THE SEASPOON

Innovative Wave Energy Converter

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***Abstract*— Energy provision is the biggest issue to face for the world's economy at any latitude. Nowadays the energy demand of developing Countries as well as that one of developed economies is huge and increasing at an unbearable pace. Considering the limited stocks of such an energy source, and the drawbacks related to the emissions associated to its utilization, the problem to find alternative energy sources and suitable conversion technologies must be solved in order to guarantee the growth and preserve the planet environment. Renewable energy sources are distributed and available all over the world in different forms and variable amounts. Among renewable energies sources, ocean waves power, around the coasts worldwide, has been estimated to be in the order of 1TW (1 TW/h 10^{12}W). The conversion of this resource into sustainable electrical power represents a major opportunity to Nations endowed with such a kind of resource. At the present time most technological innovations aimed at exploiting such resources are at early stage of development, with only a handful of devices close to be at the commercial demonstration stage. None of them, though, operates converting the wave energy contents at its very origin: the orbital motion of water particles right below the ocean surface. The Seaspoon device catches the kinetic energy of ocean waves with promising conversion efficiency, according to specific "wave-motion climate". University of Geoa aims to develop a prototype to be deployed in medium average energy content seas (i.e. Mediterranean or Eastern Asia seas) according to the interesting results of a first small scale proof-of-concept model tested in laboratory.**

I. INTRODUCTION

Ocean energy shows-up in many forms – tides, surface waves, ocean circulation, salinity and thermal gradients. This paper focuses on one of these: that found in 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 8,000-80,000TWh/y (1-10TW), which is the same order of magnitude as world electrical energy consumption. The best wave climates, with annual average power levels between 20-70 kW/m of wave front or higher, are found in the temperate zones (30-60 degrees latitude) where strong storms occur. However, attractive wave climates are also found within +30 degrees 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 700TWh/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 southwestern 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 U.S. coasts recent assessments evaluated an energy availability

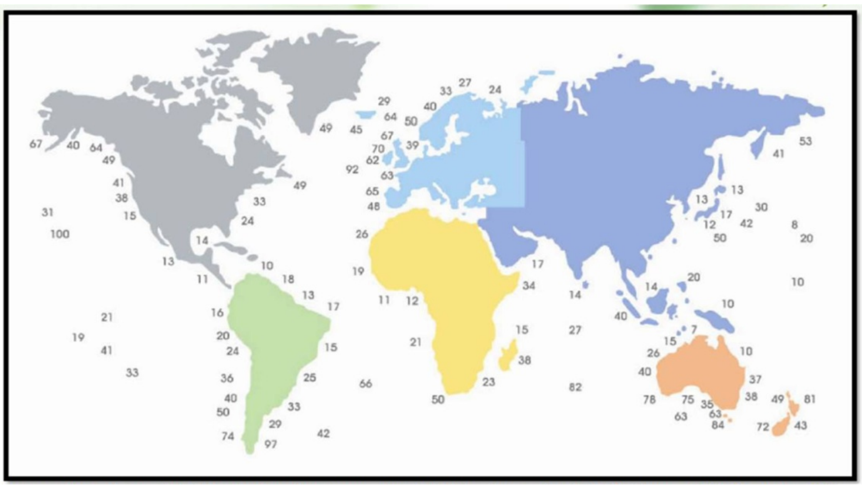

Figure 1: World's Wave Energy Potential: annual average power per front width [kW/m]

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up to 2640 TWh/yr [3]. Therefore, a widespread implementation of conversion technologies suitable for wave climate of any power could make real a very large energy production.

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 equation (1) a wave energy flux is proportional to its 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].

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

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 high 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 2 to 2.5, which means that a wave power plant in this coastal stretch would have to survive storm wave energies that would be only 40 to 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 to 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 in the southern side, and 6 kW/m in the eastern side of the peninsula with the greatest monthly averaged wave powers of 25 kW/m in winter, whereas the wave power was less than 10 kW/m around the peninsula in summer season [7]. Considering European regions overlooking Mediterranean basin, Greece has relatively low wave energy potential. It ranges from 3kW/m to 7kW/m. So the interest for sea wave energy exploitation is moderate compared to regions in the North Sea and the Atlantic Ocean where the wave energy flux is two to three times higher. In the Maltese Islands, the very restricted space available on land is compensated by the highest ratio (>12) amongst European Nations of available marine space with respect to land territory, considering the extent of territorial waters up to 12 nautical miles. Sea depths increase rapidly around most of the coast, especially on the southern perimeter of the Maltese Islands, and this poses a constraint on the location of offshore energy production installations. Energy from offshore sea waves can be a realistic option for the Maltese Islands, offering opportunities not only from direct benefits deriving from local installations, but also in developing tradable expertise in the related technologies [8]. Similar conditions can be found off the Turkish coasts where although power levels are low in general, some points can be found between 4-17 kW/m mostly in the South-Western parts of Turkish coasts that are open to the Mediterranean sea. The regions in the West of the Black Sea in the North of Istanbul Straits and off the South-Western and Western coasts of Aegean Region have been suggested as the best sites to harness the wave energy. Excluding possible areas for shipping lanes, regions for submarine training, etc., and ignoring most of the sites on the Eastern and Southern Anatolia coasts, where the wave power levels are low for commercial exploitation, wave farms that can be set up at three main regions off the coasts of Turkey can harness totally about 10 TWh/year with an annual wave power between 3 and 17 kW/m [9]. For the Italian seas, while the regions of the Adriatic, the Ionian and the Southern and Middle Tyrrhenian seas don't exceed average energy content of 4 kW/m, yet the Western part of the North Tyrrhenian shows an interesting energy availability with average yearly values up to 13 kW/m . A first assessment for wave energy around Italy highlights that in some location the energy extraction could be feasible. In particular, the Alghero potential wave energy power of 13 kW/m encourages the development/installation of pilot WEC and its commercial use [10]. In conclusion, it is important to remark that, while a wave energy resource on the order of kilowatts per meter of device width seems low when compared with European wave energy fluxes, it actually is a much more energy dense resource than either solar or wind energy at similar latitudes in the regions considered.

II. The Seaspoon concept

The energy content stored in oceans and carried by ocean waves can be converted by devices based on different principles of conversion, these devices are commonly called Wave Energy Converters (WEC). Such devices are generally categorized by the installation location and the Power Take-Off (PTO) system. Locations are shoreline, near shore and offshore. Besides, most devices can be characterized according to their positioning respect to the incoming waves and to their principle of operation, providing information on the geometry of the device [1]. The classification system above is not sufficient to encompass all device categories, though. A commonly accepted classification system includes the following six categories of devices, reported in Fig. 2 from left, clockwise: Point absorber, Submerged pressure differential, Oscillating wave surge, Attenuator, Oscillating water column, Overtopping. More than a thousand ideas have been patented in the recent years, but at this stage, only few technologies have reached a large-scale sea trial state. The research and development activities in the wave energy conversion field is paying attention to the opportunity offered by regions where the wave climate is moderate although conveniently exploitable by devices expressly designed.

The Seaspoon is an orbital motion particle converter aiming to convert the energy potential of Mediterranean sea-waves adopting economic and robust wind-derived technology [14].

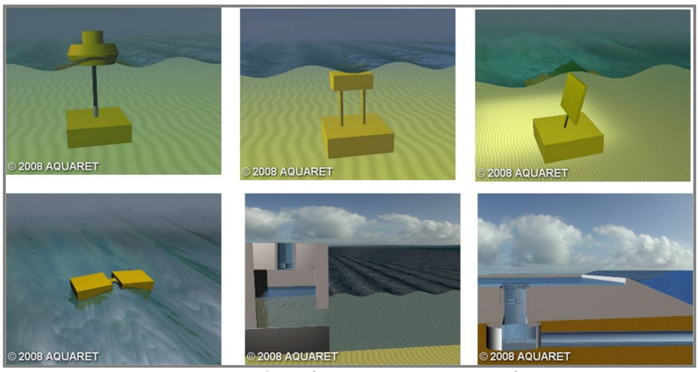

Figure 2: WEC's classification – Courtesy of Aqua-RET http://www.wavec.org

The SEASPOON: Particle Orbital Motion Converter

Particle motion converters obtain energy from the moving water particles at the origin of ocean wave propagation according to the linear wave theory [11]. The Seaspoon device (Fig. 3) captures the wave energy by mean of a horizontal axis rotor orthogonal respect to the incoming wave direction [12]. The "spoon" device, a plate stiffly coupled to the rotor, boosts the conversion efficiency of the rotor immersed in the particle flux. The rotor is shaped like a Savonius drag-type wind turbine (but could be also a Darrieus type turbine), matching simple and low cost construction, high starting torque, low operating speed and low maintenance. This device represents a good choice for small power applications. The power P that can be obtained from a Savonius turbine operating in a flux with relative speed V is according to equation (2):

$$P = 0,5 \times C_{P_S} \times A_s \times \rho \times V^3 \quad (2)$$

The Seaspoon device originates after in-depth review of existing Wave Energy Converter technologies, as well as up to date wind energy turbines. The Seaspoon is conceived with innovative distinctive features, in particular:

- Increased wave energy is captured as the rotor is placed with its spinning axis perpendicular to the incoming flow direction maximizing the equivalent cross section of the blades.
- Higher rotational speed since the device runs with the vector sum of the wave particles velocity and the rotational velocity of the entire device.
- Sea state adaptable: the device sets its working point according to the current sea-state, allowing extended operational time, survivability, invisibility.
- High robustness and low cost, due to the implementation of standard manufacturing components.

Referring to Fig. 3.a) the simplest layout of the Seaspoon consists of a rotor (1) whose spinning axis (2) is submerged at an appropriate depth, considering the sea conditions (wave period, wave height and wavelength), perpendicular to the wave propagation direction. The wave particles, while in motion, hit the rotor blades (3), which start spinning in one direction independently on the incoming water direction. A connecting rod (5) ties stiffly the rotor axis to a main spinning axis (4). The main spinning axis is placed parallel to the rotor axis. It is submerged at an appropriate depth likewise the rotor axis. The main axis is hinged to a flat plate (6), which acts as a rudder for the overall rotation. In turns, the entire device is free to spin around the main axis (4). Hence, the blades are set to move and spin around (2) and (4) at the same time. The energy conversion efficiency is increased due to the flat plate: its presence increases the relative velocity at which the blades (3) receive the incoming water, compared to the simple case configuration where the rotor axis (2) is fixed in space. Indeed, the blades are already moving at the speed u (rotational speed around (4)) when they are hit by the water particles, moving at a certain speed v. The resultant of the vector sum gives the relative velocity w, which module is significantly higher than v.

The device can be installed in deep water by mean of a slack mooring system and buoyant body or an elastic beacon hinged to the sea bottom, in any case the mooring system allows the Seaspoon to adjust to the suitable depth and position considering the occurring sea state, in order to follow the designed operating conditions in terms of orbital motion specifications.

III. THE SEASPOON NUMERICAL MODELLING

The performance of the device have been assessed through numerical model simulation performed in MATLAB environment in order to define an optimal geometry of the device for given wave parameters of height and period (H,T), and set the design for a scale model to be tested with regular waves in a wave flume conveniently equipped at the Department of Mechanical Engineering at the University of Genova (Fig. 5) facilities. Kinematics and dynamics of the sea waves represented the starting point to develop the model able to simulate the actual behavior of the Seaspoon, and allowing a better comprehension of the way the Seaspoon works. The model is mainly based on a dynamic balance equation, involving the torques due to the different forces acting on the device. The solution of this equation brings the rotational acceleration α" [rad/s^2] of the Seaspoon. Integrating the rotational acceleration α" allows to retrieve α' [rad/s] (angular Seaspoon speed) and α [rad] (angle swept by the Seaspoon). The model is developed for deep-water conditions (i.e. perfectly circular wave particle motion).

Wave data

The Seaspoon motion is determined by the action of the incident waves. Two are the main independent variables provided to the simulation model:

- The wave period T [s] (required time for two successive wave crests or troughs to pass a fixed point)

- The wave height H [m] (difference between crest elevation and trough elevation). These two parameters are arbitrarily assigned to the model. The Seaspoon performance is investigated considering two different applications. A first application is the prototype to be tested using the wave flume. The second application is an hypothetical offshore demo plant.

The goal is to provide design specifications of the Seaspoon for both cases.

Within the performed simulations, T and H were chosen according to:

• The range values to be tested in the wave tank (T = [1; 3], H = [0.1; 0.2])

• The Alghero RON (Rete Ondametrica Nazionale) data – open water conditions (T = [3; 6], H = [1; 3])

• $A_{Sav} = b \cdot D$ [m^2] rotor wet cross section

• $\Delta\alpha_{rot}$ [rad] angle between rotor and flat plate

The seaspoon simulations

A simple Savonius rotor has been modeled within the Matlab model to allow a comparative test with the Seaspoon device. Two different Savonius rotors are set up:

• One with the same dimensions of the Seaspoon rotor but located closer to the sea surface;

• The other one placed at the same operating depth of the Seaspoon ($z_{0center}$), but with the same dimensions of the entire Seaspoon

A velocity profile distribution along the blades of the Savonius, is considered. For both the Savonius, the blades are divided in ten parts, thus ten different depths defined with the following equation (3):

$$z_{(m)} = z_{0Savonius} - pRcos(y_m) \quad (3)$$

where m is the loop index, p is a number ranging from 1 to 0.1 with step size 0.1; $y_{(m)}$ is an array, updated at every loop, containing the angle swept by the blade while spinning. The $y_{(m)}$ array varies in the range [0-2π]. For each depth $z_{(m)}$, there is a free wave velocity (exponential profile). An arithmetic average is performed among these ten velocities, so that a single average speed is picked to estimate the power output of the Savonius.

The two equations to estimate the two simple Savonius configuration power output are of the kind:

$$P_{Sav(m)} = 0.5\rho_{H2O} A_{Sav} \eta_{el} \eta_{mec} \eta_{cpt} v_{Sav\_avg}{}^{3}_{(m)} \quad (4)$$

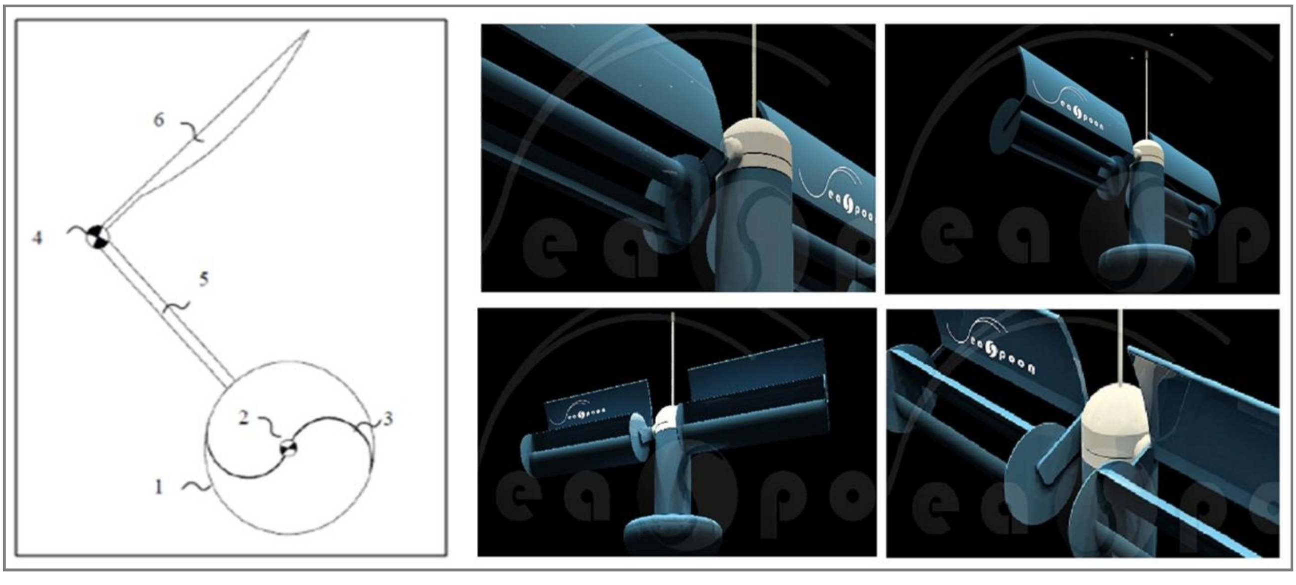

Figure 3: The Seaspoon particle motion converter: a) components scheme; b) a possible rendering

Throughout the energy plot (Figure 4), the small Savonius fixed in space is set as reference (Savonius energy =1).

In all the simulations, either Wave flume or Alghero ones, the results always showed the higher efficiency guaranteed by the Seaspoon compared to the simple rotor-based configurations. The plot of figure 4, for example, shows how the average Seaspoon energy is around four times the one provided by the “small” Savonius (rotor fixed in space) and two times the one provided by the “big” Savonius (rotor fixed in space with radius equal to the spoon tip radius). Before running the simulations, to achieve the suitable geometries for tank and Alghero environments, some tests are run in order to verify the trustworthiness of the code. Different tests are performed showing that the Matlab model responds correctly, following the predictable real physical behavior of the device. It is tested, for example, the only flat plate behavior (rotor dimensions are set zeros), with different sea regime and different geometries; also the rotor alone is tested. In the Fig.5 a plot of the power output of the Seaspoon throughout its revolution is shown.

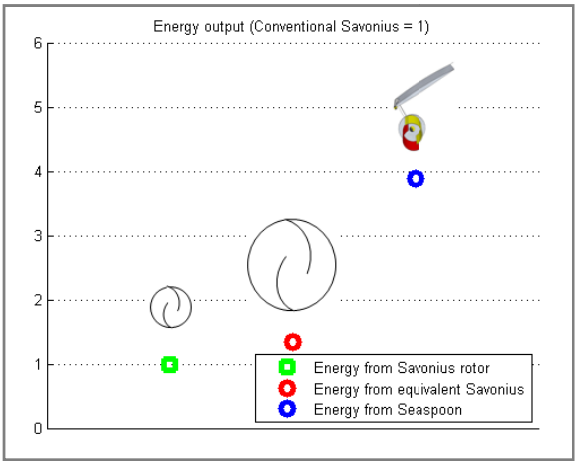

Figure 4: Seaspoon energy compared to the two Savonius ones, with the small Savonius set as energy reference (=1) (Real conditions simulation)

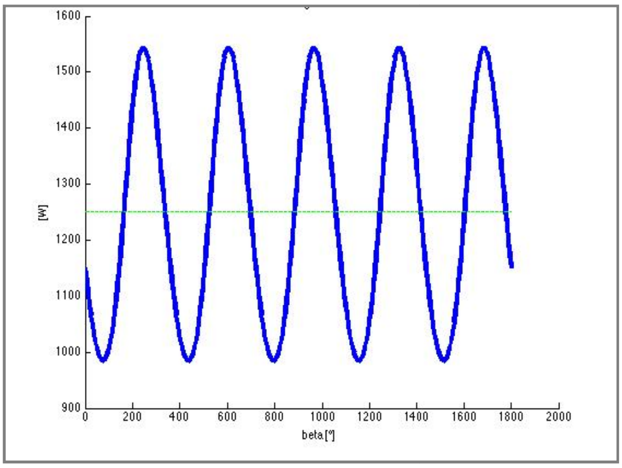

Figure 5: Seaspoon power output tracking (Real conditions simulation)

IV. Experimental Test

In order to validate the results of the numerical simulation and be able to later measure the conversion performance of the Seaspoon device, a wave flume has been designed and built at the Savona University Campus.

A physical model of the Seaspoon device was realized according to the geometric features supplied by the numerical simulation; wave train with parameters of wave height and wave period equivalent to the simulations have been generated and an experimental campaign aimed to verify the Seaspoon concept has been carried out.

Wave Flume

Modern wave-generating flumes are generally divided in two types, according to wave generating systems, thus according to the wave phenomena intended to reproduce:

- Flap wave-generating flumes: a swinging flap is hinged to the wave flume bottom and is able to reproduce deep water wave propagation conditions
- Piston wave-generating flumes: a longitudinal piston fixed to one edge side of the wave flume guarantees shallow water wave propagation conditions

The main specifications of the flume are resumed as follows:

• Flume Lenght 14.50 [m]

• Flume Width 0.55 [m]

• Flume Height 1.5 [m]

• Max still water level 1.10 [m]

• Minimum wave height 0.05 [m]

• Max wave height 0.25 [m]

• Minimum wave period 0.8 [s]

• Max wave period 2 [s]

The above specifications allow the generation of waves with period and height equivalent to those assumed in the numerical model during the first proof of concept of the Seaspoon device on simulation.

The wave flume is designed according to the one collocated at the Florida Tech University [13]. This wave flume is realized in steel wood and glass structure: 12 mm thick glass plates are placed within a main reticular frame realized with steel tubes, while the base is realized with wooden plate 3.5 cm thick.

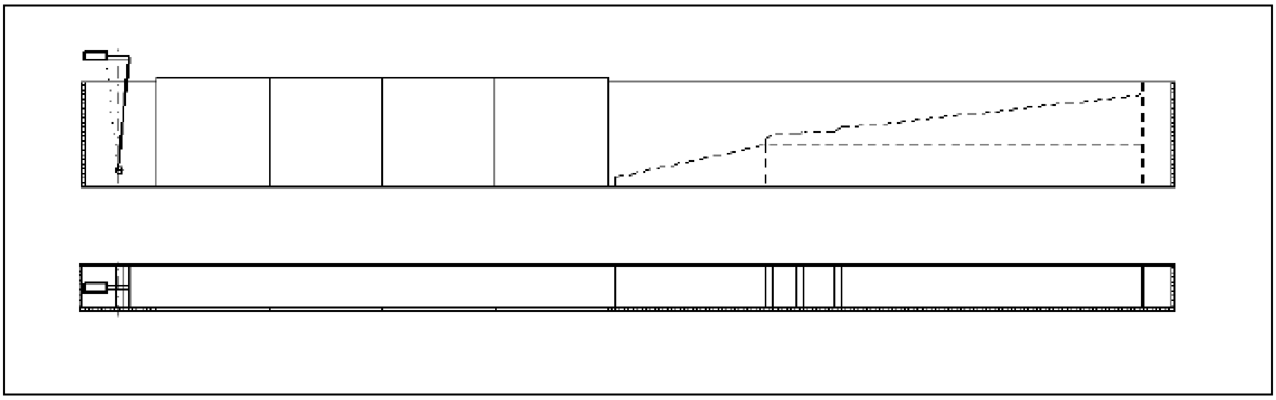

Figure 6: Savona Campus Wave flume scheme

The wave flume is designed according to the one collocated at the Florida Tech University [13]. The structure of the flume is a framework made of scaffolding pipes and clamps for construction, the surfaces of the tank, walls and bottom, are made with wooden boards, conveniently cased in the framework. The pipes diameter is 48 mm with thickness 3,2 mm, the thickness of the boards is 35 mm. In one of the wall of the flume there is a section made of

four transparent tempered glass panels allowing the monitoring of the trials running in the flume. The glass panels are 12 mm thick and the window has a total length of about 5.0 meters.

The inside surfaces are coated with a waterproof liquid membrane, the joints of the transparent wall are sealed with silicon.

The flume (Fig.6) can be divided in three section: a first section, extended for about 2 meters, where the wavemaker flap operates, a second section with length of about 5 meters that represents the trial section and corresponds with the transparent wall, and a third section about 7 meters long hosting the passive absorption beach, where the bottom has a slope ending with a gently grade lower than 10% in order to maximize the wave absorption.

Between the wave-maker section and the sloped beach there is the zone of the flume where the devices model to be tested can be deployed in the water by mean of suitable fixing. In this section the walls of the flume are made of transparent glass boards with thickness of 12.00 mm.

On the transparent wall a reference graph grid was drawn in order to easily monitor the generated sinusoidal waves propagating through the flume, verifying instantly waves height and length. The grid extends for about 2.0 m in length and measures the water level between 0.8 and 1.2 m from the horizontal bottom. Figure 7 a) and b) shows the trials monitoring section of the Savona Campus wave flume.

The equipment of the TPG's wave flume includes:

a) Desktop PC running LabVIEW software

b) National Instruments Multifunction data aquisition card PCI-6031E with SCB-100 connector

c) ON-OFF relay

d) Pneumax series 1700 Pressure proportional regulator

e) One-way flow-rate regulator

f) solenoid operated valve

g) pneumatic cylinder

h) GEFRAN PC67 position transducer

Figure 7 : the trial monitoring wave flume section

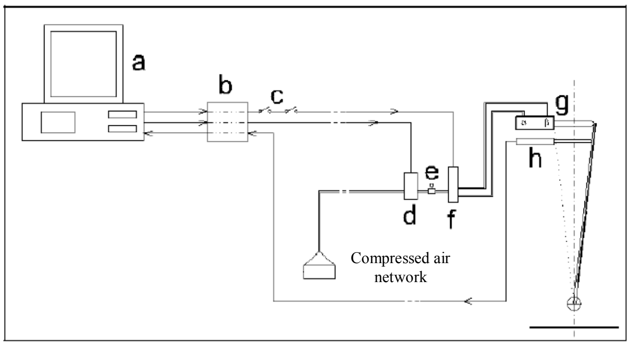

Figure 8: wave-maker control scheme

A scheme of the system designed for the wave-maker control is shown in figure 8.

The flap of the wave-maker is moved by the action of the pneumatic cylinder (g) fed by the compressed-air network of the facility that provides pressure up to 8.5 bar. The double acting cylinder has two air inputs, one for each direction: forward (α) and back (β) conveniently activated by the electro-valve (f). The pressure level of the air sent to the cylinder can be instantly set by mean of the LabView software through the PCI-6031E DAQ (b), and the pressure regulator (d); the direction of the stroke of the cylinder rod is controlled by the program via the DAQ card and the on-off relay (c) activating the solenoid operated valve 5 way and 2 position (f). The one-way flow-rate regulator (e) between the pressure regulator (d) and the solenoid operated valve (f) allows a smoother pressure control preserving the system from damages due to undesired peaks of pressure. The position transducer (h) connected in turn to an input channel of the DAQ card allows the control of the stroke of the cylinder's rod thus giving the precise position of the flap. The motion of the bottom hinged flap wavemaker is performed and controlled by means of a dedicated program in LabView 7.1 (Fig.9)

Seaspoon device model trials

The Seaspoon physical model has been plunged in the water by mean of bracket mounted on the top of the flume side-wall, at a distance of 5.0 m from the wave-maker flap in the correspondence of the glass window, and with a distance of 0.85 m between the main axis of the Seaspoon and the flat bottom of the flume; the bracket allows the reconstruction of the conditions tested with the Matlab numerical model where the main axis of the device operates at a fixed depth, parallel to the wave front, and to the flat bottom.

The geometry of the model follows the indications provided by the numerical simulation: changes in settings occurred proceeding with the tests according to the response of the model to the incident waves tested.

Test sessions were carried out with regular wave trains having constant and stable parameters (H,T) for all the duration of the session (minimum length: 5 minutes); for each session a specific record reporting test parameters and device settings has been generated, including video movie for the frame by frame video analysis; data inferred from the video analysis have been added to the test record.

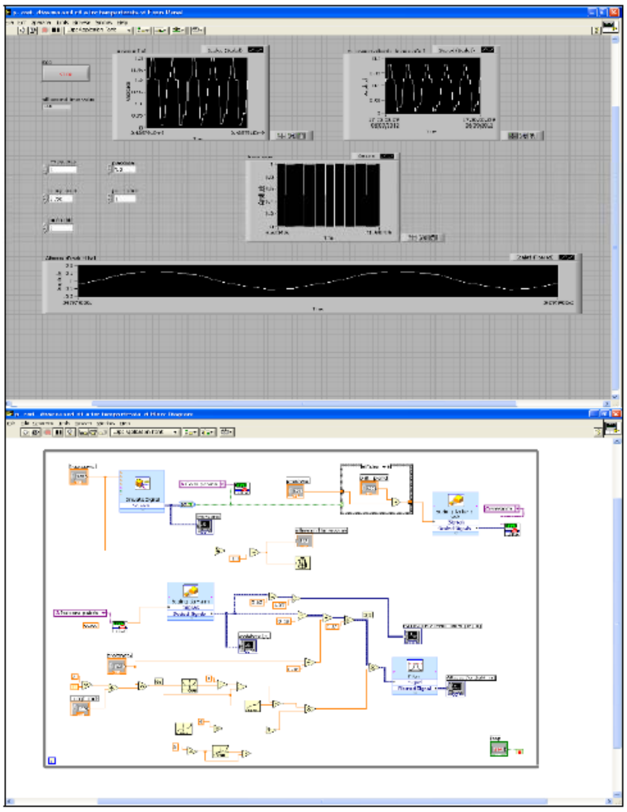

Figure 9: Control panel and Block diagram of the wavemaker control software

The main goal of the first phase of the experimental campaign on the Seaspoon model was to give proof of the results obtained by the numerical simulation; the aim of the test on the physical model aimed at demonstrating mainly two properties of the device:

1. the ability to turn in phase with the wave train

2. the increase of the rotational speed of the Savonius rotor by the effect of the spoon plate.

The development of the test session helped to improve the initial physical model design in order to achieve the expected performance: additional stabilizing masses were added in order to obtain a smoother rotation of the device, spoons of different length and width have been tested to check the effect of different drag coefficients of the plate system, three different rotor diameters and variable rotor arm length have been investigated. The monitored parameters for performance assessment are:

- the rotational speed of the Seaspoon device around its main axis

- the average revolution speed of the Savonius rotor

- the maximum rotational speed of the savonius rotor

Wave type	T [s]	F [1/s]	H [m]	L [m]	c [m/s]	c_g [m/s]	E [J/m^2]	P [W/m]	u_max = w_max [m/s]	Orbit Radius @0.9m [m]
A	1,00	1,00	0,10	1,56	1,56	0,78	12,26	9,56	0,31	0,034
B			0,15				27,59	21,52	0,47	0,050
C			0,20				49,05	38,26	0,62	0,067
D	0,80	1,25	0,10	1,00	1,25	0,62	12,26	7,60	0,39	0,027
E			0,15				27,59	17,11	0,58	0,040
F	1,25	0,80	0,15	2,41	1,93	0,98	27,59	27,04	0,38	0,059

Tab 1:generated Wave parameters

The tests showed the best performance of the device with the wave classified, according to TAB.1, as type C, with period 1.0 s and height 0.2 m, so the analysis focused on this conditions, although several tests were performed also with waves type A, B, and E. Proceeding with the tests some modifications to the above specifics were made in order to obtain the expected performance, in particular the dimensions of the spoon plate and the rotor arm have been reduced according to the needs of a better match with the radius of the water particles motion associated to the generated waves; the final configuration of the model after the experimental campaign resulted the following:

- Spoon plate length l = 8.0 cm
- Spoon plate thickness t = 1.2 mm
- Rotor arm length Beff = 3.0 cm
- Rotor radius r = 1.75 cm
- Rotor blades thickness s = 1.2 mm

The optimal angle between the rotor arm and the spoon plate ($\Delta\alpha_{rotor}$) resulted to be 40°

Trials results

The configurations of the model device tested along the experimental campaign have been the following:

- "original" geometry
- "original" geometry with stabilizing masses system
- "original" geometry with stabilizing masses system and additional spoon plate
- Spoon plate 8.0 cm long
- Spoon plate 8.0 cm long and stabilizing masses system
- Spoon plate 8.0 cm long with stabilizing masses system and additional spoon plate
- Spoon plate 8.0 cm long and arm rotor Beff 3.0 cm long

The tests done confirmed the ability of the Seaspoon model to turn in phase with the wave period, and the increase of the revolution speed of the Savonius rotor by the effect of the spoon plate. However the experimental results obtained are merely qualitative, due to the first stage of development of the designed technology and the limited performance of the experimental equipment, thus a improved equipment for further investigation is being designed [15].

Tab.2 shows the performance recorded during one of the filmed test session: after the frame by frame analysis it was possible to calculate the linear speed of the rotor blades of the Savonius rotor. The spoon plate dragging the rotor axis induces the additional speed resulting from the fact that rotor blades spin at a higher speed than the incident waves orbital motion particles maximum speed according to linear wave theory. In filmed session 794 the device had spoon plate length 8.0 cm, $\Delta\alpha_{rotor}$ =50°, the incident waves had Height H=0.2 m, period T=1 s with resulting maximum orbital particle speed of 0.62 m/s.

IMG _794a (start a 00:00:30)		
Round	Time [s]	v [m/s]
1	0.43	0.51
2	1.30	0.25
3	1.83	0.41
4	2.20	0.59
5	2.87	0.33
6	3.50	0.35
7	4.13	0.35
8	4.80	0.33
9	5.17	0.59
10	5.57	0.55
11	6.07	0.44
12	6.70	0.35
13	7.30	0.37
14	7.74	0.50
15	8.14	0.55
16	8.57	0.51
17	9.21	0.34
18	9.71	0.44
19	10.54	0.26
20	11.04	0.44
21	11.64	0.37
22	12.18	0.41
23	12.74	0.39
24	13.38	0.34
25	14.01	0.35
26	14.64	0.35
27	15.05	0.54
28	15.55	0.44
29	15.98	0.51
30	16.55	0.39
31	17.18	0.35
32	17.68	0.44
33	18.42	0.30
34	18.95	0.41
35	19.48	0.41
36	19.98	0.44
37	20.42	0.50
38	21.02	0.37
39	21.35	0.67
40	21.95	0.37
$V_{average}$		0.42
V_{max}		0.67
V_{min}		0.25

IMG _794b (start a 00:00:30)		
Round	Time [s]	v [m/s]
41	22.39	0.50
42	22.92	0.41
43	23.59	0.33
44	24.05	0.48
45	24.56	0.43
46	24.99	0.51
47	25.39	0.55
48	26.09	0.31
49	26.52	0.51
50	27.12	0.37
51	27.59	0.47
52	28.03	0.50
53	28.63	0.37
54	29.06	0.51
55	29.86	0.27
56	30.46	0.37
57	30.86	0.55
58	31.36	0.44
59	32.06	0.31
60	32.43	0.59
61	33.03	0.37
62	33.43	0.55
63	33.90	0.47
64	34.53	0.35
65	34.93	0.55
66	35.37	0.50
67	35.90	0.41
68	36.22	0.69
69	36.87	0.34
70	37.50	0.35
71	38.00	0.44
72	38.77	0.29
73	39.30	0.41
74	39.67	0.59
75	40.24	0.39
76	40.74	0.44
77	41.11	0.59
78	41.54	0.51
79	41.94	0.55
80	42.47	0.41
$V_{average}$		0.45
V_{max}		0.69
V_{min}		0.27

Tab 2: Record of measured Seaspoon performance

V. Conclusions

The innovative WEC (Wave Energy Converter) called Seaspoon has been first represented in a dynamic and kinematic model in order to fully describe and simulate the Seaspoon operating conditions.

The numerical model gave a possible Seaspoon device configuration for a future open water deployment.

The results of the numerical simulations showed that the Seaspoon (Savonius rotor coupled to spoon plate) performs better than a simple Savonius rotor, in all conditions. This means that the basic idea on which the Seaspoon is based on can work. The spoon plate eventually coupled to a rotor with even higher efficiency of the Savonius (e.g. Darrieus type rotor) can improve its efficiency converting the energy associated to gravitational waves.

At the end of this first stage of development of the wave energy converter Seaspoon, the research activity gave the followings results:

1. the spoon plate coupled to a Savonius rotor operating conveniently placed below a water surface interested by gravitational waves increase the conversion efficiency of the rotor itself by mean of an additional speed induced on the rotor blades;

2. the wave energy converter device called Seaspoon, made by the coupling of an horizontal axis rotor with a spoon plate of proper geometry is able to rotate around its main axis, working conveniently fixed at a specific depth, with an angular speed equivalent to the period of the incoming waves moving the device (Fig.11);

3. experimental tests on a model in a wave flume generating regular sinusoidal waves proved the statements above, showing that the ability of the device to behave as it was conceived is strongly dependant on the correct match between device geometry and wave parameters;

The results obtained so far gave the premises to go on with the investigations until the definition of the conversion capability of the Seaspoon in ideal condition first, and eventually in open sea.

Figure 10: the Seaspoon during first trials

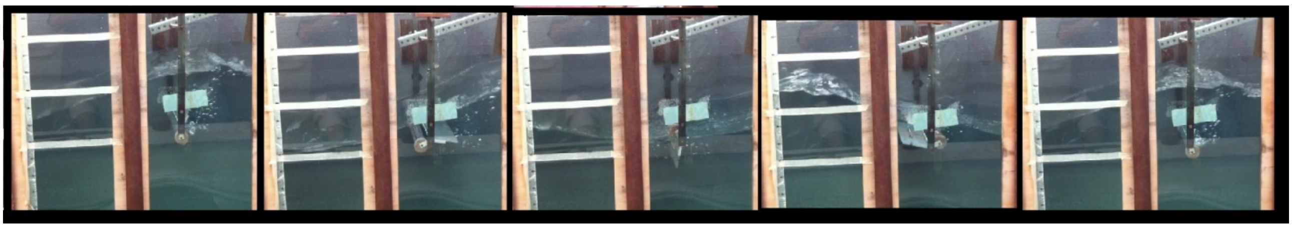

Figure 11: the Seaspoon spinning "in-phase" with the incoming waves during wave-flume trials

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NOMENCLATURE

ρ = water density [kg/m^3]
g = gravity acceleration [m/s^2]
H = wave height [m]
T = wave period [s]
C_{Ps}= Power Coefficient of Savonius rotor
P = output Power [W]
A_S = swept area of Savonius rotor (Diameter x Lenght) [m^2]
V= relative speed of the fluid particle flux [m/s]
R = Savonius rotor radius
A_{Sav} = rotor wet cross section [m^2]
$\Delta\alpha_{rot}$ = angle between rotor and flat plate [rad]
η_{el} = electric efficiency
η_{mec} = mechanical efficiency
η_{cpt} = capturing efficiency (Savonius blades)
$z_{0Savonius}$ = depth displacement of the rotor axis [m]
u_{MAX} , v_{MAX} = maximum orbital particle speed [m/s]