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Subject: **Preliminary Hydrodynamic Analysis**

1. INTRODUCTION

1.1 PROJECT OVERVIEW

Tadek Ltd has been asked to carry out a preliminary hydrodynamic analysis of TWEFDA Wave Energy Converter (WEC) and to assess the potential of the use of Dynamic Compensation Tanks (DCT) to improve the wave power absorption.

The analysis is meant to investigate the energy extraction in different scenarios, depending on whether the DCT is open or closed and whether it's retaining water inside.

1.2 DOCUMENT PURPOSE

The purpose of this document is to present the modelling and analysis of the wave energy absorption of the TWEFDA WEC and summarise the results and conclusions on the use of the DCT.

1.3 REFERENCES

[1] Email from Javier Dominguez "CFD Study" dated 9th of March 2022 to Pierpaolo Ricci

[2] P. Ricci, "Modelling, Optimisation and Control of Wave Energy Point-Absorbers", PhD Thesis, Instituto Superior Técnico, 2021.

[3] Ricci, P., Saulnier, J.-B., Falcão, A. F., & Pontes, M. T. (2008). Time-domain Models and Wave Energy Converters Performance Assessment. *Proceedings of the 27th Offshore Mechanics and Arctic Engineering Conference.* Estoril, Portugal.

[4] Ricci, P., Lopez, J., Santos, M., Ruiz-Minguela, P., Villate, J. L., Salcedo, F., & Falcão, A. F. (2011). *IET Renewable Power Generation*, 5(3), 234-244..

2. ANALYSIS METHODOLOGY

2.1 SYSTEM DESCRIPTION

Based on the information and sketches received by the Client, it is assumed that the geometry of the floater in the current concept can be modelled as a circular cylinder with a hole to host a hydraulic system to pump fluid for energy extraction. The wave energy is extracted through the heaving motion of the floater with respect to the seabed. The Dynamic Compensation Tank may add inertia to the system by trapping water when closed. The idea is to increase power absorption by appropriately tuning the opening and closing of the DCT.

A schematic of the system is shown in Figure 2-1, where the principal components and dimensions are indicated.

Whilst the WEC is entirely scalable and its geometry could potentially be adjusted to the site conditions, a set of dimensions have been considered here to generate quantifiable results, as seen in Table 2-1. As the purpose of this Note is to prove the potential of the DCT concept, the values presented here should be considered as preliminary and subject to change.

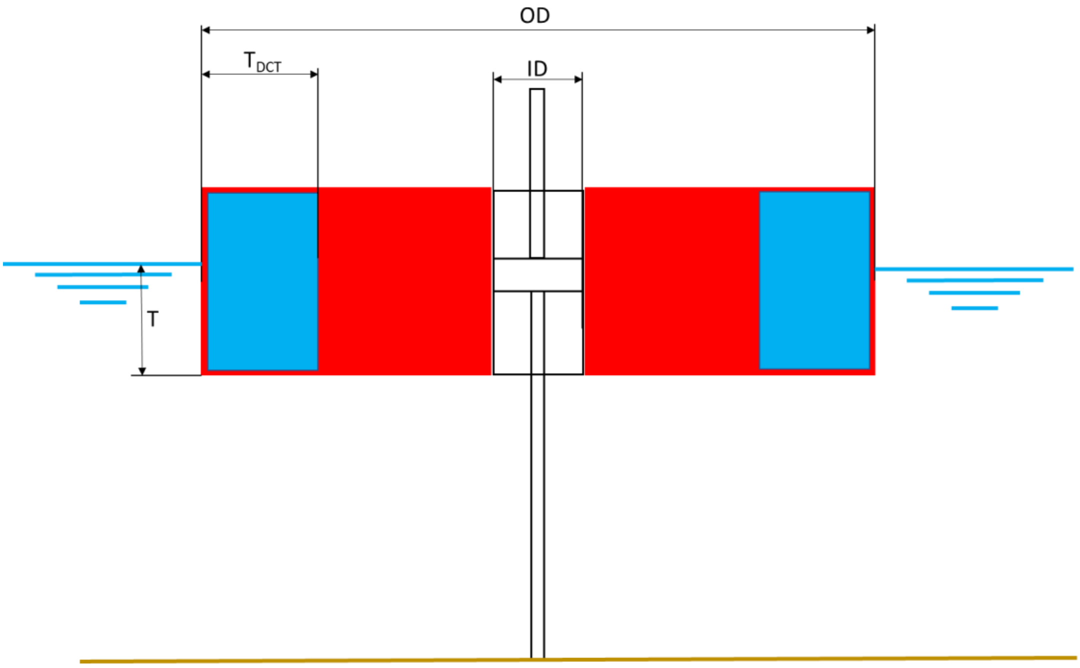

Figure 2-1: TWEFDA Concept Schematic

Parameter	Symbol	Value	Unit
Outside Diameter	OD	5.00	m
Internal Diameter	ID	1.00	m
Thickness of DCT annulus	T_{DCT}	1.00	m
Draught	T	3.00	m

Table 2-1: Principal dimensions of the TWEFDA case study considered in this Note.

For the purpose of the modelling, the following assumptions are considered:

- The DCT is made of an annulus space on the outer edge of the floater. It is assumed that the volume of the DCT can be filled with sea water by an opening on the bottom.
- When opened, the DCT allows sea water to flow in. The dynamic pressure from the waves would still generate loads on the top surface of the DCT annulus. Therefore, for simplicity, vertical wave forces will be assumed to be applied on the DCT surface, regardless of its status (open or closed).
- When closed, the DCT will entrap some amount of sea water which will act as additional mass in the system. For simplicity, it is assumed that the mass of trapped water will be equal to the one associated with the DCT filled up to the draft in equilibrium (T in Figure 2-1).
- The opening and closing of the DCT is likely to result in complex fluid dynamic process associated with the sloshing and viscous dissipation inside the DCT chamber. For simplicity, these effects are entirely neglected in this analysis.
- The opening and/or closing of the DCT is considered to be performed statically prior to the operation in three of the four scenarios investigated (see Section 2.2). To simulate the potential of dynamically opening and closing the DCT in real time whilst the system is operating, it is assumed that the opening and closing action will be instantaneous and entirely controllable.

2.2 WAVE ENERGY THEORY

2.2.1 FREQUENCY-DOMAIN ANALYSIS

From a general perspective, the TWEFDA WEC can be modelled like a typical heaving point absorber with a linear spring-damper system. In a tight-moored configuration, the motion is restrained to occur in the vertical direction only so that the modelling of the dynamics can be limited to the heave.

By assuming linear water wave theory, regular monochromatic wave excitation and linear Power Take-Off system, we can describe the motion in heave by using the equation

$$M\ddot{x}_3(t) = F_{e3}(t) - A_{33}\ddot{x}_3(t) - B_{33}\dot{x}_3(t) - \rho g S_w x_3(t) - C_{PTO}\dot{x}_3(t) - K_{PTO}x_3(t)$$

where the radiation forces can be represented as a sum of terms that are directly proportional to the velocity and acceleration of the buoy only by virtue of the hypothesis of monochromatic excitation and linear system.

If the system is linear and the excitation sinusoidal, then the motion response will be harmonic as well and can be represented as

$$x_i(t) = \mathrm{Re}\left\{\hat{X}_i e^{i\omega t}\right\}$$

where we use complex notation. The equation of motion can now be rewritten

$$-\omega^2 M\hat{X}_3 = \hat{F}_{e3} + \omega^2 A_{33}\hat{X}_3 - i\omega B_{33}\hat{X}_3 - \rho g S_w \hat{X}_3 - i\omega C_{PTO}\hat{X}_3 - K_{PTO}\hat{X}_3$$

And this leads to the straightforward solution for the motion amplitude

$$\hat{X}_3 = \frac{\hat{F}_{e3}}{-\omega^2\left(M + A_{33}\right) + i\omega\left(B_{33} + C_{PTO}\right) + \rho g S_w + K_{PTO}}$$

The former is a well-known expression of the so-called Response Amplitude Operator (RAO) in heave. The main distinction with the usual expression applied in offshore engineering consists in the introduction of the PTO coefficients that will clearly affect the device dynamics.

The instantaneous power absorbed by the PTO system is given by

$$P(t) = F_{PTO}\dot{x}_3(t) = C_{PTO}\dot{x}_3^2(t) + K_{PTO}x_3(t)\dot{x}_3(t)$$

By considering sinusoidal motion, it is easy to see that, on the average, only the first term on the right-hand side is different from zero so that the average absorbed power in regular waves can be written as

$$\bar{P} = \frac{1}{2}C_{PTO}\left|\hat{V}_3\right|^2 = \frac{1}{2}C_{PTO}\omega^2\left|\hat{X}_3\right|^2$$

The former allows the evaluation of the power absorbed by a WEC in regular waves with the sole requirement of its hydrodynamic coefficients (that will be generally computed by applying the methods described in Section 2.3).

Clearly, though the simplicity of this formulation is very useful for a global assessment of different configurations, it involves a certain degree of approximation, particularly with respect to the actual configuration of the PTO, which, in a real case, only operates in a certain range of conditions and with a specified efficiency. Real PTO models require the development of time-domain methods, like the ones presented in [3] and [4].

Other uncertainties are associated to the non-linear fluid interaction phenomena described previously. Those are very difficult to ascertain without indication from experiments and can be included only through empiric corrections with limited validity.

2.3 HYDRODYNAMIC ANALYSIS

To carry out the calculation introduced in the previous equations, the hydrodynamic coefficients F_{e3}, A_{33} and B_{33} need to be derived. These are associated with the first-order wave excitation load, added mass and radiation damping in heave, respectively. They are computed by radiation-diffraction analysis, which provides an estimate for wave loads and motions based on potential theory for the geometry of the wetted structure.

2.3.1 SOFTWARE

Three-dimensional diffraction analysis for wave load coefficients is performed using Orcawave (www.orcina.com). Orcawave is a 3D radiation diffraction solver based on potential flow theory and using the Boundary Element Method to solve the potential and source formulations.

2.3.2 WATER DEPTH AND FREQUENCY RANGE

The hydrodynamics are computed for the water depth of 25m. However, a precise water depth had not been specified and it should be noted that the results of the analysis may be subject to change if a different depth was considered.

The coefficients were computed for 56 wave periods between 2s and 60s. Only one wave direction was required, since the system is axisymmetric and would be subject to the same loads, regardless of the wave direction.

Figure 2-2 shows a screenshot of the mesh used.

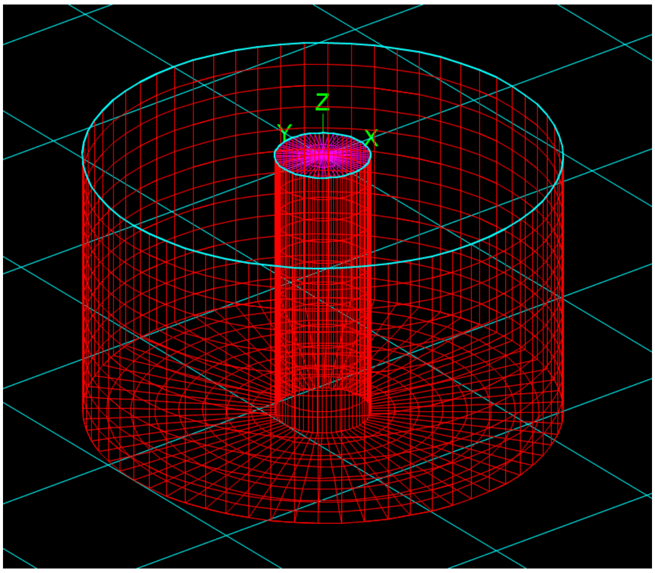

Figure 2-2: Hydrodynamic mesh used for the modelling of the floater

2.4 WAVE POWER ESTIMATE

A simple frequency-domain model based on the equations introduced earlier is used to assess the power extraction.

The power can be analysed for different PTO damping levels for the following scenarios:

A. DCT closed and empty at all times. In this case, the floater has a constant mass, derived from the displacement associated with the specified draft. Equations presented in Section 2.2.1 are applied.
B. DCT closed and full of water at all times. The floater has a larger mass and this is captured by increasing the mass (the term M in the motion equation). In practice, this would normally change the draft and lead to a different wetted volume; however the changes in the hydrodynamic coefficients should be limited and are therefore neglected in this analysis.
C. DCT open at all times. The floater is assumed to have the same mass as in A. However, due to the opening in the DCT, the system loses the buoyancy associated with the DCT annulus and the hydrostatic stiffness term is reduced accordingly. Also in this case, for simplicity, the change in draft is not considered.

The power extracted in regular waves is presented to show the global absorption capabilities of the TWEFDA geometry in different scenarios. An estimate of the average power extracted in more realistic conditions (irregular waves) is also indicated, based on the stochastic approach outlined in [2].

2.5 TIME-DOMAIN SIMULATION

An additional scenario has also been modelled:

D. DCT remains open while raising and closed while falling. This simulates an active control system that effectively improves the power absorption. As this type of scenario cannot be modelled in the frequency-domain, a time-domain model was created in Orcaflex with the introduction of an external function to apply the load associated with the additional mass depending on the vertical velocity of the floater.

The Orcaflex model is shown in Figure 2-3. In this case, the potential of the real-time control of the DCT opening and closing is demonstrated for some conditions but a full characterisation of the system is outside the Scope of this Note.

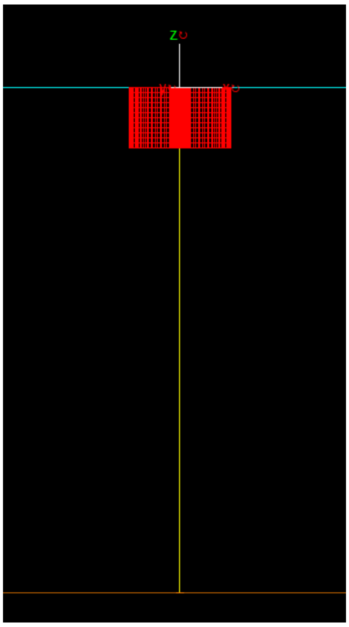

Figure 2-3: Orcaflex model for simulation of the TWEFDA WEC in real time

3. RESULTS

3.1 POWER OUTPUT IN REGULAR WAVES

The analysis was carried out for the different scenarios considering the application of a constant linear damping coefficient.

Figure 3-1 shows the heave RAO for the TWEFDA system when a constant PTO damping coefficient of 20kNs/m is applied.

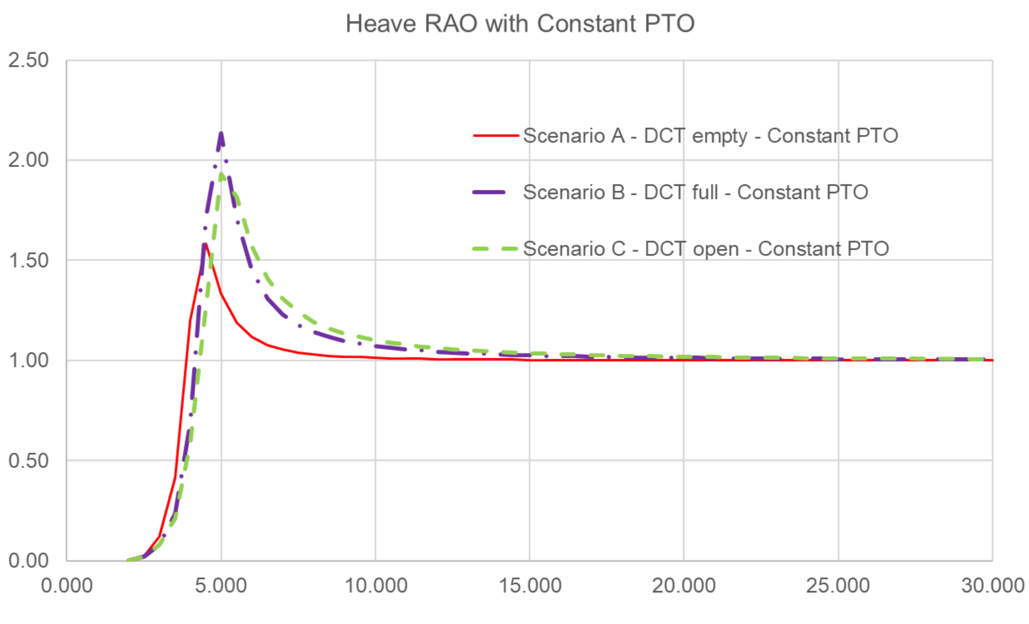

Figure 3-1: Heave RAO with constant PTO damping of 20t.s

As typical for wave point-absorbers, the system has a clear resonance peak for a specified wave period (in this case, between 4.5s and 5s). The resonance frequency is associated with the natural period derived from the mass, added mass and hydrostatic stiffness, according to the equation:

$$T_{n-heave} = 2\pi\sqrt{\frac{M + A_{33}}{\rho g S_w}}$$

Thus, an increase in the mass and/or a reduction in the hydrostatic stiffness result in an increase in the natural period. This is the reason why, as seen in Figure 3-1, scenarios B and C present a larger resonance period than scenario A.

Larger periods are associated with larger wave energy and are favourable for better absorption. This is visible in Figure 3-2, where the power output is plotted, based on the equation presented in Section 2.2.1.

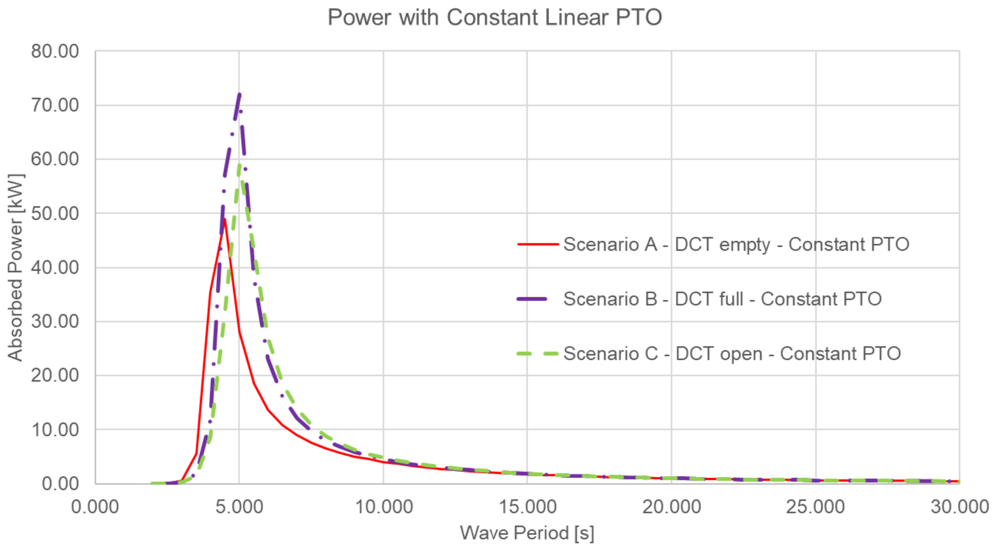

Figure 3-2: Power output with constant PTO damping of 20t.s

Both scenarios B and C, where the DCT is operated, show better power absorption capabilities than scenario A.

The definition of the PTO damping coefficient has some impact on the dynamics of the device and the resulting power output. The response of the system in regular waves can also be analysed considering an ideal PTO damping coefficient, which is optimal for the relation:

$$C_{optk} = \sqrt{B_{33}^{\ 2} + \left(\omega\left(M + A_{33}\right) - \frac{\rho g S_W + K_{PTO}}{\omega}\right)^2}$$

This assumes the possibility of changing the PTO damping depending on the wave frequency.

The heave RAO for ideal PTO is shown in Figure 3-3.

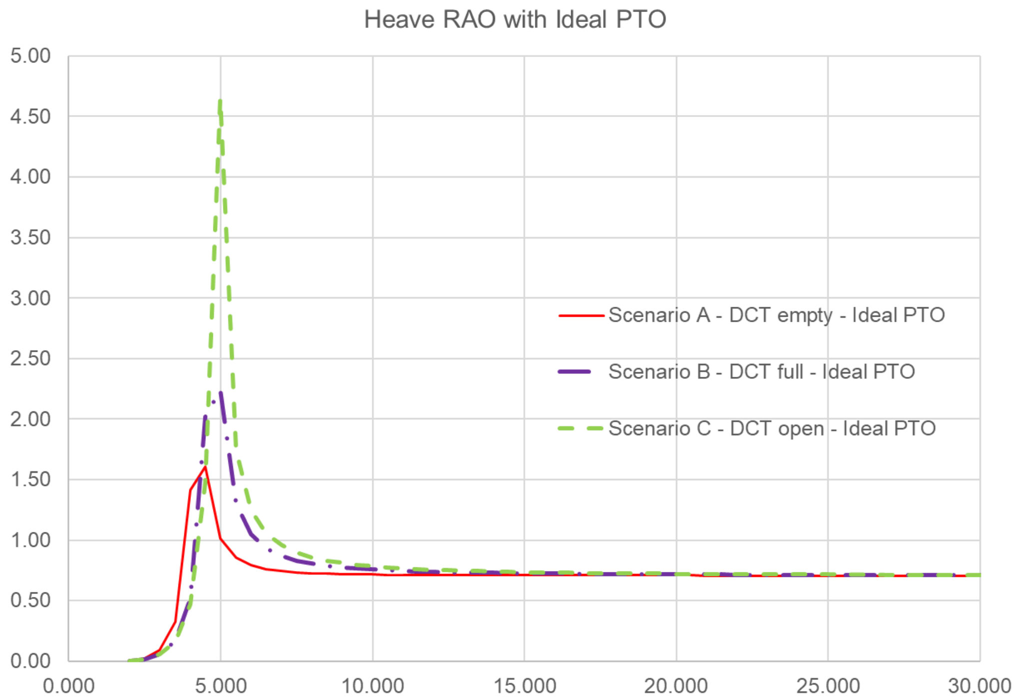

Figure 3-3: Heave RAO with ideal PTO damping

The resonance peak is located at the same period, but the amplitudes are significantly larger due to the smaller damping applied close to the resonance period.

The plot of the average power output shown in Figure 3-4 shows that Scenario B and Scenario C are characterised by larger power peaks at lower periods than Scenario A. However, Scenario A performs better at higher periods than Scenario C.

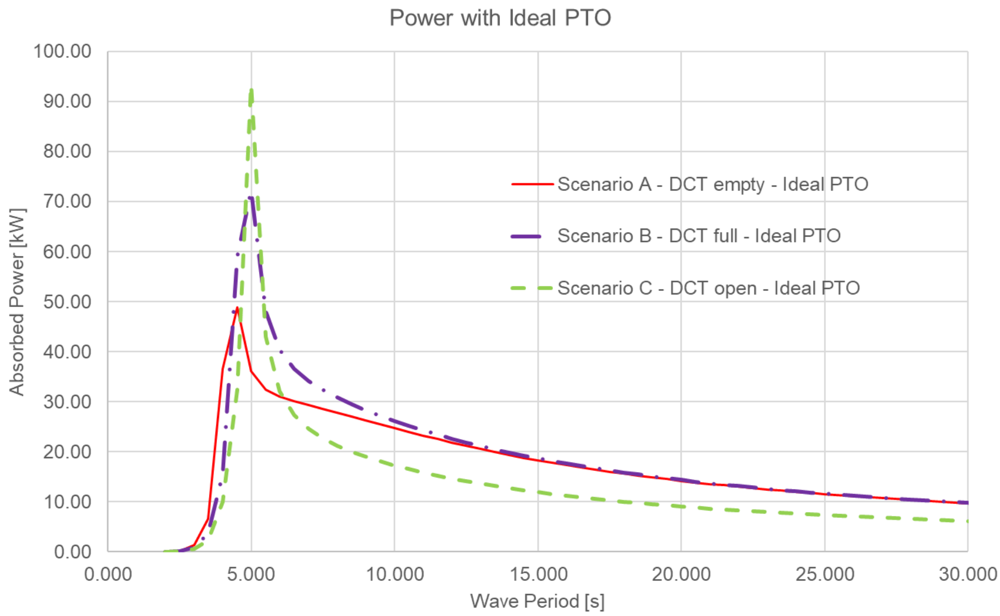

Figure 3-4: Power output with ideal PTO damping

3.1.1 POWER OUTPUT IN IRREGULAR WAVES

The application of a stochastic approach allows the estimation of the power absorbed in irregular waves.

Running the analysis for different PTO damping coefficients allows the definition of optimal values for maximum absorption. These optimal figures can then be used for setting the pressure levels in the hydraulic system of the TWEFDA WEC.

Plots for the power absorbed with varying damping are shown in Figure 3-5, Figure 3-6, and Figure 3-7 for sea states with 2m Hs and a peak period of 5s, 10s, and 15s respectively.

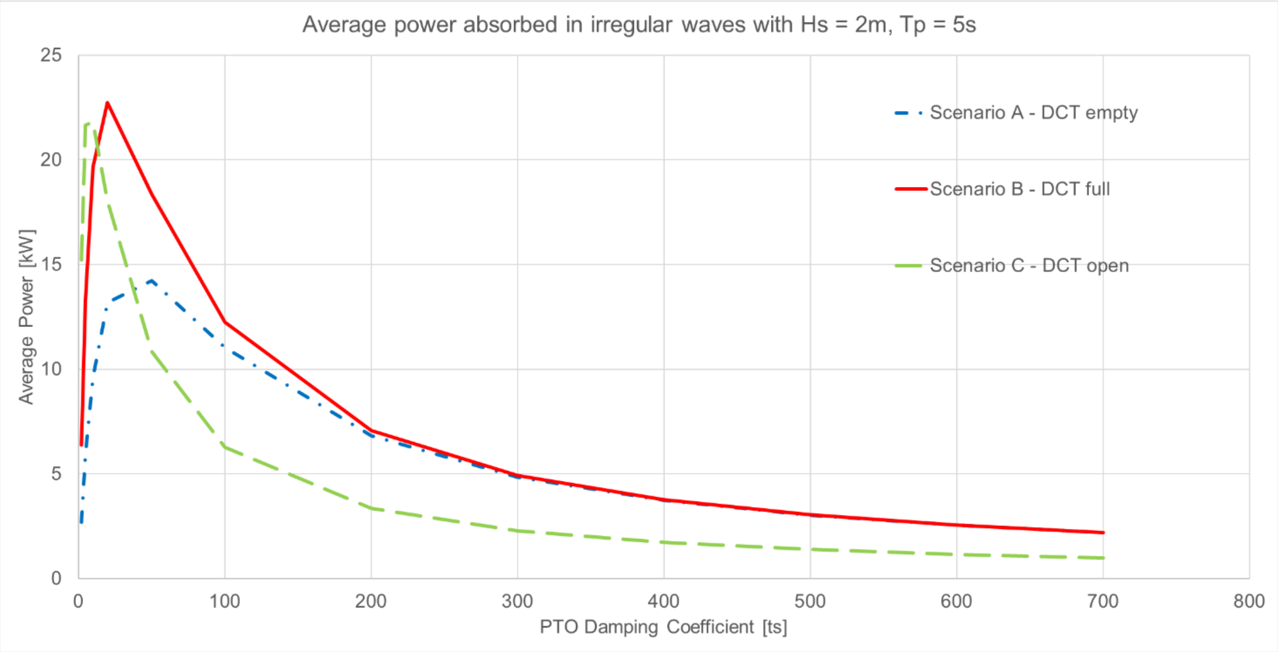

Figure 3-5: Average Power in irregular waves with varying PTO damping for Hs of 2m and Tp of 5s

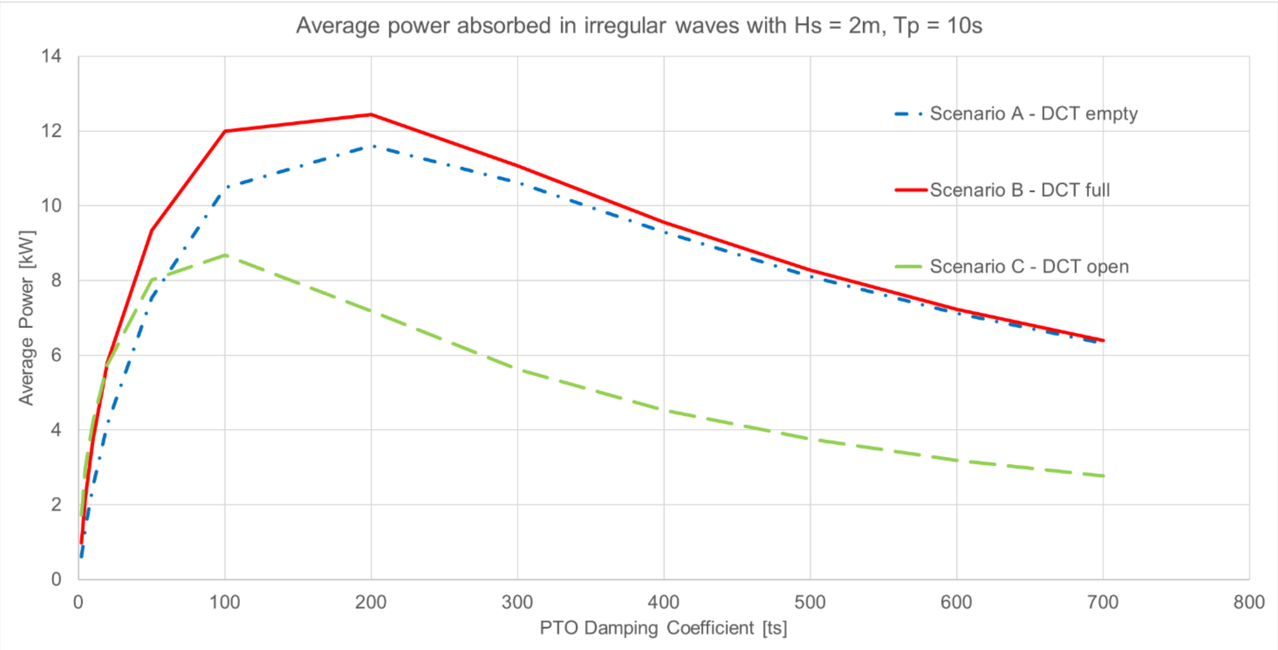

Figure 3-6: Average Power in irregular waves with varying PTO damping for Hs of 2m and Tp of 10s

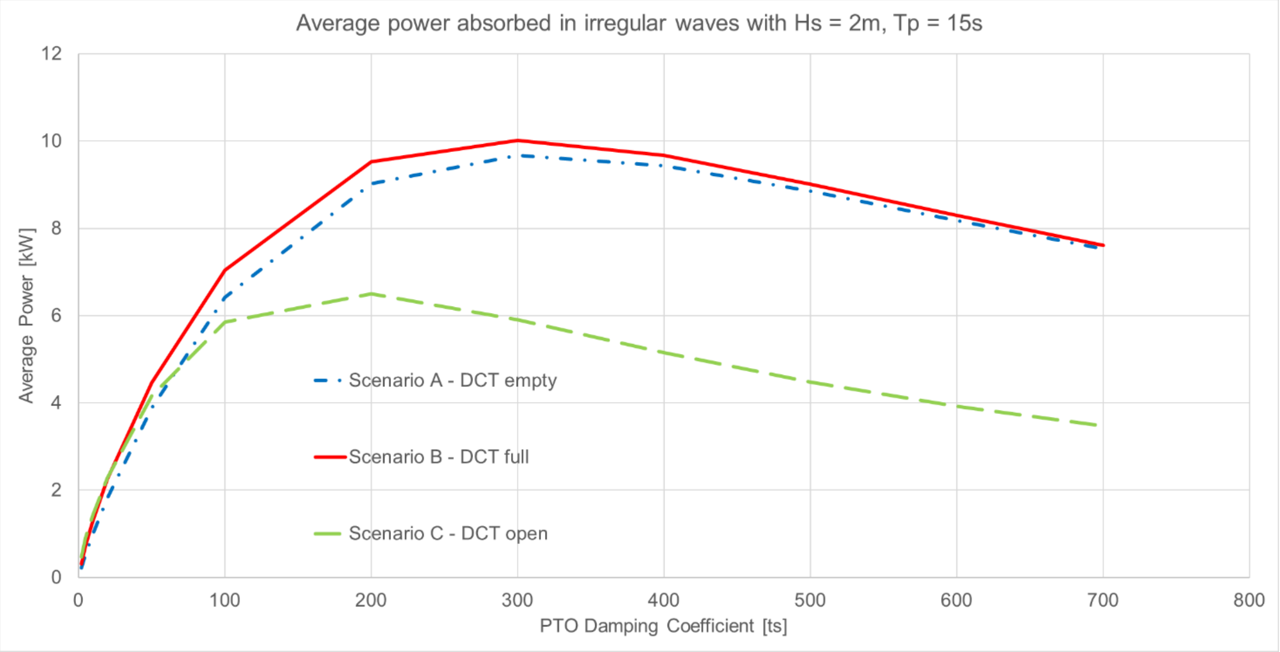

Figure 3-7: Average Power in irregular waves with varying PTO damping for Hs of 2m and Tp of 15s

In general, a larger damping force is required for optimal wave energy extraction when considering longer waves with larger periods.

Comparing the plots, Scenario B with the DCT full is systematically extracting a larger power than Scenario A and C. Scenario C, with the DCT open, performs better than Scenario A in short-period waves.

The average power can also be plotted in function of the wave peak period, as seen in Figure 3-8 and Figure 3-9 for a constant PTO damping coefficient of 20kNs/m and 100kNs/m respectively.

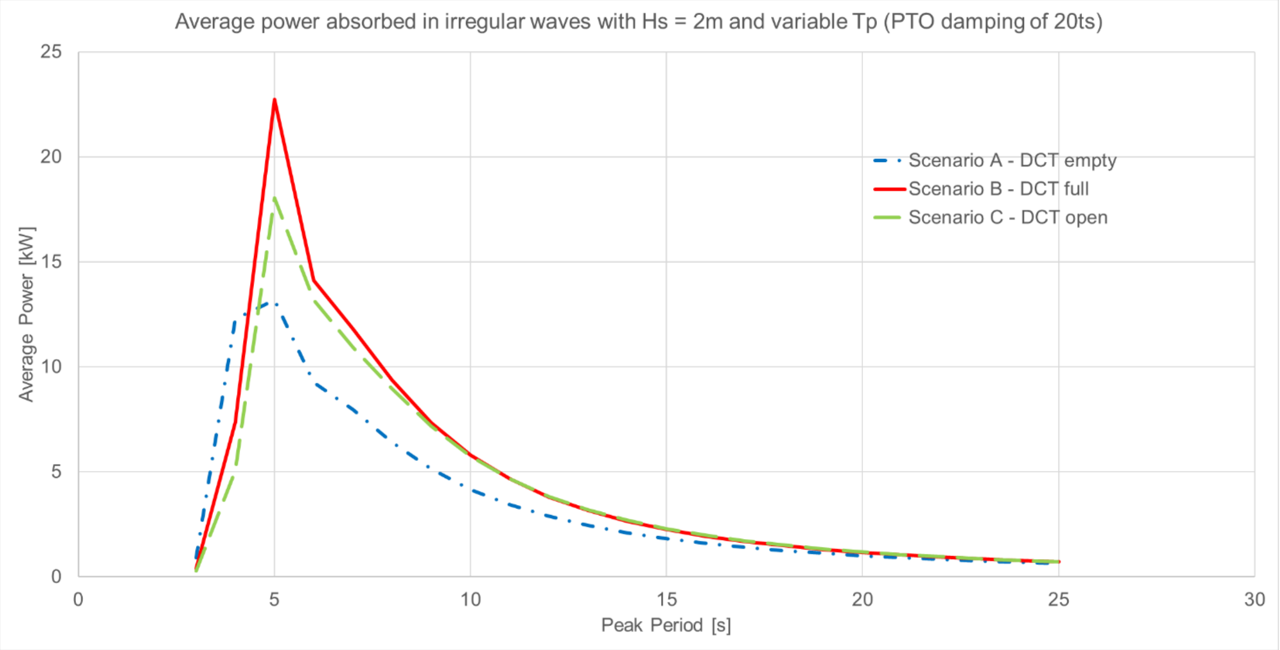

Figure 3-8: Average Power in irregular waves with for Hs of 2m and varying peak period (PTO damping of 20ts)

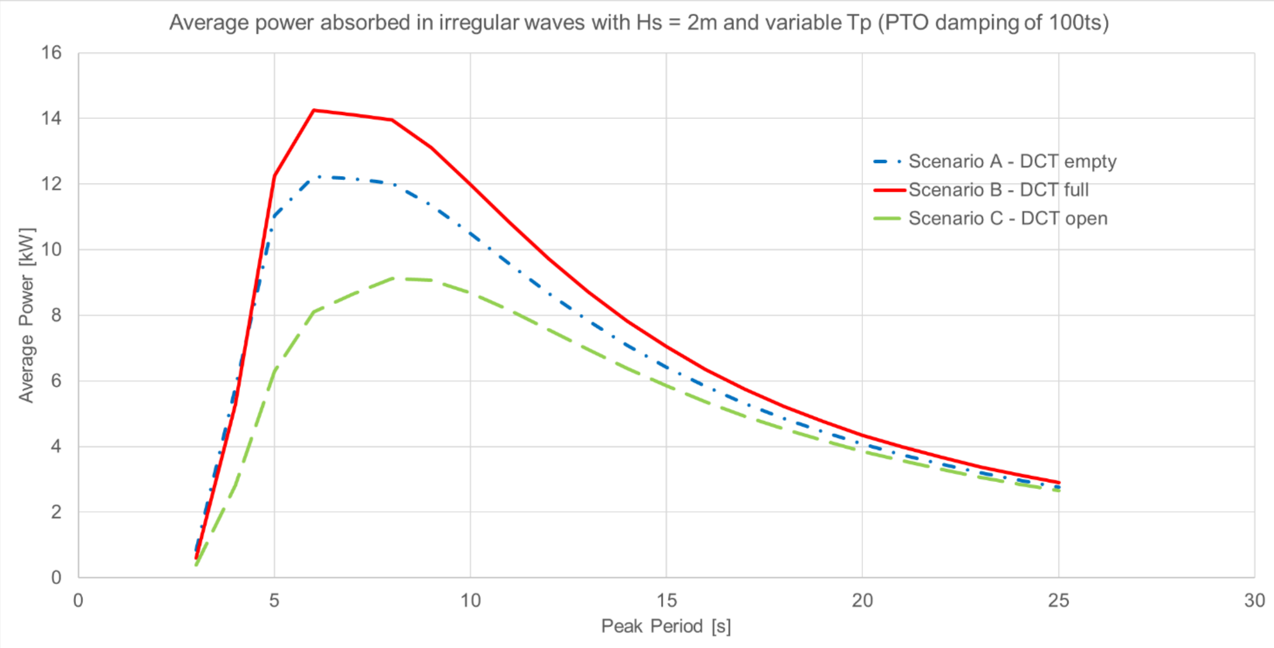

Figure 3-9: Average Power in irregular waves with for Hs of 2m and varying peak period (PTO damping of 100ts)

Scenario B allows better energy absorption across the whole range of periods in all cases. As mentioned before, Scenario C is best performing with lower damping coefficients and small periods.

3.1.2 RESULTS FOR REAL-TIME CONTROL OF DCT OPENING AND CLOSING

To carry out the simulation of Scenario D in real time, a model in Orcaflex was generated with the addition of an external function to reproduce the effect of an applied load associated with the sudden closing of the DCT chamber.

In practice, the program applies a vertical downward force corresponding the mass of the water entrapped in the DCT (21.7 tonnes) when the vertical velocity of the floater is negative. This is a simplification of the actual physics of the process as the water-body interaction during the part of the cycle when the DCT is open would likely lead to some viscous dissipation which would reduce the overall energy absorbed.

However, this modelling approach is believed to be appropriate for a preliminary proof of concept for this stage of development.

Results are presented for regular waves only, considering 1m wave amplitude and periods of 5s, 11s and 17s and a linear PTO damping coefficient of 100kNs/m. Future extensions of this work may include a full analysis of irregular wave conditions and a more accurate modelling of the energy extraction mechanism.

Figure 3-10, Figure 3-11, and Figure 3-12 are sample of the time history of the heave motion for 5s, 11s and 17s period respectively for Scenario A and Scenario D.

The increase in the motion associated with the closing of the DCT during the downward motion of the floater is clearly visible in all cases. As it may have been expected, the application of the additional mass leads to the floater sinking deeper during the downward cycle.

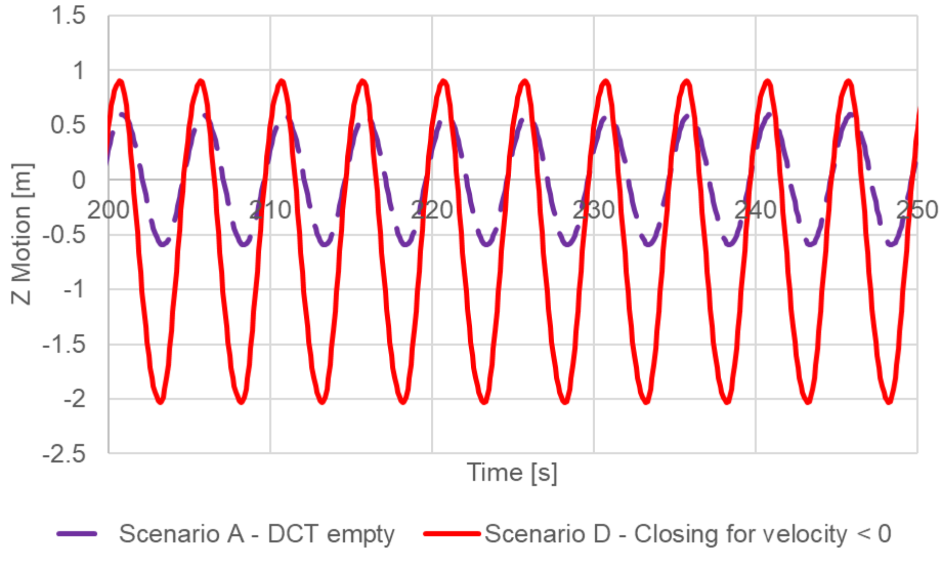

Figure 3-10: Heave motion in regular waves with 1m amplitude and 5s period

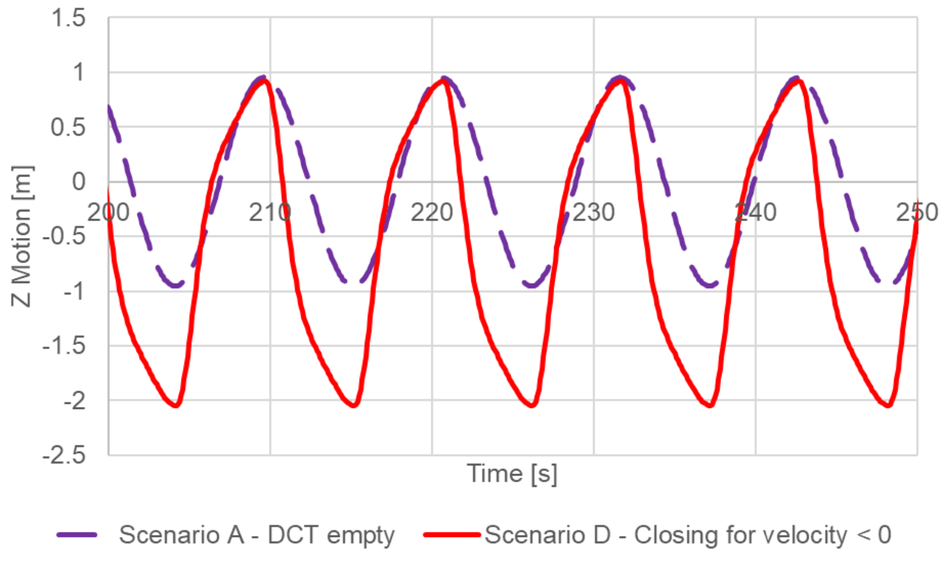

Figure 3-11: Heave motion in regular waves with 1m amplitude and 11s period

It is interesting to note that the introduction of the additional mass in Scenario D changes the amplitude of the heave motion but not the phase. In practice the peaks and troughs still happen at approximately the same instant in time.

The appearance of the heave motion in longer waves, though, is distinctly different between the two scenarios, with the Scenario D time history deviating significantly from a sinusoid.

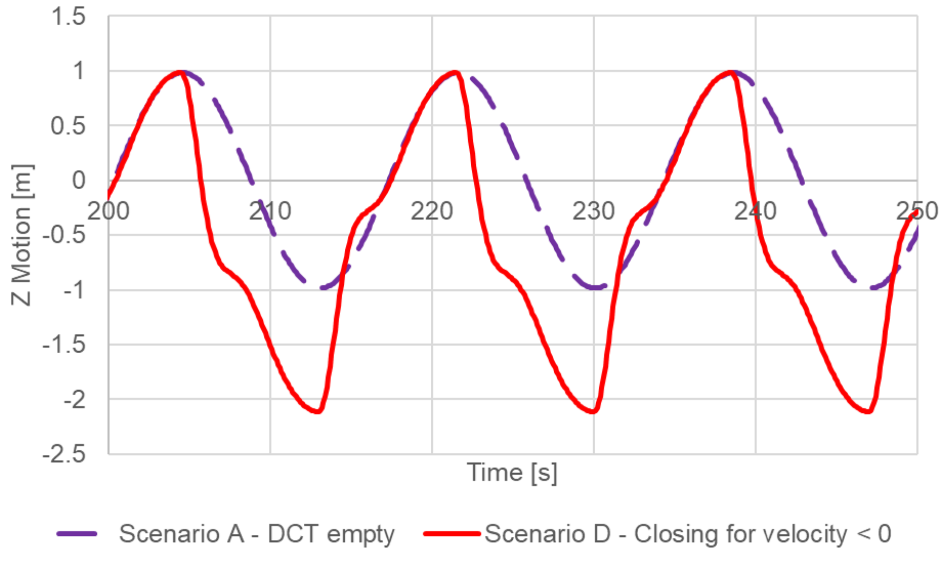

Figure 3-12: Heave motion in regular waves with 1m amplitude and 17s period

The instantaneous power absorbed given by the product between the PTO damping coefficient and the vertical velocity is plotted in Figure 3-13, Figure 3-14, and Figure 3-15 for a wave period of 5s, 11s and 17s respectively.

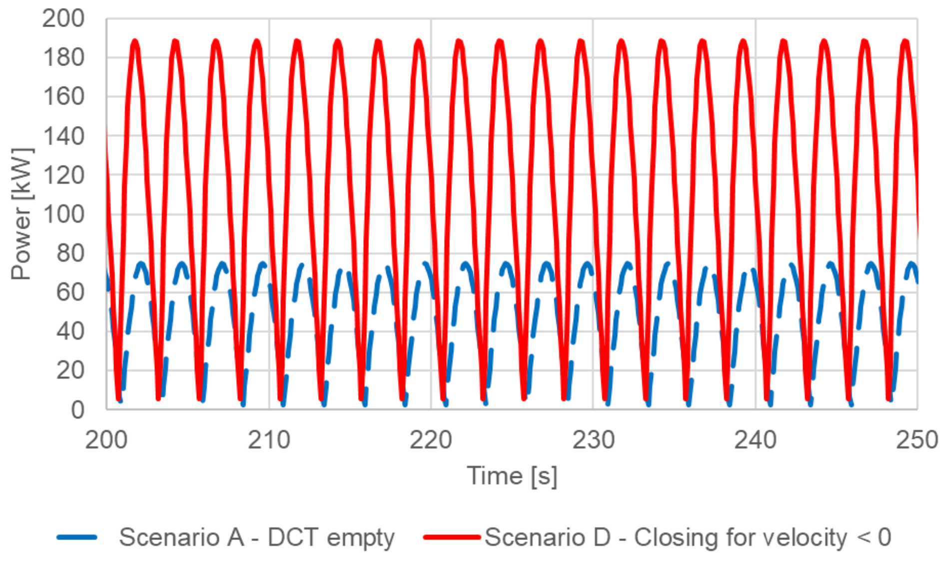

Figure 3-13: Power absorbed in regular waves with 1m amplitude and 5s period

The improvement on the power absorption for Scenario D, when the DCT is closed during the downward motion, is apparent in all cases.

In low periods, the power more than doubles but the increase is significant also in the 11s and the 17s periods.

It should be noted that the system modelled here is rather ideal and simply reproducing the effect of adding weight during the downward motion of the floater. The consideration of more realistic fluid interaction phenomena and appropriate representation of the energy extraction mechanism is likely to reduce the absorbed power.

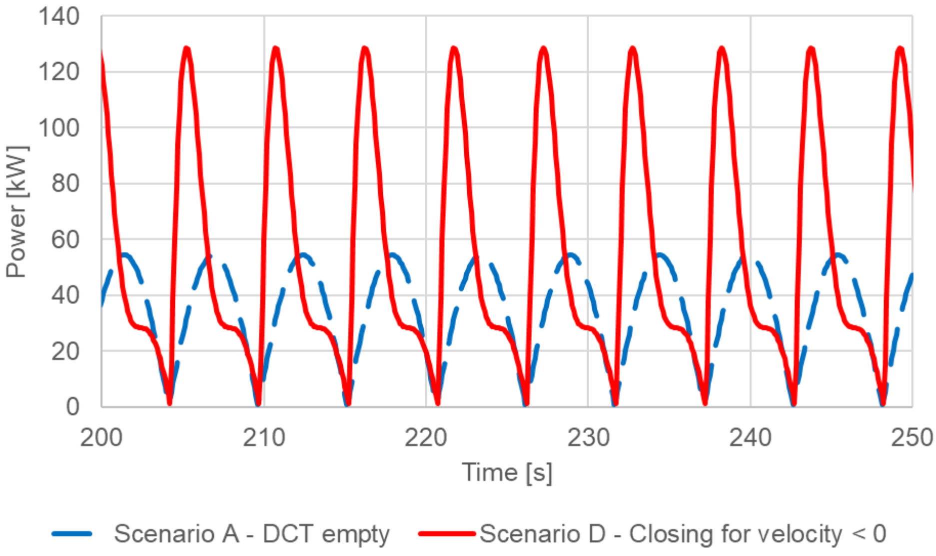

Figure 3-14: Power absorbed in regular waves with 1m amplitude and 11s period

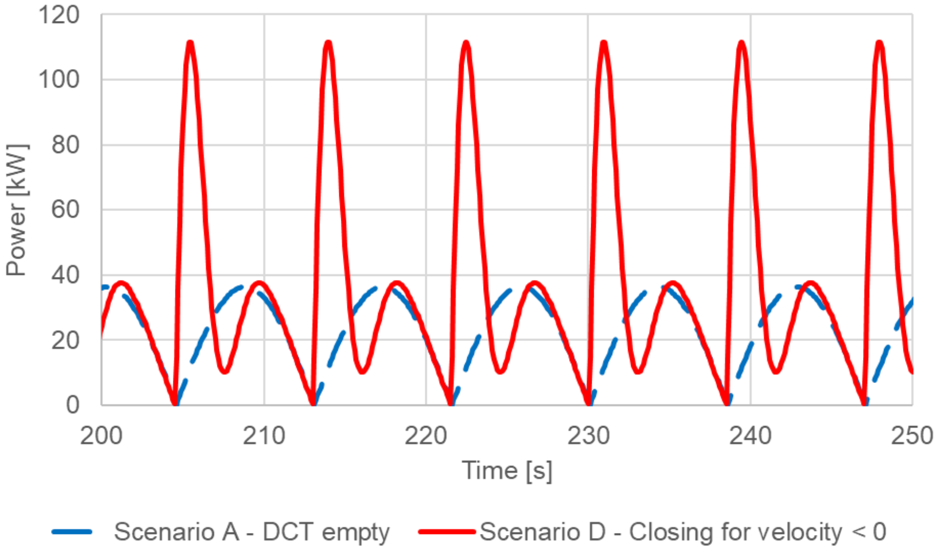

Figure 3-15: Power absorbed in regular waves with 1m amplitude and 17s period

4. CONCLUSIONS

Tadek Ltd have carried out a preliminary hydrodynamic analysis of the TWEFDA Wave Energy Converter (WEC) and a verification of the potential benefit of the use of Dynamic Compensation Tanks (DCT) to improve the wave power absorption.

The analysis investigated the energy extraction in different scenarios, depending on whether the DCT is open or closed and whether it's retaining water inside.

A simple frequency-domain model based on the equations introduced earlier is used to assess the power extraction on three of the four scenarios:

A. DCT closed and empty at all times.
B. DCT closed and full of water at all times.
C. DCT open at all times.

An additional scenario D has also been modelled in the time-domain with the DCT remaining open while the floater is raising and closed while it is falling, simulating an active control system that effectively improves the power absorption. As this type of scenario cannot be modelled in the frequency-domain, a time-domain model was created in Orcaflex with the introduction of an external function to apply the load associated with the additional mass depending on the vertical velocity of the floater.

The analysis of the power extracted in regular waves showed that an increase in the mass and/or a reduction in the hydrostatic stiffness result in an increase in the natural period. Larger periods are associated with larger wave energy and this leads to Scenario B and Scenario C being characterised by larger power peaks at lower periods than Scenario A.

Considering the energy absorption in regular and irregular waves, Scenario B with the DCT full is systematically extracting a larger power than Scenario A and C. Scenario C, with the DCT open, performs better than Scenario A in short-period waves.

The time-domain analysis indicates that the consideration of Scenario D, when the DCT is closed during the downward motion and opened when the floater is rising, improves significantly the absorption of wave power with respect to Scenario A in all wave conditions.

It should be noted that the system modelled here is ideal. The consideration of more realistic fluid interaction phenomena and a more accurate representation of the energy extraction mechanism may reduce the magnitude of the wave power absorbed in the simulation.

However, the analysis performed provides a reliable confirmation of the potential of the DCT to improve the energy extraction in the TWEFDA WEC. The introduction of a control system to open and close the DCT chamber to the surrounding sea water appears particularly promising.