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Experimental compressibility study on a Coaxial-Duct OWC

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Abstract—**This paper deals with the issues of scaling the air compressibility effects in OWCs. For this purpose, use was made of a coaxial-duct (CD) oscillating-water-column (OWC) wave energy converter (WEC) designed at Instituto Superior Técnico (IST). A small-scale model (1:100) of a fixed CD-OWC was built and tested at the wave flume of the Hydraulic Laboratory of IST. Two configurations were tested (i) one in which the air chamber is scaled as the submerged part of the structure (as in most experimental work), which does not allow the spring-like air compressibility effect to be adequately modelled, and (ii) by connecting the air chamber of the model to a rigid-walled air reservoir whose volume allows that effect to be adequately reproduced. It is important to remark that not much data are available from physical model testing with comparisons between results from procedures (i) and (ii). Results confirm the importance of studying the compressibility effects in physical model testing. This is rarely performed by developers due to the difficulties that arise when down-sizing the air chamber volume appropriately. These results represent a valuable source of data that evidences the need to better understand the phenomenon, and predict or simulate it in full-sized devices.**

Index Terms—**wave energy, oscillating-water-column, compressibility, coaxial-duct, physical modelling.**

I. Introduction

EXPERIMENTAL and theoretical investigations are required when studying wave energy converters (WECs). Physical testing may become prohibitively expensive at full-scale and, in general, is only feasible at small-scale. However, small-scale tests do not always simulate all features and performance of prototypes. Scaling issues may arise for these complex systems due to the impossibility to replicate all the geometric, kinematic and dynamic conditions of the prototype device simultaneously. Despite this, physical model testing at small-scale is necessary within WECs development pathways. In oscillating-water-columns (OWCs), appropriate scaling of the power take-off system (PTO) and of the spring-like air compressibility effect in the chamber involves special problems that are frequently ignored or tackled inadequately. The spring-like effect of air compressibility was studied theoretically for the first time in [1], where a simplified isentropic model was adopted. Another theoretical model that more realistically includes the effects the entropy variation was published in [2]. In physical model testing, the scaling of the air chamber using a "compressibility" similarity and not Froude similarity, as normally used, was probably implemented for the first time in [3], [4].

When designing WECs, there are always uncertainties that should be reduced. Starting form a large-scale design, many questions arise due to the impossibility to replicate all conditions in model testing. Questions may arise, such as: is it not possible to have all similarities achieved, in such a way that the results are adequately introduced into the large-scale design? or maybe should I consider the different scaling of the air chamber volume? and how would this affect testing campaign results when comparing to real full-scale performance? These questions are not easy to answer, and, although considerable work has been done to address these and other questions, the present situation may be regarded as an open problem.

The reader should be aware that two different situations should be considered. The first question concerns the design of a full-scale oscillating-water-column, which should involve the hydrodynamic optimisation, the air-chamber optimisation and the consequent PTO and control optimisation. These processes are complex and interlinked. Of course, there are other factors, such as moorings for station keeping, and devices interconnections, that should also be analyse in all real cases. The second issue concerns the need to perform physical model tests at small scale. This requires the geometric, kinematic and dynamic similarities between the full-sized device and its small-scale model to be adequately implemented. The research reported here addresses these issues.

This paper presents experimental results from the tests of a CD-OWC WEC at small-scale. Two different situations are compared: (i) when the same Froude scale is adopted for the part of the model subject to wave action and for the air chamber, and (ii) when the air chamber is scaled differently from the submerged part of the device in order to adequately model the aero-thermodynamic process in air.

This paper starts with a brief survey of physical modelling of WECs, especially on what concerns the compressibility effects in physical modelling of OWCS. This is followed by a description of the OWC-WEC used in the experimental work, and of the experimental set-up. Results are presented and analysed. The paper

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ends with the conclusions.

II. Model prototype similarity

Physical modelling of WECs is important to reduce the uncertainties of real device performance, and is an approach commonly used to reduce costs associated with the development of technologies. Models and full-scale designs should be similar in terms of geometry, kinematics and dynamics. This means there must be similarities (i) of the shape of the WEC and of the surrounding boundaries (geometrical similarities), (ii) of the velocities (of the flow field and of the body itself (kinematic similarity), and (iii) of forces (dynamic similarity).

Dynamic similarities implies that the ratio of representative forces be the same in both the model scale and the full scale. Most common dimensionless numbers associated to naval/ocean engineering physical modelling of devices and structures are the Froude number (Fr), the Reynolds number (Re). Fr represents the ratio between inertia and gravity forces; Re is the ratio between the inertia and viscous forces. There are other numbers as, for example, the Keulegan-Carpenter number, which can aid at identifying if a phenomenon is more drag or inertia dominated, giving orientations on the suitability of the mathematical models used and the respective assumptions, or the Weber number, which represents the ratio between inertia and surface tension forces, and the Mach's number that represents the ratio between the inertia and elastic fluid forces.

Froude and Reynolds numbers are defined as

$$\mathrm{Fr} = \frac{\text{Inertia forces}}{\text{Gravity forces}} = \frac{F_i}{F_g} \propto \frac{U}{\sqrt{gL}}, \tag{1}$$

$$\mathrm{Re} = \frac{\text{Inertia forces}}{\text{Viscous forces}} = \frac{F_i}{F_v} \propto \frac{\rho U L}{\mu}, \tag{2}$$

where, F_i represents the inertia forces, F_g the gravity forces, F_v the viscous forces, U is a characteristic velocity, L is a characteristic length, ρ is the fluid density, g is the gravitational acceleration and μ is the dynamic viscosity.

Oscillating-water-columns are complex technologies that involve a combination of physical systems. These systems make the coupling between hydrodynamics and aero-thermodynamics, which requires different scaling factors to completely represent physical processes at model scales. On the one hand, hydrodynamic forces associated to the influence of ocean waves, and, on the other hand, PTOs that affect overall dynamics, have both been challenging for engineers over decades.

A. *WEC full-scale to model similarity*

Regarding the study of the performance of a WEC through physical models, it is common to use Froude scaling for the submerged portion of the wave energy converter. It should be noted that, for a complete similarity, the equality of Re and Fr must be also ensured in both the model and the full-scale device. In order to achieve a complete similarity, it is necessary that

$$\mathrm{Fr_F} = \mathrm{Fr_M} = \frac{U_\mathrm{F}}{\sqrt{gL_\mathrm{F}}} = \frac{U_\mathrm{M}}{\sqrt{gL_\mathrm{M}}}, \tag{3}$$

and,

$$\mathrm{Re_F} = \mathrm{Re_M} = \frac{\rho_\mathrm{F} U_\mathrm{F} L_\mathrm{F}}{\mu_\mathrm{F}} = \frac{\rho_\mathrm{M} U_\mathrm{M} L_\mathrm{M}}{\mu_\mathrm{M}}, \tag{4}$$

where the subscript F represents full-scale and M represents model-scale. Inspecting in more detail these expressions, it is evident that, if the liquid has the same viscosity and density at both scales, the Reynolds number similarity would require $U_\mathrm{M} > U_\mathrm{F}$, while the Froude number similarity would require $U_\mathrm{F} > U_\mathrm{M}$, which is incompatible. Even if a liquid other than water (with a different viscosity) were to fill the wave tank, there would be, in practice, no available liquid capable of simultaneously satisfying the equality of Reynods number and Froude number, if the Froude scale is not close to unity.

Gravity is the restoring force of surface waves in the ocean. It being so, the equality of Froude number Fr in the model and the full-scale device ensures that wave resistance and other wave forces are scaled properly. On the other hand, the impossibility of ensuring equal Reynolds number Re results in relatively different viscous forces at both scales. Thus, it is expected that viscous forces are over-represented at model-scale as compared with full-scale.

B. *Compressibility effects in physical modelling of OWCs*

Oscillating-water-columns are particularly challenging to scale down in model testing. The fact of having an air chamber to convert the hydrodynamic forces into pneumatic forces, and then using as PTO an air turbine coupled to a generator, add additional complexities to the system.

Apart from the impossibility of simultaneously satisfying the equality of Fr and Re in both model and full-scale device, there is the need to scale down the air turbine and the air chamber that follow different scaling rules.

Depending on the model geometric scale, it might be unpractical to build a small air turbine complying with the geometric and dynamic similarities. In these cases, the turbine could be simulated by simpler devices, depending on the pressure-flow-rate relationship of the turbine. Approximately linear turbines, like Wells turbines, may be simulated by porous plugs, whereas orifices are frequently employed to simulate nearly quadratic turbines as is the case of radial- or axial-flow self-rectifying turbines of impulse type.

Compressibility of air in the chamber is known to be important. Consequently, a similarity condition for compressibility should be satisfied. The Froude similarity does not guarantee such a condition to be satisfied [5]. Consequently, different scales for the submerged part and for the non-submerged one must be used. Table I presents the scaling factors for some quantities in OWCs, including the air chamber volume. In the table $\lambda = L_\mathrm{F}/L_\mathrm{M}$ represents the ratio of characteristic lengths at full-scale and at model scale, and ρ_F

and ρ_M are the corresponding water densities (which are different is the tank is filled with fresh water).

The spring-like effect of air compressibility in the chamber is connected to the relationship between pressure and density of air. Here, as in [1], we assume that the process is approximately isentropic and that the amplitude of the pressure oscillation is small compared with the atmospheric pressure. In this case, for that effect to be adequately simulated at model scale, the ratio between the air chamber volume (in the absence of waves) in the model and in the full-sized device should be equal to $\lambda^2(\rho_F/\rho_M)$ (rather than λ^3). Scaling factors for the physical modelling of OWC converters are presented in Table I.

TABLE I
SCALING FACTORS FOR PHYSICAL MODELLING OF OWCS.

Physical parameter	Unit	Scaling factor	Scaling type
Length	[m]	λ	Froude
Time	[s]	$\lambda^{1/2}$	Froude
Mass	[kg]	$\lambda^3(\rho_F/\rho_M)$	Froude
Acceleration	[m/s^2]	$a_F = a_M$	Froude
Force	[N]	$\lambda^3(\rho_F/\rho_M)$	Froude
Moment	[Nm]	$\lambda^4(\rho_F/\rho_M)$	Froude
Power	[W]	$\lambda^{7/2}(\rho_F/\rho_M)$	Froude
Pressure	[Pa]	$\lambda(\rho_F/\rho_M)$	Froude
Air chamber volume	[m^3]	$\lambda^2(\rho_F/\rho_M)$	Compressibility

III. COAXIAL-DUCT OWC

The device used in this work to investigate the compressibility effect is a fixed coaxial-duct OWC, which is an axysymmetric device with two coaxial cylindrical walls. The inner wall is partially submerged and the outer one is totally submerged. A schematic representation of the device is shown in Fig. 1. The tube that is partially submerged is open at its bottom to allow the water flow in and out, and its upper top is open to the atmosphere. The totally submerged tube is closed at the bottom, and is open to the sea at the top. The system is equipped with an air turbine/generator set, located at the top of the inner duct, which constitutes the PTO.

C. *Experimental set-up*

The experimental phase of this study comprised the test of a fixed coaxial-duct OWC at 1:100th-scale [6]. The full-sized device has a characteristic diameter of 14 m, a draft of 33 m, and a total air chamber volume of 225 m^3. The experiment was designed to test three different air-chamber volumes. In a first case, the air-chamber volume is scaled down based on Froude similarity (no extra volume case). In the second case, the total air volume (including an additional air reservoir and the connecting duct) satisfies the appropriate aero-thermodynamic air compressibility similarity scaling (extra volume case). In the third case, an intermediate volume is adopted. It is 15% smaller than the required for the perfect simulation of the air compressibility, and it is identify as extra volume-15% case. Table II shows the comparison between full-scale and model scale characteristic dimension and total draft, as well

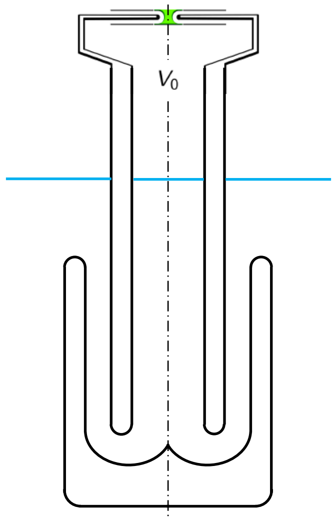


Fig. 1. Schematic representation of a Coaxial-Duct OWC.

as the volume scaled using Froude similarity and the compressibility similarity of the air chamber volume.

TABLE II
QUANTITIES OF INTEREST IN THE COMPARISON BETWEEN FULL-SCALE DESIGN AND PHYSICAL MODEL (SCALE 1:100).

Physical parameter	Unit	Full-scale	Model
Characteristic diameter (d)	[m]	12	0.12
Total draft (L)	[m]	33	0.33
Air chamber - no extra vol.	[m^3]	225	2.58×10^{-4}
Air chamber - extra volume	[m^3]	225	2.25×10^{-2}

The CD-OWC model was constructed in acrylic material with some metallic parts, as shown in Figure 2. In all cases, the turbine was emulated by an orifice of 19 mm diameter. The 0.7 m wide wave flume of the Laboratory of Hydraulics and Water Resources at IST, Lisbon, was used for the experiments. The water depth was 0.48 m. The model was placed at a distance about 7 m from the wave maker. At the end of the wave flume opposite to the wave maker, was located a breakwater. A schematic representation of the experimental set-up and some real pictures are shown in Figures 3 and 4.

Tests were performed under regular waves conditions for 15 mm of wave height at model-scale and frequencies of 0.2, 0.4, 0.6, 0.7, 0.8, 0.9, 1.0, 1.2, and 1.4 Hz. Resistive water-level gauges were used for the wave elevation and for the water column vertical displacement. Differential pressure sensors were employed to measure the pressure oscillation inside the air-chamber.

IV. RESULTS AND DISCUSSION

This section presents the results in terms of response amplitude operators (RAOs), capture widths, and pressure oscillations. This is followed by a brief discussion on the compressibility effect and the turbine induced damping.

D. *Response Amplitude Operator*

The curves of the Response Amplitude Operator (RAO) of the OWC are very similar for the three cases

Fig. 2. Physical model used in experiments (1:100th scale).

considered, as shown in Figure 5. Three zones can be identified. In the first one, for frequencies up to the natural frequency of the OWC, the RAOs are almost identical. In the second region, above the natural frequency, significant differences, up to 18.3% at 0.9 Hz, can be observed between the cases with no extra volume and with the extra volume. In the third region, for the higher frequencies, the RAOs exhibit only small differences. Figure 5 shows that the influence of air compressibility upon the RAO may be significant for frequencies about the resonance frequency of the device, but decays for frequencies away from that zone.

E. Capture width ratio

The capture width ratio, shown in Figure 6, is defined as

$$C_{\mathrm{w}} = \frac{\bar{P}_{\mathrm{exp}}}{\bar{P}_{\mathrm{w,exp}} d}. \tag{5}$$

Here, $\bar{P}_{\mathrm{exp}}$ is the time-averaged power output in [W] for given values of the wave height and wave frequency, $\bar{P}_{\mathrm{w,exp}}$ in [W/m] is the time-averaged incident wave power per unit crest length, and d is the characteristic diameter of the device in [m].

In contrast with the RAOs, the results show a substantial variation of C_{w}, as function of the volume of the air chamber, over the whole frequency range. The capture width ratio C_{w} of the case with no extra volume is the lowest at all frequencies. The converter with the full extra volume presents the highest C_{w}, except in the range between about 0.9 Hz and 1.0 Hz where it is slightly exceeded by the case with extra volume - 15%. Figure 6 shows that, at the peak of the C_{w} curve (0.8 Hz), the value of C_{w} is almost three times (more exactly 2.77 times) higher for the case with full extra volume as compared with the case without extra volume. This shows that large errors may be introduced if the air volume in the model is not correctly scaled down from the prototype in model testing.

In the present study, an arbitrary orifice diameter of 19 mm was selected for the three cases (“with no extra volume”, “with extra volume”, and “with extra volume-15%”). This orifice diameter was not optimized for any of the three volumes. Had the damping provided by the orifice been optimized for each of the volumes, larger differences between the performances, in terms of capture width ratios, between the cases without and with additional volume could be expected. This trend should be particularly interesting if the full-scale design had an optimised air-chamber volume.

F. Pressure oscillations within the air chamber

Measured air pressure oscillations as well as water surface elevations in front of the device and inside the chamber are plotted in Figure 7 over a sample time interval of 20 s, for three different frequencies (at model scale): 0.6, 0.8 and 1.0 Hz, and for the case with no extra volume and the case with extra volume. The figure shows that, independently of the frequency, the air pressure amplitude is larger for the added-volume situation compared with the no-extra-volume case. For frequencies 0.6 Hz (below resonance) and 1.0 Hz (above resonance) the ratio is about 4, and is about 2 close to the resonance frequency (0.8 Hz).

Figure 8 shows the volume flow rate of air, the pressure oscillation and the pressure time-derivative for the same time interval and the same six cases as in Figure 7. It can be seen that, for 0.6 Hz and 1.0 Hz, the volume flow rate is around twice higher for the case with extra volume as compared with the case with no extra volume.

G. Compressibility and air chamber damping

The spring-like effect of air compressibility in the chamber is related to the pressure-density relationship, and increases with chamber volume. When the air chamber volume is increased, the extra volume has an effect on the damping produced by the air-chamber-turbine set; in particular, the air spring becomes less stiff, [3], [5], [7], [8]. This spring-like effect introduces a phase difference between the air pressure oscillation and the flow rate displaced by the motion of the inner free-surface. This appears as an effect of reactive power: during a fraction of the wave cycle, the work done by the OWC motion on the air above is negative (i.e. energy is supplied to the waves rather than absorbed from them). This reactive effect decreases (and in the limit vanishes) as the air chamber volume decreases.

It should be noted that, in the experiments, the diameter of the orifice simulating the turbine-induced damping was not optimized. Naturally, the air turbine (especially the damping it induces) should be optimized depending on the volume of the air chamber, and obviously also on the wave climate and on the device geometry [8].

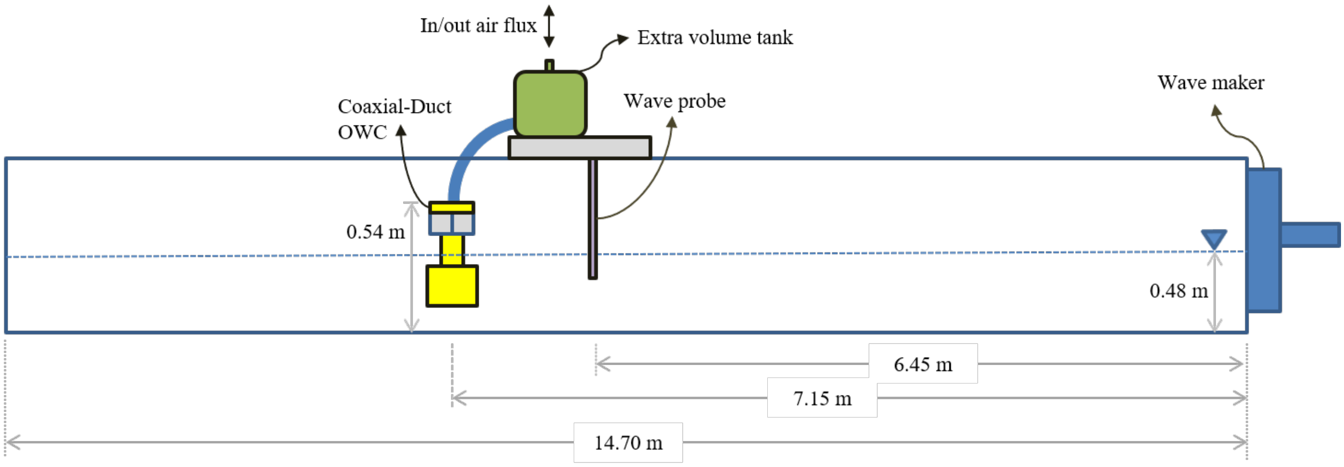
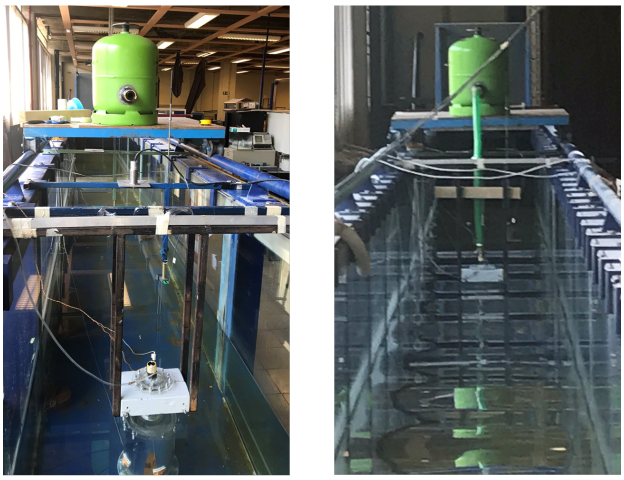


Fig. 3. Schematic representation of the experimental setting.



(a) (b)

Fig. 4. Real pictures of the experimental setting of a fixed CD-OWC for a) without extra volume added, and b) with extra volume to account for compressibility effect (1:100 scale).

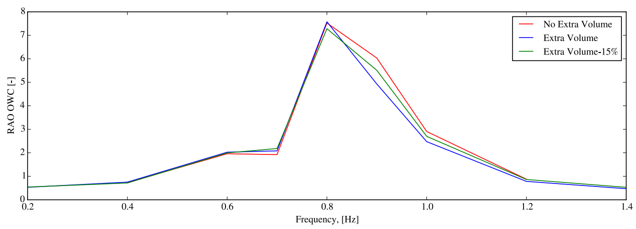


Fig. 5. RAO of OWC for the three cases tested (1:100th scale).

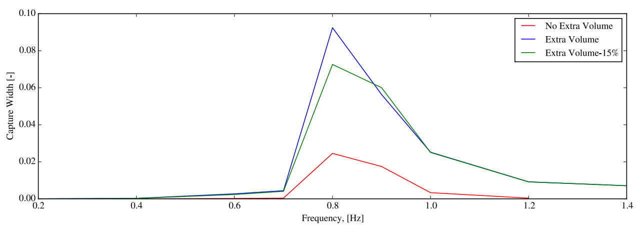


Fig. 6. Dimensionless capture width ratio for the three cases tested (1:100th scale).

In most OWC converter situations, the increase in air chamber volume produces a reduction in capture width. However, this is not a general rule, as shown in [9]. This is specially the case here, as may be seen in Figure 6 close to the resonance frequency: the capture width increases with chamber volume. Obviously, this trend must have limitations: the capture width cannot increase indefinitely with increasing chamber volume, as shown in [9].

V. Conclusions

This paper is based on experimental work on a 1:100th-scale model of a fixed coaxial-duct OWC, carried out at the wave flume of IST. The tests, with regular waves, were performed with three different volumes of air chamber: the smallest one corresponds to the Froude scale being applied to the air chamber, while the largest volume exactly reproduces at model scale the spring-like effect in the full-sized prototype. The size of the orifice that, in the model tests, simulated the turbine, was fixed and not optimized; this means that better performance results should have been expected with optimized orifices.

The results show that the volume of the air chamber affects the RAO up to about 20%. However, the influence is much more marked on the capture width, which, close to the resonance frequency, was found to increase by a factor equal to about 2.8 when the performance with the smallest chamber volume is compared with the performance with the largest volume. This behaviour is uncommon in OWC converters, and shows that the model-tested coaxial-duct OWC exhibits some characteristics that are different from most OWC converters. It is known that, in most cases reported in the literature, OWC model testing has been performed with the model chamber scaled-down as the part of the converter subject to wave action (Froude scale). The results reported here show that, had this procedure been adopted in our case, the model test results extrapolated to full-size would have been a gross misrepresentation of the device performance.

It should be noted that the tests were performed with the device model fixed, to facilitate the connection to

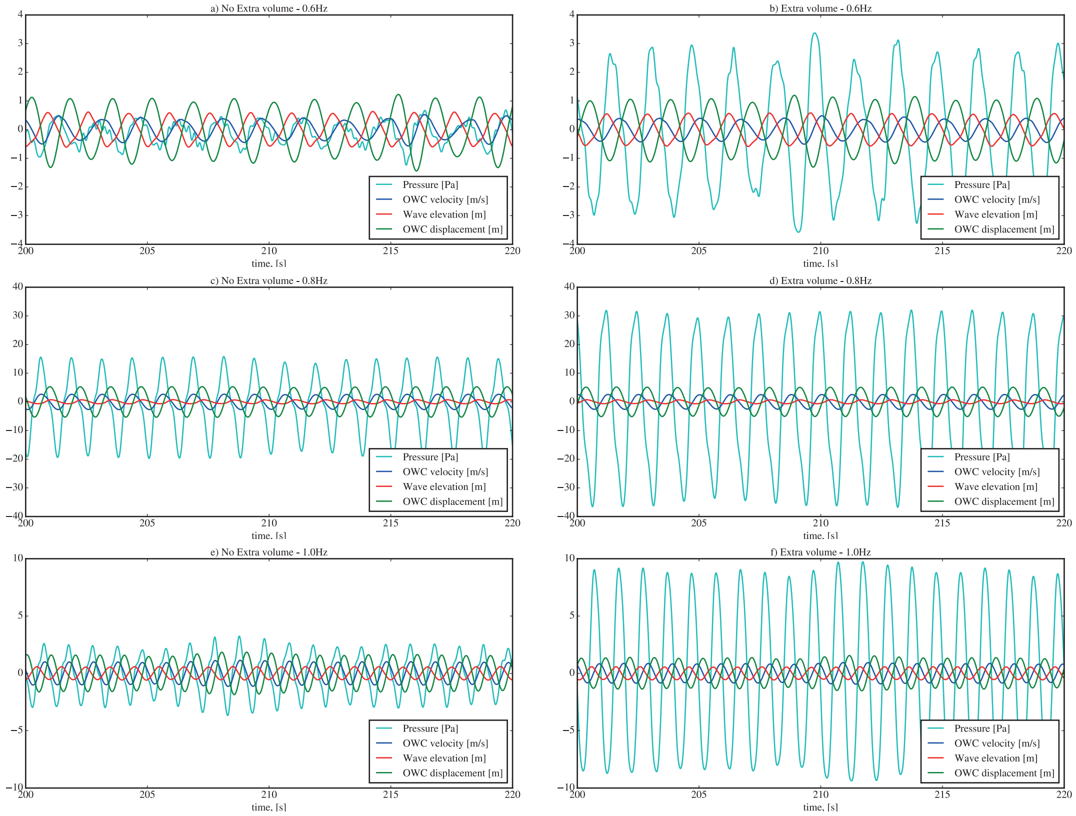


Fig. 7. Sample time series of pressure oscillation, OWC velocity, incident wave elevation and OWC displacement for: a) case without extra volume for 0.6 Hz; b) case with extra volume for 0.6 Hz; c) case without extra volume for 0.8 Hz; d) case with extra volume for 0.8 Hz; e) case without extra volume for 1.0 Hz; f) case with extra volume for 1.0 Hz (1:100th scale).

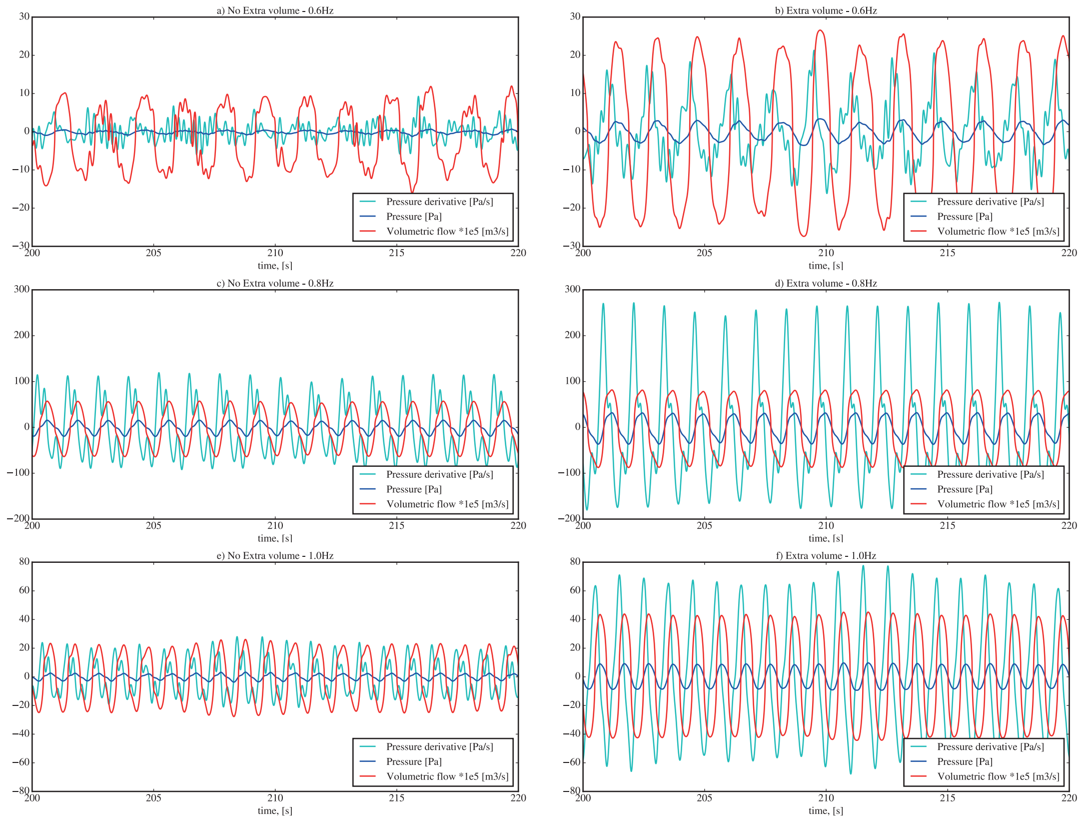


Fig. 8. Sample time series of pressure time-derivative and pressure oscillation in the air chamber, and of volume air rate through the 19 mm-diameter orifice for: a) case without extra volume for 0.6 Hz; b) case with extra volume for 0.6 Hz; c) case without extra volume for 0.8 Hz; d) case with extra volume for 0.8 Hz; e) case without extra volume for 1.0 Hz; f) case with extra volume for 1.0 Hz (1:100th scale).

the additional air reservoir. This is different from the full-sized converter that is planned to be a floating OWC. Note however that, since the water-plane area of the CD-OWC (i.e. the cross sectional wall-area of the inner duct) is quite small, the device behaves as a semi-submersible platform whose resonance frequency in heave is expected to be much smaller that the representative wave frequency. For this reason, the oscillation amplitude of the CD-OWC structure is quite small (as could be observed in the flume with the structure free to oscillate): the wave energy absorption is expected to result from the oscillation of the water inside the ducts rather than from the oscillation of the structure. For this reason, the adoption of the fixed structure in the model tests is likely not to drastically affect the realism of the results.

Future work will focus on more extensive experimental campaigns and validation of numerical modelling results.

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