Report for the period of
1st January 2023–31st December 2023

Vipin V
CSIR-SRF(NET)
Award No: 09/1026(0030)/2019-EMR-I

Under the Supervision of
Prof. Santanu Koley

BITS Pilani
Hyderabad Campus

Department of Mathematics
Birla Institute of Technology and Science-Pilani
Hyderabad Campus, India-500078

ENHANCEMENT REPORT

On Completion of the Fourth Year

1. Name of the Fellow : **Vipin V**

2. Email Address of the Fellow/Associate: vipinkumaran82@gmail.com

3. Nature of Fellowship (JRF(NET)/SRF(NET)/SRF/RA): SRF(NET)

4. CSIR Award No.: 09/1026(0030)/2019-EMR-I

5. Name, designation and address of Guide: **Prof. Santanu Koley**
Associate professor
Dept. of Mathematics
Birla Institute of Technology and Science-Pilani, Hyderabad Campus
Telangana-500078

6. Place of work (Names of the Department/Institute/University/College, etc.):
Dept. of Mathematics
Birla Institute of Technology and Science-Pilani,
Hyderabad Campus
Telangana-500078

7. Date of joining: 04/12/2019

8. Period upto which fellowship is tenable: 31/12/2024

9. Date of registration for higher degree (PhD): 04/12/2019

10. (a) Topic of Research: Mathematical Modeling for Wave-Structure Interaction Problems
(b) Broad Subject Area: Mathematical Modeling

11. Objective in undertaking work: (See Annexure I)

Period of Report: From 01/01/2023 to 31/12/2023

12. Attendance : Full

(a) Total No. of working days during the period under report: All working days
(b) Out of these, total no. of days in which the Fellow/Associate was present and worked: All (excluding the 10 days)
(c) Number of days for which leave was sanctioned: (Casual Leave 10 days)

13. Detailed report about the research work done during the above mentioned period. This should include quantitative results of research presented in Table(s)/Figure(s), discussion and conclusions drawn (separate sheets should be attached): (See Annexure II)

15 Summary of research work done during this period (in not more than 300 words: a separate sheet may be attached): (See Annexure III)

16. Plan of work for the next year (separate sheet may be attached): (See Annexure IV)

17. Research papers published/accepted for publication/communicated for publication (Details of authors, title,

journal, volume, page number and reprints of published papers/preprints of accepted papers/and manuscripts papers must be sent): (See Annexure V)

18. It is affirmed that I have devoted my full time to research and that I did not take up any other work paid or unpaid without taking written permission from CSIR. It is also certified that due acknowledgement of CSIR Financial assistance has been made in the published

Date: 06/02/2024 Signature of Fellow/Associate

19. Overall assessment and comment of the Guide:

Certified that the information provided in this report by Mr. Vipin V, an individual CSIR- SRF scholar working under my supervision on “Mathematical Modeling for Wave-Structure Interaction Problems” is correct to the best of my knowledge and belief. Mr. Vipin V is a dedicated, sincere, and hard-working research scholar. He has made satisfactory progress in the period for which the report is enclosed. This is clearly evident from the research papers published and communicated by him. Currently, he has been working in modeling of piezoelectric and oscillating water columns wave energy converter devices. I strongly recommend the extension of fellowship to Mr. Vipin V.

It is certified that the information provided above and in separate pages enclosed with this report by the Fellow/Associate is correct to the best of my acknowledge and belief.

Date: 06/02/2024 Signature of the Guide/Supervisor/Head

ANNEXURE- I

Objective of Undertaking Work

The objective of the current study focuses on the optimization of the geometric parameters of a hybrid wave energy converter device comprising a piezoelectric plate and an oscillating water column device. Firstly, the boundary element method-based numerical technique is used to solve the hydrodynamic problem associated with the total power generated by the hybrid device. To create the database for the machine learning model building, the input samples are generated using the Latin hypercube sampling technique, and the corresponding values of the target variable are calculated from the solution of the boundary element method. To optimize the device parameters, an appropriate machine learning model is identified from four tree ensemble models and a deep learning model, namely random forest(RF), extreme gradient boosting(XGBoost), light gradient boosting machine(LightGBM), categorical boosting(CatBoost), and multilayer perceptron(MLP). Spearman's correlation coefficient is employed to assess the correlation strength between the input attributes and the target variable, and subsequently, we leverage an interpretable machine learning approach, specifically Shapely values, to analyze the importance of features in the database. Further, using the extreme gradient boosting model along with the interpretable machine learning approaches, we identify the particular areas within the input space that result in optimal power generation. Moreover, the response surface methodology is applied to determine the precise parameters values of the hybrid device, aiming to optimize the total power output extracted by the hybrid device.

Signature of Fellow

Date: 06/02/2024

Signature of Supervisor

Date: 06/02/2024

ANNEXURE- II

Detailed report for 1st January 2023 to 31rd December 2023

- I have investigated the prediction, inference, and optimization of the design parameters of the hybrid OWC-PWEC device are studied. Firstly, the hydrodynamic problem associated with the ocean waves interaction with the hybrid WEC device is carried out using the BEM.
- The input database for the model building is generated using the Latin Hypercube Sampling technique and the response variable is calculated using the developed BEM. The present study identifies a suitable ML model from the five different models, namely, the multilayer perceptron model, random forest, Extreme gradient boosting, light gradient boosting machine, and categorical boosting models. The most suitable model is selected based on the smallest variance analyzed using a 10-fold cross-validation and the R^2 value obtained using the test datasets.
- Optimizing hyperparameters prior to training a machine learning model can significantly enhance both the model's performance and computational efficiency. This process helps in preventing overfitting or underfitting, thereby further refining the model's capabilities. A random search algorithm is implemented to optimize the hyperparameters of the MLP model, and the tree ensemble model's hyperparameters are optimized using the GA technique.
- The predictive model with minimum error scores and maximum R^2 values is then used to optimize the parameters of the hybrid OWC-PWEC device with the support of interpretable machine-learning approaches. As a preliminary analysis to understand the relationship between the input attributes and the target variable, the Sperman's correlation coefficient is used.
- The feature importance of the input parameters is studied using the interpretable machine learning approach, namely the Shapley values. Further, the direct effect of each of the parameters on the response variable is studied using the 1^{st}-order ALE plot, and similarly, the interaction effect is studied using the second-order ALE plots. Using these ALE plots, the specific regions of the input space that maximize the power generation are identified. Finally, the optimization of the input parameters to maximize the power generation by the hybrid OWC-PWEC device is carried out using the method of design of experiment and the response surface methodology using the L_8 orthogonal array.

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ANNEXURE- III

Summary of research work done during 1st January 2023 to 31rd December 2023

During the last years, the following research work has been pursued, whose conclusions are highlighted in brief below.

Optimization of parameters of wave energy converter device using machine learning models

In the period of the report, I have studied the mathematical modeling and optimization of wave energy converter devices to obtain the maximum power absorption. The boundary element method-based solution technique is used to model the physical problem under a regular incident wave environment. The conclusions of the study are as follows

A few conclusions of the work are:

- The total power generated by the hybrid OWC-PWEC device can be accurately predicted using the proposed XGBoost model with a comparatively smaller error in the test set as MAPE: 0.02%, MAE: 43.05, RMSE: 61.86. Further, the R^2 value is obtained to be 0.9959.
- The feature importance is identified using the XGBoost model and the Shapley values. The most important feature in predicting the total power generated by the hybrid OWC-PWEC device is PWEC plate length, and the subsequent important parameters feature-wise are the radius of the OWC device and the draft length of the OWC device, respectively.
- The optimal region of the input space is identified using the XGBoost model, the ALE plots, and the response surface methodology. The optimal range is obtained as $0.21 \leq l_1/h \leq 0.23$, $-0.08 \leq$d_1/h≤ -0.05, $0.06 \leq$g_p/h≤ 0.09, $-0.19 \leq$d_2/h≤ -0.11, and $0.63 \leq$r/h≤ 1.05.
- The exact combination of parameter values which maximizes the power generated by the hybrid OWC-PWEC device is obtained to be $l\_1/h = 0.21$, $d\_1/h = -0.08$, $g\_p/h = 0.06$, $d\_2/h = -0.19$, and $r/h = 0.63$, with a maximum power generation is $7912\ Wm^{-1}$.

Signature of Fellow

Date: 06/02/2024

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ANNEXURE- IV

Plan of Work for the Next Year

As a continuation of the ongoing research work pursued, the following research work will be pursued in the coming years.

- The study of the performance of the piezoelectric wave energy converter will extend to oblique and for irregular incident waves using the concept of the wave spectrum.
- Optimization and prediction of wave power absorption for the piezoelectric and oscillating water column wave energy converter device using highly accurate attention-based machine learning models.
- Develop a new machine learning model that will give better accuracy with less time to study supervised machine learning tasks.

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ANNEXURE-V

Research articles

Publication Title	Authors	Journal Name	Journal Volume	Issue	Pages	year
Mathematical Modeling, Prediction, and Optimization of Hybrid Oscillating Water Column-Piezoelectric Wave Energy Converter Device using Machine Learning Models	Vipin V, Trivedi K, Koley S.	Engineering Applications of Artificial Intelligence	Communicated for publication Manuscript Number: EAAI-24-1138			2024
Power Generation Prediction and Optimization of Parameters of Piezoelectric Wave Energy Converter Device	Vipin V, Koley S	IEEE Explore	Accepted for publication Manuscript Number: 24CHCS 7002			2024
Optimization of parameters of the OWC wave energy converter device using MLP and XGBoost models	Vipin V, Trivedi K, Koley S.	Results in Physics	55	NA	107163	2023
Performance of a submerged piezoelectric wave energy converter device floating over an undulated seabed.	Vipin V, Trivedi K, Koley S.	Energy Reports	8	10	182-188	2022
Mathematical modeling of a submerged piezoelectric wave energy converter device installed over an undulated seabed	Vipin V, Santanu Koley	Renewable Energy	200	NA	1382-1392	2022
Performance of a submerged piezoelectric wave energy converter device in time domain.	Vipin V, Trivedi K, Koley S.	Energy Reports	8	16	309-314	2022
Hydroelastic analysis of floating long viscoelastic plate in shallow water	Vipin V, Trivedi K, Koley S.	Materials Today: Proceedings Journal	49		2234-2238	2021
Parameter estimation of log-normal distribution based on local information	Vipin, V., D. K. Satpathi, Santanu Koley, V. V. Haragopal	AIP Conference Proceedings	2516	1	340002	2022

Scattering of Water Waves by a Quarter Circular Porous Breakwater Placed on a Porous Foundation	Vipin V, Pandurang a K., and Koley, S.	Fluid Mechanics and Fluid Power	1		403-407	2022
Estimation of Parameters of Some Continuous Distributions Using Frequency Ratio Method Based on Local Information	Vipin V, Santanu Koley	Proceedings of the Third International Conference, MMCITRE 2022 (Springer Nature)			319-327	2023
Power Generation Prediction and Optimization of Parameters of Piezoelectric Wave Energy Converter Device	Vipin V, Santanu Koley	IEEE Explore	Accepted for publication			
Mathematical modelling of a piezoelectric wave energy converter device integrated with a vertical breakwater over a stepped seabed	Vipin V, Koley S.	CRC Taylor and Francis Book Chapter	Accepted for publication			
Mathematical Modeling of a U-shaped OWC Device over the Slanted Sea Bed	Vipin V, Trivedi K, Koley S.	SUMMA-2021	doi: 10.1109/SUMMA53307.2021.9632151.		1022-1026	2021
Design optimization of a submerged piezoelectric wave energy converter device using an Artificial Neural Network Model	Vipin V, Koley S.	Energy Reports	Accepted for Publication			
Water waves scattering by a submerged thick porous breakwater placed over undulated bottom	Vipin V, Koley S.	PACE-an International Congress	Published in PACE-an International Congress, ISSN: 2791-6405			

Paper presentation

- Presented a paper entitled entitled “Power Generation Prediction and Optimization of Parameters of Piezoelectric Wave Energy Converter Device” in the 2024 Fourth IEEE International Conference on Advances in Electrical, Computing, Communications and Sustainable Technologies (ICAECT 2024). ICAECT 2024 is organized by the Department of Electrical & Electronics Engineering, Shri Shankaracharya Technical Campus (SSTC), Bhilai, Chhattisgarh, India during 11 - 12, January 2024.
- Presented a paper entitled “Optimization of a submerged piezoelectric device using an ANN Model” in the 10th International Congress on Industrial and Applied Mathematics(ICIAM-2023), held in Waseda University, Tokyo, Japan, August 20 – 25, 2023.

Invited Talk

- Presented an invited talk at International Research Outreach Programme (IROP-2022) Dong Thap University, Vietnam.

Signature of Fellow

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ANNEXURE-VI

References

[1] D. V. Evans, and R. Porter. (1995) “Hydrodynamic characteristics of an oscillating water column device.” *Applied Ocean Research*, 17.3, (1995): 155-164.

[2]E. Renzi. (2016) “Hydroelectromechanical modelling of a piezoelectric wave energy converter.” *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 472.2195, (2016): 20160715.

[3]Federica Buriani. (2019)"Mathematical modelling of wave–structure interactions with application to wave energy conversion." PhD diss., *Loughborough University*, (2019).

[4] S. P. Xu, and W. Wang. (2009) “Bending of piezoelectric plates with a circular hole.” *Acta Mechanica*, 203.3, (2009): 127-135.

[5] C. Zhang, W. Chen, and C. Zhang. (2013) “Two-dimensional theory of piezoelectric plates considering surface effect.” *European Journal of Mechanics-A/Solids*, 41, (2013): 50-57.

[6] X. D. Xie, Q. Wang, and N. Wu. (2014) “Energy harvesting from transverse ocean waves by a piezoelectric plate.” *International Journal of Engineering Science*, 81, (2014): 41-48.

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[8] S. Zheng, D. Greaves, M. H. Meylan, and G. Iglesias. (2020) “Wave power extraction by a submerged piezoelectric plate. Developments in Renewable Energies Offshore.”, *CRC Press*, (2020): 149-156.

[9] S. Zheng, M. Meylan, X. Zhang, , G. Iglesias, and , D. Greaves. (2021) “Performance of a plate-wave energy converter integrated In a floating breakwater.” *IET Renewable Power Generation*, (2021), DOI: 10.1049/rpg2.12230.

[10] K. Trivedi, and S. Koley. (2021) “Mathematical modeling of breakwater-integrated oscillating water column wave energy Converter devices under irregular incident waves.” *Renewable Energy*, 178, (2021): 403-419.