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Weakly nonlinear modeling of submerged wave energy converters

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ABSTRACT

Wave-to-Wire numerical models being developed for the study of wave energy converters usually make use of linear potential flow theory [1–5] to describe wave-structure interaction. This theory is highly efficient from a computational perspective. However, it relies on assumptions of small wave steepness and small amplitude of motion around mean positions. Often, maximization of wave energy converters' energy performance implies large amplitude motion [6–8], thus contradicting the assumption of small amplitude motion.

An alternative approach is to linearize the free surface conditions on the instantaneous incident wave elevation (Weak-Scatterer approach [9]) while the body conditions are evaluated at the exact body position. Studies of wave energy converters' dynamic response using this method are expected to be more accurate, while maintaining a reasonable computational time. With this aim, a Weak-Scatterer code (CN_WSC) was developed and used to study two submerged wave energy converters. The first is a heaving submerged sphere and the second is a bottom-hinged fully submerged oscillating flap. They are inspired respectively by the Ceto [10] and WaveRoller [11] devices.

Initial calculations were performed in linear conditions first to verify the CN_WSC against linear theory. Subsequently, calculations in nonlinear conditions were performed, using large wave steepness and amplitude of body motion. In linear conditions, results of CN_WSC showed good agreement with linear theory, whereas significant deviations from linear theory were observed in nonlinear conditions. As amplitude of body motion increases, linear theory tends to overestimate energy performance in comparison with Weak-Scatterer theory. In contrast, with smaller amplitude of motion but larger wave steepness, the opposite result is obtained: energy performance is underestimated by linear theory compared to Weak-Scatterer theory.

1. Introduction

The standard numerical tools for modeling and designing wave energy converters (WECs) rely on linear potential theory [1–5], and as such are limited to movements of small amplitude around mean positions. However efficiency of WECs relies on large amplitude motion [6]: by design, their resonant frequencies must fall in the wave excitation range. Linear potential theory has been shown to be insufficient to model the behavior of WECs in such configurations [7,8]. Thus, other numerical approaches are required. A nonlinear potential-flow model, in the context of a numerical wave-tank (NWT), was pioneered by Longuet-Higgins and Cokelet [12]. In their work, they used the mixed Eulerian–Lagrangian (MEL) approach, solving the Laplace equation in an Eulerian coordinate system, and then advecting the nodes at the mesh boundaries. Since that time, several wave tanks have been developed, in both two and three dimensions [13–16]. Issues related to the development of NWT have been reviewed by Tanizawa [17]. Recent developments have focused on accelerating three-dimensional NWT (computational requirements are still large) and address issues of gridding, numerical stability, and accuracy that can be problematic for complex geometries [18,19].

A weakly nonlinear approach, based on the Weak-Scatterer (WS) approximation, is expected to be a promising alternative that avoids or reduces the impediments of fully nonlinear potential-flow codes. Introduced by Pawlowski [9], this class of approximation is based on linearization of the free surface conditions on the incident wave elevation, allowing treatment of nonlinear steep incident waves. The body condition is evaluated at the exact instantaneous position of the body, allowing large body motions to be taken into account. The only assumption in the WS approach is that the perturbation potential is small. Thus, numerical codes based on the WS approach are expected to be accurate in cases with small to large amplitude body motions, incident

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waves of arbitrary steepness and when the perturbed wave is small. The different quantities are then decomposed into incident and perturbation components, with the incident ones as forcing terms while only the perturbation ones are solved. The main advantage of this is that the incident wave does not need to be propagated from a wave-maker, allowing the mesh to be refined only in the vicinity of the body. Moreover, since the free surface boundary is known explicitly, the WS method is expected to be more robust and stable than the fully nonlinear approach.

Several WS flow solvers have been developed in the past: SWAN-4 [20], LAMP-4 [21] and WISH [22]. Their fields of study were however mainly focused on ship with forward speed, which can indeed be considered as slender bodies. As a consequence, the scattered waves and motion responses are small and the assumptions of the WS approximation are fulfilled. In this article, the aim is to investigate whether the WS method can improve numerical modeling of WECs.

The development of this new solver is based on the experience gained by the authors in the 90's in developing a three-dimensional time domain boundary integral equation (BIE) solver for linear, second-order and fully nonlinear wave-body interaction problems [13,23,16,24]. In particular, although higher order BIE solvers are available, the choice of a linear, isoparametric BIE solver based on triangular elements has been maintained. This solution method presents some important advantages, namely the capacity to express the surface integrals in a purely analytic form, and very good efficiency (typically, the ratio of number of unknowns to number of elements is approximately 0.5). In addition, it is possible to apply efficient mesh generation schemes that originate from the finite element community, which is considered to be key to practical applications. Analytical expressions for the influence coefficients, initially unpublished [25], have been completely redeveloped by the first author during his PhD work, and are presented in Appendix A of this paper.

Comparisons with a fully nonlinear flow solver have been carried out for a submerged body in forced motions [26]. In the present paper, we extend this to the case of freely moving bodies, which requires new equations and numerical implementations to calculate the motion of the body. The Implicit method, introduced by Tanizawa [27] and based on the solution of a second boundary value problem (BVP) for the time derivative of the velocity potential, was chosen to solve the complex implicit problem of the body motion calculations. We have developed a new expression for the BVP body condition, which unifies the two expressions previously given by Tanizawa [27] and Cointe [28]; the details are presented in [29].

First, WS theory is recalled. The numerical implementations are then introduced, namely the boundary element method, the time-marching scheme and the fluid/structure interaction method. Finally, the method is applied to two submerged WECs, using the Ceto [10] and WaveRoller [11] systems as examples. For the purpose of verification, results are initially compared to linear theory in linear conditions. Simulations in nonlinear conditions, with large amplitude motions and large steepness incident wave, are then conducted.

2. Methods

2.1. Potential flow theory

Assuming a fluid to be incompressible and inviscid with irrotational flow, its flow velocity derives from a velocity potential ϕ which satisfies the Laplace Eq.:

$$\nabla^2\phi(x, y, z, t) = 0 \tag{1}$$

in the fluid domain, D. The boundary of the fluid domain is $\partial D = \Gamma = \Gamma_{fs} \cup \Gamma_b \cup \Gamma_w \cup \Gamma_d$, see Fig. 1.

In the general case, without forward speed, it can be shown [30] that the velocity potential is the solution of the following boundary value problem (BVP):

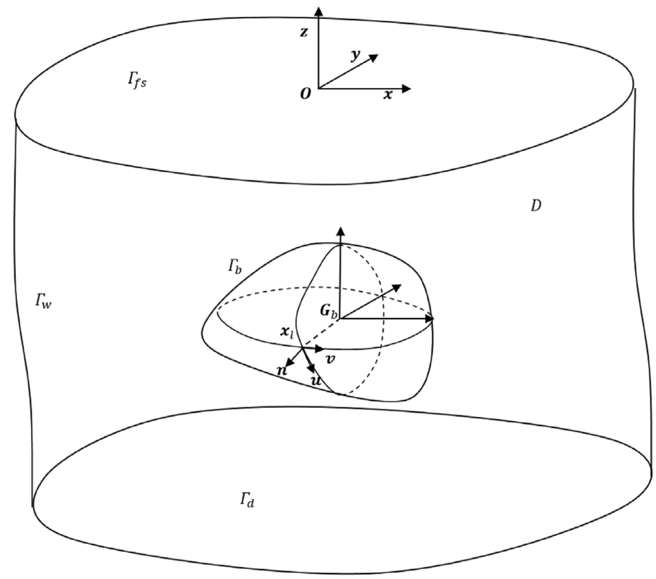

Fig. 1. Domain definition: boundaries and reference frames.

$$\begin{cases} \nabla^2\phi = 0 & \text{in the fluid domain } D \\ \frac{\partial\phi}{\partial t} = -g\eta - \frac{1}{2}\nabla\phi\cdot\nabla\phi & \text{on the free surface, } \Gamma_{fs} \\ \frac{\partial\eta}{\partial t} = \frac{\partial\phi}{\partial z} - \nabla\phi\cdot\nabla\eta & \text{on the free surface, } \Gamma_{fs} \\ \frac{\partial\phi}{\partial n} = \mathbf{V_b}\cdot\mathbf{n} & \text{on the body, } \Gamma_b \\ \frac{\partial\phi}{\partial n} = \phi_0 & \text{on the seabed, } \Gamma_d \\ \phi \longrightarrow 0 & \text{on boundaries far from the body, } \Gamma_w \end{cases} \tag{2}$$

The free surface elevation is denoted by the single-valued variable η, which means that wave overturning cannot be handled. g is the gravitational acceleration, V_b the body velocity and $\mathbf{n}$ the normal vector pointing outwards from the fluid. ϕ_0 is the velocity potential of the incoming waves.

Using Green's Second Identity along with the Rankine source, it can be shown that the resolution of the 3D Laplace equation in the fluid domain can be reduced to a surface integral equation, on its boundaries.

2.2. The Weak-Scatterer approximation

The WS approximation relies on the decomposition of the velocity potential and the free surface elevation (ϕ, η) into the incident (ϕ_0, η_0) and the perturbation (ϕ_p, η_p) components, see Fig. 2.

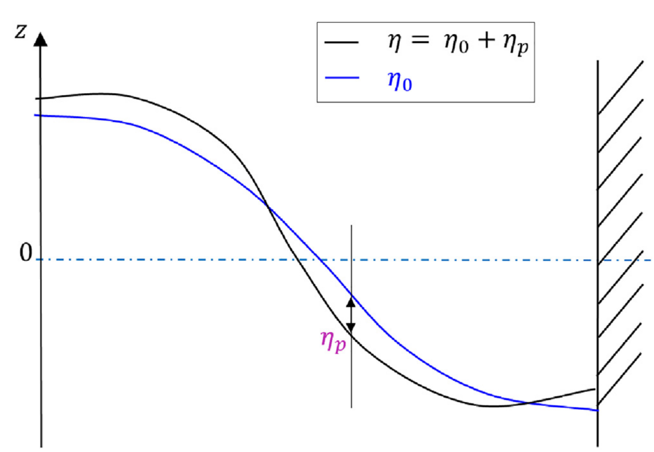

Fig. 2. Weak-Scatterer decomposition and definition of the different wave elevation components.