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An unsteady 3D Isogeometrical Boundary Element Analysis applied to nonlinear gravity waves

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Highlights

- An IGA–BEM model based on T-splines is proposed to simulate gravity waves.
- The method is stable and accurate even with important distortions of the elements.
- Complex geometric models can be constructed by direct link with CAD tools.
- The predictive capabilities and accuracy are checked with benchmark examples.
- The application for the prediction of waves in surf parks is shown.

Abstract

In this paper we describe a three-dimensional Isogeometric Analysis based on the Boundary Element Method (IGA–BEM) in the time domain. We show the capabilities and accuracy of the method for the simulation of non-linear gravity waves. The flow is assumed to be inviscid and irrotational and this leads to a mixed boundary value problem governed by the Laplace's equation. The Boundary Integral Equation is solved at each time step and the time marching scheme is performed with a fourth-order Runge–Kutta method. The hydrodynamic force is calculated with an auxiliary boundary equation. In the simulations, the analysis suitable-T-spline and NURBS basis are used to approximate both the geometry and the BEM variables in the context of the Bézier extraction framework. The main advantages of this approach are: (1) the control of the continuity and smoothness of the T-spline and NURBS basis, which makes the model numerically stable without the need of artificial smooth techniques; (2) the high geometrical approximation of the non-rational splines; (3) the refinement capabilities without affecting the geometry and BEM variables and (4) and the direct integration with computer aided geometrical design tools. Some numerical benchmark examples are analysed to demonstrate the accuracy and the stability of the method. In addition, we report simulations of waves generated by the movement of submerged foils, which have implications in some wave generator systems installed in surf parks.

Keywords: Isogeometrical Analysis; BEM; T-spline; Gravity wave; Time domain; Surf park

1. Introduction

In the last decades, numerical models have been developed for the prediction of the propagation of gravity waves in the time domain. These models have been applied to simulate tsunami generation and [1] overturning waves [2–4],

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to design breakwaters [5,6], to predict the wave pressure impact on structures [7], or to study radiation and diffraction waves produced by a wave-maker [8–11]. Nowadays, because of the increasing interest on the ocean renewable energy, in which the generation systems are installed near-shore or off-shore, new applications of such models are being used to study the fluid–structure interaction considering the effect of the waves [12–16].

Early numerical studies on the non-linear wave propagation appeared in 1976 when Longuet–Higguin and Cokelet [17] presented their bi-dimensional (2D) approach to simulate the transient surface waves. Their approach was based on the potential flow theory and used the Boundary Element Method (BEM) to solve the Laplace's equation in conjunction with a Mixed Eulerian–Lagrange (MEL) technique to update the free surface. Similar models were used to study a wide variety of non-linear water waves problems [18–22], but it was the study of Dommermuth et al. [23] that demonstrated the validity of the potential flow theory applied to the unsteady gravity wave propagation. These authors presented a successful comparison between the numerical results obtained by a 2D-BEM model and experimental results obtained in a water tank. It is worth mentioning the studies reported by Grilli et al. [2,24,25] who developed an advanced approach using 2D high order BEM. Later, Grilli et al. [3] and Guyenne and Grilli [4] extended the model to three-dimensional (3D) geometries to analyse overturning waves over an arbitrary bottom.

Some full non-linear high-order 3D BEM models have been proposed to simulate the unsteady interaction of the wave with a rigid body. An overview of such works can be found in Tanizawa [26]. Among them, Lee et al. [27] studied the non-linear waves and the hydrodynamic force generated by the movement of a submerged sphere. Bai and Taylor [10] investigated the wave radiation produced by a moving submerged truncated cylinder and the wave diffraction around a vertical cylinder [28]. They used an unstructured triangular mesh constructed with second order Lagrange elements in order to obtain a good approximation of the geometry. Later, these authors extended the model to flared floating structures [29]. Sung and Grilli [30] analysed the waves generated by an advancing surface disturbance. Following the Grilli's works, these authors used a structured mesh formed by isoparametric bi-cubic piecewise overlapping elements that provided a local smoothness of the geometry and of the physical variables. More recently, Hannan et al. [31,32] studied the interactions between water waves and fully submerged fixed or moving structures. In the same line, but limited to 2D, Dombre et al. [33] extended the early work presented in [34] to study the dynamics of free fully submerged structures.

In addition, other models have been proposed to analyse more specific problems such as the post-breaking phenomenon, the violent wave impact against structures, the large fluid movement in a confined space with steep non-linear waves or the viscous and the vortex force in the context of floating structures. In such cases, the potential flow theory is not valid and other tools based on Computational Fluid Dynamics (CFD) solvers, to resolve the full Navier–Stokes equations, or the Lattice Boltzmann method (LBM) have been used [35–40]. Most of these problems have been formulated in 2D, and despite the increase of computational power, the full 3D models require a considerable computational cost. Therefore, unless in such specific cases, the potential theory together with BEM provides good results for non-linear gravity waves problems with a reduced computational time. Some advantages are: (1) the reduced dimensionality of the domain; (2) the ability to handle complex 3D geometric models and (3) the Sommerfeld radiation condition is implicitly satisfied in the Green function.

In the last two decades, the Non-Uniform Rational B-Spline (NURBS) representation has been widely used in the marine industry through the modern Computational Aided Design (CAD) systems. NURBS exhibits multiple advantages, such as: (1) the quadratic and cubic surface can be represented exactly; (2) advanced construction techniques and shape modification tools are available; (3) the smoothness of the basis can be managed via knot and (4) h, p and k-refinement can be applied without modifying the geometry. These characteristics, in combination with other mathematical properties, give to NURBS the ability to handle complex geometries and provide suitable basis for numerical analyses. In this line, the incorporation of NURBS into the BEM to simulate wave-structure interaction has appeared recently in the literature (see for example Refs. [41–46]). These approaches use two different basis functions, one to represent the geometry and the other for the physical variables. Hughes et al. [47,48] and Cottrell et al. [49,50] introduced the concept of the Isogeometrical Analysis (IGA) in the context of Finite Element Method (FEM) that consists in the approximation of the full model with the same basis functions used for the geometry. This concept, that has acquired enough maturity in recent years, allows a direct link between the CAD geometry and the engineering analysis tools. Politis et al. [51] extended the IGA to the BEM and applied it to a 2D external potential flow problem. Simpson et al. [52] applied an IGA–BEM method to a 2D elastostatic problem. More recently, Belibassakis et al. [53] presented a 3D IGA–BEM model based on the Neumann–Kelvin problem to study the ship wave resistance and showed a novel combination of a modern CAD system with hydrodynamic solvers.