

## DEVELOPMENT OF A MATHEMATICAL MODEL FOR ANALYSIS ON SHIP COLLISION DYNAMICS

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### ABSTRACT

This research work attempts to develop a dynamics model for ship to ship collision. The collision model is fundamentally divided into two segments namely, model for simulation before collision and model for simulation after collision. In the first part, mathematical formulations are derived for finding the possibility of a collision, determining the spatial location of collision and identification of the contact points on the ships. In the later part, a mathematical model is developed to study the kinetic energy losses, collision forces and dynamic responses with respect to different variables such as coefficient of restitution, ship speed, added mass for sway force and collision time. Expressions for collision forces are derived based on changes in linear momentum, and finally dynamic responses are calculated for different collision scenarios.

**Keywords:** Ship Collision, Dynamics, Simulation, Mathematical Model.

### 1. INTRODUCTION

Bangladesh is a riverine country and about seven percent surface of the country is covered by a dense 24,000 kilometre long network of inland waterways [1]. Consequently inland waterways provide one of the best modes of transportation for carrying goods and passengers through ships, trawlers, ferries and boats. However, safety of inland water crafts has become a serious issue in recent times when numbers of catastrophic accidents have taken place killing thousands of people and destroying resources worth millions of taka. Studies reveal that fifty six percent of all the passenger launch accidents in Bangladesh are collision due to human error and twenty one percent is the loss of stability due to Nor'wester [2]. Studies on overall accident characteristics [3,4] also suggest that collisions between marine vessels are also significantly higher in comparison to other types of accidents.

The fact that concerns all is that the collision accidents are fatal and the extent of damage and loss of property are tremendously expensive which puts considerable burden on the national economy. There remain numerous deficiencies on maritime safety and the scope for improvements in this area is a contemporary demand. This study is therefore, an attempt to improve safety of ships by studying the possibility of a collision and thus inventing ways to prevent it cost effectively and efficiently. Also most importantly, this paper attempts to develop a mathematical model to study the dynamic characteristics of the vessels during a collision considering forward speed, coefficient of restitution of

the fender material and virtual mass of the ships as variables. For simplicity the study excludes the wave effects and considers uncoupled rolling motion of the struck ship since this motion is directly related to the capsizing.

### 2. BACKGROUND STUDY

The risks involved and the consequences associated with ship-ship collisions are extremely high and catastrophic. Particularly the environmental and economical issues create a huge impact in the community when these ruinous incidents take place. One of the early pioneers to recognise such problems and to conduct mathematical analyses based on empirical models was Minorsky [5]. In October 1959, Minorsky published a research paper where he analysed ship collision with reference to protection of nuclear power plant. The objective of his work was to predict with some degree of accuracy the conditions under which a nuclear ship remain intact and, consequently, what structural strength should be built into the reactor space within the hull in order to absorb safely a given amount of kinetic energy in a collision. In the original analysis the collision is assumed to be totally inelastic, and motion is limited to a single degree of freedom.

Zhang [6] in his doctoral research work developed models for ship collisions where collision energy losses, collision forces and structural damages were determined. His approach overcome a major drawback of Minorsky's well known method since it took into account the structural arrangement, the material properties and

damage modes.

During the past fifty years a number of model experiments have been carried out in Italy, Germany and Japan. The principal objectives of these tests were to design nuclear powered ships having adequate protection to the nuclear reactor from collision damage. Several authors have given detailed reviews on these experiments, for example, Woisin [7], Ellina and Valsgard [8], Samuaelides [9] and Pedersen et al. [10].

In some recent investigations, powerful computers are used to model collision scenarios using finite element methods. Simulation programs started to run into the computers and events could be seen in time frame, second by second. Such works can be found in DAMAGE [11], Brown and Chen [12], Brown et al [13] and Chen [14], who conducted extensive work in developing Simplified Collision Model (SIMCOL) based on solutions of external dynamics and internal deformation mechanics in time domain simulations for the rapid prediction of collision damage in probabilistic analysis.

Interestingly all these research works were intended to investigate the structural performances during collision with the objectives of providing watertight integrity, safeguarding the valuable passenger, cargo, and other important resources. Indeed there have been considerable advances in developing methodologies and formulations of determining the collision damages. However, none of the research works have looked upon the dynamic characteristics of the ships during a collision event, particularly the aspects of stability with reference to capsizing due to excessive rolling by collision force. Therefore, the purpose of this research is to develop a ship collision dynamics model and investigate the phenomenon under potentially dangerous circumstances.

### 3. DEVELOPMENT OF THEORETICAL MODEL

#### 3.1 Assumptions

The mathematical model developed in this study can be divided into two fundamental segments with reference to the time domain analysis; such as: (1) Before collision model and (2) During and after collision model. However, for both of the segments there are some fundamental assumptions adopted and these are as follows:

(1) There is no friction or sliding between the striking and struck ship. The ships get separated from each other after the collision.

(2) It is also assumed that the ships do not encounter a second collision after being hit at the first instance so that the ships can have free motions in space after the incident.

(3) It is assumed, only while determining the hitting position at the struck ship abaft the bow, that the ships are straight line objects and their breadths and curved body shapes are ignored.

(4) For time domain simulation the collision time (contact period between the two ships) is taken as one second. However, for additional analyses the contact period has been considered as a variable in between 1 to 5 seconds.

(5) It is also assumed while dealing with the equation

of motion that there are no waves or wind forces before and after collision.

#### 3.2 Model for Simulation Before Collision

It is assumed that two ships are plying in waters each having particular forward speeds and headings. Considering the heading paths of the ships remain straight line before hitting each other there will be a point of intersection where they are supposed to hit each other. These straight line paths can therefore, be expressed as the following for Ship A and Ship B respectively,

$$y = m_A x + c_A \quad (1)$$

$$y = m_B x + c_B \quad (2)$$

Where,  $m_A$  &  $c_A$  and  $m_B$  &  $c_B$  are the slopes and constants respectively of straight line paths of the ships which depend on the heading and relative position on the co-ordinate system. Fig 1 depicts the coordinate system.

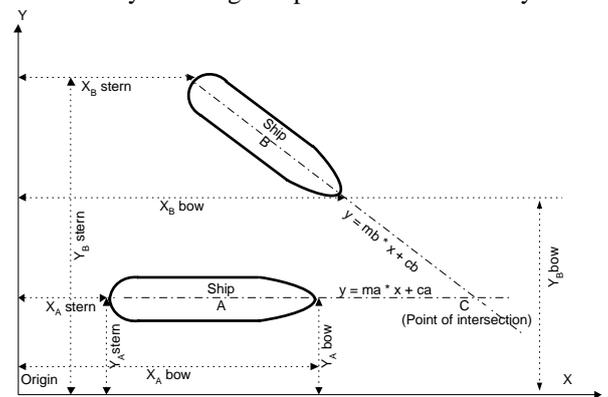


Fig 1: Coordinate system for simulation before collision

An origin is assumed at a suitable place and the slopes of these straight lines are obtained from the relative position of their sterns and bows in Cartesian co-ordinates. Let the point of intersection be defined by  $C(X_C, Y_C)$  and which could be determined as,

$$X_C = -\left(\frac{c_A - c_B}{m_A - m_B}\right) \quad (3)$$

$$Y_C = \frac{m_B c_A - m_A c_B}{m_A - m_B} \quad (4)$$

The knowledge on point of intersection gives the probable idea of the location of the potential collision. However, the incident of collision can still be avoided by altering the speeds of the vessels although their headings remain unaltered. Therefore, it is important to know whether both the ships occupy the point of intersection at the same time or not. If they occupy the point at the same time, the collision is inevitable. On the other hand, if any of the ship passes through before arrival of the other or arrives late while allowing the other to pass through, the collision could be avoided. This critical situation may well be similar to when vessels lose control of their rudder on a collision course and have only the freedom of varying their respective speeds.

Let the measured parameters of relative positions of the ships with respect to origin were taken at time  $t = 0$ . If one of the ship's bow (say Ship A) arrives at the intersection point at time  $T_{A arrival}$  and the stern leaves the

point at time  $TA_{departure}$ , then the occupying duration is the difference between  $TA_{departure}$  and  $TA_{arrival}$ . In such a case if a collision is to take place, the other ship must arrive at the point in between time  $TA_{departure}$  and  $TA_{arrival}$ . Therefore, it is essential to know the arrival and departure time of both of the ships at the point of intersection or in other words the ‘‘collision zone’’. An example is shown in Fig 2 where the scenario is depicted. In the first case both of the ships occupy the collision zone at the same time as seen by the overlapping time lines of the ships. However, in the second case the ships occupy the point at different time intervals and avoid the potentially dangerous collision. The arrival time and departure time of the ships ( $TA_{arrival}$ ,  $TB_{arrival}$ ,  $TA_{departure}$ ,  $TB_{departure}$ ) are obtained as the following,

$$TA_{arrival} = \frac{X_c - x_{A_{bow}}}{V_A \cos m_A} \quad (5)$$

$$TA_{departure} = \frac{X_c - x_{A_{stern}}}{V_A \cos m_A} \quad (6)$$

Similarly for ship B the following are obtained:

$$TB_{arrival} = \frac{X_c - x_{B_{bow}}}{V_B \cos m_B} \quad (7)$$

$$TB_{departure} = \frac{X_c - x_{B_{stern}}}{V_B \cos m_B} \quad (8)$$

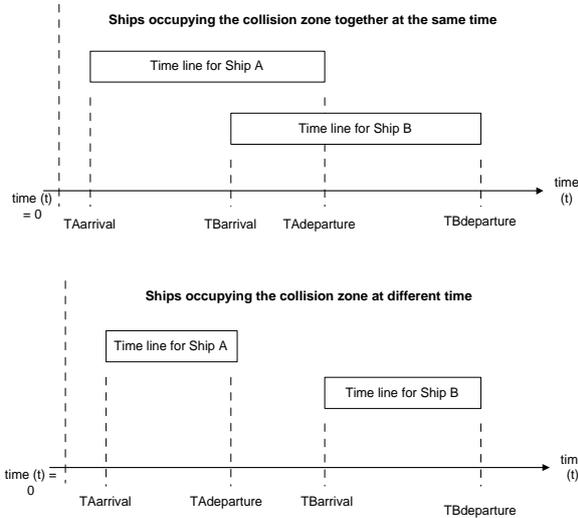


Fig 2: Time line description of the ships occupying the collision zone

If Ship A arrives at the point of intersection before Ship B and Ship A doesn't depart before arrival of Ship B (i.e.  $TA_{arrival} < TB_{arrival} < TA_{departure}$ ), in such a case Ship B hits Ship A and the collision occurs at  $TB_{arrival}$ . On the other hand, if Ship B arrives at the point of intersection before Ship A and Ship B doesn't depart before arrival of Ship A (i.e.  $TB_{arrival} < TA_{arrival} < TB_{departure}$ ), in such a case Ship A hits Ship B and the collision occurs at  $TA_{arrival}$ . Let the time be  $T_{hit}$  when the collision takes place. When Ship A hits Ship B, the point of hitting at Ship B abaft bow is obtained as,

$$H = \sqrt{\{X_c - (x_{B_{bow}} + V_B \cos \phi \times T_{hit})\}^2 + \{Y_c - (y_{B_{bow}} + V_B \sin \phi \times T_{hit})\}^2} \quad (9)$$

On the other hand when Ship B Hits Ship A, the point of hitting at Ship A abaft bow is given by,

$$H = (x_{A_{bow}} + V_A \times T_{hit}) - X_c \quad (10)$$

### 3.3 Model for Simulation During and After Collision

Considering a collision scenario, as shown in Fig 3, where Ship A strikes Ship B, two co-ordinate systems may be assumed for each ship such as X-Y for striking ship and I-J for struck ship.

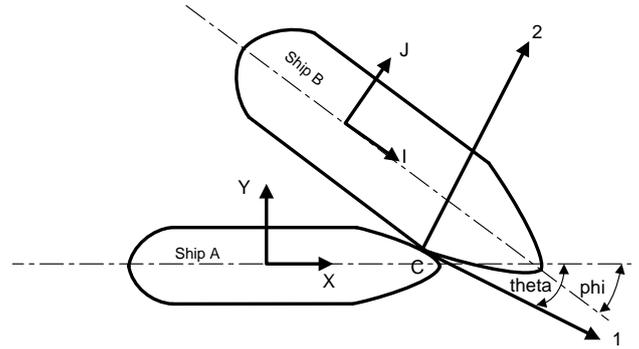


Fig 3: Co-ordinate system of a ship-ship collision

#### 3.3.1 The collision forces

Using simple trigonometric relations the collision forces in the respective axes on both the struck and striking ship may be computed. For example, forces on Ship A in X-axis and Y-axis direction are,

$$F_X = F_1 \cos \theta + F_2 \cos (90 - \theta) \quad (11)$$

$$F_Y = -F_1 \sin \theta + F_2 \sin (90 - \theta) \quad (12)$$

Similarly, forces on Ship B in I-axis and J-axis direction are obtained as,

$$F_I = F_1 \cos (\varphi - \theta) + F_2 \cos (\varphi - \theta) \quad (13)$$

$$F_J = F_1 \sin (\varphi - \theta) + F_2 \sin (\varphi - \theta) \quad (14)$$

Here, forces  $F_1$  and  $F_2$  are perpendicular forces acting at the contact point C developed from the impact between the two bodies. It is known that impact force at a particular direction is equal to change of linear momentum in that direction, i.e.  $F_1$  equals the change in momentum in 1-axis direction and  $F_2$  equals change in momentum in 2-axis direction. Therefore, by using these expressions the forces may be obtained,

For Ship A,

$$F_{A1} = M_A \frac{V_{A1after} - V_{A1before}}{T_{col}} \quad (15)$$

$$F_{A2} = M_A \frac{V_{A2after} - V_{A2before}}{T_{col}} \quad (16)$$

For Ship B,

$$F_{B1} = M_B \frac{V_{B1after} - V_{B1before}}{T_{col}} \quad (17)$$

$$F_{B2} = M_B \frac{V_{B2after} - V_{B2before}}{T_{col}} \quad (18)$$

### 3.3.2 Coefficient of Restitution and Final Velocities

The most fundamental approach of this study is that the changes of velocity after the collision are functions of coefficient of restitution and the time required to restate or simply the collision time. The application of these two variables are however, very critical and requires careful assumption to model a potentially realistic scenario. The coefficient of restitution is a measure of the elasticity of the collision between two objects. Elasticity is a measure of how much of the kinetic energy of the colliding objects before the collision remains as kinetic energy of the objects after the collision.

There are three types of collision: Perfectly Elastic, Perfectly Inelastic and Elastoplastic collision. A perfectly elastic collision has a coefficient of restitution of 1. Example: two diamonds bouncing off each other. A perfectly inelastic, collision has  $E = 0$ . Example: two lumps of clay that don't bounce at all, but stick together. On the other hand an elastoplastic collision, some kinetic energy is transformed into deformation of the material, heat, sound, and other forms of energy. For this type the coefficient of restitution varies between zero and one.

Now when a collision starts taking place the change in momentum is equal to the impulse integral and the common velocity at the beginning of the restitution time reaches the maximum level or in other words the velocity reaches maximum at the end of compression. Therefore, according to the impulse momentum theory the following may be obtained for time between start of collision ( $t=0$ ) and maximum compression ( $t=t_1$ ),  
For Ship A

$$M_A(V_{A1} - V_{A1before}) = \int_0^{t_1} F_{B1} dt \quad (19)$$

$$M_A(V_{A2} - V_{A2before}) = \int_0^{t_1} F_{B2} dt \quad (20)$$

For Ship B

$$M_B(V_{B1} - V_{B1before}) = \int_0^{t_1} F_{A1} dt \quad (21)$$

$$M_B(V_{B2} - V_{B2before}) = \int_0^{t_1} F_{A2} dt \quad (22)$$

However, according to impulse momentum theory the following relations must satisfy along the axes,

$$\int_0^{t_1} F_{A1} dt + \int_0^{t_1} F_{B1} dt = 0 \quad (23)$$

$$\int_0^{t_1} F_{A2} dt + \int_0^{t_1} F_{B2} dt = 0 \quad (24)$$

Thus operating the above relationships the common velocities are obtained along the two axes,

$$V_{A1} = V_{B1} = \frac{M_B V_{B1before} + M_A V_{A1before}}{M_B + M_A} \quad (25)$$

$$V_{A2} = V_{B2} = \frac{M_B V_{B2before} + M_A V_{A2before}}{M_B + M_A} \quad (26)$$

Similarly between the maximum compression and full separation of the ships the following relations are obtained for common velocities,

$$V_{A1} = V_{B1} = \frac{M_B V_{B1after} + M_A V_{A1after}}{M_B + M_A} \quad (27)$$

$$V_{A2} = V_{B2} = \frac{M_B V_{B2after} + M_A V_{A2after}}{M_B + M_A} \quad (28)$$

It is now possible to establish a relationship between impulse integrals with the help of Coefficient of Restitution ( $E$ ). This relation can be expressed as the following:

$$\int_{t_1}^{t_2} F dt = E \int_0^{t_1} F dt \quad (29)$$

Using equations (19) to (29) it is now possible to obtain the expressions of velocities after collision for both the ships. Such as,

For Ship A

$$V_{A1after} = V_{A1}(1 + E) - E \times V_{A1before} \quad (30)$$

$$V_{A2after} = V_{A2}(1 + E) - E \times V_{A2before} \quad (31)$$

For Ship B

$$V_{B1after} = V_{B1}(1 + E) - E \times V_{B1before} \quad (32)$$

$$V_{B2after} = V_{B2}(1 + E) - E \times V_{B2before} \quad (33)$$

The loss of kinetic energy is therefore obtained as,  
For Ship A:

$$KE_{A1} = \frac{1}{2} M_A (V_{A1before}^2 - V_{A1after}^2) \quad (34)$$

$$KE_{A2} = \frac{1}{2} M_A (V_{A2before}^2 - V_{A2after}^2) \quad (35)$$

For Ship B:

$$KE_{B1} = \frac{1}{2} M_B (V_{B1before}^2 - V_{B1after}^2) \quad (36)$$

$$KE_{B2} = \frac{1}{2} M_B (V_{B2before}^2 - V_{B2after}^2) \quad (37)$$

### 3.4 Solution of the Equation of Motion

The equation of motion needs to be solved with necessary boundary conditions in order to find the ships responses due to collision forces. During a collision the equation of motion may be expressed as the following,

$$M_V \frac{d^2 x_i}{dt^2} + b_{ij} \frac{dx_i}{dt} + c_{ij} x_i = F c_i(t) \quad (38)$$

Therefore, the general solution of the equation may be expressed as,

$$x_i = e^{at} \{A_1 \sin \beta t + A_2 \cos \beta t\} \quad (39)$$

Where,  $A_1$  and  $A_2$  are constants which are needed to be determined using appropriate boundary conditions. Assuming an initial condition when the collision force is

maximum at time  $t = t_{max} = 0$ , the displacement is  $x_i = x_{i0}$ . According to the theory of simple harmonic motion, this amplitude or displacement is maximum when the velocity reaches to zero and the velocity becomes maximum when the amplitude becomes zero units. Therefore, assuming  $x_{i0}$  is the maximum amplitude due to collision force at the time  $t = 0$ , the following unknowns are obtained from the equation of general solution as derived above.

$$A_1 = -\frac{x_{i0}}{\beta} \text{ and } A_2 = x_{i0} \quad (40,41)$$

And therefore, the general solution becomes,

$$x_i = x_{i0} e^{\alpha t} \left\{ \cos \beta t - \frac{1}{\beta} \sin \beta t \right\} \quad (42)$$

The above equation is similar to the damping part of any equation of motion where  $x_{i0}$  resembles the maximum amplitude due to an excitation and  $e^{\alpha t}$  resembles exponential decay of the motion. It is, however, important to mention that in this paper only rolling motion ( $x_r$ ) is being investigated to study the capsizing phenomena of the vessels under collisions.

### 3.5 Force as an Exponential Function of Time

The time history of force is considered absolutely vital for solving the equation of motion in time domain. However, experience suggest that in most of the practical cases the force-time data is extremely difficult to predict since it involves complicated internal structural arrangement, including the external fenders, of ship hull that are subject to progressive structural deformations/failures by buckling, shearing, tearing, crushing, bending and twisting of plates, stringers, panels etc during a collision. Awal [15] proposed several force functions in this aspect but the formulations are yet to be experimentally verified. In this particular study the force is assumed to be an exponential function of time where the force increases exponentially from time  $t_{hit}$  to time  $t_{max}$  and thereafter it reduces exponentially again from time  $t_{max}$  to time  $t_{sep}$  as shown in Fig 4.

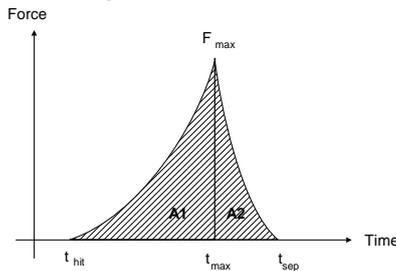


Fig 4: Collision force is an exponential function over the contact period

The particular integral of the function  $Fc_i(t) = F_{max} f(e^t)$  may be obtained as the following,

$$x_i = \frac{F_{max} [e^{t-t_{max}}]}{a_{ij} + b_{ij} + c_{ij}} \quad [t = t_{hit} \text{ to } t = t_{max}] \quad (43)$$

### 3.6 Validation of the Model

The developed model has been compared with a

number of published research works which are described in the following paragraphs.

#### 3.6.1 Comparison of Lost Kinetic Energy

The comparison of loss of kinetic energy has been computed using two similar ships of length 116 meter. The particulars are breadth 19.0 meters, draft 6.9 meters, displacement 10340 tons and coefficient of restitution zero. The collisions were taken at various angles of attack and speeds as well. It is however, considered in this validation that the hitting takes in place at the centre of the struck ship and the collision is entirely plastic. A plastic collision means that the ships remain in contact after the collision and all the kinetic energy is being used in deforming the ships hull structure and dynamic movement of the ships. The results are being compared with the loss of kinetic energy along 1-axis (KE1) and 2-axis (KE2) directions and the units expressed here are in mega joule. The results are compared with published data of Petersen [16], Hanhirova [17] and Zhang [6] as shown in Table 1.

Table 1: Comparison of loss of kinetic energy

Va (m/s)	Vb (m/s)	$\alpha = \beta$ (deg.)	KE1 (MJ)				KE2 (MJ)			
			Petersen (1982)	Hanhirova (1995)	Zhang (1999)	Present Study	Petersen (1982)	Hanhirova (1995)	Zhang (1999)	Present Study
4.5	0	90	0	0	0	0	69.6	54.4	70.1	78.52
4.5	4.5	90	24.7	41.5	21.4	26.17	64.1	54.4	70.1	78.52
4.5	4.5	60	5.2	15.8	0.2	32.72	28.8	28.3	35.3	58.89
4.5	4.5	30	49.3	7.2	0	12.62	71.9	4	7.4	19.63
4.5	0	120	9.8	14	15	19.63	54	40.9	50.1	58.89
4.5	2.25	120	40.7	51.5	45.1	26.17	60.3	42.8	57.5	58.89

The comparison suggests that there are noticeable variations among different methods adopted by different researcher; nevertheless, the results do not exceed the comparative limits and thus it may be concluded that the developed model is in good agreement.

#### 3.6.2 The Hydrodynamic Coefficients

The hydrodynamic coefficients  $a_{ij}$ ,  $b_{ij}$  and  $c_{ij}$  depend on the hull form and the interaction between the hull and surrounding water. The coefficients may also vary during a collision as well and the range of variation is even wider considering open or restricted water conditions. However, for simplicity Minorsky [5] proposed to use a constant value of the added mass coefficients of ships for the sway motion,  $m_{ay} = a_{22} = 0.4$ .

The added mass coefficient for rolling is suggested by Bhattacharyya [18] to be in between 10 to 20 percent of the actual displacement of the ship. The added mass coefficient for yaw motion of the ship,  $j_a$ , is used by Pedersen et. al [10] as 0.21. Crake [19] in his research work used an empirical relation for finding the added mass in yaw as  $a_{66} = 0.0991 \rho T^2 L_{BP}^3$ .

However, in this study the hydrodynamic coefficients were determined using the 3-D source distribution method [20] and the values are compared with existing results expressed in range of virtual mass (Table 2).

It is observed from the comparison that the hydrodynamic coefficients for surge, sway and yaw

fairly matches within the range except a few discrepancies in the sway motion. This is probably because the range is determined on the basis of ships that are relatively large and ocean going in comparison to the small vessels designed for inland transportation in Bangladesh.

Table 2: Comparison of virtual mass.

Hydrodynamic Coefficients	Range of Virtual Mass (non dimensional)	46 m Vessel (3-D Method)	32 m Vessel (3-D Method)
Surge, $a_{11}$	1.02 – 1.07	1.01	1.01
Sway, $a_{22}$	1.20 – 2.30	1.05	1.14
Roll, $a_{44}$	1.10 – 1.20	1.61	1.22
Yaw, $a_{66}$	1.20 – 1.75	1.40	1.53

#### 4. RESULTS AND DISCUSSIONS

This section reveals the results obtained from the numerical investigations and discusses the various facts revealed from the analyses. In the present study two different vessels (principle particulars are given in Table 3) were considered. Both the vessels are common inland vessels and such hull shapes are generally been used both in cargo and passenger ships. Results are presented in two different categories, (1) Analysis of non dimensional forces due to changes in different variables and (2) Time domain simulation due to changes in different variables.

Table 3: Principle particulars of the ships

Ship 1 (46 Meter)	Length	46.800 meter
	Breadth	10.564 meter
	Draft	2.3340 Meter
	Displacement	556.3 Tonne
	Angle of vanishing stability	67 degree
Ship 2 (32 Meter)	Length	30.640 meter
	Breadth	6.700 meter
	Draft	3.500 Meter
	Displacement	498.0 Tonne
	Angle of vanishing stability	75 degree

The numerical model setup consists of two ships positioned perpendicularly and potentially striking at amidships as shown in Fig 5. An important aspect to observe is the point of blow above the water level through which the collision force acts largely depends on the bow profile and the midship section of the ships. However, for this particular study it is assumed that the collision contact point is  $\frac{1}{2}$  draft above the centre of gravity.

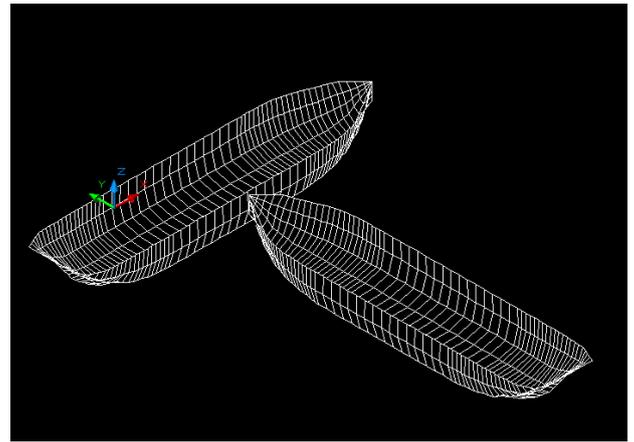


Fig 5: Model setup showing striking at 90 degree angle of attack at amidships.

##### 4.1 Analysis on Forces

It is revealed in Fig 6 that the force in sway direction varied in a range up to 6 times of the displacement or buoyancy force due to variation in striking ship speed. The speed is taken up to 12 knots (6.1782 m/sec) since generally this is the maximum allowable speed in the inland waterways. Graphically, the higher the speed of the striking ship, the higher the force in sway direction. Thus, the force in sway direction is proportional with the striking ship speed. It is also observed that at higher speeds the coefficient of restitution with lower value plays a very important role by reducing the collision force significantly.

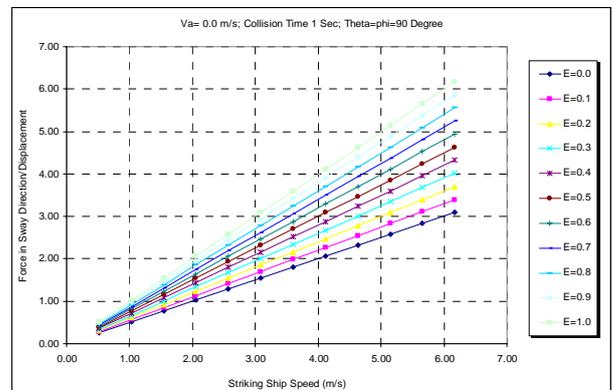


Fig 6: Force in sway direction vs. striking speed at various restitutions

Fig 7 suggests that the collision force substantially decreases with the increase in collision/contact period. For a very short collision period the variations of force in the sway direction due to different coefficients of restitution are very large but for a shorter collision period the variations are comparatively small and practically trivial.

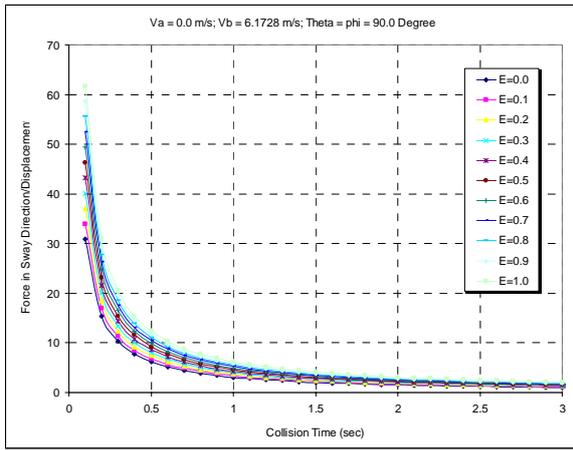


Fig 7: Force in sway direction vs. collision time at various restitutions

The collision force is also notably affected by the added mass of the ship. It is observed from Fig 8 that higher the added mass the lower is the collision force and vice versa. It is observed from the figure that for lower added mass the force varies relatively largely with the variation in coefficient of restitution while the force varies relatively less at higher added mass.

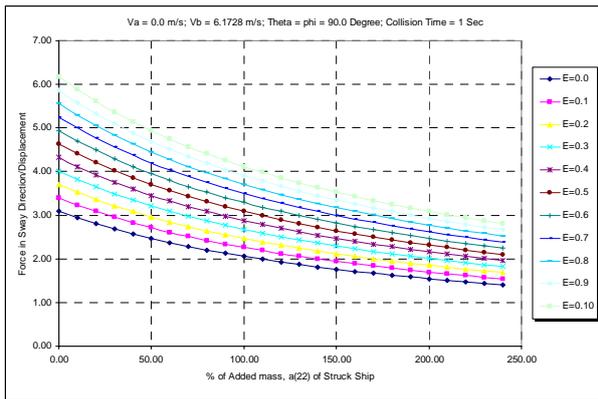


Fig 8: Force in sway direction vs. added mass for various restitutions

### 4.3 Time Domain Simulation for Different Cases

The time domain simulation of collision between ships depict clear picture of the dynamic responses of ships and provides explicit means for comprehending the total scenario. This particular study investigates seven different cases which have been summarised in Table 4.

Table 4: Summary of the collision scenarios

Case No.	Name of the Struck Ship	Name of the Striking Ship	Speed of the Striking Ship (knots)
1	Ship 1	Ship 1	1.0
2	Ship 1	Ship 1	6.0
3	Ship 2	Ship 2	1.0
4	Ship 2	Ship 2	6.0
5	Ship 2	Ship 1	1.0
6	Ship 2	Ship 1	3.0
7	Ship 2	Ship 1	6.0

Figs 9, 10 and 11 represent the time domain roll

simulation of the struck ships. It is observed that higher striking speeds cause higher the moment for rolling and thus higher rolling amplitude. Although this phenomena is nonetheless a common fact but the key aspect is to observe the amplitudes which are being reduced significantly by alteration of the coefficient of restitution.

It is observed that up to 83 percent of the rolling amplitude may be reduced if zero restitution materials are being used. This is indeed, a very important aspect of the research findings that as excessive rolling causes ships to capsize and such capsizing could be prevented by applying the lower restitution shock absorbing materials. This phenomena is simulated in Fig 10 (6 knot) and Fig 11 (3 and 6 knot) where the ships roll over the angle of vanishing stability if the coefficient of restitutions are one for all the cases. These roll amplitudes, however, are significantly less in their respective cases if the coefficient of restitutions were considered zero or close to zero. Therefore, the facts revealed here could be a mater of life and death and indeed requires due importance to be looked into while construction ship fenders and other similar protective devices.

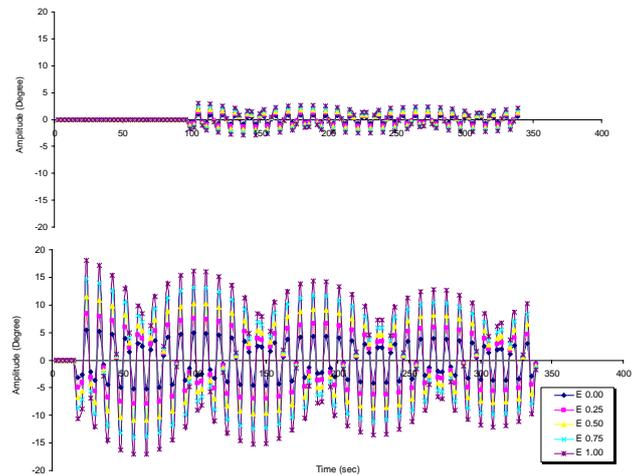


Fig 9: Time domain simulation for rolling motion for 48m vessel vs 48 m vessel at 90 degrees amidship for speeds 1 knot and 6 knot

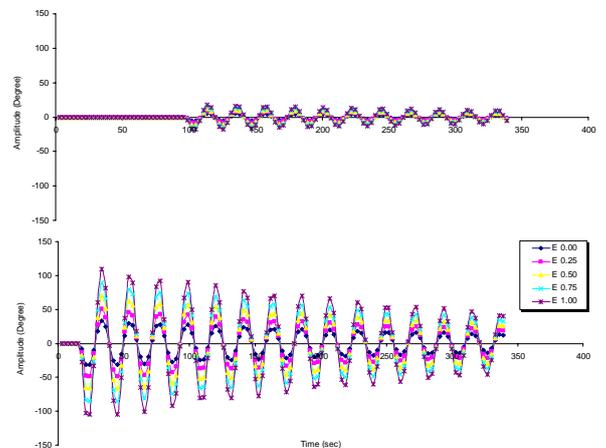


Fig 10: Time domain simulation for rolling motion for 32m vessel vs 32 m vessel at 90 degrees amidship for speeds 1 knot and 6 knot

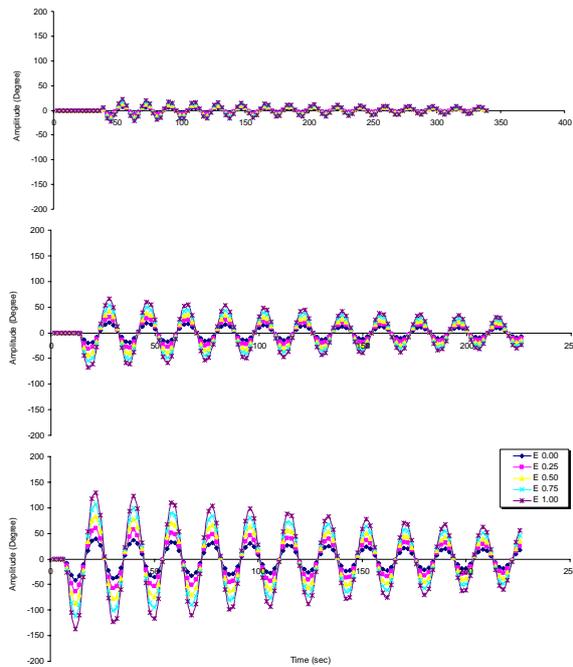


Fig 11: Time domain simulation for rolling motion for 32m vessel vs 48 m vessel at 90 degrees amidship for speeds 1 knot, 3 knot and 6 knot

## 5. CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Concluding Remarks

The research on studying the dynamic behaviour of ships for different coefficient of restitutions of the hull material is indeed a new concept and so far limited knowledge is available to the researchers in this particular area. Therefore, as a preliminary investigation this study is limited to mathematical formulations only and due to deficiency in infrastructural facilities for experimental investigations there was no other option but to validate its results with published numerical results.

### 5.2 Recommendations

(1) In order to reduce motion amplitude it is very essential that the materials used for construction of fenders and other external protective devices or structural members must have as much lower coefficient of restitution as possible. In fact zero restitution materials are recommended for maximum reduction of motion amplitude.

(2) Materials that have longer duration for restitution may be used as well. This will reduce the collision force significantly although it restitutes hundred percent but the change in momentum will be decreased due to larger restitution period which will result reduced collision force on the ship. This type of fender may be economically feasible for using in ships over a longer period.

(3) It is observed that there is a much more scope of research in this particular area of collision dynamics. Future study may be conducted on smaller country boats with more detailed description of the waterways as the river width, depth, geometry etc. Further study with wave and wind consideration is also recommended as it may

influence the ship dynamics. Experimental investigations are also suggested for future study.

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