High-precision and Large Scale Dynamic of Real-time Ocean Waves Simulation

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***Abstract*—For real-time simulation of wave and its three-dimensional characteristics, an effective method is presented. Firstly, the LOD quadtree method is taken for high-precision grid drawing and improved Gerstner model is used for water height field modeling. Secondly, use P-M spectral theory to determine the upper and lower waves frequency limits. Then solve amplitude with integration method and extend it to arbitrary spectral sampling. Finally, after determine waveform parameter based on wave spectrum, we realize simulation of high-precision and large scale dynamic of real-time ocean waves.**

Keywords—High-precision; Large Scale Dynamic; Height field; Three-dimensional Wave Simulation; LOD

I. INTRODUCTION

Large-scale ocean waves simulation and high-precision interactive water surface modeling has become a challenging research topic. Real wave is a complex immediately process [1]. We firstly use mathematical methods to describe the inherent law of water (waves) surface and analysis of the changing and complexity characteristics. In general, there are four methods of waves simulation: geometry [2], physical model [3], cellular automata [4] and particle system dynamics simulation [5] methods. Physical model method is mainly to solve the Navier-stokes equations [6], which requires high performance computation. The latter two methods apply to simulate local wave characteristics. Therefore, we study the geometric method.

Up to now, geometric method mainly consists of texture transform dynamic simulation, surface wave height field simulation, wave spectrum and FFT (Fast Fourier Transform) simulation method. The first method gets the real rough surface texture by perturbing the surface normal vector, which is proposed by Blinn [7]. Darles combined dynamic texture with attenuation of the light caused by the particle effect to simulate real wave [8]. Height field is proposed by Fishman [9] and Max used it to produce the famous film "Carla's Islan". Pierson is the first to study spectral based on S. A. Kitaigorodskii similarity theory and now there are many wave spectrums as Pierson-Moscowitz, JONSWAP, Bretschneider, Wallops and TMA spectra [10]. The classic application of wave spectrums theory is that Tessendorf method [11] (using wave spectrum and FFT to simulate waves) is applied to the "Water World" and "Titanic". Each method has different advantages and practical applications. The advantages and disadvantages simulation conditions, information and hardware requirements of each method are shown in table 1.

Wave spectrums method utilizes years of oceanographic observations to generate more realistic waves, without solution of the complex dynamic equations. Through analysis of table 1, we use the wave spectrum method to simulate high-precision and large scale dynamic of real-time ocean waves.

TABLE I. CHARACTERISTICS OF EACH GEOMETRIC METHOD

Method	①Advantages/ ②Disadvantages	①Suitable for/ ②Condition	Hardware
Texture transform dynamic simulation	①Realistic water flow and small amount of calculation. Texture generates flow and no physical concepts. ② Modeling workload no water level changes.	①Dynamic water flow effect. Wide range of applications. ② Texture image	Generally
Surface wave height field simulation	①Realistic of nearer viewpoint and local surface fluctuations. ②Cannot generate complex wave like crest curling. Limit the observed body. Large amount of computation.	①Random water level fluctuations; Numerical visual simulation; local river. ②Surface grid coordinates; Grid point elevation change	Higher
Wave spectrum and FFT	①Relatively simple, intuitive and real-time ②Need to construct the grid. Relatively poor quality and realism for avoiding repetitive FFT method when real-time rendering.	①Realistic, large-scale wave. ②Model water height and decide spectrum parameters	High

According to recent research on wave spectrum and FFT and high-precision and large scale ocean waves feature, we firstly study water height field grid construction techniques and modeling, and then using P-M wave spectrum theory to define parameters for each unit wave waveform. By simulation of each frame wave fluctuations, and calls OpenGL library to realize large scale dynamic ocean waves simulation.

II. CONSTRUCT THE WATER GRID AND HEIGHT FIELD MODELING

A. Draw High-precision Mesh LOD Based on Quadtree

Constructing a large range of surface area needs a huge number of grid points. If constructing 32768×32768 points array surface, we need calculate 10,270 million grid points. Computer renders so many mesh vertices at a time is almost impossible. Surface rendering requires real-time, realistic reproduction of three-dimensional surface of the water scene. According to reality, the scene nearer can be observed more clearly while the observation of distant scenery is fuzzy. At the same time, restricted by visual range, vision behind cannot be observed. Therefore, this article introduced terrain-quadtree thoughts to the surface of the grid structure for constructing multi-resolution LOD water grid, reducing the number of grid points need to be addressed and enhanced scene rendering in real time [12]. According to the viewpoint position, we use view-dependent grid sampling algorithm to generate quadtree, which satisfies that the farther away from the viewpoint, the less water block division. When the viewpoint is in position A, hierarchy of the grid surface divided by the viewpoint position is shown in Figure 1.

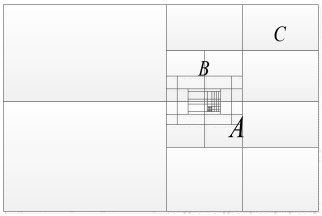

Fig.1 View-dependent Grid Hierarchy

As can be seen from figure 1, the closer from the viewpoint, the higher density mesh is. For block B and C, viewpoint A is in B and farther from C. So C does not require high detail display and need no longer divided. But block B needs to continue to divide. Flowing of large scale ocean waves and changing of viewpoint position need to recalculate quadtree scheduling according to the viewpoint position. Grid hierarchy changes are shown in figure 2 when viewpoint A is shifted from D.

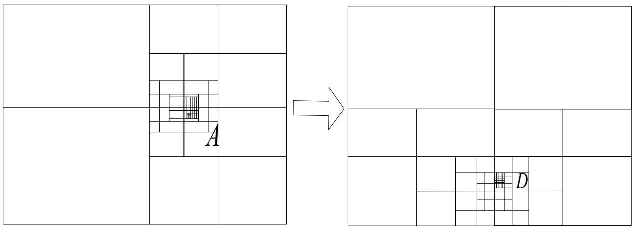

Fig.2 Grid Hierarchy Changes Affected by Viewpoint Position

The continuous and non-plana water surface must be achieved through computer processing discrete, also known as surface subdivision surfaces. The easy way to simulate water surface is to draw the uniform grid. This method can achieve good results to simulate a pond or lake. However, for high-precision and large scale dynamic of real-time ocean waves simulation, it requires a large number of polygons even if distant camera cannot see the details of the water. To overcome this problem, we need to use the LOD techniques. LOD seamless mesh surface is shown in Figure 3 and 4. We can see the outer coarse and the internal fine mesh grid are seamlessly connected together smoothly from Figure 4.

We use properties projection-grid method for grid modeling and projection space texture method to improve height field data utilization and high-precision Mesh LOD performance. By improving camera modeling in projection grids, we reduce the height field texture aliasing for adapting to non-horizontal camera and scene change with height of water.


Fig.3 The General Grid

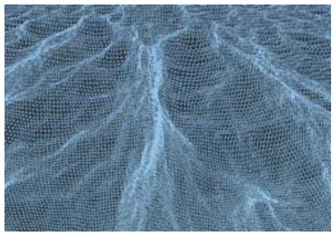
Fig.4 The High-precision Grid

B. Surface Modeling Based on Improved Gerstner Model

Wave spectrum modeling techniques, which use of oceanographic observations over the years, can generate more realistic waves without solution of complex dynamic equations [13, 14]. However, this method usually uses height field to simulate water surface and is suitable for calm water simulation, which not match with the physical characteristics of actual crest steeper waves and relatively flat valley. This method cannot be expressed crest curl waves.

The Gerstner model can solve this problem. But the argument is artificial and difficult to get more real waves. This section improves Gerstner model, construct a wind model by wind action for wave spectrum sampled of Gerstner parameter data required in the model.

According to modeling coordinates system, we assume that the static sea level as xoz plane and y axis vertically upwards. Equation of water point fluctuation with A for the movement radius (volatility) motion at time t is described as:

$$\begin{cases} x = x_0 + A\sin(kx_0 - \omega t) \\ y = y_0 - A\cos(ky_0 - \omega t) \end{cases} \tag{1}$$

x(z) is the horizontal (vertical) direction coordinate of wave particle at time t. x_0 and y_0 are stationary coordinate. A is the amplitude of the wave, which is the radius of movement of water particles. ω is the frequency of the wave and k is wave number at the point (x_0, y_o). Its orbital motion is circular or elliptical. We can get different steepness of the Gerstner wave by changing k and A values.

In order to control the waveform better, we introduce control factor μ to adjust the wave steepness and avoid overlap by changing μ value. Meanwhile, in order to increase the randomness of waves, we use random initial phase φ for the waveform phase modulation. Then waveform expression is:

$$\begin{cases} x = x_0 + \mu A\sin(kx_0 - \omega t + \varphi) \\ y = y_0 - A\cos(kz_0 - \omega t + \varphi) \end{cases} \tag{2}$$

Single wave Gerstner curve has characteristics of relatively steep peaks, flat trough and appear periodically, which is far apart with actual wave. We can correction it by composing of a linear superposition of multiple waves. Point (x, y, z) in the original coordinate system rotated into a point (x', y', z') in the new coordinate system. The conversion is:

$$\begin{cases} x' = x \cdot \cos\theta \\ y' = y \\ z' = x \cdot \sin\theta \end{cases} \quad (3)$$

Linear wave theory sees waves as superposition of an infinite number of different volatility, angular frequency cosine wave. With the above coordinate transformation, formula (3) expands into a three-dimensional discrete form:

$$\begin{cases} x = x_0 + \mu \sum_{i=1}^{m}\sum_{j=1}^{n} A_{ij}\cos\theta_j \sin\left[k_i\left(x_0\cos\theta_j + z_0\sin\theta_j\right) - \omega_i t + \varphi_{ij}\right] \\ y = y_0 - \sum_{i=1}^{m}\sum_{j=1}^{n} A_{ij}\cos\left[k_i\left(x_0\cos\theta_j + z_0\sin\theta_j\right) - \omega_i t + \varphi_{ij}\right] \\ z = z_0 + \mu \sum_{i=1}^{m}\sum_{j=1}^{n} A_{ij}\sin\theta_j \sin\left[k_i\left(x_0\cos\theta_j + z_0\sin\theta_j\right) - \omega_i t + \varphi_{ij}\right] \end{cases} \quad (4)$$

A_{ij}、k_i、ω_i and φ_{ij} respectively are amplitude, wave number, angular frequency and initial phase. The wave flows in the face xoz, and θ_j with the x axis. The total composition number of the simulation wave is $m \times n$ (m represents frequency and n represents divided number of one direction).

There are many calculation methods for formula (4). The simplest method is directly added, which has low efficiency. FFT is the most effective algorithm, which can real-time superimpose large number of unit wave. Plural sets $F_{n,m}$ ($N \times M$, $N = 2^i$, $M = 2^j$. i, j is positive integer) can be obtained through the inverse fast Fourier transform.

$$\begin{cases} x = \overline{x_0} + \mu \cdot \Im\left(\sum_k \hat{k} H\left(\vec{k}, t\right)\exp\left(i\vec{k}\cdot x_0\right)\right) \\ y = \overline{y_0} - \Re\left(\sum_k H\left(\vec{k}, t\right)\exp\left(i\vec{k}\cdot x_0\right)\right) \\ z = \overline{z_0} + \mu \cdot \Im\left(\sum_k \hat{k} H\left(\vec{k}, t\right)\exp\left(i\vec{k}\cdot x_0\right)\right) \end{cases} \quad (5)$$

$\Im$ is the imaginary part. $\Re$ is the real part. $\vec{k} = (k_x, k_z)$ is wave number vector, which size is determined by the input wavelength. $\hat{k} / \|\vec{k}\|$ is unit vector. $\overline{y_0}$ is average water. $\vec{x} = (x, z)$ is horizontal coordinates of datum point changing with time.

III. Large Scale Ocean Waves Simulation Based on Wave Spectrum Theory

A. Waveform Parameter Determination Based on Wave Spectrum

Wave spectrum represents a fixed point wave energy distribution relative to frequency, which mainly has parameters of wind direction and energy [15]. There are P-M, Phillips and BM spectrum etc. In this section, we determine waveform parameter based on wave spectrum. As discussed in the second section, $H\left(\vec{k}, t\right)$ in formula (5) consists three parts of amplitude $A(\vec{k})$, initial phase $\exp(i\varphi_{ij})$, and angular rate $\exp(i\omega_i t)$.

$$H\left(\vec{k}, t\right) = A(\vec{k})\exp(i\varphi_{ij})\exp(-i\omega_i t) \quad (6)$$

A large number of observational data indicates that ocean surface height of open area and fully grown approximate obeys normal distribution. Its amplitude obeys Rayleigh amplitude distribution. Accordingly, using two independent standard normal distribution (Mean 0 and MSE 1) random number (ζ_r and ζ_i) respectively instead of the real and imaginary part of $exp(i\varphi)$, we can prove that $\sqrt{\zeta_r^2 + \zeta_i^2}$ obeys Rayleigh distribution with MSE $\sqrt{2}$. To ensure the variance of the mean amplitude of 1, with ζ_r and ζ_i $\sqrt{2}$ times reduction, formula (6) is converted to:

$$H\left(\vec{k}, t\right) = \frac{1}{\sqrt{2}}(\zeta_r + i\zeta_i)A(\vec{k})\exp(i\omega(k)t) \quad (7)$$

For amplitude $A(\vec{k})$, a simple method is to generate a random interval. However, the simulation will randomly generate a wide gap between the energy distribution of the waves and the real sea statistics observed. And the simulation results cannot be adjusted. Based on the theory of spectral amplitudes to calculate amplitude $A(\vec{k})$ using the integral method, then extended to arbitrary spectral sampling.

The number of composed wave is K, which is related to the frequency and number of discrete angular direction. Wave energy is concentrated in a very narrow frequency domain. With low wind speed, wave energy is widely distributed and needs a wide spectral range. Conversely, with fast wind speed, wave energy relatively concentrated and needs a narrow spectral range. The composition of the composed wave frequency concentrated in a small band.

Assuming that the proportion of spectral energy distribution with total energy is μ whether high or low frequency:

$$\mu = \frac{\int_0^{\omega_{\min}} S(\omega)d\omega}{\int_0^{\infty} S(\omega)d\omega} = \frac{\int_{\omega_{\max}}^{\infty} S(\omega)d\omega}{\int_0^{\infty} S(\omega)d\omega} \quad (8)$$

Since P-M wave spectrum shows full development of the marine environment after the wind action a few hours. Variance of wave height is basically stable and energy absorption and release is basically balance. We use $\omega_{\max}$ and ω_{min} to represent of upper and lower frequency. Therefore, we can conclude from formula (7) and (8) that:

$$\begin{cases} \omega_{\max} = \left[-\frac{3.11}{\overline{\zeta}^2_{a\frac{1}{3}} \ln(1-\mu)}\right]^{1/4} \\ \omega_{min} = \left[-\frac{3.11}{\overline{\zeta}^2_{a\frac{1}{3}} \ln(\mu)}\right]^{1/4} \end{cases} \quad (9)$$

We selected $\mu = 0.005$ to make sure that the proportion of spectral range energy in total energy is up to 99%. Direction angle θ shows a single propagation direction. In theory, θ can be any values in $[0,2\pi]$. But the actual ocean energy distributed in the $\pi/2$ range direction on both sides, so we select this direction angle in $[-\pi/2,\pi/2]$.

After determining simulation spectrum and direction angle range, we need to select the sampling area $[\omega_{min},\omega_{max}]\times[\theta_{min}, \theta_{max}]$ to covering most of the energy region of directional spectrum. A simple method is to sample interval bisection method: The frequency range and direction of the interval respectively is divided M and N equally. Take a fixed size sample sub-regional $\Delta\omega\times\Delta\theta$ to make sure $\Delta\omega=(\omega_{max}-\omega_{min})/M$ and $\Delta\theta=(\theta_{max}-\theta_{min})/N$. Make frequency and orientation corresponding with each sample sub-regional centers as unit wave frequency and direction. Substituting it into formula (9) to solve the amplitude corresponded with. When all sample frequency and direction of sub-domain and amplitude values are obtained, sampling work came to an end.

$$A(\vec{k})=\sqrt{2S(\omega,\theta)\Delta\omega\Delta\theta} \tag{10}$$

Although the interval bisection method algorithm is simple and easy to implement, the number of samples is relatively large. For M = 30, N = 30, there are 900 Unit waves superposition of synthetic waves, not suitable for real-time computing. In this paper, an adaptive method is proposed. Firstly use quadtree sampling method to extract the relevant unit wave parameters and then save this unit wave into unit wave list for facilitate subsequent synthesis of computing.

Assuming P_r , P_{sr} are respectively the ratio of directional spectrum in total energy of sampling area $[\omega_{min},\omega_{max}]\times[\theta_{min}, \theta_{max}]$ and sub-sampling region. P_{lsr} is the limit proportional of directional spectrum in total energy of sub-sampling region. Quadtree sampling process is as follows:

Step1: Set wind speed, wind zone length, P_r , P_{lsr} . Step2: Calculate the total energy directional spectrum E_{ds} according to the formula (9). Step3: Solve directional spectrum isosurface S_{J-ITTC} . The spectral energy value of surrounding rectangle area of osurface orthogonal with S_{J-ITTC} is $P_r \cdot E_{ds}$. Step4: Take the rectangle area as a sample area and solve ω_{min} , ω_{max} , θ_{min} and θ_{max} .Step5: Divide the areas into four equal sub-areas, solve sub-areas frequency, direction of the boundary value, energy value and P_{sr} . Step6: Each sample sub-region pushed onto the stack. Step7: Determine whether the stack is empty, non-empty goes to Step8 or else goes to Step Step11. Step8: Last stacked sub-region stack. If the sub-region $P_{sr}>P_{lsr}$, go to Step5. Or go to Step9. Step9: Take the regional center frequency and direction angle as unit wave frequency and direction. Solve its corresponding amplitudes according to formula (10) and join the unit wave to the list. Step10: go to Step7. Step11: Sampling ends and we can get each unit wave information though traversing the list.

With quadtree sampling method, the energy density area is proportional to the sampling number. The number of samples is greatly reduced compared with the interval bisection method. As S_{J-ITTC} symmetry about face $\theta=0$ ($\theta_{max}=-\theta_{min}$), sampling can be carried out separately within region $[\omega_{min},\omega_{max}]\times[\theta_{min},0]$, then the region $[\omega_{min},\omega_{max}]\times[0, \theta_{max}]$ sampling results can be obtained by symmetry.

After determined wave parameters for each unit wave, each frame of simulation needs to calculate one times $H(\vec{k},t)$, three times FFT, 1 times the normal calculation. Our method is suitable for high-precision and large scale dynamic of real-time ocean waves Simulation.

B. Analysis of Simulation Results

Our experimental environment: PC machine（8-core CPU Intel (R) Core (TM) i7-3770@3.40GHz, Memory 1×8G, Graphics NVIDIA Geforce GTX660Ti), Microsoft Visual Studio 10.0, OpenGL 3.0. The effect of surface waves simulation result is shown in figure 4 and 5.

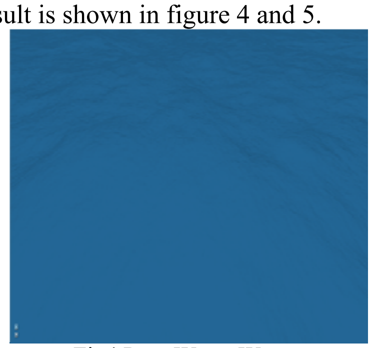

Fig4 Pure Water Waves

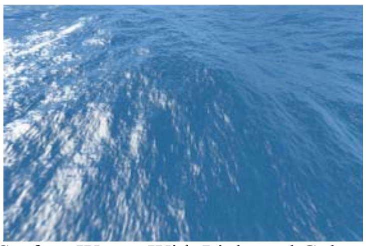

Fig.5 Surface Waves With Light and Color of Sky

We contrast pure water waves with surface waves with light and color of the sky. Without effects, such as lighting and scene (energy and grid), the entire surface is dark, poor realism and difficult to distinguish surface details. As shown in figure 4, through the wave spectrum theory building height field and multi-resolution mesh LOD drawing based on quadtree, realism enhanced a lot. You can see the water facing the light reflections as well as mixing color change of water color and light color and sky color.

IV. CONCLUSION

We propose a complete high-precision and large scale dynamic simulation of real-time ocean waves. Our approach includes: firstly analyze each method of ocean waves simulation, propose a method of quadtree to draw high-precision Mesh LOD high-precision seamless grid. Then improve wavelet Gerstner model for wave surface by introducing control factor to control individual waveform and using superposition of Gerstner unit waves with different parameters. At last, using P-M wave spectrum theory to calculate Gerstner unit waveform parameters and sampling unit wave parameters according to the principle quadtree. Through simulation, our approach has real effects of waves and works well.

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REFERENCES

[1] Yu Yuxiu. "Random Wave and its Engineering Applications." Dalian: Dalian University of Technology Press. 2003 (11): 132-143.

[2] Mitchell J L. "Real-time synthesis and rendering of ocean water." Canada: ATI Research Technical Report. 2005.

[3] Foster N, Metaxas D. "Modeling water for computer animation." Communications of the ACM. 2000,43(7): 60-67.

[4] Wang, Changbo, et al. "Real-time simulation of ocean wave based on cellular automata." Proceedings of CAD/Graphics. 2003: 197-203.

[5] Yin, Yong, Yi-cheng Jin, Hong-xiang Ren. "Wave simulation of visual system in marine simulator based on wave spectrums." Proceedings of MARSIM. 2003(3): 288-294.

[6] Wang, Jin-Liang. "A New Ocean Wave Model which do not Rely on Navier-Stokes Equations." arXiv preprint arXiv. 2013: 1304-1463.

[7] Blinn J F. "Simulation of Wrinkled Surfaces." ACM SIGGRAPH Computer Graphics. 1978,12(3): 286-292.

[8] Darles, Emmanuelle, Benoıt Crespin, Djamchid Ghazanfarpour. "Accelerating and enhancing rendering of realistic ocean scenes." Proceedings of WSCG. 2007: 287-294.

[9] Fishman B, Schachter B. "Computer display of height fields." Computers & Graphics. 1980(5): 53-60.

[10] Wang, Dinghua, et al. "Study of Real-Time Wave Simulation in Virtual Battlefield Environment." System Simulation and Scientific Computing. Springer Berlin Heidelberg. 2012: 61-69.

[11] Tessendorf, Jerry. "Simulating ocean water." Simulating Nature: Realistic and Interactive Techniques. SIGGRAPH. 2001.

[12] Wu J, Yang Y, Gong S, et al. "A New Quadtree-based Terrain LOD Algorithm. " Journal of Software. 2010,5(7): 769-776.

[13] Nielsen, Michael B, Andreas Söderström, Robert Bridson." Synthesizing waves from animated height fields." ACM Transactions on Graphics (TOG). 2013: 2.

[14] Liu, Paul C. "Contemplating Ocean Wave Measurements." International Journal of Geosciences. 2013.

[15] Rusu, Eugen, Florin Onea. "Evaluation of the wind and wave energy along the Caspian Sea." Energy. 2013.