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Research on Torque Calculation of Active Absorption Technology for Wavemaker Using Force-Feedback Control

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Abstract: In ocean engineering test basin, when the model test is carried out, the wave generated by the wavemaker generates reflected wave after being reflected from the basin wall and structural model, which propagates to the wave-making plates and reflects again to generate secondary reflected wave. The secondary reflected wave interferes with the wave field of the basin, thus reducing the accuracy of the test. The active absorption system is often used to eliminate the secondary reflection wave. The active absorbing theory is the theoretical basis for wave-maker to achieve the wave-making function. This paper investigates force-feedback active absorption theory for flap-type wavemaker. Based on the expansion of two-dimensional wave theory, the velocity potential solutions of three-dimensional irregular wave theory are obtained. According to the relationship between velocity potential solution and pressure, the analytical expression of wave torque acting on wave-making paddles is obtained. The first-order torque of regular and irregular wave derived from linear wave theory can be used as the theoretical basis for developing multidirectional absorption system.

Key words: Flap-type wavemaker, active absorption system, force-feedback, fluid force.

1. Introduction

The ocean engineering basin is used to simulate the ocean environment such as wind, wave and fluid to carry out tests and researches, especially through wave-makers to produce wave. But the flume or basin compared with the real marine environment has fixed boundary limit, so, there are often secondary reflection waves in the flume or basin. The incident wave produced by the wave-maker produces the reflection wave at basin wall opposite the wave-maker, then the reflection wave spreading to the wave paddles generates the secondary reflection waves which superpose to the original incident wave which disturbs wave field, damages test accuracy and reduces the test reliability [1].

Theoretical research shows that the flap-type wave-making system with active absorption technology is a good way to reduce or even eliminate the secondary reflection wave. According to the different sensors, active absorption system is divided into force-feedback active absorption system and position-feedback active absorption system. The former uses force sensors fixed on the wave paddles to obtain the fluid force, the latter uses wave gauges to obtain wave elevation. This paper mainly aims at the force-feedback active absorption system, compared with position-feedback, this system using force sensors for data acquisition has the following advantages:

- Firstly, force sensors measure the average of fluid pressure on the wave paddles that is the result of the pressure integration. In the presence of the secondary reflection wave, to obtain valid data we need to set multiple points on the wave paddles. Force-feedback active absorption system is more suitable for the dry-backed wave-makers. The value of fluid force is only related to the water area in front of

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the wave paddles, so force analysis is not complicated, as shown in the Fig. 1.

- Secondly, the dynamic precision of wave gauges is low, which greatly affects the effect of active absorption, and the disturbance of flap-type paddles' movement to force sensor is less, so the arrangement of force sensor is more stable for wave-making system, and the data acquisition is more accurate and convenient.

- Finally, the force sensors facilitate the combination of signals from the force sensors and velocity sensors, which makes the wave-maker and the fluid become a coupled dynamic system. In this way, the output power can be measured directly and the output signals of wave-maker can be corrected. In the regular wave test with the flap-type wave-maker, force-feedback active absorption system can reduce the generation of high order pseudo-harmonic wave in the basin [2].

But at present, active absorption research focused on the position-feedback active absorption, the study of force-feedback active absorption is still very little. Although the technology has been realized in Flowave Basin in Edinburgh, UK, a perfect theory system has not been formed in world, mainly because it has the following two key technical problems:

- The existing force-feedback theory studies are mostly based on ideal linear wave theory, ignoring the influence of nonlinear higher-order terms, resulting in large approximate errors;

- Incoming wave recognition of multidirectional irregular wave—there are many restrictions in existing theories, and the empirical calibration method is mostly adopted;

In view of the characteristics of the force-feedback active absorption system in this paper, the distribution characteristics of the velocity potential solution and pressure of the wavemaking paddles under the dry-back flap-type wavemaking conditions are studied based on the Potential Flow Theory, and the calculation and analysis method of the wave torque on the paddles under unidirectional, multi-directional, regular and irregular wave conditions is given.

2. Two-Dimensional Wave Theory

The coordinate system is established so that the z-axis coincides with the average position of the wavemaking paddles. The wave-maker is arranged along the y-axis, and the x-axis coincides with the still water surface. The still water depth is h, and the bottom of the basin is located at $z = -h$, as shown in Fig. 2.

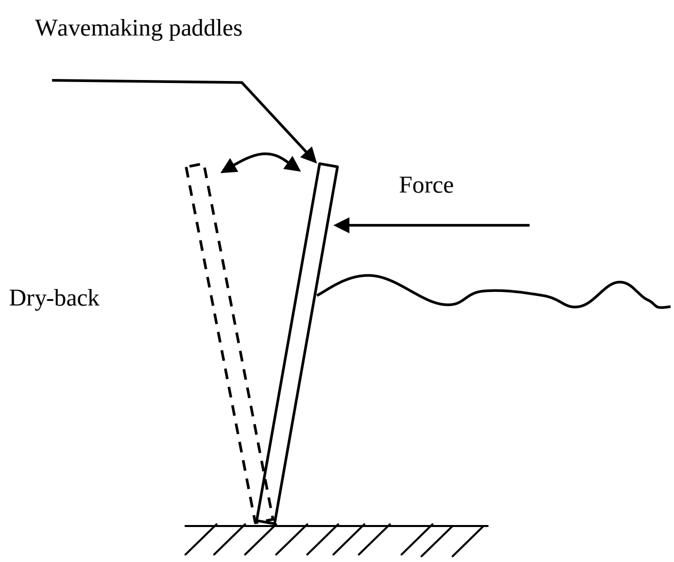

Fig. 1 Layout diagram of force-feedback active absorption test.

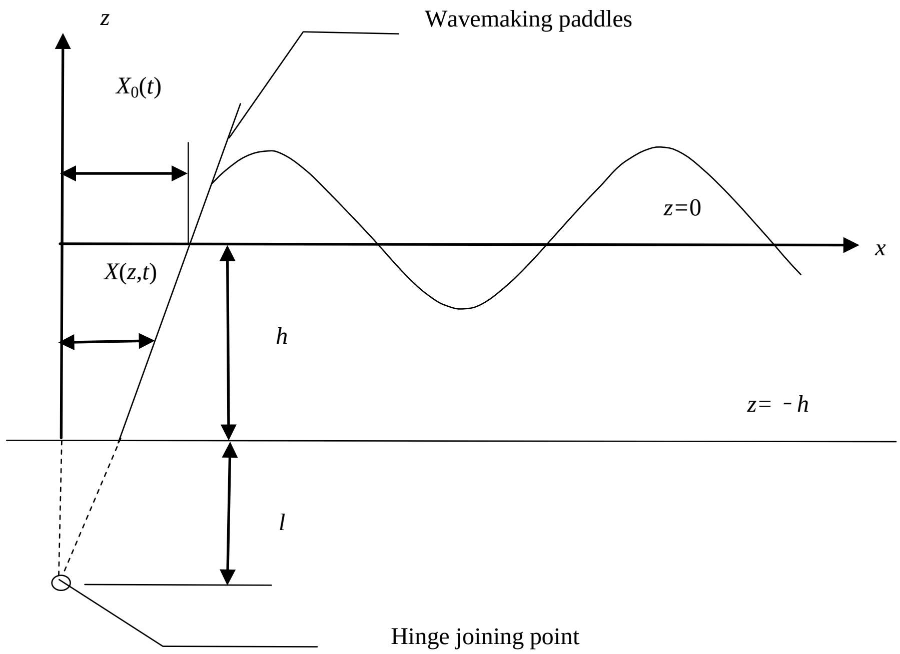

Fig. 2 Wave-maker geometry and definition of notation.

Suppose that the wavemaking paddles move in simple harmonic motion with small amplitude, the wave propagates in the positive *x*-direction. The distance between the wave paddle's hinge and the bottom of the basin is defined as *l*, and the center of rotation of the wave paddle is located at $z = -(h + l)$. If the pivot is above the bottom of the basin, $l < 0$, define the parameter $d = l$. If the pivot is located at or below the bottom of the basin, $l \geq 0$, $d \to 0$; For the piston-type wave-maker, $l = \infty$ and $d = 0$.

Assume that there is incompressible, non-viscous and irrotational fluid in the basin. In the Cartesian coordinate system (x, z) velocity potential is $\Phi(x, z, t)$, then the velocity components are given by $(u, w)^T = (\partial\Phi/\partial x, \partial\Phi/\partial z)^T$, the wave function is $\eta = \eta(x, t)$, paddles' location is $X = X(z, t)$, and the position of the paddles is $X_0(t)$ at the static water surface $z = 0$. θ, ω, g, t respectively represent angular displacement of paddles, wave frequency, gravitational acceleration and time.

(1) The governing equation

Assume that the incompressible fluid has mass conservation, therefore, the fluid satisfies the Laplace equation in the flow field.

$$\nabla^2\Phi = \frac{\partial^2\Phi}{\partial x^2} + \frac{\partial^2\Phi}{\partial z^2} = 0, \qquad -h \leq z \leq 0 \quad (1)$$

(2) The free water surface condition

Assume that the surface height is $z = \eta(x,t)$. The function of movement rule of water particle at free water surface can be expressed as:

$$F(\mathrm{x}, z, t) = z - \eta(x, t) \quad (2)$$

The streamline at the water surface section conforms to the kinematic free water surface boundary condition. According to this boundary condition, we can get:

$$\frac{\partial F}{\partial t} + u \cdot \nabla F = 0 \quad (3)$$

and

$$\frac{\partial \eta}{\partial t} = w - u\frac{\partial \eta}{\partial x} = \frac{\partial \Phi}{\partial z} - \frac{\partial \Phi}{\partial x}\frac{\partial \eta}{\partial x} \quad (4)$$

In addition, the surface pressure conforms to the dynamic free surface boundary condition. The pressure at the water surface is equal to the atmospheric pressure above it, so the pressure is zero. From Bernoulli's equation we can get:

$$g\eta + \frac{\partial \Phi}{\partial t} + \frac{1}{2}\left(u^2 + w^2\right) = 0 \tag{5}$$

Assuming a small wave amplitude (relative to the wave length), the above kinematic and dynamic free surface boundary conditions can be linearized according to the linear theory into:

$$g\frac{\partial \Phi}{\partial z} + \frac{\partial^2 \Phi}{\partial t^2} = 0, \quad z = 0 \tag{6}$$

(3) The bottom boundary condition

The bottom of the basin is horizontal and impermeable. At the bottom of the basin, the component of the fluid velocity perpendicular to the bottom of the basin is zero.

$$w = \frac{\partial \Phi}{\partial z} = 0, \quad z = -h \tag{7}$$

(4) The object surface boundary condition

The wavemaking paddles are impermeable solid boundaries. At the paddles, the velocity component of the fluid perpendicular to the paddles v_n is equal to the velocity of the paddles that:

$$v_n = r\frac{d\theta}{dt} \tag{8}$$

According to the paddles motion, the radiation radius r can be expressed as:

$$r = \sqrt{X^2(z,t) + (z+h+l)^2} = (z+h+l)\sqrt{1+\tan^2\theta} \tag{9}$$

According to the horizontal velocity and vertical velocity of the fluid (u, w), the fluid velocity perpendicular to the paddles can also be expressed as:

$$v_n = u\cos\theta - w\sin\theta \tag{10}$$

The position of the paddles can be represented by the stroke $X_0(t)$ of the paddles, $X(z,t) = f(z)X_0(t)$. Assume that the paddles' stroke is minimal relative to the its length, then $X_0/(h+l) = \tan\theta << 1$. Small-angle approximation is adopted [3], then:

$$u\cos\theta - w\sin\theta \approx u = \frac{\partial \Phi}{\partial x} \tag{11}$$

and

$$\theta \approx \tan\theta = \frac{X(z,t)}{z+h+l} = \frac{X_0(t)}{h+l} \tag{12}$$

By substituting Eqs. (9)-(12) into Eq. (8), the boundary condition at the paddles can be obtained as:

$$\frac{\partial \Phi}{\partial x} = \frac{\partial X(z,t)}{\partial t} = f(z)\frac{dX_0}{dt} \tag{13}$$

and

$$f(z) = \begin{cases} 1 + \dfrac{z}{h+l}, -(h-d) \le z \le 0 \\ 0, \quad -h \le z \le -(h-d) \end{cases} \tag{14}$$

The time factor of velocity potential is separated by the method of separating variables [4], and the velocity potential component is solved by using the governing equation and boundary conditions. Then the expression of velocity potential can be calculated as follows. Considering the object surface condition at the paddles, the velocity potential solution of the wave-makers problem under linear conditions is expressed as a complex form.

$$\Phi(x,z,t) = \frac{igS}{2\omega}C_0\frac{\cosh k_0(z+h)}{\cosh k_0 h}e^{i(\omega t - k_0 x)} + \sum_{n=1}^{\infty}\frac{gS}{2\omega}C_n\frac{\cos k_n(z+h)}{\cos k_n h}e^{i\omega t - k_n x} \tag{15}$$

where,

$$C_0 = \frac{4\sinh k_0 h}{2k_0 h + \sinh 2k_0 h}\left(\sinh k_0 h + \frac{\cosh k_0 l - \cosh k_0 h}{k_0(h+l)}\right) \tag{16}$$

$$C_n = \frac{4\sin k_n h}{2k_n h + \sin 2k_n h}\left(\sin k_n h + \frac{\cos k_n l - \cos k_n h}{k_n(h+l)}\right) \tag{17}$$

Define C_0 and C_n as transfer functions. The transfer function is the ratio between the stroke of the wave-maker and the wave amplitude, which represents the relationship between the input and output in the wave-making system [5].

The characteristic of transfer functions determines the response characteristic of system to input signal. The values of the transfer functions are related to the type of paddles, water depth, hinge depth and wave period. The analytic expression of the transfer functions in Eqs. (16) and (17) is used to solve the value of the transfer function. The influences of changes in different modes (namely order n) on the transfer functions were analyzed, and the influences of wave period, water depth and hinge depth on the transfer functions were respectively compared under 0-20 modes, as shown in Figs. 3-5.

As shown in Fig. 3, the fixed water depth is 10 m, the hinge depth is 5 m, and the wave period is set as 1 s, 2 s, 3 s and 4 s respectively. When the wave period

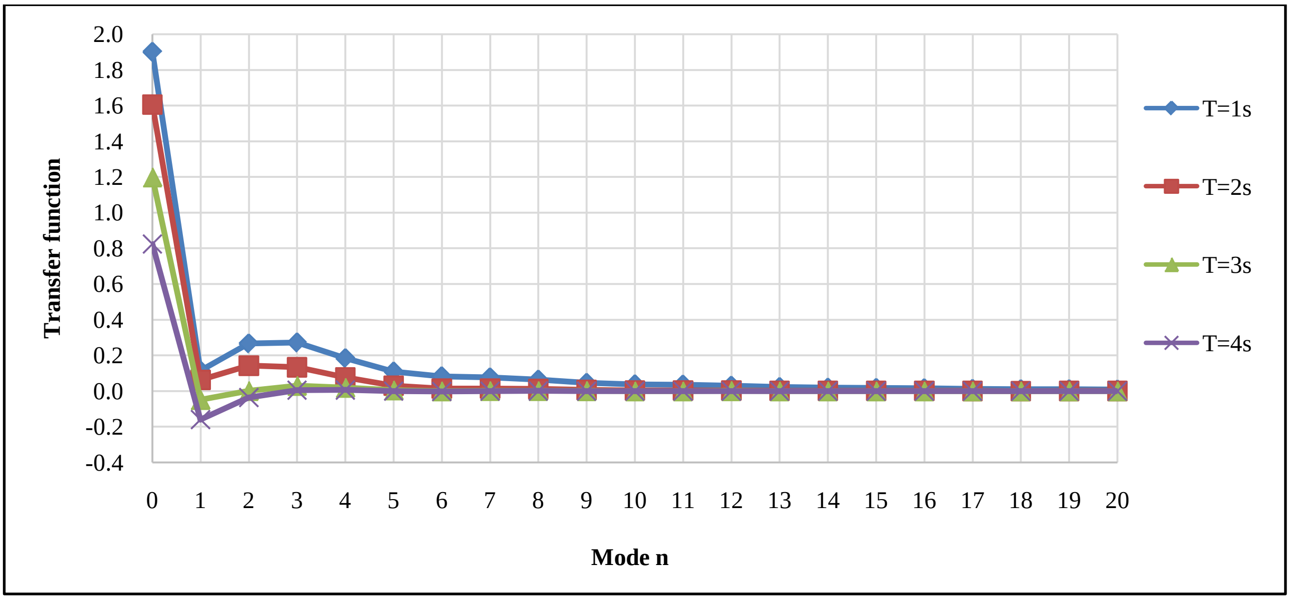

Fig. 3 The change curve of the transfer function with order in different wave periods.

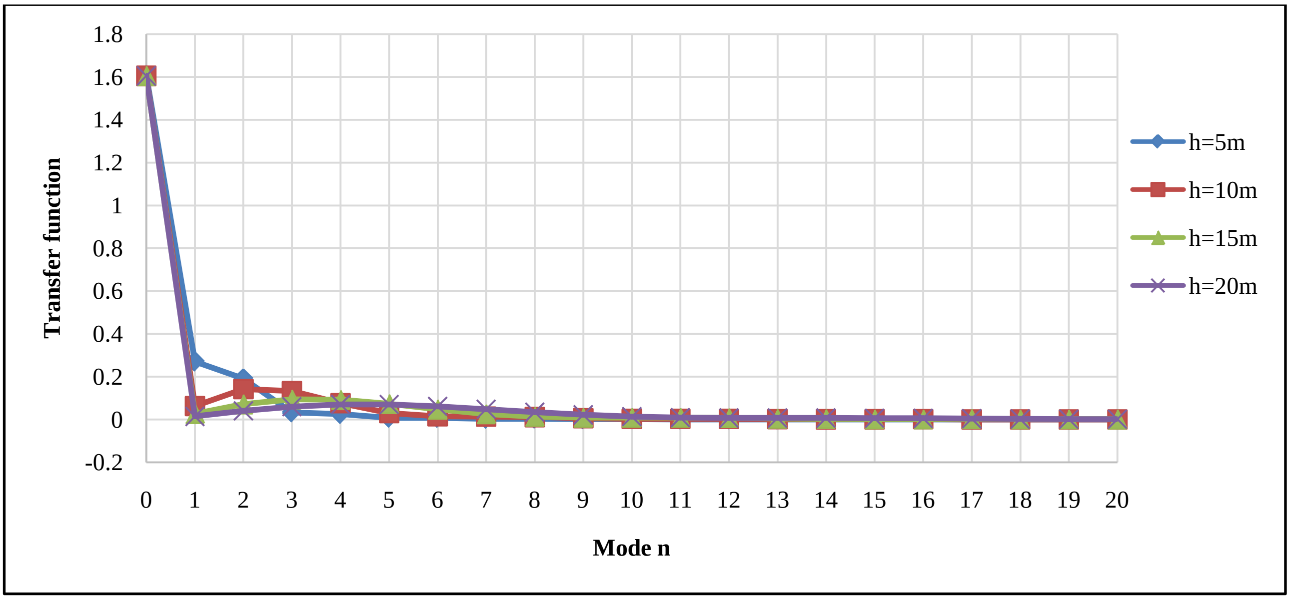

Fig. 4 The change curve of transfer function with order at different water depths.

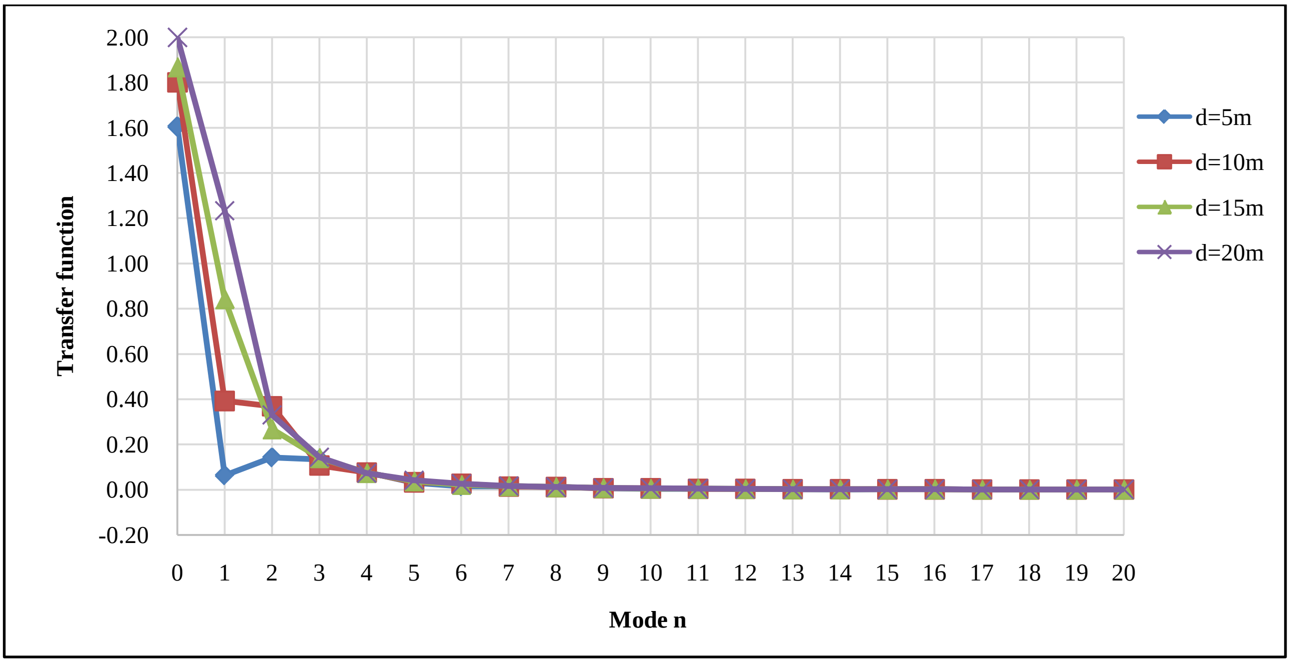

Fig. 5 The change curve of transfer function with order at different hinge depth.

increases, the decline speed of the transfer function value increases, and a negative value appears. As shown in Fig. 4, wave period was fixed as 2 s, hinge depth was set as 5 m, and water depth was set as 5 m, 10 m, 15 m and 20 m respectively. With the increase of water depth, the low mode transfer function value decreased, but in higher modes of order 3-10, the transfer function was proportional to water depth. As shown in Fig. 5, the wave period is fixed as 2 s, the water depth is 10 m, and the hinge depths are set as 5 m, 10 m, 15 m and 20 m respectively. In the first and second order modes, the larger the hinge depth is, the smaller the transfer function is. The comparisons show that the non-propagating modal transfer function changes more obviously with wave period and hinge depth.

When the zero order modal is used, C_0 approaches 2 infinitely. With the increase of modes, the transfer function decreases obviously when the modal number is small. When the mode is greater than order 4, its value gradually approaches zero, that is, when the mode is more than order 10, the non-propagating modal transfer function has little difference. Therefore, in the actual calculation of non-propagating mode, the mode can be set as 10 to meet the accuracy requirements.

3. Active Absorption Theory of Two-Dimensional Wave

According to the fluid force collected by the force sensors at the wavemaking paddles, the active absorption system based on force feedback is adopted to modify the wave-making control signals in real time so as to eliminate the secondary reflected wave [6, 7].

Assume that the velocity potential of the original target wave is Φ^g. When it moves to the basin walls or physical models opposite to the wave-makers, it generates reflected wave Φ^r that have same period, opposite direction and attenuated wave height compared with the incident wave. When the reflected waves propagate to the paddles, it reflect again, producing secondary reflected wave Φ^{rr} with the same period, same wave height and different direction compared with the incident wave. At the same time, fluid force is applied to the paddles. Assuming perfect reflection on the paddles occurs, the superposition of incident and reflected wave potential forms an anti-node on the paddles. Therefore, the body surface condition only applies to the velocity potential generated by the wave-maker, Φ^g [2].

$$\Phi^{g}=\sum_{n=1}^{N}\frac{1}{2}\left(\frac{igS_n}{\omega_n}\sum_{j=0}^{\infty}C_{jn}\frac{\cosh k_{jn}(z+h)}{\cosh k_{jn}h}e^{i(\omega_n t-k_{jn}x)}+c.c.\right) \tag{18}$$

Building on this result, related potentials of the reflected wave and the secondary reflected wave, that satisfy the bottom boundary condition and free water surface condition, are given by:

$$\Phi^{r}=\sum_{n=1}^{N}\frac{1}{2}\left(\frac{igA_n^r}{\omega_n}\frac{\cosh k_{0n}(z+h)}{\cosh k_{0n}h}e^{i(\omega_n t+k_{0n}x)}+c.c.\right) \tag{19}$$

and

$$\Phi^{rr}=\sum_{n=1}^{N}\frac{1}{2}\left(\frac{igA_n^{rr}}{\omega_n}\frac{\cosh k_{0n}(z+h)}{\cosh k_{0n}h}e^{i(\omega_n t-k_{0n}x)}+c.c.\right) \tag{20}$$

where A_n is the complex amplitude of component n and cc represents the complex conjugate of the preceding wave. From the hypothesis we can get $A_n^r=A_n^{rr}(n=1,2\ldots N)$.

Summing the three velocity potentials for each wave component in the time domain yields, and according to the relationship $U_n=i\omega X_n$ between the complex velocity and the displacement amplitude of the paddles, the displacement amplitude is replaced by the complex velocity of the paddles.

$$\Phi_{\text{n}}(t)=\Phi^{g}{}_{\text{n}}(t)+\Phi^{r}{}_{\text{n}}(t)+\Phi^{rr}{}_{\text{n}}(t) \tag{21}$$

this is

$$\begin{aligned}\Phi_{\text{n}}(t)=&\frac{igA^r}{\omega_n}\frac{\cosh k_{0n}(z+h)}{\cosh k_{0n}h}e^{i(\omega t+k_{0n}x)}+\left[\frac{igA^{rr}}{\omega_n}+\frac{gU_nC_{0n}}{\omega_n^2}\right]\frac{\cosh k_{0n}(z+h)}{\cosh k_{0n}h}e^{i(\omega t-k_{0n}x)}\\&+\frac{gU_n}{\omega_n^2}\sum_{j=1}^{\infty}C_{jn}\frac{\cosh k_{jn}(z+h)}{\cosh k_{jn}h}e^{i(\omega t-k_{jn}x)}\end{aligned} \tag{22}$$

where the second term of the above equation is zero because the progressive term of Φ^g and Φ^r cancel each other out. From Eq. (22), it is clear that the wavemaking paddles' velocity must satisfy:

$$U_{\text{n}}=-\frac{iA_{\text{n}}^r\omega_n}{C_{0n}}=-\frac{iA_{\text{n}}^{rr}\omega_n}{C_{0n}} \tag{23}$$

The force-feedback active absorption system mostly adopts the dry-backed wave-makers. That is, there is no water on the back side of the paddles, which is conducive to force sensors monitoring the stress state of the paddles. According to the linear Bernoulli equation, the first order pressure applied by the entire wave field to the paddles is expressed as:

$$P(x,z,t)=-\rho\frac{\partial\Phi}{\partial t}-\rho gz \tag{24}$$

where ρ is the density of the fluid. The first term on the right is unsteady term, which generates the first order dynamic pressure. The second term is the hydrostatic term, which produces a constant static pressure, which is usually greater than the dynamic pressure.

Take the time derivative with respect to the velocity potential and substitute it into Eq. (24) to calculate the instantaneous pressure applied to the paddles at $x=0$.

$$\frac{\partial\Phi_{\text{n}}(t)}{\partial \text{t}}=-gA^r\frac{\cosh k_{0n}(z+h)}{\cosh k_{0n}h}e^{i(\omega t+k_{0n}x)}+\frac{igU_n}{\omega_n}\sum_{j=1}^{\infty}C_{jn}\frac{\cosh k_{jn}(z+h)}{\cosh k_{jn}h}e^{i(\omega t-k_{jn}x)} \tag{25}$$

$$P_{\text{n}}=\rho gA^r\frac{\cosh k_{0n}(z+h)}{\cosh k_{0n}h}e^{i(\omega t+k_{0n}x)}-\frac{i\rho gU_n}{\omega_n}\sum_{j=1}^{\infty}C_{jn}\frac{\cosh k_{jn}(z+h)}{\cosh k_{jn}h}e^{i(\omega t-k_{jn}x)}-\rho gz \tag{26}$$

Integrate the pressure on the surface of the paddles, then the fluid force acting on the paddles is:

$$
\begin{aligned}
T_n &= -\int_{-h+d}^{0} \rho \frac{\partial \Phi_n(z,t)}{\partial t} \cdot (h-d+z)dz \\
&= \frac{\rho g A^r C_{0n}}{k_{0n}^2} \frac{k_{0n}(h-d)\sinh k_{0n}h - \cosh k_{0n}h + \cosh k_{0n}d}{\cosh k_{0n}h} \\
&\cdot e^{i\omega_n t} - \frac{i\rho g U_n}{\omega_n} \sum_{j=1}^{\infty} \frac{C_{jn}}{k_{jn}^2} \frac{k_{jn}(h-d)\sinh k_{jn}h - \cosh k_{jn}h + \cosh k_{jn}d}{\cosh k_{jn}h} e^{i\omega_n t}
\end{aligned} \tag{27}
$$

A^r is replaced by U_n to obtain the relationship between the velocity of paddles and the fluid force that:

$$
\begin{aligned}
T_n = &-\frac{\rho g U_n C_{0n}}{k_{0n}^2 \omega_n} \frac{k_{0n}(h-d)\sinh k_{0n}h - \cosh k_{0n}h + \sinh k_{0n}d}{\cosh k_{0n}h} \sin \omega_n t \\
&+ \frac{\rho g U_n}{\omega_n} \sum_{j=1}^{\infty} \frac{C_{jn}}{k_{jn}^2} \frac{k_{jn}(h-d)\sinh k_{jn}h - \cosh k_{jn}h + \sinh k_{jn}d}{\cosh k_{jn}h} \sin \omega_n t
\end{aligned} \tag{28}
$$

Sum up the fluid forces of the regular wave of n different components and the fluid force of the irregular wave is:

$$
\begin{aligned}
T &= \sum_{n=1}^{\infty} T_n \\
&= \sum_{n=1}^{\infty} \left(\begin{aligned} &-\frac{\rho g U_n C_{0n}}{k_{0n}^2 \omega_n} \frac{k_{0n}(h-d)\sinh k_{0n}h - csohk_{0n}h + \sinh k_{0n}d}{\cosh k_{0n}h} \sin \omega_n t \\ &+ \frac{\rho g U_n}{\omega_n} \sum_{j=1}^{\infty} \frac{C_{jn}}{k_{jn}^2} \frac{(h-d)\sinh k_{jn}h - csohk_{jn}h + \sinh k_{jn}d}{\cosh k_{jn}h} \sin \omega_n t \end{aligned} \right)
\end{aligned} \tag{29}
$$

For the flap-type wave-makers, suppose that the angular velocity of wavemaking paddles is Ω, with the small angle approximation the instantaneous angular velocities at the still water surface satisfies:

$$\Omega \approx \tan \Omega = \frac{U}{h+l} \tag{30}$$

4. Active Absorption Theory of Three-Dimensional Wave

Based on the active absorption theory of two-dimensional wave, the three-dimensional ones consider the direction arranged by the wave-maker, which is the *y*-direction. Assume that the wave-maker has infinite width, regardless of its boundary limits. According to the three three-dimensional velocity potentials, the three-dimensional fluid force acting on the wavemaking paddles is solved [8, 9].

The three-dimensional velocity potentials of the target wave, reflected wave and secondary reflected wave are:

$$\Phi^{\mathrm{g}} = \sum_{n=1}^{N} \frac{1}{2} \left(\frac{igX_n}{\omega_n \cos\theta} \sum_{j=0}^{\infty} C_{jn} \frac{\cosh k_{jn}(z+h)}{\cosh k_{jn}h} e^{i(\omega_n t - k_{jnx}x - k_{jny}y)} + c.c. \right) \tag{31}$$

$$\Phi^{\mathrm{r}} = \sum_{n=1}^{N} \frac{1}{2} \left(\frac{igA_n^r}{\omega_n \cos\theta} \frac{\cosh k_{0n}(z+h)}{\cosh k_{0n}h} e^{i(\omega_n t + k_{0nx}x + k_{0ny}y)} + c.c. \right) \tag{32}$$

$$\Phi^{\mathrm{rr}} = \sum_{n=1}^{N} \frac{1}{2}\left(\frac{igA_n^{rr}}{\omega_n \cos\theta} \frac{\cosh k_{0n}(z+h)}{\cosh k_{0n} h} e^{i(\omega_n t - k_{0nx}x - k_{0ny}y)} + c.c. \right) \tag{33}$$

The method is the same as that of two-dimensional fluid force, the three-dimensional fluid force can be obtained as:

$$\begin{aligned} T_n = & -\frac{\rho g U_n C_{0n}}{k_{0n}\omega_n \cos\theta} \frac{(h-d)\sinh k_{0n}h - \cosh k_{0n}h + \sinh k_{0n}d}{\cosh k_{0n}h} \sin(\omega_n t - k_{0ny} y) \\ & + \frac{\rho g U_n}{\omega_n \cos\theta} \sum_{j=1}^{\infty} \frac{C_{jn}}{k_{jn}} \frac{(h-d)\sinh k_{0n}h - \cosh k_{0n}h + \sinh k_{0n}d}{\cosh k_{jn}h} \sin(\omega_n t - k_{jny} y) \end{aligned} \tag{34}$$

Sum up the fluid forces of the three-dimensional regular wave of *n* different components, and the fluid force of the three-dimensional irregular wave is:

$$\begin{aligned} T &= \sum_{n=1}^{\infty} T_n \\ &= \sum_{n=1}^{\infty} \left(\begin{aligned} & -\frac{\rho g U_n C_{0n}}{k_{0n}\omega_n \cos\theta} \frac{(h-d)\sinh k_{0n}h - \cosh k_{0n}h + \sinh k_{0n}d}{\cosh k_{0n}h} \sin(\omega_n t - k_{0ny} y) \\ & + \frac{\rho g U_n}{\omega_n \cos\theta} \sum_{j=1}^{\infty} \frac{C_{jn}}{k_{jn}} \frac{(h-d)\sinh k_{jn}h - \cosh k_{jn}h + \sinh k_{jn}d}{\cosh k_{jn}h} \sin(\omega_n t - k_{jny} y) \end{aligned} \right) \end{aligned} \tag{35}$$

5. Conclusion

By analyzing the three different wave components existing in the wave field of the basin, the force-feedback active absorption system of the flap-type wavemaker was theoretically studied. Based on the Potential Flow Theory, the distribution characteristics of the velocity potential solution and pressure of the paddles under the dry-back flap-type wavemaking conditions are studied, and the calculation method of the torque of the wave acting on the paddles is obtained by using the single-frequency characteristics of the regular wave and the multi-frequency characteristics of the irregular wave through hydrodynamic analysis. The first-order torque of unidirectional, multi-directional, regular and irregular wave studied in this paper can be used as the theoretical basis for the development of the multi-directional absorption system of the wavemaker, which links the movement of the wave in the basin with the movement of the paddles, and theoretically proves the feasibility and effectiveness of the active absorption system of the force-feedback wavemaker for absorbing the secondary reflected wave. However, the active absorption theory and technology derived in this paper are mainly based on the first-order linear wavemaking theory, which does not consider the influence of nonlinear factors in the second-order Stokes wave, and there are limitations in dealing with the absorption of nonlinear wave, and the future study of active absorption theory based on second-order wavemaking theory is the development direction.

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