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Laboratory Scaling of the Free-Decay of an Oscillating Vertical-Axis Underwater Cylinder

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Abstract

In order to extract the energy delivered by ocean waves, efficient energy converters must be engineered. This means that they must operate at resonance with the predominant wave frequency.

The behaviour of the converters in the waves is strongly tied to the damping caused by the fluid (ocean) around them. Thus, properly understanding this damping phenomenon is critical in order to tune the converters to the required wave frequency.

In common practice, these machines are designed/tested as laboratory models which are later scaled up. In order to properly anticipate full-scale behaviour, the scaling laws (especially when it comes to damping) need to be finely determined.

For this reason, free-decay experiments have been conducted in a water tank 1.3 m deep, in which wavelengths were sufficiently short to replicate deep water conditions. Cylindrical floating bodies (modelling a point-absorber wave converter) with a length of 0.35 m and respective diameters of 0.028, 0.034, 0.043, 0.048, 0.062 m were used to mimic the energy extraction devices. These cylinders were made of PVC with an approximate absolute surface roughness coefficient of 0.0015 mm. To resemble the classic “mass-spring” system frequently used in the literature and by some companies operating full-scale wave-power machines, the cylinders were connected to a spring. They were submerged at different depths and displaced vertically. Then, the free-decay of the systems was recorded using an image processing technique from a video camera. The amplitudes of the initial displacements were 0.02, 0.03, 0.04, 0.05 m and the experiments were repeated approximately 30 times for each case. Finally, the decay rates were extracted from the curves.

The results show the expected correlation between the variation of the total damping and the respective change in diameter. However, the different damping curves suggest that, for certain regimes and diameter changes, the onset of turbulence has an influence which can prove problematic when scaling up from laboratory models of wave energy machines to real size devices.

Introduction

Ocean waves provide significant renewable energy. In Australia, for example, between Western Australia and the southern tip of Tasmania, ocean waves deliver energy about four times greater than the requirements of the whole country. Several wave-power machines aimed at harnessing this energy are proposed or under full-scale trials around Australia and the rest of the world [1].

Most wave-power converters (WECs) are designed to have a natural frequency of free oscillation matching the average local ocean wave frequency. When these frequencies match, they resonate and the converters extract maximum power from the waves [2]. However, the maximum power extracted is critically dependent on the damping of the machine’s motion, to which several fluid-dynamical phenomena contribute. At present, machine design relies on laboratory scale experiments.

The research presented here was generally aimed at clarifying the scaling relations between the hydrodynamic damping experienced by these machines and their characteristic geometry. The existence of a reciprocating regime, in which there is zero mean flow, and the consequent periodic onset of turbulence during the cyclic motion presents challenges to conventional fluid-dynamical scaling assumptions. Another goal aim was to go one step further, to break down the damping term into turbulent and viscous damping components and to analyse each of their respective contributions.

The equation of motion for a point-absorber energy converter (a buoyant cylinder attached to a power extraction unit) takes the following form [3]:

$$(m + \mathrm{A}(\omega_0))\ddot{Z} + B(\omega_0)\dot{Z} + \rho g S Z = f_{ex}(\omega_A) + f_{PTO} + f_d, \quad (1)$$

where m is the mass of the device, $A(\omega_0)$ is the added mass, $B(\omega_0)$ the radiation damping coefficient, ω_0 is the natural frequency of the system, $\rho g S Z$ the buoyancy, $f_{ex}(\omega_A)$ the driving force (energy coming from the waves), ω_A the frequency of the waves, f_{PTO} the power take off (absorption) force and f_d the drag force. The vertical/heave axis is represented by OZ. From this equation, it can be seen that the variation of the overall damping (and individual damping components) has a strong impact on the behaviour of the system. This variation needs to be correctly predicted as the geometric characteristics of the system are changed. One main parameter that is usually changed when it comes to point-absorber applications is the diameter of the cylinder [6]. Moreover, when laboratory scale-testing point-absorbers, the diameter is at least an order of magnitude smaller, and the scaling of the damping with diameter is therefore of interest.

In more detail, the experiment presented in this paper was firstly meant to investigate if there is any direct linear or non-linear relation between the variation of the main parameter of a cylindrical point-absorber –the diameter- and the variation of the damping forces acting upon it. Secondly, it was aimed to show the significance of submergence depth, displacement amplitude and other parameters on the damping experienced by the device. Thirdly, illustrate the respective contributions of different damping components (radiation, viscosity, turbulence etc).

Compared to the existing literature [4,7], this experiment had the novelty of being carried out in transitional or turbulent flow; of employing the natural restoration force of a buoy –thus being a free decay test- and of making it possible to ignore issues such as variable added mass (by having the cylinder completely submerged) and the irregularity of ocean conditions (by operating in still-water conditions).

The basic principle of the experiment was to displace the submerged model of the point-absorber a certain distance from the 0 reference point and then record its free decay until it became stationary, under the effect of a restoring force (simulated by using a spring). This was repeated as different parameters were varied.

Experimental Setup

A) The point-absorber system

The energy converter bodies were modelled by using PVC pipe closed at both ends. The tubes chosen had an approximate absolute surface roughness coefficient of 0.0015 mm.

Five different diameter models were used in the experiment, 0.028; 0.034; 0.043; 0.048 and 0.062 m, while the length was kept constant, 0.35 m.

The power take off was simulated by using a spring combined with the fluid damping. The spring had its constant experimentally determined, after the gradient of the force versus deflection curve was drawn. To check the results, two different springs were used.

The converter's body and power take off were fixed to the bottom by a non-flexible braided line.

The rough sketch of the general assembly is seen in figure 1.

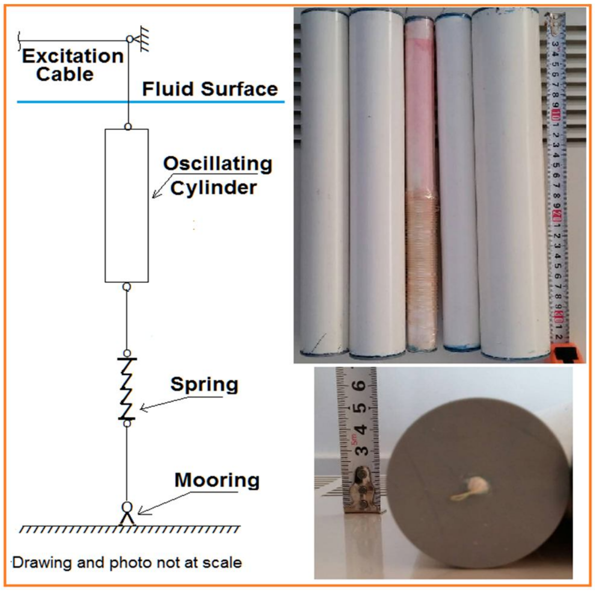

Figure 1. Point-absorber system.

B) The tank

A commercially available 6.71 x 3.66 x 1.32 m water tank was sourced. It was made out of a flexible lining suspended on a steel frame. The tank was filled with water, 0.8 m deep, this meaning that the wavelengths were small enough for the experiment to have a ratio of wavelength to depth of more than 0.5 – thus simulating the deep water regime of classical Airy wave theory.

C) Measurement equipment

A Sony HDR-AS15 waterproof action camera, being able to shoot 720p video at 120 frames per second, was used. The videos were translated into numerical measurement by a video analysis and modelling software – Tracker 4.83.

D) Overall setup

The point-absorber system was fixed in the middle of the tank, 1.83 m from the closest edges. This assured that the data could be recorded before the effect of tank wall reflection influenced the experiment. The model converter was allowed to oscillate naturally as any constraint would have resulted in some energy being lost due to guiding-mechanism friction etc. There were no structures inside the water that would influence the experiment.

For each video the measurement system was calibrated and the relative still water conditions were checked by looking at the background-wave "noise" in the videos, as seen in figure 2.

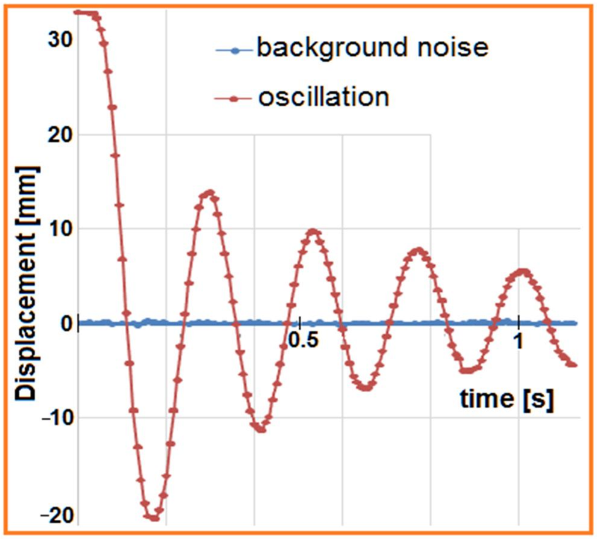

Figure 2. Background noise vs. experiment oscillation.

Experimental Conditions and Procedure

The parameters that were changed over the course of the series of experiments were the

- cylinder diameters (0.028; 0.034; 0.043; 0.048; 0.062 m),
- cylinder submergence depths (0.02; 0.03; 0.04; 0.05 m),
- initial displacements (0.02; 0.03; 0.04; 0.05 m),
- PTO response (2 different springs).

The experiment was performed as follows:

1. A given system –specific body diameter and spring – was submerged to a fixed depth of 0.05 m from the surface –maintained for all sub-experiments until point 7. Then, the system was excited with a given amplitude and the movement was recorded;
2. After the still water state was reached, the excitation amplitude was changed and the experiment repeated. This was done until the desired amplitude range (0.02 to 0.05 m with a 0.01 m step) was exhausted;
3. The buoy model was replaced with one of a different diameter;
4. Steps 1, 2 were repeated;
5. The buoy body was reset to the one used in step 1 and the spring was replaced;
6. Steps 1, 2, 3, 4 were repeated;
7. The buoy body and the spring were reset to the ones in step 1. This time the buoys were submerged at a different depth through the submergence depth range (0.02 to 0.05 m with a 0.01 m step);
8. Steps 1-6 were repeated for certain amplitudes.

Preliminary Results

Firstly, going back to figure 2, the decay of a single system (in this case a diameter of 28 mm, displaced by 40 mm from an initial location situated at 50 mm submergence), can be seen.

The particle Reynolds number for this system is: $Re_p = 1.6x10^4$. This was calculated as the cylinder moved in a single direction in the fluid at maximum speed, not for the overall oscillatory motion. The approximate maximum velocity of the 28 mm diameter body was around 0.45 m/s, occurring at the start of the first oscillation, dropping down to about 0.073 m/s for the oscillation prior to coming to a stop. In comparison, for the large diameter system (62 mm), the maximum velocity was approximately 0.29 m/s, dropping down to 0.03 m/s.

Secondly, in figure 3, the free decay of different diameter systems can be observed under the same conditions for each diameter (40 mm initial displacement, 50 mm submergence depth and spring 1).

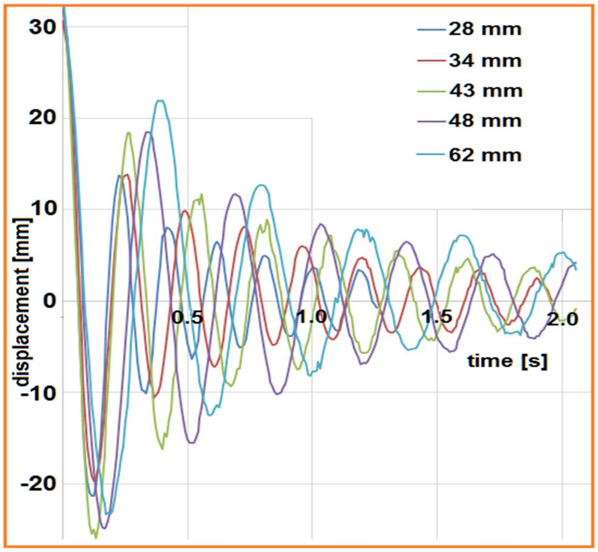

Figure 3. Different diameters under the same conditions (40 mm initial displacement, 50 mm submergence depth and spring 1).

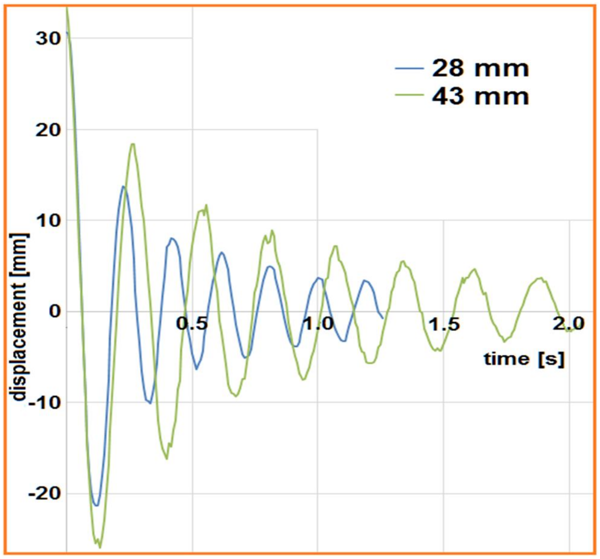

Figure 4. Different diameters under the same conditions (40 mm initial displacement, 50 mm submergence depth and spring 1); diameter change of 15 mm.

A more detailed look is shown in the following graphs (figures 4-7), in which the diameter was progressively increased (the figures to be compared side by side have the same vertical size). From these figures it can be seen that even if the change in diameter was approximately constant (with a maximum deviation of 1/28), the implied variation of the damping experienced by the systems was not constant.

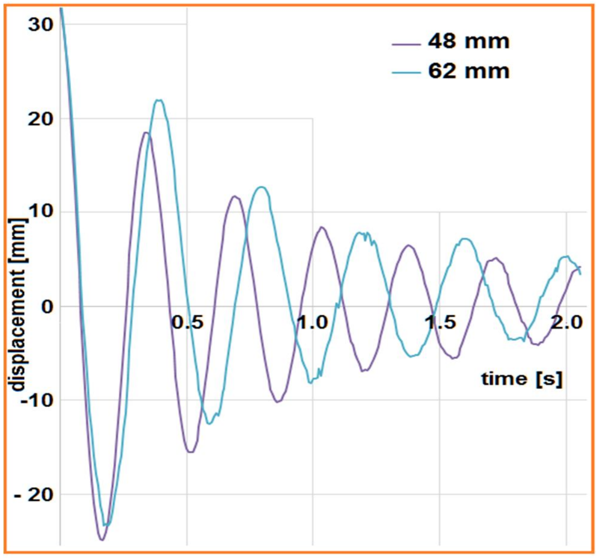

Figure 5. Different diameters under the same conditions (40 mm initial displacement, 50 mm submergence depth and spring 1); diameter change of 14 mm.

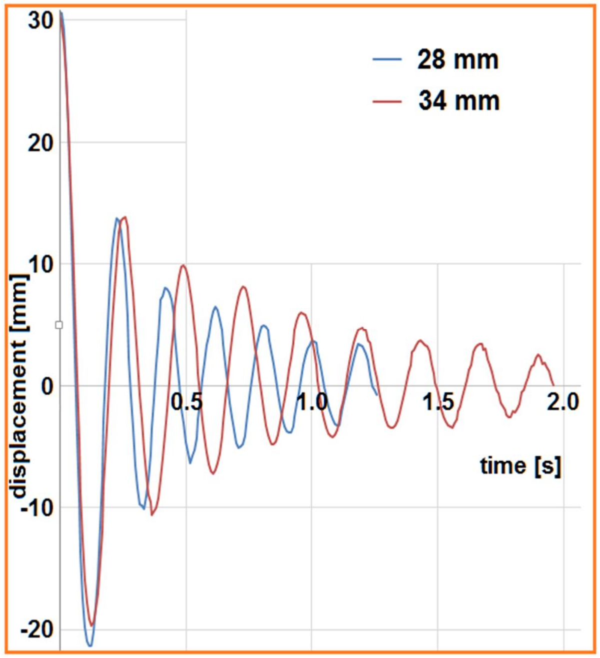

Figure 6. Different diameters under the same conditions (40 mm initial displacement, 50 mm submergence depth and spring 1); diameter change of 6 mm.

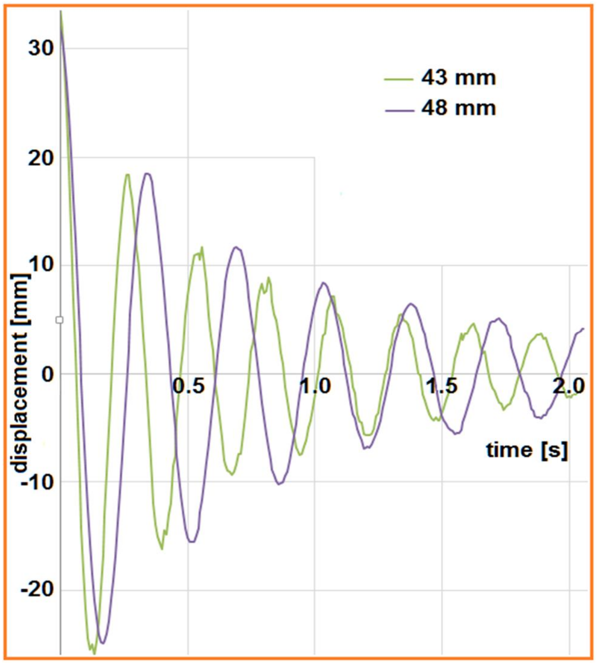

Figure 7. Different diameters under the same conditions (40 mm initial displacement, 50 mm submergence depth and spring 1); diameter change of 5 mm.

The same inconsistent variation in damping versus variation in diameter can be noticed when drawing the decay curves, as seen in figure 8. It can be observed (by comparing the equations of the curves) that the distance between the decay curves enveloping similar changes in diameter (as mentioned in the previous paragraphs) is not constant from one case to another. Thus, the overall effect of the damping components from equation (1) is not linearly tied to the change in diameter.

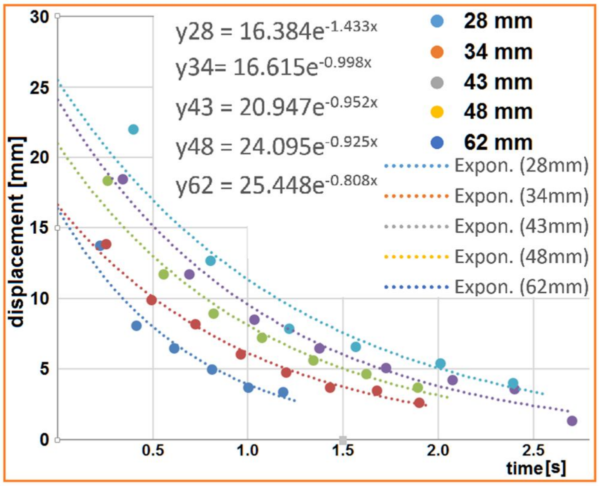

Figure 8. Decay curves for different diameters under the same conditions (40 mm initial displacement, 50 mm submergence depth and spring 1).

Even with a generous margin of error for the equation exponents estimated to +/- 0.1, the difference between the curves is obvious. Thus, for a 6 mm change in diameter (28 mm and 34 mm cylinders) the exponent difference is 0.435, while between the curves representing a 5 mm change in diameter (43 mm and 48 mm cylinders) the difference is 0.027. The same is valid when comparing a 15 mm and a 14 mm change in diameter: for the 28, 43 mm cylinders and the 48, 62 or 34, 48 mm cylinders. The difference between exponents is 0.481 and 0.117, 0.073 respectively. As a side-note, curves with a difference in coefficients of 8 and a 0.09 difference in exponents (these being the maximum differences between similar curve equations) can be approximated to being identical for this experiment.

Discussion

Preliminary results show a close relation between the change in overall fluid damping on an energy converter's body and the change in diameter of the point-absorber (cylinder), as expected.

However, the change in diameter and the change in damping are not linearly connected. Thus, under the same conditions the same change in diameter might yield different changes in the damping experienced by the system. This is mainly caused by the fact that different diameter systems travel at different velocities, even if the external and excitation conditions are the same, as the restoration force from the spring is constant, while larger diameter bodies experience greater damping. Thus, the proportion between viscous and inertial forces is changed as the regime changes between laminar and transitional/turbulent. Furthermore, the alternation between flow directions, which is specific to oscillatory conditions, leads to flow separation and the formation of vortices, especially before and during the change of direction. The effect of these vortices on the drag on the body need not scale linearly with diameter. This adds to the complexity which would normally be presented in the case of a uni-directional, turbulent/transitional flow [5].

Conclusions

In the light of these findings, it can be assumed that the scaling laws from laboratory models to real ocean devices are complex and not identical for specific variations in diameter. Future work on experimental data interpretation will outline the variation of each individual damping components from equation (1).

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