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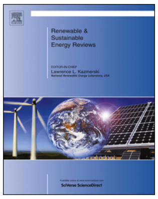

Real time hybrid modeling for ocean wave energy converters

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ABSTRACT

Accurate modeling of ocean wave energy converters is limited mainly due to the reciprocating nature of the exciting force and consequent complications, particularly in the fluid domain. Direct simulation is usually computationally expensive, and experiments are constrained by scaling rules that cannot be satisfied simultaneously, and of course, by the costs. Many modeling problems, including several in ocean wave energy, can be divided into sub-domains that for each, one modeling scheme (e.g. numerical simulation or experiment) is practical and preferred. The idea behind hybrid simulation is to solve each sub-domain using the preferred method, while sub-domains communicate with each other at their common boundaries via sensors and actuators, with the prime objective of solving the main problem as a whole. We are particularly interested in the set of problems in which the subdomains are strongly coupled and hence significantly influence each other. The challenge is when one of the subproblems is to be modeled experimentally and therefore as a result the entire hybrid simulation modeling has to be carried out in real time. We review here the background and details of the real time hybrid simulation scheme with the specific focus on the modeling of ocean wave energy devices. We elaborate major challenges via a case study of a newly proposed seabed mounted pressure-differential wave energy converter called "Wave Carpet". We find the optimum parameters of the power takeoff units as well as their optimal positioning in order to achieve the highest overall efficiency of the Wave Carpet.

Contents

1. Introduction

Numerical and experimental techniques today can address the modeling of a large class of problems. For some problems, accurate computational treatment is extremely expensive, but experimental investigation is realizable. Examples of such problems include those involving complicated turbulent and highly nonlinear flows, problems with impact forces such as sloshing and slamming, and problems that involve wave breaking. Another group of problems is easy to be treated numerically, but is difficult or non-practical to be investigated experimentally. For example, trans-ocean propagation of long waves or problems involving multi-physics processes (such as hurricanes) fall in this category.

There is a third group of problems that cannot be fully modeled experimentally, nor numerically, but can be divided into two (or more) sub-problems in such a way that for each sub-problem

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one of the techniques can be employed. An example of such problem is a complex system involving more than one scaling factor. For instance, experimental modeling of a floating object under the combined action of wind and waves (e.g. under storm condition) requires matching of both Froude number and Reynolds number, which is simply impossible. Direct numerical simulation of this problem, particularly in the wave domain and under strong wave conditions where nonlinear effects are important, requires a very fine computational mesh that makes it computationally very expensive.

The idea of hybrid simulation is to divide the problem into multiple sub-problems and use a suitable technique for each of the domains which are communicating with other domains at their interfaces. Specifically, what this paper aims at is when the two domains are strongly coupled, i.e. sub-problems cannot be solved independently. If at least one of the domains is to be modeled experimentally, then the entire hybrid modeling must be performed in real time. Real time modelings are now closer than ever to be realized owing to the state-of-the-art advancement in both computational capabilities and experimental techniques (e.g. sensors' and actuators' response times, fast data acquisition).

In a hybrid simulation modeling, measurements at the interface are guided to a central control unit (CCU) at each time step, where signals are interpreted as physical variables, e.g. pressure and speed. The variables are then fed into the computational domain and either the kinematic quantities, e.g. displacements of the interface, and/or forces exerted on the interface are calculated. This may require geometric transformation or condensation of degrees of freedom to match the physical constraints (limitations) dictated by the physical setup. The command signals are subsequently sent to actuators for the corresponding action to be applied on the interface. Clearly, the new status of the interface modifies the experimental domain. At the beginning of the next time step the new measurements are collected from the modified experimental domain and the loop continues. The entire process mentioned above has to be achieved in just a fraction of second (the target time scale is less than 10 ms).

Hybrid simulation has a long history in seismic-resistant civil engineering [1]. The first operational concept of hybrid testing was proposed in the late 1960s by Hakuno et al. [2] and was further developed by Takanashi et al. in 1975 [3] who used simple controlled actuators to apply virtual seismic loads on scaled structures. Since this point the methodology of hybrid testing became a wide used technique in earthquake engineering. The hybrid simulation techniques are historically connected to the methodology of “pseudo-dynamic testing”. This pseudo-dynamic testing procedure includes a simultaneous simulation and a control process. While the inertia and damping properties of the assessed system are simulated, the stiffness properties are acquired from the experimental structure itself. The methodology behind pseudo-dynamic tests implies the calculation of dynamic displacements by including the inertia and damping properties from the simulation as well as the assessed systems' stiffness properties. The structural response under loads (e.g. seismic motion) is then simulated in quasi-static fashion [4]. A further developed form of the pseudodynamic testing is the so-called pseudodynamic substructuring, which allows us to facilitate full-scale testing through replacing specific parts of the system with actuators. Another methodology is the so-called “Continuous Pseudodynamic Testing” [5]. In contrast to the regular pseudodynamic testing and the substructuring methodology, which are based on a quasi-static time scale and often run approximately 20 times slower than the real time scale, the continuous pseudodynamic testing methodology provides continuous actuator movement. Thus only a reduced hold phase of the actuator exists, which reduces any force relaxations in the assessed system. Nevertheless this methodology which was introduced by Ohi et al. [5] in 1983 evolved over the past 30 years. The continuous development of substructuring methods and the noteworthy improvements in actuator and sensor technology subsequently led to a repeated experimental implementation, especially in the field of earthquake engineering/structural dynamic research. Meanwhile the term of “Hybrid Simulation/Modeling” evolved and became more and more common in this area of research.

Today the term “Real Time Hybrid Simulation” refers to the extremely small loop period scale to nearly achieve a 1:1 time scale in displacement, velocity or acceleration control. Even though there does not exist a defined time limit for one feedback-forward loop, the literature states a loop period between 5 and 20 ms, depending on the application [6,7]. While Real-Time hybrid simulation always includes a computational domain, in which parts of the experiment are simulated or numerically modeled, ‘Effective Force Testing’ is based on a force control algorithm. This method is usually used, for systems, which can be modeled as a series of lumped masses. Contrary to the pseudodynamic and hybrid testing the forces are known a priori for any acceleration record of the system. Therefore no computational time is required for the EFT method in determining the load which is applied on the experimental structure [8–11].

The aim of this research is to investigate the modeling of wave energy harvesting devices using the hybrid simulation. Specifically, we model the fluid domain and the fluid–structure interaction in the experimental domain, and the response of the power takeoff unit to the hydrodynamic forces is calculated and implemented by the actuators at the interface of the two domains. The major difference between what traditionally is used in earthquake engineering and hybrid modeling of a wave energy harvester is the very strong coupling and interaction of the two domains: the response of the wave energy harvester may substantially affect the wave field, and the wave field strongly affects the power taken off.

As a case study, we consider a newly developed wave energy convertor called “Wave Carpet” that is a seabed mounted pressure-differential wave energy harvester [12–14]. The Wave Carpet is a flexible mat that is fully submerged and connected to the seabed by reciprocating fluid pumps working as power takeoffs. The flexible mat moves up and down, as the overpassing waves travel above it, and exerts vertical force on pumps resulting in fluid being pumped. Experimental modeling of a scaled Wave Carpet with reciprocating fluid pumps is limited in accuracy due to the fact that waves and pumps do not scale down similarly. The wave and flexible mat components are scaled down by Froude and Cauchy numbers which do not interfere with each other, while pumps are scaled down by the Reynolds number that cannot be matched with Froude scaling. In fact, in a small scale lab test the flow in the pump can barely go beyond laminar, making predictions less correct [15].

In a hybrid modeling of the Wave Carpet the wave part is modeled in the experimental domain and the power takeoff (i.e. pumps) part is modeled in the computational domain. The two domains will then interact via a hybrid framework. Specifically, effect of the pumps on the mat will be replaced by the action of actuators. At each time step sensors (force transducers) on the shaft connected to the carpet will measure the force. The measured signal and the known position of the actuator from the last time step are sent to the Central Control Unit (CCU) where they are processed and then sent to the computational unit where response of the pumps is numerically calculated in terms of force and displacement. These are fed back to the CCU and proper actuator command signals are calculated and are sent to the actuators. The loop then continues. Note that in a hybrid simulation framework a strong coupling between computational and experimental domain exists and therefore the problem is transient all the time. The time step must be chosen to be small enough such that important small scale phenomena are properly resolved.