Ocean Engineering 124 (2016) 274–286

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Diffraction of waves past two vertical thin plates on the free surface: A comparison of theory and experiment

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A R T I C L E I N F O

Article history:
Received 29 October 2015
Received in revised form
28 June 2016
Accepted 11 July 2016
Available online 6 August 2016

Keywords:
Diffraction
Transmission
Reflection
Two vertical thin plates
Resonance
Wave energy

A B S T R A C T

Diffraction of waves past two vertical thin plates on the free surface is studied theoretically and experimentally. A particular attention is paid to the wave motions depending on the relationship between the wavelength (λ) and the width (b) between the two plates for a given draft (d) and water depth (h). For $d/h = 0.19$, at resonance modes when $b/\lambda = 0.245$ (first), 0.695 (second), 1.11 (third), 1.55 (fourth), etc., the overall transmission features the maximum with no reflection. In the first mode, the water column between the plates moves up and down with no wave motions. In the second mode, it shows the fundamental standing wave motion. In the remaining modes, it shows another standing wave motions with relatively higher frequencies. As d/h increases (0.1–0.4), the resonance points move to values $b/\lambda = 0$, 0.5, 1, 1.5, etc., and, at those resonance points, the peaks of reflection and transmission coefficients become more sharp and narrow. The loss of energy of incoming waves is also observed at every transmission in the two plate system, and, in particular, more energy loss near a resonant frequency. In addition, it is found that energy is lost mainly due to the transmission process not the reflection process.

1. Introduction

Two-dimensional diffraction of linear progressive waves has been an important subject in the fields of wave barriers and wave energy converters such as OWC (Oscillating Water Column). To understand underlying physics, many theoretical and experimental studies have been carried out with reference to the case of wave diffraction passing a single vertical thin plate and two vertical thin plates on the free surface. First, for the case of wave diffraction passing a single vertical thin plate, it is well known that the transmission increases as the wavelength increases, or the reflection increases as the wavelength decreases. Assuming inviscid and irrotational fluid flow, Wiegel (1960) calculated analytically the relative amount of transmitted wave amplitude compared to the incoming wave amplitude without considering the reflected waves. In his theory, he assumes that the net transmitted wave energy behind the thin plate is equal to the fraction of the incoming wave energy passing below the thin plate. However analytically found transmitted wave amplitudes do not agree with those from his experiment. Although widely adopted as a first approximation as a closed-form solution, the neglect of reflected waves unavoidably results in considerable errors in the overall energy conservation before and after the diffraction. To overcome this, Kriebel and Bollmann (1996) performed a similar analytical inviscid calculation including the effect of reflected waves, but their calculation also cannot satisfy the overall conservation of energy before and after the diffraction. The reason is that both theories neglect the existence of evanescent or parasitic waves near the plate, and only progressive waves are considered. Moreover, not all the boundary conditions are not satisfied on the plate and below the plate, where the fluid velocity is zero on the plate and both the fluid velocity and the pressure (or the velocity potential) are continuous below the plate. Compared to these, a more rigorous mathematical theory has been applied to this problem by Losada et al. (1992). With the assumption of inviscid and irrotational fluid flow, the velocity-potential based Laplace equation subject to all the boundary conditions on the plate and below the plate is solved numerically, where the existence of many parasitic waves on the plate are now all accounted for (Losada et al., 1992). The resultant overall wave energy is conserved before and after the diffraction. The same problem was solved by Porter and Evans (1995) using Galerkin method and the result is the same as Losada et al. (1992).

For the case of wave diffraction passing two vertical thin plates on the free surface, it was theoretically and experimentally found that there exist resonant conditions where the overall transmission and reflection feature extrema at particular wavelengths. Approximate analytical solutions are proposed by Srokosz and Evans (1979) and Ohkusu (1974) based on the assumption that the plates are spaced far enough for the local wave field in the vicinity

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http://dx.doi.org/10.1016/j.oceaneng.2016.07.013

Please cite this article as: Shin, D.M., Cho, Y., Diffraction of waves past two vertical thin plates on the free surface: A comparison of theory and experiment. Ocean Eng. (2016), http://dx.doi.org/10.1016/j.oceaneng.2016.07.013

of one plate not to influence the other plate (wide-spacing approximation). The approximation is equivalent to saying that the wavelength is small compared to the distance between the two plates. The applicability of this approximation is compared to the experiment by Stiassnie et al. (1986). The comparison between the theory and the experiment is in a good agreement in terms of the overall transmission and reflection behaviors according to the wavelength. However, at resonant wavelengths, the number of experimental data is not enough to fit the sharp peaks predicted by the theory. For more general cases without approximations aforementioned, Wu and Liu (1988) exactly solved the oblique wave diffraction problem passing two finite-width plates on the free surface. With the assumption of inviscid and irrotational fluid flow, the velocity-potential based Laplace equation subject to all the boundary conditions on the two plates and below the two plates is solved numerically, where the existence of many parasitic waves on the two plates are now all considered. The resultant overall wave energy is conserved before and after the diffraction. Their solution method for the two plates is equivalent to the one for a single plate by Losada et al. (1992). The former uses a so-called eigenfunction expansion method and the latter uses a least square method, which are mathematically equivalent to each other. Recently, the same problem was studied by McIver (1985) and Das et al. (1997). In their analytical formulations, by splitting the velocity potential into symmetric and antisymmetric parts, they treat the original double-plate problem as two single-plate problems. However, in terms of their solution methods, the former uses the eigenfunction expansion method while the latter uses the Galerkin method. In the abovementioned studies, the plates are assumed to be impermeable. For the case of permeable plate system, Isaacson et al. (1999) solved the problem of wave diffraction past two slotted or permeable vertical thin plates on the free surface and Liu and Li (2011) solved the problem of wave diffraction past two vertical thin plates, one permeable and the other impermeable. They all use the eigenfunction expansion method.

Many existing studies concentrate on the overall reflection and transmission passing the two-plate system without paying much attention to the wave motion between the two plates, which is not much of a concern in the design of wave barriers. However, for the case of wave energy converters such as OWC (Oscillating Water Column), not only the overall reflection and transmission characteristics outside the plates but also the local wave motion between the plates are important subjects to be considered. In particular, at resonant conditions, i.e., no reflection and total transmission conditions, the detailed wave motion between the plates has hardly been reported theoretically or experimentally and this is the main subject of this paper. A particular attention is paid to the wave motions depending on the relationship between the wavelength (λ) and the width (b) between the two plates for a given draft (d) and water depth (h). To summarize in advance, for $d/h = 0.19$, it is both experimentally and theoretically found that the resonance occurs when $b/\lambda = 0.245$, 0.695, 1.11, 1.55, etc.

In this paper, the same analytical and numerical approach as the ones by Losada et al. (1992) and Wu and Liu (1988) is extended and applied to the problem of diffraction of 2-D waves passing two vertical thin plates on the free surface. The analytical formulation and its numerical treatment are provided in Section 2. Then, associated experimental details are explained in Section 3. In Section 4, the comparison between the theory and the experiment is shown, in terms of the overall reflection and transmission characteristics and local wave motions between the two plates.

2. Theory

In Fig. 1, a schematic is shown for the analysis of the reflection and transmission of left-going incident 2-D linear gravity waves past two vertical thin plates (draft d, inter-distance b) on the mean free surface, where the water depth is h. The origin is placed at the intersection of the right plate and the mean free surface. Cartesian coordinates system (x,z) is adopted with x-axis being horizontal and the z-axis being vertically upward. The fluid domain is composed of three regions. Region I includes left-going incident waves and reflected waves ($0 < x < \infty$, $-h < z < 0$), region II includes transmitted waves past the right plate and reflected waves from the left plate ($-b < x < 0$, $-h < z < 0$) and region III includes transmitted waves past the left plate ($-\infty < x < -b$, $-h < z < 0$). Assuming that the fluid is inviscid and incompressible, and the flow is irrotational, the velocity potentials ϕ_1, ϕ_2, ϕ_3 in each region which satisfy the Laplace equation can be written as follows, in complex forms with the implication of taking the real part.

$$\phi_j(x, z, t) = \mathrm{Re}\left\{ \varphi_j(x, z) e^{-i\omega t} \right\}; \qquad j = 1,\ 2,\ 3 \tag{1}$$

where ω is the angular frequency, t is time. The corresponding surface-wave elevation is

$$\zeta_j(x, t) = \mathrm{Re}\left\{ \zeta_0 e^{-i(kx+\omega t)} \right\}; \qquad j = 1,\ 2,\ 3 \tag{2}$$

where k is the wavenumber. These velocity potentials and wave elevations satisfy following linearized boundary conditions. The bottom boundary condition is

$$\frac{\partial \phi_j}{\partial z} = 0; \qquad j = 1,\ 2,\ 3 \quad \text{at } z = -h. \tag{3}$$

The kinematic free-surface boundary condition is

$$\frac{\partial \zeta_j}{\partial t} = \frac{\partial \phi_j}{\partial z}; \qquad j = 1,\ 2,\ 3 \quad \text{at } z = 0. \tag{4}$$

The dynamic free-surface boundary condition is

$$\zeta_j = -\frac{1}{g}\frac{\partial \phi_j}{\partial t}; \qquad j = 1,\ 2,\ 3 \quad \text{at } z = 0. \tag{5}$$

Then, the velocity potentials (time-independent part) which satisfy boundary conditions Eqs. (3)–(5) can be expressed as

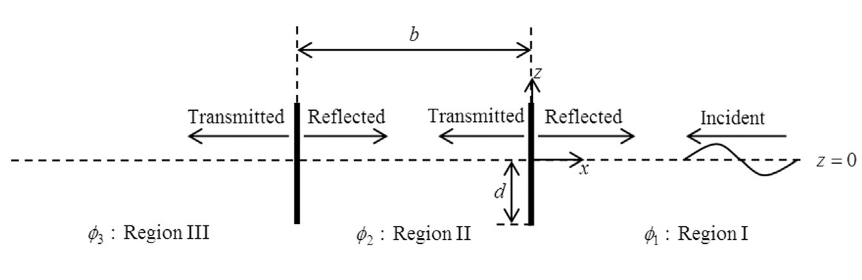

Fig. 1. Schematic of the reflection and the transmission of incident 2-D linear gravity waves past two vertical thin plates on the mean free surface, where the water depth is h.

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