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Three-dimensional numerical wave generation with moving boundaries

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ABSTRACT

In this work the numerical model IHFOAM is extended to incorporate moving-boundary wave generation and absorption capabilities. The goal is to obtain a solver that includes free surface flow through porous media, able to replicate the wave generation procedures of physical wave basins. For this purpose a new boundary condition to mimic the action of multi-paddle piston wavemakers is developed and the dynamic mesh capabilities present in OpenFOAM® are enhanced. A set of experiments is carried out in the laboratory and is reproduced numerically to validate the correct operation of the new module. Additional numerical experiments are carried out to test the efficiency of active wave absorption. The results indicate a high degree of accordance between the experimental and numerical results and a correct performance of active wave absorption at the moving boundary.

1. Introduction

Numerical modelling (NM) is a set of tools and techniques that can replicate physical processes with the help of computers. This approach can currently be considered as completely established in a large number of fields, as for example in industrial, chemical or aeronautical engineering. The introduction of NM in coastal engineering, has occurred more recently and major developments are still in progress. However, during this relatively short period of time the NM technique has proven valuable to gain further insights of complex processes.

Currently there are several approaches to perform NM in the frame of coastal engineering. Each of them presents a different set of initial assumptions or simplifications, and has been developed to a different extent, therefore, the field of application of each type of models is different.

Potential flow models, solving simplified Navier–Stokes equations usually averaged on the vertical, include the Boussinesq type (FUNWAVE, Wei and Kirby, 1995; COULWAVE, Lynett and Liu, 2002; Mike 21, Sørensen et al., 2004) and the Nonlinear Shallow Water (NLSW) type (SWASH, Zijlema and Stelling, 2011) models. They are ideal for wave propagation involving refraction, diffraction and shoaling. Due to their relatively simple equations, they are suitable to simulate large domains (kilometres) and time series (sea states of several hours) in very competitive computational times (from minutes to hours).

Other models that can offer finer details are grouped under the denomination of Computational Fluid Dynamics (CFD). CFD codes require significantly more computational resources than potential flow models. Nevertheless, the rapid increase of computational power undergone in the last years has opened new perspectives. Problems that were nearly impossible to solve a decade ago are now straightforward to simulate.

CFD models solve the Navier–Stokes equations, following either an Eulerian (continuous) or Lagrangian (discrete) specification of the flow field. Smooth Particle Hydrodynamics (SPH) models are the best-known representative of the latter. In SPH the movement and interaction of spherical particles reproduces the behaviour of the equations. Currently, the most advanced models are GPUSPH (Dalrymple and Rogers, 2006) and ISPH (Shao, 2010). The main disadvantage of this approach is its high diffusivity, that induces an artificial loss in wave height, limiting the size of the simulation domains. As a reference, domains of 50×50 m can be simulated at a rate of tenths of seconds per hour, thanks to GPU computing. It must be noted that SPH is a very promising approach, but since it was introduced in coastal engineering less than a decade ago, it has not reached a high level of development yet.

The Eulerian approach encompasses the Reynolds-Averaged Navier–Stokes (RANS) models. Historically, the first RANS models were 2DV (two-dimensional vertical plane), for example, COBRAS (Lin and Liu, 1998), VOFbreak (Troch and De Rouck, 1998) or IH2VOF (Lara et al., 2008). Due to their low computational cost they have proven to be adequate for engineering applications. This is one of the reasons why they are widely used today, even as a design tool for real structures. The generalization of 3D RANS models is opening the door to a new revolution, as real 3D wave-structure interaction processes can now be captured accurately. Among the most advanced 3D models are: CADMAS-SURF (Kim et al., 2010), FLOW-3D (Choi et al., 2007), IH3VOF (del Jesus et al., 2012) and IHFOAM (Higuera et al., 2014). RANS models are prepared to offer fine detail, simulating larger domains than SPH, but not as large as the potential flow models can. As an order of magnitude IHFOAM

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is capable of simulating a real domain of 500 × 500 m at a rate of 30 s per day with an HPC.

In order to obtain accurate results with a numerical model, it must be validated, to prove that it is capable of reproducing the processes of interest. Sometimes, when the model depends on adjustable parameters, they might need to be set according to experimental results as well (calibration). Therefore, NM must be regarded as a tool complementary to physical modelling. In fact, there is a field called composite modelling that promotes the integrated and balanced use of physical and numerical models (Gerritsen and Sutherland, 2011), and offers countless advantages, as outlined in Zhang et al. (2007).

The benefits of composite modelling appear at every stage of research or consultancy projects. Before starting the study itself, NM can help in the predesign of the experiments in an approximate way. NM is significantly cheaper than physical experiments and it can be applied as a tool to highlight the zones of interest, to find the most suitable places where the measuring devices can be placed, to anticipate problems, or even to select the most relevant cases to be tested physically. While the experiments are ongoing, the model can be validated to create a *numerical mirror* of the experimental facility. Once the experiments have ended, NM can be applied to extend the database obtained with purely numerical results. Additional numerical measurements can also be collected at this final stage, overcoming some experimental restrictions, as probing can be performed for any field at any location without disturbing the flow. Moreover, additional cases can be run at prototype scale, avoiding scale effects.

A new concept has been introduced in the previous paragraph: "numerical mirror". A *numerical mirror* is a setup (mesh, boundary conditions, calibrated parameters…) of a model that has proven to mimic the physical processes that take place at a given experimental facility. This conception may seem novel in coastal engineering, but it has been applied for long time in other fields. The paradigm is aerodynamics, in which composite modelling is fully developed, as *numerical mirrors* of wind tunnels are extensively applied.

The main goal of this paper is to develop a three-dimensional boundary condition to mimic the physical wavemakers, including multiple moving paddles. After this introduction, a brief literature review on wave generation is presented. Next, the numerical model IHFOAM is introduced. The new dynamic capabilities are described, giving special emphasis to the solutions for the problems found. Then, the model is validated using a set of physical experiments. Additional cases to investigate the accuracy of active wave absorption are studied afterwards. Finally, the conclusions of this work are highlighted.

2. Review of wave generation methods

Waves are often the primary dynamic in coastal engineering and a realistic wave generation is needed to accurately represent the actual physical processes. In this sense, the ultimate requirement for wave generation procedures is the generation of three-dimensional multi-directional random sea states. There are 3 main mechanisms to simulate waves in numerical models: internal, static-boundary and moving-boundary wave generation and absorption.

The first one to be reviewed is internal wave generation. The oscillatory flow is generated within a region in which water is pumped in or out according to mathematical expressions. This procedure is linked to numerical dissipation zones (also known as sponge layers), as waves are radiated in all the directions and those travelling away from the region of interest need to be absorbed. Examples of internal wave generation exist for RANS (2D: Lin and Liu, 1999; 3D: Ha et al., 2013), for potential flow models (Schäffer and Sørensen, 2006; Wei et al., 1999), and very recently for SPH models (Liu et al., 2015).

The second type is static wave generation and absorption (i.e. Dirichlet-type boundary conditions). In this case both processes are handled at the boundaries according to different wave theories, thus, saving significant computational cost because dissipation zones are not needed. The most remarkable examples also include RANS (2D: Troch and De Rouck, 1999; Torres-Freyermuth et al., 2010; 3D: Higuera et al., 2013a) and potential flow models (Wei and Kirby, 1995).

The third procedure derives from the need to replicate the exact wave generation mechanisms of the experimental facilities (i.e. the actual wave-making machines). Therefore, a moving boundary driving the generation and absorption of water waves is required. Two-dimensional (Mahmoudi et al., 2014) and three-dimensional (Farahani et al., 2014, applying a single paddle, though) examples can be found. This approach used to be the only one available for wave generation in SPH models until Liu et al. (2015).

Moving-boundary wave generation is not so common yet for Eulerian potential flow and RANS models, as it involves mesh deformation, which is slower than static wave generation. Yet, this approach is usually faster than the internal generation due to the smaller number of cells. Nevertheless, this procedure may prove important for cases very sensitive to the change in the length of the domain due to the movement of the paddles (Higuera et al., 2013b), as when reproducing seiches or harbour resonance. Applications are present in literature for potential flow models (Grilli et al., 2002; Orszaghova et al., 2012) and for RANS models as well (2D: Lara et al., 2011; 3D: Kiku et al., 2014).

3. Numerical model: IHFOAM

IHFOAM (Higuera et al., 2014) is an open source numerical model to simulate wave interaction with coastal structures. The solver inherits its basic structure from OpenFOAM®. It is prepared to solve the Volume-Averaged Reynolds-Averaged Navier–Stokes (VARANS) equations for free surface flows composed of two incompressible fluids, generally water and air. It applies a finite volume discretisation and the volume of fluid (VOF) method. Moreover, it supports a large number of turbulence models (e.g. $k-\epsilon$, $k-\omega$ SST and LES). The features that make this model unique include wave generation and active wave absorption (Higuera et al., 2013a) working at static boundaries. Therefore, the computational cost does not noticeably increase, unlike for internal methods. IHFOAM is also prepared to simulate porous structures (e.g. rubble-mound breakwaters). For extensive model validation, the reader is referred to Higuera et al. (2013b, 2014).

3.1. Moving boundary wave generation

A new boundary condition (BC) has been developed to replicate the movement of piston-type wavemakers. The new module works in 2D (single paddle) or 3D (multi-paddle).

The only inputs that are required are the time series of displacement for each paddle. These signals can be theoretical (i.e. obtained by applying analytical expressions), in which case they must comply with the limitations of the device that they are trying to replicate (i.e. maximum velocity, acceleration and stroke). Alternatively, the signals may come from measurements of paddle motion from experimental facilities. In this case it is important to distinguish between the target and the feedback signal of the wave machine. The second one (if available) includes all the mechanical and control loop effects of the wavemaker as the response time (delay) and inertia. If active wave absorption is to be connected, the time series of water elevation at each paddle are also required. Again, these can come from theoretical values or from actual measurements from the free surface gauges mounted on the front of the paddles.

During runtime the BC performs several operations. First, it computes the limits of each paddle, dividing the boundary into a given number of vertical slices with equal width. It then distributes the vertices of the boundary between all the paddles, depending on their position.

Next, the displacement of such points is set according to the time series provided. The first problem arises at this stage because adjacent paddles in wavemakers move independently one from another and often have a different displacement. In fact they only present the same displacement when generating regular waves or long-crested irregular