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Technical Note

On a new wave energy absorber

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Abstract

It is a commonly held opinion that only a forced resonance is possible between random wind-generated waves and wave energy absorbers; the forced resonance being pursued by means of devices for phase control. We show, instead, that it is possible to obtain an impressive natural resonance between random wind-generated waves and a new kind of absorber beneath the sea level. The proof is given through a small scale field experiment. This finding should enable us to defend coasts with a very low environmental impact and to use breakwaters for converting large quantities of wave energy into electric power.

Keywords: Wave energy conversion; Shore protection; Caisson breakwaters

1. Introduction

Wave energy converters known as OWCs (oscillating water columns) consist of a box partially immersed and an air-duct connecting the box to the atmosphere (Fig. 1). Under wave motion air flows alternately into the atmosphere and into the box and drives a self-rectifying turbine (Mc Cormick and Surko, 1989; Raghunathan, 1995). A lot of work was done (see Jefferys and Whittaker, 1986; Sarmento et al., 1990; Falcão and Justino, 1999) to improve OWCs' efficiency with some control devices, and in particular with devices for phase control in each individual wave. For the OWCs working with random wind-generated waves it was suggested to use feedback control to build in a characteristic "imitating" resonance into the velocity response (Korde, 1991). More in general, phase control is deemed necessary, though very difficult to perform, for any kind of converter interacting with random wind-generated waves. In particular this is the case of point absorbers which consist of mobile floating bodies whose phase control is known as "latching" (Budal and Falnes, 1980).

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Nomenclature

C_a	absorption coefficient
C_r	reflection coefficient
C_1, C_2	safety factors
h	energy per unit weight
h_f	head losses
H_s	significant wave height
q	bearing pressure
Q	water discharge
t	time
T_p	peak period of the wave spectrum
u	water velocity in the vertical duct
V	total volume of the open air reservoirs
ξ	actual height of the air pocket
$\bar{\xi}$	average height of the air pocket
Δp	pressure fluctuation

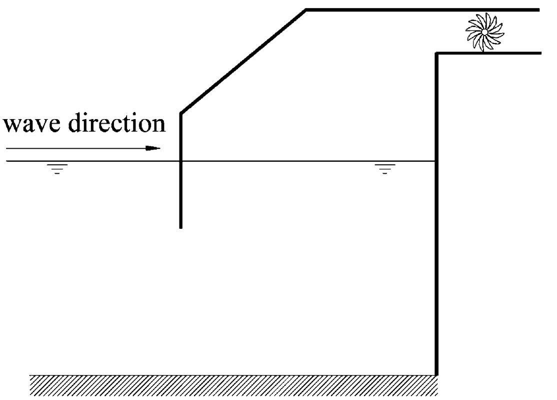

Fig. 1. Schematic cross-section of a plant OWC for wave energy conversion.

Fig. 2 shows the scheme of a new kind of wave energy absorber which was disclosed by Boccotti (1998) with the aim of defending coasts and converting wave energy into electric power. Under wave action the pressure on opening 2 of the vertical duct fluctuates and, as a consequence, water flows up and down in the vertical duct and in the box, and air pocket 1 acts as a spring. The air quantity must be regulated so that the eigenperiod of oscillations be close to wave periods of the sea state; which implies that we must vary the air quantity with the same gradualism as the sea state varies in the course of a storm, and there is no need for phase control in individual waves.

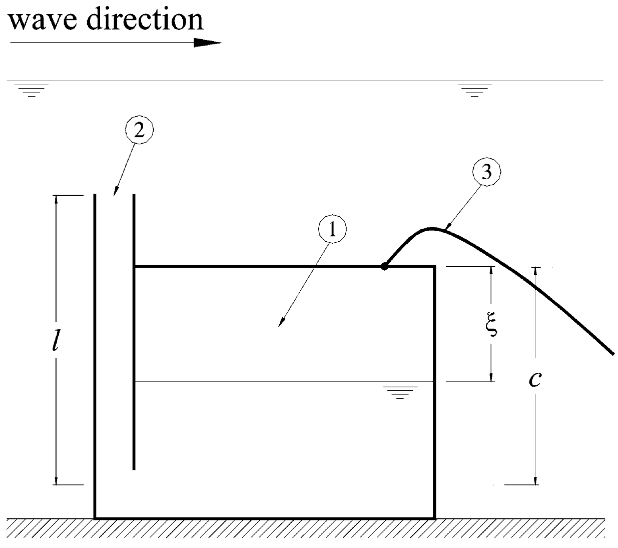

Fig. 2. Schematic cross-section of the wave energy absorber of Boccotti (1998) (see the legend of Fig. 4).

Given that the scheme of Fig. 2 exploits a natural resonance, it can work with a relatively small outer opening, and this fact enables us to conceive some very compact plants. At present we are researching two kinds of plants based on the scheme of Fig. 2. Here we show results of a small scale field experiment on a plant of the first kind. To our knowledge, this is the first small scale field experiment on a wave energy absorber. Previous experiments, from the tests of Salter (1974) and Swift et al. (1975) to the recent tests of Czitrom et al. (2000), were done in tanks with waves generated by wavemakers.

2. The two kinds of plants

Fig. 3 is a hypothesis of a plant of the first kind—it is a caisson in reinforced concrete which can be built in a dry dock, towed and sunk; the solid mass on the roof of the caisson is made after the caisson is sunk. Many caissons like this, in contact with each other, make up a submerged breakwater, and a number of land-based compressors feed air into these caissons. The environmental impact is very low because boats can pass over this breakwater, the water behind it is not stagnant and the landscape is not disfigured. The more this breakwater can do with respect to conventional breakwaters is to suck a share of the incident wave energy.

Fig. 4 is a hypothesis of a plant of the second kind. The absorber of Fig. 2 is on the wave-beaten side of this plant, and the base of the absorber becomes a part of the base of the plant. Air-duct 5 with a Wells turbine (Raghunathan, 1995) connects air pocket of the absorber and four reservoirs 4^{I}, 4^{II}, 4^{III}, and 4^{IV}. Pressure fluctuations in the air pocket 1 and in the reservoirs yield an alternate flow in the air-duct, which

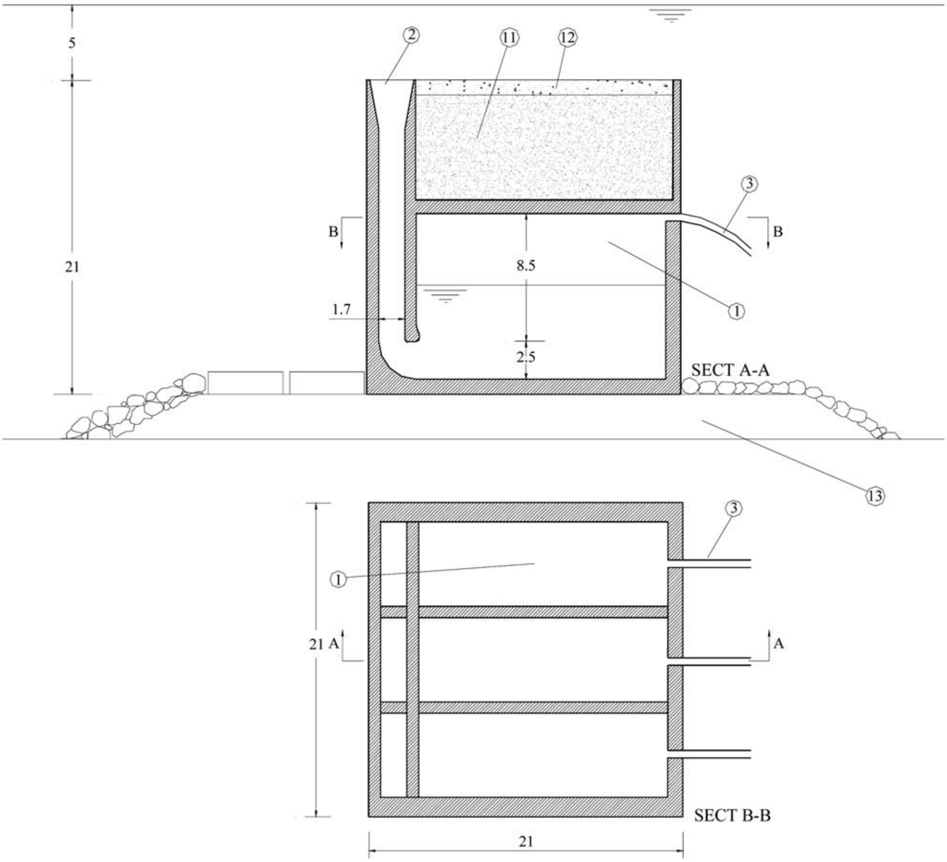

Fig. 3. A hypothesis of a plant of the first kind, which is used as a basis for further investigation. See the legend of Fig. 4.

can drive the self-rectifying turbine. To modify the eingenperiod (Fig. 5) we may change volume V of the open reservoirs and/or height $\bar{\xi}$ of the air pocket ($\bar{\xi}$ being the average height in the wave cycle). To change V one has simply to work on the valves: with only 7^{I} open, V=55 m^3; with only 7^{II} open, V=110 m^3; and so on.

3. The small scale field experiment

The plants of Figs. 3 and 4 are based on the following idea: through regulation of the air quantity, one can obtain resonance between the random process of wind-generated waves and the random process of oscillations inside the caisson. To verify this idea we made a small scale field experiment off the eastern coast of the Straits of Messina where, typically, wind waves have H_s (the significant wave height) between 0.2 m and 1.0 m, and T_p (the peak period of the spectrum) between 2.0 s

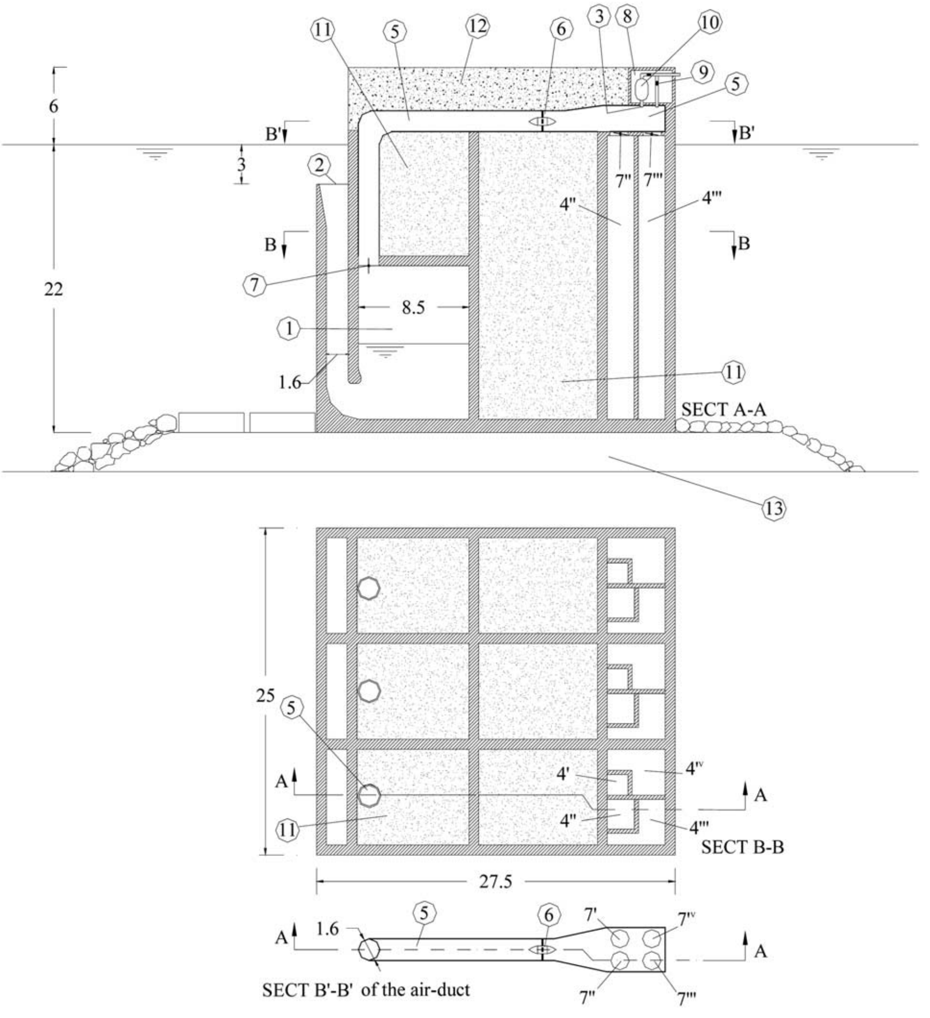

Fig. 4. A hypothesis of a plant of the second kind which is used as a basis for further investigation. Legend: 1 air pocket; 2 outer opening; 3 air feed; 4 air reservoir; 5 air-duct; 6 Wells turbine; 7 butterfly valve; 8 service room; 9 exhaust valve; 10 compressor; 11 sand filling; 12 superstructure cast in concrete; 13 rubble mound foundation. Volumes of reservoirs: 4^{I}, 55 m^3; 4^{II}, 110 m^3; 4^{III}, 220 m^3; 4^{IV}, 275 m^3.

and 4.0 s, and the tide amplitude is within 0.10 m. We made a 1:10 scale model of the caisson (Fig. 3), with some modifications in the interior. Specifically, the width of the vertical duct was reduced from 0.17 m to 0.10 m, and the height of the interior room was enlarged from 0.85 m to 1.55 m. Both these modifications served to increase the eigenperiod of oscillations inside the plant. This is because, from full scale to model, the eigenperiod of oscillations is reduced more than the wave period. The small caisson was isolated so that it did not exploit wave amplification due to reflection.

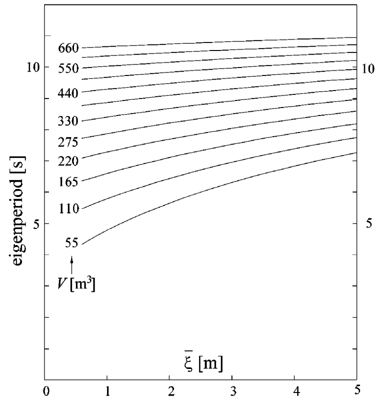

Fig. 5. Eigenperiod of free harmonic oscillations inside the plant of Fig. 4 vs. height $\bar{\xi}$ of the air pocket. Each line is relevant to a new volume V of the open reservoirs.

Incident waves were recorded by two ultrasonic probes, respectively, 5 m and 7 m apart from the caisson. The caisson was equipped with three pressure transducers: (a) in the air pocket, (b) at the outer opening of the vertical duct, (c) on the roof. A fast response thermocouple was inserted in the air pocket. Average height $\bar{\xi}$ was obtained from the average pressures recorded by transducers (a) and (c). Volume V of the air pocket was obtained from the pressure and temperature through the perfect-gas law. The water discharge was obtained by differentiating volume V with respect to time. Each record was of 5 min and comprised a number of individual waves from 100 to 175. The sampling rate was 10 Hz for all gauges.

For each sea state we calculated the value of $\bar{\xi}$ for which the eigenperiod of free harmonic oscillations inside the caisson equalled the peak period of the spectrum of the pressure fluctuations Δp_2 recorded at outer opening 2 of the vertical duct. We regulated the air quantity inside the caisson so that height $\bar{\xi}$ was close to this calculated value. In all cases (130 records of 5 min) we observed a clear phenomenon of resonance like that of fig.6. In each record the root mean square displacement of pressure head waves in the air pocket proved to be from 1.5 to 4.0 times greater than the root mean square displacement of surface waves (the amplification being the greater, the smaller the H_s was). The energy absorption occurred because of a 180° phase angle between Δp_2 and Q (the water discharge, positive outwards) as we may see in Fig. 6. Sometimes, Δp_2 and Q went out of phase for short time intervals (there are two of these time intervals in Fig. 6, being pointed by arrows). The amplitude of the pressure fluctuations in the air pocket diminished in these short intervals, and then Δp_2 and Q went back spontaneously to oscillating with the 180° phase angle.

The experiment served also to check the computation method. To this end, we calculated Q and Δp_1 (the pressure fluctuations in air pocket) using the time series data of Δp_2 as input. The flow equation (see Fig. 2) is

$$\frac{c-\xi}{g}\frac{\mathrm{d}^2\xi}{\mathrm{d}t^2}+\frac{l}{g}\frac{\mathrm{d}u}{\mathrm{d}t}=h_1-h_2-h_f, \tag{1}$$

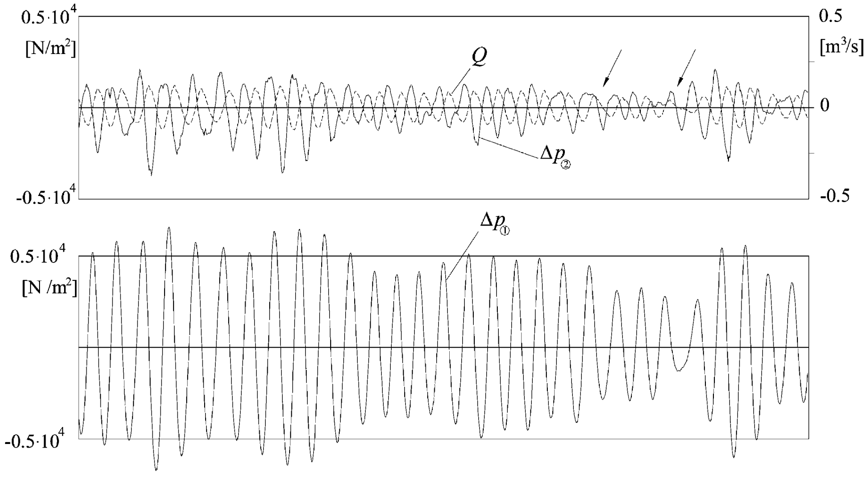

Fig. 6. 100 s time series data of: pressure fluctuations Δp_2 at outer opening 2 water discharge Q (positive outwards), pressure fluctuations Δp_1 in the air pocket. The water discharge is that of caisson's central duct. The incident waves had H_s of 0.42 m, T_p of 3.4 s, and narrow-bandedness parameter $\psi *$(Boccotti, 2000) of 0.65.

where u is the velocity in the vertical duct (positive upward), h and h are the energies per unit weight, respectively, at the air–water interface in the caisson and at the upper opening of the vertical duct, and h_f are the losses per unit weight. h is related to height ξ, time rate $d\xi/dt$, and to the pressure in the air pocket, and head loss h_f is expressed in the form $h_f^* u/|u|$, where h_f^* is the head loss in the permanent flow. Eq. (1) taken together with the equation of state and the continuity equation yield a non-linear differential equation of second order of $\xi(t)$ which can be solved numerically for given $\Delta p_2(t)$ and initial conditions. The equation of state $p_{air}\xi^k = \text{cost}$ (with p_{air} being the absolute pressure in the air pocket) which best fitted the time series data of the experiment was that with a k of about 1.03 (nearly isothermal). The flow in the vertical duct was turbulent (average Reynolds number ranging from 6×10^4 to 2.1×10^5), and we assumed a friction factor of 0.025 in the Darcy–Weisbach formula and a coefficient of minor losses (cf. Streeter et al., 1998) of 0.75. This coefficient was that giving the best agreement between predictions and data in the whole set of records.

The agreement between the predictions done with this method and the time series data of Δp_1 and Q proved to be really very good, as we may infer from Fig. 7.

4. Expected performances at full scale

The same calculation method was applied for predictions on performances at full scale. For a conservative estimate, the assumption was made of adiabatic flow, which leads to the lowest estimates on wave energy absorption. For the air-duct we assumed a friction factor of 0.025 and a coefficient of minor losses of 3.0. Finally, we used

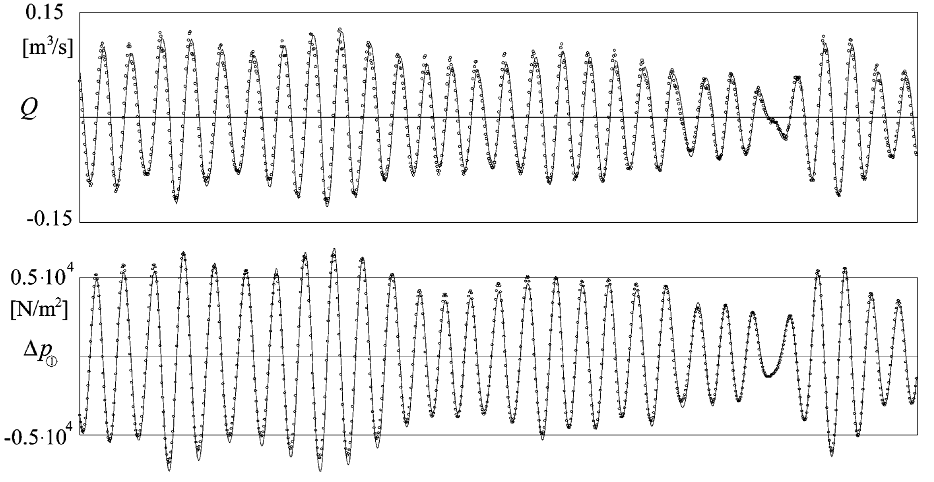

Fig. 7. 100 s time series of Δp_1 and Q: predictions vs. data. The prediction was made on taking the time series data of Δp_2 as input.

dimensionless plots of Curran and Gato (1997) for the pressure drop across the turbine and turbine efficiency for a simple monoplane Wells turbine with an overall solidity of 0.64 and rotor angular speed of 160 rad/s. The pressure fluctuations at the depth of the outer opening of the vertical duct were numerically simulated using the linear theory of random wind-generated waves (Phillips, 1967; Borgman, 1969). These pressure fluctuations depend only on the frequency spectrum (Boccotti, 2000) which was assumed to be the JONSWAP spectrum (Hasselmann et al., 1973) with the following relationship (Boccotti, 2000) between T_p and H_s:

$$T_p = 8.5\pi\sqrt{H_s/(4g)}. \tag{2}$$

The numerical simulation gave the pressure fluctuations in the incident waves which were multiplied by the amplification factor

$$f_{amp} = 1 + C_r(1-C_a), \tag{3}$$

where C_r is the reflection coefficient and C_a is the absorption coefficient which was obtained through an iterative approach. For the plant of Fig. 4, C_r was assumed to be 1. For the plant of Fig. 3, C_r was assumed to be equal to the quotient between the mean energy flux from the seabed to the breakwater elevation and the total mean energy flux of the incident waves. For the analysis of stability we used Goda's formula (see Goda, 2000) which gives the maximum expected wave force in a sea state of given characteristics. The wave pressures given by this formula were multiplied by $f_{amp}/2$, given that the formula is valid for conventional caisson breakwaters whose f_{amp} may be assumed to be 2.

With the computation method we estimate that the plant of Fig. 3 can absorb from 30% to 45% of the incident wave energy of wind waves with H_s between 2 m and 7 m. On the same range of H_s, the plant of Fig. 4 is expected to absorb from 40%

to 55% of the incident wave energy. Moreover, one single caisson of the plant of Fig. 4 is expected to give an average electric power of 100, 250, and 500 kW, with H_s of, respectively, 2.8, 4.0, and 5.9 m. These figures are for wind waves and have been obtained with relationship (2) between T_p and H_s. Swells have some greater periods and produce more power, with increments possibly greater than 50%. A static analysis of the breakwater of Fig. 4 for a very strong sea state of 9 m H_s gives C_1=1.3, C_2=1.8 and q=380 kN/m^2 (C_1 and C_2 being the safety factors against sliding and overturning, on assuming a friction factor of 0.6, and q being the bearing pressure on the foundation).

Further research is necessary on the submerged breakwater and, especially, on the plant for converting wave energy into electric power. The results obtained so far encourage us to go on with this research because of the high capacity of absorbing wave energy which emerges from our calculations, and because of the confirmations from the first small scale field experiment. Moreover, submerged breakwaters like that of Fig. 3 seem valuable for the low environmental impact, and breakwaters like that of Fig. 4 should be able to protect a port with an efficiency greater than that of a conventional caisson breakwater, because of the wave energy absorption which reduces the overtopping discharge and the wave height before the breakwater.

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