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A quasi-cloaking phenomenon to reduce the wave drift force on an array of adjacent floating bodies

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ABSTRACT

The mooring of offshore floating structures, such as offshore platforms, in large waves against drift forces and rotational moments is a challenging problem in offshore engineering. To accurately investigate such problems, called positioning problems, the time-averaged steady forces of the second order known as the wave drift forces must be taken into account. Fortunately, a cloaking phenomenon occurs under certain conditions and dramatically reduces the wave drift force acting on such a floating body, as previously reported by several researchers. In the diffraction problem of water waves, cloaking refers to the condition where there is no scattering in the form of radial outgoing waves. The reduction of wave drift force on a truncated cylinder with the occurrence of cloaking phenomenon has been numerically and experimentally confirmed. In this paper, the arrangement of several small circular cylinders at regular intervals in a circle concentric with a fixed floating body is considered as an effective means of reducing the wave drift force. Using a combination of a higher-order boundary element method (HOBEM) and wave interaction theory, the influences of the geometric parameters of the outer surrounding cylinders on the wave drift force and the total scattered-wave energy are systematically investigated and discussed. A quasi-cloaking phenomenon is first found and reported in the present study, which is beneficial and flexible for application in practical engineering. More than one quasi-cloaking trigger (where a trigger is an occurrence condition) can be found simply by varying the distance between the inner and outer floating bodies.

1. Introduction

Recently, analyses of the hydrodynamic interactions among multiple adjacent floating structures, such as side-by-side arrangements of Liquefied Natural Gas Floating Production, Storage, and Offloading (LNG-FPSO) units, have gained practical importance in engineering design for such structures. In particular, positioning problems have always been strongly focused on wave-body interactions. To reduce the mooring load, the reduction of the wave drift force, which is of the second order, is critical and can be achieved via quadratic products of the first-order quantities. Fortunately, a cloaking phenomenon occurs with the proper selection of the geometric dimensions of the outer floating bodies, which can reduce the wave drift force acting on the bodies, dramatically or even perfectly to zero. In a diffraction problem, the term cloaking implies that there is no wave scattering in the form of radial outgoing waves. Considering that the wave drift force can be calculated from the amplitudes of scattered outgoing waves, reduction of the wave drift force can be effectively realized if all scattered waves are trapped.

The cloaking phenomenon was originally derived by Pendry et al. [1] in electromagnetic fields. Recently, Porter [2] investigated the possibility of cloaking a single cylinder and confirmed that it can be done for a certain incident-wave frequency by modifying the submarine topography. Alam [3] has reported that by installing ripples in the corresponding area below the water, a floating body can be protected through the transformation of surface gravity waves into internal waves in the floating-body-containing area to be protected. Porter and Newman [4] cloaked a bottomed-mounted cylinder by varying the bathymetry in an annular region outside the cylinder. Dupont et al. [5] studied the cloaking phenomenon of an vertical cylinder surrounded by an annular structure via homogenization in the mild-slope equation. Newman [6,7] has investigated a creative cloaking phenomenon under the condition in which a circular cylinder, which is fixed to a free surface in a fluid of infinite depth and finite draft, is regularly surrounded by several circular

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cylinders. His computational results show that the scattered-wave energy can be reduced to practically zero by optimizing the geometric parameters of the outer cylinders and that the corresponding wave drift force acting on the entire structure becomes very small. Following Newman's works, Iida et al. [8] have proven that the cloaking phenomenon is effective in reducing the wave drift force acting not only on the inner body but also on all bodies. The optimized geometric dimensions of the outer bodies (such as the draft, d_{out}, and the distance from the inner body, R) have been determined by adopting the binary-coded genetic algorithm to minimize the wave drift force on the inner floating body against a large range of incident-wave frequencies for eight surrounding cylinders ($N = 8$). Kashiwagi et al. [9] experimentally confirmed the reduction of wave drift force with cloaking configuration. However, previous studies focus on the perfect cloaking by surrounding a structure with finite cylinders, which cannot be realized that has been mathematically proved by McIver [10]. And only few optimized results can be obtained due to the limitation of optimized program, for example the search scope of optimized parameters and terminal condition et al. According to their works, it is not clear if there exists other optimized configurations which can also reduce the wave drift force for certain wave frequency.

In order to obtain more flexible dimensions of outer cylinders to effectively reduce the wave drift force acting on inner cylinder, the effects of the geometric parameters of the outer surrounding cylinders, including their radius and draft, and the distance between the inner and outer floating bodies on the wave drift force and total scattered-wave energy are investigated for a wide range of incident-wave frequencies. A quasi-cloaking phenomenon is first found, and the influence of the geometric parameters on this phenomenon is analyzed. For numerical accuracy and efficiency, the higher-order boundary element method (HOBEM) introduced in [11] is employed to compute the diffraction characteristics of each cylinder. To account for the hydrodynamic interactions among the floating bodies, the wave interaction theory introduced in [12–14] is adopted to evaluate the wave drift force and the total scattered-wave energy. Based on the principle of momentum conservation, the wave drift force can be computed from quadratic products of the first-order velocity potential at a given distance from the cylinder of interest; this approach is known as the far-field method and was originally proposed by Maruo [15]. However, only the total force on the bodies as a whole can be obtained using this method. To calculate the wave drift force on each body separately, a new solution using a cylindrical coordinate system and Graf's addition theorem for Bessel functions is introduced. Benefiting from the combination of the HOBEM and wave interaction theory, the quasi-cloaking phenomenon and the influences of the geometric parameters of the outer surrounding cylinders on this phenomenon are systematically investigated and discussed. The wave amplitude inside the structure has also been studied to clarify this phenomenon.

2. Theory

2.1. Structural arrangement

Several small circular outer cylinders are regularly placed in a circle concentric with a fixed floating body (inner cylinder), as shown in Fig. 1. The hydrodynamic phenomena affecting these multiple 3-D floating bodies are complicated because of the wave interactions among them. The incident waves are assumed to arrive from the direction of the negative x axis.

Both the diameter and draft of the inner cylinder are normalized to unity ($d_0 = 1.0$, $r_0 = 0.5$). All geometric dimensions of the outer floating bodies are normalized with respect to the diameter of the inner floating body. The fixed inner floating body is surrounded by outer cylinders of radius r_{out} and d_{out} arranged in the form of a circle that is concentric with the inner body, as shown in Fig. 2. The number of outer columns is N. In order to obtain more flexible parameters which can reduce the wave drift force acting on inner cylinder (the wave drift force F_x acting on single cylinder equal to 0.1192), the effects of the geometric parameters of the outer surrounding cylinders, including their diameter and draft, and the distance between the outer and inner floating bodies on the wave drift force and the total scattered-wave energy are investigated here for a wide range of incident-wave frequencies. The wave drift forces acting both on the inner floating body and on the floating bodies as a whole are systematically calculated and investigated for different numbers of outer surrounding bodies ($N = 2$, 4, 8).

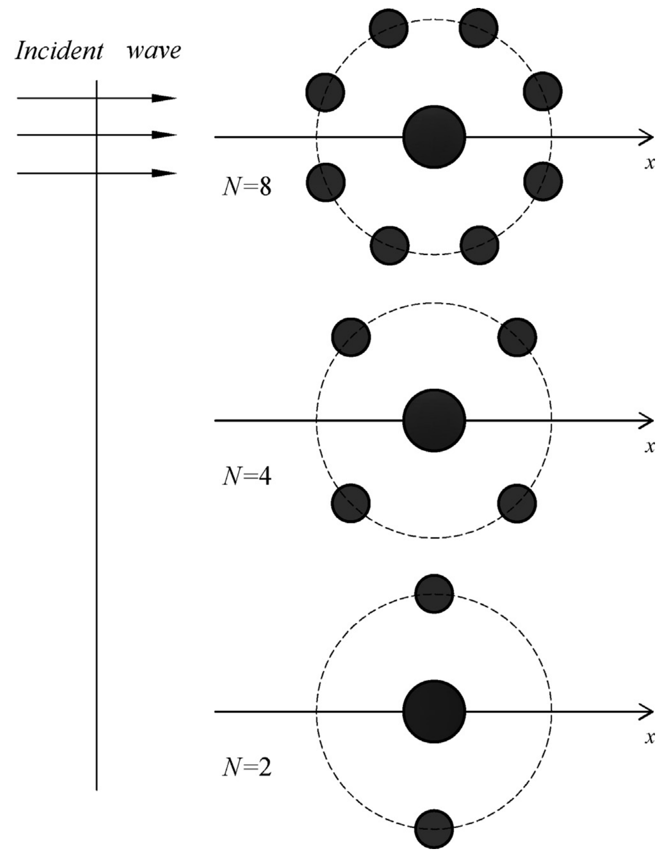

Fig. 1. Diagrams of the cylinder arrangements and the incidence direction of the waves.

2.2. Velocity potential and wave drift force

To investigate this complicated multi-body problem, two coordinate systems are introduced, as shown in Fig. 3. One is the global coordinate system $o - xyz$ with respect to the center cylinder; the other is the local coordinate system $o_n - x_n y_n z_n$ fixed at the center of the nth cylinder. In addition to Cartesian coordinate systems of the form $o - xyz$, cylindrical coordinate systems $o - r\theta z$ are employed. The positive direction of the z axis is in the downward vertical direction, and the origin of each coordinate system ($z = 0$) is placed on an undisturbed free surface.

The fluid is assumed to be incompressible and inviscid, with irrotational motion. Therefore, a velocity potential can be introduced. The Laplace equation is taken as the governing equation of the flow field to establish the boundary value problem. More-