Numerical Simulation of Dynamic Behavior of a Passenger at Ship Collision

Tadashi Shibue, Takashi Hayami
School of Biology Oriented Science and Technology, Kinki University
Kinokawa, Wakayama, JAPAN

Izumi Muramoto
JAIST School of Materials Science
Japan Advanced Institute of Science and Technology
Nomi, Ishikawa, Japan

ABSTRACT

This paper describes a series of numerical simulation of a transient behavior of a seated passenger on a high speed ship at collision. A three dimensional FE (Finite Element) model of human body is developed with reduced degrees of freedom to obtain practical accuracy within an allowable calculation time. Transient behavior of the human body at collision is estimated by using an explicit FE code to see the effects of colliding angle, colliding velocity and other factors.

KEY WORDS: high speed ship, collision, transient behavior, passenger, safety, simulation, seat

INTRODUCTION

Accidental collisions of high speed ships such as collisions of hydrofoil ships against a quay or a drift wood have been reported to cause injuries to passengers. Measures on the safety of the passenger at the collision are required. In spite of the strengthening of the watch at the navigation bridge and the obligating of seat belts wearing, there still exist injured passengers. It is necessary to understand the behavior of passenger's body in detail at the accident for keeping the passenger's safety. If passenger's behavior at the accident can be understood accurately, the forces generated within the body can be estimated and the parts of the body which collides with the seats and the floor can be specified. Therefore, offering the means to do the development of a safer seat and the development of a safer fixation method of passenger's body reasonably becomes possible.

In this study, the development of the method to estimate the dynamic behavior of a seated passenger's body under the collision impact using the explicit FE method which is suitable for the estimation of transient response behavior is described. Authors have studied this problem by using the two dimensional model for the problem of the head-on collision. Afterwards, a three dimensional model has been newly developed from the necessity for the approach of not only the head-on collision but also a angled collision. For two dimension model, the reduction of simulation time is enabled by reducing the degree of freedom of the model. For the three dimensional model, the degrees of freedom of the human model is also largely reduced by using the concept of unit which consists from beam elements and solid elements.

To reproduce the movement of the human body accurately, the joint which rotates under a constant torque is adopted. The sizes and the mass distributions of the human body model are decided based on those of aged women who are dangerous to fail their bones in the falling accident.

The floor plate that imitated the ship's hull is made and the seat is fixed to the floor plate to reproduce the impact when the high speed ship collided with the quay.

The collision analysis is divided into two stages. Acceleration of gravity is added to the passenger, the seat and the floor plate to make the passenger be seated at the first analysis. Based on the converged solutions of the first analysis, initial velocity is applied to the passenger, the seat and the floor, to force the floor to collide with the quay for the reproduction of the response of the human body at collision. There are factors which effect on the human body's behavior at the time of ship collision. They are direction of collision, velocity of collision, the handrails of the seat and the back rest height of the seat. In this study, the effects of these factors are examined through a series of numerical simulation.

SIMULATION MODEL

The model which employed in this paper consists from 3 parts. The first part is a three dimensional FE model of a human body. The human body model is used to reproduce the transient behavior of actual human body at collision. The second part is a ship body with two seats on the floor arranged fore and aft. The ship body is used to carry the human body model with the seats at the relative velocity of collision, and reproduce the movement of the ship after collision. The seat supports the human body and generates the reactive force to the human body at the time of contact. The third part is a quay with which the ship body collides. The quay generates reactive force to the ship body at the time of collision. The whole model with a colliding angle of 30 degrees is shown in Fig.1 and its major sizes are shown in Fig.2.
The human body model is shown in Fig.3 Sizes of the human body are decided to be the average of Japanese aged female based on the AIST (National Institute of Advanced Industrial Science and Technology Japan) database of human body sizes. Major sizes of the human body model are shown in fig.4. The human body model is composed by 12 units. The concept of unit is used to make the model generation easier. The mass distribution of the human body is decided according to the mass ratio of the human body, and the mass of each unit is shown in table 1. The bone diameters of each unit are also shown in table 1. The joint connects two units, allowing rotation movement under the certain torque values. A typical unit is shown in fig.5. Each unit has hexahedron solid elements at the ends of beam elements. Solid elements represent soft tissue which transmits the external force applied on its surface. Beam elements represent bones which support whole unit structure. Each joint is set to rotate under the certain value of applied torque between the limit angles as shown in fig.6 to imitate the

![Figure 1 The whole model in case of oblique collision](image1)

![Figure 2 Major scantlings of the whole model (mm)](image2)

![Figure 3 The human body model](image3)

![Figure 4 Major sizes of the human body model](image4)

![Table 1 Mass distribution and bone diameters](table1)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Mass (kg)</th>
<th>Bone Diameter do(mm)</th>
<th>di(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>4.9</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>Humerus</td>
<td>2.9</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>Forearm</td>
<td>2.8</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>Chest</td>
<td>8.5</td>
<td>60</td>
<td>10</td>
</tr>
<tr>
<td>Abdomen</td>
<td>5.6</td>
<td>60</td>
<td>10</td>
</tr>
<tr>
<td>Hip</td>
<td>6.4</td>
<td>60</td>
<td>10</td>
</tr>
<tr>
<td>Thigh</td>
<td>12.5</td>
<td>40</td>
<td>10</td>
</tr>
<tr>
<td>Leg</td>
<td>5.9</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>49.5</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Figure 5 Unit structure and joint between units](image5)

![Figure 6 Typical joint rotation angle and required torque](image6)
actual joint behavior. At the time when a torque is applied, the rotation angle increases according to the applied torque value. When the torque value reaches a preset value, the joint keeps rotating under the constant torque value until the joint reaches the limit angle. The torque values and limit angles for each joint are shown in table 2. The FE model of human body has 674 nodes and 340 elements.

The ship body model is just a flat floor with two seats on it. It is used to carry the human body with two seats against a quay and transmit the force at collision to the human body. The shape of the floor model is made to be used for various colliding angles. The colliding angle of head on collision is defined as 0 degree, and side collision is defined as 90 degrees.

The foremost part of the ship body model which collides with the quay is made to have different material properties to represent the shock-absorbing effects of the crushing bow. The thickness of the floor is set to 30mm. The major scantlings of the tandem seats with high back support and armrests are shown in fig. 7. Four kinds of seats are used for the simulation as shown in table 3. They are characterized by the back support height and existence of armrests. The typical two kinds of seats are shown in fig. 8. Both of the cushions at seat bottom and seat back are supported by the frame made of aluminum sheets. The aluminum sheets have the equivalent stiffness to the 10mm thick aluminum sheet.

The material properties of each part are shown in table 4. There are five parameters considered in this paper. They are colliding angle, colliding velocity, height of seat back support, existence of armrests and bow stiffness. The conditions for the numerical simulation are summarized in table 5. The standard value of colliding velocity for the series of numerical simulation is set as 5m/s (9.72kts). And two kinds of velocities are employed to estimate the effects of colliding velocity. The standard colliding angle is set as 0 degree (head on collision). And three other angles (30, 60 and 90 degrees) are employed to estimate the effects of colliding angle on the dynamic behavior of the passenger. The main seat model is the seat with low height back support and without armrests. It is because this model shows largest movement of the passenger. Based on this model, the seats with high back support or the seats with armrests are employed for the simulation. The effects of the bow stiffness are also considered by using the normal and soft bow stiffness.
stiffness variations.

PROCEDURE OF SIMULATION

The numerical simulation is divided into two steps. At first, gravity load is applied. Initial stress within the human body is generated at the first step. The human body contacts with the seat bottom cushion and the seat back support under the gravity load. As the gravity load is applied suddenly, strong vibration is generated both within the human body and within the ship model. To obtain the converged solution within a short time, artificial dumping is introduced as a practice of solution technique. The converged solution is saved and used in the second step as a part of initial condition.

Then, initial velocity and gravity load are applied to the human body and the ship body model including two seats, based on the solution of the first step. The ship body collides with the quay and rebounds to the opposite direction. The human body moves at the same velocity with the ship, at first. After the time of collision, the ship body and the seats change their direction while the human body keeps its velocity and direction. As a result, the human body comes into contact with the back surface of back support of the front seat. In case of oblique collision, the direction of initial velocity and the position of the quay are changed.

SIMULATION RESULTS

Only the results of the second step simulation are presented. An example of dynamic behavior of a passenger is shown in fig.9. This is the case that the ship collides with the quay at the angle of 60 degrees with the velocity of 5m/s. The passenger is seated on the seat of low back height without armrests (LW). At first, the initial velocity of 5m/s is given to both the ship body and the passenger's body, to the
In case of 0 degree of colliding angle, the passenger’s knee comes in contact with the back surface of the front seat. As the distance from the right knee to the center of gravity of the passenger's body is not so small, the reactive force on the right knee rotates the human body in right direction around her vertical axis and fore direction around her horizontal axis at a time. The human body moves to fore and left direction with rightward and forward rotation. As a result of these movements, the passenger's body moves from her original seat position and the back of her head is hit on the floor after falling down.

The dynamic behavior of a passenger's body seated on the LW seat at the colliding velocity of 5m/s is shown in Fig.10 for 0 degree of colliding angle, and Fig.11 for 90 degrees of colliding angle. In these figures movements at the bottom of the left foot and at the top of the head are shown.

In case of 0 degree of colliding angle, the passenger's knee comes in contact with the back surface of front seat and the passenger's body rebounds and jumps up for all cases. Then the body drops on the floor from her back. The passenger's body drops to the original seated position after the collision in the cases of colliding velocities of 2.5m/s and 5.0m/s. The falling behaviors are largely different between the two cases with the colliding velocity of 5.0m/s and 7.5m/s, whereas the magnitudes of jump up height are almost the same. Both forward displacement and transverse displacement of the top of head show large differences due to the velocity. Both of these displacements increase their values proportionally to the value of velocity.

In case of 90 degrees of colliding angle, the passenger's body moves to the left and the bottom of foot contacts with the floor in front of the passenger's body. As results, the passenger's body falls down on the floor, rotating to the right in all cases. The passenger's hip contacts with the floor while keeping her pose in the case of colliding velocity of 2.5m/s, and slightly rotates to the rightward. In case of colliding velocity of 5.0m/s, the rightward rotation of the body increases by the contact of the foot and the floor. The passenger's body moves to the left while keeping her legs down. Then the right foot contacts with the floor and the body rotates around the right foot.

Finally the body collides with the floor, keeping her right side of the body down. In case of colliding velocity of 7.5m/s, the rightward rotation of the body is small. And the hip collides with the floor from her back.

The dynamic behavior of a passenger's body seated on the LW seat at the colliding velocity of 5m/s with various colliding angles (0, 30, 60 and 90 degrees) are shown in Fig.12 to see the effects of the colliding angle. The results of colliding angles of 0 and 90 degrees are already shown.

In case of 30 degrees of colliding angle, the passenger's body...
moves to the front and left by the applied initial velocity. Only the right knee collides with the back surface of front seat. Then the initiated reaction force causes forward and rightward rotation to the passenger's body. Finally the passenger's body collides with the floor, keeping her head down. In case of 60 degrees of colliding angle, the passenger's body moves almost the same to that of 30 degrees. As the transverse component of the initial velocity increases, the rightward torque which is generated by the contact with the right knee and the back surface of the front seat, increases. Finally, the body collides with the floor, at her right side back surface of the head.

The dynamic behavior of a passenger's body seated on the four kinds of seats (HA, HW, LA and LW) at the colliding velocity of 5m/s with the colliding angle of 90 degrees is shown in Fig.13 to see the effects of the height of back support and the existence of the armrests.

The dynamic behavior of the passenger's body on the seat with armrests and that on the seat without armrests are very different. In case of HA seat, with high back support and armrests, the passenger's body keeps its position on the seat during the collision. At first, the passenger's right side of the hip collides with the armrest, and the body rebounds and inclines to the left until it almost reaches to the horizontal level. Then, the left humerus collides with the armrest and the body returns to its original position.

In case of LA seat, with low back support and armrests, the passenger's body falls to the right from the seat. At first, the passenger's right and left hips collide with the armrests. Then, the body jumps up. And the body drops on the right side armrest from its hips. Finally, the body turns to the right and falls to the right from the seat.

In case of LW seat, with low back support without armrests, the passenger's body collides with the floor at her hips. At first, the passenger's body moves to the left, contacting her foot to the floor. The body begins to rotate rightward and her hips collide with the floor from the back.

In case of HW seat, with high back support without armrests, the passenger's body collides with the floor at her hips. At first, the passenger's body moves to the left, contacting her foot to the floor. The body rotates to the right slightly, and her right hip collides with the floor.

The dynamic behavior of a passenger's body seated on the LW seat at the colliding velocity of 5m/s with the colliding angle of 0 degrees is shown in Fig.14 to see the effects of the bow stiffness. There are very small differences between these two cases, with small bow stiffness (SB) and with normal bow stiffness (RB). In SB case, the passenger's body tends to rotate forward a little more than RB case.

Fig. 13 Effects of seat back height and existence of armrests on the time history of human body movement in case of side collision of LW model

Fig. 14 Effects of bow stiffness on the time history of human body movement in case of right angle collision of LW model
CONSIDERATIONS AND CONCLUSIONS

A series of numerical simulation is carried out to estimate the dynamic behavior of a seated passenger of a high speed ship at collision, changing the colliding velocity, the colliding angle, the height of seat back support, existence of the armrests and bow stiffness. The effects of these factors on the falling behavior of the seated passenger are obtained as follows.

- The effects of the colliding velocity in case of the head on collision are observed. The falling behavior from the seat is observed more frequently according to the increase of the velocity. It is caused by the collision between the passenger's body and the front seat. It is thought that the seatbelt is effective for the protection of the body in this case.

- The effects of the colliding angle are remarkable in case of the seat without armrests. With the colliding angle more than 30 degrees, the passenger's body moves from the seat and collides with the floor at her hips or at her back surface of the head.

- The effects of the height of seat back support are negligible. It may be because the upper part of the seat back support in these cases does not effectively support the body at the time of collision.

- The effects of the armrests are significant in cases of angled collision more than 30 degrees. The existence of the armrests protects the passenger's body from the falling down to the floor, or from the collision to the floor.

- The effects of bow stiffness are not clearly observed. It may be because the reduction of bow stiffness does not create remarkable cushion effects.

When we think of the passenger's damage, the relative velocity just before the collision between the body and the floor has strong relation to the passenger's damage. The relative velocity is deeply related to the rotation motion of the body. So, it seems to be important to estimate the rotation motion caused by the collisions, such as contact between the human body and the ship body.

REFERENCES