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EDITORIAL

Guest Editorial: Advances in Wave Energy Conversion Systems

Ocean waves are a largely untapped energy resource, and the global wave energy potential is estimated at about 32,000 TWh/year. Due to its great potential to provide renewable and sustainable electricity without carbon dioxide emission, wave energy conversion technology has attracted extensive attention from multi-disciplinary communities. Compared with wind and solar power, power from ocean waves is characterised by high power density and high spatio-temporal availability. However, the levelised cost of energy (LCoE) from ocean waves is higher than that from wind and solar radiation. The LCoE of wave energy can be reduced by technical innovations, especially in novel concepts, key components, real-time control systems and so forth. In addition, wave energy conversion systems can be integrated into offshore structures to provide cost-effective power and form multifunction platforms.

This Special Issue aims to update recent advances related to wave energy conversion systems all over the world. There are, in total, 32 papers accepted for publication after careful peer review and revisions. The authors are based in 13 different countries/regions, including United Kingdom, Ireland, China, Australia, America, Brazil and so forth, covering five continents, that is, Europe, Asia, Australia, North America and South America. These selected papers are broadly categorised into six topics: (A) wave analysis and prediction, (B) modelling of wave energy converters (WECs) and wave farms, (C) control system design and implementation, (D) model validation and case studies, (E) novel concepts and integrated systems and (F) WEC optimisation and grid connection.

All these six topics are, to a greater or lesser extent, referred to in the review paper, entitled 'A review of wave energy technology from a research and commercial perspective' by Guo and Ringwood, with in-depth discussion of their influence on WEC commercialisation. This review paper also summaries the historical and ongoing research and commercialisation efforts devoted to wave energy technology. Significant spatio-temporal variability in wave power resource plays a fundamental role in diversifying the successful development of WEC concepts, with a need for a collective approach to common fundamental issues, for example, modelling, power take-off (PTO) design, control, survivability, performance metrics and so forth. Historical analysis indicates that investor risk must be reduced by providing more certainty in national and international supporting programmes and policies, focussing on common technological challenges to reduce LCoE, LCoE uncertainty and to examine limitations in supply chains and marine licensing arrangements, while maximising the potential of industry-academy-government collaboration.

The other 31 papers are broadly categorised into the aforementioned 6 topics, with a summary of each topic given below. Readers are highly recommended to read the full papers if interested.

TOPIC A WAVE ANALYSIS AND PREDICTION

Lemessy et al., in their paper 'Analysis of the Caribbean wave climate for wave energy harvesting', analyse ten-year wave data in the Caribbean region. Characteristic parameters, for example, average wave height, wave period, and wave energy flux, to represent the wave climate in the Caribbean Sea, are obtained. Extreme sea states are also determined by using the peak over threshold method. This statistical analysis identifies the design requirements for WECs targeted at the Caribbean Sea.

Bento et al., in their paper 'Ocean wave power forecasting using convolutional neural networks', propose a new approach to forecasting wave power with a short-term horizon, based on convolutional neural network (CNN) models. This study validates the capability of CNN architectures to work as a wave prediction engine, even for horizons up to 6 h. Numerical results imply that the input data dependencies and the feature extraction conducted by the CNN models are useful to improve the forecasting accuracy. The CNN-based wave power forecasting approach shows a potential in power management, as it can provide accurate wave power prediction with a horizon up to 6 h.

Shahroozi et al., in their paper 'Considerations on prediction horizon and dissipative losses for wave energy converters', investigate the dependency of prediction horizon length on power maximising control and the level of dissipative losses in the conversion chain. The sensitivity to noise, amplitude constraints, and other effects encountered in a realistic system are discussed and considered to reveal their influence on prediction horizon length. Intensive numerical simulations conclude that the prediction horizon length, required to achieve maximum power output for realistic systems, is shorter than has generally been assumed to date, ranging from a few seconds to half a wave period.

TOPIC B MODELLING OF WAVE ENERGY CONVERTERS AND WAVE FARMS

Faedo et al., in their paper 'LMI-based passivation of LTI systems with application to marine structures', propose an optimisation-based passivation technique for linear time-invariant (LTI) systems, which can be applied to model the dynamics of marine structures in ocean waves, for ensuring model passivity. Based on a given state-space model, a properly designed perturbation is introduced and computed by solving a set of linear matrix inequalities (LMIs) to minimise a linear objective. An offshore platform and a WEC device are exemplified to demonstrate the effectiveness and importance of the proposed passivation technique in dynamic modelling of offshore structures.

Tan et al., in their paper 'Power absorption modelling and analysis of a multi-axis wave energy converter', numerically investigate the power absorption performance of a multi-axis WEC operating in 3 degrees of freedom (DoFs). Compared with a single DoF device, the multi-axis WEC is capable to absorb more power from harmonic waves. In this study, real sea states, at seven Zhejiang nearshore sites in the East China Sea, are used for numerical simulation, indicating that the absorbed power by the multi-axis WEC is up to 5 kW. The efficiency up to 29% is reported at the most energetic site of Shengshan.

Kurniawan et al., in their paper 'Numerical simulation of parametric resonance in wave energy converters using simplified models', present a computation-efficient and simplified method to simulate non-linear parametric resonance in WECs. Different from the non-linear Froude-Krylov method, the simplified method considers the time-varying body's centres of gravity and buoyancy in modelling, rather than evaluating non-linear Froude-Krylov forces according to instantaneous wetted surface. Although no non-linear wave forces are included, and the hydrostatic forces are only accounted for approximately, the simplified model can predict the parametric resonance in pitch to a reasonable accuracy. The proposed model offers a computationally efficient way to simulate parametric resonance in the time domain.

Song et al., in their paper 'The study on the anti-impact performance of the oscillating buoy with various air cushions', investigate various air cushions with a variety of shapes to mitigate the peak impact force and enhance the survivability of an oscillating buoy in ocean environments. Qualitative analysis shows that the cylindrical air cushion performs well as an anti-impact mechanism. Both numerical and experimental results conclude that the improvement in impact resistance of the air cushion can be slowed down by the increase in the air cushion volume, and there exists an upper performance limit that is positively correlated with the impact velocity of the buoy.

Dizon et al., in their paper 'Modular horizontal pendulum wave energy converter: Exploring feasibility to power ocean observation applications in the U.S. Pacific Northwest', examine the feasibility of applying a horizontal pendulum WEC to power the Self-Contained Ocean Observations Payload (SCOOP) of the National Data Buoy Center, deployed off the coast of Washington State, U.S. The pendulum's radius arm, mass, and PTO damping are parametrically studied to examine their effect on WEC power output subjected to seasonal variation in wave climate. It is concluded that a 20 kg pendulum mass is required to satisfy the SCOOP base power requirement of 5 W throughout the year. This study clearly proves the feasibility of utilising WECs for ocean observation applications.

Wei et al., in their paper 'Modelling of a wave energy converter array with nonlinear power take-off using a mixed time-domain/frequency-domain method', propose a mixed time-domain/frequency-domain approach to model dense WEC arrays with nonlinear PTO systems. The harmonic balance method is applied to describe the response of WEC arrays in the frequency domain while the nonlinear PTO forces and system dynamics are evaluated and solved in the time domain. The case study on the dynamics of an Ocean Grazer WEC array, equipped with adaptable piston pumping PTO systems demonstrates the influence of some key parameters on modelling accuracy and computational cost. Numerical results conclude that the mixed time-domain/frequency-domain modelling method can effectively reduce the computational costs, while remaining an acceptable modelling accuracy for dense WEC arrays. It has the potential to serve as a predictive model in model predictive control of wave farms based on wave measurements.

TOPIC C CONTROL SYSTEM DESIGN AND IMPLEMENTATION

Haider et al., in their paper 'Application of real-time nonlinear model predictive control for wave energy conversion', propose the development of a mathematical framework to implement a non-linear model predictive controller (NMPC) for maximising WEC energy production, when the cost function of some design parameters is non-quadratic, piecewise and discontinuous. The proposed NMPC framework is based on pseudo-quadratisation and weight scheduling, and is confirmed numerically and experimentally by using a real-time target machine and a WEC emulator.

Gu et al., in their paper 'Power maximising control of a heaving point absorber wave energy converter', propose a causal feedback controller, as a combination of PID control and quadratic damper control, for power maximising. A fully submerged spherical point absorber in heave, considering nonlinear viscous drag force, is exemplified as a case study to evaluate the performance of the proposed control framework. Numerical analysis in regular and irregular waves shows that the proposed controller is efficient to compute and easy to implement. Compared with a conventional PI controller, the proposed control strategy performs better in terms of bandwidth and power capture.

Yang et al., in their paper 'Modelling and analysis of inertia self-tuning phase control strategy for a floating multi-body wave energy converter', propose a phase control strategy to maximise the capture width ratio (CWR) of a floating multi-body (FMB) WEC by automatically tuning the total mass of the WEC hull. Numerical simulations in regular and irregular waves validate the effectiveness of the proposed control strategy in meeting the optimal phase condition. Therefore, significant improvement in CWR can be achieved for the FMB WEC.

Xu et al., in their paper 'Maximum power point tracking control for mechanical rectification wave energy converter', propose a mechanical rectification mechanism, to transfer the reciprocating linear motion of a heaving point absorber WEC into rotary motion through a ball screw. The rotary motion drives a permanent magnet synchronous generator to produce electricity. The maximum power point tracking control algorithm is applied to enhance the power conversion efficiency. Numerical simulations confirm the feasibility of the proposed control algorithm under various wave conditions.

Hillis et al., in their paper 'Wave energy converter platform stabilisation and mooring load reduction through power take-off control', investigate the feasibility and potential of modifying PTO control f to reduce platform motion and mooring loads. An approximate velocity tracking control strategy is used to demonstrate that the proposed controller can significantly reduce the loading on mooring system, while capturing the same amount of mean power as a passive controller. Thus, the proposed control method highlights its potential in reducing the LCoE by mitigating cyclic loading and failure risk of the mooring system, which is one of the major cost-driver factors in WEC design.

Faedo et al., in their paper 'Energy-maximising moment-based constrained optimal control of ocean wave energy farms', propose a moment-based optimal control strategy for WEC arrays, considering practical constraints in state variables and control input. To mitigate the computational burden of the proposed optimal control, a framework is developed to map the optimisation objective to a tractable quadratic program with a finite dimension. A WEC farm consisting of 5 CorPower-like devices is exemplified to evaluate the performance of the proposed control strategy. Numerical simulations show that the proposed optimal control framework is computationally effective and capable to maximise energy production while ensuring physical limitations.

Machado et al., in their paper 'Hierarchical control and emulation of a wave energy hyperbaric converter', develop a real-time emulation system and a hierarchical control framework for a hyperbaric WEC for evaluating control strategies with laboratory facility. A numerical model is developed to represent the dynamics of WEC floats and a hydro-pneumatic storage system (HSS), while the hierarchical control scheme is implemented by laboratory facility to control a doubly fed induction generator, considering the optimal HSS pressure under wave conditions. Conventional PI controllers are adopted to evaluate the performance of the developed emulation system and control scheme, and other advanced control methods will be applied in the future.

TOPIC D MODEL VALIDATION AND CASE STUDIES

Li et al., in their paper 'Analysis and wave tank verification of the performance of point absorber WECs with different configurations', examine four configurations of point absorber WECs, including a single body heaving WEC, a two-body heaving WEC, a two-body WEC with a damper plate (Reference Model 3), and a two-body WEC with a cylindrically shaped secondary body. For these WECs, dynamic models are derived and then verified by wave tank tests. It is revealed that the wave power captured by the two-body WEC, with a streamlined shape, can be more than two times (up to 66.5%) of that by the single body WEC or the Reference Model 3 WEC. Coupling other motion or mooring dynamics can increase the relative motion stroke, which in turn improves the wave power absorption of the point absorber WECs.

Wu et al., in their paper 'Experimental analyses of two-body wave energy converters with hydraulic power take-off damping in regular and irregular waves', investigate experimentally the power performance, in terms of CWR, of a two-body heaving point absorber with various hydraulic PTO damping coefficient in both regular and irregular waves. The optimal hydraulic load and wave frequency are identified for achieving the maximum value of CWR.

Davidson et al., in their paper 'Opening the air-chamber of an oscillating water column spar buoy wave energy converter to avoid parametric resonance', review the theoretical background regarding the occurrence of parametric resonance in the oscillating-water-column (OWC) spar-buoy and report the wave flume physical modelling results of the parametric resonance behaviour of two configurations, that is, (1) closed and (2) fully open-air chamber, of the spar-buoy OWC at a scale of 1:100. It is observed that the coupling between the buoy and the OWC within can be weakened by opening the air chamber. Moreover, the damped natural heave frequency of the system is shifted in comparison with the closed chamber configuration. Correspondingly, the parametric resonance characteristics of the chamber are altered due to the coupling between heave and roll/pitch modes. These findings show that the control of a pressure relief valve installed on top of the spar-buoy OWC is one possible avenue to depress parametric resonance after its detection of occurrence.

Silva et al., in their paper 'Air pressure forecasting for the Mutriku oscillating-water-column wave power plant: Review and case study', summarise an overview of wave forecasting methods and models. Based on the experimental data, obtained at the Mutriku wave farm in the Basque Country, Spain, a least squares support vector machine (LS-SVM) approach is developed, as a case study to predict the air pressure in OWC air chambers. The LS-SVM prediction errors are found to vary from 9% to 25%, for prediction horizons ranging from 1 to 3 s. Regressive models, that is, AR and ARMA models, demonstrate slightly better performance (8% to 22%) at much lower computational costs, thus, are preferred by MPC-like control strategies.

TOPIC E NOVEL CONCEPTS AND INTEGRATED SYSTEMS

Ermakov and Ringwood, in their paper 'Rotors for wave energy conversion—Practice and possibilities', review some existing ideas that create a fundamentally new direction for WEC development, particularly those harnessing energy from the elliptical motion of fluid particles in waves with the employment of a rotor. Three main aspects of the rotor-based WECs are reviewed: (1) experimental studies of existing prototypes, (2) derivation and development of mathematical modelling, and (3) control philosophies for the proposed WEC devices. It shows that there is a large variation in the design of rotors, and the convergence on an optimal geometry is not reached yet. Some problems, for example, torque and velocity fluctuation, need to be addressed for the development of the rotor-based WECs. The control technology may present an effective avenue in bringing wave energy rotors to operational reality.

Huang et al., in their paper 'Numerical calculation and model experiment of a novel external buoy type wave energy converter for navigation lighted buoys', propose a novel WEC consisting of a 'Sharp Eagle' buoy and a pontoon with vertical and horizontal damping plates. To evaluate the performance of the device, a numerical model is developed based on linear potential flow theory and the generalized mode method. Additionally, some physical tests are also carried out in a wave tank. Numerical and experimental studies show that the device's CWR can be significantly improved with a proper selected PTO damping coefficient. This device is expected to effectively provide continuous power supply for navigation lighted buoys of small or middle size.

Zheng et al., in their paper 'Performance of a plate-wave energy converter integrated in a floating breakwater', propose a novel plate-wave energy converter (pWEC), which is moored in front of a floating and stationary breakwater. The pWEC is composed of a submerged flexible plate with piezoelectric layers bonded to both faces of it. As water waves propagate through the system, the elastic motion of the plate can be transformed into useful electricity due to the piezoelectric effect. To study the performance of the system, an Eigen function matching method-based hydroelastic model is developed in the framework of linear potential flow theory with the electromechanical and the hydrodynamic problems of the pWEC coupled together. The effects of the width, submergence and edge types of the plate, and the width and draft of the breakwater, on wave power absorption and wave attenuation are investigated. It is revealed that the wave power absorption is dramatically influenced by the edge types and the width of the pWEC.

Ning et al., in their paper 'Theoretical investigation on an oscillating buoy WEC-floating breakwater integrated system', propose an integrated system consisting of an oscillating buoy WEC and a floating breakwater, to reduce the LCoE by the cost-sharing concept. An Eigen function matching and variable separation-based two-dimensional theoretical model is developed to study the hydrodynamic performance for the proposed integrated system. The integrated system with surging front-pontoon is found to perform better than that with pitching one in terms of wave power absorption, especially under high-frequency wave conditions. It is concluded that the CWR peaks are associated with the increase in front-pontoon motion, which is induced by the 'hydrodynamic constructive effect', and the gap resonance.

Peng et al., in their paper 'Experimental investigation of a triple pontoon wave energy converter and breakwater hybrid system', propose a novel hybrid WEC-floating breakwater system, consisting of three floating pontoons, with PTO modules, to extract wave energy in heave mode and, meanwhile, attenuate waves for coastal protection. Different from the studies of this subject in the literature, the three pontoons are close to one another, providing benefits to reduce the LCoE by sharing the same foundation. Two types of setups, that is, pontoons with equal drafts and step-change drafts, are tested in a water tank. Tank testing shows that the integration of multi-pontoon WEC is robust in stabilising the power output. The floating pontoons with equal drafts are advantageous in wave power absorption, whereas the floating pontoons with step-change drafts perform better in attenuating wave energy. Further optimisation should be conducted to balance the performance metrics in harvesting power and attenuating wave.

TOPIC F OPTIMISATION AND GRID CONNECTION

Garcia-Teruel and Clark, in their paper 'Reliability-based hull geometry optimisation of a point-absorber wave energy converter with power take-off structural reliability objectives', develop a geometric optimisation framework based on point absorber WECs to compromise the power performance with PTO system Damage Equivalent Loading (DEL), in order to improve the structure reliability of the PTO system. Optimised results indicate that a larger and more convex WEC hull leads to a greater power production and DEL, while a smaller and more concave WEC geometry results in a lesser power production and DEL. These findings highlight the importance of conducting WEC hull optimisation at early stage of WEC design, to optimise the LCoE, energy production, and system reliability.

Bao et al., in their paper 'Parametric study and optimization of a two-body wave energy converter', propose a backpropagation neural network model for predicting WEC power capture of a two-body heaving point absorber with nine design parameters. The Taguchi method is used to study the comprehensive influence of the nine design parameters on WEC power output. A 1:20 scale model is tested in a wave-current tank to verify and confirm the effect of some key parameters on WEC performance in power conversion. Both numerical and experimental results reveal that the proposed optimisation method is applicable to design the two-body heaving point absorber targeting at a specific site.

Sergiienko et al., in their paper 'Importance of drivetrain optimisation to maximise electrical power from wave energy converters', investigate the importance of optimising the drivetrain of a heaving WEC to improve the level and quality of its electrical power. The exemplified WEC is composed of a spherical buoy and a permanent magnet synchronous generator, coupled by a mechanical drive. A wav-to-wire model is derived, and a model predictive control framework is used to maximise electrical power from the incident wave to the generator. Drivetrain optimisation are performed numerically to optimise the gear ratio or/and flywheel inertia. Simulation results conclude that the optimised gear ratio or/and flywheel inertia can change the loading on the generator, allowing it to operate at higher efficiencies. Optimised flywheel inertia can also significantly reduce the peak-to-average power ratio to improve power quality.

Said and Ringwood, in their paper 'Grid integration aspects of wave energy—Overview and perspectives', present a comprehensive and informative overview of various aspects of grid integration of WECs, including WEC classification according to their impact on grid integration, grid requirements imposed by the grid codes, and storage technologies used for grid integration. After analysing dense studies of grid integration, it is concluded that the WEC hydrodynamic characteristics are seldom considered in grid connection. Therefore, it is urgent to develop a wave-to-grid WEC model, which takes into account all dynamic aspects of the power train from wave power to mechanical power, and to electrical power for grid connection.

Murad et al., in their paper 'Control of linear generator based on hysteresis-SVPWM current rectification and bidirectional buck/boost converter used for energy storage', develop a two-level electric energy conversion control mode, with a three-phase AC/DC rectifier controlled by a proportional resonance controller and a bidirectional buck/boost DC/DC converter controlled by a PI controller. The energy storage system consists of super-capacitors and batteries to buffer the power fluctuation of WECs. The three-phase AC/DC rectifier and the bidirectional DC/DC converter are modelled with properly designed energy storage, and numerical simulations validate the effectiveness of the proposed control method.

Blavette et al., in their paper 'Upgrading wave energy test sites by including overplanting: a techno-economic analysis', compare several of electrothermal models for the export cable of wave farms and develop a techno-economic model to determine the profitability of upgrading wave energy test sites. Two case studies are investigated numerically, with the first one to determine a precise and computation-efficient electrothermal model, while the second one analyse the techno-economical performance of upgrading existing wave farms. Numerical simulations conclude that, under the worse-case conditions in this study, it is not profitable to upgrade WEC test site. However, further detailed analysis is needed for a more general case.

SUMMARY/CONCLUSION

All the selected papers in this Special Issue, entitled 'Advances in wave energy conversion systems', have shown recent improvements in wave energy technology across the fields of wave analysis and prediction, modelling of WEC devices and arrays, control system design and implementation, model validation and case studies, novel concepts and integrated systems, and WEC optimisation and grid connection. Recent advances in WEC systems reported by the 32 papers have clarified a pathway to reduce the LCoE and to advance the commercialisation level of WEC technology by enhancing industry-academia-government collaboration to bridge the valley of death between R&D and high-TRL commercialisation activities.

With increasing emphasis on the provision of carbon-free energy, and a need to diversify the mix of renewable energy sources, wave energy is well poised to supplement, and complement, existing and more mature renewable energy technologies. The next decade will be crucial in deciding if wave energy can make the breakthrough needed to become a mainstream renewable energy technology.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Prof. Bingyong Guo, Northwestern Polytechnical University, China (Lead Guest Editor). Bingyong Guo graduated from Northwestern Polytechnical University, China, with B.Eng. and M.Sc. degrees in Information Countermeasure Technology and Underwater Acoustics, in 2010 and 2013, respectively. He received a Ph.D. degree in Electronic Engineering at the University of Hull, UK, in 2017. He worked as a post-doctoral researcher in the Nonlinear Dynamics and Control Lab, University of Exeter, UK, in 2019–2021, and as a Marie Curie Postdoctoral Research Fellow at the Centre for Ocean Energy Research, Maynooth University, Ireland, in 2019–2021. His research interests lie in numerical modelling, experimental verification and optimal control system design of wave energy conversion devices.

Dr. Siming Zheng, University of Plymouth, UK (Lead Guest Editor). Siming Zheng received a Ph.D. degree in Hydraulic Engineering at Tsinghua University, China in 2016. From April 2020 up to now, he works at the University of Plymouth, UK as a research fellow. Before that, he was a postdoctoral research fellow at the University of Plymouth, UK and Tsinghua University, China after completing his Ph.D., and prior to that, he used to work at University College Cork, Ireland for 12 months as a visiting Ph.D. student. His research revolves around marine renewable energy, hydroelasticity of plates, and wave scattering from metamaterial structures. The focus of his research is on hydrodynamic modelling of wave energy converters.

Prof. John V. Ringwood, National University of Ireland Maynooth, Ireland (Guest Editor). John Ringwood received the B.Sc. (Eng.) in Electrical Engineering from TU Dublin and the Ph.D. in control systems from Strathclyde University. He spent a number of years in Dublin City University as a member of academic staff in the School of Electronic Engineering, with concurrent terms as a visiting academic in Massey University and the University of Auckland. He joined Maynooth University in 2000, as founding head of the department of Electronic Engineering and built the department from a greenfield site, also serving as Dean of Engineering from 2001 to 2006. He is currently a professor in Electronic Engineering and Director of the Centre for Ocean Energy Research in Maynooth University. He is Associate Editor for IEEE Transactions on Sustainable Energy and the Journal of Ocean Engineering and Marine Energy, Subject Editor for Energies, and Deputy Subject Editor for IET RPG. His research interests are in ocean and renewable energy, control systems and biomedical engineering

Dr. João C. C. Henriques, University of Lisbon, Portugal (Guest Editor). João C. C. Henriques is an assistant professor at the Department of Mechanical Engineering of Instituto Superior Técnico (IST), University of Lisbon, Portugal. He received his Ph.D. in Mechanical Engineering from the Technical University of Lisbon in 2006. From 1993 to 2007, his main research topic was the development of numerical methods for simulating high-speed compressible flows. Since 2008, his main research areas have been the numerical and experimental modelling of wave energy converters (WECs), control of the power take-off system of WECs and the aerodynamic design of air turbines for oscillating water column WECs. He published 57 papers in peer-refereed journals. He also holds five patents, four in the field of wave energy and another in wind power. He participated in eight European projects on wave energy conversion.

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