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Ocean Wave Focusing: Experiments and Nonlinear Computations

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ABSTRACT

We performed experiments of wave focusing using two kinds of Fresnel lenses 20 m long, namely a flat plate type and a circular cylinder type, in a wave tank of 30 m × 50 m × 2.4 m. The experimental results show that waves are concentrated on the designed focal point, but that the wave power magnification is affected by the lens' shape and nonlinearity of a free surface. The three-dimensional singularity distribution method demonstrates the effects of the lens' shape and indicates that a Fresnel lens significantly reduces the predicted wave power magnification by the slender ship theory because of its discontinuous shape. As for nonlinearity of a free surface on a lens, the breaking limit of waves passing over a submerged plate and an array of submerged circular cylinders are obtained by experiments. Moreover, one-dimensional concentration of transient water waves and an approximated nonlinear water wave theory estimate the nonlinear effects of a free surface with increase of wave slope around a focal point fairly well.

INTRODUCTION

An ocean wave focusing lens (from now on the word ocean is omitted) concentrates ocean waves on a certain focal point by transforming straight crest lines of incident plane waves into circular ones just like an optical lens. A wave height at the focal point is higher than that of the incident waves and a calm sea area is created. This device has been attracting ocean engineers as one of the most promising wave control techniques because it helps effective utilization of wave energy and ocean space.

In some previous works (Mehlum and Stamnes, 1979; Stamnes et al., 1983; Kudo et al., 1986), a wave focusing lens consisted of a horizontally submerged flat plate and its performances were investigated. Stamnes et al. (1983) discussed nonlinear effects of a free surface around a focal point using an approximated nonlinear wave theory qualitatively. Kudo et al. (1986) proposed a crescent-shaped flat plate type lens and showed a concrete design procedure in real sea. However, inevitable reflected waves by a flat plate reduce the wave height magnification and increase the drift force on it. On the other hand, in order to determine a shape of an ideal lens which concentrates the total power of incident waves without reflection, Murashige and Kinoshita (1990) derived a hydrodynamic singularity distribution for it, assuming its slenderness and high frequency of incident waves and using slender ship theory, and found that its sectional shape should satisfy necessary conditions, which are equivalent to geometrical optics, as follows: It reflects no waves and transmits waves which have the required phase lag to design the lens. Next, we found that an array of submerged circular cylinders almost satisfies the above necessary conditions in a wide band of wave frequencies using numerical computations and experiments. In addition, numerical computations using the slender ship theory demonstrated that a circular cylinder type lens can have higher wave focusing performances than a flat plate type lens, which has been used in the previous works, particularly in irregular waves.

In the present work, we performed experiments of wave focusing by two kinds of Fresnel lenses 20 m long, namely a flat plate type and a circular cylinder type, in a wave tank of 30 m × 50 m × 2.4 m. The objective is to make clear the effects of a lens' slenderness, wave breaking on a lens, and nonlinear modulation of waves around a focal point, all of which could not be examined by the slender ship theory. Although Stamnes et al. (1983) carried out similar experiments, they did for only one case of the wave height of incident waves and could not consider the nonlinear effects of a free surface with increase of the wave height quantitatively. On the other hand, this work represents scarce data for the nonlinear effects, in particular for the decrease of wave height magnification at a focal point with progression of the wave shape, and represents how to estimate it using a simple experiment in a narrow wave tank and an approximated nonlinear wave theory.

EXPERIMENTS

Design Procedure of a Wave Focusing Lens

Let us consider wave focusing of incident plane waves progressing in the positive x-direction at a focal point on the x-axis by a lens placed along the y-axis. The coordinate system is defined in Fig. 1. The phase lag distribution along the lens $\varepsilon(y')$ as (Murashige and Kinoshita, 1990):

$$\varepsilon(y')=K\left(\sqrt{\left(\frac{L}{2}\right)^2+\ell^2}-\sqrt{y'^2+\ell^2}\right), \tag{1}$$

where y' denotes a position on a lens. Here the phase lags at both ends of a lens are set to zero, $\varepsilon(y' = \pm L/2) = 0$. A whole shape can be designed using this equation and the relation between the phase lag ε and some parameters, namely a wave frequency f, a submerged depth h, and a plate's width a, or a cylinder's diameter a_c. The relation can be obtained by numerical computations or experiments (Murashige and Kinoshita, 1990). In the present experiment, we treat only a Fresnel lens because it is smaller and more

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KEY WORDS: Ocean wave focusing, ocean wave lens, wave energy utilization, ocean space utilization, wave breaking, nonlinear modulation of ocean waves.