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Optimization of a flexible floating structure for wave energy production and protection effectiveness

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ABSTRACT

In the present paper, a multi objective optimization process of a novel Flexible Floating Structure (FFS) subjected to regular and irregular incident waves is developed and presented. The FFS introduced here is considered as an effective structure capable for both wave energy production, with the utilization of a linear hydraulic Power Take-Off (PTO) mechanism, and protection effectiveness. FFS consists of a grid of floating modules connected flexibly in two directions by PTOs with known linear damping characteristics and by connectors with known properties. The optimization process includes two distinct optimization stages; the first one is related with the identification of the optimal set of non dominated solutions and the second one with the selection of the optimum design configuration of the FFS. The performance criteria considered for the selection of the optimum design of the FFS are the produced power, the protection effectiveness and the structural integrity of structural parts that compose the FFS and more specifically of the connectors of the floating modules of the FFS. The performance criteria are thoroughly depended upon design variables, continuous and discrete, associated with the excitation and the characteristics of the structure. The optimization process, based on genetic algorithms and global criterion method, is developed and applied for specific predefined wave field characteristics in order to properly address the characteristics of the structure toward a most preferable (optimum) design. The results that are obtained demonstrate the suitability of the proposed optimization process and the capability of the novel introduced FFS to operate up to a desired level for both wave energy production and protection effectiveness.

1. Introduction

Flexible Floating Structures (FFSs) present nowadays attractive types of offshore and coastal structures that can be utilized in the sea environment in order to develop modern and sophisticated projects that address new trends and needs and satisfy new requirements. The climate change, the requirement of sustainable development in all aspects of human life, the problem of land scarcity, the necessity of the usage of renewable energy sources in conjunction with the well-known advantages of these structures (i.e. reduced environmental impact, reallocation ability, etc.) have enhanced the significance of the FFSs and have redefined their role. The design and construction of an effective FFS in terms of desired performance is the key element for their successful further implementation and development. Their dominant design objectives, which are related to their operational design requirements, are constrained by the structural integrity of structural parts that compose the FFS. For the effective design of an FFS, the development of an appropriate process is required for the accurate calculation of all the quantities that describe the performance of the FFS and also for the identification of the optimum design configuration of the FFS.

FFS are utilized in coastal areas as an alternative solution to conventional bottom fixed breakwaters for protection effectiveness operating as floating breakwaters. Their application is dictated by the existence of specific environmental design parameters, such as poor foundation and/or deep water conditions, water circulation and/or aesthetic considerations and by the existence of particular demands, such as relatively short duration of installation, mobility and relocation ability, flexibility for future extensions as referred by Wang et al. [1]. A large number of proposed floating breakwater types is described by McCartney [2] and by Oliver et al. [3]. The most commonly used type of floating breakwaters is the one that consists of rectangular modules connected flexibly to each other with connectors of appropriate mechanical characteristics as well as with a lengthwise shape as a whole. Their

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dominant design objective is the protection effectiveness of the coastal and inland water areas in terms of the wave elevation behind the FFS. The protection effectiveness of FFSs that operate as breakwaters has been addressed and investigated by many researchers using numerical models based on hydrodynamics of rigid body [4–6] and/or on hydroelasticity [7,8]. The effects of the connectors' stiffness, translational and/or rotational, on the response and the protection effectiveness of an FFS, which consists of flexible modules connected with flexible connectors in longitudinal and transverse directions, under the action of regular waves was investigated by Michailides et al. [7].

On the other hand, ocean waves are an extremely abundant and promising resource of alternative and clean energy with significant benefits compared to other forms of renewable energy as: higher energy density, which enables the devices to extract more power from a smaller volume, limited negative environmental impact, large operational time and more predictable energy [9]. FFSs as oscillating bodies present a major category of wave energy converters that up to now enumerate a very large number of proposed and developed energy devices [10,9,11]. One major category, which includes a large number of oscillating wave energy devices is based on the harnessing of the relative motion between (a) two or more oscillating modules and (b) an oscillating module and the sea bed, and converting this motion into power with the utilization of a hydraulic Power Take Off (PTO) mechanism. PTO is considered to behave linearly and consequently, it consists of a linear damper and a linear spring; this allows the linear frequency domain analysis to be adopted [12,13]. Fundamental design process and numerical modeling of this kind of wave energy converters are based on linear hydrodynamic analysis as have been developed by Falnes and Budal [14], Falnes [15,16], Payne et al. [17] and Gomes et al. [18]. Michailides and Angelides [19,20] proposed a numerical modeling of the same kind of wave energy converters (oscillating modules and hydraulic PTO) based on linear hydroleastic analysis. According to Michailides and Angelides [20], the existence of a PTO affects the protection effectiveness that the FFS exhibits, and the value of the connectors' rotational stiffness affects directly the produced power by the FFS.

FFS are characterized by flexibility, since they have large horizontal dimensions compared to the vertical one and are usually constructed by connecting multiple modules with connectors. The investigation of the performance of FFS requires the inclusion of hydroelasticity in the corresponding numerical analysis that considers the effect of the flexibility of the structure. Regarding the hydroelastic response of floating multi module connected oscillating bodies, Newman [21] and Lee and Newman [22] examined the hydroelastic response of rigid floating modules that are connected with hinges, while Fu et al. [23], Gao et al. [24,25], Yoon et al. [26] and Michailides et al. [27] performed hydroelastic analysis of flexible structures interconnected with flexible connectors.

For the two operating functions of an FFS, namely, as a wave energy converter and as a floating breakwater, the dominant design objective is the increase of the produced power in terms of the averaged power that the PTO can extract and the increase of the protection effectiveness in terms of free surface elevation behind the FFS. The performance optimization process for the above two operating functions (as described above) of an FFS has been treated so far as a single optimization problem [28,29,30,18,31,32].

Genetic algorithms are stochastic optimization algorithms that gradually and effectively have been implemented in single, as well as, in multi objective optimization problems [33,34]. Holland [35] introduced the concept of genetic algorithms; over the last few decades, genetic algorithms have been successfully applied to a large number of engineering problems. Genetic algorithms are well suited to solve multi-objective optimization problems and to produce an optimal set of non dominated solutions. Therefore, genetic algorithms have been a popular heuristic approach to multi objective design and optimization problems as referred by Poirier et al. [36].

In the present paper, a multi objective optimization process of an FFS subjected to regular and irregular incident waves is developed and presented. The FFS introduced here is considered as an effective structure capable for both wave energy production, with the utilization of a linear hydraulic Power Take-Off (PTO) mechanism, and for protection effectiveness. In particular, FFS consists of a grid of floating modules connected flexibly in two directions by: (a) PTO with known linear damping characteristics and (b) connectors with known properties. The performance criteria considered for the selection of the optimum design of the FFS are the produced power, the protection effectiveness and the structural integrity of structural parts that compose the FFS and more specifically of the connectors of the modules of the FFS. The performance criteria thoroughly depend upon design variables, continuous and discrete, associated with the excitation and the characteristics of the structure. The optimization process includes two distinct optimization stages; the first stage includes the identification of the optimal set of non dominated solutions and the second stage includes the selection of the optimum design configuration of the FFS. Results obtained by appropriate hydroelastic analysis of the FFS for a predefined set of design variables are used as input data for the genetic algorithm based optimization process developed in this study. This is achieved through the formation of Look-up Tables [37]. For the solution of the performance optimization problem of the FFS, two objectives exist without an explicitly described mathematical form. A mathematical approach based on genetic algorithms is developed and applied in order to generate a set of non dominated solutions in the space of the design variables. The set of solutions is the well known Pareto optimal set. Each of the set of these solutions satisfies the objectives at an acceptable level without being dominated by any other solution and, also, suffices the structural integrity constraints. Once the set of the Pareto optimal set is obtained, the method of the global criterion is then applied in order to select the final solution, from the Pareto optimal set, that optimizes the structure toward its most preferable (optimum) design. The developed optimization process is applied for the case of an FFS with predefined design parameters as well as design variables for different wave field characteristics. The results that are obtained demonstrate the suitability of the proposed optimization process and the capability of the introduced FFS to operate up to a desired level for both wave energy production and protection effectiveness.

2. Multi objective optimization process of FFS

The FFS is placed in an area of water depth d, under the action of incident regular waves of varying wave frequency and/or under the action of irregular waves. The configuration of the FFS in the case that it consists of four rectangular-shaped floating modules and two PTOs is shown in Fig. 1; some basic quantities, namely, the length, L_f, the width, B, the height, H_f the draft, d_r, the coordinate system, xyz and the six rigid body degrees of freedom, ξ_1, ξ_2, ξ_3, ξ_4, ξ_5 and ξ_6, are also shown in the same figure.

2.1. Mathematical formulation and numerical modeling of the optimization process

The mathematical formulation that represents thoroughly the physical problem of the optimization process for the FFS that is capable for wave energy production and protection effectiveness is precisely defined first. Thereafter, the numerical modeling that