MODELING AND COMPUTER ANIMATION OF DAMAGE STABILITY

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ABSTRACT

A mathematical model and a computer animation of a damaged ship in beam seas are introduced. The model combines a method developed by Ursell and Tasai [1] for calculation of Diffraction and Radiation forces and moments, a method developed by Hamamoto [2] for calculation Froude-Krylov forces and moments and a method developed by Vassalos [3] for calculation the amount of water on deck. Based on the model as well as the computer animation technique developed by Hasegawa [4], a computer animation for damage stability was realized.

1. INTRODUCTION

Since the capsize of Herald of Free Enterprise and Estonia, two kinds of RO/RO passengers ships, which killed many people, the discussion on the stability of that kind of ships came into a surface. Some researches on this topic, especially on the problems of damage stability, have been carried out in many countries. Several problems of the damaged RO/RO ships are concerned with the following points:

- Flooding or accumulated water on bulkhead deck caused by waves
- Dynamic of the accumulated water and its effects to ship motions

The two points above affect the stability of the RO/RO ships. However, how much they affect the stability can not be determined until now. Some researches show that when a damage occurs there are complicated effects to the ship stability, not only hydrostatic effects but also hydrodynamic effects. To predict these effects, simulations on the damage ship are important. This paper discusses the two points in detail, by establishing a mathematical model with three degree of freedoms, those are sway, heave and roll motions. In this model, radiation and diffraction forces and moments are approximately calculated based on the theory developed by Ursell and Tasai [1] in still water, however Froude-Krylov forces and moments are calculated by taking into account changes of submerged hull in waves, based on a method developed by Hamamoto [2]. Moreover, flooding into a damaged compartment is calculated based on the simple model of Vassalos [3]. Combining these three methods, some simulations of a damaged RO/RO passenger ship were carried out. Furthermore, to clarify the results qualitatively, so that every occurrence in each part of the ship can be seen easily, a 3D animation of the damaged ship was realized.

2. MATHEMATICAL MODEL OF A DAMAGED SHIP

General Equation of Motion for a Damaged Ship

A damaged ship with progressive flooding can be regarded as one dynamic system. Equations of motions for the flooded ship can be generally expressed in vector forms as follows:

$$\mathbf{F} = \frac{d}{dt}\left[m_s \mathbf{V}_{Gs}\right] + \frac{d}{dt}\left[m_w(t)\mathbf{V}_{Gw}\right] \tag{1}$$

$$\mathbf{M}_0 = \frac{d}{dt}\iiint_V \mathbf{x} \times \rho_s \mathbf{V} dV + \frac{d}{dt}\left[\mathbf{x}_{Gw} \times m_w(t)\mathbf{V}_{Gw}\right] \tag{2}$$

where $\mathbf{F}$ is a vector of forces, $\mathbf{M}_0$ vector of moments, m_s ship mass, $m_w(t)$ mass of accumulated water which varies with time, $\mathbf{V}_{Gs}$ velocity of the center of gravity, $\mathbf{V}_{Gw}$ velocity of the center of the accumulated water, $\mathbf{x}$ vector position, $\mathbf{x}_{Gw}$ vector position of the accumulated water. Considering three dominant motions in beam seas, heave, way and roll motions, in earth axis systems, the equations of motions can be written in scalar forms as the following:

$$m_s\ddot{\eta} + \dot{m}_w(\dot{\eta} + \dot{y}_{Gw}) + m_w(\ddot{\eta} + \ddot{y}_{Gw}) = Y \tag{3}$$

$$m_s\ddot{\zeta} + \dot{m}_w(\dot{\zeta} + \dot{z}_{Gw}) + m_w(\ddot{\zeta} + \ddot{z}_{Gw}) = Z \tag{4}$$

$$\begin{aligned} I_{xx}\ddot{\phi} &+ \dot{m}_w(y_{Gw}\dot{\zeta} - z_{Gw}\dot{\eta} + y_{Gw}\dot{z}_{Gw} - z_{Gw}\dot{y}_{Gw}) \\ &+ m_w(\dot{y}_{Gw}\dot{\zeta} - \dot{z}_{Gw}\dot{\eta} + y_{Gw}\ddot{\zeta} - z_{Gw}\ddot{\eta} + y_{Gw}\ddot{z}_{Gw} - z_{Gw}\ddot{y}_{Gw}) = K \end{aligned} \tag{5}$$

Here, Y and Z are total forces of sway and heave acting on a hull and K is total roll moment. These forces and moment are considered consist of Frode-Krylov, radiation and diffraction parts. The radiation and diffraction forces and moments are calculated by using Ursell-Tasai method [1] for sectional Lewis forms in still water. The Froude-Krylov forces and moment are calculated by taking into account variations of submerged hull in waves, The forces and moments are given as follows:

$$\begin{aligned} Y = &-\int_L m_y(x)dx\,\ddot{\eta} - \int_L m_y(x)l_n' dx\,\ddot{\phi} - \int_L n_y(x)dx\,\dot{\eta} - \int_L n_y(x)l_n' dx\,\dot{\phi} \\ &- \int_L m_y(x)dx\,\dot{v}_y\Big|_{z=d/2}^{y=0} - \int_L n_y(x)dx\,v_y\Big|_{z=d/2}^{y=0} + Y_{FK} + Y_{Drift} + Y_{current} \end{aligned} \tag{6}$$

$$Z = -\int_L m_Z(x)dx\,\ddot{\zeta} - \int_L n_Z(x)dx\,\dot{\zeta} - a\cos\omega_e t\int_L e^{-kd}\omega^2 m_Z(x)dx$$
$$- a\sin\omega_e t\int_L e^{-kd}\omega n_Z(x)dx + Z_{FK} + W_{flood} \tag{7}$$

$$K = -J_{xx}\ddot{\phi} - N\dot{\phi} + K_{FK} + y'_{Gw}W_{flood} \tag{8}$$

where $m_y(x)$ and $m_z(x)$ are sectional added masses of sway and heave, $n_y(x)$ and $n_z(x)$ sectional damping coefficients of sway and heave, l'_n and l'_w moment levers, y'_{Gw} and z'_{Gw} centers of accumulated water in the earth axis coordinate systems, W_{flood} weight of the accumulated water, ω_e encounter frequency, v_y wave velocity in η direction

Modeling Water Ingress into a Damaged Ship

Flooding into a damaged compartment is a complex phenomenon. One way to describe this phenomenon is by using a CFD technique. However, the technique is not completed yet to solve such sophisticated phenomenon. Vassalos et.al [3] proposed a simplified method. According to this method, water ingress and egress depend on water level inside and outside of the damaged compartment. The value of accumulated water can be estimated by the following integration

$$\dot{m}_W = K\int_{Damage} sign(h_{out} - h_{in})\sqrt{2g\left|h_{out} - h_{in}\right|}dA \tag{9}$$

where h_{out} is water level outside the flooded compartment, h_{in} water level inside the flooded compartment measured from the lower part of an opening.
In this model all difficult problems that influence the phenomenon such as configuration of opening area, wave condition, etc. are concentrated in the flooding coefficient K. In this paper $K = 0.7$, which was obtained from experiments of a damaged RO/RO ship in University of Strathclyde is used.

Residual Stability and Its Calculation

Residual stability indicates static stability to affect a ship hull after flooding. This stability is the most important factor to a damaged stability because this stability is used as a standard in damaged stability regulations. The stability can be calculated by using an added math method, where the accumulated water in the damaged compartment can be regarded as a cargo whose weight is the same as the weight of the accumulated water. From Fig.1, the residual stability can be calculated as follows:

$$GZ_{Damage} = y'_B - y'_{GG'} = y'_B - \frac{y'_{Gw}W_{flood}}{W + W_{flood}} \tag{10}$$

where W is ship weight

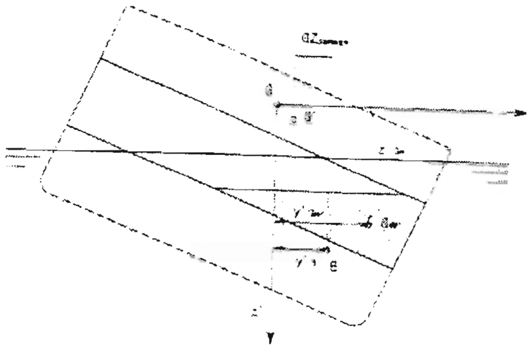


Fig.1. Calculation of residual stability of a damaged ship

The center of each section of the ship hull is calculated by Hamamoto method. The method considered that heave and pitch of the ship are in balance so that they satisfy the following condition:

$$Z'_{FK} + W + W_{Flood} = 0 \quad (11)$$

$$M'_{FK} + x'_{Gw} W_{Flood} = 0 \quad (12)$$

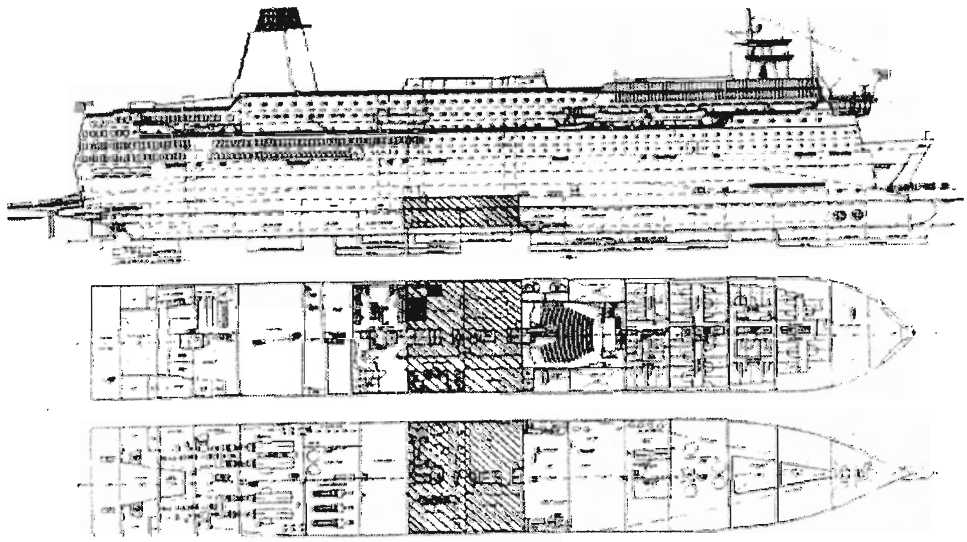


Fig.2. RO/RO passenger ship used in simulations

The heave displacement, ζ_G and pitch angle, θ, are calculated numerically by using Newton-Raphson method. Some results of residual stability calculations of a wall sided RO/RO passenger ship, in Fig.2, are shown in Fig.3 for GM=1.5m, 1.76m and 2.0m in case of flooding at two watertight compartments under bulkhead deck. The dash lines show the stability before damages and the solid lines show the stability after damages. All these results satisfy the regulations of SOLAS 90 and SOLAS 92, since the ranges of positive GZ curves for the three cases are more than 15 degrees, the areas under the curves are more than 0.015 m-rad and the maximum GZs are more than 0.1m. Fig.4 shows the residual stability when flooding occurs at two watertight compartments above bulkhead deck. In case of GM=1.5m and 1.76m do not satisfy the regulations but for GM=2.0m the regulations are satisfied.

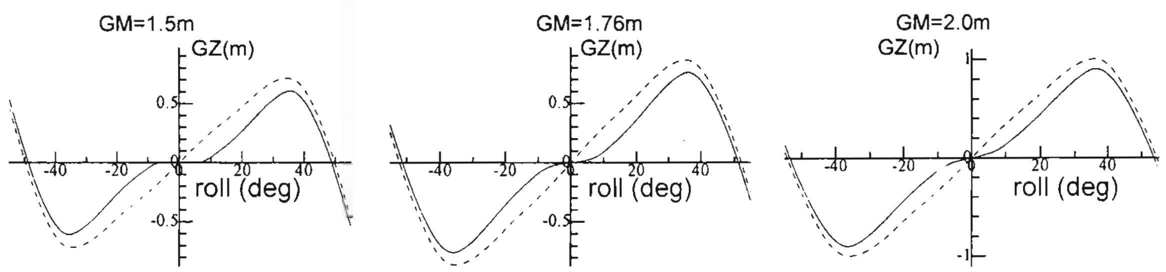


Fig.3. Residual stability in case of flooding into two compartments

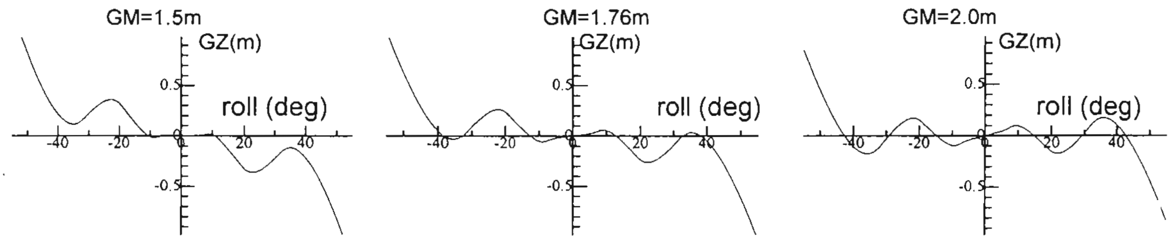


Fig.4. Residual stability in case of flooding into car deck

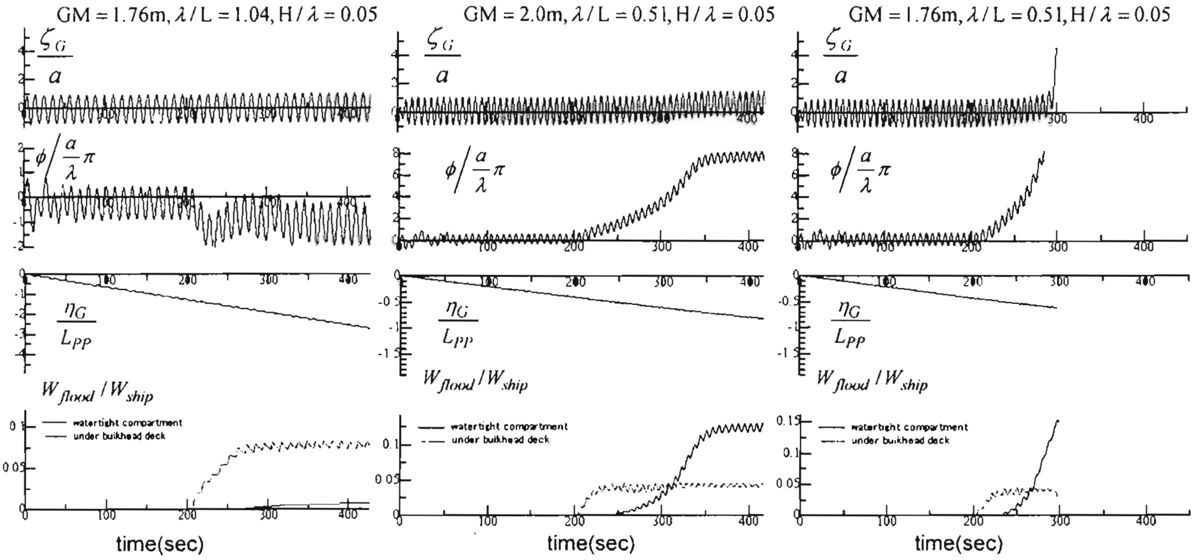
3. SIMULATION OF A DAMAGED SHIP

Selected Model and Capsizing Scenario

In this paper, a model of a wall sided RO/RO passenger ship like Estonia as in Fig.2, which capsized in 1994, was used in simulations. Based on IMO regulations for improving the safety of a ship, a capsizing scenario of the passenger ship was selected. The scenario is that there are two openings, which become the cause of flooding. The flooding, into watertight compartments under the bulkhead deck and a car deck above the bulkhead deck, occurs simultaneously and it ends with capsizing.

Result of Simulation

Simulations of the damage stability were carried out by using Runge-Kutta method for 500 seconds. For the first 200 seconds of time simulation is concerned with intact stability and the last 300 seconds damages and flooding occur. There are three steady state conditions of the ship after flooding, the ship may heel to the weather side, she may heel to the lee side and she may capsize. In case of the ship heels to the lee side, the opening position will be higher than the water surface, the flooding on the bulkhead deck does not occur. For this case, capsizing never occurs. Time series of this case are shown in Fig.6a. On the contrary, when the ship heels to the weather side, the opening is lower than the water surface so that flooding on the bulkhead deck occurs. This condition may end with capsizing or without capsizing. In the case of the ship heels to weather side without capsizing, there are possible two reasons. The first one is the heel moment of accumulated water is in balance with the moment inclination of the ship. This balance condition actually has the same meaning with the calculation of the GZ curves. The second reason is the water level of the accumulated water is same as the level of wave surface. This means that the ship will heel until $\mathrm{H_d}$, the difference between h_{out} and h_{in}, becomes zero. However, in waves, this condition may never be reached since the level of water surface always changes with time.



(a) heel to lee side (b) heel to weather side (c) capsize

Fig.6. Time history of the damaged RO/RO ship motion in waves

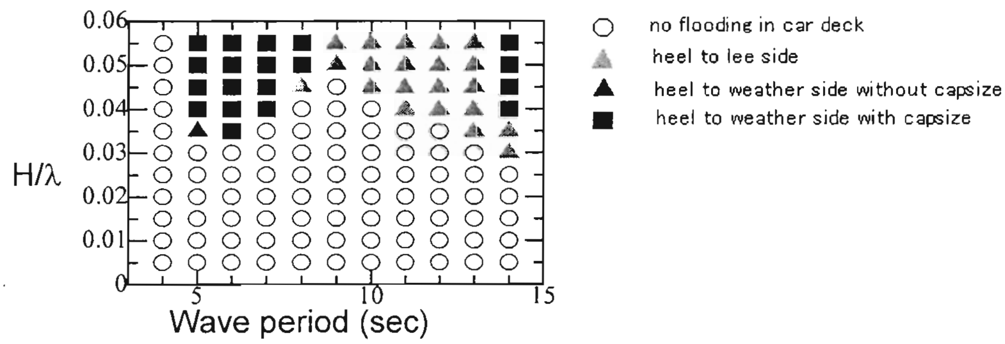


Fig.7. Steady state condition of the damaged RO/RO ship with GM=1.76m

This parameter becomes an important factor in studying of damage stability of RO/RO vessels. Time series of this case are shown in Fig.6b. In the case of the ship heels to weather side and ends with capsizing, the possible reason for this case is the roll moment of waves larger than restoring moment of the ship. When the ship heels, the water enter into flooding compartments, this makes the restoring moment becomes worse, if the ship does not have the intact restoring moment large enough, while the moment from waves is large, the ship will capsize. Time series for this case are shown in Fig.6c. In Fig.6b for GM=2.0m the ship does not capsize, while for GM=1.76m, in Fig.6c, the ship capsizes. Fig.7 shows several steady states from the simulations for GM=1.76m. The blank circles show the flooding does not occur in car deck. The dot triangles show the ship heels to lee side, the dark triangles show the ship heels to weather side and the dark rectangular show the ship capsizes as function of wave steepness and wave period.

4. COMPUTER ANIMATION OF A DAMAGED SHIP

The results obtained from simulation, as in Fig.6, qualitatively, may not give detail understanding on the changes of accumulated water inside the flooding compartments, flooding areas, ship motions in many degrees of freedoms, interaction between waves and accumulated water in the damaged compartments and interaction between waves and the ship motions. Considering the important of such qualitative understanding, we made a 3 dimensional animation of a damaged ship in waves. The animation was made based on the diagram in Fig.8. The animation constitutes of three separate programs, a wave making program, a ship motion program and a 3D animation program.

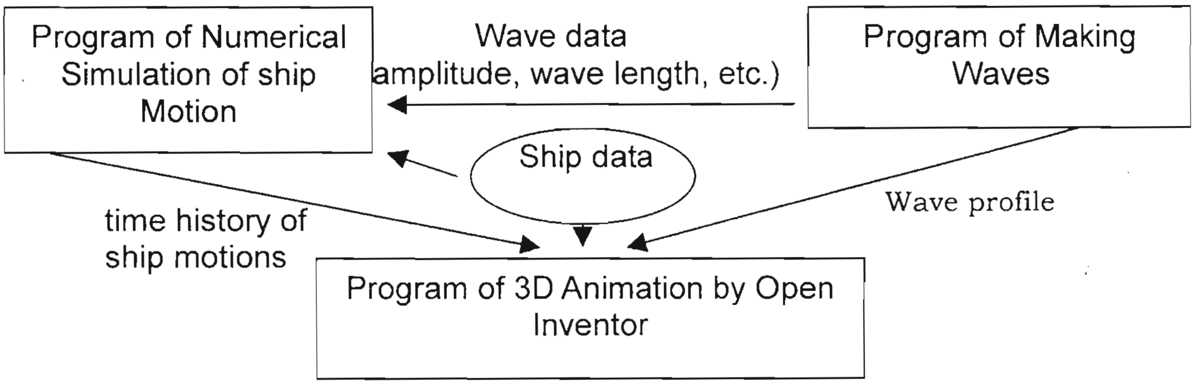


Fig.8. Diagram of 3D animation program

The first program is to make a regular wave profile to be used in the 3D animation program as well as in the ship motion program. The ship motion program calculates ship motions before flooding and when the flooding occurs. This program needs some inputs such as wave data from the first program and ship data, such as ship principal dimension, offset data, etc. The results of this program are time series of ship motions, these are roll motion, heave motion, sway motion and time series of accumulated water in flooded area as done in the simulations above. All these time series, ship data and time series of wave profile are inputted to the third program, to be realized as

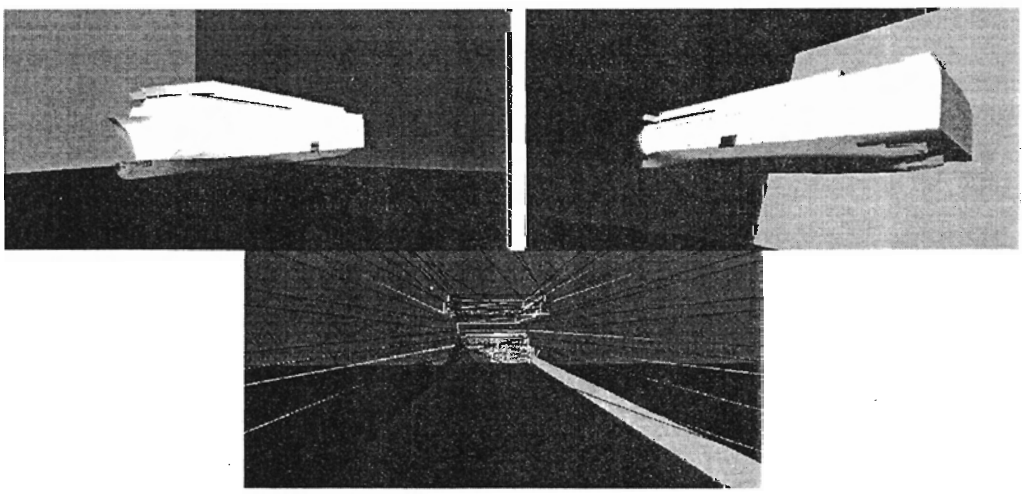


Fig.9. 3D animation of the damaged RO/RO ship in waves

an animation of a damaged ship in waves. Some results of the animation program are shown in Fig.9.

Specification of the Animation

This animation has some important specifications below:
- To show ship motions, waves and accumulated water inside the flooded compartments at the same time
- To show real time in 10 frame/second
- A point of view can be moved freely with a mouse during the animation, so that one may see what happens in every part of the ship during the animation

Development Environment

Hardware
- The Alpha computer 500 MHz
- The graphic board corresponding to Open GL

Software
- Windows NT 4.0
- Visual C++ version 4.0 (RISC Edition)
- Open Inventor ver 2.1.0

5. CONCLUSION

- A mathematical model of damaged RO/RO passenger ships in waves has been made and 3D animation of the damaged ship has been realized.
- Three steady state conditions of the damaged ship are identified, the ship heels to lee side, heels to weather side without capsizing and heels to weather side and ends with capsizing.

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