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A Novel Approach to Simulate Wind-driven Ocean Waves in the Deep Ocean

Maheshya Weerasinghe[#1], Damitha Sandaruwan[#2], Chamath Keppitiyagama[#3], Nihal Kodikara[#4]
[#]*School of Computing, University of Colombo*
35, Reid Avenue, Colombo 7, Sri Lanka
[1]`au.maheshya@ieee.org`
[2]`dsr@ucsc.cmb.ac.lk`
[3]`cik@ucsc.cmb.ac.lk`
[4]`ndk@ucsc.cmb.ac.lk`

Abstract— **In computer graphics, there are several mechanisms to display the ocean waves on screen. Albeit there are many models to simulate oceanic behavior, yet there is no rendering mechanism for wind-driven deep ocean waves, with a satisfactory outcome. Moreover, there is no way to plug those wave models onto existing maritime training simulators. Thus, the oceans computed and rendered by those models have no bearing on the computed sway, surge, heave, yaw, pitch, or roll of the vessels. This paper presents a novel approach to simulate wind-driven deep ocean waves which include marine dynamic models and their integration for the purpose of developing a simulator. It's subsequent to a survey on ocean wave models and rendering techniques which are frequently used in computer graphics to simulate deep ocean water surfaces. While exploring the prevalent methods, three main approaches have been identified to model the formation of an ocean water surface based on geometrical description models, spectral description models, and physically based models from Computational Fluid Dynamics (CFD). In the context of oceanography and computer graphics, there is a considerable body of literature on ocean water generating and rendering techniques. According to the literature, ocean water rendering techniques in computer graphics can be categorized into three major domains, viz. spatial domain, spectral domain and hybrid methods combining the two. This paper analyses the above wave models, rendering techniques and proposes a novel approach to develop a computer simulation program in which the physical models are implemented in order to achieve a realistic representation of a vessel in a virtual environment considering physical characteristics of the vessel. Further, introduces a spectral wave model and rendering by using a hybrid method with the focus of user perception. Hence, it consists of model parameters which describe the user perception.**

Keywords— **Computer graphics, virtual reality, ocean wave simulation, training simulators**

I. INTRODUCTION

Real-time three-dimensional (3-D) computer graphics is a subfield of computer graphics which has been substantially matured during the last few decades. As a result of the rapid and the cheaper augmentation of computer graphics and hardware systems, the use of virtual simulation systems has swiftly become a necessity. In real-time computer graphics, we conventionally try to reproduce parts of our world in the most lifelike possible way.

Natural phenomena like fluid motions and water surfaces are intrinsic and ubiquitous parts of the everyday environment we dwell in. Representing natural phenomena more realistically are one of the most important factors to improve virtual reality, especially in the various fields related to the computer graphics applications. However, the reproduction of many natural phenomena like, fluid motions and water surfaces are still an open problem in computer graphics.

The realistic simulation of ocean water has become an important arena, not only in computer visualization but also in virtual reality as well. Thus, this paper focuses on the fluid motions, water surfaces and ocean water simulation methods. There are diverse methods specifically designed for ocean scenes, but also more general water simulation techniques that can be applied to ocean simulation. However, due to the highly dynamic behavior of ocean water it's hard to perceive the reality and it is a highly complex natural phenomena. Hence, the ocean water simulation has become a computationally expensive process which requires visually feasible 3-D effects at high frame rates at high frame rates.

Different models can be used to represent ocean dynamics: First approach is based on geometrical models which construct an animated height field by linear combination of travelling periodic functions [1], [2], [3], [4]. It aims at computing the path of water particles and describes the free surface with parametric equations which are based on real observations. The second approach is based on physical models and it uses Navier-Stokes Equations (NSE) [13], [38] to represent breaking waves near the shore [10], [11], [12]. NSE can represent dynamics of all types of fluid, including the dynamic behavior of the ocean. Final approach is based on spectral models which uses empirical laws from oceanographic research [7], [8], [9]. It is commonly used method to simulate of ocean scenes in the deep water domain, without breaking waves. It approximates the state of the sea by using wave spectrum and computes wave distribution according to the wave amplitudes and frequencies.

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Ocean water rendering techniques can be grouped into three categories: spatial domain, spectral domain and hybrid methods combining the two.

Spatial methods use a height map computed as a sum of periodic functions [1], [2], [3], [4], [5] and animated with a simple phase difference, in order to represent the ocean surface. Spectral approaches use a wave spectrum to describe the surface in the spectral domain and a Fourier Transform is used to obtain its transformation in the spatial domain [7], [9], [14], [15]. The combination of the above two is known as the hybrid methods, produces more convincing surfaces that can be animated easily [8], [20], [21], [22].

Naval and maritime training simulators are one of the main applications which use the deep ocean water modelling and rendering. In order for a maritime training simulation system to be a truly useful instruction tool for safety and navigation, a trainee using it needs to have a completely realistic feeling of being on a real ship, including believable behavior of the ocean waves and changes to wind conditions. Hence, providing highly realistic visual simulation of ocean waves is an essential aspect of such systems. Otherwise, real world visual clues and simulated visual clues may be different.

The proposed approach suggests a new substantive model of wind generated ocean waves, which provides physically meaningful interaction information sufficiently rapidly to be integrated into a naval training simulator by managing the underlying physics of natural phenomena. It also uses user experiences/perception as an input to the wave model. It tackles bounded ocean surfaces, with realistic distributions of wind-driven waves, more user-controllable parameters and real time rendering capability.

II. OCEAN WAVE MODELS

A wave model is a universal term for mathematical models designed to simulate the generation, propagation, interaction, refraction, reflection, etc. of ocean waves. These mathematical models are used to predict wave behavior for complicated wave profiles and bathymetry [29].

A. Shapes of Ocean Waves

The shape of an ocean wave is frequently depicted as a "sine wave" (Fig. 1), but the experimentally observed wave shape is described as a "trochoid" (Fig. 2) [26].

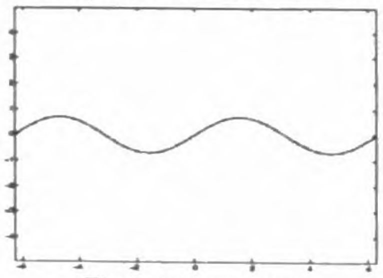

Fig.1 A sine wave

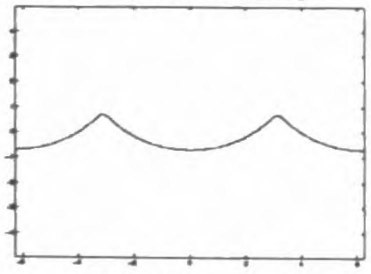

Fig.2 A trochoid wave

1) *Sine Wave*: The most simplistic shape for a water wave is to simply use a sine wave and move it across the height field along time. A sine can be described as the curve traced out by a point on a circle as the moving circle rotates with constant angular velocity as depicted Fig. 3.

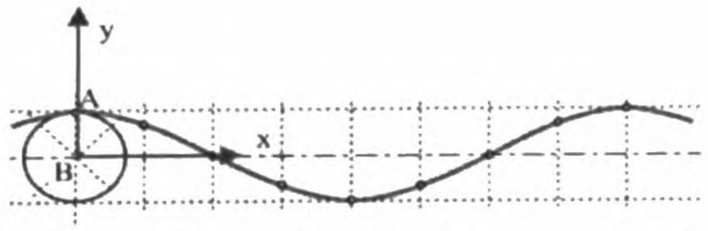

Fig.3 A sine curve is traced out by point A as the moving circle rotates with constant angular velocity as regards B [30]

Using the general equation for a sinusoidal wave, the wave elevation at geographic location x is defined by [31]:

$$y = A \sin(kx - \omega t) \quad (1)$$

where A is the wave amplitude, k is the wave number, this number is defined as $2\pi / \lambda$ by the wave length λ. ω is the pulsation which is defined as the $2\pi f$ by the frequency f. A, k, and f are all varied by the time t.

2) *Trochoid Wave*: Actual water waves are shaped is such a way that they have long deep troughs and sharp, pointy peaks. This predicts that water waves form a trochoid. A trochoid can be described as the curve traced out by a point on a circle as the circle rolls along a line as depicted in Fig. 4.

Fig.4 A trochoid curve is traced out by point A as the outer circle rolls along the base of line B [30]

Using the trochoid parametric equations the x and y coordinates are defined by [32]:

$$x = a\theta - b \sin\theta \quad (2)$$
$$y = a - b \cos\theta \quad (3)$$

where the θ is the variable angle through which the circle rolls.

B. Geometrical models

The simple and well-known geometrical models are a popular technique for modelling water surfaces. The start works of Fournier and Reeves [3] as well as Peachey [2] can be seen as forerunners of the geometric-based category. The ocean surface represented by these models are unable to break up. Thus, the spray and some complex wave phenomena cannot be modelled by this method. However, its characteristics are simple and real-time to render the ocean surface. But the generated scenes are less realistic, especially when only one or two wave trains are simulated.

C. Physical models

In physical based wave model's, the motion of fluids is described by a set of nonlinear partial differential equations, called the Navier-Stokes equations (NSE) introduced in 1987 [13], [38]. Following equation shows one formulation of the NSE, for an incompressible Newtonian fluid.

$$\rho \frac{\partial v}{\partial t} + (v.\nabla)v = -\nabla P + \gamma \nabla^2 v \quad (4)$$

where v is the fluid velocity at a specified position and time, ρ is the density, P is the pressure and γ is the viscosity of the fluids.

Numerous papers have addressed computational fluid dynamics in the context of computer graphics. Earlier, in this respect, Foster and Metaxas [11] modified the classic marker and cell (MAC) method [33] to obtain realistic fluid behavior. Stam [10] departed from the finite-difference scheme used by Foster and Metaxas [11] and initiated the stable semi-Lagrangian methods for computing the advection part of the Navier-Stokes equations. Foster and Fedkiw [12] introduced a hybrid model in their modelling and animation of liquids by adapting the semi-Lagrangian method introduced by Stam. But, most problems based on the NSE are too complex to lend themselves to analytical solution, and must be solved numerically. Numerical methods for solving such problems are well adapted for scientific simulation, but typically unsuitable for real-time purposes, due to computational intensity.

D. Spectral models

A wave spectrum is a representation of the distribution of wave energy as a function of the wave frequency. The waves in a particular sea state are identified by their wave spectrum, $S(f)$ and wave spectra are constructed based upon empirical studies that describe oceanic conditions.

Multidirectional wave spectra are customarily expressed in the form [34]:

$$F(\theta,f) = S(f)\,D(\theta,f) \tag{5}$$

where $S(f)$ is a standard wave frequency spectrum and D is a wave directional spreading function.

In 1952 researchers began developing mathematical representations of wind-generated wave phenomena. In order to obtain the spectrum of ocean waves on the downwind side of a region, various idealized, analytical and empirical spectra are used in oceanography. The most common spectra are: Pierson-Moskowitz (PM) [16], JONSWAP [17], Phillips [18] and Texel Marson Arsole models (TMA) [23].

Mastin et al. [7] use an empirical frequency spectrum of wind-driven ocean, given by the Pierson-Moskowitz filter, to sample an appropriate set of frequency components. Thon et al. [8] also use the Pierson-Moskowitz spectrum, but do not transform sampled data into spatial images. Tessendorf [9] replaces the Pierson-Moskowitz filter with the Phillips spectrum, which is directly applicable to noise in the Fourier domain.

III. PRACTICAL OCEAN WAVE ALGORITHMS

A. Gerstner Waves

Gerstner waves were first found as an approximate solution to the fluid dynamic equations almost 200 years ago. Gerstner wave model as trochoidal shaped waves. It describes the surface in terms of the motion of individual points on the surface [9].

If a point on the undisturbed surface is labeled $X_0 = (x_0, z_0)$ and the undisturbed height is $y_0 = 0$, the point on the surface is displaced at time t to:

$$X = X_0 - \left(\frac{\mathbf{k}}{k}\right) A sin(\mathbf{k} \bullet X_0 - \omega t) \tag{6}$$

$$y = A cos(\mathbf{k} \bullet X_0 - \omega t) \tag{7}$$

when a single wave with amplitude A passed by.

The wave vector **k** points in the direction or travel of the wave, and it has magnitude:

$$k = \frac{2\pi}{\lambda} \tag{8}$$

This will only result in a single wave passing the surface, not very realistic. Instead we are summing a set of sine waves to create a more complex profile. One selects a set of wave vectors $\mathbf{k}_i$, amplitudes A_i, frequencies ω_i, and phases Φ_i, for i = 1, . . . , N, to get the expressions

$$X = X_0 - \sum_{i=1}^{N} \left(\frac{\mathbf{k}_i}{k_i}\right) A_i \sin(\mathbf{k}_i \bullet X_0 - \omega_i t + \Phi_i) \tag{9}$$

$$y = \sum_{i=1}^{N} A_i \cos(\mathbf{k}_i \bullet X_0 - \omega_i t + \Phi_i) \tag{10}$$

To animate the Gerstner waves we change the frequency ω_i. There is a known relationship between these frequencies and the magnitude of the wave vector k_i.

$$\omega^2(k) = gk \tag{11}$$

where g is the acceleration due to gravity, which is 9.8 m/s^2

B. Fast Fourier Transformation

Oceanographic literature tends to downplay Gerstner waves as a realistic model of the ocean. It uses statistical models based on experimental observations of the real sea [9].

In the statistical model of sea, wave height is a random variable of horizontal position $\mathbf{x} = (x, z)$ and time, $h(\mathbf{x}, t)$.

It decomposes the wave height-field into a set of sinusoidal waves with different amplitudes and phases. We use FFT to evaluate these sums. FFT allows us to evaluate the following:

$$h(\mathbf{x}, t) = \sum_{k} \tilde{h}(\mathbf{k}, t) \exp(i\mathbf{k}.\mathbf{x}) \tag{12}$$

The wave vector $\boldsymbol{k}$ points in the direction of travel of the wave, and it has magnitude:

$$k = \frac{2\pi}{\lambda} \tag{13}$$

When we want to generate a height-field we start by calculating h_0

$$\tilde{h}_0(\mathbf{k}) = \frac{1}{\sqrt{2}}(\varepsilon_r + i\varepsilon_i)\sqrt{P_h(\mathbf{k})} \tag{14}$$

where, ε_r *and* ε_i are ordinary independent draws from a Gaussian random number generator, with mean 0 and standard deviation 1. $P_h(\mathbf{k})$ is the Phillips spectrum [18].

Now when we have calculated $h_0(\mathbf{k})$ we can animate the set with

$$\tilde{h}(\mathbf{k},t) = \tilde{h}_0(\mathbf{k}) \exp(i\omega(k)t) + \tilde{h}_0^*(-\mathbf{k}) \exp(-i\omega(k)t) \quad (15)$$

$$\omega^2(k) = gk \quad (16)$$

where g is the acceleration due to gravity, which is 9.8 m/s^2

C. Choppy Waves

The FFT approach generates nice looking waves with rounded tops. This is satisfactory for scenarios where the weather is good, but not for situations involving stormy conditions. In order to make the waves have sharper tops an algorithm can be implemented.

The idea is to displace the grid points slightly in the horizontal plane to make the waves more sharp and the valleys between the waves wider [9]. The equation is as follows:

$$X' = X + \mu \boldsymbol{D}(X,t) \quad (17)$$

where X is the vertical position, $X = (x,z)$, μ is a scale factor and $\boldsymbol{D}$ is the displacement vector calculated with the FFT:

$$\boldsymbol{D}(X,t) = \sum_k -i\frac{\mathbf{k}}{k}\tilde{h}(\mathbf{k},t)\exp(i\mathbf{k}.X) \quad (18)$$

IV. WAVE GENERATION AND ANIMATION

Ocean water synthesis for computer graphics can be broken into three classes, first, those describing the ocean surface directly in the spatial domain, then those describing the surface in the spectral domain and finally hybrid methods combine the two.

A. Spatial Domain Approaches

Spatial domain approaches simulate ocean water surfaces by using a sum of periodic functions and known geometrical models of ocean water. Several computer graphics researchers have studied the large scale motion of water in waves in the spatial domain.

Fig.5 Rendered image of ocean water obtained in Fournier and Reeves [3]

First, Max [1] generated a height field by composing a series of sinusoids with high and low amplitudes with added noise. Max chose the frequencies of these waveforms so that the motion of the waves could be reused each cycle of the animation. In Max's work the ocean surface is represented as a height map with height $y = h(x,z,t)$ computed at each point (x,z) at time t by:

$$y = -y_0 + \sum_{i=1}^{T_w} A_i \cos(k_{i_x}x + k_{i_z}z - \omega_i t) \quad (19)$$

where, T_W is the total number of waves, A_i is the amplitude of the i$^{\text{th}}$ wave, $\overrightarrow{k_i} = (k_{i_x}, k_{i_z})$ its wave vector, ω_i is the frequency and y_0 is the height of the free surface. In order to obtain a realistic effect, the wave vector of each wave is computed using the scattering relationship in the deep water domain, assuming that the bottom of the sea is at infinite depth.

Peachy [2] generated a height field by computing the superposition of several long-crested waveforms. Instead of using trochoids, Peachy blended a quadratic function with the underlying sinusoids to give a more realistic cycloidal choppy appearance. Furthermore, he introduced a depth parameter to compute the wave number of each wave:

$$k_i = 2\pi / \sqrt{\frac{g\lambda_i}{2\pi} tanh \frac{2\pi d}{L_i}} \quad (20)$$

where, g is acceleration due to gravity and λ is the wavelength of each individual wave and d is the depth of a point related to the bottom of the sea.

The noteworthy works by Fournier and Reeves [3] relied on a mix of Gerstner and Biesel swell models. Fournier and Reeves enhance this Gerstner and Biesel model by considering the transformation of the path of water particles following the topographical changes of the sea bed, and by renovating their circular path into a more realistic elliptic motion.

Ts'o and Barsky's [4] approach, called wave tracing, consists in generating a spline surface by casting rays from the skyline in a uniform 2D grid, progressing with Bresenham's algorithm [6].

Gonzato and Le Saec [5] address this problem by generating new rays in under-sampled areas, presenting a better depiction of the ocean surface around the bays or islands for example. This method called "Dynamic Wave Tracing" can handle wave reflection, refraction and diffraction which occur due to obstacles.

B. Fourier Domain Approaches

The main goal of Fourier domain approaches is to simulate ocean water surfaces by utilizing the spectral distribution of waves, obtained from theoretical or measured data.

Fig.6 Rendered image of an ocean-scape obtained in Tessendorf [9]

This approach was introduced by Mastin et al. [7] with the Pierson Moskowitz spectrum. Mastin transformed white noise from the spatial to the Fourier domain using a PM spectral envelope [16]. The inverse FFT of this spectrum resulted in a realistic ocean water height map, which was then animated by appropriately shifting the phase in the Fourier domain each frame.

Premoze and Ashikhmin [14] pursued the same idea by using the JONSWAP spectrum [17]; a modified version of the Pierson-Moskowitz's which changes the frequencies and thus raises waves' amplitudes.

Tessendorf [9] described a similar approach which has been used in famous computer-generated scenes in Hollywood movies; *Waterworld* and *Titanic* productions, as well as real-time, maritime simulation software [19]. Tessendorf starts in the frequency domain, using the Phillips spectrum [18], and then transforms a Fourier domain description of the ocean water motion to the spatial domain via the inverse FFT.

Mitchell [15] implemented Tessendorf's method on the GPU by only considering frequencies generating a significant perturbation of the surface. A white noise is first generated using Phillips' spectrum [18], then frequencies are divided into two sets. Low frequencies accounting for the global motion of waves are stored as a displacement map in a vertex shader.

Fourier domain approaches do not account for the effects of bathymetry [29]. However, this approach can be used with other methods where the effects of bathymetry are used to generate the input parameters related to the wave characteristics.

C. Hybrid Approaches

Hybrid approaches are a combination of spatial and spectral methods, generating a geometric representation of the surface while describing the components of wave trains in a realistic manner.

Fig.7 Ocean surface obtained in Lee et al. [20] at wind speed 3m/s, water depth 100m.

Fig.8 Real-time synthesized ocean water obtained in Lachman [22]

The method proposed by Thon & Ghazanpour [8] computed the height field by selecting a set of high amplitude trochoids from the Pierson Moskowitz spectrum [16] and directly calculating their superposition in the spatial domain.

Lee et al. [20] combine a superposition of sinusoids and the TMA spectrum [23], creating a better statistical distribution of waves. This method provides more scope for the end user to be in command by providing more user-controllable parameters to generate a variety of ocean scenes including deep or shallow, windy or calm oceans.

Hinsingert et al. [21] apply a Level of Details (LOD) scheme to the method of [24] by reducing both the sampling resolution of the surface mesh and the number of trochoidal components depending on the distance to the viewer.

A real-time simulation method for ocean scenes was proposed by Lachman [22] designed an open architecture for ocean water simulation with a flexible and scalable framework. This method is also highly controllable, allowing the user to modify parameters such as the bottom depth or the disturbance of the sea (defined by the Beaufort Scale [28], [39]).

D. Discussion

Most of the ocean wave simulation mechanisms were based on physical models uses Navier-Stokes Equations (NSE) reasonably well when modelling infinitely deep water. For instance, it can be used to represent breaking waves and more generally ocean surface near the shore. However, because of the complexity of these equations the simulation usually cannot be computed in real time. This is especially true when attempting to model large bodies of water, because in the spatial domain the numerical model must be evaluated at each vertex and at each time step, as it is dependent upon time and space. On the other hand, the simulations are calculated on the whole simulation domain, thus enabling simulation of a wide variety of phenomena. The results are very convincing and the simulations look very precise and realistic.

Most of the simulations based on geometrical models use the spatial domain approach. The main advantage of the spatial domain approaches is their ability to produce a simple and fast simulation of the ocean surface. But it requires a large number of periodic functions for a visually believable result. Several optimizations have been proposed such as GPU implementation to reduce the number of periodic functions according to the distance to the viewer. Thus, these types of simulations are considerably faster and can be used for real-time ocean wave rendering but the waves appear less realistic.

The ocean wave modelling and rendering approaches which use oceanographic spectra, frequency spectrum and directional spectrum are usually belonging to the spectral domain method. Spectral domain methods address the previous problems by using oceanographic data and allow disturbances the surface according to physical parameters such as wind speed, which brings more realistic results.

In this context, hybrid approaches represent a good compromise between the visually believable, but computationally intensive and hence slowly-produced, results of spectral models and the less realistic but fast geometrical models. Through a hybrid approach we can achieve waves of realistic appearance whilst still maintaining good computational performance, as required for real-time simulations. A complete summary of the methods presented in this section is shown in TABLE I.

Although these methods have the capability to generate numerous realistic images, there are some drawbacks, including requiring too much computation, lack of consideration of the effect of wind on wave generation (dynamic behavior), a limited number of controllable parameters (TABLE II). Furthermore, all these methods have limited possibilities for being integrated with other physics engines or simulation systems, such as maritime training simulators.

TABLE I

CLASSIFICATION OF THE SIMULATION METHODS FOR DEEP WATER; WHERE G-GEOMETRICAL MODELS, ST- SPECTRAL MODELS, SP-SPATIAL DOMAIN, F- FOURIER DOMAIN, N-NO AND Y-YES

Preceding work		Wave Model	Ship Interaction	Rendering Technique
1981	Max [1]	G	N	SP
1986	Peachey [2]	G	N	SP
1987	Fournier et al. [3]	G	N	SP
1987	T's O et al. [4]	G	N	SP
1987	Mastin et al. [7]	ST	N	F
1986	Foster et al. [11]	P	N	-
1999	Stam [10]	P	N	-
2000	Premoze et al. [14]	ST	N	F
2000	Thon et al. [8]	G/ST	N	H
2000	Gonzato et al. [5]	G	N	SP
2001	Cieutat et al. [40]	G	Y	SP
2001	Tessendorf [9]	ST	N	F
2001	Foster et al. [12]	P	N	-
2002	Hinsinger et al. [21]	G	N	H
2005	Mitchell [15]	ST	N	F
2007	Lachman [22]	ST	N	H
2007	Lee et al. [20]	G/ST	N	H

TABLE II

COMPARISON OF THE OCEAN SIMULATION METHODS; WHERE WD-WIND-DRIVEN, UC-USER CONTROLLABLE PARAMETERS, RT-REAL-TIME, SW-SHALLOW WATER, DO-DEEP OCEAN

	Preceding work	Model Features
1981	Max [1]	DO
1986	Peachey [2]	DO
1987	Fournier et al. [3]	DO
1987	T's O et al. [4]	DO
1987	Mastin et al. [7]	WD,UC,DO
1996	Foster et al. [11]	DO
1999	Stam [10]	DO
2000	Premoze et al. [14]	WD,DO
2000	Thon et al. [8]	WD,DO
2000	Gonzato et al. [5]	DO
2001	Cieutat et al. [40]	DO/SW/RT
2001	Tessendorf [9]	RT,DO
2001	Foster et al. [12]	DO
2002	Hinsinger et al. [21]	DO
2005	Mitchell [15]	RT,DO
2007	Lachman [22]	RT,DO
2007	Lee et al. [20]	WD,UC,RT,SW,DO

V. NOVEL APPROACH

The main objective of this novel approach is to develop a general methodology for designing an ocean wave model to generate wave geometry according to the variations of wind conditions while including user experiences as inputs and map that wave model onto a "standard vessel" in a 3D virtual environment which can be used in simulators such as naval tactical training systems.

When consider the wind generated waves phenomena, the major generating force of the waves is the wind acting on the interface between the air and the water [14]. From the mathematical point of view, the surface is made up of many sinusoidal waves generated by the wind, and they are travelling across the ocean.

A. System Design

The simulation system is divided into modules. In general, it is very unusual in this type of simulation to have a single block including all the modelling equations together. Especially in this study, where the principal objective was not only to model ocean waves but also to use and to integrate ship motion model, the modularity was a necessity. Based on this fact, the simulator is composed of three main modules: Virtual environment module, ship motion prediction module and graphic module. Fig.8 shows the block diagram of the system.

1) *Virtual Environment Module*: The virtual environment module consists of two sub models: The ocean wave model and special effects model. The structural design of the ocean wave model contains a mathematical model of wind generated waves subclass based on the Phillips spectrum [18]. This ocean wave model derives a height field system to simulate an ocean water surface for a deep ocean region. The special effects model treats daylight and fog issues to enhance the immersive effects of the environment.

2) *Graphic Module:* Graphic module represents two sub models: The graphic engine and user controllers model. The graphics engine model is responsible for rendering the virtual simulated scene. There are many tools to help in the development of virtual reality systems due to the high complexity of the applications. To start the rendering using only the original OpenGL functions is practically impossible. The graphic engine used in this research is called OGRE (Object-Oriented Graphics Rendering Engine) [36], is a scene-oriented, flexible 3D engine written in C++ designed to make it easier and more intuitive for developers to produce games and demos utilizing 3D hardware. The class library abstracts all the details of using the underlying system libraries like Direct3D and OpenGL and provides an interface based on world objects and other intuitive classes. User controllers model is in charge of accepting commands that set internal parameters associated with the ocean wave model and environment related parameters.

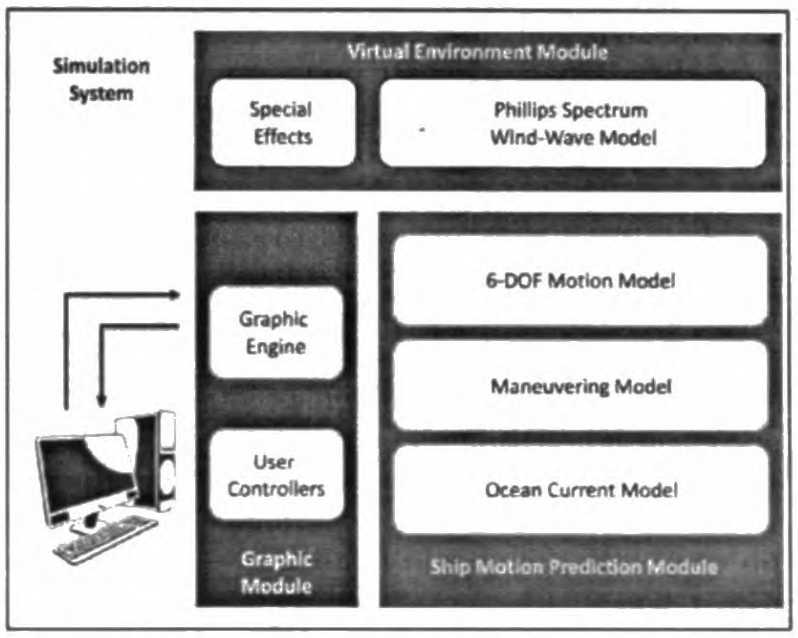

Fig.9 Architectural system modules

3) *Ship Motion Prediction Module:* The ship motion prediction module holds three sub models. Each sub model plays a specific role in the dynamics that contribute to representing the expected ship behavior. We derived simplified 6-DOF motion model by using six degrees of freedom ocean surface vehicle model introduced by Sandaruwan et al. [35]. All six possible degrees of freedom (6-DOF) in a motion of a ship can be illustrated in TABLE III. Surge, heave, and sway are translational motions. Roll, yaw, and pitch are rotational motions.

The surge motion, yaw motion and sway motion of a ship is described by using a simplified non-linear speed equations and transfer functions. By solving them, it is possible to compute the ship's position orientation vector in the XY-horizontal plane with respect to time. That means we can calculate x, y, u, v and ψ. Then according to Archimedes' principle [37] we assume the translational motion (heave) and rotational motions (pitch, and roll) are generated by the swellness of water under the ship. It can be calculated by using the height variation of the sea surface. We assume that the shape of the ship is cubical as illustrated in Fig. 10 and the ship body is vertically projected onto the sea surface to get the l×w bounding box. It is divided into 1m×1m cells for mathematical convenience. We evaluate the height fields at the center points of each 1m×1m cells and we presume the ship is not actually presented when the height field is calculated. We assume that the projected bounding box and its points move with the ship. Then, any time we can calculate height fields according to ship's orientation and the wave propagation. We can obtain forces and moments to generate the heave, pitch and roll motions by calculating the height fields for overall bounding box, calculating difference of height fields between the front and rear halves of the bounding box and calculating difference of height field between the Port and starboard halves of the bounding box respectively.

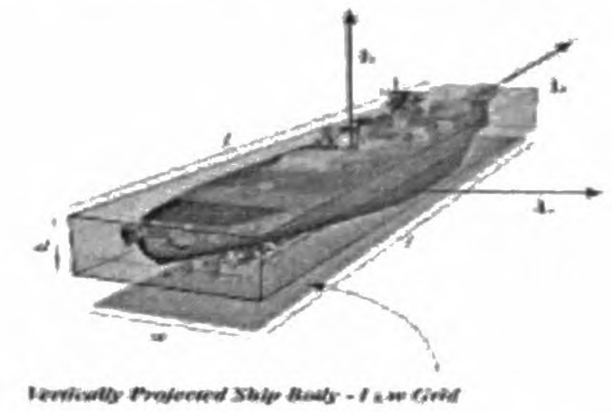

Fig.10 The shape of the ship is identical to a cubical [35]

The heave motion can be calculated by the following equations as described in Sandaruwan et al. [35] paper.

K_h, M, $\dot{w}$, w denote the resistance coefficient for heave motion, Mass of the ship, heave acceleration and heave velocity and S_w is Sea water density [35]. The equations are listed below.

$$R_h = K_h M|w|^2 \tag{21}$$

$$F_h = H_a S_w - R_h \tag{22}$$

$$\dot{w} = {F_h}/{M} \qquad \dot{w}\Delta t = \Delta w \tag{23}$$

where, the sum of height fields in vertically projected ship body is:

$$H_a = \sum_{i=\frac{-l}{2}}^{\frac{l}{2}} \sum_{j=\frac{-w}{2}}^{\frac{w}{2}} h_{i,j} \tag{24}$$

To set the pitch motion of the ship, the net force for pitch *(F_p)*, pitch angular acceleration ($\dot{q}$) and pitch angular velocity *(q)* is calculated by the following equations [35]:

$$R_p = K_p I_p q \tag{25}$$

$$F_p = H_p S_w - R_p \tag{26}$$

$$\dot{q} = {F_p}/{I_p} \qquad \dot{q}\Delta t = \Delta q \tag{27}$$

where, S_w, K_p, R_p, I_p denote the sea water density, resistance coefficient for pitch motion, resistance force against the pitch motion and the ship's moment of inertia along Y-axis respectively and;

$$I_p = \frac{1}{12} M(l^2 + d^2) \tag{28}$$

H_p is the height field difference between the front and rear halves of the ship.

$$H_p = \sum_{i=\frac{-l}{2}}^{\frac{l}{2}} \sum_{j=\frac{-w}{2}}^{\frac{w}{2}} h_{i,j} \frac{i}{|i|} \tag{29}$$

As in the pitch motion calculations we can calculate the net force for roll motion, roll angular acceleration and roll angular velocity. H_r is the height field difference between the port side and starboard side halves of the ship [35].

$$H_r = \sum_{i=\frac{-l}{2}}^{\frac{l}{2}} \sum_{j=\frac{-w}{2}}^{\frac{w}{2}} h_{i,j} \frac{j}{|j|} \qquad (30)$$

Fig.11 Motions caused by sea waves

TABLE III
6-DOF SHIP MOTIONS AND NOTATIONS

DOF	Description	Forces Moment	Linear/ Angular Velocity	Positions Euler Angel
Surge	Motions in the x-direction	X	u	x
Sway	Motions in the y-direction	Y	v	y
Heave	Motions in the z-direction	Z	w	z
Roll	Rotations in the x-direction	K	p	φ
Pitch	Rotations in the y-direction	M	q	θ
Yaw	Rotations in the z-direction	N	r	ψ

The ocean current model used in this study is a simple two-dimensional current model. It is commonly used in surface vessel applications. This model considers the local effect of the current, applied to the ship movements.

B. Assumptions

The proposed approach has limitations such as, consider only the deep water phenomena, in which the ocean surface is being subjected to small perturbations; and the optical behaviors of water surface, such as reflection, refraction and propagation of light will be neglected in the scope. When modelling the ocean waves, this study assumes that the transfer of energy in the wave field is achieved only through the surface stress applied by the wind. For the mathematical convenience/real-time calculations, the proposed solution assumes the shape of the ship is identical to cuboids. One of the main intentions of this approach is to generate realistic looking ocean scenery, and hence to provide an 'immersive' to the users. Thus, the quality of the field of view (FOV) of the observer's eye is important.

VI. RESULTS AND VALIDATION

A. Simulation Results

The proposed approach was implemented and tested with the Microsoft Visual Studio environment. It is a multi-threaded C++ application and the threads communicate via shared memory. The simulation program runs as an application layer which was built over the OGRE 3D API (Application Program Interface) [36]. The Main Program block creates the threads and the events needed to control the access to the shared memory area. In the current solution, only one vessel is implemented (Fig. 18), but it supports for multiple vessels with few changes.

This simulation system was implemented and tested on; Intel (R) Core (TM) i5-2410M CPU (2.30 – 2.90 GHz, 8 Cores) and DDR3 (1066 MHz) 8GB memory with RADEON graphics hardware.

The Beaufort Sea State scale can be used to give an approximate/concise description of sea conditions [28], [39]. Fig. 12 - 16 show the comparison of real world sea states and corresponding simulated sea states.

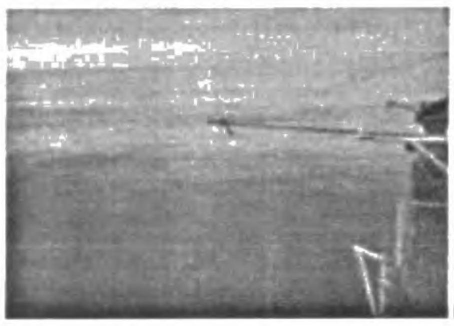

Fig.12 Real world ocean, Sea state 0, wind speed less than 1 knot [39]

Fig.13Simulated ocean, Sea state 0, wind speed less than 1 knot

Fig.14 Real world ocean, Sea state 3, wind speed 7-10 knot [39]

Fig.15 Simulated ocean, Sea state 3, wind speed 7-10 knot

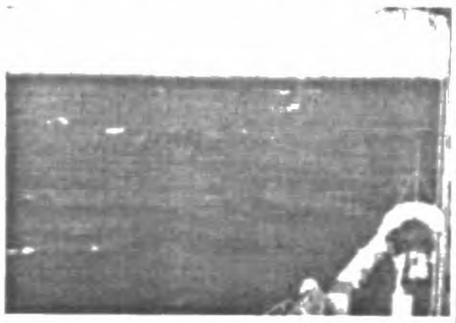

Fig.16 Real world ocean, Sea state 6, wind speed 22-27 knot [39]

Fig.17 Simulated ocean, Sea state 6, wind speed 22-27 knot

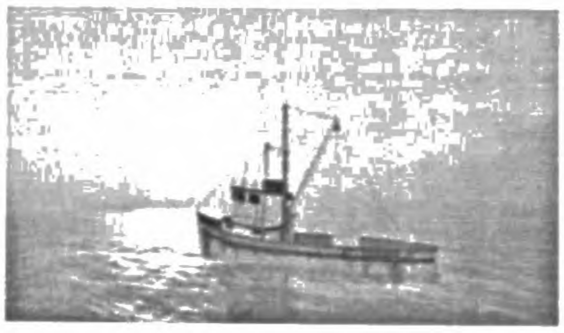

Fig.18 A boat in the simulated ocean

B. Validate Motions Caused by Sea Wave: Heave, Pitch and Roll

Simplified real-time ship motion algorithms were selected and it is more suitable for vessels with approximately box type geometric formations. The relationship between vessel motion and the ocean wave physical characteristics are generally measured by using the Response Amplitude Operators (RAO) [40], [41],

[42]. The response is achieved as response spectra for given wave spectra. Fig. 19, 20 and 21 respectively presents the typical heave, roll and pitch RAOs for a floating body on the ocean wave.

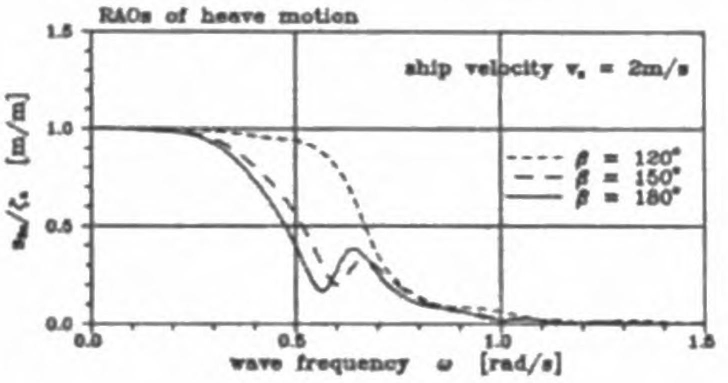

Fig. 19 Heave RAO behavior with respect to wave frequency [42]

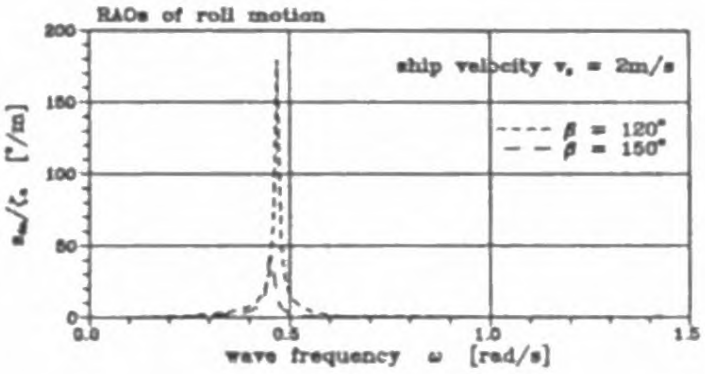

Fig. 20 Roll RAO behavior with respect to wave frequency [42]

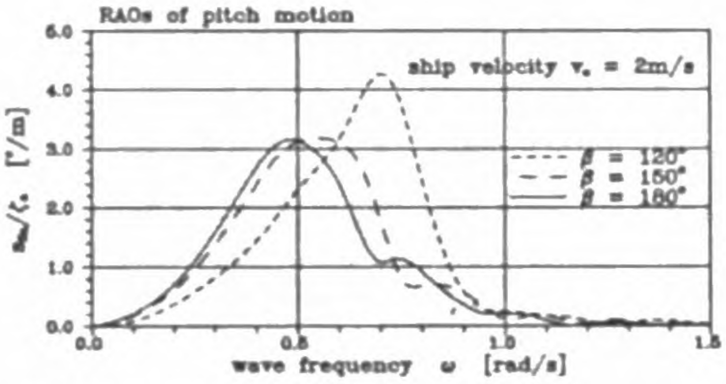

Fig. 21 Pitch RAO behavior with respect to wave frequency [42]

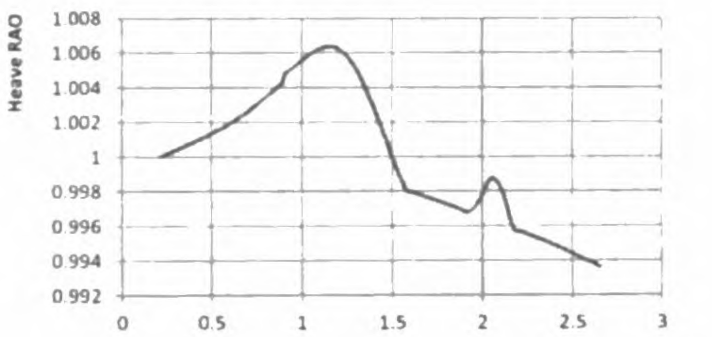

Fig. 22 Observed heave RAO behavior with respect to wave frequency

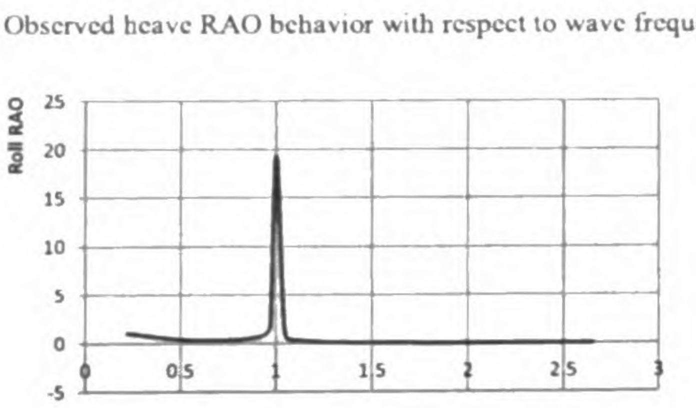

Fig. 23 Observed roll RAO behavior with respect to wave frequency

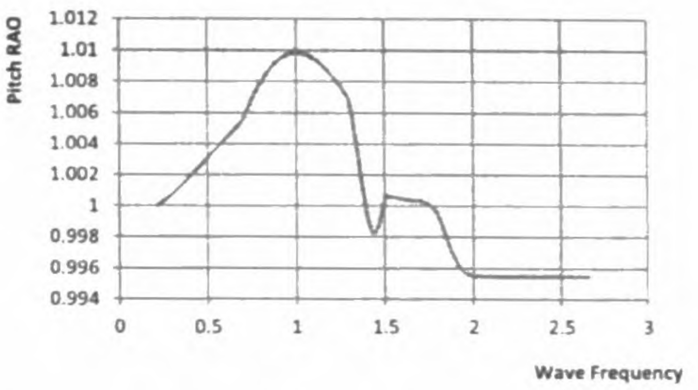

Fig. 24 Observed pitch RAO behavior with respect to wave frequency

According to the above graphs heave and pitch are well damped and as such are not "sharply tuned" (amplified). Roll motion is sharply tuned, lightly damped, and very susceptible to the encounter frequency.

The comparison of typical RAO curves of a vessel and obtained RAO curves of our simulation system gives a noteworthy output. However, it does not give a perfect result, since the motion of a ship is affected by the characteristics of the vessel's hull [43]. However, in this solution we assumed vessel's hull formation is cuboids. Also when calculating the heave, roll and pitch several parameters were approximated. Hence, there should be a deviation in simulated results and real world scenario.

VII. CONCLUSIONS AND FUTURE WORK

There are many approaches to simulate ocean behavior but each having multiple inherent assumptions and initial conditions. However, the computation of ocean surface variation and rendering of these models does not have a bearing on the computed sway, surge, heave, yaw, pitch, or roll of the vessels. Hence there is no strong relationship between vessel motions, ocean wave modelling and rendering. At the same sense, although these methods have capable of generating numerous realistic images, they all still have drawbacks such as high computation requirements, less consideration of wind effect on wave generation (dynamic behavior), limited number of controllable parameters, resistance to incorporate with other physics engines and simulations such as ship simulators.

To overcome the limitations and drawbacks in the existing deep ocean wave modeling and simulation, the new substantive model is proposed. This proposed approach can be used with well-known deep ocean water surfaces rendering techniques in computer graphics. It also provides physically meaningful ship-wave interaction which can be integrated into a naval tactical training. In this solution, more precise ocean wave model is used. Hence, users can control more parameters to create various ocean scenes. This approach also uses a user feedback process, where the system adjusts some parameters if the user indicates that the simulated outcome is unrealistic.

There are three major important features in the proposed solution:

- One to one mapping between the vessel motions and rendering wave model.

- Attach the user experiences as an input to the wave model.
- Supports to incorporate Auxiliary user controllable parameters.

Further evaluation of the proposed model and rendering methodology is needed and there are future works such as measure computational efficiency/accuracy, design and conduct user tests to identify the degree of visual fidelity.

Designing of a new substantive hybrid model of wind generated ocean waves using computational fluid dynamics and oceanography spectrums is the next stage of the proposed solution.

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