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TECHNICAL ASPECTS OF WAVE-GENERATION SYSTEMS (WEC: WAVE ENERGY CONVERTERS)

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ABSTRACT

The main purpose of this article is to point out the actual progress on wave energy converters by stressing their construction differences in all their main parts and by indicating their main working principle as well as their installation characteristics. Resulting from the effect of wind on marine surfaces (the power of the waves is substantially proportional to the power of the wind speed), wave energy represents a net availability of 1 to 5% of the world's annual electricity demand. Recoverable energy could reach up to 2000TWh/year with more efficient conversion systems. However, it is necessary to consider the relatively low conversion efficiency (of approximately 10% on annual averages) of the current recovery systems.

Keywords: wave energy converters, generator, wells turbines.

1. INTRODUCTION

Solar energy captured annually on the surface of the earth represents more than 6,000 times the total primary energy consumption of humanity. As oceans occupy roughly two-thirds of the globe's surface, they capture, transfer and accumulate huge amounts of energy, but they also play a major role in global climate balance. Life, which is developing in the waters of the globe, exploits a portion of these renewable resources and is also an important biomass reserve and a biological energy transformation system.

Apart from the non-renewable resources (fossil fuels, including methane hydrates) that lie beneath the oceans, the maritime expanses capture a large amount of solar energy and provide access to various forces of nature (wind, wave, sea currents etc.). Their waters also store an immense amount of heat that can be partially exploited in favoured areas by overcoming the problems associated with intermittency. Winds and thermal (continuous) ocean currents originate directly in solar radiation. The wave is a by-product of the action of the wind on the surface of the water. Tidal (alternative) currents are created by gravitational earth-moon-sun interactions and are not related to solar radiation.

Renewable marine electricity generation technologies are still relatively mature. Exploitation of offshore wind turbines began in earnest in 1991 in Denmark, and cumulative experience is beginning to be significant. The sea thermal energy recovery systems are still in the state of demonstrators, and it is the same for those of the marine currents and the waves.

In the following, an overview of the available resources and then the main technological solutions of their conversion into electricity will be presented.

2. WAVE ENERGY CHARACTERISTICS

The waves are created and maintained locally by the wind and take its direction, their periodicity rarely exceeding 8 seconds. The wave, for its part, spreads outside the area where the wind has given birth to it, with slower oscillations, typically 10 seconds, with a long wavelength (150 m) and a speed of propagation (or phase velocity) of about 14 m/s. The period can reach 25 seconds and the wavelength 900 m by very large sea (36 m/s). Ideally (pure sinusoidal wave and infinite depth), the wavelength is related to the velocity of propagation and to the period by the classical relation:

$$\lambda = c \cdot T \tag{1}$$

In deep water and at long wavelengths in front of the capillary length (about 3 mm), we have gravity waves whose propagation velocity c and the period T are functions of the wavelength λ:

$$c = \sqrt{\frac{g\lambda}{2\pi}} \quad \text{and} \quad T = \sqrt{\frac{2\pi\lambda}{g}} \tag{2}$$

The depth of the seabed also plays an important role in that shallow depths promote energy dissipation. Thus, when arriving on the coast, the wave has generally lost much of its energy potential. Unfortunately for the simplicity of its characterization, a wave field is composed of multiple waves that do not propagate all in the same direction. A simplified way to characterize the random wave is to be limited to only two parameters: a peak height to hollow noted H_s (significant height calculated as the average of one third of the highest waves, sometimes also noted $H_{1/3}$) accompanied by a period T_p, these two parameters making it possible to represent a random sea state by referring to a standard model of spectral energy distribution (T_p is then the period of the spectral peak). The period of stability of this sea state in nature is generally estimated at one to three hours. Very long-term wet measurement buoys at a given site can be used to compile statistics and establish monthly or annual scatter diagrams of T_p and H_s, such as Figure 1 or as a table showing the number of hours accumulated per year according to T_p and H_s. Databases already exist and many areas are fairly well characterized. The producible power characteristics of wave-generators are also defined according to T_p and H_s by a production matrix, which makes it possible to easily evaluate the annual productivity on a given site by "crossing" these two matrices.

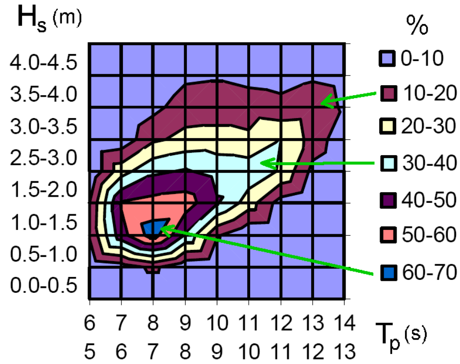

Fig.1. Examples of a T_p and H_s wave resource distribution diagram at a site

The power of a pure progressive wave (perfectly sinusoidal and unidirectional) can be calculated quite easily if the depth of the mid-place in which it is propagated is supposed infinite (in practice greater than the half-wavelength). Under these conditions, it can be demonstrated that the power (average) transmitted per unit of wave front width in the direction of propagation is expressed by:

$$P_w = \frac{\rho \cdot g^2}{32\pi} \cdot H^2 T \approx 980 \cdot H^2 T \tag{3}$$

where ρ is the density of the water, g is the acceleration of gravity, H is its peak to hollow height of the wave and T is its period. With seawater (density of 1024 kg / m3), the coefficient $\frac{\rho g^2}{32\pi}$ is about 980 SI units. For an irregular sea whose spectrum is specified by the significant height H_s and its period T_p we obtain:

$$P_w \approx 420 \cdot H_s^2 \cdot T_p \quad (W/m) \tag{4}$$

These expressions may appear a priori surprising, because we could expect a power proportional to the inverse of the period. The result of expressions (3) and (4) is due to the behaviour of gravity waves (see expressions (1) and (2)). Thus, it is shown that the power per unit of wave-front width is well proportional to T or c.

The resource is sometimes characterized by its average height H_m and its average period of transition to zero T_z. The equivalences respectively with the significant height H_s and with the period T_p are given by: $Hs \cong 1{,}6Hm$ and $Tp \cong 1{,}4Tz$.

In addition to the fact that the waves at low frequency generate instantaneous power fluctuations, the average power of the resource fluctuates considerably depending on the sea state. If the expression (4) is applied in random waves, the following orders of magnitude of linear power are obtained for a shallow sea (5s, 0.6m) 0.7kW/m and for a "very large sea" (15s, 18m) 2MW/m. It is the range of this incident wave power range that shows the challenge to engineers who need to design systems that can work from medium to low power sea conditions (the most common ones) while surviving to extremes sea conditions whose colossal power is capable of ruining large offshore platforms or ships of very large tonnage. The recoverable power then depends on the wave width sensed and the efficiency of the conversion device. Wave generators often have a relatively well-tuned behaviour for a given wave type and, although advanced control can optimize power extraction under varying conditions, their output power characteristics are not really proportional to $H_s^2 \cdot T_p$.

When an elongated float (such as a ship) is stressed by the wave, it undergoes movements according to its 6 degrees of freedom: 3 in translation (cavally, heave and yaw) and 3 in rotation (pitch, roll, yaw). The caval, the lurching and the heave are respectively the translational movements with respect to the longitudinal axis, the transverse axis and the vertical axis. The roll, the pitch and the yaw are the rotational movements with respect to the axes respectively longitudinal, transverse and vertical. To partially measure the complexity of wave characterization, Figure 2 shows an example of height fluctuation over one year scale.

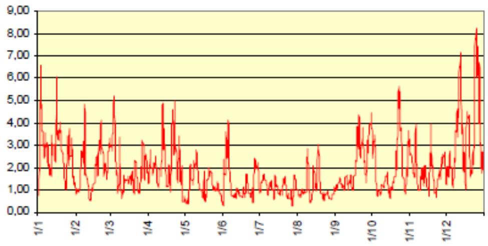

Fig.2. Example of significant height fluctuations H_s over a year

Figure 3 provides an example of fluctuations in the power of the resource at the scale of a few minutes (instantaneous fluctuations). In this last figure, we can observe variations on the scale of the period T_p but also "puffs", with lower frequency, called groups of waves, phenomenon well-known to swimmers and surfers.

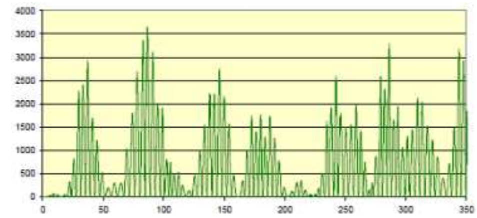

Fig.3. Example of fluctuations in the instantaneous power of the resource over 350 seconds (in ordinate - arbitrary scale, in abscissa - time in seconds)

3. DIVERSITY OF CONVERSION SYSTEMS

As often, technologies have an old history. This is the case of wave energy recovery. There are two patents (Girard 1799 and Barrufet 1885), in which the inventors have tried to design machines exploiting the heave motions (vertical component) of the waves. Barrufet proposed an ingenious machine consisting of independent floats and transmitting their reciprocating movements to a common transmission shaft in continuous rotation, thus smoothing local fluctuations relatively well. Apart from the very harsh constraints of the marine environment, one of the difficulties is precisely to try to solve the problem of fluctuations, at least on the scale of the period T_p. Since the 1970s, many devices have been designed, patented and/or tested. We can propose a simplified classification:

- breaking systems: the seawater breaks on a ramp, crosses its threshold and fills a tank located behind, it is then turbined at "low fall" to return to the sea. These systems have the advantage of smoothing the power and of obtaining a relatively regular production, in any case, one which does not fluctuate with the rhythm of the waves. Formerly, they were confined to the coast by exploiting the natural configuration of the land to create the basin to less expensive (lagoon for example) but there are now floating systems;

- systems with oscillating water column: placed on the ribs or on floating machines, a cavity opened to the action of the waves by a submerged mouth sees its internal free surface oscillate like a liquid piston. The air in the cavity is then alternately expelled and then admitted via an outlet pipe to the atmosphere. A turbine, whose direction of rotation does not change according to the direction of air flow, is placed in the pipe. The turbine drives an alternator which thus continuously produces energy;

- systems with bodies driven by waves: a great many floating systems on the surface or immersed have been imagined. Some, presenting several bodies animated by the wave, work the relative movement of these bodies - it is called internal reference (or embedded reference). Others make work the movement of a single body with respect to a fixed reference (usually the seabed via fixed structures or tense moorings) - it is called external reference.

A second criterion is that of the location according to whether the devices are on the coast (shoreline), at sea but in the vicinity of the coast (nearshore) with funds less than 50m to allow anchoring in particular, or finally offshore (offshore). Coastal production plants must meet many constraints, including adaptation to the topology of the site but also acceptability, their main advantage being the ease of connection to the power grids. Nearshore or offshore systems, meanwhile, make it possible to consider more standardized heaters and benefit from a stronger energy resource. They generally consist of groups of identical modules installed in parks, electrically connected together to pool power generation by requiring only one cable common to the coast. We can also speak about the wave power farms.

In general, the wave-generators, by taking a portion of the resource, dampen the wave by reducing the height peak to hollow. Although wave characteristics and recuperator technology play an important role, it can be estimated that 10-30% of the resource can be recovered. The characterization in watts per meter of wave front makes it difficult to estimate the recoverable power per unit of marine surface. Some evaluations have been carried out, notably with the Pelamis system, which is described below. For example, in an environment with a resource of about 75kW/m, it can extract 30MW per km^2 of occupied sea space and an annual energy of 110GWh/km^2, about 6 times more than in offshore wind farms, but the space is also occupied more intensely than in wind.

3.1 Ramp systems

Two systems will be mentioned: the Tapchan (Tapered channel), built in 1985 on the coast on the site of Toftestallen in Norway, with a power of 350kW and stopped following a storm in 1991 and the Wave Dragon, a floating system of which a 1/4.5 scale prototype was put into service in 2003 in Denmark. The principle of Tapchan is shown in Figure 4.

The quality of the basin fill depends on the height of the waves relative to that of the surf break, but also the effects of tides. More recent solutions make it possible to better adapt to the height of the wave by exploiting a breaking ramp including a system of staggered catchment along the ramp.

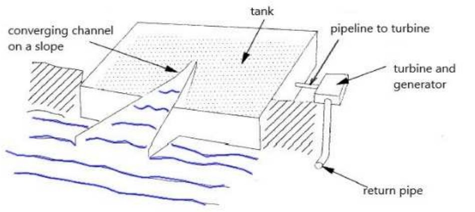

Fig.4. Principle of the Tapchan flood system

The Wave Dragon Wave-generator is floating and moored, its floatation height is adjustable depending on the characteristics of the wave. The dimensions of the scale version 1 are 300m (distance between the ends of the arms), 170m (length) and 17m height including 3 to 6m above sea level. The total mass is 33.000 tons with a tank with a capacity of 8.000 m^3. Its maximum power is 7MW, with an annual productivity of 20GWh for an average resource of 36kW/m. Thus the number of hours in equivalent at full power reaches 2800. The water is turbined in low drop turbines (a priori Kaplan). It is interesting to exploit several turbines of small power (here 16 to 20), rather than only one, which makes it possible to improve the yield according to the flow available. The resulting yield curve is thus greatly improved. Variable speed magnifiers also increase overall efficiency. On the scaled-down system, with the same maximum installed power, switching from a fixed-rate Kaplan 2-turbine system to a Kaplan 16 variable-speed turbine system increases the annual energy from 1.79 to 2.04 GWh and reduce the ratio P_{max}/P_{avg}, indicator of fluctuations in production from 12.4 to 10.1. On the UK Atlantic coast bordering Wales, the installed production capacity per km^2 of ocean surface is about 28MW, and is even higher on the Irish and Scottish coasts. The first 1/1 scale machine was installed in 2007 in Wales (Milford Haven). Figure 5 shows two schematic views of the Wave Dragon device and Figure 6 shows a photograph of the reduced-scale device (20kW, 237 tonnes, 58m x 33m, 55m^3 tank).

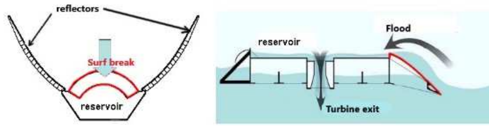

Fig.5. Top and profile views of Wave Dragon Floating System

Fig.6. Photography of Wave Dragon scaled (58 x 33 m)

3.2. Oscillating water column systems (OWC)

It is perhaps one of the most used principles, it is also borrowed from nature where the "blower holes" present in the rocky shores well highlight the ebb and flow of air trapped in a cavity subject to wave fluctuations.

For coastal systems, the Kvaerner column (Norway)should be noted, which operated between 1985 and 1988 (total height: 25m, internal free area 56m, turbine 500kw at 1500rpm), the European Pico pilot project, named after the Azores island in Portugal (chamber 12x12m by 8m high, 400 kW, Wells turbine with variable pitch), the Energetech 1MW converter in Australia (modular system with parabolic collector: 35m opening) and Wavegen's Land Installed Marine Powered Energy Transformer (LIMPET), installed on the coast of Islay Island in Scotland with a capacity of 500 kW, and finally the installations in Haramashi and Sakata harbors in Japan, as well as that of Kerala in India.

Further on, there are provided some details of the LIMPET system, installed in Islay, from Wavegen. The first prototype (1991) had a power of 75kW, a second version of 500kW was commissioned in 2001 and is connected to the electricity grid of the

United Kingdom. The current system captures the pressure variations of 3 water columns with a total surface area of 169m². The turbogenerator consists of two Wells turbines with a fixed pitch of 2.6m counter-rotating diameter, each directly driving a 250kW asynchronous dual-feed generator operating at variable speed (700 to 1400rpm). The Wells turbine has the advantage of a motor torque that does not change sign with the flow direction of the air flow. The Pico Island system operates a Wells turbine with variable pitch. Acoustic noise, known to be a disadvantage of these turbines, is attenuated here by a specific acoustic chamber. Wells turbines make it possible to exploit the alternating air flows produced by the oscillations of the free water surface of the columns and make it possible to optimize the damping in order to maximize power recovery. In the LIMPET system, the turbines have a fixed pitch, their yield curve, depending on the "tip speed ratio" λ ($\lambda = v/(R \cdot \Omega)$, where v is the average speed of the air flow and $R \cdot \Omega$ is the peripheral speed at the end of the blades), is bell-shaped enough pointed. For the same reasons as for wind turbines, the variable speed makes it possible to better maximize the efficiency of the turbine as a function of the average air flow. The peak efficiency is greater than 70% in continuous mode, but it drops to less than 30% on a cycle. The high moment of inertia of the rotating parts (1200kg.m² in this example) produces a good smoothing of the power fluctuations of the resource.

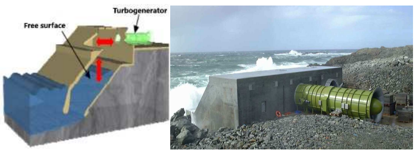

Fig.7. Oscillating column device LIMPET

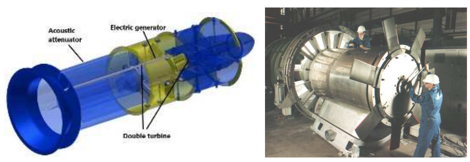

Fig.8. Wavegen Turbo-Generator with Wells Turbines (500 kW group)

The company Wavegen offers different applications of its concept including a wave-break wall incorporating several generators type LIMPET.

Note that the 1 MW converter of the Australian company Energetech operates a variable pitch turbine (Denniss-Auld type, like the Wells turbine, its torque retains the same sign during flow reversals) associated with an asynchronous cage generator (12 poles) at variable speed (2 pulse width modulated three-phase inverters: one machine side and one network side). The system is anchored and placed on feet adapted to the local depth. Figure 9 shows the power characteristic network of the Energetech wave-generator.

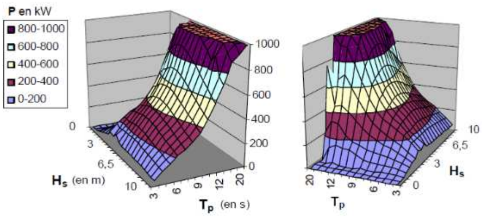

Fig.9. Power curves (in kW) of the Energetech wave-generators

Finally, among the floating and anchored offshore oscillating column systems, there will be:

- the Sperboy (UK) consists of a float 4m in diameter under which there are tubes (oscillating water columns) down to 12 m below the surface and above which is the conversion system containing the chambers of compression and a set of 4 horizontal generators generating a total power maximum of 140 kW;

- the Mighty Whale (Jamstec: Japan Marine Science and Technology Center) is a prototype vessel 50m by 30m and 12m deep, commissioned in 1998. The maximum power is 110 kW for Hs = 8m and Tp = 10 to 15s. The conversion system comprises 3 oscillating column chambers associated with 3 Wells asynchronous generator generators (1 x 50kW and 2 x 30kW) with variable speed (300 to 1800 rpm).

3.3. Body systems driven by waves

One of the most famous representatives of this very large family is the Salter duck ("Salter duck"), named after its inventor, designed in the 1970s. Its principle is to use watertight caissons of asymmetrical shape and eccentric rolling around an axis by operating hydraulic pumps. This principle has encountered many technological difficulties, particularly related to the holding of a long axis facing the waves. Although this system has been the subject of many improvements, it now seems surpassed by other devices whose only future will say which will have survived the "natural selection".

Let's mention some of these features:

- Power Buoy (Ocean Power Technologies, Inc., USA) submerged buoy, fixed part tense anchorage and oscillating part to the rhythm of the wave, the relative movement is damped to be converted into electricity. Only a beacon indicates the presence of the underwater system for navigation. This system, whose frequency makes its performance very sensitive to the wave period, requires specific control to maximize the extraction of energy, including predictive behavior. The conversion device comprises a pump, a battery and a hydraulic motor, the latter driving an electric generator. Direct linear electromagnetic generator versions are also studied. A model of 40kW was tested between 1997 and 2002: it is 9m high and has a diameter of 1.5m at the float, for a mass of 2140kg. Models of 150 and 250kW are envisaged. On 20.000m², 40 buoys of 250kW would allow to install a production capacity of 10 MW.

- Archimedes Wave Swing (AWS, The Netherlands): The pilot version, tested in 2004 off Portugal, has a nominal power of 1MW (average on cycle) and a peak of 2MW. Each production unit is immersed at 8m below the surface, a cylindrical float 21m high and 9.5m in diameter is oscillated by the waves and compresses the air trapped between itself and an anchored cylinder. Basically, it drives the moving part of a synchronous direct linear generator with magnets (1MN, 2m/s). Thanks to an electronic power converter and an adapted control, the system makes it possible to optimally exploit periods of wave between 9 and 20 seconds. Thanks to a mechanical resonance effect, a wave amplitude of 1m can give movements of 7m (maximum generator travel). Unlike the final solution envisaged, which will be anchored via cables, the experimental device is placed on a base (a barge cast on the spot) which allows it to be easily removed. The commercial version is planned with a diameter of 12m, a maximum stroke of 12m and an average power of 4.75MW.

- Searev (autonomous electrical system for the recovery of wave energy, project carried by Ecole Centrale de Nantes). The Searev concept consists of a completely closed float inside which a pendulum mass (400 tons) is oscillated by the indirect solicitations of the wave. In the prototype version, there are hydraulic cylinders that damp the pendulum and charge the accumulators. A real-time mechanical control, controlled by embedded computing, keeps the pendular system in a parametric resonance state despite the irregular nature of the excitation due to the waves. Hydraulic motors drive asynchronous generators for a maximum power of 500kW. An all-electric direct drive solution is also under study.

- Pelamis (Ocean Power Delivery, Scotland). The Pelamis system, currently marketed (model P750), consists of a set of 4 floating metal cylinders interconnected by three joints with two degrees of freedom, and resembling a snake, 4.6m in diameter, and a total length of 123m (700 tons, including 380 tons of steel). The behaviour of the system makes it follow more or less the deformation of the free surface, which makes it a "profiler" more than a resonator like the previous systems.

This general shape allows it to withstand very varied waves and to exploit their energy well. In each articulation (see fig.10), there are four hydraulic cylinders, two of which exploit and dampen wave movements (vertical) and two others, those of lurching (transverse). These pumps accumulate energy in the form of pressurized oil in a tank (100 to 350 bar). Two hydraulic motors, which rotate regularly, each drive an asynchronous generator of 125kW at 1500 rpm (fixed speed). Thus, this device has the advantage of smoothing a naturally fluctuating energy. Its life expectancy is 15 years. The maximum electrical power is 750kW (3 joints each comprising two 125 kW generators).

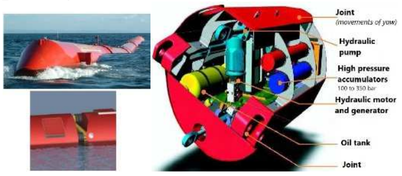

Fig.10. Pelamis P750 (750 kW) wave-generator, detail and exploded active joint

Figure 11 shows the power mapping according to the two characteristic parameters of waves H_s and T_p. On the curve, at constant resource period, there is a growth then a clipping, necessary for the sizing of the system. The architecture of Pelamis gives it a relatively well-tuned behaviour, which means that the recovered power does not follow the growth of the wave power with the period.

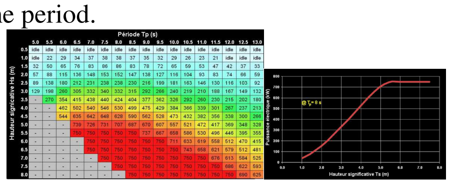

Fig.11. Electric power mapping Pelamis P750 (750 kW), and curve as a function of H_s for a period of 8 s

Three P750 units were installed in 2006 at 5km from the coast of Portugal forming an experimental 2.2MW hydroelectric generating plant. In principle, an area of 1 km² allows to install a production capacity of 8 to 30 MW. As in offshore wind farms, the units, spaced about 150m apart, are organized into clusters.

4. CONCLUDING REMARKS

The potential of marine energy resources is immense and their variety is such that in most parts of the world a very significant participation in the global production of electricity, but also of hydrogen and freshwater can be envisaged. Technological solutions are still evolving. Most of them have not yet been confronted with the constraints of nature and the market and there is still generally a lot of research and development work. Given the barely initiated economic learning curves, the potential for lower investment costs for most marine technologies is very high, suggesting very attractive production costs in the long term. So, it is especially important to develop sufficiently, to experiment as quickly as possible in the real and difficult conditions of the marine environment, obviously taking risks.

We now know that all large-scale energy transformations are more or less disturbing the environment. It is therefore essential to carry out serious environmental impact studies but, levy rates must remain low. This is why consumption reductions are one of the priorities of sustainable development.

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