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# Surrogate modelling of wave energy converter arrays using polynomial chaos expansion

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## ABSTRACT

Wave energy holds substantial promise as a renewable resource, but its commercial deployment remains limited. Research primarily focuses on individual wave energy converter (WEC) devices, while the interactions within WEC arrays have received less attention. Optimizing these interactions is essential for maximizing energy capture and minimizing operational costs. However, due to the variability of wave conditions, it is unlikely that a single WEC configuration will be effective across all scenarios. Therefore, to optimize performance, a large number of simulations are required, which is computationally expensive with traditional high-fidelity numerical methods. This paper addresses this challenge by utilizing a surrogate model based on polynomial chaos expansion (PCE), which efficiently captures the behavior of a WEC array over a 30-year probabilistic based on a high-fidelity wave dataset. The surrogate model is compared to a frequency domain model, demonstrating a high efficiency. The surrogate model is used to simulate the performance of an array of five point absorber WECs under varying wave conditions. The study highlights the following requirements for optimal array performance: the spatial configuration of WECs must consistently produce optimal power throughout the operational period and must adapt to the high variability of wave parameters. The results reveal that the fixed array configuration under study, produces power that is inconsistent over varying sea conditions, showing suboptimal energy production under most wave conditions, and higher power output only under less probable wave scenarios. These findings provide insights into the physical interactions influencing WEC array performance and can inform future design methodologies for wave energy farms. The proposed surrogate modeling framework offers a highly efficient tool for conducting large-scale probabilistic analyses of WEC arrays, significantly reducing computational effort while enabling more accurate performance predictions.

KEY WORDS: wave energy converters; surrogate models; frequency domain model; ECHOWAVE dataset; optimization.

## INTRODUCTION

Wave energy has immense potential (Guo & Ringwood, 2021; Khojasteh et al., 2023) as a renewable resource, yet it remains significantly underutilized . Advanced research is essential for the efficient commercial deployment of wave energy converter (WEC) devices as integrating wave energy farms with existing wind and solar farms can enhance energy production while minimizing installation and operational costs (Babarit et al., 2012). Current research predominantly focuses on individual WEC performance and design, with limited investigation into the interactions within WEC arrays. Present practices aim to position WECs to avoid mutual interference, thereby restricting the optimal use of the available resources. A comprehensive understanding of how different WEC configurations influence energy capture can lead to optimum power production with minimal costs. However, it is unlikely that one particular configuration of wave energy converters can produce high power at all wave conditions. Therefore, there is a need for faster models (Stavropoulou et al., 2023, 2025) that can run a high number of simulations in a reasonable duration of time to study the performance of WEC arrays over a long period of time ensuring consistent power generation for a wide range of wave parameters.

The objective of efficient harvesting of ocean wave energy presents a significant challenge due to the complex hydrodynamic interactions between wave energy converters (WECs) in an array. The power output of an array is mainly affected by two factors. Firstly, the spatial configuration of individual WECs, making optimization a critical aspect of array design. Secondly, high stohasticity and variability in the wave parameters over the expected period of operation. In order to study the influence of both the factors mentioned above, a large number of simulations are needed. Traditional high-fidelity numerical simulations are computationally expensive, making it difficult to conduct large-scale probabilistic studies necessary for optimizing performance of WEC arrays under realistic wave conditions. To address this challenge, this study employs a surrogate model based on polynomial chaos expansion (PCE). This surrogate efficiently captures the behaviour of a WEC array over a probabilistic wave dataset spanning 30 years, based on the ECHOWAVE hindcast (Alday & Lavidas, 2024).

The methodology presented can be used to train the surrogate models for any wave dataset. The paper demonstrates the efficiency of the surrogate compared to the hydrodynamic frequency domain model by (Tan & Lavidas, 2024). This model will be used in future works for the spatial layout optimisation of arrays in varying wave conditions. A simple point absorber type WEC is used for the purpose of this paper which is discussed in detail in the following sections.

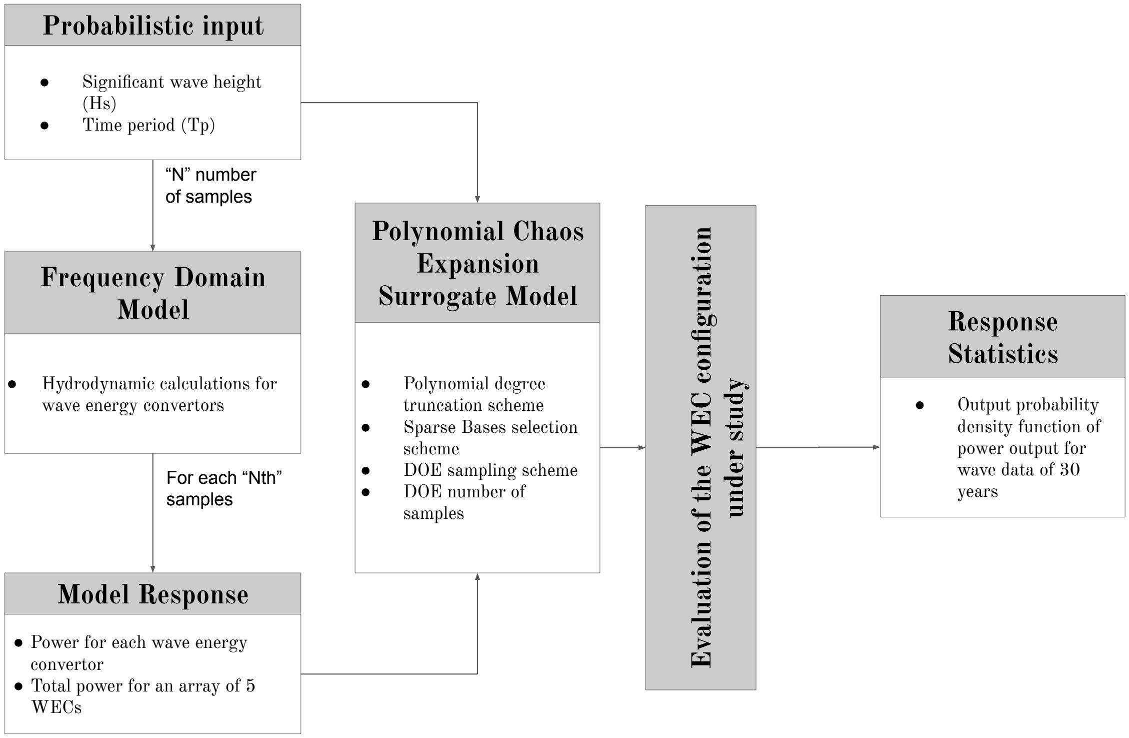


Fig. 1 Flowchart showing steps for creating a surrogate model for evaluation of wave energy converter arrays.

## METHODS

The frequency domain model is used to compute the power capture of individual WECs and the total power output of various array configurations. A Latin hypercube sampling technique is employed to generate 100 samples of wave parameters. The generated dataset is used to construct a surrogate model using data-driven PCE, allowing us to approximate the power response of the array for a wide range of wave conditions. By running the surrogate model for all significant wave height ($H_s$) and peak period ($T_p$) combinations, we evaluate a total of $10^6$ cases, enabling a comprehensive probabilistic analysis. Figure 1 Shows the methodology to create a surrogate model using polynomial chaos expansion to evaluate the performance of an array of a configuration of five wave energy converters (WECs). In the following section, each step of Figure 1 will be discussed in detail.

### Probabilistic input

The probabilistic input for wave parameters used in this work has been adopted from ECHOWAVE 30-years hindcast dataset. Figure 2 shows the workflow of processed data to sampling for the surrogates. In the first step, 30 years of raw data was transformed into contour showing the number of occurrences associated with different $H_s$ and $T_p$ combination. This contour was used to fit a surface to the joint probability distribution of $H_s$ and $T_p$ using a gaussian copula which was then used to sample input variables for the simulations.

The ECHOWAVE 30-years hindcast provides spatial (~ 2.3 km) and temporal (1 hr) resolution of wave fields and spectral data within the European coastal shelf. One of the main characteristics of this dataset is the use of the TUD-165 parameterisation and wind intensities correction proposed by (Alday & Lavidas, 2024). The use of TUD-165, together with the selected forcing fields, helped to reduce the overall wave heights' biases in the North-East Atlantic. Adjustments that led to the proposed parametrisation were extensively verified (and then validated) with measurements from the ESA Sea State CCI V3 altimeter product (Piollé et al., 2022). The resolution and accuracy of ECHOWAVE is an excellent tool for a detailed estimation of the energy flux within areas of interest for the development of wave energy projects (typically in depths below 200m).

### Frequency domain model

The frequency domain (FD) modelling approach is extended from the framework of the frequency domain (FD) modelling, and the flowchart of implementing the FD modelling is illustrated in Figure 3. The coefficients are derived based on the stochastic linearization method and the details of the FD model can be found in (Tan & Lavidas, 2024), the model is fully validated. The frequency domain model was developed for a single wave energy converter and was extended to an array of five WECs for this work as shown in Figure 4. The geometric details of the WEC are discussed below.

**Geometric details** Figure 4b shows the geometry of the WEC used in this study and Figure 4a shows the co-ordinates (x,y) of each WEC in the array studied in this work. The WEC used in this work is a floating heaving point absorber, which is illustrated in Figure 4b. The geometry of the floating buoy is considered as a sphere with a radius of 2.5 m. The mass of the buoy is assumed to be the same as that of the displaced water by the buoy. The details regarding the WEC can be found in (Tan & Lavidas, 2024)

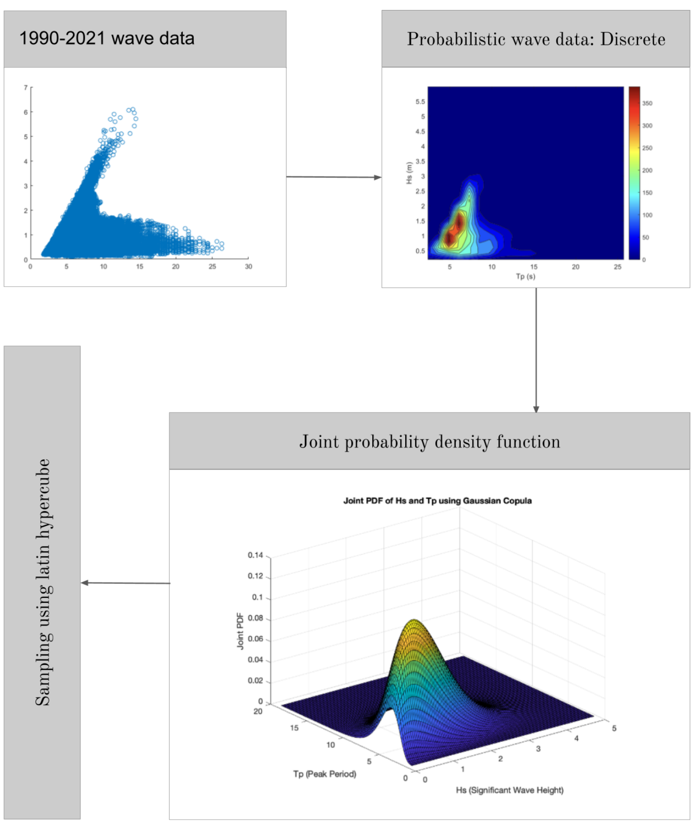


Fig. 2 Sampling process used to create surrogate from ECHOWAVE dataset.

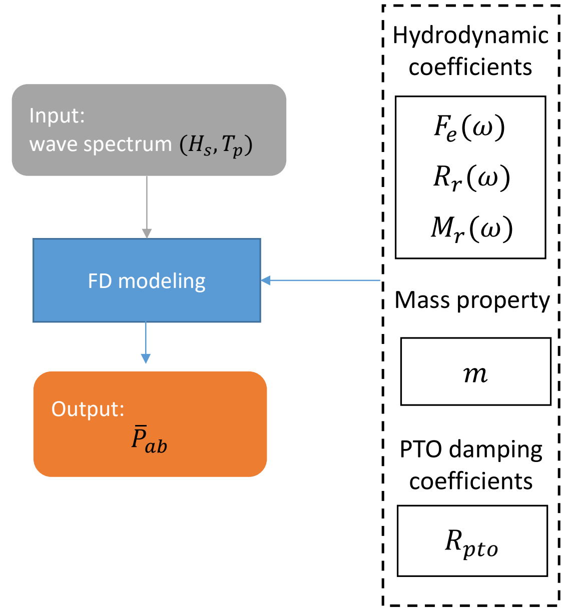


Fig. 3 The steps involved in the formulation of the frequency domain model (Tan & Lavidas, 2024) for training the surrogates.

### Model Response:

The power produced by each WEC in the array is computed in addition to the total power produced by the WEC array configuration under study for each of the combinations of $H_s$ and $T_p$. In the end, a probability density function of the total power output of the configuration was obtained to evaluate the performance of the array over a span of 30 years of operation.

### Polynomial Chaos Expansion

The advantages of Polynomial Chaos Expansion (PCE) models as opposed to other surrogate model approaches are several. Firstly, these models are non-intrusive and do not require any modification to the underlying FD simulations. Secondly, PCE models are transparent in terms of the theoretical underpinnings of their performance. Lastly, the post-processing of PCE model coefficients provides analytically computed Sobol indices, which can be used for global sensitivity analysis.

The PCE model in this work is built using UQlab, a framework developed at ETH Zurich (Marelli & Sudret, 2014; Sudret, 2008). This framework provides a high-level implementation of Uncertainty Quantification analysis. A hyperbolic ($q$-norm) polynomial degree truncation scheme (Blatman & Sudret, 2011) with $q = 0.75$ was chosen in the search of optimal basis. The other details regarding PCE parameters can be found in (Jain et al., 2024).

## RESULTS AND DISCUSSION

This section presents some results to show the efficiency of the surrogate model developed in this study and the power produced by the array of 5 WECs for varying wave parameters over a period of 30 years.

### Comparison of frequency domain and surrogate model results

Table  shows the comparison of the power computed for each WEC in the configuration and the total power produced by the array using the frequency domain model and the surrogate model. The values presented in the table are computed for $H_s$ and $T_p$ around the mean of the input variables shown in Figure 5(a) and 5(b) for both the models under comparison. It can be seen that the surrogate model shows great efficiency (error percent = 3.8) in computing total power with as little as 20 iterations of FD model. However, when considering the efficiency of surrogate model to compute the power produced by each WEC, increasing the number of iterations improves the effectiveness of surrogate model. Nevertheless, it is shown that the surrogate model shows a close resemblance to the FD model used to train it. In terms of computational efficiency, 100 evaluations using FD model takes 8400s compared to 2s for 1 million iterations using the PCE surrogate model.

The surrogate model developed can be used for different locations (different wave conditions) to evaluate the efficiency of the given WEC array.

$$\%Error = \frac{(P_{sd} - P_{pce}) * 100}{P_{pce}} \quad (1)$$

The error percentage has been calculated using the equation 1, where $P_{sd}$ is the power computed using FD model and $P_{pce}$ is the power computed using the surrogate model.

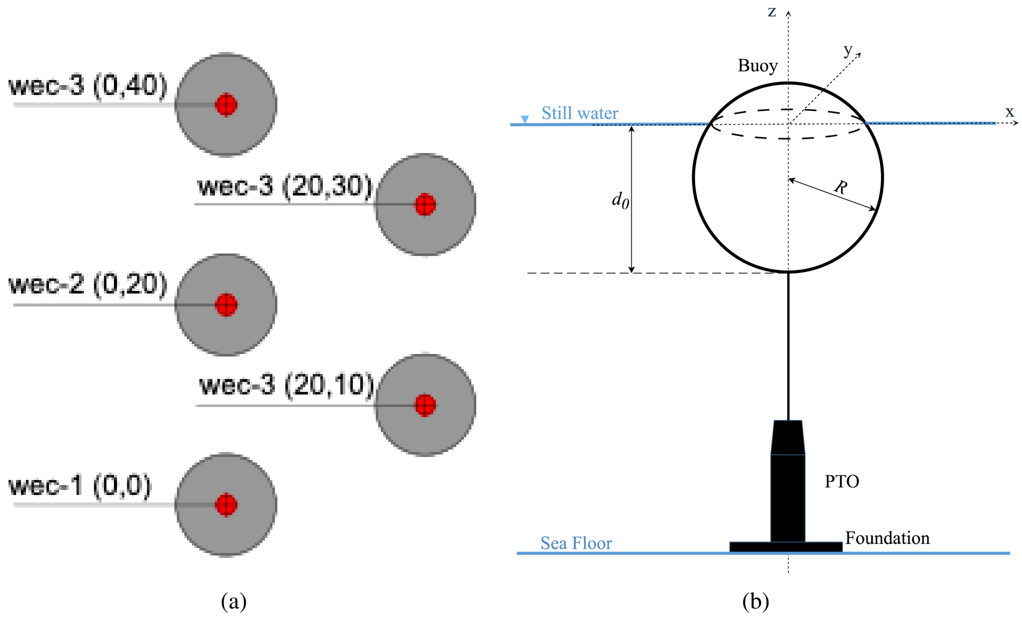


Fig. 4 Geometric details of (a) WEC array and (b) point absorber type WEC.

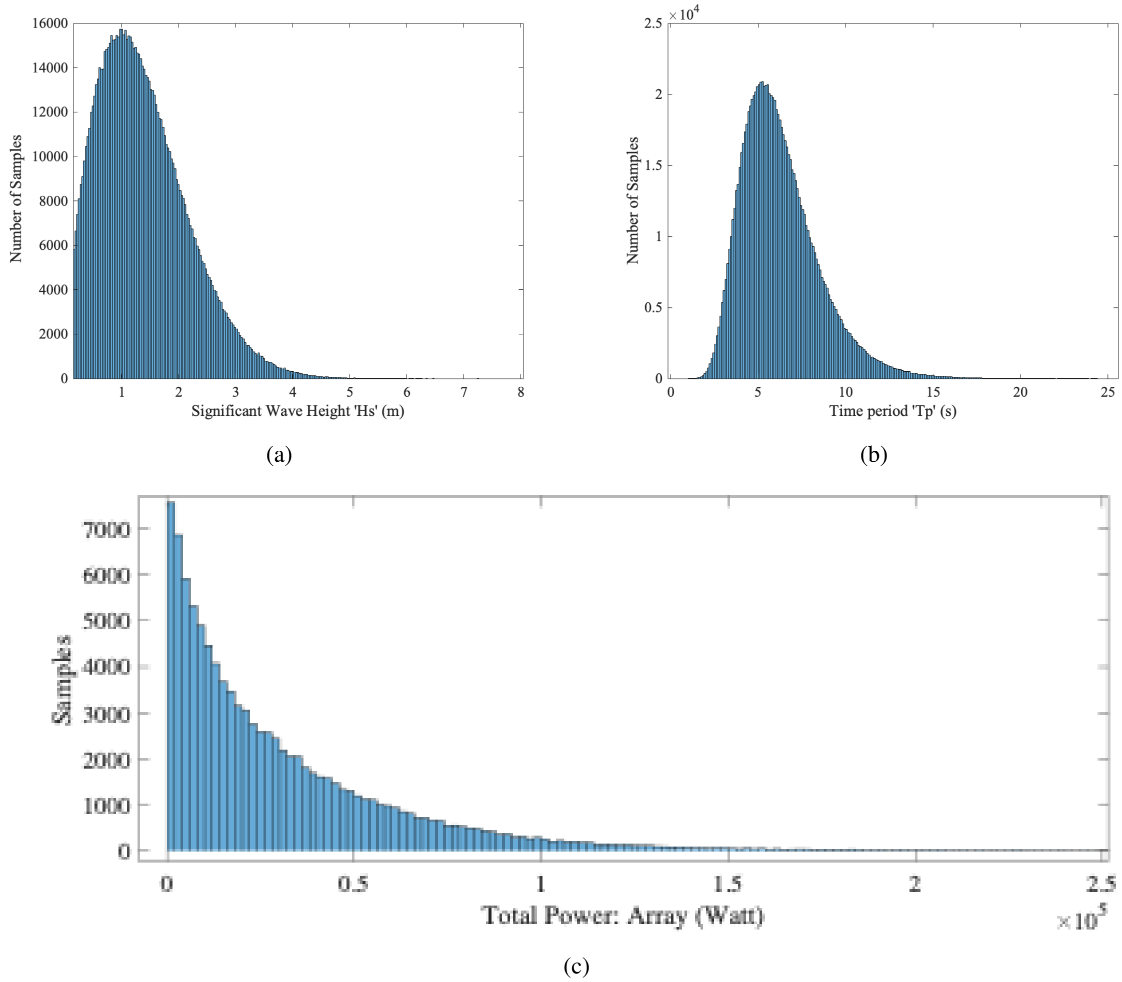


Fig. 5 Distribution of input parameters (a) $H_s$, (b) $T_p$ and output (c) total power.

| Number of iterations | | % Error | | | | | |
|---|---|---|---|---|---|---|---|
| Surrogate model | FD model | $P_1$ | $P_2$ | $P_3$ | $P_4$ | $P_5$ | $P_{tot}$ |
| $10^6$ | 20 | 2.0% | 14.5% | 2.0% | -0.5% | -0.5% | 3.8% |
| $10^6$ | 50 | -6.3% | -1.4% | -6.3% | -2.0% | -2.1% | -3.8% |
| $10^6$ | 100 | 0.5% | -0.7% | 0.5% | -1.2% | -1.2% | -0.3% |

Table 1 Comparison of the Frequency domain model and the surrogate model.

### Probability density function of input and output

Figure 5 shows the distribution of samples used for input variables $H_s$ and $T_p$ and the output (total power) of the WEC array configuration under study. The distribution of total power generated for 1 million samples of input variables shows the consistency of power produced by the particular configuration under evaluation over a period of 30 years. It can be clearly seen that the configuration under study is not optimum for the dataset used as it produces suboptimal power for most of the time of operations. This can be suggestive of sub-optimal power take-off damping, non-optimal geometry or spatial configuration for the given wave conditions. This needs a further investigation before the model can be used for optimization purposes.

## CONCLUSIONS

This paper presents the efficiency of the surrogate model developed using polynomial chaos expansion against the frequency domain model used to train it. The surrogate model was then used to evaluate the performance of an array of five wave energy convertors (point absorbers) over a probabilistic wave dataset of 30 years. The PCE surrogate was shown to be very efficient (0.3% error) in capturing the behaviour of FD model. Moreover, the power produced by the array over the operational period of 30 years was found to be inconsistent as it produced suboptimal power for most of the wave height and wave period combinations and produced high power for only certain (less probable) wave parameter combinations. The results provide insights into the physical interactions governing WEC array performance and inform design methodologies for future deployments. The proposed framework demonstrates the effectiveness of using surrogate modelling techniques to perform large-scale probabilistic analyses of wave energy converter arrays with significantly reduced computational effort.

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