Study of wave load computation based on diffraction theory

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Abstract. With the development of the ocean resources, the design of the offshore platform attracts increasing attention. The wave load computation is an important part for the design of the offshore platform. Currently, model experiments are mainly used to get the wave load of the offshore platform, which is complex, inefficient, and error-prone. To improve the efficiency of calculation, more simplified formulas for the wave load computation were deduced based on the wave diffraction theory. Moreover, a simple method was proposed based on the Matlab and software was developed to calculate the wave load. Experiments were conducted by a designed cylinder floater model to obtain the values of the wave load. Some simulations were made to calculate the wave load under the condition that water depth, wave frequency and other relevant parameters were same with the experiments. The wave load values calculated by the software had similar change trends with that of the experiment data, which proved the feasibility of the formulas for the wave load computation based on diffraction theory and the accuracy of the numerical algorithm in the computation of wave load based on Matlab. Compared with the model experiments, the software based on the diffraction theory was a cheaper and convenient way to obtain the values of wave load when the platform in the ocean is designed. So the new method will improve the efficiency in the wave load computation and is in favour of the design of offshore platform.

1. Introduction

Broadly speaking, all energies on earth come from solar energy. Oceans occupy 71% of the earth's surface and are the world's largest solar absorber, containing a large amount of renewable energies. The wave energy, tidal energy, thermal energy, salinity gradient energy and others are the primarily forms of marine renewable energies. The actual utilized amount of wave energy is about 3×10⁷kW, which is richer than the most marine renewable energy [1]. With the development of society, the rapid consumption of fossil fuels, the global energy shortage and the problem of air pollution greatly promote more countries to realize the importance of ocean wave energy conversion technology. A large amount of research funding has been used to improve the key technology for the utilization of the marine resources, especially the design and development of offshore platform. However, the current wave load computation for the offshore platform contains cumbersome steps, which affects the development efficiency of offshore platform.
Newman [2] deduced the force and moment of the wave load with the Haskind relations. Patankar and Spalding [3] utilized the method of SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) to study the wave load. Hulme [4] deduced the hydrodynamic coefficient of a floating hemisphere under periodic forced vibration, which has significant promotion effect on the development of wave load computation. The effect of the flow field caused by the floater, the wave diffraction, and the wave radiation should be taken into consideration in the research of wave load, where the diffraction theory is necessary, especially compared with the wavelength, the offshore platform that feature size is relatively large [5].

In this research, a brief interpretation about the diffraction theory was introduced first of all. The numerical method for the wave load computation was deduced based on the diffraction theory. The software for rapid computation of the wave load was developed based on the deduced numerical method, using the Matlab and a semi analytical method. Experiments were conducted by a designed cylinder floater model to obtain the values of the wave load. Some simulations were made by the developed software to calculate the wave load with the same parameters as the experiments. Compared with the data from the experiments and simulations, the wave load values had similar change trends with time, which proved the accuracy of the deduced numerical method.

2. Wave diffraction theory
In 1954, Mac Camy and Fuchs put forward the diffraction theory [6], which assumed that the fluid is ideal incompressible and the movement is potential. Besides, the theory takes the boundary of structural component as part of the fluctuant boundary of the fluid. And then the diffraction velocity potential \( \Phi'(x,y,z,t) \) (which is formed by the incident wave on the boundary of structural component) and the velocity potential \( \Phi''(x,y,z,t) \) (which is formed by the incident wave without the disturbance of the structural component) are available [7]. The summation of \( \Phi'(x,y,z,t) \) and \( \Phi''(x,y,z,t) \) is the total velocity potential \( \Phi(x,y,z,t) \) (which focus on the boundary of structural component with disturbance ), and then the accurate analytical solution can be deduced with the linear Bernoulli equation [8] as Eq (24), which is described in detail in the following.

For the movement of large-scale component in the slight wave, the wave load can be divided into diffraction load and radiation load. An outward scattered wave will be created on the surface of the barrier when the wave comes to a barrier. The scattered wave and the incident wave will couple into a new steady flow field, and the function of the flow field on the structural component is the diffraction load. The large-scale offshore platforms, such as the large oil storage tanks and the large sea buoys, have significant effects on the wave motion. Therefore, the diffraction effect and free surface effect should be taken into consideration and the wave diffraction theory should be used to calculate the wave load.

3. Establishment of the kinetic equation
3.1. Establishment of the coordinate system
To use the diffraction theory for the solution of the velocity potential and the wave load, the following assumptions should be made to simplify the problems:
(1) The fluid in the flow field is ideal and the motion of fluid in the wave field is irrotational, which follows the potential flow theory;
(2) The incident wave is a kind of linear small amplitude wave. The wave amplitude can be calculated based on the linear small amplitude wave theory under the condition that the wave amplitude is much smaller than the wavelength or water depth [9].

Assuming that the floater is an equal diameter cylinder. The cylindrical coordinate system \((r, \theta, z)\) is set as the coordinate system of floater movement [10], the coordinate origin is defined on the intersection of the floater center line and the static water surface, marked as O. The Z axis is vertical to the horizontal plane, the incident wave is a kind of linear small amplitude wave, whose amplitude is A.
As shown in Figure 1, the incident wave goes along the X axis direction in the cylindrical coordinate system [11]. In addition, a represents the cylinder diameter, b represents the draft, l represents the water depth (the line of flotation coincides with the x-axis) in Figure 1. The circular frequency of the wave is \( \omega = 2\pi / T \), where T represents the wave period.

3.2. Velocity potential function

Based on the assumptions above, the fluid in the flow field is potential, and its motion can be described by potential function as [12]:

\[
\Phi(x, y, z, t) = \text{Re} \left\{ \varphi(x, y, z)e^{-i\omega t} \right\}
\]

(1)

where \( \Phi(x, y, z, t) \) is the potential function, \( \text{Re} \) means the real part of the function, \( i \) is the symbol for imaginary number, \( t \) is the movement time.

The velocity potential function should follow the Laplace equation, the boundary condition of seabed, the boundary condition of free surface and the boundary condition of material surface, as [13]:

\[
\nabla^2 \Phi(x, y, z, t) = 0 \quad \text{(the Laplace equation)}
\]

(2)

\[
\frac{\partial \Phi(x, y, z, t)}{\partial z} = 0 \quad \text{at} \quad z = -l
\]

(3)

\[
\frac{\partial^2 \Phi(x, y, z, t)}{\partial t^2} + g \frac{\partial \Phi(x, y, z, t)}{\partial t} = 0 \quad \text{at} \quad z = 0
\]

(4)

where \( g \) represents the acceleration of gravity.

\[
\begin{align*}
\frac{\partial \Phi(x, y, z, t)}{\partial r} & = 0 \quad \text{at} \quad r = a, -b \leq z \leq 0 \\
\frac{\partial \Phi(x, y, z, t)}{\partial z} & = 0 \quad \text{at} \quad 0 \leq r \leq a, z = -b
\end{align*}
\]

(5)

\[
\lim_{r \to \infty} \nabla \Phi(x, y, z, t) = 0
\]

some radiation condition at infinity, no longer discussed in the paper (6)

As shown in Figure 1, the inner domain (Domain 1, where is expressed as number 1) and the external domain (Domain 2, where is expressed as number 2) together form the flow field. Domain 1 refers to the bottom of the floater and the columnar domain with the equal sectional area of the floater. Domain 2 refers to the floater itself and the flow field out of the Domain 1. The Domain 1 contains only one velocity potential, denoted by \( \Phi_i(x, y, z, t) \), while the incident velocity potential (denoted by
\( \Phi_{21}(x, y, z, t) \) and the diffraction velocity potential (denoted by \( \Phi_{2D}(x, y, z, t) \)) constitute the total velocity potential (denoted by \( \Phi_2(x, y, z, t) \)) in Domain 2. There are some mathematical equations used to describe the velocity potential as following:

\[
\Phi(x, y, z, t) = \begin{cases} 
\Phi_1(x, y, z, t) & (0 \leq r < a, -l \leq z \leq b) \\
\Phi_2(x, y, z, t) = \Phi_{21}(x, y, z, t) + \Phi_{2D}(x, y, z, t) & (a \leq r, -b \leq z \leq 0)
\end{cases}
\]  

(7)

On the juncture of Domain 1 and Domain 2, \( \Phi_1(x, y, z, t) \) and \( \Phi_2(x, y, z, t) \) must follow the transfer conservation conditions of speed, pressure and mass, as:

\[
\Phi_1(x, y, z, t) = \Phi_{21}(x, y, z, t) + \Phi_{2D}(x, y, z, t) & (r = a, -l \leq z \leq -b) \\
\frac{\partial \Phi_1(r, \theta, z)}{\partial r} = \frac{\partial \Phi_{21}(r, \theta, z)}{\partial r} + \frac{\partial \Phi_{2D}(r, \theta, z)}{\partial r} & (r = a, -b \leq z \leq 0)
\]

(8)

(9)

3.3. Simplification of velocity potential function

\( \Phi_1(r, \theta, z) \) can be expressed by the series expansion as:

\[
\Phi_1(r, \theta, z) = \frac{gA}{\omega} \sum_{m=0}^{\infty} \Psi_{1m}(r, z) \cos m\theta \cdot e^{i\omega t}
\]

(10)

where \( m \) is the order.

A special solution of modified Bessel function can be obtained in the method of separation of variables, as:

\[
I_m\left(\frac{n\pi r}{l-b}\right) = \sum_{k=0}^{\infty} \left(\frac{n\pi r}{2(l-b)}\right)^{m+2k} k!(m+k+1)!
\]

(11)

where \( n \) and \( k \) are the coefficients for the special solution of Bessel function.

Under the boundary condition, the characteristic function of \( \Phi_1(r, \theta, z) \) (denoted by \( \Psi_{1m}(r, z) \)) can be described as:

\[
\Psi_{1m}(r, z) = \frac{1}{2} A_0^m \left(\frac{r}{a}\right)^m + \sum_{n=1}^{\infty} A_n^m \left(\frac{n\pi r}{l-b}\right)^m \cos \left(\frac{n\pi(l+z)}{l-b}\right)
\]

(12)

where \( A_n^m \) is the coefficient which is undetermined.

\( \Phi_{21}(r, \theta, z) \) can be described as:

\[
\Phi_{21}(r, \theta, z) = \frac{gA}{\omega} \cosh k_0 (z+l) \sum_{m=0}^{\infty} \epsilon_m^m J_m(k_0 r) \cos m\theta \cdot e^{-i\omega t}
\]

(13)

where \( J_m(x) \) is the \( m \) order Bessel function of the first kind, \( k_0 \) is the wave number, \( \epsilon_m^m \) is Neumann constant, \( \epsilon_m^m = 1 \) when \( m=0 \) and \( \epsilon_m^m = 2 \) when \( m \geq 1 \).
\( \Phi_{2D}(r, \theta, z) \) can be divided into two parts: the diffraction velocity potential for the floater (denoted by \( \Phi^{(1)}_{2D}(r, \theta, z) \)) and the diffraction velocity potential for Domain 1 (denoted by \( \Phi^{(2)}_{2D}(r, \theta, z) \)), as:

\[
\Phi_{2D}(r, \theta, z) = \Phi^{(1)}_{2D}(r, \theta, z) + \Phi^{(2)}_{2D}(r, \theta, z)
\]  

(14)

\( \Phi^{(1)}_{2D}(r, \theta, z) \) can be described by the characteristic function (denoted by \( \Psi_{21}^{m}(r) \)) as:

\[
\Phi^{(1)}_{2D}(r, \theta, z) = \frac{gA}{\omega} \frac{\cosh k_0 (z + l)}{\cosh k_0 b} \sum_{m=0}^{\infty} e_m^{m+1} \Psi_{21}^{m}(r) \cos m \theta \cdot e^{-i \omega t}
\]  

(15)

\( \Psi_{21}^{m}(r) \) can be described as:

\[
\Psi_{21}^{m}(r) = C_m H_m(k_0 r)
\]  

(16)

where \( H_m(k_0 r) \) is the Bessel function of the third kind, \( C_m \) is the undetermined coefficient determined by the boundary condition. \( \Phi^{(2)}_{2D}(r, \theta, z) \), which can be solved by the method of separation of variables, as:

\[
\Phi^{(2)}_{2D}(r, \theta, z) = \frac{gA}{\omega} \sum_{m=0}^{\infty} \Psi_{22}^{m}(r, z) \cos m \theta \cdot e^{-i \omega t}
\]  

(17)

\( \Psi_{22}^{m}(r, z) \) can be described as:

\[
\Psi_{22}^{m}(r, z) = B_m^m H_m^0(k_0 r) Z_0(z) + \sum_{q=1}^{\infty} B_m^q K_v(k_q r) Z_v(z)
\]  

(19)

\[
Z_0(z) = \frac{\sqrt{2} \cosh k_q (z + l)}{1 + \frac{\sin 2 k_q l}{2 k_q l}} \quad (q = 0)
\]  

(20)

\[
Z_v(z) = \frac{\sqrt{2} \cos k_q (z + l)}{1 + \frac{\sin 2 k_q l}{2 k_q l}} \quad (q = 1, 2, 3 \ldots)
\]  

(21)

where \( B_m^m \) and \( k_q \) are undetermined coefficients, and the value of \( k_q \) is solved below. \( K_v(k_q a) \) is the derivative of \( K_v(k_q a) \).

\( \Phi_{2}(r, \theta, z) \) is associated with Eqs (13) to (21) and can be solved, and can be described by the characteristic function, as:

\[
\Phi_{2}(r, \theta, z) = \Phi_{21}(r, \theta, z) + \Phi^{(1)}_{2D}(r, \theta, z) + \Phi^{(2)}_{2D}(r, \theta, z) = \frac{gA}{\omega} \sum_{m=0}^{\infty} \Psi_{2}^{m}(r, z) \cos m \theta \cdot e^{-i \omega t}
\]  

(22)

\[
\Psi_{2}^{m}(r, z) = e_m^{m+1} \frac{\cosh k_0 (z + l)}{\cosh k_0 b} \left[ J_m(k_q r) - \frac{J_v(k_q a)}{H_v(k_q a)} H_v(k_q r) \right] Z_0(z) + \sum_{q=1}^{\infty} e_q^{m+1} \frac{K_v(k_q r)}{K_v(k_q a)} Z_v(z)
\]  

(23)
3.4. Wave excitation force computation

The pressure of any point (denoted by p) in the flow field can be calculated by the linear Bernoulli equation, as:

\[ p = \rho \frac{\partial \Phi}{\partial t} \]  

(24)

where \( \rho \) is the density of seawater. The total wave excitation force is available based on the pressure of any point in the flow field and the material surface integral, as:

\[ F = \iint_S p \cdot n(x, y, z) \, dS \]  

(25)

where \( n(x, y, z) \) means the unit normal vector on the floater surface and \( S \) means the wet surface of the floater. As the floater is a cylinder, there are only two kinds of loads, the vertical swing (\( x \) direction) and the heave swing (\( z \) direction), as:

\[ F_x = \rho g A \pi a^2 \left\{ \frac{2i}{k_0 \cosh k_0 l} \left[ J_1(k_0 a) - \frac{J_1'(k_0 a)}{H_1'(k_0 a)} H_1(k_0 a) \right] \right\} e^{i\omega t} \]  

(26)

\[ F_z = \rho g A \pi a^2 \left\{ \frac{1}{2} \frac{iA^0}{a \pi} - \frac{2i}{a \pi} \sum_{n=1}^{\infty} \frac{(-1)^n}{n I_0(n \pi a/l - b)} I_1(n \pi a/l - b) \right\} e^{-i\omega t} \]  

(27)

4. The vertical wave load computation

4.1. Computation of coefficients

\( k_0 \) can be obtained by dispersion equation Eq (28) [14]:

\[ \omega^2 = g k_0 \tanh k_0 l \]  

(28)

As the dispersion equation is a kind of transcendental equation, if the value of water-depth is available, the result can be obtained by the figure drawn by the Matlab. Usually, \( l \) and \( \Omega \) determine \( k_0 \). The value of \( k_0 \) is obtained by direct solution.

As for \( k_q^l \), it is the positive root of the Eq (29). As Function tan ( ) is a kind of special function, the direct solution has large deviation. The result can be obtained by the figure drawn of the Matlab.

\[ \omega^2 = -g k_q^l \tan k_q^l \]  

(q=1,2,3…)  

(29)

The \( k_q^l \) can be taken as a whole and Eq (29) can be deformed as:

\[ \tan k_q^l = -\frac{\omega^2 l}{g k_q^l} \]  

(30)

As shown in Figure 2, the abscissa represents \( k_q^l \). \( k_q^l \) is meant by value of the abscissa for the point of intersection. Under the condition of \( \Omega \) is within a certain range, \( k_q^l \approx \pi \) as \( q = 1 \), \( k_q^l \approx 2\pi \) as \( q = 2 \), \( k_q^l \approx 3\pi \) as \( q = 3 \) and so on. \( k_q^l \) can be taken as \( q \pi / l \) approximately [15].
There are undetermined coefficients $A_m^n$ and $B_q^n$ in Eq (26) and Eq (27), which can be deduced based on the orthogonality of trigonometric functions [16], as:

$$B_q^n = \sum_{m=0}^{\infty} G_{qn}^m A_m^n \quad (m, q = 0, 1, 2 \cdots) \quad (31)$$

$$A_m^n + \sum_{q=0}^{\infty} D_{mn}^q \sum_{q=0}^{\infty} G_{qn}^m A_m^n = R_n^m \quad (m, n = 0, 1, 2 \cdots) \quad (32)$$

### 4.2. Model experiments

A cylinder-type model is used to test the vertical wave load, which is designed by reference to the actual equipment, as shown in Figure 3. The model consists of two parts, the floater and the buoy. The cylinder floater is 0.6 m in diameter, 0.16 m in height and 11.25 kg in quality. The physical model was designed according to the scale ratio of 10:1, which is based on the structure and size of the actual equipment.

The experiment of model hydrodynamic were carried out in a wave-making pool. In the experiment the buoy was immersed into water while the floater floated on the water surface, which moved with the wave, as shown in Figure 4. The acceleration can be measured with the sensors on the floater and the wave load can be deduced.

The main object of this paper is solving the wave load. Waves propagate forward by gravity, which is called gravity wave. Therefore, the conditions of gravity similarity and inertia must be satisfied between the entity and the model, that is, the Fudard number and the Stowha number are equal [17].

$$\frac{v_m}{\lambda} = \frac{V_s}{\lambda}, \quad \frac{\rho_m}{\rho_s}, \quad \frac{\rho_m}{\rho_s}, \quad \frac{V_s T_m}{L_m} = \frac{V_s T_s}{L_s} \quad (33)$$

Where $v$ represents the velocity, $L$ represents the characteristic length, $T$ represents the period, $m$ represents the model, $s$ is the prototype. According to the main scale of the prototype device and the scale of the pool, the scaling ratio of this model test is determined as 10:1. $\lambda$ represents the linear scaling ratio of the model, $\lambda=10$.

Wave Load $F$ satisfies the similarity criterion equation Eq (34)

$$\frac{F_s}{F_m} = \gamma^3 \lambda^3 \quad (34)$$

Where $\gamma$ represents the ratio of seawater to freshwater density.

### 4.3. Wave load computation

![Figure 3. The cylinder-type model.](image3)

![Figure 4. The experiment test of model.](image4)
The software to calculate the wave load of large-scale cylinder floater was developed based on the wave diffraction theory and the Matlab language. The results from the experiments is compared with that from the numerical computation on the purpose of verifying the correctness of the theoretical derivation and the numerical computation.

The waves of experiment are caused by wave machines in the pool. The wave parameters are consistent and the model float diameter is determined. By adjusting the draft of the floating body, increase the number of experimental groups, and explore the influence of draft depth on the wave load. In the numerical computation, parameters are set followed the experiment. The draught depth of the model float is selected according to the design parameters of the actual device. The cylinder floater is 0.16 m in height. The initial draught depth is set to the half of the height of the model float. In group A (shown in Figure 5) the draft depth is 0.08m (b=0.08m) and in group B (shown in Figure 6) the draft depth is 0.04m (b=0.04m) which is reduced in order to provide a control experiment group.

In group A, the diameter of the floater is 0.6m (a=0.6m), draft depth is 0.08m (b=0.08m), the period of wave is 1.2s (T=1.2s), the wave height is 1.2m in the pool. The test value from the experiment and the computation value from the software of the vertical wave load are shown in Figure 5. It can be seen from Figure 5 that the test value and computation value of the vertical wave load have the similar change trends with time. But it is hard to control the wave height in the experiment. Although it changed a lot because of randomness of the wave, the computation value is consistent with the test value in the maximum and minimum.

In group B, another experiment was conducted to verify the diffraction theory. In the experiment, the diameter of the floater is 0.6m (a=0.6m), the draft depth is 0.04m (b=0.04m), the wave period is 1.2s (T=1.2s), the wave height is 0.8m. The test value from the experiment and the computation value from the software of the vertical wave load are shown in Figure 6. It can be seen from Figure 6 that the wave load changes become smaller with the decrease of the wave height. From the comparison we know that the test value and the computation value of the vertical wave load has a better similarity in the change trends with time, which means the change trends of the wave load can be deduced by the diffraction theory accurately.

What’s more, the comparison of the test value and computation value shows that the value in numerical computation is smaller than that in the experiment. It is because that the diffraction theory only takes the diffraction effects of the floater into consideration in the numerical computation, ignoring the radiation effect.

Through a comparative analysis of the group A and the group B, it is found that the draft of the floating body has little effect on the wave load.

![Figure 5. Comparison of the test value and computation value when b=0.08m. (group A).](image1)

![Figure 6. Comparison of the test value and computation value when b=0.04m. (group B).](image2)
5. Conclusion and outlook

The numerical method for the wave load computation was concluded based on the diffraction theory. The wave load expressions could be deduced from the numerical method easily, shown as Eq (26) and Eq (27). The two expressions show that the wave load is periodic and has the same period with the wave. Besides, the magnitude of the wave load is related to the parameters of the wave and the seawater, such as the wave amplitude, the wave period, and the seawater density. The relations between the wave load and relevant parameters all are nonlinear.

The numerical method makes wave load computation in computer possible. The software for the wave load computation was developed just based on the numerical method. The Figure 5 and Figure 6 show that the data from the experiments by a designed cylinder floater model and the simulations by the software has similar change trends with time, which indicates the software could show the wave load change trends in a period. What’s more, the two figures show the maximum and the minimum from the software are approximately equal to that of the experiments, which indicates the numerical method could calculate the wave load. Compared with the model experiments, the software based on the numerical method is a quicker and cheaper way to obtain the wave load.

Because of the time and the cost, no experiment on the real large-scale offshore platform was conducted. In the further study, a physical floater can be produced to conduct the sea experiments and to record corresponding experimental data. Based on the data, compensations can be integrated into the numerical computation method to improve the accuracy.

Acknowledgements

Work is financially supported by the Joint Research Fund under cooperative agreement between the National Natural Science Foundation of China (NSFC) and Shandong Provincial People's Government (U1706230), Marine Renewable Energy Fund Project (GHME2017YY01), Shandong Province Major Science and Technology Innovation Project (2018CXGC0104), and national key research and development plan (2017YFE0115000), hereby thanks. Liu Yanjun (Email: lyj111ky@163.com) and Xue Gang (Email: xuegangzb@163.com) are the corresponding authors of this paper.

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