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Measurements of Water-Wave Cloaking by an Array of Circular Cylinders

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An experiment is performed to demonstrate water-wave cloaking of a surface-piercing cylinder by an array of eight surrounding cylinders. The objective is to confirm cloaking for one wave number (5 rad m^{-1}) and steepness (3.5%) by measuring the second-order mean drift force on the inner cylinder and the far-field surface elevation. The influences of the tank walls and viscous forces are explored, and uncertainties in the measured quantities are evaluated. A geometry is selected using a linear potential-flow solver coupled with an optimizer, and an apparatus is built for tank testing. For the configuration tested, tank-wall effects are important, but viscous forces and load-cell cross talk effects are small. Elimination of the measured second-order mean drift force is observed with the addition of the outer cylinders. Experimental wave amplitudes are in agreement with numerical predictions at almost all measurement points.

INTRODUCTION

Invisibility has long captured the public imagination. Over the last decade it has also drawn the interest of the scientific community, with researchers in various fields pursuing methods of concealing objects from distant observers. Pendry et al. (2006) proposed a method of deflecting electromagnetic waves around a hidden cloaked volume by manipulating the properties of a surrounding cloaking region. Cloaking has since been theoretically investigated and experimentally demonstrated for wave phenomena including microwaves (Schurig et al., 2006), and elastic waves in solids (Milton et al., 2006).

When applied to surface water waves, cloaking describes a reduction in the far-field scattering that occurs when a wave interacts with a fixed structure. Perfect cloaking occurs when scattering is eliminated and the structure's presence is not revealed by diffracted waves. In the general uncloaked case, the amplitude of scattered waves can be related by momentum conservation to the time-averaged, second-order mean drift force exerted on the body. This relationship dictates that the mean drift force is zero if there are no scattered waves. Such elimination of the second-order mean drift force may be of practical use in reducing the size of moorings for large offshore structures.

Several methods have been proposed of achieving water-wave cloaking in monochromatic linear waves. Porter and Newman (2014) considered cloaking a bottom-mounted vertical cylinder by modifying the local water depth and provided strong numerical evidence that perfect cloaking is possible for nonaxisymmetric bathymetries. However, achieving cloaking using bathymetry variation is of limited practical use, particularly in deep water. Newman (2014) therefore investigated cloaking a surface-piercing cylinder of limited draft by surrounding it with either an array of circular cylinders or a ring. Such a ring would potentially be easier and cheaper to install around the legs of large structures. For a prescribed inner body, the objective was to optimize the dimensions and locations of the outer bodies in a manner that minimised the energy scattered from the entire structure. This minimized energy was normalized with respect to the energy scattered by the inner body alone to form an energy ratio, with a low value associated with successful cloaking. Computation of the optimized geometry was achieved by coupling the three-dimensional linear potential-flow solver WAMIT (Lee and Newman, 2012) with the multivariate optimizer PRAXIS (Brent, 2002).

The numerical results presented by Newman (2014) for arrays of cylinders and continuous rings indicate that structures can be designed with energy ratios as small as 10^{-9} at a specified wavelength. While McIver (2014) has more recently demonstrated that perfect cloaking is not possible for the circular arrays investigated by Newman, the possibility that continuous rings may provide perfect cloaking has not been excluded. From a practical perspective, numerical results have demonstrated that very significant reductions in scattered energy and mean drift force may be realized at a specified wavelength by carefully controlling the geometry of the surrounding bodies. For offshore structures, subjected to waves with a variety of frequencies and propagation directions, the potential of cloaking assemblies to reduce mooring loads will depend on the predominant wave conditions at the structure.

The numerical results described above have been confirmed by the work of Iida et al. (2014) as part of a wider wave-interaction theory for multiple bodies proposed by Kashiwagi (2017). Using a higher-order boundary-element method, these researchers also demonstrated that, at a specified wave number, the second-order mean drift force on a fixed cylinder can be reduced to small values by an array of surrounding cylinders. In an inspiring paper, Iida et al. (2016) conducted an experiment to confirm their earlier numerical predictions. The selected geometry consisted of a surface-piercing central cylinder surrounded by eight smaller cylinders. With the structure rigidly mounted, measurements of the surface elevation were performed at a variety of locations close to the cylinders, and recordings were made of the wave mean drift force acting on each cylinder. Numerical and experimental results were in good agreement.

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KEY WORDS: Water wave, cloaking, mean drift force, diffraction.