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# A Ship Motion Simulation System

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**Abstract** In this article, efficient computational models for ship motions are presented. These models are used to simulate ship movements in real time. Compared with traditional approaches, our method possesses the ability to cope with different ship shapes, engines, and sea conditions without the loss of efficiency. Based on our models, we create a ship motion simulation system for both entertainment and educational applications. Our system assist users to learn the motions of a ship when encountering waves, currents, and winds. Users can adjust engine powers, rudders, and other ship facilities via a graphical user interface to create their own ship models. They can also change the environment by altering wave frequencies, wave amplitudes, wave directions, currents, and winds. Therefore, numerous combinations of ships and the environment are generated and the learning becomes more amusing. In our system, a ship is treated as a rigid body floating on the sea surface. Its motions compose of six degrees of freedom: pitch, heave, roll, surge, sway, and yaw. These motions are divided into two categories. The first three movements are induced by sea waves, and the last three ones are caused by propellers, rudders, currents, and winds. Based on Newton's laws and other basic physics motion models, we deduce algorithms to compute the magnitudes of the motions. Our methods can be carried out in real time and possess high fidelity. According to ship theory, the net effects of external forces on the ship hull depends on the ship shape. Therefore, the behaviors of the ship are influenced by its shape. To enhance our physics models, we classify ships into three basic types. They are flat ships, thin ships, and slender ships. Each type of ship is associated with some predefined parameters to specify their characteristics. Users can tune ship behaviors by varying the parameters even though they have only a little knowledge of ship theory.

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**Key words** Ship motions, physics engine, computer games, simulation

## 1 Introduction

Ships have been used in traveling, trading, and war for thousands of years. They are necessities in human societies. Simulating ship motions is an important issue in education systems and entertainment industries. Ship motion simulation systems help students and game players to learn the maneuver of ships under different sea conditions. The procedures for ship motion simulation can be attributed to two categories. In academic institutes, complicated mathematical equations are solved to calculate ship motions. This type of computation requires extensive computing resources and usually produces massive numerical results which need special expertise to comprehend. The process itself is always boring to ordinary people. Learners may quickly lose their interests to know more about ship maneuvering. Therefore, this type of methods is inadequate for education and entertainment. On the other hand, in computer game industries, simple physical models are used to simulate ship motions. The computation is fast and the results can resemble some simplest ship movements. However, these models can not simulate complicate ship motions and they lack the flexibility to cope with different ship models and sea conditions.

Virtual reality (VR) techniques have long been used to create virtual scenarios for driving training and games. As pointed out in [5, 9, 18], a good VR system must possess the following components:

- a physics engine for computing the vehicle dynamics,
- a virtual environment database,
- efficient graphics procedures for scene rendering,
- integration procedures connecting the physics engine, the visual systems, and the user interface.

Compared with other components, the physics engine module is immature in most VR systems. A physics engine must calculate the behaviors of moving objects as realistic as possible under a severe constraint of time. Therefore, pursuing accurate numerical solutions is impractical. Instead, simplified but physically meaningful models should be adopted for simulating object motions. In this article, we present effective mathematical models ship motions. Our methods can be

employed to develop physics engines for ship handling simulation systems, computer games, and other maritime applications. Based on the models, we create a simulation program which can be directly used in the physics classes on floating body motions and the development of computer games.

### 1.1 Related Work of Ship Motion Simulation

The hydro-dynamics for ship motions are difficult to solve. Most numerical algorithms are based on *strip theory* developed in [8, 15]. However, it takes hours to produce a set of accurate solutions for just one or two motions by using modern computers [1]. These numerical procedures are impractical for real time simulation. Others use simplified models for the estimation of ship motions. In [16], Kalman filter techniques are utilized in ship motion estimation. However, their method requires the knowledge of the ship, and if the ship parameters are unavailable their method is not applicable. In [10], an improved method is proposed. It requires less information about the ship, though the accuracy of the method still depends on the availability of ship parameters. In computer game design, ship models are fabricated. No real data can be retrieved. This method is not convenient either. In [18], Zhang et al. develop mathematical models for ship motions. They estimate the total forces acting on the ship first, then based on Newton's law, they deduce first order differential equations to model the relation between forces and accelerations. The equations are solved by using Runge-Kutta method. Since their applications focus on handling ships inside or near harbor areas, only the physics models for surge, sway, and yaw are given.

Another work is presented in [4]. The authors propose wave models based on the work of [6]. Then they compute heave, pitch, and roll of a ship by using sea surface height under the ship. For estimating pitch and roll, the tangent plane of sea surface is computed first. Then the ship is rotated such that its orientation is aligned with the tangent plane. Their mathematical models are too simplified. Since only the sea surface height is taken into consideration, ships of different shapes will produce the same behavior if the wave condition is the same. However, a war ship and a craft do not share the same maneuvering characteristics. Thus their methods are not flexible enough to simulate the behaviors of different ship models. Another research trend is to predict ship motions based on the previous status of the ship. In [19], ship status and motions at previous steps are recorded and a tensor field is created by using these data. Then the eigen values and eigen vectors of the tensor field are computed and a minor component analysis method is used for predicting ship motions. This method is useful for short-term motion prediction but not suitable for simulating ship motions. There are also some commercial software available for ship motion simulation, for example, *Nord-Control* and *Transas*. These systems are usually expensive and complicated. Users need a lot of maritime knowledge and training to operate them. The other disadvantage is that they are closed systems. It is not easy for end-users to add their ship models or software modules into these systems.

### 1.2 Overview

In this paper, a simulation and visualization system is presented to simulate ship motions for education and games. Users can use our system as a tool for learning ship motions or they can utilize its numerical modules to develop computer games or more advanced simulation systems. Since the calculation of ship motion is difficult, three basic assumptions are adopted in our system to simplify the computation:

1. A ship is a rigid body. Its elastic deformation is neglected.
2. The sea is deep and sea waves are comprised with sinusoidal waves of different frequencies, speeds, and angles.
3. The magnitudes of motions are relatively small. The six degrees of freedom can be calculated separately and superimposed to generate the overall movement of the ship.

Under these constraints, the physics models of ship motion are greatly simplified and a real-time simulation for ship motion is obtained.

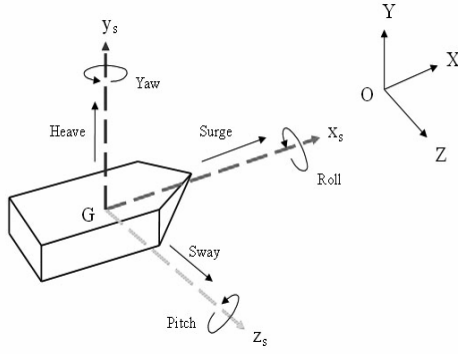
This paper is organized as follows: In Section 2, fundamental knowledge and definitions of ship motions are introduced. Therefore, more advanced material can be presented in the following sections. In Section 3, the mathematical models for heave, pitch, and roll are presented. These motions are caused by sea waves. The numerical methods of estimating other three motions are deduced in Section 4. Implementation details and ship characteristics are discussed in Section 5. Visualization and testing results are shown in Section 6 and followed by conclusion and future work.

## 2 Fundamentals

### 2.1 Coordinate system and ship motions

To designated directions and positions, two coordinate systems are defined in our system. The first one is the world coordinate system whose origin is fixed at a position on the sea surface. The sea surface is spanned by the  $X$  and  $Z$  axes, and the  $Y$  axis points vertically. The second coordinate system is attached to the ship. It is moving with the ship. The origin,  $G$ , is at the geometrical center of the ship. The  $X_s$  is aimed at the forward direction of the ship. The  $Z_s$  axis is pointed to the starboard (right hand side) of the ship, and the  $Y_s$  axis directs upward. The two coordinates systems are shown in Figure 1.

When floating on the sea surface, a ship possesses six degrees of freedom. The six ship motions are shown in Figure 1. They are heave, pitch, roll, surge, sway, and yaw. In the view point of the local coordinate system of the ship, surge, heave, and sway are translate motions in  $X_s$ ,  $Y_s$ , and  $Z_s$  directions while roll, yaw, and pitch are rotations about  $X_s$ ,  $Y_s$ , and  $Z_s$  axes. However, based on computational aspects, we divide the six motions into another two categories. The first category include the motions induced by waves. They are heave, pitch, and roll. The second group of motions is caused by propellers, rudders, currents, and winds. Surge, sway, and yaw belong to this group. The motions of the first group do not change the ship position in the  $X - Z$  plane. They influence



**Fig. 1** The coordinate systems and six degree of freedom of ship motion

the ship's *posture* only. The course of a ship is decided by surge, sway, and yaw. Totally, these six motions determine the trajectory and vibration of the ship on the sea surface.

## 2.2 Ship classification

The ship shape is an important factor for ship motions. For example, a warship are less sensitive to sea waves than a small fishing boat. We classify ships into three basic types based on their lengths  $L$ , widths  $B$ , drafts  $D$  and the wave length  $\lambda$ . The first type of ship is the *thin ships* [12]. Their shapes satisfy the following constraints:

$$B \ll L, \frac{D}{\lambda} \cong \frac{D}{L}.$$

For example, a fishing boat is a thin ship. The second type is *flat ships* [7]. The criteria for a flat ship are:

$$D \ll L, \frac{B}{\lambda} \cong \frac{B}{L}.$$

A flat has a shallow draft and its length and breadth are of the same order. It is very sensitive to the variation of sea surface. A raft is a flat ship according to these criteria. The last type is *slender ships* [17]. Their shapes meet the following conditions:

$$B \ll L, D \ll L, \lambda \cong L.$$

Slender ships are the most used ships. They include, for example, war ships and cargo ships. Slender ships are narrow and their draft are deep. They are less sensitive to sea waves. Since wave length is considered in the classification, ship type is not invariant. When encountering wave of large amplitude and length, a slender ship may become a thin ship. By using this ship classification, it is easier to assign characters to ships. In our work, a mechanism is developed for specifying ship parameters via a graphical user interface. Therefore, ships' behaviors will not go wild while ships can still possess certain maneuvering characters.

## 2.3 Wave models

The wave models used in our system is based on the work of [6, 13]. To increase fidelity, we assume the sea wave is composed of multiple sinusoidal waves of different frequencies, amplitudes, and directions. Our wave model is similar to that of [11]. To model the animation of the sea surface, the sea surface is treated as a height field which can be computed by using the following equation:

$$h(x, z, t) = \sum_{i=1}^n \zeta_i \sin \frac{2\pi}{\lambda_i} ((x \cos \theta_i - z \sin \theta_i) - \omega_i t),$$

where  $\zeta_i$ ,  $\lambda_i$ , and  $\omega_i$  are the amplitude, wave length, and speed of the  $i$ -th wave respectively, and  $\theta_i$  is the angle between  $X$  axis of the world coordinate system and the incoming direction of this wave, and  $t$  is the time variable. To render the scene, a regular grid is super-imposed on the sea surface. The  $X$  and  $Z$  coordinates of the grid points are substituted into the equation to calculate the  $Y$  coordinates. Then, by using finite difference method, the gradients (normals) of the points can be computed, and the sea surface can be shaded. In previous sub-section, wave length is treated as a factor for ship classification. Though there may be multiple waves present on the sea surface, only the wave with the largest amplitude is taken into consideration for ship classification.

## 3 Motions Induced by Sea Waves

The motions induced by sea waves include heave, pitch, and roll. In ship theory literatures, these motions are regarded as oscillations with damping effects. Each motion can have an exact solution if the frequency of the wave is known and the vibration frequency of the ship in still water is available [14]. However, in our system, waves are comprised with multiple waves and ships are virtually fabricated, both information is not available. Therefore we go for other numerical procedures for computing these motions. We assume that the swellness of water under a ship causes the ship to perform these 3 movements based on Archimedes' principle. In order to measure the swellness, the heights of the sea surface has to be computed. A *moving grid* is attached with the ship as shown in Figure 2. To generate the grid, the ship body is vertically projected onto the sea surface (the  $X$ - $Z$  plane), and the bounding box of the projection is calculated. Then a uniform grid of  $L \times W$  cells is superposed on the bounding box. The grid-lines are aligned with the  $X_s$  and  $Z_s$  axes of the local coordinate system of the ship. The gap between two grid-lines is set to 1 meter. When evaluating the height field at a grid point, we assume the ship is not presented and the height field is calculated by using the wave model presented in the previous section. Once the height fields in the moving grid are computed, the swellness of the water is decided by multiplying the average height field with the area of the grid, and the force for ship motions is computed. Subtracting resistance force from the force of water, the net force is obtained, and accelerations are calculated by applying Newton's law. Then velocities are

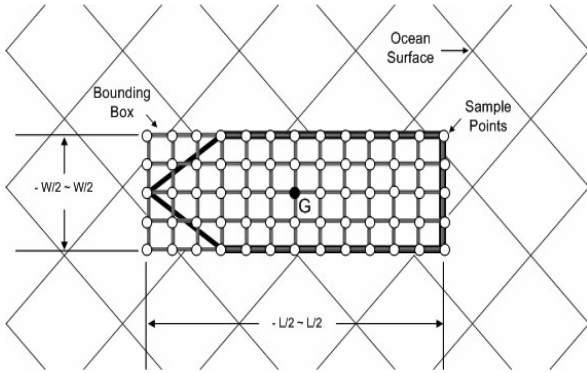


Fig. 2 The computational grid for ship motion.

updated and the magnitudes of motions are obtained by multiplying the velocities with the time step size.

### 3.1 Heave

Assume that the variation of sea surface in vertical direction produces force for heave. To calculate the vertical variation of sea surface, the average height field,  $H_a$  of the grid is computed. If the resulted height field is not zero, the swell of sea surface produces force to raise up (or pull down) the ship. We assume the force is related to the volume of water swelled under the ship. The other force for heave is the resistance of water acting on the ship hull. The resistance is the anti-force for heave. It is related to the current distance of heave and the displacement force. Since the heave distance is computed by multiplying heave velocity with time step size and the displacement force is related to the ship mass, we assume the resistance force is related to the moment of the ship. Therefore, the net force for heave is estimated by:

$$\begin{aligned} R_h &= b_h M \mathbf{v}_h, \\ H_a &= \sum_{i=-L/2}^{L/2} \sum_{j=-W/2}^{W/2} h_{i,j} / (L * W), \\ F_h &= K_h H_a A - R_h, \end{aligned}$$

where  $R_h$  is the resistance which is computed by multiplying the moment of the ship,  $M \mathbf{v}_h$ , with the resistance coefficient of water,  $b_h$ . The mass of ship is represented by  $M$  and  $\mathbf{v}_h$  is the current heave velocity. The variable  $H_a$  is the average height field, and  $h_{i,j}$  are the height fields at the grid points. The volume of the water swelled under the ship is  $H_a A$ , where  $A$  is the area of the grid. The force for heave is computed by multiplying the swelledness of water with the coefficient  $K_h$ . The net force  $F_h$  is obtained by subtracting the resistance from the force. The two coefficients,  $b_h$  and  $K_h$  are determined by ship shapes and can be modified by users. Once the net force has been calculated, the acceleration and velocity are computed and updated by:

$$\begin{aligned} a_h &= F_h / M, \\ \mathbf{v}_h &= \mathbf{v}_h + a_h \Delta t, \end{aligned}$$

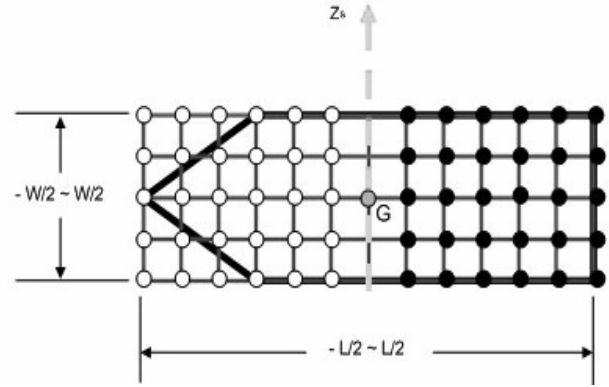


Fig. 3 Classification of height fields for pitch. The height fields in the first half have positive weights while the weights of the height fields of the other half are negative.

where  $a_h$  and  $\mathbf{v}_h$  are the acceleration and new velocity respectively, and  $\Delta t$  is the time step size. Then, the magnitude of heave is calculated by:

$$heave = \mathbf{v}_h \Delta t. \quad (1)$$

The resistance coefficient  $b_h$  is critical for heave motion. It can be used to simulate a floating object vibrating on a still water surface. In our system, we assume that the ship stops heave quickly if waves disappear. Therefore, we set  $b_h = 1.3$ , and the heave motion is *over-damped*. The ship becomes steady fast once no external force acting on it.

### 3.2 Pitch

Assume pitch is driven by the difference of height field between the front and rear halves of the ship. This height difference is multiplied with the grid area to compute the variation of water volume, and then modulated with a coefficient,  $K_p$  to estimate the force for pitch. When the ship pitches, damping effect of water will restore the ship position from oscillation. The damping force is proportional to the velocity of pitch but exerting on the ship in opposite direction. Totally, the net force for pitch is determined as follows:

$$\begin{aligned} H_p &= \sum_{i=-L/2}^{L/2} \sum_{j=-W/2}^{W/2} \text{sign}(i) h_{i,j} / (L * W), \\ F_p &= K_p A H_p - b_p I_p \omega_p. \end{aligned}$$

The first equation is used to compute the height field difference of the two halves of the grid. Each height field is associated with a weight of 1 or -1, depending on the sign,  $\text{sign}(i)$ , of its  $X_s$  coordinate. The height fields with positive and negative weights are depicted in Figure 3. In the second equation, the force for pitch is calculated by multiplying the height difference with the grid area  $A$ , and scaling down by using the pitch coefficient,  $K_p$ . The net force is obtained by subtracting the damping force from the force of sea water. The damping force is determined by the damping coefficient,  $b_p$ , the *inertia of moment*,  $I_p$ , and the pitch velocity,  $\omega_p$ . Then the Newton's

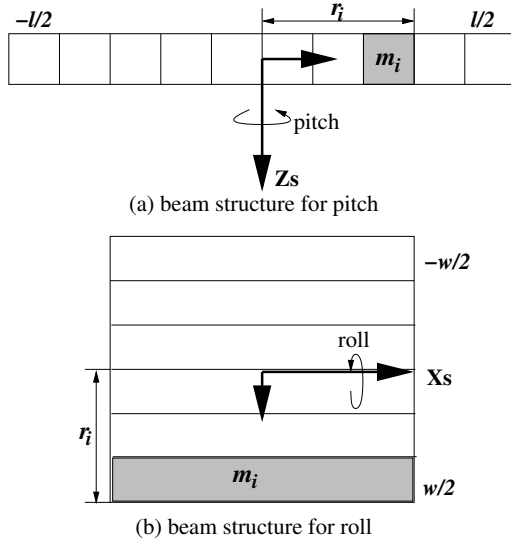


Fig. 4 Ship body is regarded as a beam for computing inertia.

law for rotation can be applied to calculate the acceleration and velocity of pitch:

$$\alpha_p = F_p / I_p, \quad (2)$$

$$\omega_p = \omega_p + \alpha_p \Delta t, \quad (3)$$

$$\theta_p = \omega_p \Delta t, \quad (4)$$

where  $\alpha$  is the angular acceleration and  $\theta$  is the angle of pitch. If the damping coefficient  $b_p$  is greater than but close to 1.0, for example  $b_p = 1.3$ , then the ship will pitch one or two times if the sea surface suddenly becomes still. This phenomenon matches real ship behaviors. Thus we adopt this method for specifying the damping coefficient.

The *inertia moment*,  $I_p$ , plays the same role as the mass  $M$  does in translation motions [3]. To compute  $I_p$ , we assume the mass center of the ship is at its geometrical center  $G$ . The ship is regarded as a beam structure shown in part (a) of Figure 4. The beam is composed of  $l$  cross-sections of mass,  $m_i$ . Assume the mass of each cross-section is a constant  $m$ , and the total ship mass  $M = ml$ . Then the inertia moment can be computed by:

$$\begin{aligned} l &= L/W, \\ I_p &= \sum_{i=-l/2}^{l/2} m_i r_i^2, \\ &= m \sum_{i=-l/2}^{l/2} r_i^2, \\ &= 2m \sum_{i=1}^{L/2} i^2, \\ &= (ml)(l+1)(l+2)/12, \\ &\sim Ml^2/12. \end{aligned}$$

In the first equation, we set  $l$  to be the ratio of ship length  $L$  to ship width  $W$ . Then  $I_p$  is solved and approximated by using  $Ml^2/12$ .

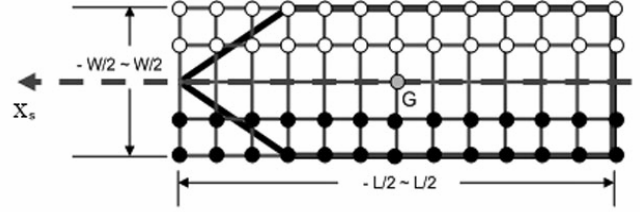


Fig. 5 The weights of grid points is related to their  $Z_s$  coordinates. Height fields in the right side have positive weights while the weights of the height field in the other side are negative.

### 3.3 Roll

The mathematical model of roll is similar to that of pitch. We divide the grid by using the  $X_s$  axis. The height fields on the right side are given a positive weight 1 while the height field on the other side are associated with a negative weight  $-1$ . The computational grid for roll is displayed in Figure 5. The height difference between the two sides is calculated by summation over the grid. The height difference is then multiplied with a roll coefficient,  $K_r$ , and the grid area,  $A$ , to estimate the force for roll. The net force is obtained by subtracting the damping force from the force of roll. Then the net force is used to compute the acceleration of roll. The roll velocity is updated as the acceleration is available. The roll angle is decided by multiplying the roll velocity with the time step size.

$$H_r = \sum_{j=-W/2}^{W/2} \sum_{i=-L/2}^{L/2} \text{sign}(j) h_{i,j} / (L * W), \quad (5)$$

$$F_r = K_r A H_r - b_r I_r \omega_r, \quad (6)$$

$$\alpha_r = F_r / I_r, \quad (7)$$

$$\omega_r = \omega_r + \alpha_r \Delta t, \quad (8)$$

$$\theta_r = \omega_r \Delta t, \quad (9)$$

where  $b_r$  and  $\omega_r$  are the damping coefficient and the velocity of roll; the angle of roll is represented by  $\theta_r$ , and  $I_r$  is the inertia moment of roll. Since the magnitude of roll is usually small and the ship will stop roll quickly if the sea surface becomes flat. We suggest that damping coefficient be set to 1.2. To deduce  $I_r$ , the ship is treated as a beam structure with  $w$  cross-sections as shown in part (b) of Figure 4. Then, by using a similar method for computing the inertia moment of pitch,  $I_r$  is approximated by:

$$\begin{aligned} w &= W/D, \\ I_r &\sim Mw^2/12. \end{aligned}$$

In this model,  $w$  is equal to the ratio of ship width to ship draft. The roll of a ship is depicted in Figure 6. In part (a), the ship is in a rest posture. When encountering waves, the ship roll about  $X_s$  as shown in part (b).

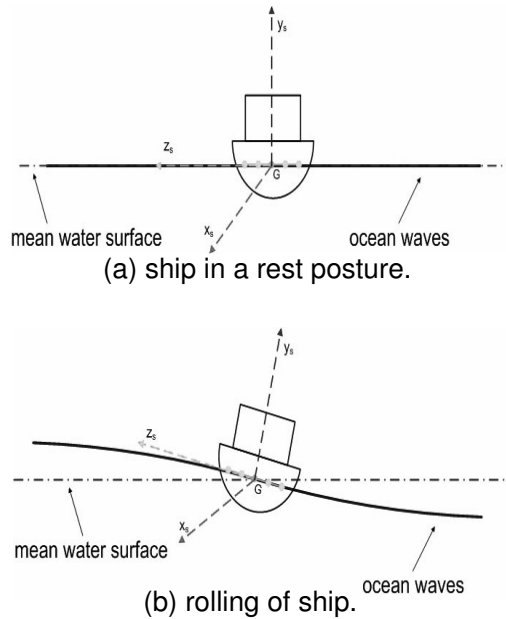


Fig. 6 Roll motion of ship.

#### 4 Motions Induced by Internal and External Force

The wave-induced motions can not change the position of the ship on the sea surface. Only the powers of propellers, the forces of rudders, winds, and currents can move the ship to a new position. These forces produce surge, sway, and yaw motions for the ship. In this section, the models for the 3 motions are deduced.

##### 4.1 Surge

When a ship rests on sea surface without any internal force or external force acting on it, its forward velocity is 0. If its propeller is turned on, the ship is accelerated and driven forward. As the ship moves, the drag force of water will slow down the ship. Gradually, the force of propeller is canceled by the drag force, and the ship reaches a steady speed. Theoretically, drag force is proportional to the square of speed and the area of ship hull surface submerged in water. It can be formulated as [2]:

$$R_s = b_s A_s \|\mathbf{v}_s\|^2,$$

where  $R_s$  is the resistance (drag force),  $\mathbf{v}_s$  is the velocity of surge,  $b_s$  is the drag force coefficient, and  $A_s$  is the area of ship hull submerged in water. However,  $A_s$  is difficult to decide. Instead, we replace it with ship mass  $M$ . The resistance is computed by:

$$R_s = b_s M \|\mathbf{v}_s\|^2.$$

Let the force produced by the propeller be  $T$ , and assume the cross-section of ship is narrow enough such that currents and winds make no contribution for surge, then the net force for surge is  $T - R_s$ . The force of the propeller is related to its

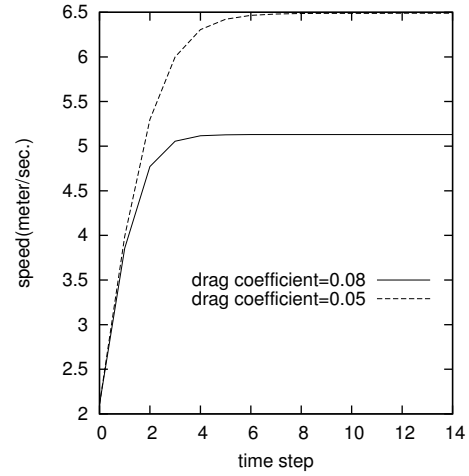


Fig. 7 The ship speed becomes steady as the drag force cancels the thrust of propeller.

revolution speed  $n$  and diameter  $D$  [14]. The surge motion magnitude is deduced as follows:

$$T = K_T n^2 D^4, \quad (10)$$

$$a_s = (T - R_s)/M, \quad (11)$$

$$\mathbf{v}_s = \mathbf{v}_s + a_s \Delta t, \quad (12)$$

$$\text{surge} = \mathbf{v}_s \Delta t, \quad (13)$$

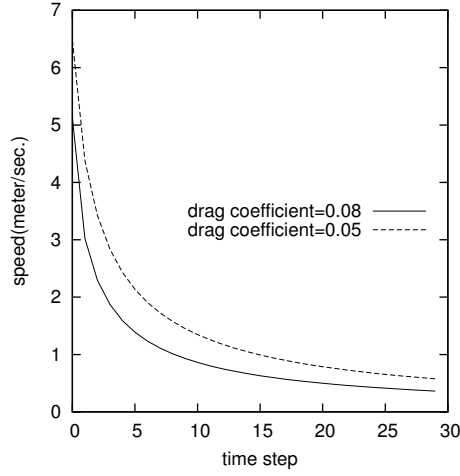
where  $K_T$  is the thrust coefficient of propeller. In the first equation, the thrust force of the propeller is computed. In the second equation, the acceleration is obtained by dividing the net force with the ship mass. Then the velocity is updated by using the acceleration. The magnitude of surge is computed by multiplying the velocity with the time step size.

According to this model,  $b_s$  plays a key role in the surge motion. To demonstrate its effects, two examples are shown in Figures 7 and 8. In these example, the ship mass is 570Kg and the propeller force is 1200 newtons. The drag force coefficient is set to 0.05 and 0.08. Initially, the speed of ship is zero. Then the engine is turned on and the ship is sped up until it reaches a threshold speed. The speed of the ship is shown in Figure 7. As revealed in the figure, if  $b_s$  is smaller, then the ship can be accelerated longer before the drag force cancels the propeller thrust. Therefore its final speed is quicker. In the second test, the propeller is turned off when the ship moves at the threshold speed. The drag force slows down the ship. The ship speed is reduced more quickly, if the drag force coefficient is higher. The results are displayed in Figure 8.

##### 4.2 Yaw

We assume that the rudder of the ship is the major force of yaw. The rudder force is related to the area of the rudder, the angle of the rudder, and the square of the velocity of water passing the rudder surface. Many simplified formulae have been suggested for calculating rudder force [14]. We adopt the follow one for approximating the rudder force:

$$F_{rd} = K_{rd} A_{rd} \|\mathbf{v}_w\|^2 \theta_{rd},$$



**Fig. 8** As the propeller is shut down, the drag force causes the ship to stop.

where  $F_{rd}$  is the rudder force, and  $K_{rd}$  and  $A_{rd}$  are the rudder coefficient and the area of the rudder. The symbol  $v_w$  is used here to represent water speed. For simplicity, the angle of rudder,  $\theta_{rd}$ , is assumed to be the angle between the rudder and the surge direction,  $X_s$ . The angle of rudder is limited to 35 degrees to avoid *stalling*[14]. In reality, the rudder force is not a linear function of the rudder angle. However, since the rudder angle is limited to within  $[-35, 35]$ , a linear function is a good approximation. In [14], the details of computing rudder force can be found. As the rudder force enables the ship to yaw, the resistance of water produce anti-force for yaw. Assume the resistance is related to the yaw speed. The net force for yaw is computed by:

$$F_y = F_{rd} - b_y I_y \omega_y,$$

where  $b_y$  is the resistance coefficient for yaw,  $I_y$  is the inertia moment for yaw, and  $\omega_y$  is the angular velocity of yaw. Based on Newton's second law for rotation, the angular acceleration for yaw is obtained by:

$$\alpha_y = F_y / I_y.$$

We assume that the ship is a beam structure as shown in part (a) of Figure 4, and  $I_y$  is the same as the inertia moment of pitch,  $I_p$ :

$$I_y \sim ML^2/12.$$

Then the velocity and magnitude of yaw are computed by:

$$\omega_y = \alpha_y \Delta t, \quad (14)$$

$$\theta_y = \omega_y \Delta t. \quad (15)$$

In reality, the ship will deviate a little from its course if the angle of rudder is changed because of the moment. But it is difficult to simulate the process. In our system, we set  $b_y$  to a small value. Therefore, the ship will move straightforward once the rudder angle changes to zero degree.

### 4.3 Sway

Sway motion can be generated by winds, currents, or even propellers. (Some large ships are equipped with propellers which can make sway motion inside harbors.) In our work, only winds and currents are counted for sway. To estimate the force of winds acting on the ship, the component of wind velocity in  $Z_s$  direction is computed. Then the velocity component is scaled with a coefficient,  $K_w$ , to produce the wind force for sway:

$$F_w = K_w \langle \mathbf{V}_w, \mathbf{Z}_s \rangle,$$

where  $F_w$  is the force of wind,  $\langle, \rangle$  is the inner-product operator, and  $\mathbf{V}_w$  is the wind velocity. The coefficient  $K_w$  is related to the profile of the ship. A larger ship profile will result in large wind coefficient. By analogy, the force of current is estimated by:

$$F_c = K_c \langle \mathbf{V}_c, \mathbf{Z}_s \rangle,$$

where  $F_c$  is the force of current acting on the ship hull in  $Z_s$  direction,  $V_c$  is the velocity of current, and  $K_c$  is the coefficient of currents. Let  $b_{sw}$  be the resistance coefficient of sway and  $\mathbf{v}_{sw}$  the velocity of sway, then the net force for sway is:

$$F_{sw} = F_w + F_c - b_{sw} M \|\mathbf{v}_{sw}\|^2.$$

The last term on the right hand side represents the drag force for sway. It is similar to the drag force for surge. Then the acceleration and velocity of sway are computed by:

$$a_{sw} = F_{sw} / M,$$

$$\mathbf{v}_{sw} = \mathbf{v}_{sw} + a_{sw} \Delta t.$$

The magnitude of sway is computed by multiplying sway velocity with the time step size:

$$sway = \|\mathbf{v}_{sw}\| \Delta t. \quad (16)$$

## 5 Other Implementation Issues

### 5.1 System Overview

The flow chart of our system is shown in Figure 9. The system composes of three stages. At the first stage, the height fields of the sea surface are computed by using the wave model mentioned in Section 2.3. The output of this stage is forwarded to the second and third stages for computing ship motions and rendering the scene. Once all three stages are completed, another step of simulation is triggered and the simulation continues until it is terminated by users.

Several coefficients are introduced in our physics models for ship motions which are presented in Sections 3 and 4. To specify these characteristics for a ship, users have to figure out the meanings and reasonable values of these parameters. It could be a difficult task for amateur users. In order to simplify the process, we create some basic ship models off line and load the models from disk files before the program running. Our system also offers graphical user interface which enables users to change wave parameters and ship characteristics during the simulation. Therefore, users can try numerous combinations of ships and waves.



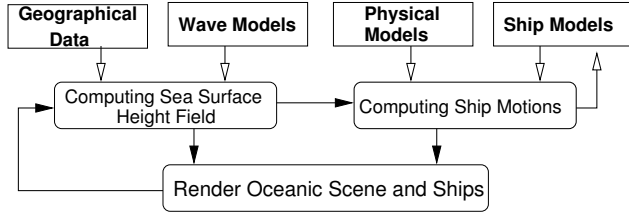


Fig. 9 Structure of the ship motion simulation program.

|         | heave | pitch | roll | surge | sway | yaw   |
|---------|-------|-------|------|-------|------|-------|
| wave    | med.  | med.  | med. | no    | no   | no    |
| wind    | no    | no    | no   | small | med. | small |
| current | no    | no    | no   | med.  | med. | med.  |

Table 1 The influence of external forces upon the motions of a thin ship. *med.*=medial

|         | heave | pitch | roll  | surge | sway  | yaw   |
|---------|-------|-------|-------|-------|-------|-------|
| wave    | large | large | large | no    | no    | no    |
| wind    | no    | no    | no    | med.  | med.  | med.  |
| current | no    | no    | no    | large | large | large |

Table 2 The influence of external forces upon the motions of a flat ship.

|         | heave | pitch | roll  | surge | sway  | yaw   |
|---------|-------|-------|-------|-------|-------|-------|
| wave    | small | small | small | no    | no    | no    |
| wind    | no    | no    | no    | small | small | small |
| current | no    | no    | no    | small | small | small |

Table 3 The influence of external forces upon the motions of a slender ship.

### 5.2 Ship Models and External Forces

The major external forces that influence ship motions include waves, winds, and currents. When an external force is exerted on a ship, the net effect of the force on the ship is related to the shape of the ship. A ship with shallow draft and flat bottom is very sensitive to the motion of waves. On the other hand, a war ship can endure moderate weather conditions without generate significant motions. In our system, ships are classified into three basic models based on the criteria listed in Section 2.2. The classification gives users hints for defining the maneuvering parameters of ships. In Tables 1, 2, and 3, the influences of external forces upon ship motions for the three ship models are expressed. These tables suggest some basic knowledge for users to tune the parameters of ships. Since a war ship (a slender ship) has a narrow and streamlined shape, currents make little contribution to its surge. The mass of a war ship is large and its draft is deep, its motions are less sensitive to waves. On the other hand, a raft (a flat ship) has a shallow draft, and its mass is relatively small. Therefore, its motions are significantly influenced by waves and currents. However, its profile is usually low, and winds are not an essential factor for its motions. The properties of a fishing boat (a thin ship) are between those of the two models. A fishing boat does not possess a big mass, and thus its motions are influenced by waves, currents and winds. However, its shape is

|                      | war ship | fishing boat | raft  |
|----------------------|----------|--------------|-------|
| length               | 125m     | 38m          | 10m   |
| width                | 15m      | 8m           | 10m   |
| mass                 | 3000 ton | 250 ton      | 2 ton |
| rudder area          | 10 $m^2$ | 1 $m^2$      | 0     |
| number of propeller  | 4        | 2            | 0     |
| propeller diameter   | 4m       | 2m           | 0     |
| propeller revolution | 360 rpm  | 180 rpm      | 0     |

Table 4 The dimensions of three ships. Length, width, and draft are measured by meters, and the masses are measured by tons.

|              | $K_h$ | $K_p$ | $K_r$ | $K_T$ | $K_{rd}$ | $K_w = K_c$ |
|--------------|-------|-------|-------|-------|----------|-------------|
| warship      | 0.4   | 0.4   | 0.4   | 1.0   | 0.9      | 0.2         |
| fishing boat | 0.7   | 0.8   | 0.7   | 0.9   | 0.8      | 0.3         |
| raft         | 1.0   | 0.9   | 0.9   | 0.0   | 0.0      | 0.9         |

Table 5 The coefficients of the ship motion models for three different types of ships.

streamlined, currents and winds create little effects for surge motion.

## 6 Some Simulation Results

### 6.1 Visualization Results

The system is built upon a desk-top PC with 512 mega-byte main memory and a 1.7 GHz cpu. Three basic ship models are given in our program. They are a war ship, a fishing boat, and a raft. The dimensions of these ships are listed in Table 4. The revolutionary speed of propeller is measured by r.p.m. (revolutions per minute). Though, a ship may have more than one rudder, only the total area of the rudders is presented. The raft does not equipped with any engine or rudder. Its motions are entirely decided by external forces. The coefficients of the motion models of these ships are listed in Table 6.1, where  $K_h$ ,  $K_p$ ,  $K_r$ ,  $K_T$ , and  $K_{rd}$  represent the coefficients of heave, pitch, roll, thrust, and rudder. For simplicity, we use the same values for wind and current coefficients,  $K_w$  and  $K_c$ . Since the raft does not equipped with any propeller or rudder. Therefore, its thrust and rudder coefficients,  $K_T$  and  $K_{rd}$ , are zero. Furthermore waves, winds, and currents are significant external forces for the motions of the raft, therefore the related coefficients are high. The war ship has low heave, pitch, roll, and current coefficients to exhibit its endurance against waves and currents. High values are assigned to its thrust and rudder coefficients such that it has an efficient control mechanism. The fishing boat has medial values for its coefficients to match with its characteristics. Three sinusoidal waves are superposed to create the height fields for the simulation. The parameters of the waves are depicted in Table 6.1. The wave amplitudes and lengths are measured by meters. The advancing angles are the angles between the  $X$  axis of the world coordinate system and the advancing directions of the waves.

Some visualization results are displayed in Figures 13, 14, and 15. In Figure 13, the motions of a war ship are por-

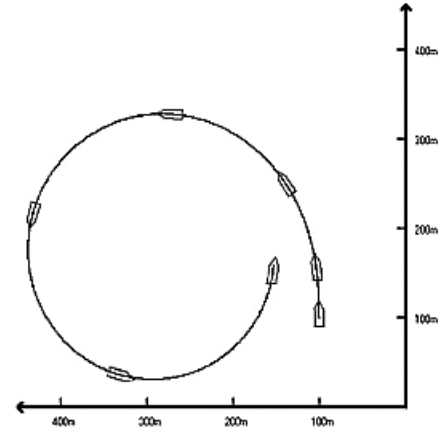
|        | amplitude | wave length | advancing angle |
|--------|-----------|-------------|-----------------|
| wave 1 | 3.0m      | 47.5m       | 240°            |
| wave 2 | 0.3m      | 60m         | 135°            |
| wave 3 | 0.3m      | 80m         | 210°            |

**Table 6** The parameters of the waves for the ship motion simulation.

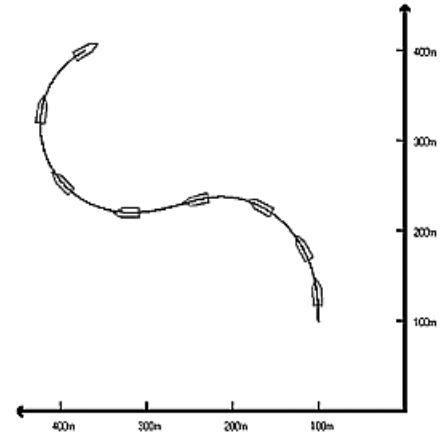
trayed. In the simulation, only heave and pitch are allowed. In part (a), one wave reaches the tip of the war ship and another wave crest is under the warship. The warship pitches forward slightly. In part (b), a wave crest is under the middle of the ship. Therefore, the ship heaves upward. When the wave crest passes to the rear end, the ship meets another wavefront. It pitches backward slightly. The image is displayed in part (c). Since the warship is insensitive to sea waves and the wave amplitude is not large, the motions are not significant. For comparison, the heave and pitch motions of a craft are shown in Figure 14. In part (a), a wave crest just passing the rear end of the craft, and the craft pitches forward. When the craft is above a wave crest, it heaves upward. The result is displayed in part (b). The effect of the craft encountering a wavefront is exhibited in part (c). As the image shows, the craft pitches backward. Since the craft is a flat ship. It is very sensitive to the variation of sea surface. In Figure 15, the heave, pitch, and roll of a fishing boat are depicted. In part (a), the boat is above a wave trough, and a wavefront is approaching. The boat starts to pitch. Since the crest line of the wave is not orthogonal to the boat's course direction, it rolls left slightly. When the wavefront reaches the front end of the boat, it pitches as shown in part (b). As the boat is above the wave crest, it heaves upward and roll right. The result image is portrayed in part (c). According to the test results, our physical models and ship classification are verified. Our procedures offer efficient and virtually realistic ship motion simulations.

## 6.2 Maneuverability Testing

When a ship has been built, it has to go through a series of testing to verify her maneuverability. Three tests are supported in our system for examining virtual ship models. These tests are *turning cycle*, *zig-zag maneuver*, and *braking*. The turning cycle testing is used to verify the efficiency of the rudder. The test is performed by setting the rudder angle to its maximum value as the ship is advancing. The ship will gradually change her heading direction. Her trajectory forms a cycle which serves as an indication of the efficiency of her rudder. Another testing for the rudder is the zig-zag maneuver. When the ship moves straightforward at a fixed speed, the rudder angle is set to 20 degrees and held until the heading direction of the ship also changes by 20 degrees. Then the rudder angle is changed to 20 degrees in the opposite direction and held until the ship's heading angle also changes by 20 degrees in the opposite direction. The path of the ship creates an S-shape curve which is used to measure the responses of the ship to her control system. In the braking test, the propeller is turned off as the ship moves straightforward.



**Fig. 10** Turning cycle of the war ship.

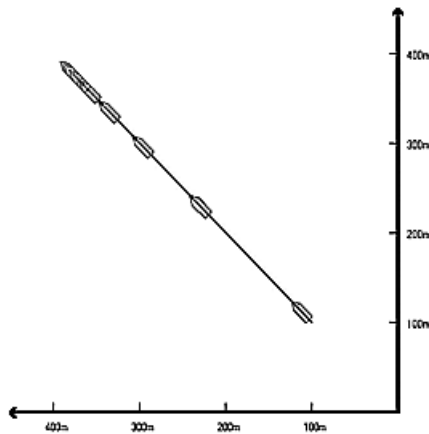


**Fig. 11** Zigzag maneuver test of the war ship.

The speed of the ship will decrease gradually because of the drag force of water. A streamline-shape ship can proceed for a long distance before her velocity is worn off by the resistance of water. Our system supplies users two windows for displaying the simulation results. The first window shows the 3D scenes of the simulations. The second window displays the 2D images of the paths of the ships. The 2D images are better media for showing the results of the maneuver tests. Three example images are displayed in Figures 10, 11, and 12. The war ship is used for the maneuver tests. Her turning cycle is depicted in Figure 10. The result of the zigzag maneuver test is contained in Figure 11. The braking test result is shown in Figure 12. Since the war ship possesses a high rudder coefficient, the diameter of her turning cycle is small. In the braking test, it moves for a long distance before fully stopped. Only part of the path is shown.

## 7 Conclusion and Future Work

In this article, we propose a simulation system for ship motions. By using our program, users can simulate motions of

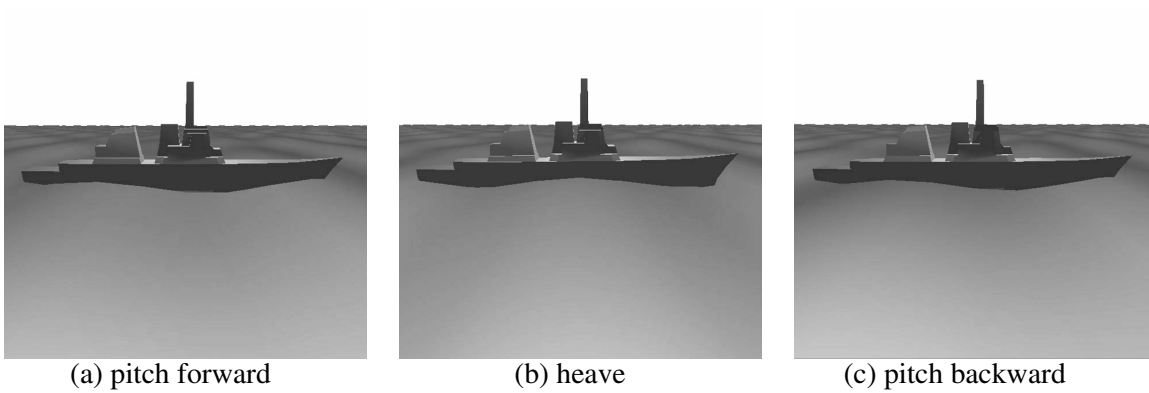


**Fig. 12** Braking test of the war ship.

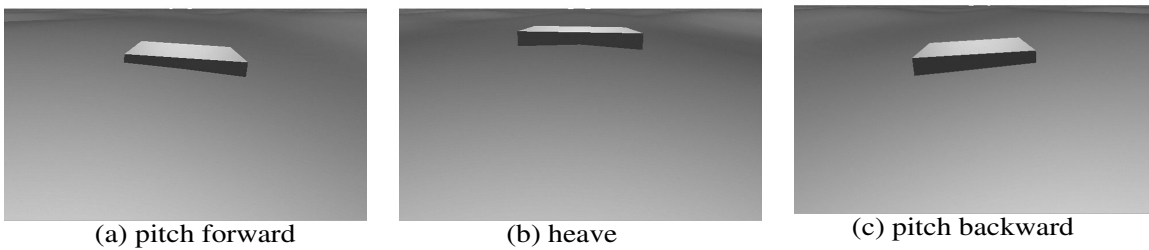
ships under the influences of waves, winds, currents, and the internal forces of the ships. Our system is easy to use and possess flexibilities for users to modify wave parameters and ship shapes. It is suitable for the development of games and educational applications about ship motions. Handling ships inside harbors or water channels is an important issue for navigation simulation. Traveling ships, breakwaters, and piers can produce irregular wave and current patterns inside a harbor. However, our wave model is not capable of simulating these phenomena. More sophisticated and efficient wave models have to be employed for ship motion simulation in harbors. In this work, less efforts are paid in rendering the scene. The illumination model of sea wave is very complicated. It prohibits real-time rendering of oceanic scenes. Furthermore, foams, sprays, and wakes produced by ships increase the complexity. Advanced graphics techniques need to be developed in rendering sea surfaces and ships. The other interesting topic is the stability of ship. When encountering huge waves or strong winds, a ship may lose her stability, capsizes and sinks. Currently, we assume the ship always retains her stability even though the waves are severely rough. A physics model needs to be developed and implemented for simulating the motions of a ship under severe weather conditions such that our system can offer more realistic scenario for sea-keeping training.

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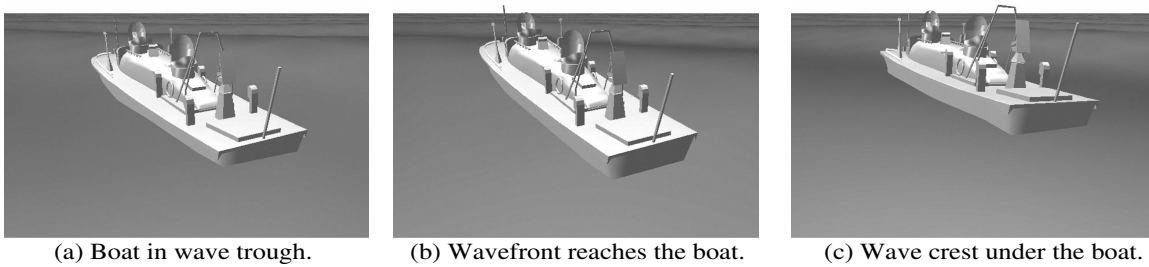
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**Fig. 13** Pitch and heave motions of a war ship.



**Fig. 14** Pitch and heave motions of a craft.



**Fig. 15** Motions of a fishing boat encountering wave.