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Influence of wave breaking on the hydrodynamics of wave energy converters: A review

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A B S T R A C T

Difficulties associated with the commercial realization of wave energy harnessing devices are many. Efficient operation of wave energy converters (WECs) depends on the achievement of resonance between the ocean wave field and the energy converting device. Attainment of resonance is strongly susceptible to fluctuations in the excitation force and viscous damping that originate from non-linearities in the surface wave field. A predominant source of such non-linear effects is wave-breaking. Apart from directly influencing WEC functioning through hydrodynamic loading and energy dissipation, wave breaking also exerts certain indirect influences that need more attention from a technological perspective. The target of this review is to highlight these indirect influences. To this effect, the processes of wave breaking and wave energy harnessing have been correlated. The phenomenon of wave breaking has been segregated into various sub-processes based on turbulent, vortical and interfacial energy transfer. The categorized processes are then visualized side-by-side in an energy transfer cascade. From the cascades, few sub-processes are identified which induce a backscatter of wave energy onto the wave field and modulate it; thus inducing non-linearity in the response of a WEC. This would reduce the amount of energy successfully harnessed. The findings of the present review qualitatively establish an indirect relation between wave breaking and hydrodynamics of WECs.

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1. Introduction

Wave energy is manifested from wind-induced local displacements of the atmosphere-ocean interface and accounts for more than half of the energy content of the ocean. Since wind originates from differential solar heating of the atmosphere, waves can essentially be considered to transport concentrated solar energy in the form of mechanical oscillations of the ocean surface. These oscillations can in turn be harnessed to drive a linear alternator to produce electricity. Wave power is generally quantified per unit crest length of a wave (kW/m) and exhibits a geographic distribution as shown in Fig. 1. This wave resource distribution can be applied to statistically estimate the total wave power available on Earth which, according to recent calculations, is about 2.11 ± 0.05 TW [2] with 95% confidence. If the entirety of this resource were to be hypothetically harnessed, it could address more than 12% of the total energy consumption of the world[1] which is estimated by the International Energy Agency (IEA) to be about 17.7 TW [3]. Recent studies have also attempted more detailed "regional estimates" of available wave power [2,4] to aid policy-making in the renewable energy sector as listed in Table 1. The data indicates that both global and regional resource estimates are influenced by the period (in years) over which the analysis is carried out. However, even if resource variability were to be considered, the total wave power is still sufficient to address atleast 10% of the total world energy consumption which demonstrates that ocean waves represent a vast, yet untapped, reservoir of renewable energy.

Attempts targeted towards harnessing wave energy have been made since antiquity with the first wave power utilization patent being filed in 1799 by Girard and his son in France. Since then, hundreds of patents have been filed by researchers and inventors around the world claiming the development of (often unique) devices which could capture the energy of propagating ocean waves and convert it to (commercially useful) power. This interest in harnessing of wave energy was particularly intense during the 1970s oil crisis; the period witnessed a dramatic surge in the development of wave energy converters. Considering the resource distribution depicted in Fig. 1, it is seen that wave power is "naturally abundant" in some regions/countries of the world when compared to others. Through the oil crisis era till the present day, such countries have spearheaded the effort in harnessing wave power and have emerged as pioneers in wave energy research. The top eleven countries in this context are listed in Table 2 and have been ranked based on the number of wave energy harnessing concepts proposed according to the European Marine Energy Centre (EMEC) [5]. In addition to this data, Table 3 lists prominent wave power projects that have been conceptualized by some of these pioneer countries. From Table 3 it can be appreciated that a majority of the projects have been "grid connected", that is, they are in operation. At the same time, it can also be seen that few projects had to be decommissioned either due to a withdrawal of the firm from the venture (AquaBuOY [11]) or due to harsh oceanic conditions (Oceanlinx-blueWAVE [19]). This is indicative of the economic, policy-making and environmental challenges surrounding wave energy conversion in the current renewable energy scenario. In fact, renewable energy extracted from waves is currently the most expensive form of power available on Earth [24]. The previous statement is quantitatively supported by numerous "cost analyses" studies predicting the commercialization of wave power; a few of which have been listed in Table 4. The economic feasibility of a power resource is generally evaluated based on the Levelised Cost of Electricity (LCOE) metric which can be regarded as the cost at which electricity must be generated in order to break-even over the lifetime of the project. Table 4 indicates that although non-conventional sources such as onshore wind and solar power had been expensive in the past (when compared to conventional sources), recent advancements in technology and policy-making in these sectors has led to a reduction in LCOE values [26,28,29]. Wave power on the other hand, alongwith offshore wind and tidal power, represents a nascent group of renewable technologies that is yet to attain the maturity required for the LCOE to reduce to a level comparable to other established renewable technologies. There might be exceptions to this trend which is evident from the LCOE estimates for Canada[2] [27] (see Table 4). However, the LCOE values in general indicate that wave energy is the costliest form of power available.

The high cost of wave power is largely due to the fact that the process of using wave energy for power generation is faced with many challenges. These challenges have been identified in considerable detail by Falnes [31], Tiron et al. [34] and Falcao [35] and the same have been depicted as a pictorial hierarchy in Fig. 2. It is observable that the harnessing problem has four aspects: *(a) the process of energy extraction itself, (b) device survivability, (c) environmental consequences of WEC deployment and (d) design and laboratory analysis of WEC devices.* A variety of solutions can be proposed against these problems. For instance, the chances of survivability of a WEC can be enhanced by improving the techniques used for predicting extreme wave events. Further, the issue of biofilm formation can be addressed through conventional anti-fouling paints or other non-conventional techniques such as the use of UV light or sound vibration [34]. In addition, development of fluid–structure interaction based CFD codes can facilitate the analysis of strongly non-linear effects that occur during the interaction of a WEC with steep waves [34]. However, it can be seen from Fig. 2 that the task of extracting energy from the waves itself proves to be the most challenging. Review articles, recently published in this context [24,31–34] pose an argument that many unresolved issues related to wave energy harnessing are *hydrodynamic* in nature because any localized non-linear effect in the ocean would primarily influence the hydrodynamics of the wave-WEC system. Understanding this susceptibility of wave energy systems forms the primary motivation of the present paper and is hence elaborated in the following paragraphs.

The mechanisms manifesting wave energy are quite different from its flow-based counterpart, namely tidal energy. Since tidal energy essentially emerges from tidal flows, it can be suitably harnessed as flow energy by turbines.[3] Wave energy, being influenced by a host of local effects, is not that straightforward to harness. Apart from the question of survival in harsh oceanic conditions [24,34], the principles governing wave energy conversion impose stringent operational requirements on harnessing devices (see Fig. 2). For instance, the motion of the harnessing device has to be devised such that a form of resonance could be achieved between the WEC and the wave motion [31,33,35,36]. The need for resonance makes the system susceptible to non-linear effects (such as wave breaking) which act to modulate the wave motion or induce viscous damping. Difficulties also exist at the analysis stage as the viscous effects arising from turbulence and wave-structure interaction cannot be addressed by linear theory or frequency domain approaches [31,33]. The level of complexity necessitates the use of fully coupled Navier–Stokes equation methods (NSEM). All these factors have led to a compounding of the effort necessary for analyzing WEC behavior in actual oceanic conditions. As a consequence, contemporary investigations in wave energy research have been focused on the

[1] Currently, the actual share of all renewable energy resources combined is 3.5%.

[2] The study carried out by Dunnett and Wallace [27] indicates that AquaBUoY based wave power may prove economically viable in some regions of Canada where it can be competitively priced against conventional power.

[3] Major installations of tidal energy converters include the 1.2 MW SeaGen deployed in Strangford Lough in Northern Ireland, the 3.2 MW Jiangxia tidal power station located in China and the Rance tidal power plant situated in France having an installed capacity of 240 MW.