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A method for comparing wave energy converter conceptual designs based on potential power capture

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A B S T R A C T

The design space for ocean wave energy converters is notable for its divergence. To facilitate convergence, and thereby support commercialization, we present a new simple method for analysis and comparison of alternative device architectures at an early stage of the design process. Using Thévenin's theorem, Falnes crafted an ingenious solution for the monochromatic optimal power capture of heaving point absorber devices by forming a mechanical impedance matching problem between the device and the power take-off. However, his solutions are limited by device architecture complexity. In this paper, we use the mechanical circuit framework to extend Falnes' method to form and solve the impedance matching problem and calculate the optimal power capture for converter architectures of arbitrary complexity. The new technique is first applied to reprove Falnes' findings and then to assess a complex converter architecture, proposed by Korde. This work also provides insight into a master-slave relationship between the geometry and power take-off force control problems that are inherent to converter design, and it reveals a hierarchy of distinct design objectives unbeknownst to Korde for his device. Finally, we show how application of the master-slave principle leads to the reduction in the dimensionality of the associated design space.

1. Background

Ocean waves are a vast, high-density renewable energy resource. The IEA estimates annual global wave energy potential of 29,500 TWh [1], which represents approximately 150% of annual global electricity demand [2]. In spite of this tremendous potential, there is currently no commercial deployment of a Wave Energy Converter (WEC) and, as is typical of a pre-commercial sector, proposed WEC conceptual designs vary widely [3–5]. This divergent design space exists, in part, due to the absence of an adequate method for comparing the power capture potential of WEC *architectures* at an early stage of the design process. In the absence of such a comparative method, increasingly complex WEC designs are endlessly proposed which may not necessitate improved performance, thus dispersing focus and slowing collective progress. Current numerical modelling approaches are based on an assumed device *configuration* [6]. Results, therefore, cannot be extrapolated beyond that *configuration* precluding determination of an optimal solution from a design space that includes alternative *configurations*.

To promote rapid design convergence and stimulate commercial adoption, we propose a concise method founded in the fundamental principles of vibration theory, capable of assessing the power capture potential of any WEC *architecture*, regardless of complexity, and thus enabling WEC designers to identify promising concepts early in the development process. Our method uses a frequency domain methodology, which converts any linearized representation of a resonant WEC of a particular *class* into an equivalent and fundamental *architecture*, or *canonical form*, for comparison on an *apples-to-apples* basis. Operating within the confines of linear monochromatic theory, results can be compared across WEC device *classes*. The method analytically determines the linearized power capture ceiling $(P_{U_{Max}}|_{opt})$ for a given *architecture* and may be used as performance assessment criterion for coarsely estimating the Technology Performance Level (TPL) early in the conceptual design phase as recommended by Weber [3].

To frame our objective, we define a hierarchy to organize WEC designs comprising: *configuration, architecture,* and *class*. A *configuration* is a design defined by a set of physical parameters

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governing the system characteristics (e.g. WaveBOB™). An *architecture* is the set of *configurations*, which share the same device topology; for example, the Self-Reacting Point Absorber (SRPA) with the PTO load connected between two wave activated heaving bodies. A *class* comprises of all *architectures* which operate on the same physical principle (e.g. point absorbers, attenuators, terminators) [4,5]. To exemplify these definitions, the single body point absorber [7], SRPA [8], and Korde's WEC [9], shown in Fig. 1, all belong to the point absorber *class*, but represent distinct *architectures*. In addition, PowerBuoy™ and WaveBOB™ represent the same *architecture*, but possess different *configurations* and performances [10].

Through this hierarchical structure, the complexity of the *architecture* grows with the number of components in the embodied design. It is in part, the growth of components in modern WEC designs, as illustrated in Fig. 1, which is driving the divergence of the design space. There is thus an important choice of which *architecture* is most appropriate to the local environmental conditions of the design problem. The following section clarifies *architecture* complexity by classifying the parameters, which influence the various stages of the energy conversion process, to establish why the number of components is increasing in contemporary designs, and how this growth influences the overall power capture optimization problem.

1.1. Geometry control and WEC complexity

To illustrate the divergence of the conceptual design space, an overview of features common to emerging WEC designs, and discussion of how these design features influence the energy conversion pathway, is needed.

Wave energy conversion comprises the transmission of power: 1) from the ocean wave; 2) onto the device bodies; 3) into the device Power Take-Off (PTO). Each stage in the energy conversion process is governed by a set of physical parameters that influences the overall conversion efficiency [5,11].

Wave excitation forces do work on the WEC wetted hull(s) resulting in body motion and thus transmit power to the device. The body inertial and hydrodynamics properties, manifestations of the bodies' geometries, influence this conversion process. Providing a means to vary these geometric parameters during WEC operation leads to the possibility of increasing the power producing bandwidth of the system at the expense of a more complex system *architecture*. WEC complexity can, thus, arise as a physical manifestation of the geometric parameters. Price defined 'geometry control' as active variation of parameters that alter the intrinsic impedance or wave excitation forces in a WEC system [12]. A growing number of WEC designs are introduced into the wave energy community, which propose various features enacting geometry control, while further diluting the design space. For example, WaveSpring™ is a technology capable of varying the buoyancy stiffness, and thus, the natural frequency of a floating body, leading to an increase in the power transmitted between the ocean wave and WEC system [13].

To capture power in the PTO, the WEC body motion works against a PTO reaction force. For a linearized system, this force is usually modelled as a viscous dashpot. It is advantageous to manipulate the system into resonance to maximize power capture. This is achieved by shaping the PTO force response using the well-established optimal PTO amplitude and phase control conditions [14]. Optimal phase control ensures the body velocity is in phase with the incoming excitation force and may be achieved outside of the system natural frequency, through injection of reactive power via the PTO reaction force [14].

As these two stages in the energy conversion processes are linked serially, the PTO force control is inherently influenced by the upstream geometry control establishing a two tier power capture optimization problem. This problem is described as selecting the optimal: 1) geometry to maximize the power transferred from the ocean resulting in body motion; 2) PTO reaction force to maximize the power captured by the PTO subject to the optimal geometry control condition.

To isolate the influence of the geometric parameters on power capture, the WEC must always operate under optimal PTO force control, leading to a master-slave relationship in which the PTO force parameters (slave) follow the geometric parameters (master). Therefore, as the complexity of WEC designs enacting geometry control grows, so does the complexity of the associated master-slave relationship.

1.2. Power capture

To achieve our goal of conceptual design convergence, a unified approach to analytically optimize the power production potential for an *architecture* is key. In doing so, we use the following terms P_U, $P_{U_{Max}}$, and $P_{U_{Max}}|_{opt}$ to clarify the monochromatic time-average power capture in terms of our hierarchy. Each term is respectively defined as the power captured for a WEC *architecture* subject to: no constraints on the PTO and geometric parameters (P_U); constraints enforcing only optimal PTO parameters ($P_{U_{Max}}$); and constraints enforcing both optimal geometric and PTO parameters ($P_{U_{Max}}|_{opt}$). In the literature, $P_{U_{Max}}$ (or more frequently capture width [14]) is often reported and determined through execution of various numerical or experimental methods using an assumed *configuration* [4]. As *architectural* complexity grows, so does the number of design parameters. For numerical models of complex WEC *configurations*, parameter values are assumed to simplify optimization efforts, inhibiting comparisons across all *configurations* within an *architecture*. Hence, an analytical method impartial

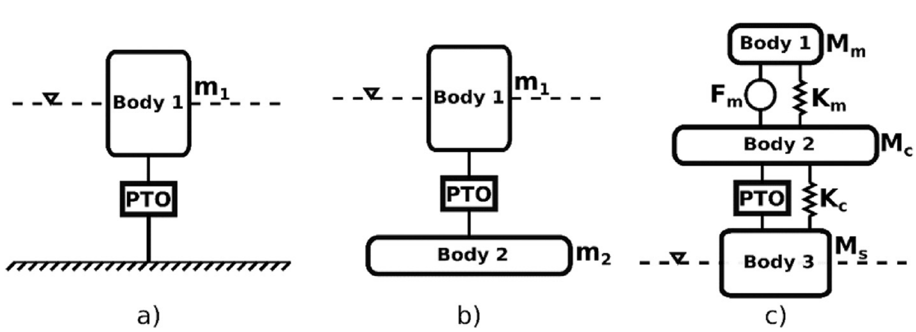

Fig. 1. WEC architectures of growing complexity in the point absorber class. a) Single-body; b) Self-Reacting Point Absorber; c) Korde's WEC [9].