Compressible degree of freedom (CDOF): A potentially disruptive strategy for boosting wave energy converter (WEC) performance

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The addition of a compressible degree of freedom (CDOF) has been shown to significantly increase the power absorption compared to a traditional rigid WEC of the same shape and mass for a variety of architectures (Kurniawan et al 2014). An extension of this work, summarized below, demonstrates that a compressible point absorber, with a passive power-take-off (PTO) and optimized damping, can achieve the same performance levels as an optimally controlled rigid point absorber using reactive power from the PTO. Eliminating the need for a reactive PTO could be a game changer for the WEC industry. It would substantially reduce costs by reducing PTO design complexity. In addition, it would negate the adverse effects of reactive PTO efficiencies on absorbed power demonstrated by Genest et al. (2014), who show that the theoretical performance gains of optimal reactive control to increase absorbed power, even with a 90% PTO efficiency, is reduced by 60% due to energy losses incurred when transferring large amounts of power for control bi-directionally from the floating body to the PTO. For PTO efficiencies below 50%, Genest et al. conclude that “reactive control becomes useless.”

Like Kurniawan et al., the present study used simple linear frequency domain numerical models (restricted to heave) to demonstrate significant increases in energy capture with the addition of a compressible air volume within a common point absorber, as illustrated in Fig. 1. The improvements to performance were quantified by comparing this compressible point absorber to a conventional rigid one with the same shape and mass. Wave energy is converted to mechanical energy in both cases using a linear damper PTO connected between a fixed structure and the point absorber (Fig.1). Extending the work of Kurniawan et al. (2014), the PTO coefficient was optimized for each resonance frequency and compressible volume.

The dynamic model of the WEC used for this study is the same as in Kurniawan et al., which is based on linear potential theory for describing the wave-body interaction. In particular, the WEC has been modeled as a single degree of freedom heaving body, with an additional generalized mode describing the motion of the compressible surface; the resulting equation of motion is:

$$\left(\quad \omega^2\big(M + m(\omega)\big) + i\omega R(\omega) + K\right)\begin{bmatrix}\xi_3\\ \xi_r\end{bmatrix} = \begin{bmatrix}F_3\\ F_7\end{bmatrix},$$

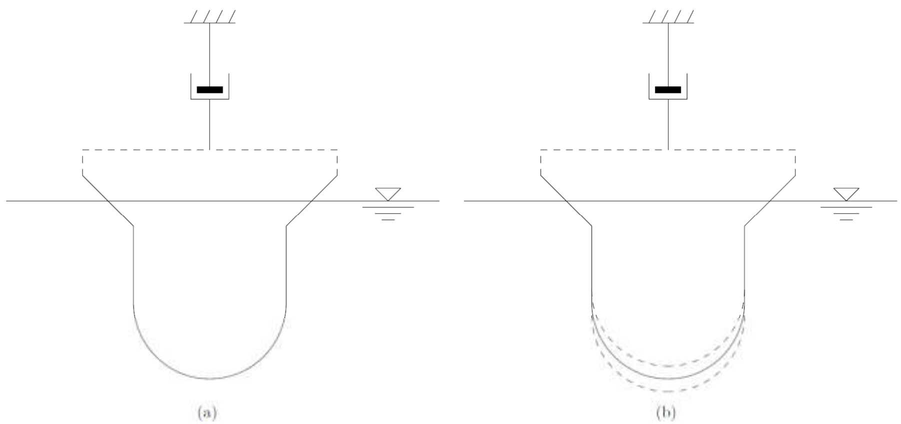

Fig. 1: (a) Rigid body point absorber WEC, and (b) Compressible (CDOF) point absorber WEC.

where $\xi_3$and ξ_r are, respectively, the displacement of the WEC with respect to a fixed reference and the relative displacement of the compressible surface with respect to the WEC. The excitation force on the WEC is denoted by F_3 whereas the excitation force on the compressible surface is denoted by F_7 .Additionally, M is the mass matrix, $m(\omega)$is the added mass matrix, $R(\omega)$is the radiation resistance matrix, and $K$is the stiffness matrix. Complete details on the derivation of the dynamic model are provided in Kurniawan et al.; however, it is interesting to highlight in the present paper that the equilibrium pressure p_0 and the compressible volume v_0 affect the resonance frequency of the WEC by acting directly on the stiffness matrix, as

$$K = \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} + \dfrac{p_0}{v_0}\gamma S^2 \end{bmatrix},$$

where γ is the adiabatic index and S is the water plane area of the WEC.

Results of the model simulations are shown in Fig. 2, which depicts the power absorption width (the amount of power absorbed relative to the amount of wave power available per unit width) as a function of the angular frequency. The red curve (labelled λ/2 π) is the maximum theoretical limit for power absorption for a heaving symmetrical body; and, therefore, represents the absorption width of an optimally controlled heaving-body WEC. Optimal control is achieved using reactive power and it requires a PTO capable of such functionality. The blue curve depicts the absorption width of the rigid point absorber, which uses an optimally tuned passive PTO and achieves its maximum theoretical power absorption width, 9.5 m, at its natural angular resonance frequency of 1. The improvements introduced by the CDOF are clearly evident by comparing the black curves, depicting the absorption widths of the compressible point absorber for different values of σ, with the blue curve; where σ is the ratio of the compressible volume with the submerged volume of the point absorber. The black curves show that the natural frequency of the compressible point absorber can be tuned to different frequencies by changing the compressible volume. In practice, the CDOF allows the point absorber to be tuned to the existing sea state and absorb a larger amount of power than a passively tuned rigid one. Furthermore, the compressible point absorber can approximate the behavior of an optimally controlled rigid point absorber (red line: λ/2 π) by changing the compressible volume using valves to open and close chambers inside the point absorber, based on the current sea state. The implementation of optimal control for a WEC requires highly efficient PTO components and the overall absorption capture is very sensitive to the

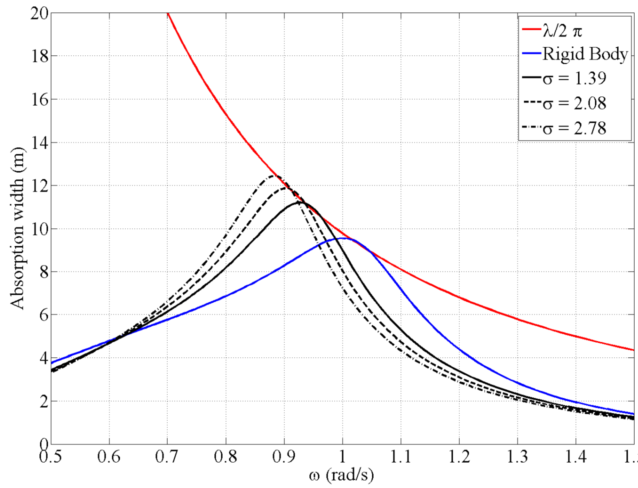

Fig. 2: WEC power absorption width as a function of angular frequency. The value for σ denotes the ratio of the compressible air volume relative to the submerged volume of the point absorber.

efficiency of the PTO [Genest et al.]. By means of the CDOF, it is possible to achieve a capture width close to optimal by using a passive PTO, thus reducing complexity and with less stringent requirements on the efficiency, both factors that strongly affect the capital cost of WECs. Additionally, the passive PTO with linear damper control is more robust, reducing maintenance costs, because it requires less complex hardware compared to a reactive PTO.

The large compressible volumes required to tune the compressible point absorber to the desired frequency are a practical limitation that needs to be addressed with further research, especially for low frequencies. In fact, all compressible volumes exceed the submerged volume of the point absorber by significant amounts, requiring auxiliary compressible volume storage units that are connected to the air chamber in the submerged portion of the point absorber. While realistic, these auxiliary units would increase the CapEx and OpEx costs, potentially reducing the aforementioned benefits gained by CDOF. Alternative approaches to implement CDOF without the large compressible volume requirements require further research, including the development of flexible surface panels tuned with mechanical springs. Also, further performance gains are possible for compressible point absorbers with multiple degrees-of-freedom in motion and compressibility.

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