Input-Unknown Estimation for Arrays of Wave Energy Conversion Systems via LTI Synthesis

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ABSTRACT

The incoming menace of global overheating and depletion of fossil fuels, highlight the need for alternative, renewable, energy sources. In this context, ocean wave energy has a massive potential to contribute towards global decarbonisation. In optimising wave energy converters (WEC) productivity, state-of-the-art, model-based optimal control techniques are fundamental to enhance energy absorption efficiency. However, the vast majority of these optimal approaches inherently require wave excitation force estimators. In particular, in array configurations, the interaction between WEC devices has to be taken into account to achieve a consistent excitation force estimation. In this paper, a linear time-invariant (LTI) estimation approach for a WEC farm is proposed. The technique proposed is based upon the so-called 'simple and effective estimator', recently presented in the WEC literature, which reformulates the wave excitation force estimation problem as a traditional tracking loop. The results show that the proposed approach provides accurate estimates of the exciting force for every device in the array, with almost no design effort, and mild computational requirements.

INTRODUCTION

In the actual context of severe climate change, and constant increase of pollution (mainly provoked by fossil fuels combustion for energy production), renewable energy sources are gaining relevance as power generation systems. Their main strength resides in the clean, carbon-dioxide free, operation, constituting a valuable alternative for electricity generation. Among available renewable energy sources, the most realisable and well-established are wind and solar conversion systems [1]. In contrast to well-established renewable energy sources, such as wind and solar, the wave energy field is still rather 'immature', *i.e.* technology has not yet converged to a particular standard [2]. In such scenario, research activity in the wave energy field plays a crucial role in allowing wave energy conversion technology to reach maturity, and hence develop its untapped potential [3].

A key stepping stone for the progress of wave technology is to maximise power extraction of Wave Energy Converters (WECs), hence directly minimising the associated levelised cost of energy. As already well-established within the WEC literature (see [4, 5]), such an objective can be achieved by tailored control technology, which aims at maximising the energy conversion from ocean waves by means of a suitably designed control law, applied through the associated power take-off (PTO) system. This technology, together with the development of so-called WEC arrays (or farms), which effectively incorporate several devices in a common sea area, constitute key stepping stones towards successful commercialisation of WEC technology.

Apart from notable exceptions (see e.g. [6]), the vast majority of state-of-the-art wave energy control strategies are based upon availability of the so-called wave excitation force, i.e. the force exerted by the waves on the WEC device [7–10]. Such a quantity is virtually always unmeasurable (see e.g. [11]), which translates to an inherent need for suitable wave excitation force estimators for the successful implementation of optimal WEC control technology.

Design and synthesis of state-of-the-art wave excitation force estimators can often be counter-intuitive, virtually always requiring an implicit model (differential equation) describing the nature of the wave excitation force, which is not trivial to compute [11]. This not only has an impact on the quality of the final estimation, but also requires the definition of an 'augmented' system, incorporating such excitation force model, potentially leading to an increased computational burden.

A recent study [12] shows an innovative procedure to design and synthesise a *simple and effective* wave excitation force estimator for WEC systems, without the need of any assumption on the wave force model. The main idea of the approach presented in [12] relies upon a novel interpretation of the unknown-input estimation problem in terms of a classical tracking loop, allowing the utilisation of well-known control algorithms to obtain an estimate of the wave excitation force. Nonetheless, the strategy presented in [12] focuses on a one single devices, hindering the potential performance of the estimator for the more realistic WEC array case. Motivated by the appealing characteristics of the estimator in [12], this study aims at developing a wave excitation force estimator for arrays of wave energy converters based on [12], using linear time-invariant (LTI) theory.

The reminder of this paper is organised as follows. Section 1 describes the procedure to derive the model of the WEC array under scrutiny. Section 2 presents the fundamentals of wave generation, while section 3 describes the design of the proposed estimator. Finally, Section 4 presents a numerical appraisal of the proposed strategy, while Section 5 summarises the main conclusions of the present study.

1 POINT ABSORBER WEC MODELLING

The WEC structure considered in this study (Fig. 1) is a point absorber with a spherical hull whose diameter is 4 [m]. The hull is then anchored to the PTO, positioned on the seabed. The device is constrained to move on its vertical direction only, hence being able to extract power only on its vertical direction z.

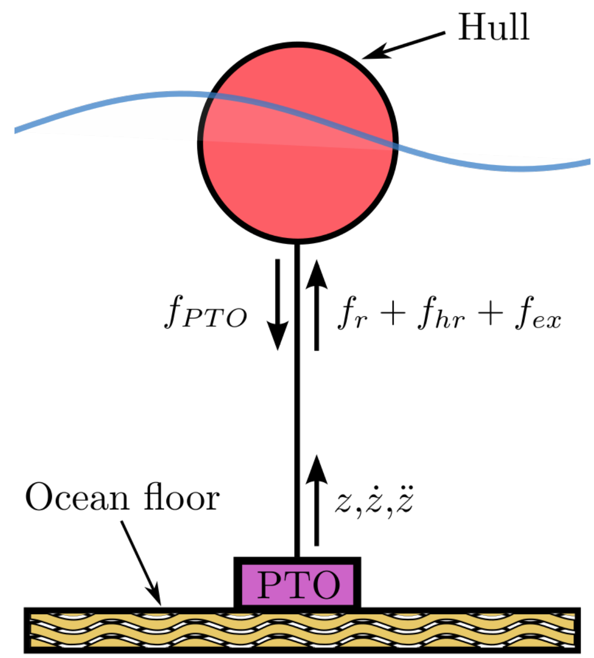

FIGURE 1. SCHEMATIC ILLUSTRATION OF A SINGLE POINT ABSORBER.

In time domain the WEC array heaving motion is described by the following dynamical system Σ:

$$\Sigma : \begin{cases} m\ddot{z}(t) = f_r(t) + f_{ex}(t) + f_{hr}(t) - f_{PTO}(t), \\ y(t) = \dot{z}(t), \end{cases} \tag{1}$$

where m is the WEC hull mass, f_r represents the radiation force, accounting for fluid memory effects, f_{ex} is the wave excitation force (*to be estimated*), f_{hr} is the restoring force, and f_{PTO} is the control action applied via the PTO system.

The restoring force f_{hr} can be expressed as a linear function of z (see e.g. [13]) i.e.

$$f_{hr}(t) = -k_0 z(t), \tag{2}$$

in which the linear coefficient k_0 is called *hydrostatic stiffness*.

Within linear potential flow theory, the force $f_r(t)$ can be represented in terms of a convolution operation through the so-called *Cummins* equation [14]. Considering just the heaving motion, the equation can be rewritten (see [15]) as:

$$f_r(t) = -m_\infty \ddot{y}(t) - \int_{\mathbb{R}} k_r(\tau) y(t-\tau) d\tau, \tag{3}$$

where $k_r \in L^2(\mathbb{R})$ is the radiation impulse response function, and where m_∞ is the so-called added mass at infinite frequency [16].

Given that the estimator design procedure presented in [12] requires the transfer function equivalent G_0 of system Σ, mapping the dynamic response from the total input force (intended as the algebraic sum between f_{ex} and f_{PTO}) to the WEC velocity, the following input-output approach to model the system has been adopted (see e.g. [17]). In particular, a boundary element method (BEM)-based software, OrcaWave, has been fed with a mesh of the chosen array configuration, depicted in in Fig.2. Note that the devices are deployed in a 'cross' configuration, in which each inter-distance is set to 20 [m].

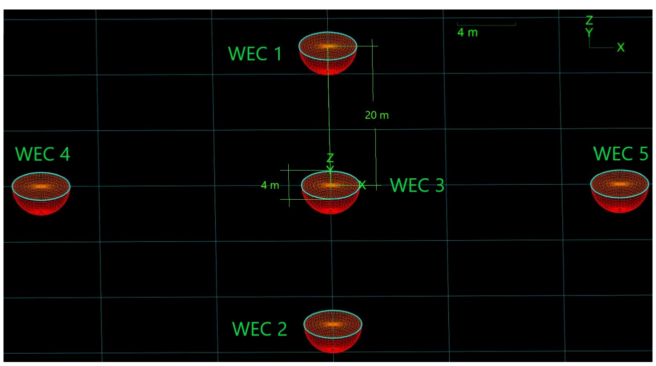

FIGURE 2. ARRAY CONFIGURATION

Since the Laplace transform of system (1) is always well-defined [15], the force-to-velocity (on the heave DoF) response mapping of the WEC array G_0 can be written, in the frequency-domain, as

$$G_0(j\omega) = \left(B(\omega) + j\omega(A(\omega) + m) + \frac{k_0}{j\omega} \right)^{-1} \tag{4}$$

where

$$K_r(j\omega) = B(\omega) + j\omega(A(\omega) - m_\infty), \tag{5}$$

with K_r the Fourier transform of the radiation impulse response map k_r in (3). With the values of $\{B(\omega), A(j\omega), k_0\}$, namely the radiation damping, the radiation added mass and the hydrostatic stiffness linear coefficients, facilitated through OrcaWave, one can obtain a parametric representation of G_0 through classical frequency-domain system identification techniques (see e.g. [18, 19]), and I the identity matrix.

It is important to note, at this point, that the frequency-response mapping in (4) must be computed taking into account the complete array characteristics, i.e. including all relevant interactions, represented via the set $\{B(\omega), A(j\omega), k_0\}$. Not considering such existing coupling can lead to an imprecise characterisation of the WEC array behaviour, as exemplified in Fig. 3. In particular, Fig. 3 shows the frequency-response Bode diagram of WEC 1 (see Fig. 2), where a difference can be appreciated between considering (solid) and ignoring (dashed) the corresponding hydrodynamic interactions, especially in the phase plot.

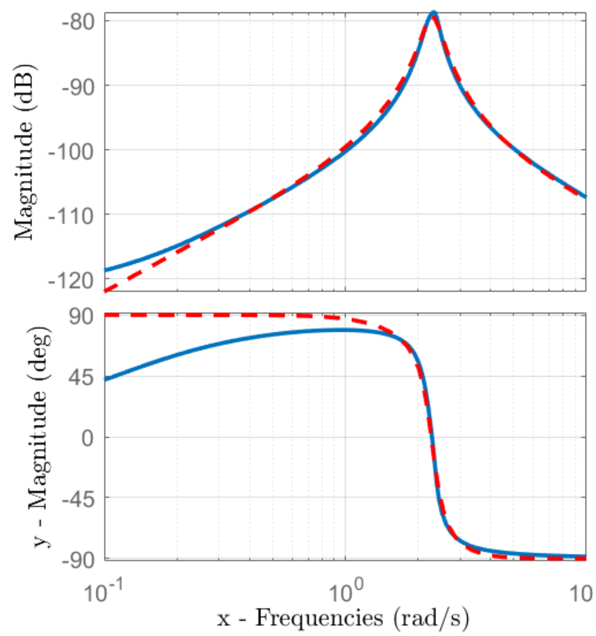

FIGURE 3. WEC 1 FREQUENCY RESPONSE: IN BLUE, THE INPUT OUTPUT RESPONSE FROM THE COUPLED SYSTEM, IN RED THE SINGLE WEC IDENTIFIED SYSTEM

With respect to the parameterised G_0, subsequently used in Section 2 for estimator design, Fig. 4 presents the so-called singular value diagram (also commonly known as sigma-plot within the system dynamics literature) of G_0, defining the WEC array dynamics. The identification has been performed in terms of a parametric model with order (dimension) of $n = 10$.

Fig. 4 presents the so-called singular value decomposition associated with the map G_0, i.e. the amplification (in [dBs]) produced by G_0 in each corresponding principal direction (the reader is referred to [REF] for further detail on singular value analysis of multi-input multi-output systems).

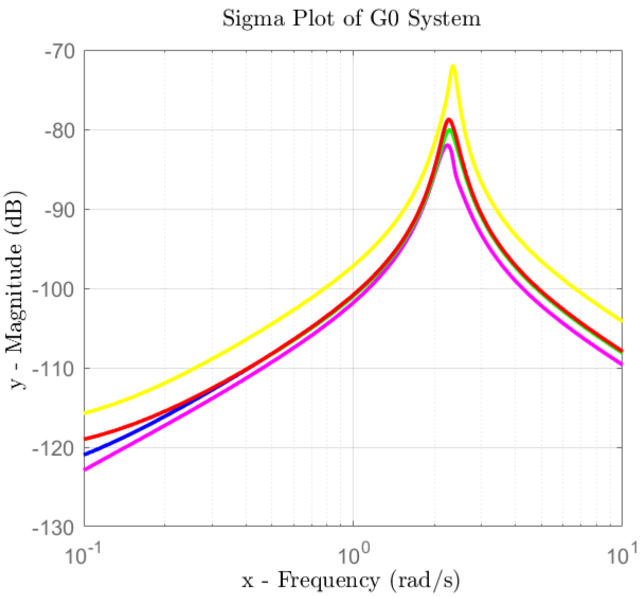

FIGURE 4. SINGULAR VALUES DECOMPOSITION PLOT OF THE PASSIVE SYSTEM.

If correctly parametrised, the transfer function G_0 must respect the following (physical) dynamical properties (see e.g. [12])

- G_0 is bounded-input bounded-output (BIBO) stable.
- G_0 is strictly proper.
- G_0 is passive.

These properties are effectively crucial in order to have a well-posed design procedure for the proposed estimator. Though BIBO stability and strict properness can be ensured via relatively standard system identification techniques, the last property listed above can be potentially complex to guarantee within the parameterisation procedure. In this paper, the passivation technique [20] is considered, rendering a representation of the WEC array dynamics G_0 capable of respecting all the fundamental physical properties underlying the wave energy absorption process.

2 WAVE GENERATION

In order to analyse the behaviour of the WEC array system, we consider standard ocean engineering numerical wave generation methods. In particular, it is assumed that the free surface-elevation map η can be modelled as the superposition of trigonometric polynomials [21], i.e.

$$\eta_t(t) = \sum_{k=1}^{M/2} A_k \cos(\omega_k t + \phi_k), \tag{6}$$

where $M/2$ denotes the number of chosen frequencies, ω_k is the k-th frequency component, with a corresponding amplitude defined by A_k. Finally, the value ϕ_k denotes a random phase shift, chosen such that $\phi_k \in [0, 2\pi]\ \forall k$. Note that the free-surface elevation for each WEC in the array is affected by a corresponding 'extra' phase component, accounting for the difference in distance (location) between devices.

Each corresponding wave component is generated in terms of a stochastic process, with an associated spectral density function $S(\omega)$, using a deterministic amplitude scheme fashion. For this application, a JONSWAP spectrum $S(\omega)$, a peak enhanced Pierson-Moskowitz spectrum, has been chosen, characterising a Pantelleria wave site. The map $S(\omega)$, illustrated herein in Fig. 5, is defined via two key parameters, i.e. significant wave energetic height H_s and energetic period T_e. In this case study, the incoming wave has supposed to be oriented as the inverse y axis in Fig.(2), i.e. (0,-1).

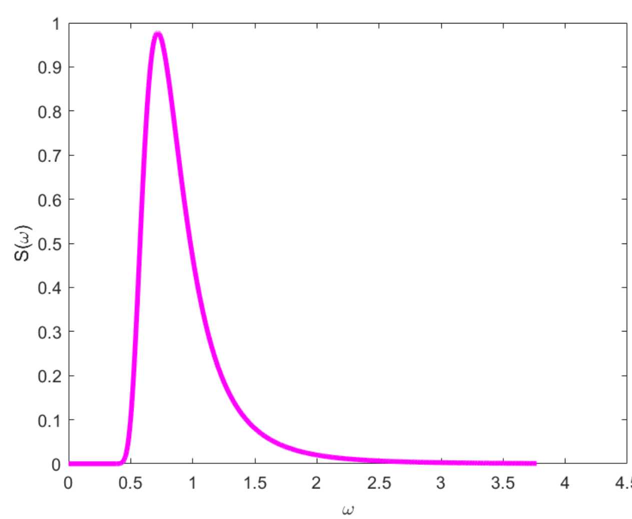

FIGURE 5. JONSWAP SPECTRUM FOR T_e = 6 [s] AND H_s = 1.5 [m].

3 ESTIMATOR DESIGN

To begin with the design of the estimator, based upon the theory presented in [12], let $v_m \in \mathbb{R}^5$ be the measured velocities

	Wave parameters		WEC Identifier					
	T_e	H_s	WEC 1	WEC 2	WEC 3	WEC 4	WEC 5	AVG
Wave 1	5.5	0.2	0.0034	0.0034	0.0033	0.0033	0.0033	0.0033
Wave 2	6.5	0.4	0.0033	0.0031	0.0031	0.0032	0.0032	0.0032
Wave 3	5	0.4	0.0037	0.0041	0.0037	0.0037	0.0037	0.0037
Wave 4	6	0.8	0.0028	0.0029	0.0031	0.0029	0.0029	0.0029
Wave 5	5.75	0.4	0.0034	0.0029	0.0031	0.0034	0.0034	0.0032
Wave 6	6.5	1.5	0.0033	0.0031	0.0031	0.0032	0.0032	0.0032
Wave 7	6.75	1.8	0.0027	0.0025	0.0027	0.0027	0.0027	0.0027
Wave 8	6.75	2	0.0027	0.0025	0.0027	0.0027	0.0027	0.0027
Wave 9	8	3.1	0.0026	0.0028	0.0026	0.0026	0.0026	0.0026
Wave 10	7.5	2,8	0.0024	0.0024	0.0024	0.0025	0.0025	0.0024
AVG			0.0030	0.0030	0.0030	0.0030	0.0030	**0.0030**

TABLE 1. Performance results for the proposed estimator in terms of NRSME.

for each WEC composing the array, $v \in \mathbb{R}^5$ the velocities generated from the WEC model G_0, and $u \in \mathbb{R}^5$ the control actions provided by the tracking controller K (see Fig. 6).

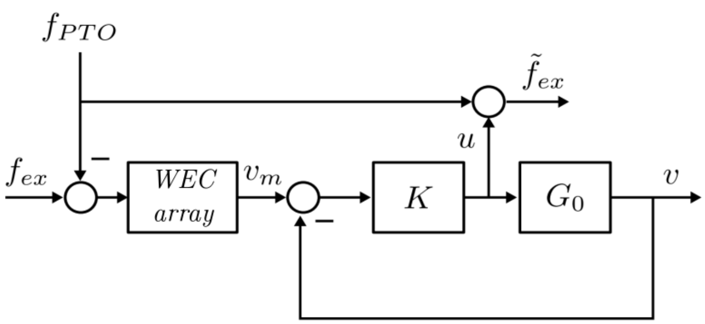

FIGURE 6. ESTIMATOR WORKING ARCHITECTURE

If the system G_0 describes well (i.e accurately) the behaviour of the real WEC array system, and the measured velocity signal v_m is effectively tracked asymptotically, it is straightforward to show [12] that

$$\lim_{t\to\infty} \|u - (f_{ex} - f_{PTO})\| \approx 0. \tag{7}$$

This directly implies that both the real system array, and the identified model of the system G_0, must be affected by the same input force, to produce the same output as $t \to \infty$. Moreover, since f_{PTO} is a user-defined (assumed measurable) variable, it is straightforward to provide an estimate for the wave excitation force as $\tilde{f}_{ex} = u + f_{PTO}$.

With respect to the design of the tracking controller K, a Youla-Kucera parametrization has been chosen (see [22]), following [12]. This technique is based upon the definition of a stable transfer function $Q(s)$ which parametrises the so-called family of all stabilizing controllers:

$$K(s) = (\mathbb{I} - Q(s)G_0(s))^{-1} Q(s). \tag{8}$$

Following [12], and given that G_0 is minimum-phase (as a consequence of its passivity property), Q is chosen as an approximation of the inverse of G_0. In particular, the mapping Q is defined as

$$Q(s) = G_0(s)^{-1} F_q(s), \tag{9}$$

where $F_q(s)$ denotes a *shaping filter*. For this application, F_q has been chosen in terms of a second-order filter with coincident real stable poles at $s = 50$, i.e.

$$F_q(s) = \frac{1}{(1+s\frac{1}{50})^2}\mathbb{I}. \tag{10}$$

4 SIMULATION RESULTS

This section presents simulation results to evaluate the performance of the proposed estimator. In particular, the numerical analysis has been have been carried out for 10 different sea states characterising the Pantelleria wave site. Each simulation has a time-length of 600 [s], and results are reported in Tab. 1. 600 [s] is a time length suitable for simulation, since almost all the frequency components of a typical irregular wave are produced, exciting the dynamical response of the estimator system. To be specific, Tab. 1 presents the normalised root mean square error (NRMSE) between the target wave force exciting the WEC, and that estimated by means of the the proposed technique. Note that the NRMSE is defined herein as

$$\text{NRMSE} = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(\tilde{f}_{ex} - f_{ex})^2}}{(\max|\tilde{f}_{ex}| - \min|\tilde{f}_{ex}|)/2}. \tag{11}$$

It can be appreciated, from Tab. 1, that the performance of the estimator is highly accurate for the totality of the evaluated sea-states, showing the potential of the proposed strategy. To further illustrate the accuracy of the synthesised estimator, Fig. 7 presents estimation results for a particular sea-state realisation, where it can be appreciated that both target (solid) and estimated (dashed) wave excitation forces are virtually indistinguishable from each other.

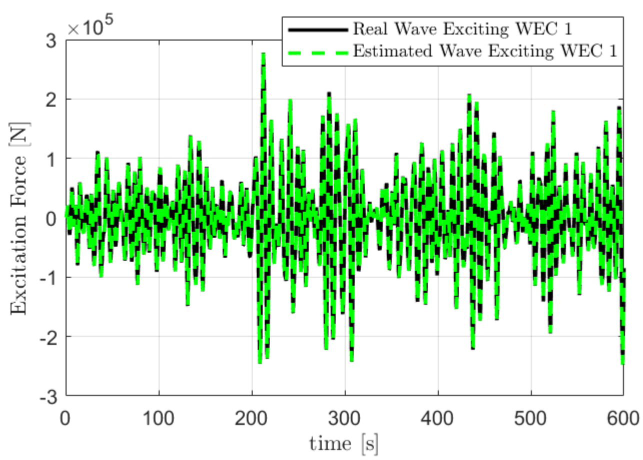

FIGURE 7. ESTIMATION RESULTS FOR A PARTICULAR SEA-STATE REALISATION

Fig 8 shows the behaviour in terms of phase delay between the real force exciting the WEC and the estimation provided.

It is worth noticing that tests have been performed with different values of T_e and H_s. However it has been assumed to be irrelevant to exceed $T_e = 9\ s$, since no realistic waves (speaking about the considered Mediterranean sea spot, in Pantelleria) overcome such energetic period in their spectrum realisation. Moreover, such sea state components are damped by the system, since they are enough far from the resonance peak of the devices. In contrast, since the estimator system is basically a low - pass filter, it has been found superfluous to analyze sea satte with too large wave periods.

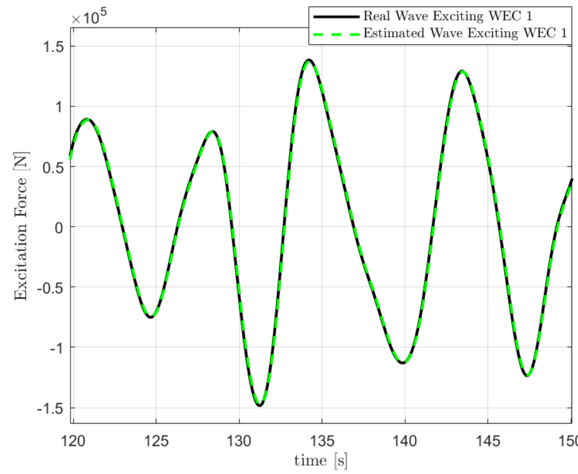

FIGURE 8. CLOSE UP OF FIGURE 7 BETWEEN 120 [s] AND 150 [s].

5 CONCLUSIONS

In this paper, the excitation force estimator for wave energy converter developed in [12] is considered for the case of an array configuration of five spherical point absorbers. This is achieved via a suitable (physically consistent) definition of the corresponding WEC array model, and the design and synthesis of a particular tracking loop. The estimator is shown to be both highly accurate, and simple to design, without the need of a particular model for the wave excitation force input, and fully based upon well-established LTI theory. Future work will analyse the extension of this framework for nonlinear WEC array systems.

REFERENCES

[1] Astariz, S., and Iglesias, G., 2015. "The economics of wave energy: A review". *Renewable and Sustainable Energy Reviews,* ***45***, May, pp. 397–408.

[2] Trueworthy, A., and DuPont, B., 2020. "The Wave Energy Converter Design Process: Methods Applied in Industry and Shortcomings of Current Practices". *Journal of Marine Science and Engineering,* ***8***(11), Nov., p. 932. Number: 11 Publisher: Multidisciplinary Digital Publishing Institute.

[3] Mattiazzo, G., 2019. "State of the Art and Perspectives of Wave Energy in the Mediterranean Sea: Backstage of ISWEC". *Frontiers in Energy Research,* ***7***.

[4] Ringwood, J., 2020. *Wave energy control: status and perspectives 2020*. July.

[5] Ringwood, J. V., Bacelli, G., and Fusco, F., 2014. "Energy-Maximizing Control of Wave-Energy Converters: The Development of Control System Technology to Optimize Their Operation". *IEEE Control Systems Magazine,* ***34***(5), Oct., pp. 30–55. Conference Name: IEEE Control Systems Magazine.

[6] Pasta, E., Veale, T., Papini, G., Carapellese, F., Bracco, G., and Mattiazzo, G., 2021. *Collaborative strategy for model-free control of arrays of wave energy converters: A genetic algorithm approach*. Sept.

[7] Hals, J., Falnes, J., and Moan, T., 2010. "Constrained Optimal Control of a Heaving Buoy Wave-Energy Converter". *Journal of Offshore Mechanics and Arctic Engineering,* ***133***(1), Nov.

[8] Cretel, J. A. M., Lightbody, G., Thomas, G. P., and Lewis, A. W., 2011. "Maximisation of Energy Capture by a Wave-Energy Point Absorber using Model Predictive Control". *IFAC Proceedings Volumes,* ***44***(1), Jan., pp. 3714–3721.

[9] Li, G., and Belmont, M. R., 2014. "Model predictive control of a sea wave energy converter: a convex approach". *IFAC Proceedings Volumes,* ***47***(3), Jan., pp. 11987–11992.

[10] Faedo, N., Olaya, S., and Ringwood, J. V., 2017. "Optimal control, MPC and MPC-like algorithms for wave energy systems: An overview". *IFAC Journal of Systems and Control,* ***1***, Sept., pp. 37–56.

[11] Peña-Sanchez, Y., Windt, C., Davidson, J., and Ringwood, J. V., 2020. "A Critical Comparison of Excitation Force Estimators for Wave-Energy Devices". *IEEE Transactions on Control Systems Technology,* ***28***(6), Nov., pp. 2263–2275. Conference Name: IEEE Transactions on Control Systems Technology.

[12] Faedo, N., Bussi, U., Peña-Sanchez, Y., Windt, C., and Ringwood, J. V., 2022. "A Simple and Effective Excitation Force Estimator for Wave Energy Systems". *IEEE Transactions on Sustainable Energy,* ***13***(1), Jan., pp. 241–250. Conference Name: IEEE Transactions on Sustainable Energy.

[13] Faedo, N., Scarciotti, G., Astolfi, A., and Ringwood, J. V., 2021. "Nonlinear Energy-Maximizing Optimal Control of Wave Energy Systems: A Moment-Based Approach". *IEEE Transactions on Control Systems Technology,* ***29***(6), Nov., pp. 2533–2547. Conference Name: IEEE Transactions on Control Systems Technology.

[14] Cummins, W., C, D. T. M. B. W. D., and Basin, D. W. T. M., 1962. *The Impulse Response Function and Ship Motions*. Report (David W. Taylor Model Basin). Navy Department, David Taylor Model Basin.

[15] Falnes, J., and Kurniawan, A., 2020. *Ocean waves and oscillating systems: Linear interactions including wave-energy extraction*, Vol. 8 of *Cambridge Ocean Technology Series*. Cambridge University Press, UK.

[16] Bosma, B., Zhang, Z., Brekken, T. K., Özkan Haller, H. T., McNatt, C., and Yim, S. C., 2012. "Wave energy converter modeling in the frequency domain: A design guide". In 2012 IEEE Energy Conversion Congress and Exposition (ECCE), pp. 2099–2106. ISSN: 2329-3748.

[17] Bacelli, G., Coe, R. G., Patterson, D., and Wilson, D., 2017. "System Identification of a Heaving Point Absorber: Design of Experiment and Device Modeling". *Energies,* ***10***(4), Apr., p. 472. Number: 4 Publisher: Multidisciplinary Digital Publishing Institute.

[18] Ozdemir, A. A., and Gumussoy, S., 2017. "Transfer Function Estimation in System Identification Toolbox via Vector Fitting". *IFAC-PapersOnLine,* ***50***(1), July, pp. 6232–6237. arXiv: 2003.06289.

[19] Drmac, Z., Gugercin, S., and Beattie, C., 2015. "Quadrature-Based Vector Fitting: Implications For H2 System Approximation". *SIAM Journal on Scientific Computing,* ***37***(2), Jan., pp. A625–A652. arXiv: 1403.4655.

[20] Faedo, N., Peña-Sanchez, Y., Carapellese, F., Mattiazzo, G., and Ringwood, J. V., 2021. "LMI-based passivation of LTI systems with application to marine structures". *IET Renewable Power Generation,* ***15***(14), pp. 3424–3433. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1049/rpg2.12286.

[21] Mérigaud, A., and Ringwood, J. V., 2018. "Free-Surface Time-Series Generation for Wave Energy Applications". *IEEE Journal of Oceanic Engineering,* ***43***(1), Jan., pp. 19–35. Conference Name: IEEE Journal of Oceanic Engineering.

[22] Youla, D., Bongiorno, J., and Jabr, H., 1976. "Modern Wiener–Hopf design of optimal controllers Part I: The single-input-output case". *IEEE Transactions on Automatic Control,* ***21***(1), Feb., pp. 3–13. Conference Name: IEEE Transactions on Automatic Control.