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Energy conversion of orbital motions in gravitational waves: Simulation and test of the Seaspoon wave energy converter

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ABSTRACT

The conversion of ocean wave power into sustainable electrical power represents a major opportunity to Nations endowed with such a kind of resource. At the present time the most of the technological innovations aiming at converting such resources are at early stage of development, with only a handful of devices close to be at the commercial demonstration stage. The Seaspoon device, thought as a large energy harvester, catches the kinetic energy of ocean waves with promising conversion efficiency, and robust technology, according to specific "wave-motion climate". University of Genoa aims to develop a prototype to be deployed in medium average energy content seas (i.e. Mediterranean or Eastern Asia seas). This paper presents the first simulation and experimental results carried out on a reduced scale proof-of-concept model tested in the laboratory wave flume.

1. Introduction

Ocean energy shows-up in many forms: tides, surface waves, ocean circulation, salinity and thermal gradients. This paper focuses on the energy conversion of wind-driven waves, derived ultimately from solar energy. The worldwide wave power resource potential is huge. The global power potential has been estimated to be around 8000–80,000 TWh/y (1–10 TW), which is in the same order of magnitude of the world electrical energy consumption. The best wave climates, with annual average power levels between 20 and 70 kW/m of wave front or higher, are found in the temperate zones (30–60° latitude) where strong storms occur. However, attractive wave climates are also found within +30° latitude where regular trade winds blow, the lower power levels being compensated by the smaller wave power variability [1]. More detailed regional studies suggest that the accessible resource in waters solely around the UK (which takes into account constraints on available sites for a wide variety of reasons) could be as much as 700 TWh/y [2]. In the Mediterranean basin, the annual power level off the coasts of the European countries varies between 4 and 11 kW/m, the highest values occurring for the area of the south-western Aegean Sea. The entire annual deep-water resource along the European coasts in the Mediterranean is of the order of 30 GW, the total wave energy resource for Europe resulting thus to 320 GW [1]. Considering American continents, only around the US coasts recent assessments evaluated an energy availability up to 2640 TWh/y [3]. Therefore, a widespread implementation of conversion technologies suitable for wave climate of any power could make real a very large energy production (see Fig. 1).

2. Wave energy in mild climate seas

Wave energy refers to the kinetic energy and potential energy in waves on ocean surface. According to linear waves theory and Eq. (1) the wave energy flux is proportional to the wave period of motion T and to the square of its height H, and it is one of the most stable energy resources, with good forecastability [4].

$$P = \frac{\rho g^2}{64\pi} H^2 T \tag{1}$$

When evaluating a potential site for wave energy project development, dealing with the forces imposed by a dense fluid like water, the extreme conditions occurring during storms and associated to the highest energy flux entering a wave energy converter (WEC) is fundamental: in fact, the extreme wave heights may be under-predicted in some locations due to certain limitations of forecast tools [5]. The properties of a WEC correspond with the climate of the sea: a perfect technology for a sea around Portugal may not be successful in a milder climate. An important parameter at the beginning of a energy wave conversion project is the wave energy development index (WEDI) value of the site, obtained by dividing the average annual wave energy flux by the storm wave energy flux (occurring in extreme storm conditions). A lower value

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Nomenclature

A_{Sav}	swept area of Savonius rotor (Diameter × Length) (m^2)
$\Delta_{\alpha rot}$	angle between rotor and flat plate (rad)
C_{Ps}	power coefficient of Savonius rotor
g	gravity acceleration (m/s^2)
H	wave height (m)
η_{el}	electric efficiency
η_{mec}	mechanical efficiency
η_{cpt}	capturing efficiency (Savonius blades)
P	output power (W)
R	Savonius rotor radius
ρ	water density (kg/m^3)
T	wave period (s)
TPG	thermochemical power group
u_{MAX}, v_{MAX}	maximum orbital particle speed (m/s)
V	relative speed of the fluid particle flux (m/s)
WEC	wave energy converter
$z_{0Savonius}$	depth displacement of the rotor axis (m)

of the WEDI reflects a severe design penalty that has to be paid in terms of capital cost for a wave power plant to harness the annual average wave energy resource available at a particular site [6]. In fact, during the worst expected storm, wave power plant structures and foundations (or moorings for a floating device) must be able to absorb the storm wave energy which highly exceeds the energy under routine operating conditions. As highlighted by Hagerman [6], for example, the most promising stretch of United States coastline for wave power development, from Newport, Rhode Island, to Nantucket Shoals, has WEDI values ranging from 0.02 to 0.025, which means that a wave power plant in this coastal stretch would have to survive storm wave energies that would be only 40–50 times the annual average wave energy flux. Hence, many future developers of wave energy projects may seek out locations where the wave energy resource is moderate and fairly steady throughout the year and where the extreme waves are relatively benign [5], even though this will imply to address some efforts in designing devices of smaller size choosing to exploit minor energy fluxes and extended operational time. In fact, many wave energy devices that have been and are being developed to be competitive off the Atlantic coasts of Europe might not be attractive in other locations with lower average energy sea climate. At first this may seem discouraging, but it is important to remember that in addition to the wave energy development work that is being done in Europe, there also continues to be a strong wave energy development program in other countries, where prototype devices in the output range of tens to hundreds of kilowatts like the Japanese Kaimei, and Mighty Wales are more suitable. Furthermore, any wave energy device that can be value-engineered to be economically feasible in milder sea climate will have a much larger global export market than a device that is economically attractive in the high wave energy environments of Western Europe only. The Pacific coastlines of East and SouthEast Asia, for example, have wave power densities in the range of 5–10 kW/m, which would be out of range for devices designed for climates of 30 kW/m or more [6]. In China, central region of Zhejiang, Taiwan, North to Haitan Island in Fujian in the South Eastern coast of the country, and Bohai Strait in the North Eastern coast have a resource in wave energy density up to 5–8 kW/m [4]. The wave energy is being increasingly regarded as a major and promising resource in South Korea because the Korean peninsula is surrounded on all sides by Yellow Sea, East China Sea and East Sea, nevertheless the wave energy potential of South Korea has only been evaluated by global wave modeling [5]. Details on the wave energy resources around the Korean peninsula remain poorly defined, but an annual mean wave power was found to be 11 kW/m in the Southwestern side, 4 kW/m

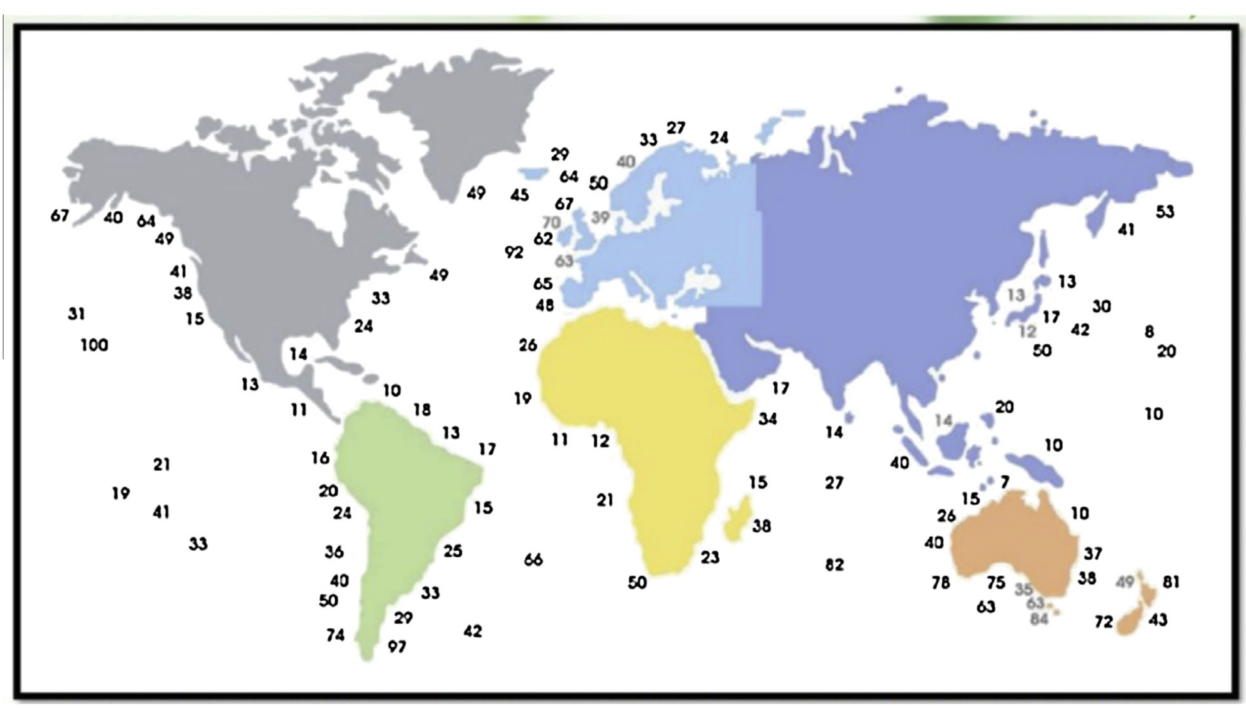

Fig. 1. World's wave energy potential: annual average power per front width (kW/m).