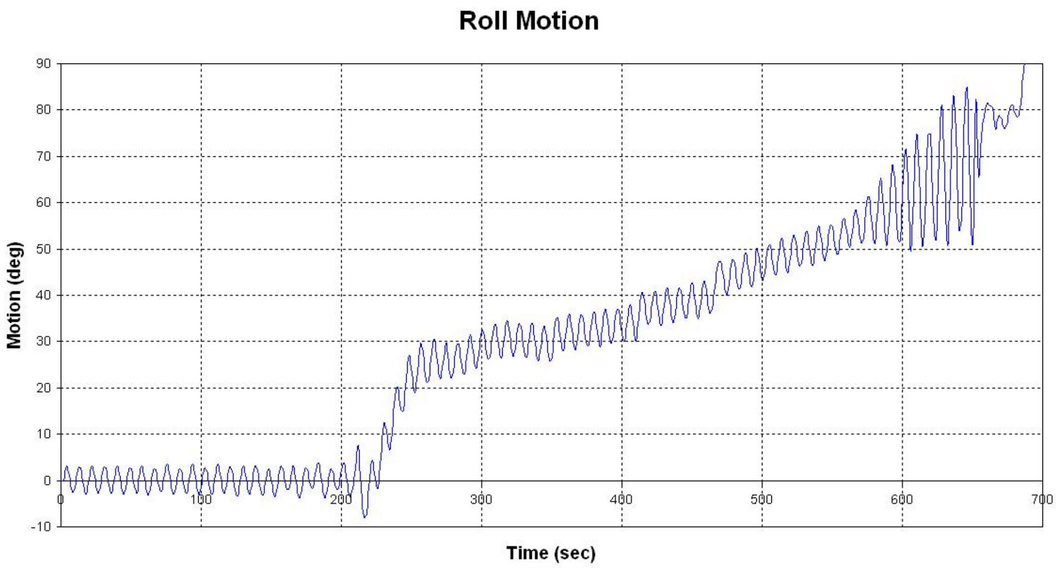


Figure 8.12a Time histories of ship motions during progressive flooding, KG = 1.1 m, WH = 0.2 m.



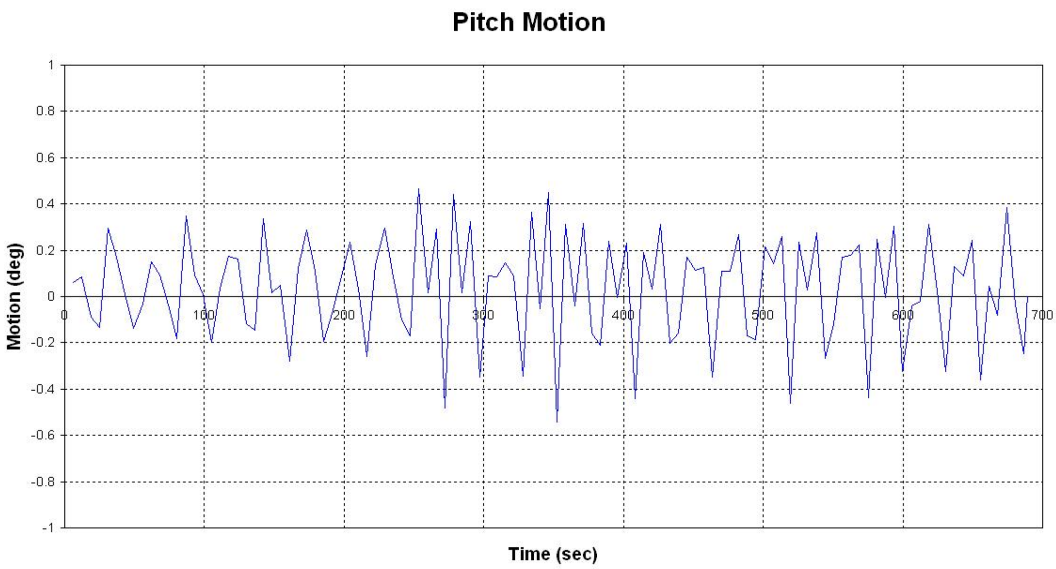
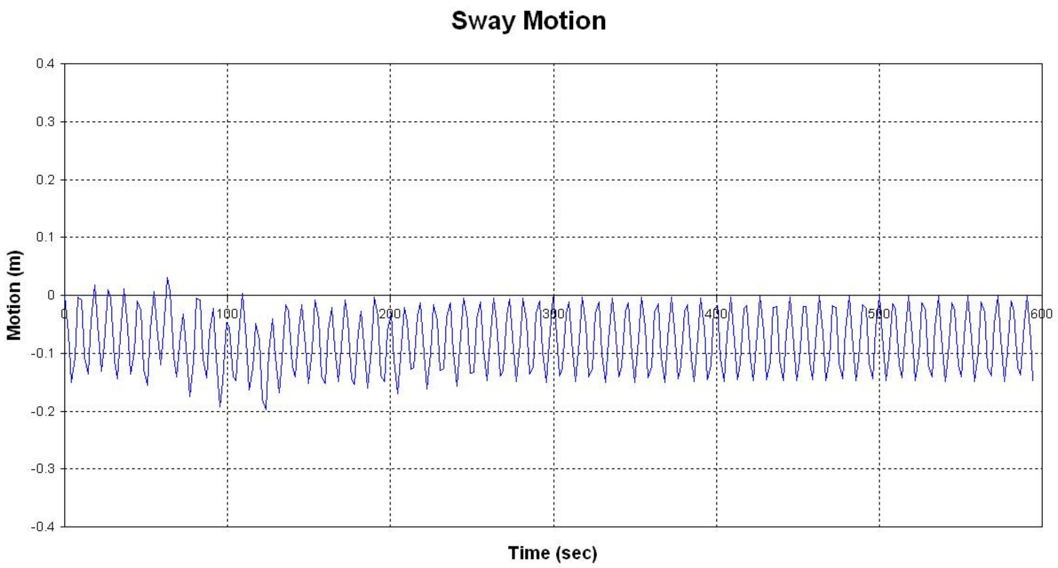


Figure 8.12b Time histories of ship motions during progressive flooding,

KG = 1.1 m, WH = 0.2 m.



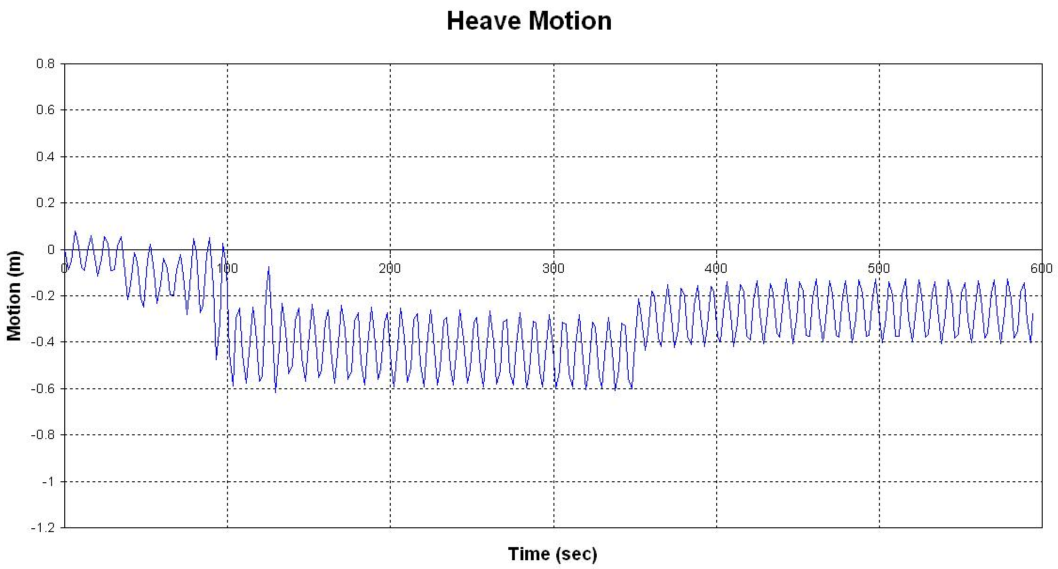
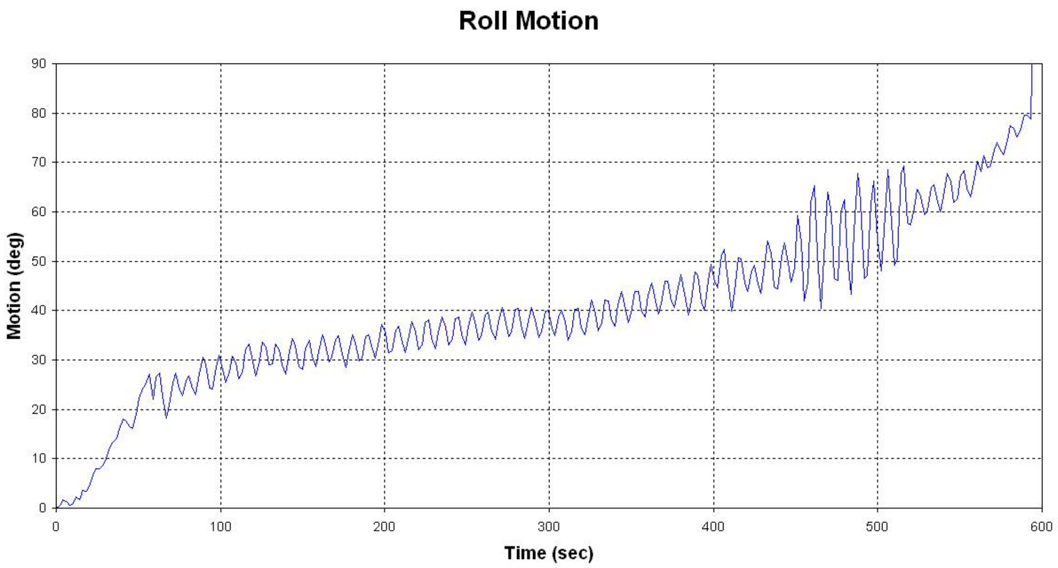


Figure 8.13a Time histories of ship motions during progressive flooding,

KG = 1.2 m, WH = 0.2 m.



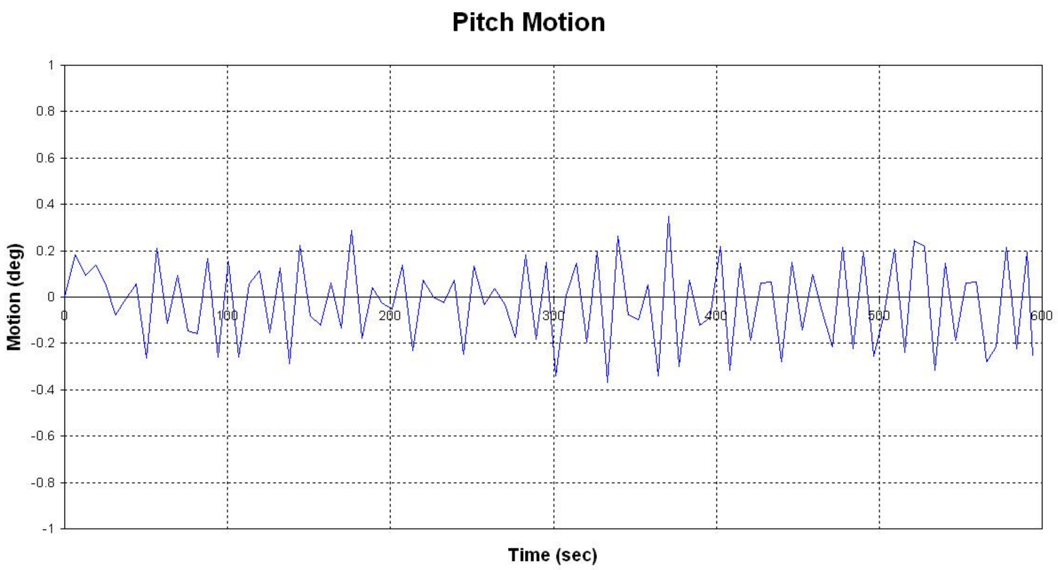
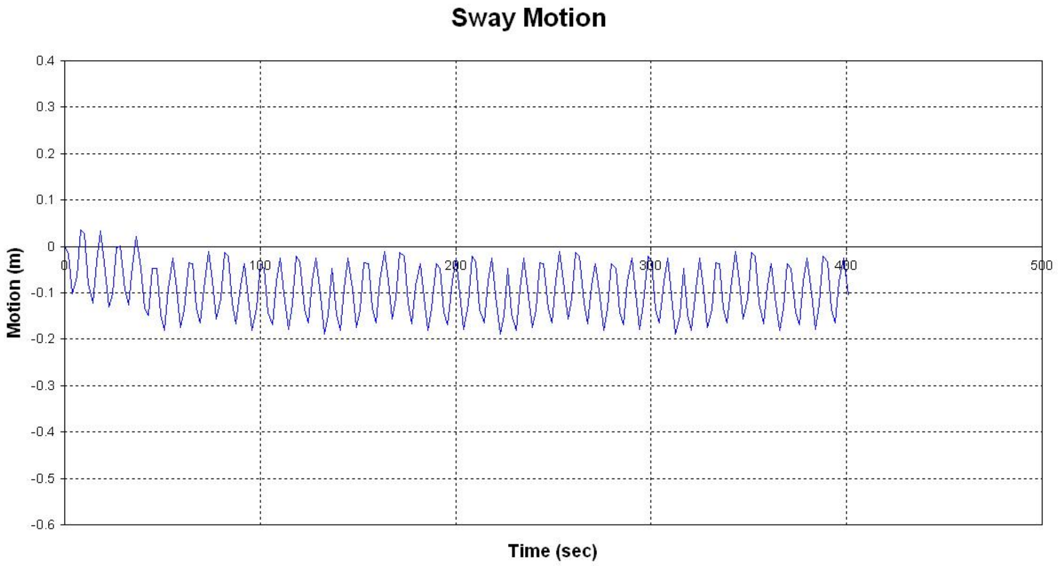


Figure 8.13b Time histories of ship motions during progressive flooding,

KG = 1.2 m, WH = 0.2 m.



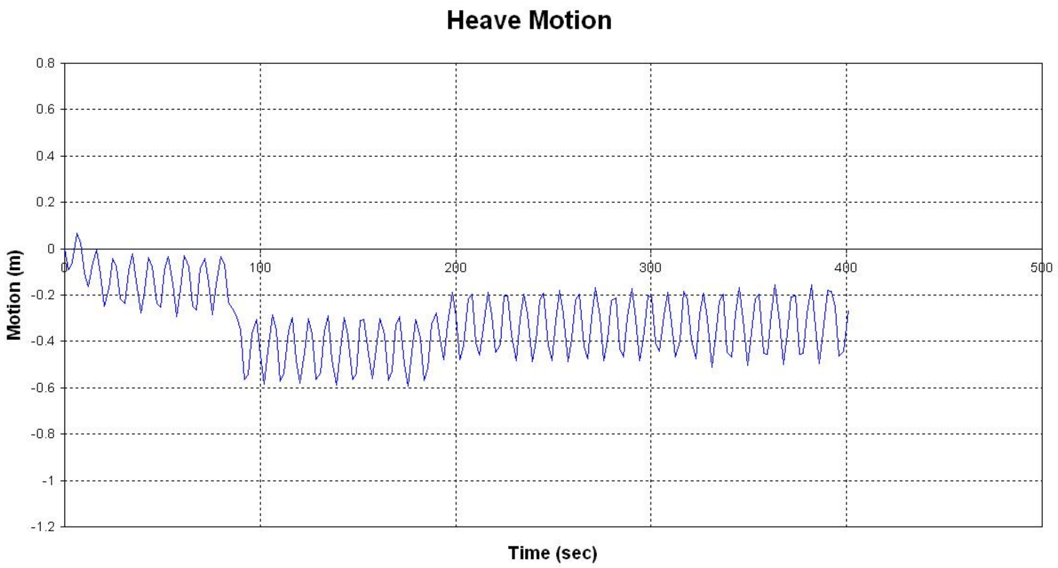
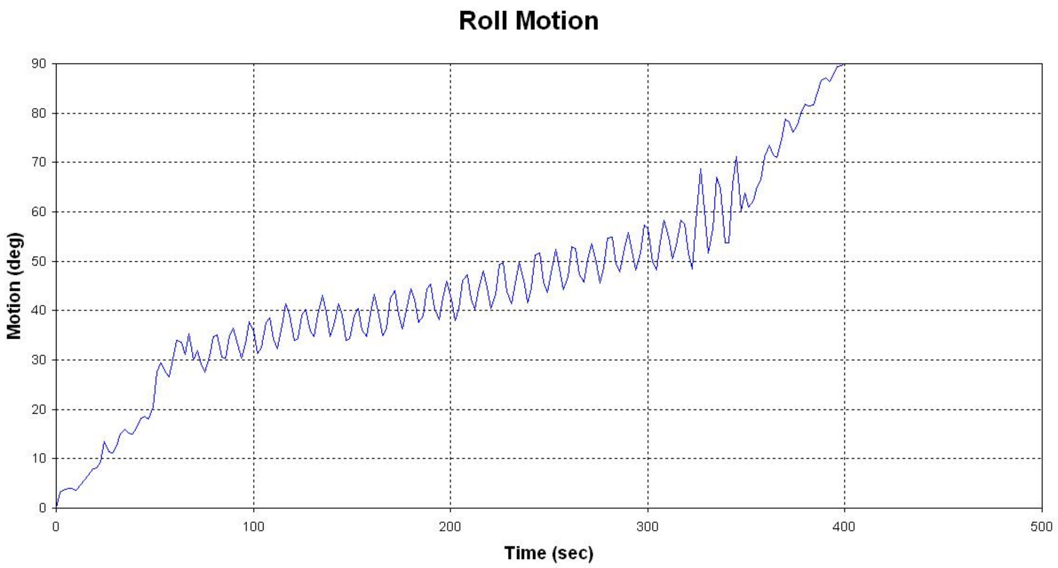


Figure 8.14a Time histories of ship motions during progressive flooding, KG = 1.3 m, WH = 0.2 m.



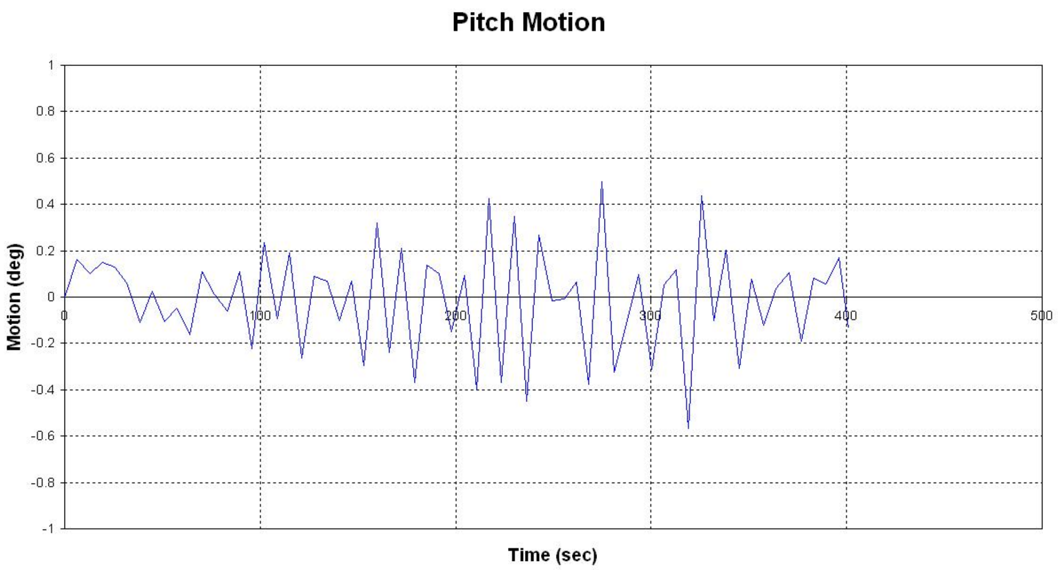
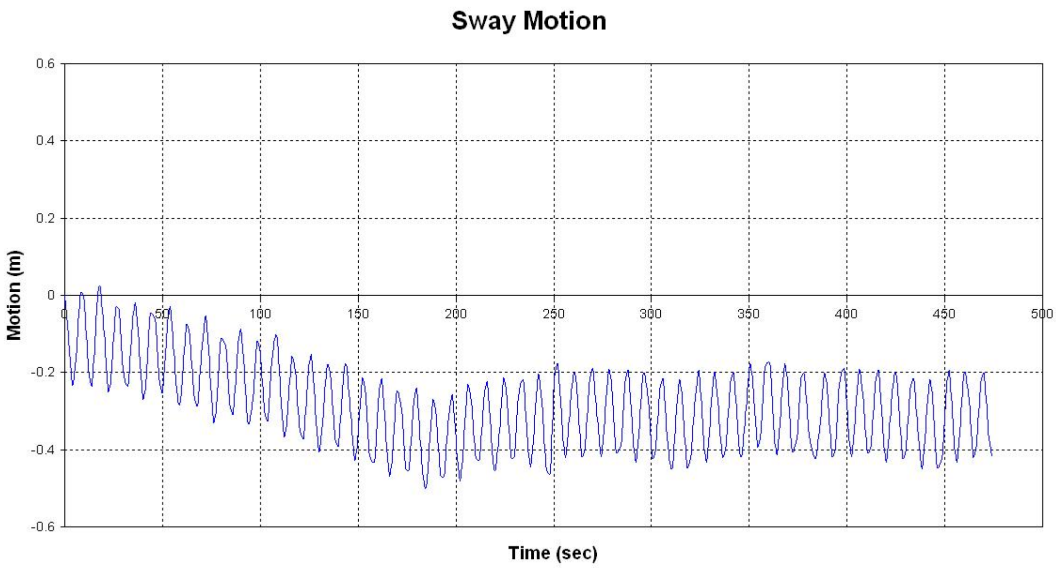


Figure 8.14b Time histories of ship motions during progressive flooding,

KG = 1.3 m, WH = 0.2 m.



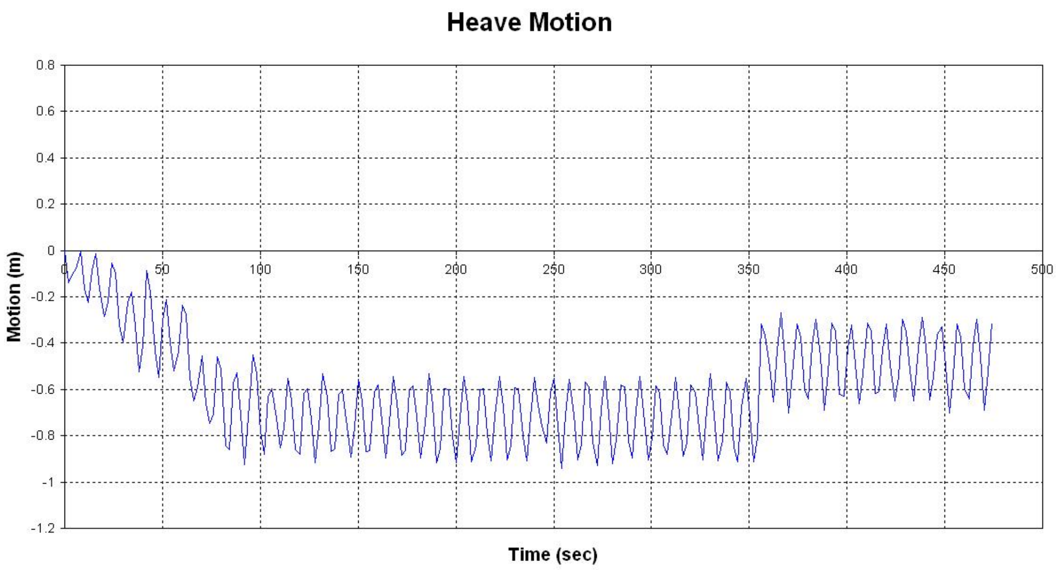


Figure 8.115a Time histories of ship motions during progressive flooding, KG = 1.1 m, WH = 0.3 m.

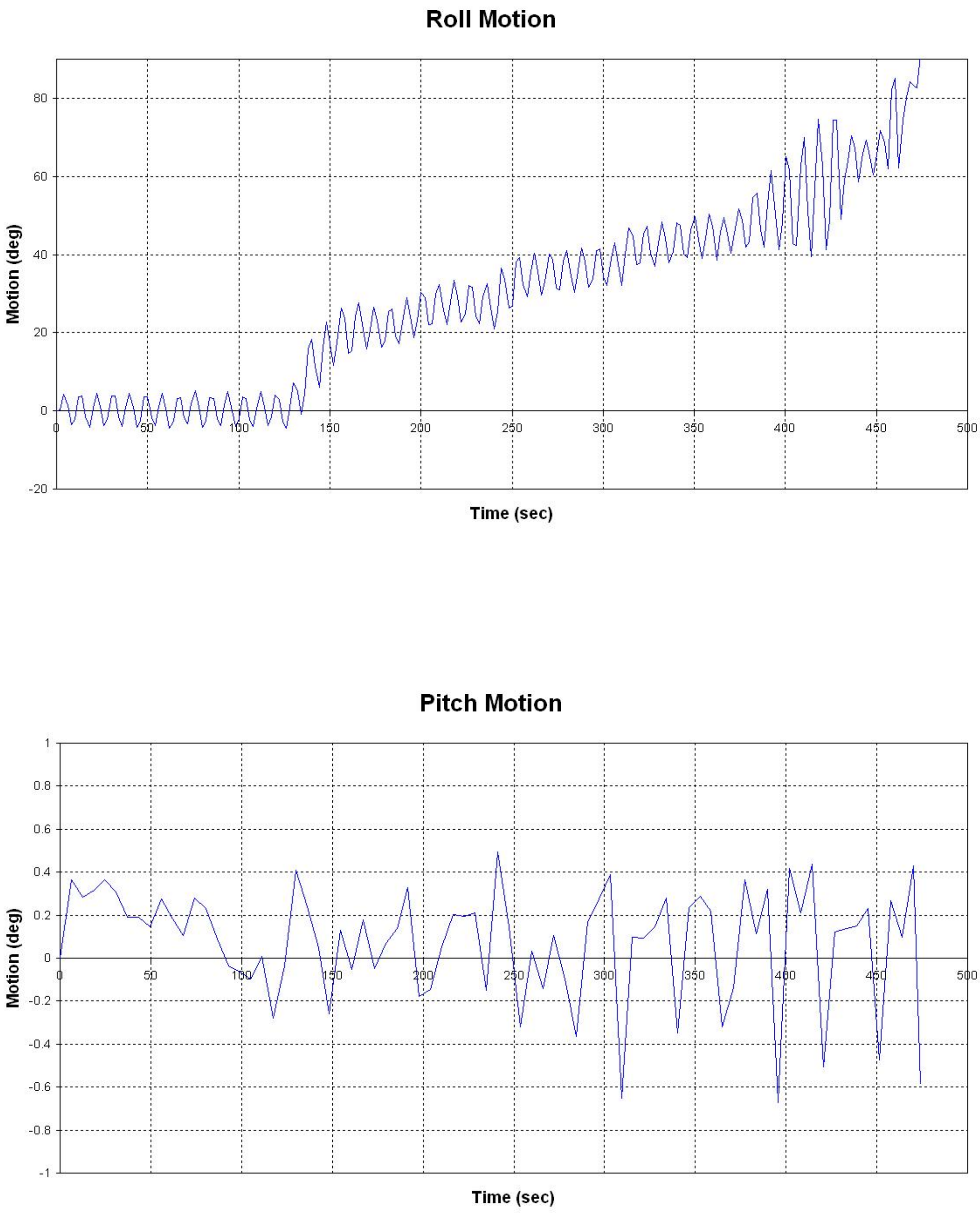
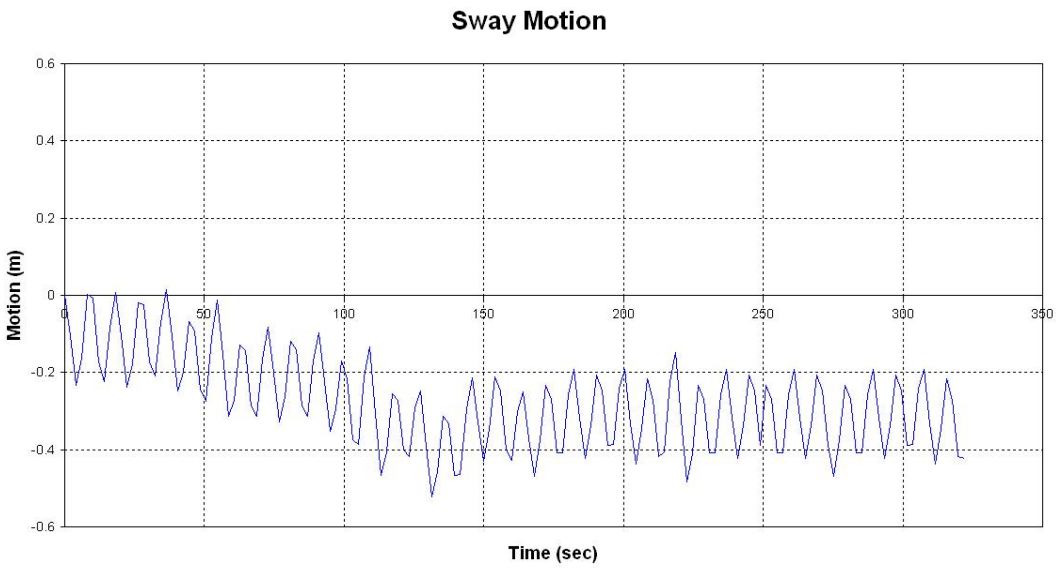


Figure 8.15b Time histories of ship motions during progressive flooding,

KG = 1.1 m, WH = 0.3 m.



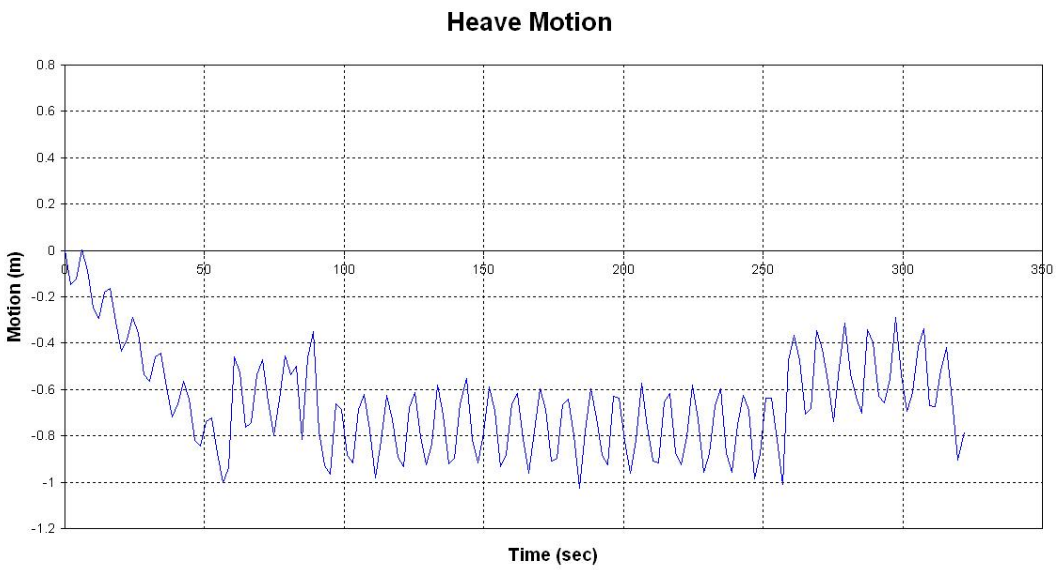
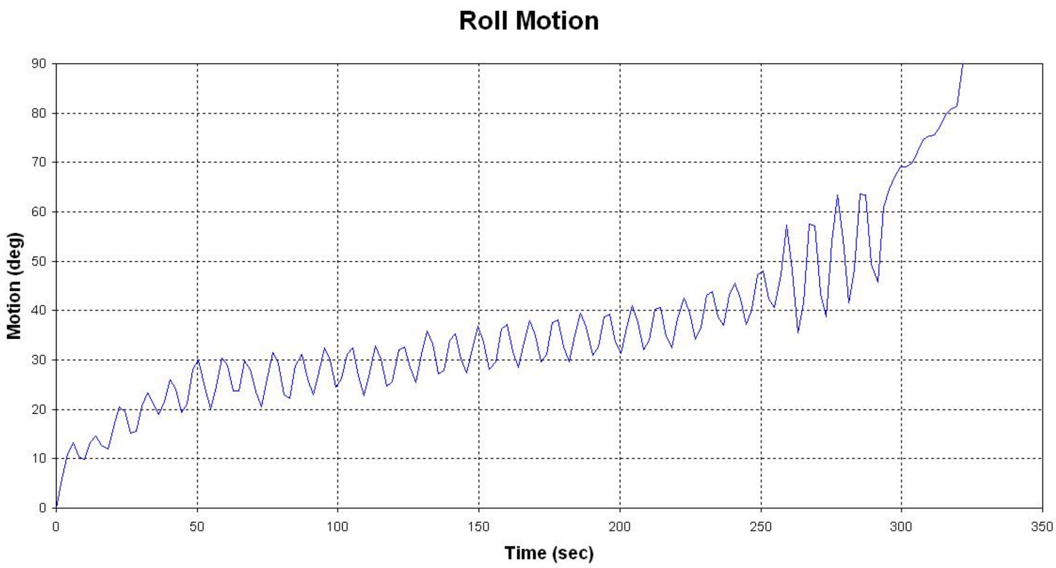


Figure 8.16a Time histories of ship motions during progressive flooding, KG = 1.2 m, WH = 0.3 m.



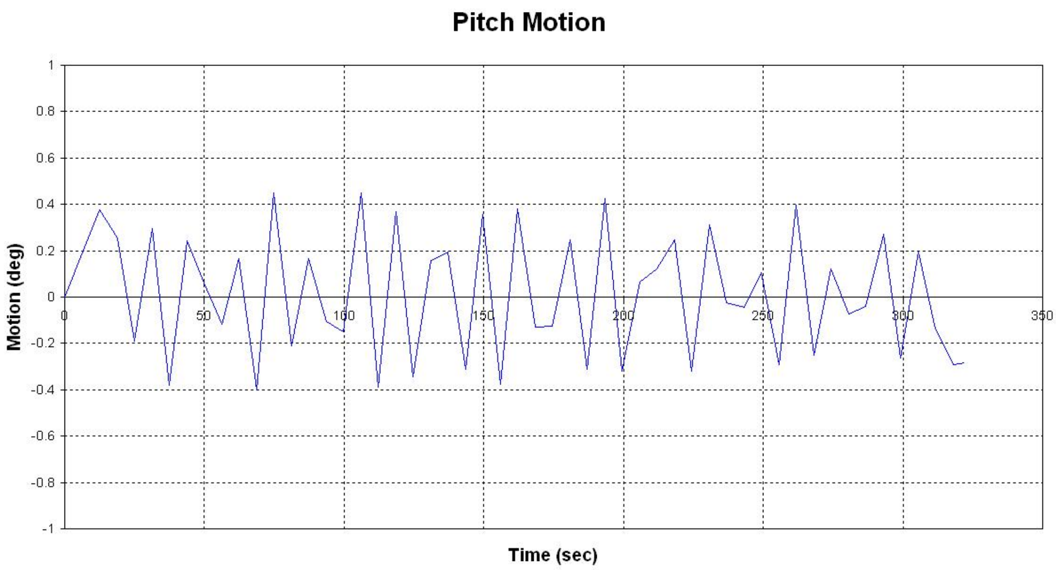
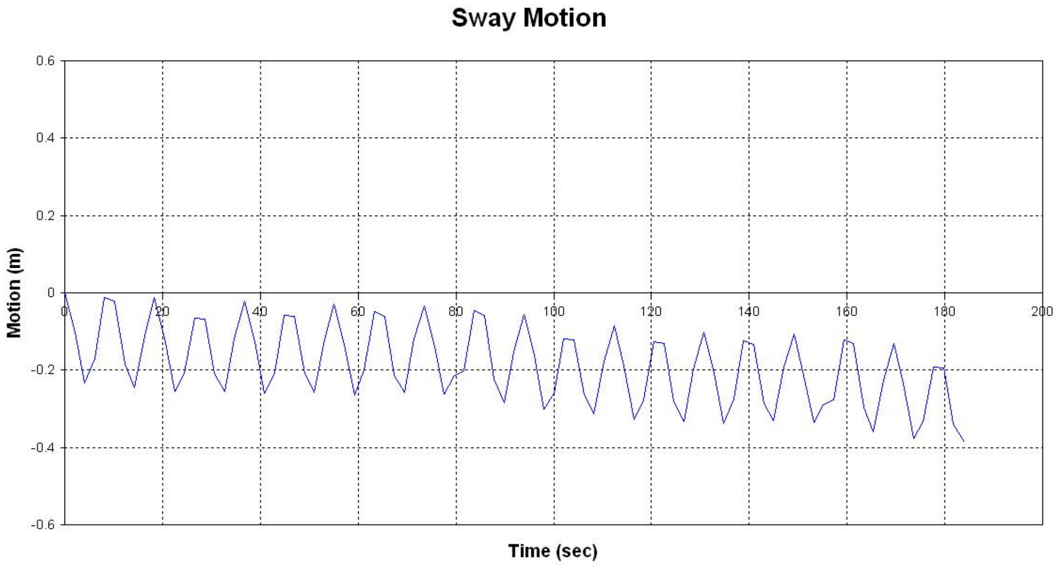


Figure 8.16b Time histories of ship motions during progressive flooding,

KG = 1.2 m, WH = 0.3 m.



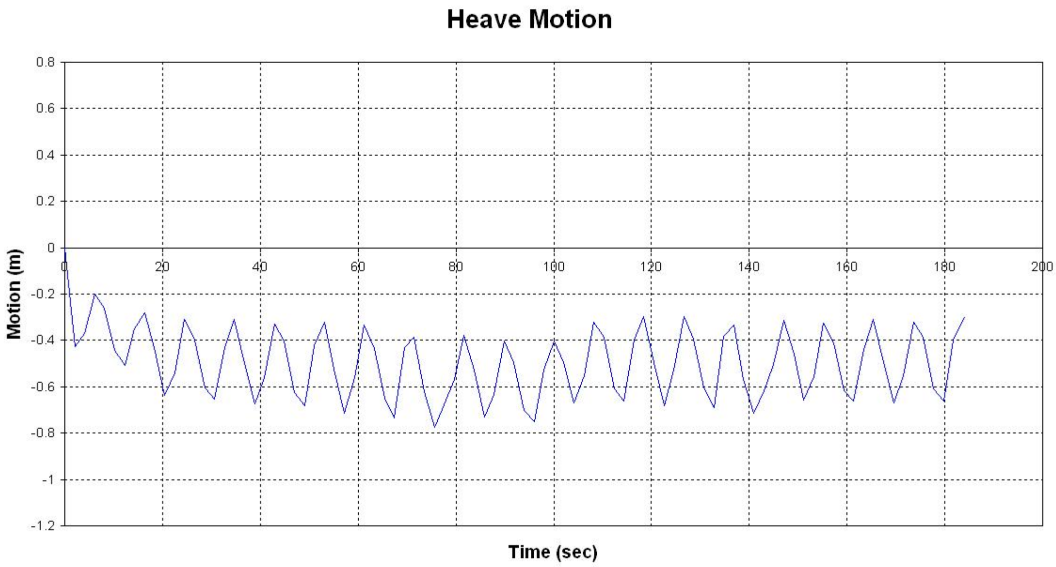
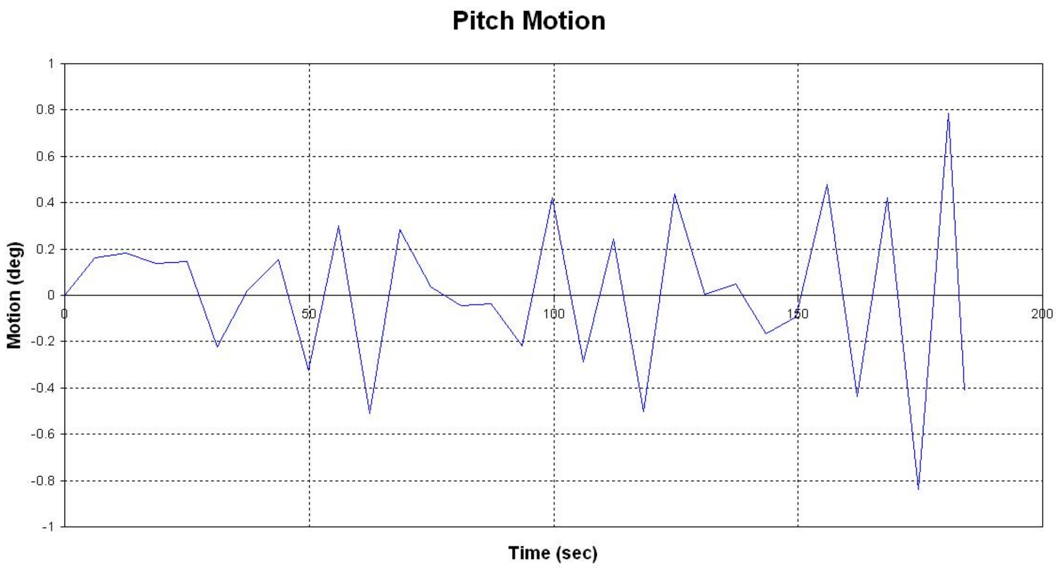


Figure 8.17a Time histories of ship motions during progressive flooding, KG = 1.3 m, WH = 0.3 m.



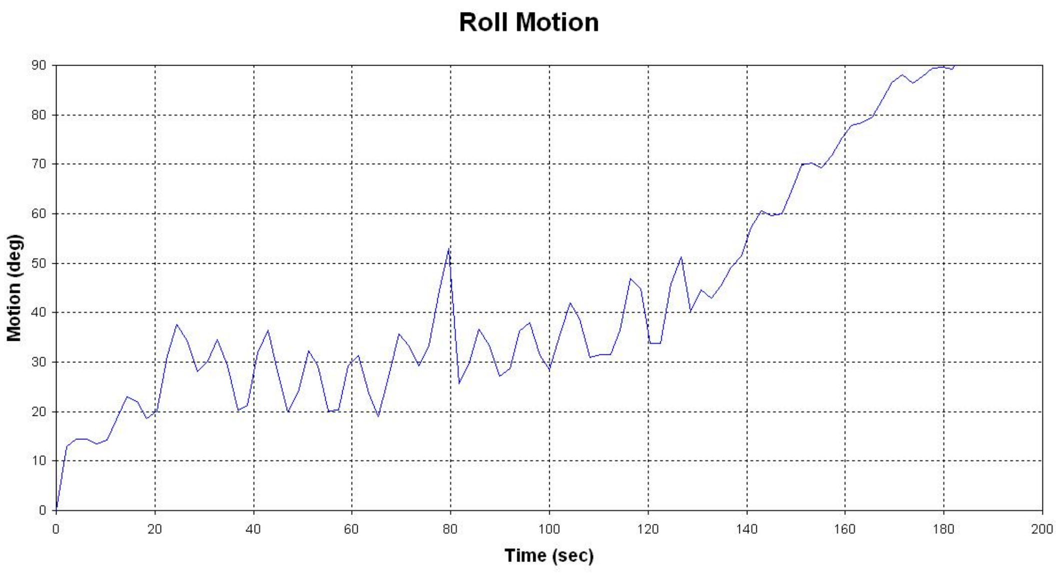


Figure 8.17b Time histories of ship motions during progressive flooding,

KG = 1.3 m, WH = 0.3 m.

From Figure 8.9 to 8.17, the safe and unsafe conditions of the vessel are determined. The safe condition is assumed when the time to capsize is reached within short period of 300 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 8.18 shows safe / unsafe conditions through a plot of KG against wave height.

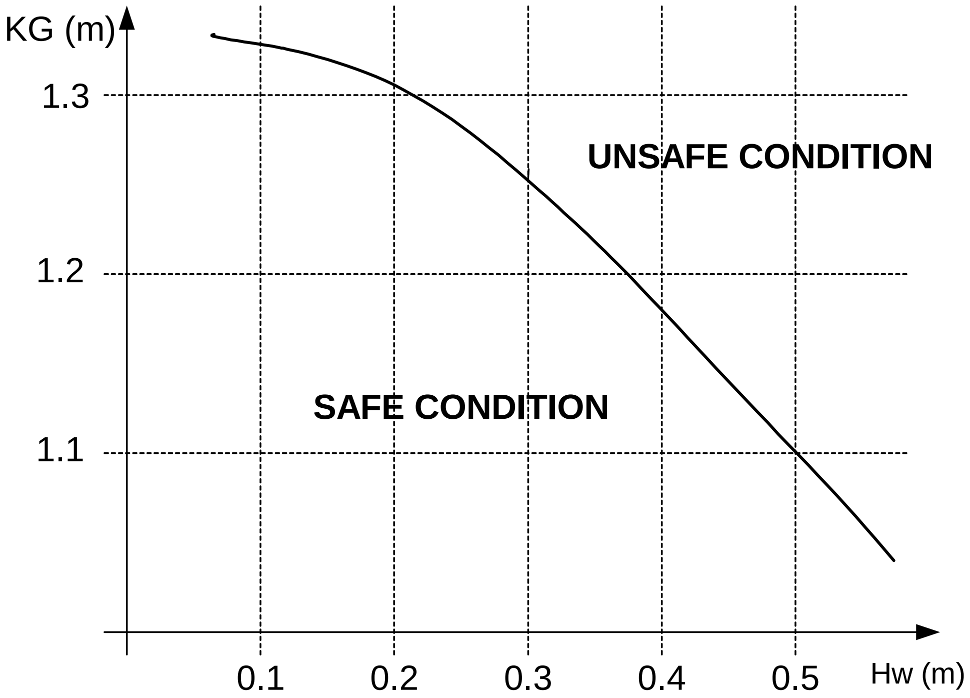


Figure 8.18 Safe and unsafe condition of the Sarawak Fast Ferry

This study clearly shows that flooding the main deck is very dangerous and it is more than likely that the ship will capsize as was proved in the case of the Herald of Free Enterprise.

8.10 Concluding Remarks

Optimizing the simulations by varying the aforementioned parameters near the critical situation to achieved the main goal. Wave height and loading conditions are the main parameters that influence the ship's stability in damage condition. Water ingress which depends on the wave elevation and damage location is applied on the simulation give the good results. In the condition that the main deck assumed to flooded and the water ingress occurs on one of the compartment due to collision which is located at the aft of the vessel then the water will flow from the damaged compartment to the adjacent compartment through a passageway similar to flow over a weir; The survivability of Sarawak Long-Boat can be considered as critical. The ship can only survive at small wave height and low KG conditions during progressive flooding.

CHAPTER 9

CONCLUSIONS AND FUTURE WORKS

9.1 General

Damage stability of small vessel is considered to be a complex matter as compared to the large vessel. The main reason is due to the size, specific mission and design of small vessel is totally different from large vessel. 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.

The reasons lead the small vessel to be more sensitive to the damage. If the progressive flooding takes into the compartment of small vessel on damage condition, the motion of vessels will be significantly become bigger, especially for rolling motion that leads to capsize even on small wave height. As a result, a small vessel could be capsized in the damaged situation even it has satisfied the damage stability criteria requirement. Present damage stability assessment of small vessels such as IMO and HSC Code are concerned with only residual static stability represented by residual GM, GZ and extent of damage. Under these circumstances, the dynamic effects in the assessment of damage stability and survivability of vessels are needed.

9.2 Discussion

Unfortunately safety and commercial gain conflict, and as a result if new rules are introduced, it would take a very long time to implement them fully, therefore achieving solid progress becomes difficult. A Stability assessment procedure and adopted stability standards can be seen to be successful if they produce a meaningful relationship between safety, vessel design, and operational and environmental conditions. The link between these three main factors can be derived by using a mathematical model, model tests or full scale trials.

9.2.1 Mathematical Model

The mathematical modelling route, trusted and validated within the limits of the theory was followed in the approach adopted in this thesis. The mathematical model offers a cost effective solution while having flexibility and versatility since it is suitable for systematic studies of different parameters over a wide range of limits. Moreover, an investigation of the parameters involved, which will be very difficult to examine by model tests or trials, can be undertaken

On the other hand, the mathematical model has drawbacks due to different reasons, such as the limits of the theory used and the nonexistence of solutions. However, with the use of justifiable assumptions it is still possible to obtain meaningful results.

Investigation also revealed that the mathematical model must include progressive flooding and accumulation of water, and coupled vessel motions must be solved for realistic environmental conditions. To combine all the effects in the mathematical model, the time domain technique, which solves equations of coupled surge, sway, heave, roll, pitch and yaw motions using numerical methods, was employed.

9.2.2 Dynamic Stability of Damage Vessel

Physical understanding of the damage stability of a vessel must be gained and the main problems and needs must be identified. In order to achieve this, the available published studies in the field of stability over the years are probably the most valuable source. However, besides identifying the problems and gaining physical understanding in the subject, the approach to combine all these effects and the solution technique are also equally important. Therefore, development in other fields such as computer technology and numerical solution techniques have to be employed in the development of a new approach.

Review of previous work emphasized that stability of the vessel whether it is intact or damage, is a dynamic phenomenon, so that it has to be treated in a fully dynamic form. However, despite the numerous number of published works in intact stability and dynamic damage stability suffers from limited available information on modelling certain phenomena such as water ingress, accumulation of water, etc.

For instance, water ingress was modeled using fixed flow rate or approximated water ingress coefficients as explained in Chapter 4. Although these approximations are very useful achievements in this field, since no other information is available, and meaningful result were achieved as shown in Chapter 4, they stopped short from offering a general calculation procedure. Since water ingress is a determining factor in affecting vessel survivability, a more accurate estimation of water ingress would improve the dynamic damage stability assessment. Therefore, this subject deserves careful consideration and the experiment should be conducted to validate the empirical calculation.

The adopted approach is the theoretical approach used to treat the damage stability of a vessel in a fully dynamic manner while investigating the associated phenomena extensively and realistically. In addition, an investigative structure has been developed that allows the approach to be enriched without any difficulty and without affecting other parts of the approach.

9.2.3 Effect of Main Parameters

It is important in identifying parameters affecting the vessel's stability, and in establishing relationships between environmental and vessel design parameters, and stability characteristics. Therefore, the strategy, contents and limits of the parametric investigation play an important part in how valuable the achievements are in the damage stability field.

Probably the most fundamental idea adopted for the parametric study in this thesis is the "Damage and flooding may occur at any location in the vessel and can be of any extent". Taking the location and. extent of damage as the basis, different parameters such as wave height, loading condition, water flow etc. were investigated extensively. As a result of this investigation some key findings can be listed as follows:

- Location and extent of flooding is vital to vessel's survivability
- Amount of water on deck is a determining factor on survivability
- Waves are also important in affecting vessel survivability
- Vessels can be lost as a result of progressive flooding
- The vessel's loading condition is one of the very important parameters affecting the survivability of the damaged vessel as well as other related parameters such as vessel roll, amount of water on deck etc.

Results of this investigation helped to establish clearly the level of critical damage stability. Wave height was also identified as an important factor on water ingress. However, the available information allows for a selection of the most important factors in damage stability and for proposing a methodology to derive survivability criteria.

Within the limits of the parametric investigation, it is believed that the survivability of a vessel is represented in a most meaningful and realistic way, linking the environmental effects, loading conditions and vessel design parameters through the vessel motions, and can be used to define limiting stability criteria.

9.2.4 Model Experiment

The important thing should be considered in the experiment is its set up of its self. A result of water ingress experiment was shown that flow coefficient (K) was obtained from experiment is give a confidence result for time domain simulation program. The flow coefficient (K) is in the range of empirical formula was developed by Walshaw and Jobson (1979).

The result of damage stability experiment was used to validate the simulation output. Comparison shows the experimental and simulation results are quite similar. It also shows that time to capsize for damage vessel between simulation and experiment is found to be quite similar. However, further improvement of the experimental set up should be done because of the pitch motion between simulation and experiment is not same. The improvement can be done by changing the spring that holds the model during beam sea test with other spring that is more elastic.

9.3 Conclusions

Based on the results of the study, the following conclusions can be drawn:

i. Present study successfully shows that the Time Domain Simulation program are suitable for investigating the stability of a damaged vessel and can predict the vessel's behaviour including continuous flooding with sufficient accuracy.

ii. The image processing technique is a good tool to measure the motion of damage vessel in beam sea condition. In the validation, the comparison between the simulation and experimental results gives confidence to assess the dynamic stability of damage vessel by utilising the Time Domain Simulation program.

iii. The effect of flooding depends crucially on the location and extent of damage. It is more likely that progressive flooding can cause a vessel to capsize before she reaches the final equilibrium position.

iv. Water on the main deck is the determining factor affecting vessel capsizing with the critical amount of water to capsize the vessel decreasing considerably by increasing the vertical centre of gravity. However if water ingress into the main deck is not prevented or restricted, the vessel will sink regardless of her loading condition (KG).

v. 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.

vi. This thesis represents the systematic study into the dynamic damage stability of passenger vessel, successfull in providing a strong indication of the need to address vessel safety by considering dynamic behaviour in a realistic environment. However, several areas still need careful attention. These include: effect of hull form, different wave directions, different damage location, shifting of cargo, forward speed, water ingress and sloshing.

vii. 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.

9.4 Future Works

The present work has demonstrated a methodology for assessing damage stability of small vessel and a limited parametric investigation was carried out. As a result a number of key parameters were identified and some relationships were established. However, there is no doubt that in this area, a considerable amount of research still needs to be carried out before achieving the ultimate goal, which is establishing realistic damage stability criteria. Therefore, some suggestions for further research are summarized in the following.

9.4.1 Water Ingress

Water is a very influential factor on vessel stability and capsizing, especially if there is damage above the bulkhead deck. Instantaneous water ingress, which depends on wave elevation and direction and on vessel motions, is presently calculated only in an approximated way. However, modeling of the instantaneous water ingress must be further improved because of the complexities involved with hydrodynamic pressure on the free surface. Water flow is affected by wave direction relative to damage as was proven by model experiments, Dand (1990), as well as by wave-vessel interactions.

In order to develop an accurate model of the water ingress, systematic experiments must be carried out to establish relationships between water inflow, outflow, wave elevation and wave direction. This can be done by measuring the amount of water flowing in at different wave heights and directions, so that an inflow coefficient, which is function of wave height and direction can be derived. An outflow coefficient can be derived by measuring the amount of water flowing out and by establishing a relationship between the amount of water flowing out and roll acceleration. Measuring the net amount of water flooding the deck as a result of inflow and outflow would help to calibrate the derived coefficients.

9.4.2 Wave Direction

In the calculations presented here, only beam sea is considered, but the damaged vessel may face waves from different directions. Although it is assumed that beam waves are the worst case for a vessel without forward speed, the vessel may be excited severely by waves from other directions, depending on the condition of the vessel. Due to progressive flooding, the vessel may have static heel and a different underwater form. In this case, the vessel can be excited by waves coming from any direction, which would not excite the vessel in normal circumstances (roll in following or head seas) or some other motions such as pitching which may cause more serious water ingress, depending on the damage location. In order to develop general criteria, the effect of different wave directions at different damage conditions must be investigated, so that conditions or scenarios, which must be avoid or catered for, can be identified.

9.4.3 Hydrodynamic Coefficient

In order to estimate the vessel motions accurately the relevant hydrodynamic coefficients must be determined as accurately as possible. However, large motions and continuously changing hull form, due to flooding, makes the estimation of the correct values of coefficients very difficult. As indicated earlier, in the time simulation model, hydrodynamic coefficients are calculated for the initial conditions of the vessel, before simulation starts, and the same coefficients are used during the one time simulation- run.

However, since there is progressive flooding, which may cause sinkage and heel; the hydrodynamic coefficients may change considerably as proven in this research as well as by other studies. These changes in hydrodynamic coefficients during the time simulation may also change the vessel's behaviour especially near the roll natural frequency. It has to be investigated whether changes in hydrodynamic coefficients change the vessel's behaviour or whether initially calculated hydrodynamic coefficients can be used throughout the time simulation without losing accuracy significantly. If it is necessary to use instantaneous hydrodynamic coefficients, then the most suitable procedure to include these must be developed and validation is carried out experimentally. This recommendation is elaborated in detail below.

Calculating the coefficients for each instantaneous position during the time simulation can be one of the solutions, but practically it becomes impossible considering the computer time required for this. Another option can be to create a coefficient data bank which includes coefficients for different heel and trim angles as well as draughts to simply be used during simulation.

9.4.4 Water Accumulation

Accurate modelling the accumulation of water on deck is highly complex and a complete solution does not exist at present. It appears that experimental studies are the only approach which can provide some clear information and therefore the behaviour of water on deck must be analysed experimentally. So far all experiments on this problem have been carried out using tanks, which oscillate around the roll axis and have a fixed water depth. However, experiments must be carried out as realistically as possible by continuously flooding the compartment of the vessel oscillating in the presence of waves.

From the experiments, the instantaneous forces and moments, due to water accumulation, must be measured together with the phase angle between roll motion and excitation for different excitation frequencies. Comparison between experimental results and computational results should aim to identify the frequency range at which computational results and experimental results deviate and attempt to identify the reasons for it.

9.4.5 The Effect of Vessel Design and Hull Form

In order to find the optimum vessel hull form and principal dimensions, considering the dynamic damage stability, the effect of certain vessel parameters on the dynamic damage stability must be examined. Probably this investigation must start from the main vessel dimensions such as L/B, B/T, D/T, Cb etc. Results of this investigation can offer valuable guidance on new designs.

Since the compartmentation of. the vessel is part of the design, the sample parametric study in this thesis on the effect of compartment length on capsizing, must be expanded by carrying out more analyses on the compartmentation of the main deck and its effect on vessel transportation and damaged stability.

However, almost all passenger vessels and ferries have some sort of roll stabilizers. The effect of bilge keel on the reduction of roll motion has been proven and bilge keels are fitted to most of the vessels. Therefore their effect on the behaviour and the stability of damaged vessels must be examined and included in the damage stability assessments and limiting stability curves.

9.5 Concluding Remarks

The procedure applied in this study successfully solves the problem of damage stability of small vessel in beam seas. As mentioned earlier, damage stability of the vessel in waves is closely related to the large amplitude and non-linear capsizing sequence. For this reason Time Domain Simulation approach is the most appropriate method used in this situation. In the analysis, the effect of wave parameters, water ingress and loading conditions are the main effect to be considered. By considering these effects, a damage stability assessment of small vessel has been developed. For future development, the main focus is to be given on the improvement of the mathematical model of water ingress of small vessel. In order to develop general criteria, a detail study on the damage stability of small vessel in other wave direction situation has to be done. Since the relevant hydrodynamic coefficients must be determined as accurately as possible, more experiments may have to be carried out to improve the mathematical model. Experiments also must be carried out as realistically as possible by continuously flooding the compartment of the vessel oscillating in the presence of waves to improve the mathematical modelling of water accumulation.

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APPENDIX A

HYDRODYNAMIC FORCES

A.1 General Definitions and Assumptions

As the formulation of these forces in regular waves is also the basis of the forces due to irregular waves, in the following, the formulation for the wave excitation forces will be given for the regular waves. It is assumed that fluid is ideal, of infinite depth and that its motion is irrotational. It will be assumed that the incident wave and resulting motion response is sufficiently small in amplitude to justify a linear description, then general motion problem can be assumed to be a linear superposition of the following boundary value problem:

- The incident wave encountered by the strip section will be diffracted from it by assuming the strip section id rigidly held in its fixed position. This is called "Diffraction Problem".

- As soon as the incident waves are diffracted due to the pressure of the section, it is assumed that the motion can be represented by the oscillations of this section in initially calm water with some frequency on the waves. This is known as "The Radiation Problem".

Thus the total velocity potential of the fluid motion generated by the regular waves, with the stationary strip section undergoing small amplitude oscillation, can be described by the time dependent potential

$$\Phi(x,y,z,t) = \Phi_I(x,y,z,t) + \Phi_D(x,y,z,t) + \Phi_R(x,y,z,t) \qquad \text{(A.1)}$$

The nature of the linear boundary value problems imposes the following conditions which should be satisfied by the sectional velocity potential:

- The Laplace equation in the fluid domain
- The linearised free surface condition on the free surface
- The bottom condition at the sea floor
- The radiation condition at a large distance from the strip section
- The kinematic boundary condition on the section contour given by

$$\frac{\partial\phi}{\partial n} = \frac{\partial(\phi_I + \phi_D + \phi_R)}{\partial n} = V_n \qquad \text{(A.2)}$$

Within the linear analysis further decomposition of the kinematic boundary condition yields the following for the radiation problem.

$$\frac{\partial\phi_R}{\partial n} = V_n \qquad \text{(A.3)}$$

and for the diffraction problem it is assumed that the body was rigidly held thus

$$\frac{\partial\phi_I}{\partial n} + \frac{\partial\phi_D}{\partial n} = V_n \qquad \text{(A.4)}$$

A.2 Wave Excitation Forces

In the beamwise strip domain, the incident wave (Froude-Krylov) and diffracted wave potential can be represented as follows:

$$\Phi_I(x,y,z,t) = \phi_I(y,z)\, e^{i(\gamma x \cos(\mu - \omega t))} \qquad \text{(A.5)}$$

$$\phi_I(y,z) = -\frac{i\,g\,a}{\omega}\, e^{\gamma z}\; e^{i(\gamma y \sin\mu)} \tag{A.6}$$

The diffraction potential, Φ_D is a disturbance therefore it can be represented by a distribution of wave source potential along the strip section wetted parameter with the aid of Green's formula:

$$\Phi_D(x,y,z,t) = \phi_D(y,z)\, e^{i(\gamma x \cos\mu)}\; e^{-i\omega t} \tag{A.7}$$

$$\phi_D(y,z) = \int_S Q_d(\zeta,\eta)\, G(y,z,\zeta,\eta)\, ds \tag{A.8}$$

The unknown source strength Q_d is found by the application of the kinematic boundary condition on the strip domain.

The numerical solution of the above defined velocity potential problem is carried out by using the Frank-Close-Fit Technique which is based on Green's Function Integral Equation Method. This method is applicable to any two-dimensional simply connected shape. It has a great advantage in that it represents the fluid potential directly due to any shape of disturbance. This facility allows the computation of hydrodynamic forces on the asymmetric hull section at heeled position. According to this procedure the strip contour (C) is approximated by a series of straight line segments with a single pulsating source at the midpoint of each segment. The strengths of the forces are assumed constant along the segment length but vary from segment to segment.

By solving [Eq A.6] with the aid of the Close-Fit technique, the unknown source strength and consequently the required diffraction potential is obtained.

Having obtained the velocity potential for the incident and the diffracted wave potential, the pressure distribution around cross section can be calculated from the linearised Bernoulli equation as follows:

$$p^{(i)} = p_I^{\,(i)} + p_D^{\,(i)} = -\rho\, \frac{\partial(\phi_I^{\,(i)} + \phi_D^{\,(i)})}{\partial t} \tag{A.9}$$

Sectional excitation forces ($f^{(i)}$) can be obtained by integrating the pressure as:

$$f^{(i)} = f_{FK}{}^{(i)} + f_D{}^{(i)} = \int_S (p_I{}^{(i)} + p_D{}^{(i)})\, n^i\, ds \qquad \text{(A.10)}$$

With regard to the separate components, the total force of the ship due to the Froude-Krylov (F_{f-k}) and diffraction components (F_d) can be written as:

$$\begin{bmatrix} F_{f-k}{}^{Sway} \\ F_{f-k}{}^{Heave} \\ F_{f-k}{}^{Roll} \end{bmatrix} = \int e^{i\gamma x \cos\mu} \begin{bmatrix} i\, f_{f-k}{}^{Sway} \\ f_{f-k}{}^{Heave} \\ i\, f_{f-k}{}^{Roll} \end{bmatrix} \begin{bmatrix} dx \\ dx \\ dx \end{bmatrix} e^{-i\omega t} \qquad \text{(A.11)}$$

Total Diffraction Force and Moments

$$\begin{bmatrix} F_d{}^{Sway} \\ F_d{}^{Heave} \\ F_d{}^{Roll} \end{bmatrix} = \int e^{i\gamma x \cos\mu} \begin{bmatrix} f_d{}^{Sway} \\ f_d{}^{Heave} \\ f_d{}^{Roll} \end{bmatrix} \begin{bmatrix} dx \\ dx \\ dx \end{bmatrix} e^{-i\omega t} \qquad \text{(A.12)}$$

Both the Froude-Krylov and Diffraction components comprise terms in phase with the acceleration (i.e. real, F_R) and velocity (i.e. imaginary, F_I) which can be transformed to the time dependent force function as:

$$F(t) = F\cos(\omega t + \varepsilon) \qquad \text{(A.13)}$$

where F is the maximum of the force given by

$$F = \sqrt{F_R{}^2 + F_I{}^2} \qquad \text{(A.14)}$$

and Phase angle between Maximum force and Maximum wave is calculated as

$$\varepsilon = \tan^{-1}\left(\frac{F_R}{F_I}\right) \qquad \text{(A.15)}$$

A.3 Hydrodynamic Coefficients

In order to obtain the motion-induced coefficients (i.e. added mass and damping), the velocity potential for the radiation problem is solved similar to the previously solved diffraction problem with the different kinematic boundary condition which is given by [Eq. A.3]. That is the radiation potential is represented as:

$$\phi_R{}^i = \int_S Q_R{}^i(\zeta,\eta)\, G(y,z,\zeta,\eta)\, ds \qquad \text{(A.16)}$$

Where $Q_R{}^i$ is the unknown source strength which will be found with the aid of the Frank-Close-Fit technique.

By solving the unknown source strength the radiation potential is evaluated for each section. The resulting potential consists of components in phase with the acceleration (i.e. real component) and velocity (i.e. imaginary component). The hydrodynamic pressure along the strip contour is obtained from this potential expression using the linearised Bernoulli equation. Integrals of the pressure along the contour yield the corresponding sectional added mass/inertia in phase with the acceleration and the wave damping in phase with the velocity.

Finally the sectional added mass and damping are integrated along the ship to obtain the total coefficients of a vessel.

Sectional added mass;

$$a_{ij} = \rho \int_S \Phi_{RR}{}^{(j)} \cos(n, j)\, ds \qquad \text{(A.17)}$$

Sectional damping;

$$b_{ij} = \rho\omega \int_S \Phi_{RI}{}^{(j)} \cos(n, j)\, ds \qquad \text{(A.18)}$$

APPENDIX B

WATER INGRESS

B.1 Water Flow Through Orifice Type of Openings

Water flow into the damaged compartments has been always dealt with by using the existing hydraulic theories in civil engineering application. The hydraulic principal is based on the Bernoulli equation and is applied to the steady motion of an ideal fluid along the framed system. This equation is probably more widely used in hydraulics than any other and is capable of explaining at least qualitatively, many of the phenomena that are encountered in fluid mechanics. It suggests that the height, pressure and velocity cannot increase simultaneously in a system.

The Bernoulli principal, which assumes that ideally energy in the fluid system remains constant, which can be denoted as total hydraulic head, can be written as follows:

$$\frac{p}{\rho\gamma} + z + \frac{u^2}{2g} = H \qquad \text{(B.1)}$$

If two points are assumed, one is point A at the water surface of the tank (indices o) and other is point B, which is at the exit of the orifice (indices 1, Fig B.1).

$$\frac{p_0}{\rho\gamma} + z_o + \frac{u_0^2}{2g} = \frac{p_1}{\rho\gamma} + z_1 + \frac{u_1^2}{2g} = H \qquad \text{(B.2)}$$

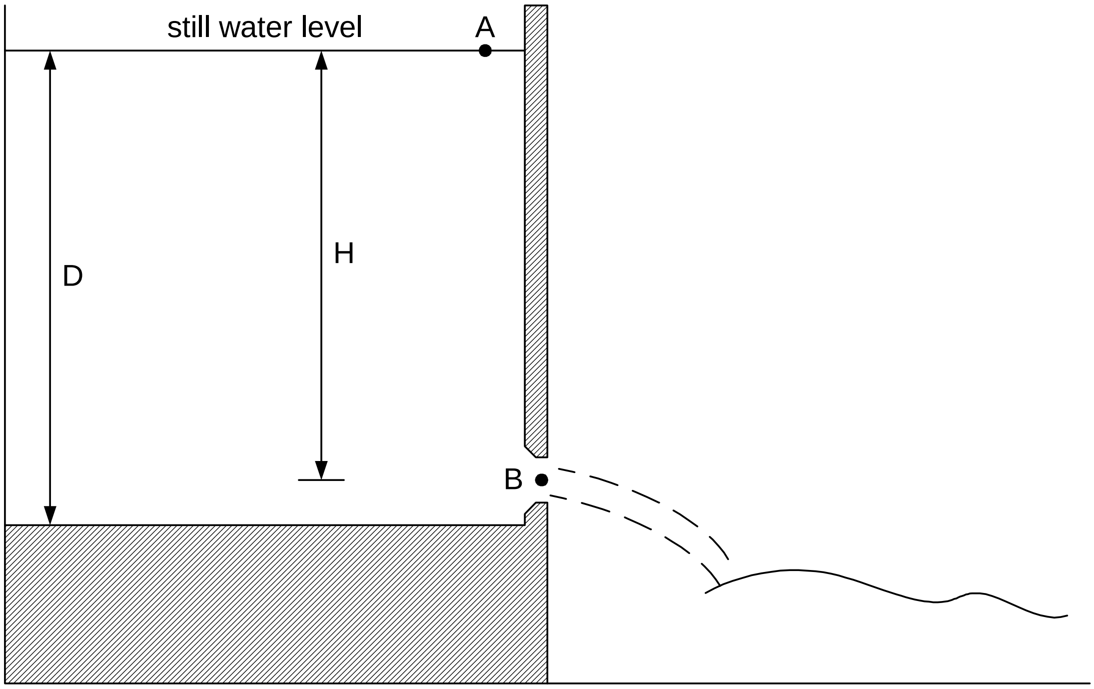

Figure B.1 Flow through an orifice

However at the tank surface and the exit of the orifice, pressures $P_o$and P_1 are zero since the fluid is open to the atmosphere. Furthermore, velocity of the water at the water surface is assumed to be zero since the water level is kept constant. In this case the above equation can be written as follows:

$$0 + H + 0 = 0 + 0 + \frac{u_1^2}{2g} = H \tag{B.3}$$

or more generally the total pressure head at point B is:

$$H = \frac{U^2}{2g} \tag{B.4}$$

$$U = \sqrt{2\,g\,H} \tag{B.5}$$

and flow rate,

$$Q = U\,A_{op} \tag{B.6}$$

However, in practice, there are frictions, losses, sudden discontinues of the section and shape of the orifice. Due to all these effects the real flow decreases. In hydraulic engineering these effects are considered by introducing some coefficients.

One of the coefficients is called the contraction coefficient, which is related to the edge of the orifice. For a perfectly sharp edge the contraction coefficient (C_c) is around 0.6 and this increases progressively with the lip radius until it finally approaches the value 1 for a "bell mouthed" opening which flows full (Walshaw and Jobson, 1979).

In practice there is a slight energy loss due to contraction, and conditions may not be uniform across the orifice. These effects reduce the effective mean velocity and are included in the equation as coefficient of velocity (C_v), which generally changes between 0.95 and 0.99.

In hydraulic applications all these coefficients are represented in one coefficient which is called discharge or flow coefficient (K) :

$$K = C_v C_c \qquad \text{(B.7)}$$

In practice flow coefficient is determined directly from experimental measurements for a constant head H. This coefficient also includes the corrections due to the approximations in formulations. Therefore in reality, flow rate through an opening below the water surface can be determined using the following formula:

$$Q = K\, U\, A_{op} \qquad \text{(B.8)}$$

B.2 Flow Through an Opening Above the Water Surface

Existing estimations are based on open channel hydraulics, which must have a free surface, which is subject to the atmospheric pressure. In general this is defined as flow over a weir or notch. The characteristics of flow over a weir were recognized early in hydraulics as the basis for overflow spillways. It is assumed that the horizontal velocity component of the flow is constant or does not exist and only force acting on a free flow is the gravity (Walshaw and Jobson, 1979 and Ackers et al, 1978).

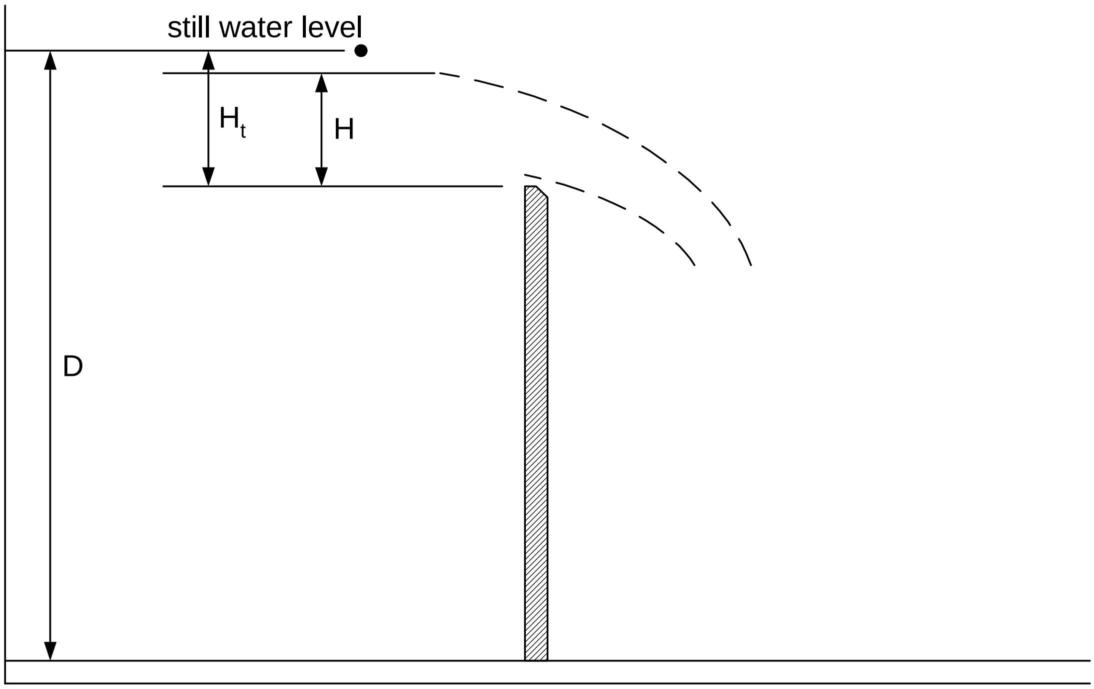

Figure B.2 Flow over a weir

Assuming that the above and below nappe is ventilated, which means atmospheric pressure must exist at all points within it. Weisbach (Ackers et al, 1978) suggested that the velocity U at a point at elevation z above the crest would be given by equating the velocity head plus potential head to the total head just upstream of the weir (Fig B.2):

$$H_t = z + \frac{U^2}{2g} \tag{B.9}$$

In that case, velocity would be a function of the elevation (z):

$$U = \sqrt{2\, g\,(H_t - z)} \tag{B.10}$$

The flow rate for per unit width passing trough an element on height Δz at elevation z is:

$$\Delta q = U\,\Delta z \tag{B.11}$$

and if integration is done between still level and the surface level:

$$q = \int_0^H U\;dz = \int_0^H \sqrt{(H_t - z)\,dz} \tag{B.12}$$

$$q = \frac{2}{3}\sqrt{2\,g}\left(\sqrt[3]{(H_t)^2} - -\sqrt[3]{(H_t - H)^2}\right) \tag{B.13}$$

However as some of the parts of this formula have no fundamental significance (Ackers, 1978), the formula for flow rate for per unit width can be simplified and the flow coefficient included as follows:

$$q = K\sqrt{g}\left(\sqrt[3]{H^2}\right) \tag{B.14}$$

Although H_t represents the total energy relative to crest elevation, H is easier to use since it can be measured directly whereas H_t cannot. However the differences is included in the equation via flow coefficient K (Ackers et al, 1978).

This formula can be more generalized to calculate the volumetric flow for full width of any geometry such as rectangular weir triangular notch.

$$Q = K\,A_{op}\,\sqrt{g\,H} \tag{B.15}$$

Most of the flow coefficients (discharge coefficient) for different shapes and flow depths are available (Chow, 1959) and they have been determined experimentally. Although flow coefficient can change depending on the shape, for free flow in general they vary between 0.5 and 0.6. However, for triangular notches this may go down to 0.45 (Walshaw and Jobson, 1979).

As suggested above, for different shapes, edges and conditions flow coefficients must be estimates experimentally. At present, due to lack of research and data about the water inflow/outflow into/from damage compartment, the existing formulas and coefficients for hydraulic engineering must be used. However, in the case of water ingress into damage compartments, the shapes of the damage holes or the conditions of the edges can change considerably while effect of wave on water ingress must be included in the estimation of flow coefficient. Therefore it is necessary to determine specific flow coefficients for water flow trough a damaged hole in a ship in wave environment.

APPENDIX C

NUMERICAL SOLUTION OF THE EQUATION OF MOTIONS

First, the original equations can be written as follows:

$$(M + A_{11})\dot{u} + (B_{11})u + R_T = F_1 wave \tag{C.1}$$

$$(M + A_{22})\dot{v} + (B_{22})v + (A_{23})\dot{w} + (B_{23})w + (A_{24})\dot{p} + (B_{24})p + (A_{25})\dot{q} + (B_{25})q + (A_{26})\dot{r} + (B_{26})r = F_2 wave \tag{C.2}$$

$$(M + A_{33})\dot{w} + (B_{33})w + C_{33}(t, z, \theta, \phi) + (A_{32})\dot{v} + (B_{32})v + (A_{34})\dot{p} + (B_{34})p + (A_{35})\dot{q} + (B_{35})q = F_3 wave + F_3 wod \tag{C.3}$$

$$(I_{xx} + A_{44})\dot{p} + (B_{44})p + C_{44}(t, z, \theta, \phi) + (A_{42})\dot{v} + (B_{42})v + (A_{43})\dot{w} + (B_{43})w + (A_{45})\dot{q} + (B_{45})q + (A_{46})\dot{r} + (B_{46})r = M_4 wave + M_4 wod \tag{C.4}$$

$$(\mathrm{I}_{yy} + \mathrm{A}_{55})\dot{\mathrm{q}} + (\mathrm{B}_{55})\mathrm{q} + \mathrm{C}_{55}(\mathrm{t}, \mathrm{z}, \theta, \phi) + (\mathrm{A}_{52})\dot{\mathrm{v}} + (\mathrm{B}_{52})\mathrm{v} + (\mathrm{A}_{53})\dot{\mathrm{w}} + (\mathrm{B}_{53})\mathrm{w} + (\mathrm{A}_{54})\dot{\mathrm{p}} + (\mathrm{B}_{54})\mathrm{p} = \mathrm{M}_5\mathrm{wave} + \mathrm{M}_5\mathrm{wod} \tag{C.5}$$

$$(I_{zz} + A_{66})\dot{r} + (B_{66})r + (A_{64})\dot{p} + (B_{64})p + (A_{65})\dot{q} + (B_{65})q + (A_{63})\dot{w} + (B_{43})w + (A_{62})\dot{v} + (B_{62})v = M_6 wave \tag{C.6}$$

Forces can be written as;

$$F_1 = F_1 wave$$

$$F_2 = F_2 wave$$

$$F_3 = F_3 wave + F_3 wod$$

$$M_4 = M_4 wave + M_4 wod$$

$$M_5 = M_5 wave + M_5 wod$$

$$M_6 = M_6 wave$$

For the computational solution, these equations can be arranged as follows:

$$\dot{u} = \left(\frac{1}{(M + A_{11})}\right)\left[F_1 - \left[(B_{11})\, u + R_T\right]\right] \tag{C.7}$$

$$\dot{v} = \left(\frac{1}{(M + A_{22})}\right)\Big[F_2 - \big[(B_{22})\, v + (A_{23})\,\dot{w} + (B_{23}) w + (A_{24})\,\dot{p} + (B_{24})\, p + (A_{25})\,\dot{q} + (B_{25})\, q + (A_{26})\,\dot{r} + (B_{26})\, r\big]\Big] \tag{C.8}$$

$$\dot{w} = \left(\frac{1}{(M + A_{33})}\right)\Big[F_3 - \big[(B_{33})\, w + C_{33}(t, z, \theta, \phi) + (A_{32})\,\dot{v} + (B_{32})\, v + (A_{34})\,\dot{p} + (B_{34})\, p + (A_{35})\,\dot{q} + (B_{35})\, q\big]\Big] \tag{C.9}$$

$$\dot{p} = \left(\frac{1}{(I_{xx} + A_{44})}\right)\Big[M_4 - \big[(B_{44})\, p + C_{44}(t, z, \theta, \phi) + (A_{42})\,\dot{v} + (B_{42})\, v + (A_{43})\,\dot{w} + (B_{43})\, w + (A_{45})\,\dot{q} + (B_{45})\, q + (A_{46})\,\dot{r} + (B_{46})\, r\big]\Big] \tag{C.10}$$

$$\dot{q} = \left(\frac{1}{(I_{yy} + A_{55})}\right)\Big[M_5 - \big[(B_{55})\, q + C_{55}(t, z, \theta, \phi) + (A_{52})\,\dot{v} + (B_{52})\, v + (A_{53})\,\dot{w} + (B_{53})\, w + (A_{54})\, p + (B_{54})\, p\big]\Big] \tag{C.11}$$

$$\dot{r} = \left(\frac{1}{(I_{zz} + A_{66})}\right)\Big[M_6 - \big[(B_{66})\, r + (A_{62})\,\dot{v} + (B_{62})\, v + (A_{63})\,\dot{w} + (B_{43})\, w + (A_{64})\,\dot{p} + (B_{64})\, p + (A_{65})\,\dot{q} + (B_{65})\, q\big]\Big] \tag{C.12}$$

This system of second order non-linear equation given above are solved in the time domain using the Runge-Kutta numerical integration technique. The Matlab

Library routine provide several different numerical methods for solving non-linear equations. 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. This can be done by using the following changes:

For Surge (U)

$$x = U_1$$
$$u = \dot{U}_1 = U_2$$
$$\dot{u} = \dot{U}_2$$

For Sway (S)

$$y = S_1$$
$$v = \dot{S}_1 = S_2$$
$$\dot{v} = \dot{S}_2$$

For Heave (H)

$$z = H_1$$
$$w = \dot{H}_1 = H_2$$
$$\dot{w} = \dot{H}_2$$

For Roll (R)

$$\phi = R_1$$
$$p = \dot{R}_1 = R_2$$
$$\dot{p} = \dot{R}_2$$

For Pitch (P)

$$\theta = P_1$$
$$q = \dot{P}_1 = P_2$$
$$q = \dot{P}_2$$

For Yaw (Y)

$$\psi = Y_1$$

$$r = \dot{Y}_1 = Y_2$$

$$\dot{r} = \dot{Y}_2$$

In the case total number of the equation will be doubled for the computational solution and can be written in the new form as follows:

Surge

$$\dot{U}_1 = U_2$$

$$\dot{U}_2 = \left(\frac{1}{(M + A_{11})}\right)\left[F_1 - \left[(B_{11})\, U_2 + R_T\right]\right] \tag{C.13}$$

Sway

$$\dot{S}_1 = S_2$$

$$\begin{aligned}\dot{S}_2 = \left(\frac{1}{(M + A_{22})}\right)\Big[F_2 - \big[&(B_{22})\, S_2 + (A_{23})\,\dot{H}_2 + (B_{23})H_2 + (A_{24})\dot{R}_2 + (B_{24})R_2 \\ &+ (A_{25})\,\dot{P}_2 + (B_{25})\,P_2 + (A_{26})\dot{Y}_2 + (B_{26})Y_2\big]\Big]\end{aligned} \tag{C.14}$$

Heave

$$\dot{H}_1 = H_2$$

$$\begin{aligned}\dot{H}_2 = \left(\frac{1}{(M + A_{33})}\right)\Big[F_3 - \big[&(B_{33})\, H_2 + C_{33}(t, H_1, P_1, R_1) + (A_{32})\,\dot{S}_2 + (B_{32})\,S_2 \\ &+ (A_{34})\,\dot{R}_2 + (B_{34})R_2 + (A_{35})\,\dot{P}_2 + (B_{35})\,P_2\big]\Big]\end{aligned} \tag{C.15}$$

Roll

$$\dot{R}_1 = R_2$$

$$\begin{aligned}\dot{R}_2 = \left(\frac{1}{(I_{xx} + A_{44})}\right)\Big[M_4 - \big[&(B_{44})\, R_2 + C_{44}(t, H_1, P_1, R_1) + (A_{42})\,\dot{S}_2 + (B_{42})\,S_2 \\ &+ (A_{43})\,\dot{H}_2 + (B_{43})\,H_2 + (A_{45})\dot{P}_2 + (B_{45})\,P_2 + (A_{46})\dot{Y}_2 + (B_{46})Y_2\big]\Big]\end{aligned} \tag{C.16}$$

Pith

$$\dot{P}_1 = P_2$$

$$\dot{P}_2 = \left(\frac{1}{(I_{yy} + A_{55})}\right)\Big[M_5 - \big[(B_{55})P_2 + C_{55}(t, H_1, P_1, R_1) + (A_{52})\dot{S}_2 + (B_{52})S_2 + (A_{53})\dot{H}_2 + (B_{53})H_2 + (A_{54})\dot{R}_2 + (B_{54})R_2 \tag{C.17}$$

Yaw

$$\dot{Y}_1 = Y_2$$

$$\dot{Y}_2 = \left(\frac{1}{(I_{zz} + A_{66})}\right)\Big[M_6 - \big[(B_{66})Y_2 + (A_{64})\dot{R}_2 + (B_{64})R_2 + (A_{65})\dot{P}_2 + (B_{65})P_2 + (A_{63})\dot{H}_2 + (B_{43})H_2 + (A_{62})\dot{S}_2 + (B_{62})S_2\big]\Big] \tag{C.18}$$

In order to solve the above equations a number of boundary conditions which is equal to the number of equations in the system is required. This is so called an initial value problem because these boundary conditions are specified values at certain points such as the ones given below. These initial values are the initial displacements and velocities of the ship motions.

$U_1 = U_1o \quad at\ time = to$
$U_2 = U_2o \quad at\ time = to$

$S_1 = S_1o \quad at\ time = to$
$S_2 = S_2o \quad at\ time = to$

$H_1 = H_1o \quad at\ time = to$
$H_2 = H_2o \quad at\ time = to$

$R_1 = R_1o \quad at\ time = to$
$R_2 = R_2o \quad at\ time = to$

$P_1 = P_1o \quad at\ time = to$
$P_2 = P_2o \quad at\ time = to$

$$Y_1 = Y_1 o \qquad at\ time = to$$
$$Y_2 = Y_2 o \qquad at\ time = to$$

These initial condition would enable the solution technique to integrate the equations numerically from the point t = t_0 to specified end-time. For this integration the MATLAB Library routine named as ODE45 is used.

APPENDIX D

SIMULATION PROGRAM

D.1 Flow Diagram of Simulation Program

PROGRAM FLOW.m

Main program	Subroutine
CALL INDATA	SUB. INDATA To read the control data
READ INPUT DATA	
CALL SSC	SUB. SSC To calculate the hydrostatic values at initial condition

SET THE INITIAL CONDITIONS

Calling Math. Library
CALL ODE45

STOP, END

SUBROUTINE ODE45

MATLAB Library routine

Routine	Subroutine
CALL EQUATIONS	SUB. OUT To write the results into the output files
CALL OUT	

SUBROUTINE EQUATIONS

Solution of the differential equations

CALL PRESSURH

CALL SOS

SOLVE THE DIFFERENTIAL EQUATIONS

SUB. SOS
To calculate instantaneous volume and forces in damaged compartment

----

D.2 Description of the Program

i) FLOW

- The main program for time simulation of ship stability.

ii) INDATA

- To read in all the necessary control values and filenames for correct execution from the chosen option of the stability program.

iii) SHIPREAD

- To read in the vessel hull form and appendages.

iv) APPEND_READ

- To read in the appendage or damaged section data.

v) PROFREAD

- To create mirror of the hull form by taking into consideration the scaling factor.

vi) STATION_TRIM

- This routine eliminates the odd points in defining the contour of a section i.e. the middle point is ignored when three points defined a straight line.

vii) SSC

- Driving routine to calculate a number of righting lever curves regardless of the geometry of the immersed body.

viii) DELTA

- To setup the parameters for the calculation so that the displacement is equal to the original DISIN (initial displacement).

ix) DIRCOS

- This routine calculates the direction cosines of the transformation between the wave system and the ship system.

x) DIS_ITER

- To obtain the moments about the three axes of the ship coordinate system corresponding to the condition that the displacement is equal to the original DISIN.

xi) VOLUMES

- To access STATION routine to find immersed area and moments of each section.
- To integrate the sectional areas and moments to provide the volume and moments of volume for the vessel.
- The moments then used to calculate the coordinates of the centre of buoyancy and then the cross product of the buoyancy force and the position vector with respect to the center of gravity (C.G). Notes: Moments of volume are given with reference to the centre of mass of the vessel.

xii) STATION

- The routine calculates the immersed area of a section, given by the N points Y, Z at distance X from the origin of the ship coordinate system, as well as the first moments of this area.

xiii) ZIRW

- This routine calculates the vertical distance of a point (X,Y,Z) from the free surface. Positive distance means point inside the water.
- This function also has the capability of including a random wave realization as opposed to the simple wave function.

xiv) AREAS

- This routine calculates the areas, first and second moments of area for the contour supplied in the arrays XA, and YA.

xv) TRIANG

- This routine calculates the area and the centroid of the area of the contour defined by the arrays X, Y assuming that the contour is a curved one and thus by splitting it into triangles no error occurs.

xvi) CONTOUR_LENGTH

- To find the length of the contour maximum breadth and height whose coordinates are specified in the arrays Y and Z. The supplied contour is open i.e. first and last points are not the same.

xvii) FI

- Function for interpolation.

xviii) A1_SIMPLINT

- Use Simpson integration to calculate the total volume and moments of volume with reference to the centre of mass.

xix) HYDRO

- Calculation for ship hydrostatics. (Wave height=0, Wave length=1)

xx) WAP_CAT

- This routine calculates the waterplane area (WPA), the moments of area (FMX, FMY), and the second moments of area (IXX, IYY, IXY) to the wave system of a ship.

xxi) WPAREA

- This routine calculates the waterplane area, the moments of area, and the second moments of area to the wave system of a ship.

xxii) APPEND_INT

- Calculation of moments and volumes of appendages.
- To integrate the areas and moments of the appendages or damages sections. The difference between a buoyant appendage and a damaged section is controlled by the permeability (PERM).

xxiii) MAX_MIN

- This routine finds the first maximum and minimum values of the array X of N points as well as the positions (IMAX, IMIN) where they occur.

xxiv) ADSHIP

- Extract the coordinate data that describe the compartment from X_INT, Y, and Z and stores them into a 4D array (X2, Y2, Z2).

xxv) EQUATIONS

- This routine calculates the values of F at the time TI when the values of YV are known.
- To calculate water accumulation due to progressive flooding (continuous flooding or instantaneous flooding).

xxvi) PRESSUREH

- This subroutine calculates the intersection point between section and the wave profile.

xxvii) SOS

- To set up the parameters for the calculation of moment and the volume of the ship at the given time.

xxviii) DIS_ITER2

- To obtain the moments about the three axes of the ship coordinate system corresponding to the condition that the displacement is equal to the DAMVOL (amount of water in the damaged compartment).

xxix) VOLUMES2

- To access STATION2 routine to find immersed area and moments of each section of the damaged compartments.
- To integrate the sectional areas and moments to provide the volume and moments of volume for the damaged compartment through APPEND_INT2.

xxx) STATION2

- This routine calculates the immersed area of a section (for damaged compartments only), given by the NOAF (number of points), Y2, and Z2 at distance X2 from the origin of the ship coordinate system, as well as the first moments of this area.

xxxi) CONTOUR_LENGTH2

- To find the length of the contour maximum breadth and height whose coordinates are specified in the arrays Y2 and Z2. The supplied contour is open i.e. first and last points are not the same.

xxxii) APPEND_INT2

- To integrate the areas and moments of the appendages or damages sections. The difference between a buoyant appendage and a damaged section is controlled by the permeability (PERM).

D.3 Ship Hull Form Data Format

```
TITLE
L  B  D   SCALE
NS
NOF(1)   X_INT(1)  DAM(1)
YP(1,1)  ZP(1,1)
YP(1,2)  ZP(1,2)
YP(1,3)  ZP(1,3)
........  .......
........  .......
........  .......
........  .......
YP(1,NOF(1))  ZP(1,NOF(1))
NOF(2)  X_INT(2)  DAM(2)
YP(2,1)  ZP(2,1)
YP(2,2)  ZP(2,2)
YP(2,3)  ZP(2,3)
........  .......
........  .......
........  .......
........  .......
YP(2,NOF(2))  ZP(2,NOF(2))
NOF(NS)  X_INT(NS)  DAM(NS)
YP(NS,1)  ZP(NS,1)
YP(NS,2)  ZP(NS,2)
YP(NS,3)  ZP(NS,3)
........  .......
........  .......
........  .......
........  .......
YP(NS,NOF(NS))  ZP(NS,NOF(NS))
B
NOAPPEND NOSHIP  NODAP1  NODAP2  NODAP3
AP_NOS(1)  PERM(1)
NOF(NS + 1)  X_INT(NS + 1)  DAM(NS + 1)
YP(NS + 1,1)  ZP(NS + 1,1)
YP(NS + 1,2)  ZP(NS + 1,2)
YP(NS + 1,3)  ZP(NS + 1,3)
............  ............
............  ............
............  ............
YP(NS,NOF(NS + 1))  ZP(NS,NOF(NS + 1))
............  ............
```

```
............  ............
............  ............
NOF(NS + AP_NOS(1))  X_INT(NS + AP_NOS(1))  DAM(NS + AP_NOS(1))
YP(NS + AP_NOS(1),1)  ZP(NS + AP_NOS(1),1)
YP(NS + AP_NOS(1),2)  ZP(NS + AP_NOS(1),2)
YP(NS + AP_NOS(1),3)  ZP(NS + AP_NOS(1),3)
............  ............
............  ............
............  ............
YP(NS + AP_NOS(1)  NOF(NS + AP_NOS(1)))  ZP(NS,NOF(NS + AP_NOS(1)))
AP_NOS(2)  PERM(2)
NOF(NS +2)  X_INT(NS + 2)  DAM(NS + 2)
YP(NS + 2,1)  ZP(NS + 2,1)
YP(NS + 2,2)  ZP(NS + 2,2)
YP(NS + 2,3)  ZP(NS + 2,3)
............  ............
............  ............
............  ............
YP(NS + 2,NOF(NS + 2))  ZP(NS + 2,NOF(NS + 2))
............  ............
............  ............
............  ............
............  ............
AP_NOS(I)  PERM(I)
NOF(NS + AP_NOS(I))  X_INT(NS + AP_NOS(I))  DAM(NS + AP_NOS(I))
YP(NS + AP_NOS(I)1,1)  ZP(NS + AP_NOS(I)1,1)
YP(NS + AP_NOS(I)1,2)  ZP(NS + AP_NOS(I)1,2)
YP(NS + AP_NOS(I)1,3)  ZP(NS + AP_NOS(I)1,3)
............   ............
............   ............
............   ............
YP(NS+AP_NOS(I),NOF(NS+AP_NOS(I)))   ZP(NS+AP_NOS(I),NOF(NS+AP_NOS(I)))
```

Explanation of Variables

TITLE	:	Name of the ship for identification
L	:	Length of the ship (Lbp)
B	:	Breadth of the ship
D	:	Depth of the ship. It must be the depth up to the upper most continuous deck
SCALE	:	The scale if the scaled dimensions are used. It is suggested to keep this value as 1
NS	:	Total number of half sections to define the main hull of the ship
NOF(I)	:	Total number of points used to define the half section
X_INT(I)	:	Longitudinal location of the ship section from the origin(amidship)
DAM(I)	:	Control parameter. It is 0(zero) for the main hull
		1(One) for symmetric damage or appendage
		2(Two)for asymmetric damage or appendage
YP(I,J),ZP(I,J)	:	Port co-ords of each point on the vessel's section
B	:	This shows that there are appendages or damaged compartments
NOAPPEND	:	Total number of independent appendages or damaged compartments
NOSHIP	:	Total number of independent damaged compartments (maximum 3, used for the added weight method)
NODAP1	:	Total number of damaged appendages in the damaged compartment 1(used for added weight method)
NODAP2	:	Total number of damaged appendages in the damaged compartment 2(used for added weight method)
NODAP3	:	Total number of damaged appendages in the damaged compartment 3 (used for added weight method)
AP_NOS(I)	:	Number of sections in each appendage (intact or damaged)
PERM(I)	:	Permeability of the appendage. If appendage is the damaged one, PERM(I) must be negative (-, maximum -1, while it must be positive (+, maximum +1), if the appendage is intact.

D.4 Example Ship Hull Form Data Format

```
SARAWAK_LONG_BOAT
33.500      2.942       3.12   1
20
9    -16.225  0
      0.0000      0.5500
      1.3500      0.6000
      1.3750      0.6052
      1.4000      0.6247
      1.4100      0.6587
      1.4200      0.7087
      1.4300      0.8000
      1.4710      1.6000
      0.0000      1.6000
............  ............
............  ............
............  ............
B
1     1     1     0     0
7     -0.85
9     -6.975      1
      0.0000      0.8500
      1.4325      0.8500
      1.4710      1.6000
      1.3489      2.3779
      1.2989      2.4461
      1.1768      2.5222
      0.7355      2.6086
      0.4413      2.6420
      0.0000      2.6700
............  ............
............  ............
............  ............
```

D.5 Control File Format

```
XG YG ZG DISIN T
BBK XBK1 XBK2 AKEEL
VEL TRANG SIGMA PHIDF ANG_IN
WL WH NPOS NWI YBARI
KTRIM EXROL EXEP THETA WVEL
DR_INIT DR_FIN DR_INC
```

Explanation of Variables

XG	:	Longitudinal centre of gravity in m. (used by time simulation program)
YG	:	Transverse center of gravity in m. (used by time simulation program)
ZG	:	Vertical center of gravity from base line in m. (used by time simulation program)
DISIN	:	Initial displacement of the intact ship at equilibrium condition (Tonnes). It must be set to zero if draught (T) is used for the initial calculations
T	:	Draught of intact ship at equilibrium position (m)
BBK,XBK1,XBK2	:	Respectively breadth, starting and finishing station of bilge keels if any (0 = none)
AKEEL	:	Projected area of bar keel
VEL	:	Ship velocity (m/sec).
TRANG	:	Trim angle (deg) (used by time simulation program)
SIGMA	:	Heading angle of ship (deg) (used by time simulation program)
WL,WH	:	Wave length and height respectively. (used by time simulation program). They are used for the regular waves
NPOS,NWI	:	Number of wave positions and iterations.
YBARI	:	Position of wave crest w.r.t centre of mass of vessel
WVEL	:	Wind velocity (m/sec). (used by time simulation program)

KTRIM	:	If fixed trim then =0, else =1. (used by time simulation program)
EXROL	:	Natural Roll period.of the ship (sec)
EXEP	:	Excitation period (sec). (used by time simulation program). In case of irregular waves, modal period must be provided
THETA	:	Amplitude of roll for wave damping procedure
DR_INIT	:	Initial draft for the hydrostatic calculations
DR_FIN	:	Final draft for hydrostatic calculations
DR_INC	:	Increment between drafts for hydrostatic calculations

D.6 Example Control File Format

```
-1.19   0.0     1.2     0.0     1.0
0.0     0.0     0.0     0.0     0.0
0.0     0.0     90.0    60.0    0.0
31.5    0.1     3.0     3.0     0.0
1.0     4.138   4.472   0.35    0.0
1.0     1.0     0.0
```

D.7 Motion File Format

```
A22 M22 B22 A23 B23 A24 B24 A25 B25
A33 M33 A32 B32 B33 A34 B34 A35 B35
A44 I44 A42 B42 A43 B43 B44 I45 A45 B45
A55 I55 A52 B52 A53 B53 I54 A54 B54 B55
A66 I66 B66 A11 M1 B11
F1SUR P1SUR F2SWA P2SWA F3HEA P3HEA
F4ROL P4ROL F5PIT P5PIT F6YAW P6YAW
SURGE_IN  ASW_IN  HEA_IN  AR_IN  PITCH_IN  YAW_IN  TTIME
T1_STEP
VOLUMEIN1 VOLUMEIN2 VOLUMEIN3
TVOLUME1 TVOLUME2 TVOLUME3
TST1 TST2 TST3
TDUR1 TDUR2 TDUR3
VOLUMEDEC1 VOLUMEDEC2 VOLUMEDEC3
INHE TIMINC
ISIP1  ISIP2  ISIP3  IAPD1  IAPD2  IAPD3  ISTA1  ISTA2  ISTA3
ISNUM
Z1MIN Z2MIN Z3MIN
ZH1 ZM1 B1H ZH2 ZM2 B2H ZH3 ZM3 B3H DB BHD SWL1 COTR
```

Explanation of Variables

i,j : motion indices

1 shows surge motion

2 shows sway motion

3 shows heave motion

4 shows roll motion

5 shows pitch motion

6 shows yaw motion

i = j shows the coefficients for pure motion mode

i = j shows the coupling coefficients

A_{ij} : Added mass and inertia coefficient of the ship

B_{ij} : Damping coefficients

M_{ij}	:	Mass of the ship. It is same for all the motions
I_{ij}	:	Mass moment of inertia
F1SUR	:	Maximum amplitude of wave excitation force for SURGE (used for regular waves)
P1SUR	:	Phase angle for SURGE (used for regular waves)
F2SWA	:	Maximum amplitude of wave excitation force for SWAY (used for regular waves)
P2SWA	:	Phase angle for SWAY (used for regular waves)
F3HEA	:	Maximum amplitude of wave excitation force for HEAVE (used for regular waves)
P3HEA	:	Phase angle for HEAVE (used for regular waves)
F4ROL	:	Maximum amplitude of wave excitation moment for ROLL (used for regular waves)
P4ROL	:	Phase angle for ROLL (used for regular waves)
F5PIT	:	Maximum amplitude of wave excitation moment for PITCH (used for regular waves)
P5PIT	:	Phase angle for PITCH (used for regular waves)
F6YAW	:	Maximum amplitude of wave excitation moment for YAW (used for regular waves)
P6YAW	:	Phase angle for YAW (used for regular waves)
SURGE_IN	:	Initial surge motion at time t = 0 (m)
ASW_IN	:	Initial sway motion at time t = 0 (m.)
HEA_IN	:	Initial heave motion at time t = 0 (m.)
AR_IN	:	Initial roll motion at time t = 0 (deg)
PITCH_IN	:	Initial pitch motion at time t = 0 (deg)
YAW_IN	:	Initial yaw motion at time t = 0 (deg)
TTIME	:	Total simulation time (sec)
T1_STEP	:	Time interval for the output of motion results
VOLUMEIN1	:	Initial amount of water in the damaged compartment 1 (m^3)
VOLUMEIN2	:	Initial amount of water in the damaged compartment 1 (m^3)
VOLUMEIN3	:	Initial amount of water in the damaged compartment 1 (m^3)

TVOLUME1	:	Total amount of water flooding into the damage compartment 1 after the final stage of flooding (used for the option 1 of the water ingress (m^3)
TVOLUME2	:	Total amount of water flooding into the damage compartment 2 after the final stage of flooding (used for the option 1 of the water ingress (m3)
TVOLUME3	:	Total amount of water flooding into the damage compartment 3 after the final stage of flooding (used for the option 1 of the water ingress (m3)
TST1	:	Starting time of the flooding for the damaged compartment1 (sec)
TST2	:	Starting time of the flooding for the damaged compartment2 (sec)
TST3	:	Starting time of the flooding for the damaged compartment3 (sec)
TDUR1	:	Total time of progressive flooding in damaged compartment 1 (sec). Used for option 1 of water ingress
TDUR2	:	Total time of progressive flooding in damaged compartment 2 (sec).Used for option 1 of water ingress
TDUR3	:	Total time of progressive flooding in damaged compartment 3 (sec).Used for option 1 of water ingress
VOLUMEDEC1	:	Flow rate of water into the damaged compartment 1 per time interval (m^3). This is used for the option 1 of the water ingress
VOLUMEDEC2	:	Flow rate of water into the damaged compartment 2 per time interval (m^3). This is used for the option 1 of the water ingress
VOLUMEDEC3	:	Flow rate of water into the damaged compartment 3 per time interval (m^3). This is used for the option 1 of the water ingress
INHE	:	0
TIMINC	:	Time interval used for the flow rate of the water into the damaged compartments (sec.).This is used for the option 1 of the water ingress

ISIP1	:	Identification for damaged compartment 1 it must always be 1. It is used for the option 2 of water ingress
ISIP2	:	Identification for damaged compartment 2 it must always be 2. It is used for the option 2 of water ingress
ISIP3	:	Identification for damaged compartment 3 it must always be 3. It is used for the option 2 of water ingress
IAPD1	:	Number of the appendage in the damaged compartment 1 which is used to locate the water elevation in the appendage for the option 2 of water ingress
IAPD2	:	Number of the appendage in the damaged compartment 2 which is used to locate the water elevation in the appendage for the option 2 of water ingress
IAPD3	:	Number of the appendage in the damaged compartment 3 which is used to locate the water elevation in the appendage for the option 2 of water ingress
ISTA1	:	Number of section in damaged appendage (IAPD1) of the damaged compartment 1 which is used for option 2 the water ingress. It is suggested to use the middle section in the damaged appendage (IAPD1).
ISTA2	:	Number of section in damaged appendage (IADP2) of the damaged compartment 2, which is used for option 2 the water ingress. It is suggested to use the middle section in the damaged appendage (IAPD2).
ISTA3	:	Number of section in damaged appendage (IAPD3) of the damaged compartment 3 which is used for option 2 the water ingress. It is suggested to use the middle section in the damaged appendage (IAPD3)
ISNUM	:	Number of the section of the main hull which is used to find the intersection points between wave profile and the ship. It is used for the option 2 of water ingress
Z1MIN	:	Min Z (vertical) coordinate of the section (ISTA1) in damaged appendage (IADP1) (m). It is used for the option 2 of water ingress

Z2MIN	:	Min Z (vertical) coordinate of the section (ISTA2) in damaged appendage (IADP2) (m). It is used for the option 2 of water ingress
Z3MIN	:	Min Z (vertical) coordinate of the section (ISTA3) in damaged appendage (IADP3) (m). It is used for the option 2 of water ingress
Z1H	:	Min Z (vertical) coordinate of the section (ISTA1) in damaged appendage (IADP1) (m). It is used for continuous flooding.
ZM1	:	Max Z (vertical) coordinate of the section (ISTA1) in damaged appendage (IADP1) (m). It is used for continuous flooding.
B1H	:	Width (transverse) coordinate of the section (ISTA1) in damaged appendage (IADP1) (m). It is used for continuous flooding.
Z2H	:	Min Z (vertical) coordinate of the section (ISTA2) in damaged appendage (IADP2) (m). It is used for continuous flooding.
ZM1	:	Max Z (vertical) coordinate of the section (ISTA2) in damaged appendage (IADP2) (m). It is used for continuous flooding.
B1H	:	Width (transverse) coordinate of the section (ISTA1) in damaged appendage (IADP2) (m). It is used for continuous flooding.
Z3H	:	Min Z (vertical) coordinate of the section (ISTA3) in damaged appendage (IADP3) (m). It is used for continuous flooding.
ZM3	:	Max Z (vertical) coordinate of the section (ISTA3) in damaged appendage (IADP3) (m). It is used for continuous flooding.
B3H	:	Width (transverse) coordinate of the section (ISTA3) in damaged appendage (IADP3) (m). It is used for continuous flooding.

DB	:	Height of the double bottom from the origin (m). It is used for the option 2 of water ingress
BHD	:	Height of the bulkhead deck from the origin (m). It is used for the option 2 of water ingress
SWL1	:	Length of the ship at waterline (m). It is used for the option 2 of water ingress to define the longitudinal extension of the damage at the waterline
COTR	:	Water flow coefficient. It is used for the option 2 of water ingress

D.8 Example Motion File Format

```
56.69   60.94   23.87   0.00    0.00    12.2876   1.9361   0.00     0.00
76.39   60.94   0.00    0.00    136.51  0.00      0.00     0.00     0.00
21.50   79.51   12.28   1.936   0.00    0.00      6.4366   0.00     0.00
0.0
3984.4  3745.7  0.00    0.00    0.00    0.00      0.00     0.00     0.00
0.0
9.45    174.23  29.99   113.6   3.000   -5.0      5.1234   -24.987
0.0     0.0     10.0    0.0     1000    1
0.5     0.0     0.0
0.0     0.0     0.0
0.0     0.0     0.0
0.0     0.0     0.0
0.0     0.0     0.0
0.0     1.0
1       2       3       1       0       0       2       0       0       3
0.85    0.0     0.0     0.85    2.67    32.05   0.35
```

APPENDIX E

HULL FORM PARTICULARS

E.1 Sarawak Fast Ferry and Model Particulars

Table E.1 : Particulars for Sarawak Fast Ferry and Model

Particulars	Full Scale	Ship Model
Length:	31.5 m	315 cm
Breadth:	2.942 m	29.42 cm
Depth:	1.6 m	16 cm
Draught:	1 m	10 cm
Displacement:	59.6543 tonnes	59.6543 kgs
Block coefficient:	0.6184	0.6184
Midship coefficient:	0.7535	0.7535
Prismatic coefficient:	0.8206	0.8206
Waterplane coefficient:	0.8713	0.8713
KG:	1.2 m	12 cm
GMT:	0.371 m	3.71 cm
Scale:	1	10

E.2 Sarawak Fast Ferry Detail Drawing

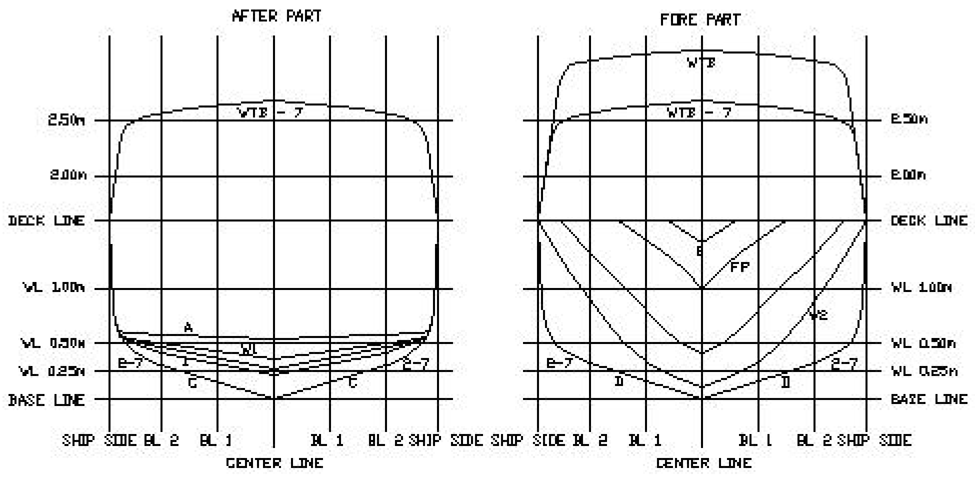

Figure E.1 Body plan of the Sarawak Fast Ferry

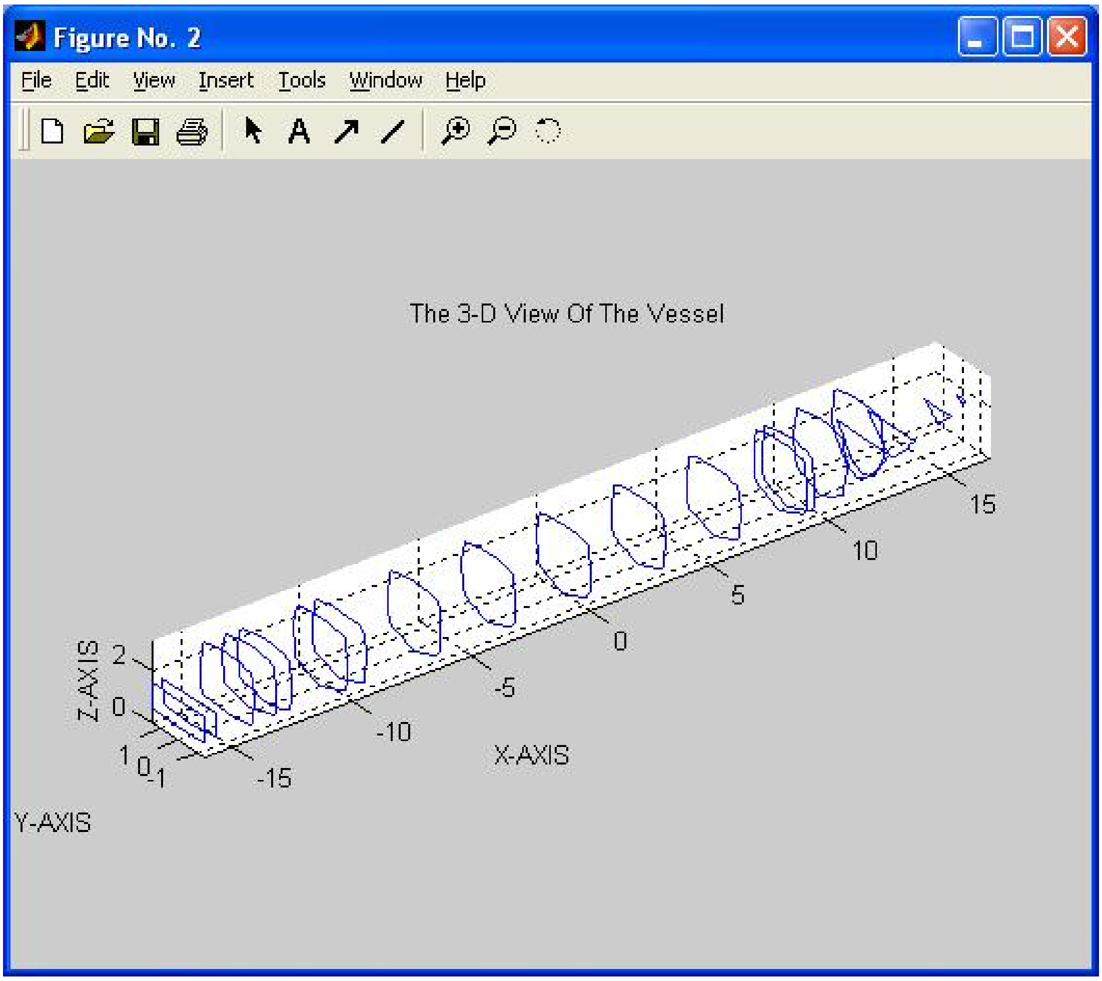

Figure E.2 3-D view of the Sarawak Fast Ferry

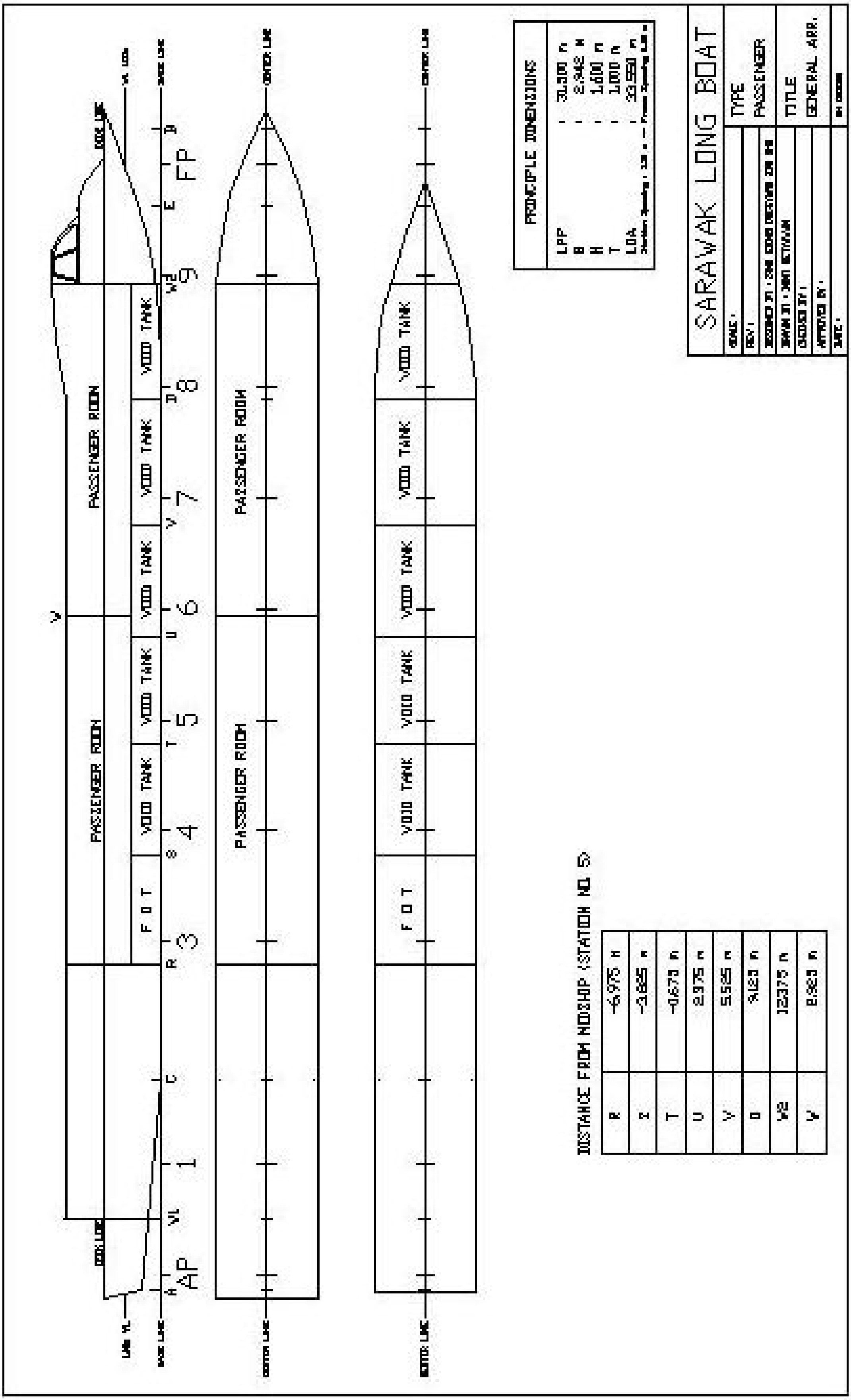

Figure E.3 Tank Arrangement of the Sarawak Fast Ferry

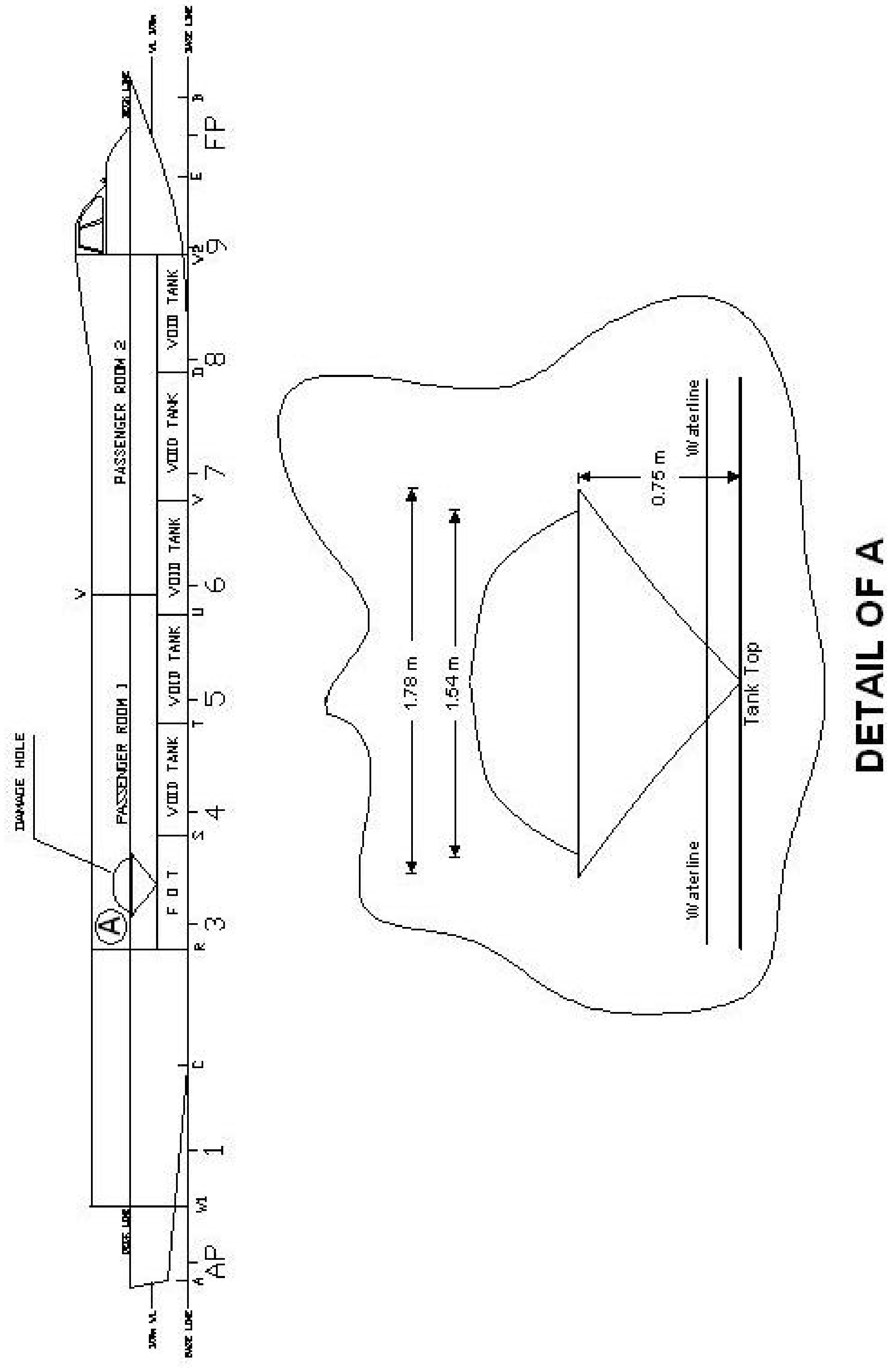

Figure E.4 Location and detail of damage hole

E.3 Ship Model

Figure E.5 Ship model

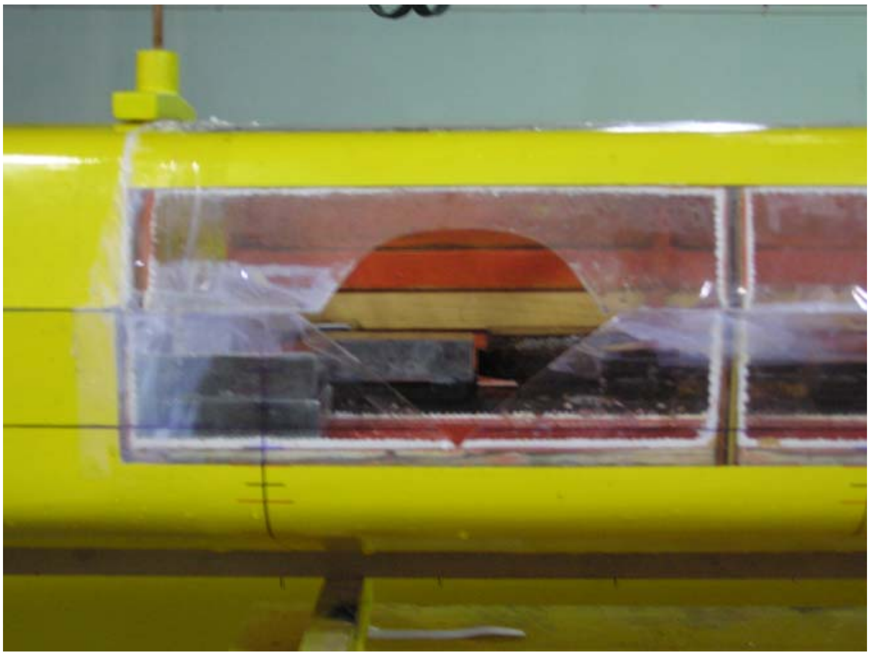

Figure E.6 Damage hole on ship model

APPENDIX F

MODEL EXPERIMENT

F.1 Ballasting of Ship Model

Figure F.1 Ship model on swinging frame

F.2 Roll Decay Test

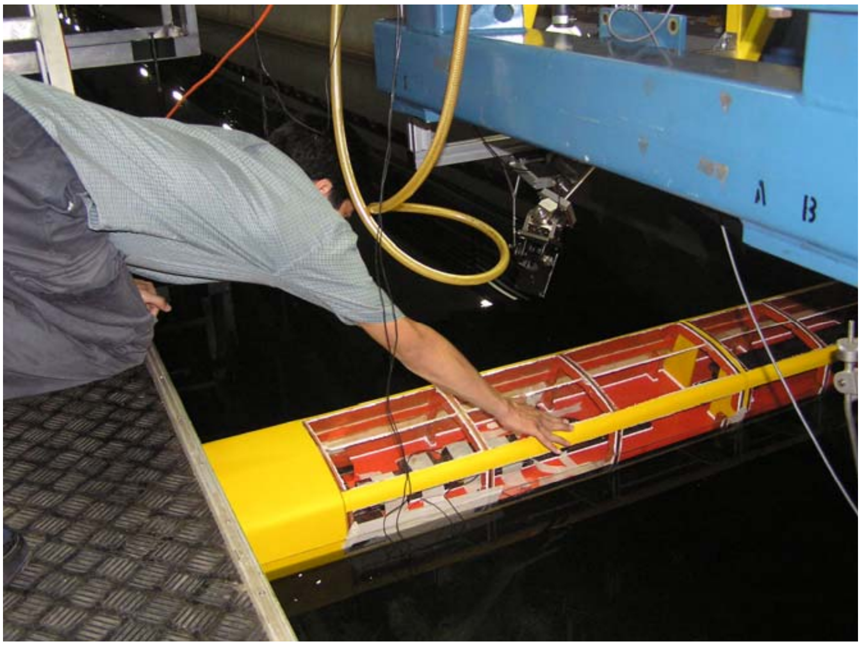

Figure F.2 Roll decay test

F.3 Water Ingress Experiment

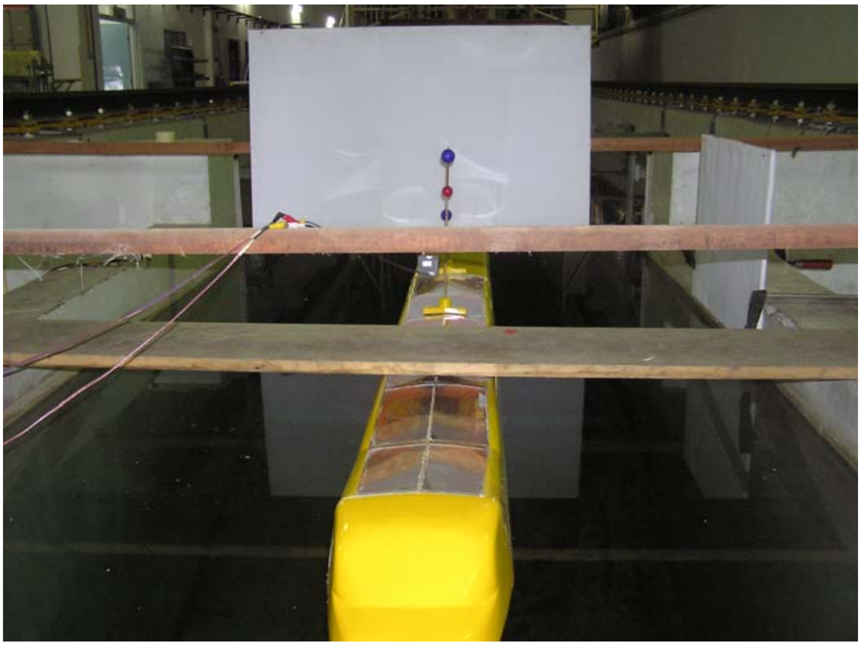

Figure F.3 Water ingress experimental set up

Figure F.4 Measure the weight of water ingress for each time step

F.4 Damage Stability Experiment

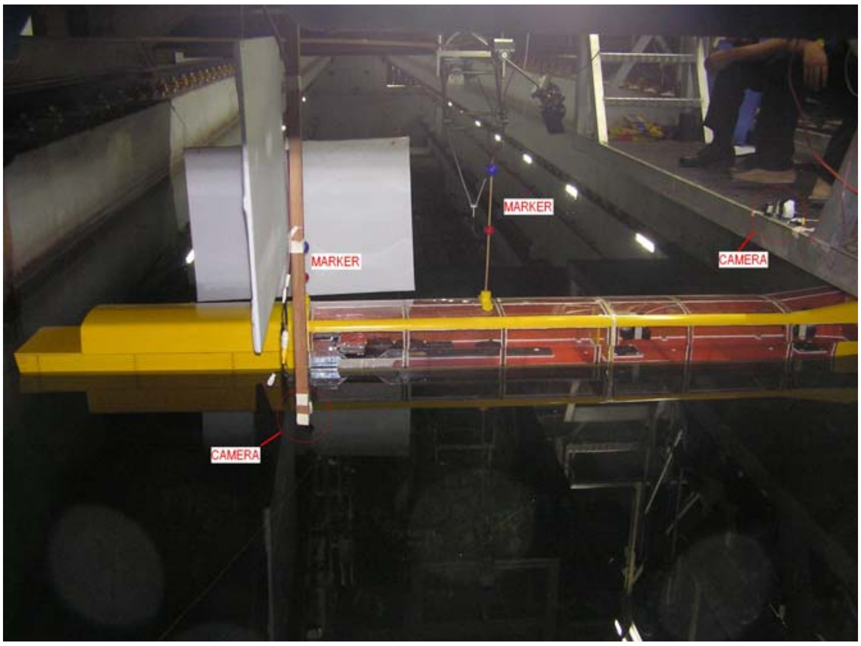

Figure F.5 Cameras and markers set-up

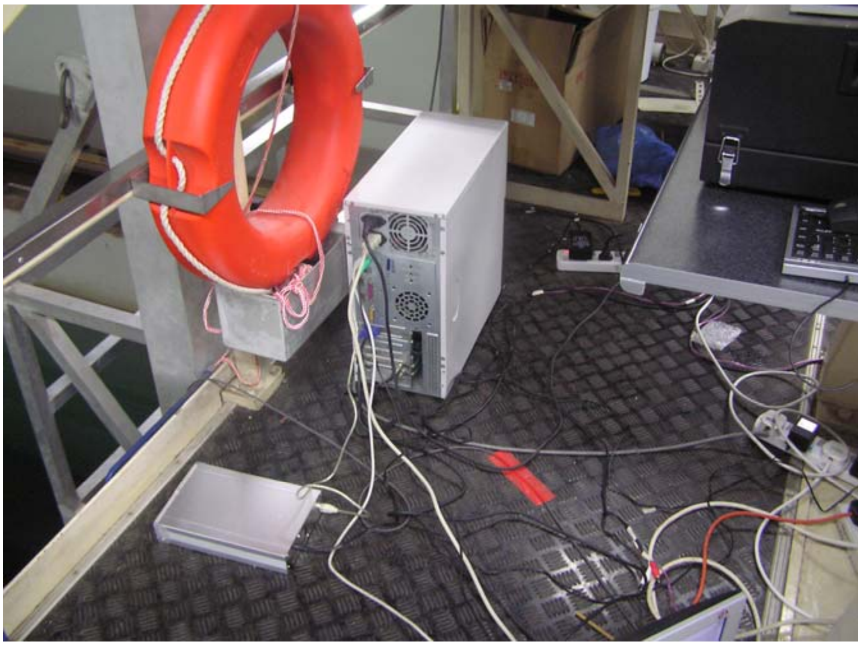

Figure F.6 Instrumentation set up

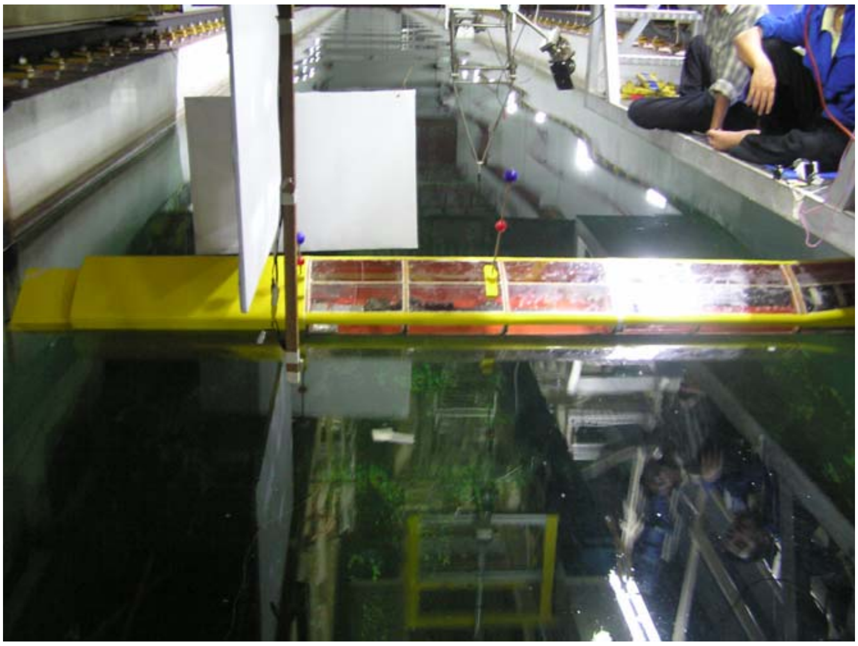

Figure F.7 Image processing on damage stability experiment - condition 1

Figure F.8 Image processing on damage stability experiment - condition 2

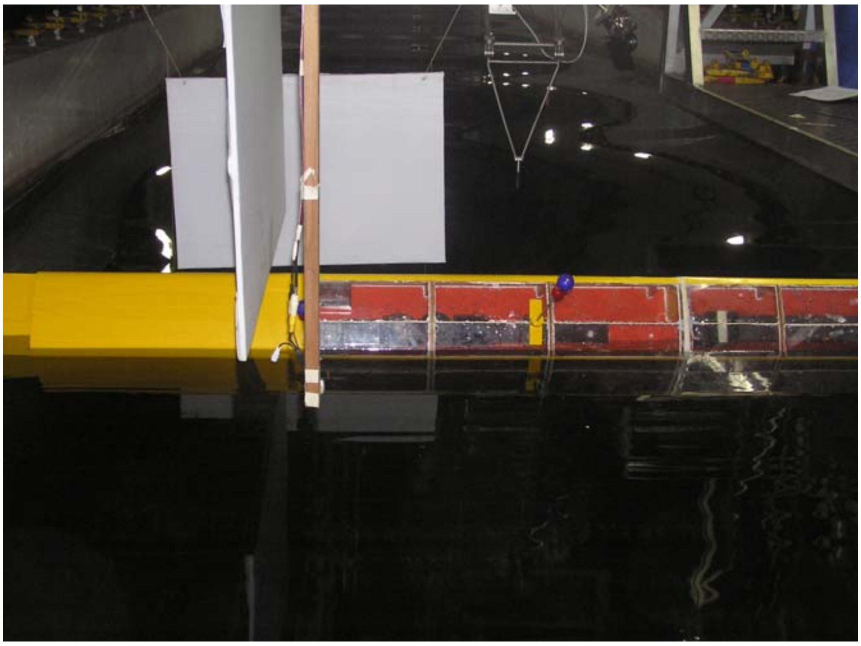

Figure F.9 Image processing on damage stability experiment - condition 3

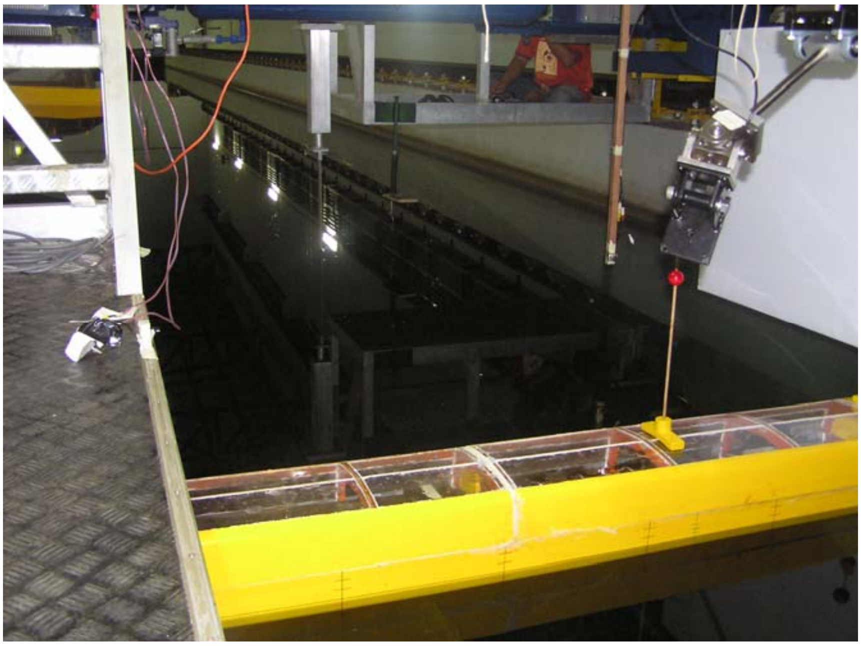

Figure F.10 Image processing on damage stability experiment - condition 4