Numerical assessment of negative spring on spar OWC based in the IVV method

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Abstract

Wave power is largely unpredictable. The fact that the energy output of Wave Energy Converters (WECs) depends on the match between wave frequency and natural frequency of the system makes the adaptability one of the main issues of this technology. The negative spring concept is proposed as a possible solution, providing a shift in the resonance frequency that can be regulated depending on the sea state conditions. This study concerns a negative spring implementation using the Immersed Variable Volume (IVV) on a Spar Buoy WEC. The system was modelled both analytically and numerically, in the latter case with the use of WAMIT and MATLAB programs. The goal was to understand how interesting the effect of the IVV method could be. The study was applied to two different cases: single WEC and an array of devices. Constraints in the method were found and discussed and feasibility considerations were provided.

Keywords: Negative Spring - Resonance Frequency - OWC - Renewable Energy - Wave Energy

1 Introduction

This work has been carried out during an internship at WavEC, Lisbon, Portugal and it covers a part of the WETFEET project, funded by Horizon 2020 and coordinated by WavEC, with the goal of propose technological innovations to improve the overall performance of wave energy technologies. This study regards the technological innovation of the negative spring concept via the Immersed Variable Volume (IVV) method, aiming to evaluate the potential of improving an already existing wave energy device, the Oscillating Water Column (OWC). The expected improvements of the negative spring concept consist in a wider spectrum of the Response Amplitude Operator (RAO), but also a shift of the resonance frequency; the focus of the work was addressed on the latter. The IVV method is implemented on a floating OWC, namely a Spar Buoy. The influence of the IVV negative spring was considered for an isolated single WEC and for the case of an array of multiple WECs.

The problem was approached according to the following steps:

- Mathematical formulation with development of the analytical model
- Identification of a reference geometry
- Computation of hydrodynamic coefficients using the software WAMIT
- Numerical model implementation in MATLAB

- analysis of numerical model results

The approach was the same for both single WEC and array cases.

2 State of the art

Studies in wave energy began in Japan in 1940s with the figure of Yoshio Masuda, but the global interest in this field came after the oil crisis in 1973 and Europe started to run several research programs. Until the 1990s the work carried out in Europe had been mainly academic, however it was fundamental to build a basic common knowledge about this very complex topic.

The technology is still at a relatively early stage because of various reasons; among them, model testing in wave basin is expensive and time-consuming, final stage prototypes have to be full-scale devices in order to correctly match with the wavelength and also the maintenance has to face harsh conditions. For these reasons wave technology has not reached yet a level of maturation such to allow the identification of the best design and the number of different prototypes keeps increasing.

Among the various methods to classify WECs, according to the working principle the three identified categories are oscillating water column, oscillating body and overtopping devices. This work only focuses on the first type mentioned.

The first OWCs successfully developed from the 1990s were fixed onshore structures, with the Pico plant, in Azores, Portugal, probably being the most famous example. These fixed OWCs were considered as demonstration prototypes because of the easy access on foot and the special condition at their location, difficult to replicate elsewhere; for this reason they have also been used as experimental infrastructures. A possible strategy to decrease the costs of design and construction was to consider the integration of the OWC plant in a breakwater. OWC can also be floating structures: since the early days of wave energy conversion the two main exponents of this category are the Backward Bent Duct Buoy (BBDB) and the axisymmetric floating OWC, also called Spar Buoy, which consists in a relatively long vertical tube, open at both ends and attached to a floater. Thanks to its simplicity the OWC spar-buoy is considered to be the lowest risk and most economic option for further development. A new design of floating OWC presents the water column not connected to the outer sea water, but rather enclosed in the floating structure; an example of this technology is the U-Gen prototype. The advantage of this design is having the air turbine protected from the corrosive and mechanical effects of sea water.

For both fixed and floater structures devices with multiple OWC have been studied and prototyped.

3 Linear mathematical formulation of the WEC

The IVV method studied in this work is conceived to be applied on the Spar Buoy WEC. For simplicity, it was assumed all degrees of freedom were negligible except for the heaving mode.

The equation of motion was defined under the assumption of linear wave theory, with irrotational and unviscous fluid, thanks to which the analysis could be developed in the frequency domain. The linearity of the model allows to decompose the forces acting upon the device in different terms; by doing that the equation of motion of a linear WEC, without considering PTO and moorings, presents the following form.

$$z\left[-\omega^2\left(m+A\right)+\rho g S+i\omega B\right]=F_e \tag{1}$$

Where z is the vertical displacement, ω the wave frequency, m the mass of the device, A the added mass, ρ the water density, g the acceleration of gravity, S the cross area of the device at sea surface, B the damping coefficient and F_e the exitation force. The terms on left hand side of the equation which are multiplied for the vertical displacement represent the total impedance of the system.

By considering that the system reaches resonance when the real part of the total impedance is null, the formula of the peak frequency was found obtained from the equation of motion and a general negative spring term was identified.

$$\omega_0=\sqrt{\frac{\rho g S}{m+A}} \tag{2}$$

4 IVV concept

The negative spring concept considered in this study is the method of the Immersed Variable Volume (IVV), proposed by Prof. Antonio Sarmento and developed at WavEC.

It consists in a volume of air located underwater and connected to the WEC. The air is located inside a chamber open on the bottom: as the OWC main body and the internal water surface heave, a relative motion between them may arise, thus changing the immersed volume. Hence, the restoring force of the main body changes accordingly with the immersed volume variation.

The negative spring effect is given by the compressibility of air and related to the difference in pressure between the outside and the inside of the air chamber. By regulating the dimensions of the air volume with several chambers in series and valves, the IVV method allows to control the Response Amplitude Operator (RAO) of the device by shifting the resonance frequency to a lower value. Thanks to this effect it is possible to adapt the response to different sea states, and so to exploit the resource at best.

5 Single WEC analysis

The dynamics of a complete IVV integrated device was then modelled both analytically and numerically with the use of the software Wamit and Matlab. The WEC has been modeled using the piston mode description of the OWC, which assumes the free surface inside the chamber as flat and moving just in one degree of freedom: heave. With this approximation it is possible to consider the equations of motion of the two internal water surfaces as for rigid bodies. Therefore, there are three equations of motion, for the floater structure, the central water column, and bottom chamber water free surface.

Analytical investigation has been carried out in order to find out the adequate air volume of the bottom chamber which would lead to the required negative spring effect. For a simpler approach, this analysis started by assuming a cylinder open in its bottom and closed on the top, partially filled with air, representing the air chamber whose volume is expected to vary. The formula of the net vertical force on the cylinder describes the negative spring force in the system of equations of motion. It is the difference between the external and internal pressures acting on the top of the cylinder. Compressions and expansions of the air inside the chamber are considered to be isentropic. A relation between the net force and the air volume of the chamber was found. By introducing the term relative to the net force in to the resonance frequency formula, the new peak frequency was found. The shift in peak frequency was defined as the ratio between the new peak frequency and the frequency without negative spring term.

As a result of the explained procedure, the shift in frequency was represented as a function of the air volume, which was one of the objectives of the study. The function has an asymptote for frequencies equal to $\sqrt{1-\frac{S_b}{S_f}}$. T asymptote separates positive volume values from negative ones.
The physical interpretation of this behavior is that the bigger gets the air volume, the more compressible is the air and so the less the structure and water surface are affected by the air pressure. For an infinite air volume there is no change in pressure at all and the effect of the negative spring appear as above. This is an ideal situation where as a result of a decrease in volume due to a change in the vertical position of the body, the pressure does not increase. To pass this limit means to be in conditions where the air would react to compression by decreasing its pressure, which is a behavior whithout physical meaning: this justify the negative volume passed the asymptote. Another result is that if $S_b = S_f$ the asymptote occurs for shift ratio equal to 0, and for $S_b > S_f$ the asymptote is located in the negative part of the x axes. In these situations the shift in peak frequency does not present any physical constraint, differently than when the top floater cross area is larger than the bottom chamber one.

The model was implemented numerically using hydrodynamic coefficients computed with the software WAMIT. It is a radiation/diffraction panel program developed by the Massachusetts Institute of Technology for the analysis of the interaction of surface waves with various types of floating and submerged structures.

6 WAMIT

Wamit is a boundary element method code, a three-dimensional radiation-diffraction panel models based on the linear water wave theory and potential flow. It consists of two subprograms which are run in sequence. Among the inputs it requires there is the geometric data, the potential control and the force control files. The outputs used for the model implementation were the added mass, hydrodynamic damping and the excitation force coefficients.
The geometry used in WAMIT during the tests is depicted in fig. 1. It consists of a top floater, a vertical central tube of the oscillating water column, and the bottom chamber assembled around the tube. Both the central tube and the bottom chamber are open below to the fluid domain. In this reference geometry the three rigidly connected components are defined as vertical cylinders, with different radii and heights.

Figure 1: open bottom design

The new OWC geometry was first tested with bottom chamber closed below: in this case there is no negative spring effect as there is no volume variation. These configuration was used to find a geometry dataset to be used as new reference. A frequency range was taken from a real scatter diagram. Then, a tuning process was carried out by sensitivity analysis of the geometry of the WEC, in order to have it resonating at the highest frequency of the selected range. The same geometry was then tested with the bottom chamber open below: this is the case where there is an extra heaving free surface, which brings along a sinusoidal pressure variation and so the negative spring force. The results of the simulation were then compared with the closed chamber case in order to define the effects of the IVV implementation. WAMIT outputs were used to implement the numerical model, based on the analytical formulation. The code procedure is as follows:

1. Reading of Wamit output files to obtain hydrodynamic coefficients
2. Re-arrangement of WAMIT datasets in matrices
3. Generation of inertia and hydrostatic matrices
4. Solution of the equations of motion.

The results obtained with the numerical approach matched the analytical model. It was concluded that, to obtain an interesting shift in the resonance frequency through the IVV method, the necessary volume of the bottom chamber was too large, compared with the size of the device itself. Therefore, the method results unfeasible for a single WEC, since it represents a disproportionate increase in the costs.

7 Array

A possible solution to overcome the aforementioned volume problem is to consider a common air volume shared by multiple devices: each bottom chamber can be connected through a pipe to an extra air container. The container can then provide the necessary large volume to match the frequency shift requirements. Hence, the cost of the extra volume is divided by all devices of the array. Furthermore, the extra structure can be designed in such a way so it can be part of the mooring system.
The IVV method was then studied considering its implementation in devices arranged in array, each of them connected to a common air volume. The behavior of a device within the array is different from the single WEC case; in fact the common volume connects every WEC between each other. This means that the immersed volume variation of a given device depends on the heaving motion of every device and every bottom chamber internal free surface, since the air pressure is the same in every individual chamber. It is assumed that the air can flow between the chambers and the extra common

structure instantaneously. The combination between the wavelength and the location of the various WECs in the array might lead to a difference in phase of the respective heave motions.
$f(t) = \sum_{n=1}^{N} \sin(\omega t + kx_n)$ is the element which introduces the difference between the model of a single WEC and an array. Being the study in the frequency domain the time dependence of the function was not considered, but rather its maximum value which consists in the complex amplitude, called f_{max}. The negative spring force was then defined taking into account this new term and equally to the single WEC case, a relation between air volume and peak frequency shift was found and asymptote identified for the same conditions depending to the ratio between the cross areas of bottom chamber and top floater. In the array model the asymptote is reached not only for infinite volume but also for f_{max} equal to zero.
The numerical modeling of the array was carried out for a specific example of 4 WECs located 30 meters far from each other along the wave direction. The common air volume was considered to be underneath the devices and with a cylindrical shape. The relation between the chamber volume and the corresponding resonance frequency change was obtained numerically, solving the equations of motion for a wide range of volumes. The numerical results were compared with the analytical ones, showing a good matching.

8 Conclusions

The IVV method consists in equipping an OWC with an air chamber located on the bottom of the structure. Being the chamber open below and the air compressible, the air volume variates along the heave motion of the WEC.
This variation generates a force which acts in the opposite direction of the hydrostatic restoring force, that is, it acts as a negative spring. The effect of the IVV force on the system dynamics is to change the resonance conditions, bringing the resonance frequency towards lower values. By controlling the volume of the bottom air chamber it is therefore possible to control the system resonance and improve its adaptability to various sea states.
The system was modeled both analytically and numerically. For the considered geometry it was found that, in order to have an interesting change in the resonance frequency, the required volume of the bottom chamber was very large. This would represent an increase in the global cost, that is not balanced by the positve effect of the IVV method. The reason is that the key factor for the IVV negative spring effectiveness is the compressibility of air, and with small volumes the air behaves almost as an incompressible fluid. The effect of compressibility becomes tangible with very large volumes, that are not worth to be equipped on a single device.
The analysis was then carried out for the case of arrays, with the goal to overcome the problem of the necessary large volume. In fact the array solution allows to consider a large volume common for all devices and connected to each bottom chamber through pipes. The system had to be described with a slightly different model than the single WEC case, since the phase difference between the devices introduces additional terms and further complexity. A specific case with four WECs distributed along the wave propagation, with a distance between consecutive devices of 30 meters, was taken into account. The necessary dimensions of the air volume considered as common for an array of OWCs are more acceptable and guarantee a more interesting shift in the peak frequency

of each device. Another consideration that can be addressed regarding the air container is that it can be built of a cheaper material, or it can be made of an inflatable structure. In this way the costs could be further reduced and the feasibility of the implementation increased.

The IVV method is affected by a second limitation which is not due to air compressibility. In fact, while the size of the volume deals with the problem of a fluid not compressible enough, a different issue arises when the air acts as fully compressible: which means its pressure does not change with the reduction of the bottom volumes in the different WECs due to their heaving motions. This situation describes the limit case of an infinite volume, in which in response to a compression the pressure does not change. The force associated to the negative spring in this case is similar to the hydrostatic restoring force on the floater. It causes a shift in resonance frequency proportional to the ratio between the cross areas of the bottom chamber and the top floater. As a consequence, for floater cross surfaces larger than the bottom chamber ones, the shift in frequency can not go further a specific asymptotic value. On the other hand, if the floater radius is equal or smaller the chamber radius, this constraint does not occur.

For future work it will be important to better understand the IVV implementation in arrays. With an adequate layout configuration it may be possible to obtain more benefit from the phase difference between devices.