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A NOVEL CONCEPT FOR A SUBMERGED WAVE ENERGY CONVERTER

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Abstract

Wave energy represents an important renewable resource with significant potential for sustainable energy production. As interest in alternative energy sources continues to grow, this paper presents the conceptual design and preliminary laboratory testing of a novel submerged wave energy converter based on differential pressure conversion. The submerged wave energy converter will be evaluated and optimized in the Hydraulics and Environmental Protection Laboratory of the Technical University of Civil Engineering Bucharest, under controlled wave conditions with varying wavelengths and periods. Preparatory measurements of wave characteristics will guide the optimal dimensioning of the device to maximize energy capture efficiency. Preliminary results identify relevant wave parameters and indicate potential power generation efficiency. The advantages of the device are primarily based on the concentration of the large but diffuse hydraulic energy of waves into the high-pressure hydraulic energy of a working fluid, enabling operation of industrial installations with superior efficiency. Additionally, the research investigates the device's effect on reducing wave energy, contributing to coastal protection and the preservation of marine ecosystems.

Key words*: costal protection, wave energy, differential pressure conversion, energy capture efficiency, submerged wave energy convertor.*

INTRODUCTION

Wave energy constitutes a significant renewable resource due to its high-power density, widespread availability in coastal regions, and minimal environmental emissions. Sea waves are generated primarily by wind transferring energy from the atmosphere into the sea surface. Waves effectively concentrate solar energy over vast areas of the world's oceans and seas. As a result, the theoretical global potential of wave energy resources has been estimated to reach tens of thousands of terawatt-hours per year (Wen & Low, 2026). This value exceeds current annual global electricity consumption, in principle indicating a substantial but largely untapped energy reservoir.

For the Romanian coastline along the Black Sea, which stretches approximately 200 km, studies estimate a potential wave energy around 8 TWh/year. The technically exploitable potential is assessed at roughly half of this value, approximately 4 TWh/year (Degeratu & Bandoc, 2007). The wave energy potential of the Black Sea is significantly lower than that of offshore wind energy. This suggests that, although wave energy may contribute to the Romanian national energy mix, it is unlikely to match the scale of offshore wind resources.

However, wave energy remains attractive for coastal regions where land availability is limited, or energy costs are high. This is due to the higher power density of waves compared to many other renewable sources (Guillou et al., 2020). Moreover, wave energy's predictable nature offers potential advantages for grid integration and energy planning relative to more variable sources (Wen & Low, 2026).

Even though the technological maturity and commercial implementation of wave energy converters (WECs) is behind solar and wind technologies, ongoing research highlights the potential of wave energy to contribute significantly to future sustainable energy systems and climate change mitigation strategies (Azam et al., 2024).

There are three main concepts of wave energy converters (WECs): (a) oscillating water column converters; (b) overtopping (reservoir-type) converters; and (c) oscillating body converters. The devices from the last category, oscillating body converters, can be either floating or submerged and includes attenuators and point absorbers. Attenuators are elongated, articulated

structures positioned parallel to the direction of wave propagation, and the captured energy is generated through the flexing of their joints. Point absorbers are relatively small floating bodies that oscillate vertically (heave motion). The energy is extracted from the relative movement between the floating body and a fixed reference point. The WECs with oscillating body category includes, also, differential pressure converters. Those devices are typically installed on the seabed in near-shore coastal areas.

In Romania, a few research efforts have been undertaken in the field of wave energy harvesting. Moreover, regarding differential pressure converters, have not yet resulted in commercially developed products (Tatu, 2014).

This paper introduces the conceptual design and preliminary laboratory evaluation of a novel submerged wave energy converter (WEC) that operates on the principle of differential pressure conversion. The proposed device is intended to harness the energy of sea waves by exploiting pressure variations of the water at the seabed, due to the variation of water level induced by the waves.

The advantages of the device are based, first at all, on the fact that the large, but diffuse, hydraulic energy of the waves is concentrated into the hydraulic energy of a working fluid at high pressures which then can be taken over by a hydraulic Power Take-Off system (PTO). PTO converts hydraulic energy into electrical energy through a generator. Second at all, the proposed device offers potential advantages in terms of stability, reduced visual impact, and resilience in harsh marine conditions.

Experimental investigations are conducted at the Hydraulics and Environmental Protection "Dumitru Cioc" Laboratory of the Technical University of Civil Engineering Bucharest (UTCB), under fully controlled wave conditions (Figure 1).



Figure 1. Wave channel, Hydraulics and Environmental Protection "Dumitru Cioc" Laboratory

The testing program will systematically vary wavelengths, periods, and amplitudes to assess the device's performance, characterize its energy conversion efficiency, and provide data to inform subsequent design optimization and scale-up for nearshore deployment. The results of this study are expected to contribute to the development of efficient, site-adapted submerged WECs suitable for the Romanian Black Sea coast and similar environments worldwide.

The paper also presents preliminary results aimed at identifying relevant wave parameters and estimating the potential power generation efficiency of the proposed device. Furthermore, the research investigates the attenuation effect of the converter on incident wave energy, with implications for coastal erosion protection and the mitigation of extreme wave event impacts.

CONCEPTUAL DESIGN OF THE DIFFERENTIAL PRESURE CONVERTOR

The wave energy convertor (Figures 2 and 3) consists of a fixed part, the base frame of the device (7), and a movable part, a light plate (2) that rests on two flexible steel springs (3) (Figures 2 and 3). The movable plate together with the springs is enclosed in a waterproof foil (1), fixed to the upper part of the base frame

through a waterproof foil fixing frame (8). Water access is made at the base of the device, through holes (4) provided with valves (5) that allow unidirectional access, in the direction of water flow.

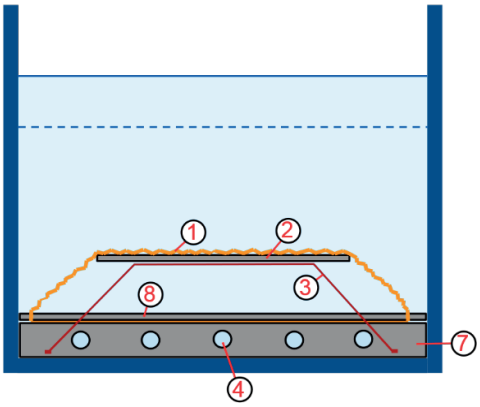


Figure 2. Schematic of the wave energy capture device – front view of the device in the wave channel

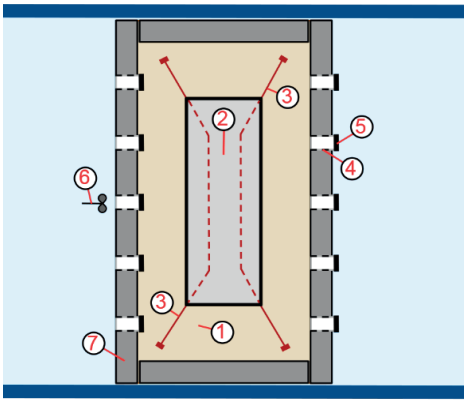


Figure 3. Schematic of the wave energy capture device – top view of the device

The notations in the Figure 2 and Figure 3 represent: 1- waterproof foil, 2- light plate, 3 - steel wire (spring), 4 - holes, 5 - valves, 6 - mill, 7 base frame, 8 waterproof foil fixing frame.

PRELIMINARY MEASUREMENTS FOR WAVE CHARACTERISTICS DETERMINATION

For the dimensioning of the differential pressure converter, experimental determinations were carried out in the wave channel under fully controlled wave conditions to determine the relevant wave parameters.

The wave channel has a length of 16 m and a width of 1 m. The maximum water depth in the channel is 0.9 m, and the generated waves correspond to water depths ranging from 0.2 m to 0.6 m. The wave channel is equipped with a wave generator at one end. The wave generation system consists of a movable flap, articulated at the bottom of the channel and set in motion at the top by a connecting crank-slider mechanism. At the opposite end of the channel a wave energy attenuator is installed. This is designed to dissipate the wave energy and prevent the occurrence of the wave reflection phenomenon, which can outhouse alter the characteristics of the incident waves (Iancu et al., 2024).

The experimental determinations systematically varied the wavelengths, periods and amplitudes of the waves generated in the wave channel at different water depths. To measure the wave amplitude and height, two level sensors placed at 4 m from each other were used, as shown in Figure 4.



Figure 4. Placement of pressure sensors in the wave channel

The wavelength and period of the wave were determined by measuring the distance and time between two consecutive wave peaks. Based on those measurements, the wave propagation speed (celerity) of the waves was calculated, using the formula:

$$c = \frac{\lambda}{T}$$

The results obtained from the experimental tests are presented in Table 1.

Table 1. Waves characteristics determined from experimental test

Water depth H (cm)	Wave height h (cm)	Wavelength λ (m)	Period T (s)	Wave celerity c (m/s)
20	2	1.32	1.05	1.26
	3	1.02	0.89	1.15
	3	0.96	0.82	1.17
	4	0.85	0.76	1.12
	4	0.65	0.68	0.96
30	6	0.68	0.63	1.08
	7	1.42	1.01	1.41
	8	1.20	0.88	1.36
	8	1.03	0.85	1.21
	8	0.84	0.73	1.15
40	8	0.66	0.61	1.08
	10	1.50	1.00	1.50
	10	0.81	0.70	1.16
	13	1.19	0.85	1.40
	14	1.12	0.89	1.26
50	10	0.74	0.72	1.03
	12	0.95	0.76	1.25
	13	1.74	1.15	1.51
	14	1.14	0.82	1.39
	15	1.28	0.85	1.51
60	13	0.82	0.68	1.21
	15	1.03	0.76	1.36
	16	1.18	0.86	1.37
	20	1.34	0.90	1.49
	24	1.67	1.04	1.61

The parameters experimentally determined in the wave channel and considered were those corresponding to the waves that characterize, at natural scale, the waves in the Black Sea, in the Romanian coastal area.

Wind-generated waves have periods of approximately 1 to 30 s, with dominant periods for storm surges being between 5 and 15 s (Coveianu, 2016).

Figure 5 presents a schematic of the differential pressure converter's placement in the wave channel, along with the wave parameters that will determine the device dimensions and efficiency.

Based on these experimental determinations, a preliminary estimate of the device's energy generation efficiency was performed using the theoretical framework of differential pressure conversion.

These estimates will be validated upon scaled physical model testing of the converter in the wave channel under the wave conditions established herein.

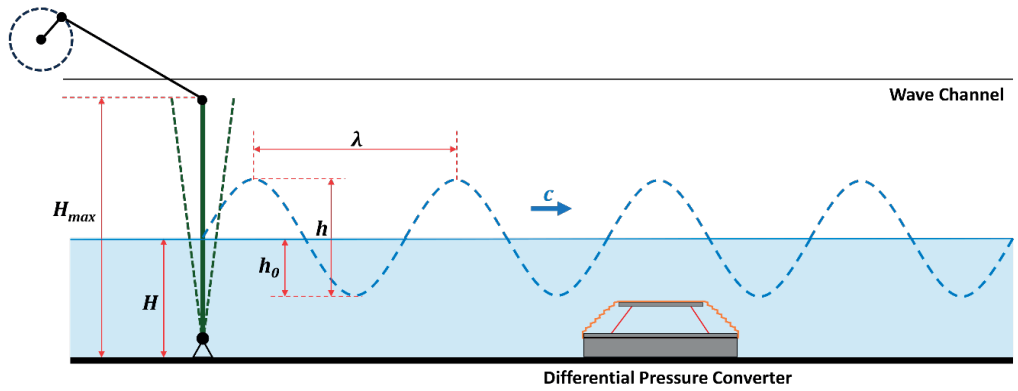


Figure 5. Schematic of the wave energy capture device – front view of the device in the wave channel

PERFORMANCE ANALYSIS OF THE DIFFERENTIAL PRESSURE CONVERTER

Essentially, the energy converter behaves like a volumetric pump. Volumetric pumps are hydraulic machines that transfer fixed volumes of fluid at equal intervals of time between the suction and discharge sections of the pump, using a piston driven by a crank-rod mechanism.

The power of such a pump is calculated using the formula:

$$P = \Delta p \cdot \Delta Q \text{ (Watt)}$$

where Δp is pressure variation created by the piston (Figure 6) (force applied to the piston / piston surface) (N/m^2) and ΔQ is flow variation (piston displacement, i.e. volume swept by the piston / half-period of the reciprocating motion) (m^3/s).

In the case of the converter, the piston is represented by the movable cover (light plate).
The pressure variation created by the piston Δp is the pressure variation given by the wave and which produces the oscillation of the cover placed on the springs. The suction and discharge are represented by the access and exit slots provided with one-way valves.
Unlike the classic volumetric pump, in the case of the converter, the displacement of the piston (light plate) and, implicitly, ΔQ are not a fixed value. These and, implicitly, the performances of the converter proposed in the work, depend on several parameters:

- wave characteristics (H, h, λ);
- the mass of the device cover (light plate), m;
- the elastic constant of the springs, k;
- the hydraulic resistance of suction and discharge valves.

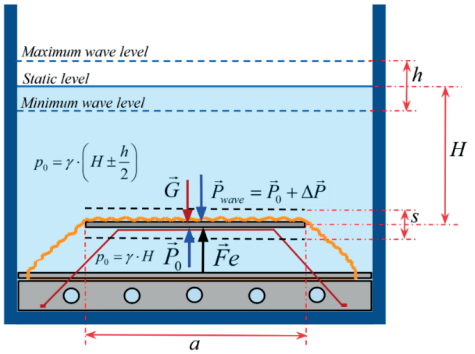


Figure 6. Representation of the forces acting on the energy converter

In addition, the mass of the movable cover together with the elastic constant of the springs is defined as the natural oscillation period of the system, $T = 2 \cdot \pi \cdot \sqrt{\frac{m}{k}}$ which is conjugated to the wave period.
The outer part of the movable cover, the one exposed to the wave action, is subjected to a variable pressure, between the limits:

$$p = \gamma \cdot \left(H \pm \frac{h}{2}\right),$$

which transmits to the water inside the device the pressure variation:

$$\Delta p = \gamma \cdot \frac{h}{2}.$$

and this value can be calculated.

In nature, the pressure variation given by the oscillatory movement of the waves can be calculated with the relationship (Luca & Luca, 2002; Sorensen, 2006; Holthuijsen, 2007):

$$\Delta p_H = \pm\rho \cdot g \cdot \frac{\frac{h}{2}}{ch\left(\frac{2 \cdot \pi \cdot H}{\lambda}\right)}$$

where:

- Δp_H (Pa) represents the pressure variation at depth H (m);
- λ (m) represents the wavelength of the wave;
- h (m) represents the height of the wave;
- ρ (kg/m^3) represents the density of water;
- H (m) represents the depth of water at which the converter is located.

Instead, as shown, ΔQ and, implicitly, the converter's performance, depend on those parameters mentioned above and the experimental measurements on the reduced-scale model in the wave channel aim to find the influence of these parameters with the final goal of finding that combination that leads to maximum efficiency. During the experiments, it is possible to know, respectively measure, in addition to the wave characteristics (period, wavelength):

- the mass of the cover;
- the elastic constant of the springs;
- the vertical displacement/oscillation of the cover from which ΔQ results;
- the hydraulic resistance of suction and discharge valves.

The power absorbed by the converter can then be calculated for each combination of the mentioned constructive parameters.
To this end, it is proposed:

- measuring the water velocities through the orifices provided with valves;
- measuring the vertical displacement/ oscillation of the cover.

The advantages of the proposed constructive structure are the following:

- all the previously mentioned parameters can be easily changed; the elastic system supporting the movable cover can be removed from the box, allowing the change of the elastic constant k by replacing the springs;
- the additional masses on the movable cover can be changed, allowing the calculation of the elastic constant with precision;

- since the converter box is equipped with one-way valves (flaps), the Archimedean force is equal to zero, so the converter box can be easily placed on the bottom of the channel; the waterproof foil allows water access to the box only through the valves.

CONCLUSIONS

The paper introduces a novel submerged wave energy converter operating on the principle of differential pressure conversion, starting with a preliminary experimental program carried out under controlled conditions in the wave channel. The proposed converter, comprising a movable cover supported by calibrated steel springs, enclosed within a waterproof membrane and equipped with unidirectional valves, constitutes a structurally simple yet physically coherent solution for harnessing the oscillatory pressure field generated by surface waves at seabed level. The experimental measurements conducted across a systematic variation of water depths (20-60 cm), wave heights (2-24 cm), wavelengths (0.65-1.74 m), and periods (0.61-1.15 s) provided a comprehensive characterization of the wave parameters reproducible in laboratory conditions. The wave celerity values recorded, ranging from 0.96 to 1.61 m/s, are consistent with theoretical predictions for shallow-water wave propagation and confirm the reliability of the measurement methodology employed. These determinations establish the hydrodynamic baseline required for dimensioning the differential pressure converter, ensuring that the natural oscillation period of the cover-spring system can be tuned to resonate with the incident wave period, a condition essential for maximizing energy capture efficiency.

From an analytical standpoint, the converter behaves as a volumetric pump in which the pressure variation, governed by the wave height and water depth, drives a variable volumetric flow through the system. The theoretical framework presented demonstrates that the output power is a function of both wave characteristics and constructive parameters – specifically the mass of the movable cover, the elastic constant of the spring system, and the hydraulic resistance of the valves – all of which are independently adjustable in the proposed experimental setup.

Beyond its energy harvesting function, the proposed device presents a secondary benefit of considerable practical relevance: through the attenuation of incident wave energy, the converter contributes to the reduction of coastal erosion. This dual functionality, energy generation and wave energy dissipation, positions the proposed device as a potentially valuable component of integrated coastal management strategies, particularly in environments such as the Romanian Black Sea coast where wave energy resources, although modest in comparison to offshore wind potential, remain largely unexploited.

Based on preliminary wave characterization measurements, the estimates of the potential energy generation efficiency will be subject to confirmation through direct experimental testing of the converter at reduced scale in the wave channel.

The results are expected to provide the empirical basis for the design of a nearshore prototype suitable for deployment in the specific marine conditions of the Romanian coastal zone.

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