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A numerical tool for the frequency domain simulation of large arrays of identical floating bodies in waves

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ABSTRACT

The finite-depth interaction theory (IT) introduced by Kagemoto H. and Yue (1986) enables one to drastically speed up the computation of the added mass, damping and excitation force coefficients of a group (”farm”) of floating bodies when compared to direct calculations with standard widely available boundary element method (BEM) codes. An essential part of the theory is the calculation of two hydrodynamic operators, which characterize the way a body diffracts and radiates waves, known as Diffraction Transfer Matrix (DTM) and Radiation Characteristics (RC) respectively. Two different strategies to compute them for arbitrary geometries have been proposed in the literature (Goo, J.-S. and Yoshida, 1990; McNatt J. C. et al., 2015). The purpose of this study is to present the implementation of the former in the zeroth-order BEM solver NEMOH and to compare it with the latter by providing an insight into the DTM and the RC of a truncated vertical circular cylinder and a square box. A very good agreement between the hydrodynamic operators computed with both methodologies is obtained. In addition, hydrodynamic coefficients generated by means of the IT are verified against direct NEMOH calculations for two different array layouts. Results show the effect of hydrodynamic interactions as well as the importance of the evanescent modes truncation for closely spaced configurations.

1. Introduction

Because of the limits of the energy conversion capacity of single devices, it is nowadays well-accepted that commercial exploitation of wave energy will require the deployment of wave energy converters (WECs) in array. As the advancement of WEC technology continues, there is an increasing interest in developing numerical tools to investigate how WECs will interact with one another in the first generation farms.

It has been shown that wave interactions may affect the forces acting upon the WECs and the energy production of the wave farm to varying degrees depending on the layout (Budal, 1977; Falnes J. and Budal, 1982; Falnes, 1984). Forces due to wave radiation and scattering in the array can be well represented by matrices of linear radiation and excitation force coefficients. However, due to memory and time restrictions, the direct computation of these matrices for large arrays of bodies $O(100)$ is beyond the capabilities of standard Boundary Element Method (BEM) codes.

The methodology developed by Kagemoto H. and Yue (1986), known as Direct Matrix Method interaction theory and that we shall refer to herein as IT, combines the features of the Direct Matrix approach in Spring B. H. and Monkmeyer P. (1974) and Simon (1982), and the multiple-scattering technique by Twersky (1952) and Ohkusu (1974). It enables one to accelerate the computation of the hydrodynamic coefficients, for multi-body arrays under certain circumstances, including finite water depth and no vertical overlap. IT computations can generate the coefficients for large arrays, which could not be computed directly with a BEM code. The IT computation is based on mathematically characterizing how an individual isolated device scatters and radiates waves. For this, two hydrodynamic operators known as Diffraction Transfer Matrix and Radiation Characteristics that we shall refer to herein as DTM and RC respectively need to be computed. Kagemoto H. and Yue (1986) provided a method to obtain the DTM and RC for axisymmetric bodies. Goo, J.-S. and Yoshida (1990) developed an approach based on a cylindrical representation of the Green's function by Fenton (1978) to calculate the elements of the DTM and RC for an arbitrary geometry using a BEM.

The approach by Goo, J.-S. and Yoshida (1990) was used to study the forces on the fixed (Chakrabarti, 2000) and floating (Chakrabarti, 2001)

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modules of an interconnected multi-moduled floating offshore structure used by the US Navy. It was also employed by Peter M. A. and Meylan H. (2004) to study the interactions between ocean waves and large fields of ice floes in the marginal ice zone. For that, the extension of the theory to infinite-depth was required. Based on Kagemoto H. and Yue (1986), Kashiwagi (2000) derived a hierarchical interaction theory aimed at studying hydrodynamic interactions among a great number of bodies in very large floating structures. More recently, in the context of wave attenuation in the marginal ice zone, Montiel F. et al. (2016) proposed an approach known as slab-clustering method which combines the Direct Matrix Method with a one dimension multiple scattering technique to solve the multiple-scattering problem in arrays composed of thousands of ice floes.

The methodology of Goo, J.-S. and Yoshida (1990) requires the modification of the standard diffraction problem boundary conditions, as well as access to the source strength distribution on the discretized wetted surface of the body. This output is not accessible to the user in the majority of standard BEM codes which only provide the standard hydrodynamic excitation forces and radiation coefficients after integration over the body surface. As a result, the IT has been applied mainly in cases where WEC geometries are such that an analytical expression of its hydrodynamic operators exists (Child B. and Venugopal, 2010; Göteman, M. et al., 2015). To overcome such limitation, McNatt J. C. et al. (2015) developed and validated an alternative approach to the one of Goo, J.-S. and Yoshida (1990) to calculate the DTM and RC using the standard output of available BEM codes like WAMIT .[1] A shortcoming of the method provided by McNatt J. C. et al. (2015) is that it is unable to include evanescent wave modes in the IT computation.

A key goal of this study is to verify the outputs of a new implementation of the method developed by Goo, J.-S. and Yoshida (1990) in the open-source, BEM-code NEMOH [2] to the outputs using the method developed by McNatt J. C. et al. (2015) by comparing the DTM and the RC of two different geometries, a truncated vertical circular cylinder and a cube. This comparison also serves to illustrate the frequency-dependent patterns of the DTM and RC, which, despite their necessity in IT, have not received much attention in literature.

In the following sections, we first present the solution to the Boundary Value Problem (BVP) for an isolated body in cylindrical coordinates and introduce the concept of partial cylindrical waves. We then consider the multi-body BVP and its exact algebraic solution by means of the IT method derived by Kagemoto H. and Yue (1986). The procedure to obtain the radiation and excitation force coefficients from the solution to the multiple-scattering problem is also presented. Following that, the methodologies of Goo, J.-S. and Yoshida (1990) and McNatt J. C. et al. (2015) for computing the DTM and the RC are presented and compared in section 3. Details of the numerical implementation of the procedure by Goo, J.-S. and Yoshida (1990) in the open-source BEM solver NEMOH are given in section 4. Section 5 presents numerical results as the hydrodynamic operators for a truncated vertical cylinder and a cube. Verifications of IT with direct BEM computations are made via comparison of the free surface elevation and the hydrodynamic coefficients. These results show the importance of selecting the correct truncation value for cases where bodies are placed in close proximity, which has not been shown in previous studies. Finally, verification of the hydrodynamic coefficients computed by NEMOH is made by comparison of a semi-analytical solution for vertical cylinders in a particular array layout which includes near trapped-modes.

2. Interaction theory

The Direct Matrix Method interaction theory (IT) by Kagemoto H. and Yue (1986) is based on the linear potential flow theory (Newman, J.N, 1999). Thus, the constraints of linearity of the governing equations and perfect fluid characteristics are assumed to be satisfied. The former applies as long as a small wave steepness and a small amplitude of the body motions with respect to its characteristic dimension can be assumed. The latter holds if the fluid can be characterized as inviscid and incompressible and the flow as irrotational. In this case all the flow quantities of interest can be derived from a scalar field known as velocity potential Φ and such that $\overrightarrow{v} = \nabla\Phi$. If in addition, a harmonic time dependence is assumed, the spatial and time variation of Φ can be decoupled as $\Phi = Re\{\phi(x, y, z)\, e^{-i\omega t}\}$, where ϕ is the complex spatial part of Φ, (x, y, z) are the spatial coordinates in a global Cartesian reference system, $i = \sqrt{-1}$, ω the angular frequency and t the time.

For an array of floating bodies, and given the linearity of the problem, the total potential in the fluid domain can be computed as a superposition of the different forms of the velocity potential:

$$\phi = \phi^I + \sum_{j=1}^{N_b} \phi_j^S + \sum_{j=1}^{N_b} \sum_{k=1}^{Df_j} \phi_j^{R,k} \tag{1}$$

where ϕ^I is the ambient incident wave potential, ϕ_j^S is the scattered potential by body j in the array when held fixed, $\phi_j^{R,k}$ is the radiated potential by body j moving in its kth degree of freedom, N_b represents the number of bodies in the array and Df_j stands for the number of degrees of freedom k of body j.

2.1. Partial waves

In a large array, waves emanating from each body due to scattering and radiation will propagate and interact with its neighbours. This will lead to a succession of scattering events which are referred to as multiple-scattering (Martin, 2006). In this context, the representation of the scattered potential by body j can be described by the outgoing wave solution to the BVP in cylindrical coordinates (a full derivation can be found in Child (2011) 3.4.1):

$$\phi_j^S = \sum_{m=-\infty}^{\infty} \left[\left(A_j^S\right)_{0m} \frac{\cosh k_0 \left(z_j + d\right)}{\cosh k_0 d} H_m^{(1)}\left(k_0 r_j\right) + \sum_{n=1}^{\infty} \left(A_j^S\right)_{nm} \cos k_n \left(z_j + d\right) K_m\left(k_n r_j\right) \right] e^{im\theta_j} \tag{2}$$

where $H_m^{(1)}$ is the Hankel function of the first kind of order m (see Fig. 1a,1b,1c), K_m is the modified Bessel function of the second kind of order m (see Fig. 1d,e,1f), $(A_j^S)_{nm}$ are scattered complex coefficients, subindices m and n are the modes representing the angular and depth variation of the scattered potential respectively, d is the water depth, (z_j, r_j, θ_j) are the cylindrical coordinates local to body j and k_0 and k_n are

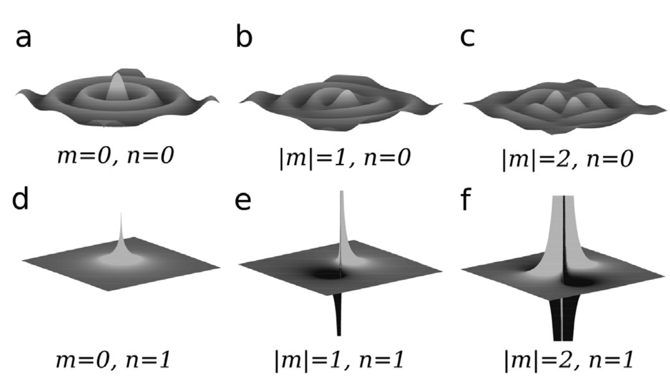

Fig. 1. Partial waves modes. Progressive term $H_m^{(1)}(r)$ (a, b, c); evanescent term $K_m(r)$ (d, e, f).

[1] www.wamit.com.
[2] http://lheea.ec-nantes.fr/doku.php/emo/nemoh/start.