Observer-based fault estimation applied to a point absorber wave energy converter

Guglielmo Papini*, Giuliana Mattiazzo, and Nicolás Faedo

Abstract—**In the context of increasing interest in renewable energy systems as fossil-free power generation sources, wave energy can play a crucial role inside the future energy mix. In the path towards economic viability, a fundamental role is played by energy-maximising control structures in charge of optimising the power extracted from the wave motion. A large part of such strategies rely on models, *i.e.* descriptions of the system in charge of capturing the fundamental dynamics of the wave energy extraction process. Nonetheless, the harmful marine environment can change the corresponding system dynamics by introducing faulty conditions, which can compromise the effectiveness of standard energy-maximising control algorithms. In this context, a crucial role is played by fault diagnosis and isolation (FDI) structures, which are designed to detect eventual faults in dynamical systems. FDI routines are a fundamental part of the so-called active fault-tolerant control structures, able to accommodate the fault effects. Motivated by this, this paper proposes the implementation of a FDI strategy based on an unknown input observer (UIO), to estimate system faults in spite of the constant disturbance introduced by the wave signal exciting the WEC. The UIO is then tested under different irregular wave conditions, showing consistency of fault estimation on both actuator and velocity sensor components.**

Index Terms—**Wave energy, optimal control, fault diagnosis and isolation, model-based observer, unknown-input observer**

I. Introduction

THE recent harmful situation concerning CO_2 emissions is pushing research towards alternative, fossil-free energy sources [1]. Among them, renewable energies are tracing the way, thanks to the theoretic inexhaustible primary sources, *e.g.* wind and solar energy, and the absence of CO_2 production during power generation. Among renewable systems, wave energy is a promising solution [2], exploiting the wave motion to convert the mechanical power generated by the sea into electrical energy. The devices in charge of accomplishing this task are termed wave energy converters (WECs), such as electro-mechanical actuated floating buoys, which exploit the wave motion to generate electrical power.

Nonetheless, WECs development is facing economic viability challenges [3], which are to be adequately faced to allow an effective commercialisation of the technology. In this direction, energy-maximising optimal control (OC) algorithms [4], [5] are valuable tools to extract the maximum power available from the wave motion while respecting the set of technological limitations of the controlled device, *e.g.* given limits on the actuator action magnitude and/or maximum displacement of the WEC floating buoy. As a matter of fact, a large part of OC algorithms relies on mathematical descriptions of WEC systems, which are intended to capture the most relevant dynamics of the system concisely, without being excessively burdening from a computational complexity point of view [6]. In this framework, the complex environment in which WEC systems operate regularly constitutes a relevant obstacle, since extreme circumstances contribute in damaging the system [7], and thus in changing its dynamical behaviour. Such a serendipitous circumstance is not considered directly in the optimisation of classical model-based OC strategies and, as a consequence, a consistent discrepancy between the model and the actual system behaviour can effectively incur, leading to the loss of optimality of the control solution obtained by energy-maximising optimal controllers.

In this context, a functional role is played by fault diagnosis, isolation and estimation (FDI) algorithms [8], [9], which are in charge of detecting eventual faults acting in dynamical systems. This information can be used for both detecting the specific faulty components and, more importantly, accommodating their effects on energy-maximising performance, by exploiting fault-tolerant control (FTC) routines [10]. In particular, active FTC algorithms are effective in accommodating, on the basis of the information provided by FDI systems, the effect of faults, even in the context of control optimality.

An additional aspect to be considered is related to the excitation force (disturbance) exerted by the wave motion on the device. Such a signal influences the dynamical behaviour of the WEC system, essentially acting as a stochastic input disturbance. Knowledge of this disturbance is, in general, effectively employed by OC strategies to compute the optimal control condition, which maximises power extraction. Nonetheless, the wave excitation force can not be measured in practice [11], and the most common solution to retrieve approximate information is performed via model-based wave estimators, which can be structurally affected by the same model-system model discrepancy described immediately above this paragraph.

Following this reasoning, this paper proposes a FDI unknown input observer (UIO) [12], which is designed to estimate actuator and sensor faults without the explicit knowledge of the wave excitation force. In

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particular, the estimator is designed on the basis of a system model, and features the ability to be insensitive, *i.e.* rejecting, to the wave excitation signal and any other eventual sources of uncertainty with the same (system) input map. Such an observer is intended to be the auxiliary structure for eventual FTC algorithms, in charge of increasing the energy-maximising control strategy optimality condition resilience with respect to unpredictable changes in the system dynamical behaviour provoked by eventual faults. The proposed observer is designed to estimate the faulty conditions independently on the sea state exciting the WEC, *i.e.* it is fully insensitive to the wave excitation force while accurately reconstructing the fault signal shape.

The remainder of this paper is structured as follows. Section II introduces the mathematical background of the models employed in the observer design. Section III describes the UIO architecture and features, while Section IV is intended to briefly illustrate the energy-maximising control strategy included in the simulation/observer assessment stage. The main results of this work are given in Section V, where the fault estimation performances are evaluated and discussed. Section VI provides the main concepts obtained from this study and underlines possible future directions for the field.

II. Modelling preliminaries

Within this study, a cylindrical vertical point-absorber wave energy converter is considered. The buoy is moved by the waves, and a power take-off (PTO) system is in charge to drive the device motion to extract the mechanical energy transmitted by this wave force. The system considered in this study is constrained to move in a single degree-of-freedom (DoF), *i.e.* the vertical motion on the z axis (see figure 1). The physical parameters of the system are described in Table I.

TABLE I
System modelling parameters nomenclature.

Parameter	Symbol
Buoy mass	m
Added mass at infinite frequency	m_∞
Hydrostatic Coefficient	k_h
System (7) dimension	n
Radiation state dimension	n_r
Motor system state dimension	n_m

Within linear potential flow conditions, the system dynamical behaviour in z can be hence described as

$$\ddot{z} = M^{-1}(f_h + f_r + f_w + u), \tag{1}$$

where $M = m + m_\infty$ is the total mass, $u : \mathbb{R}^+ \to \mathbb{R}$ is the control force applied via the corresponding PTO system, and $f_w : \mathbb{R}^+ \to \mathbb{R}$ is the wave excitation force. The map $f_h : \mathbb{R}^+ \to \mathbb{R}$ is the hydrostatic restoring force, defined as

$$f_h = -k_h z, \tag{2}$$

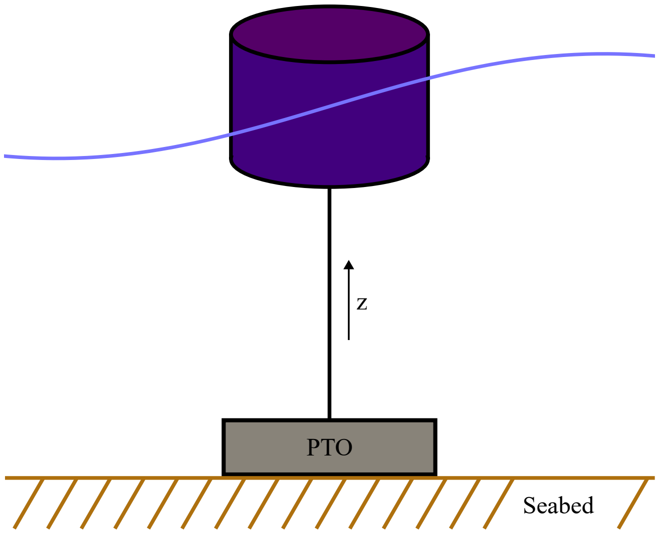

Fig. 1. Schematic representation of the cylindrical point absorber.

while the radiation force $f_r : \mathbb{R}^+ \to \mathbb{R}$, according with [13], is described with the convolution integral in (3)

$$f_r = -\int_{\mathbb{R}} k_r(\tau)\dot{z}(t-\tau)\mathrm{d}\tau, \tag{3}$$

where k_r is the impulse response map of the radiation force. In order to solve the integral in (3), boundary element methods software, *e.g.* NEMOH [14] or OrcaWave [15], can be employed for providing a numerical characterisation of k_r. Given this, it is possible to represent (3) is a state-space form

$$\begin{cases} \dot{\xi} = A_r\xi + B_r\dot{z}, \\ f_r = C_r\xi \end{cases} \tag{4}$$

with the radiation system state $\xi \in \mathbb{R}^{n_r}$, $A_r \in \mathbb{R}^{n_r \times n_r}$, $B_r \in \mathbb{R}^{n_r}$, $C_r \in \mathbb{R}^{1 \times n_r}$. The term u in (1) represents the actual control signal provided to the system. Nonetheless, such input is effectively influenced by the dynamics of the PTO system, which are modelled as a dynamical system

$$\begin{cases} \dot{\phi} = A_m\phi + B_m u_m, \\ u = C_m\phi, \end{cases} \tag{5}$$

with the PTO system state $\phi \in \mathbb{R}^{n_m}$, the control reference input $u_m(t) \in \mathbb{R}$ $A_m \in \mathbb{R}^{n_m \times n_m}$, $B_m \in \mathbb{R}^{n_m}$, $C_m \in \mathbb{R}^{1 \times n_r}$.

Defining

$$A = \begin{bmatrix} 0 & 1 & 0 \\ -k_h M^{-1} & 0 & -C_r M^{-1} \\ 0 & B_r & A_r \end{bmatrix}, \quad B = B_w = \begin{bmatrix} 0 \\ M^{-1} \\ 0 \end{bmatrix}$$
$$C = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix}, \tag{6}$$

$A \in \mathbb{R}^{n \times n}$, $B \in \mathbb{R}^n$, $C \in \mathbb{R}^{2 \times n}$, and the system state vector $x = [z, \dot{z}, \xi^\intercal]^\intercal \in \mathbb{R}^n$, $y = [\dot{z}, z]^\intercal$, the system in (1) can be described in state-space form as

$$\Sigma : \begin{cases} \dot{x} = Ax + Bu + Bf_w, \\ y = Cx, \end{cases} \tag{7}$$

III. Observer design

As discussed in Section I, the objective is to design a reliable unknown-input observer which is insensitive with respect to the wave excitation force f_w, and is able to guarantee a correct state estimation without considering a specific dynamical model of the fault acting on the system. In this section, the authors propose a step-by-step procedure to design such an observer, following the theoretical background in [12].

Since the scope is to estimate both actuator and sensor faults, the observer must be sensitive to those quantities. As discussed later in Remark 2, the consequence of defining a wave-insensitivity condition, *i.e.* with respect to the input dynamics B_w in (7), is to reject also the control input u influence on the state observation. Therefore, if the actuator is not influencing the state estimate, it is not possible to reconstruct eventual faults on such control signal either. A possible solution is to estimate as well the system (5) states and then reconstruct u on the basis of such an estimate.

Defining the state $x_a = [x^\intercal, \phi^\intercal]^\intercal$, and the matrices as

$$\begin{aligned} A_a &= \begin{bmatrix} A & BC_m \\ 0 & A_m \end{bmatrix}, \qquad B_a = \begin{bmatrix} 0 \\ B_m \end{bmatrix}, \qquad B_{wa} = \begin{bmatrix} B_w \\ 0 \end{bmatrix}, \\ C_a &= \begin{bmatrix} C & 0 \end{bmatrix}, \qquad C_{am} = \begin{bmatrix} 0 & C_m \end{bmatrix}, \end{aligned} \tag{8}$$

the augmented system dynamics are

$$\begin{cases} \dot{x}_a = A_a x_a + B_a u_m + B_{wa} f_w, \\ y = C_a x_a, \\ u = C_{am} x_a, \end{cases} \tag{9}$$

with the system matrices of appropriate dimensions.

Following [12], the UIO structure can be represented as

$$\begin{cases} \dot{\zeta} = F\zeta + TB_a u_m + Ky, \\ \hat{x}_a = \zeta + Hy, \\ \hat{y} = C_a \hat{x}_a, \\ \hat{u} = C_{am} \hat{x}_a, \end{cases} \tag{10}$$

where $\hat{x}_a$ stands for the augmented system state estimate.

The observer in (10) can be made insensitive w.r.t. f_w if and only if the following rank condition

$$\text{rank}(B_{wa}) = \text{rank}(C_a B_{wa}), \tag{11}$$

is satisfied. Then, the observer (10) is made insensitive to f_w if the matrix H solves the following linear matrix equation:

$$HC_a B_{wa} = B_{wa}, \tag{12}$$

which decouples the unknown term f_w dynamics from the observer state estimate convergence. A special solution of (12) is

$$H = (C_a B_{wa})^\dagger B_{wa}, \tag{13}$$

where the symbol $\dagger$ is for the Moore-Penrose left pseudo-inverse operation.

The objective is to make the dynamical behaviour of the state estimation error in (10) only dependent on F, *i.e.*

$$\dot{e} = Fe, \tag{14}$$

where $e = x_a - \hat{x}_a$. Defining the set of equations

$$\begin{aligned} T &= \mathbb{I} - HC_a, \\ F &= A_a - HC_a A_a - K_1 C_a, \\ K_2 &= FH, \end{aligned} \tag{15}$$

where $K = K_1 + K_2$ is a free design parameter, and $\mathbb{I}$ denotes an identity matrix with appropriate size.

The satisfaction of (15) with (13) effectively achieves the objective in (14). Thus, one has to design the matrix K to ensure that F is Hurwitz, consequently ensuring the asymptotic convergence of the estimation error. Note that the stabilisation of F in (15) can be achieved when the detectability condition is satisfied for the pair (A_1, C_a), where $A_1 = A_a - HC_a A_a$. In our case, this condition is not achieved, and an observable canonical decomposition of the system has to be employed, which is given by

$$\begin{aligned} WA_1W^{-1} &= \begin{bmatrix} A_{11} & 0 \\ A_{12} & A_{22} \end{bmatrix}, \\ C_a W^{-1} &= \begin{bmatrix} \bar{C}_a & 0 \end{bmatrix}, \end{aligned} \tag{16}$$

where $A_{11} \in \mathbb{R}^{n_1 \times n_1}$, $\bar{C} \in \mathbb{R}^{2 \times n1}$, n_1 is the rank of (A_1, C_a) pair observability matrix, and W is a suitably selected equivalent transformation. With this choice, it is evident that if the submatrix A_{22} has eigenvalues with positive real part, it is not possible to stabilise F. An additional condition, is that the pair $(A_{11}, \bar{C}_a)$ is observable, so that a feedback gain K_{1w} can be designed so that

$$\begin{aligned} F &= A_1 - K_1 C_a = W^{-1} \begin{bmatrix} A_{11} - K_{1w}\bar{C}_a & 0 \\ A_{12} - K_{2w}\bar{C}_a & A_{22} \end{bmatrix} W, \\ WK_1 &= \begin{bmatrix} K_{1w} \\ K_{2w} \end{bmatrix}. \end{aligned} \tag{17}$$

It has to be noticed that, in principle, matrix K_{2w} can be chosen arbitrarily, since its choice does not affect the eigenvalues of F.

Remark 1. *In the case of non-detectability condition of the pair (A_1, C_a), the dynamics of the observer are affected directly by the eigenvalues of A_{22}. This implies that some undesired filtering behaviour may be introduced in the observer performance, e.g. if A_{22} introduces low-frequency poles, which lead to low-pass filter properties, and high-frequency faults cannot be adequately estimated.*

As mentioned in Section I, FDI algorithms analyse the system behaviour utilising quantities named residuals, which are intended to represent in some way the relationship between the system faultless and damaged cases. In some scenarios, such signals are intended to give information about the specific faults, but not necessarily a direct estimate of them. Nonetheless, the observer (10) is designed to minimise the estimation error of both the velocity sensor and the control measurements, thus, such an architecture consents to retrieve the direct estimate of possible faults on the aforementioned components.

Remark 2. *The wave signal insensitivity condition in* (13) *has to be considered carefully, especially when a desired outcome for the observer is to reconstruct the eventual* *actuator fault. Actually, if the control input dynamics B_a coincides with the disturbance matrix is spanned by the same columns space of B_{wa}, the conditions in* (13) *and* (15) *lead to an observer insensitivity towards the actuator signal, i.e.* $TB_a = 0$. *This motivates the choice in* (8), *where matrices B_a and B_{wa} are generated by linear independent basis vectors.*

IV. Control architecture

As mentioned in Section II, the design of the control input acting on the WEC is performed in terms of an energy-maximising criterion. In this case, the choice is based on the impedance-matching control principle (or complex-conjugate control), parameterised in terms of a proportional-integral (PI) structure [16]. Such a law is based on generating, within the chosen control structure, the equivalent of maximum power transfer condition in electrical circuits by matching the control structure with the complex inverse conjugate of the system response for a specific frequency. In this work, the Laplace transform of a given function f, given its existence, is $F(s)$, $s \in \mathbb{C}$. Additionally the WEC velocity $\dot{z}$ can be also denoted with $\dot{z} \equiv v$.

For the subsequent control design, it is convenient to introduce system (1) Laplace domain equivalent

$$sM^{-1}V(s)+K_r(s)V(s)+\frac{k_h}{s}V(s) = F_w(s)+U(s). \quad (18)$$

Following [17], and writing the input-output force-to-velocity response,

$$V(s) = G(s)[Fw(s) + U(s)], \quad (19)$$

re-writing $K_r(s)$ as $K_r(s) = K_{rN}(s)/K_{rD}(s)$, $G(s)$ is

$$G(s) = \frac{K_{rD}(s)s}{M^{-1}K_{rD}(s)s^2 + K_{rN}(s)s + K_{rD}(s)k_h}. \quad (20)$$

Letting the control system be represented by the complex mapping $I : \mathbb{C} \to \mathbb{C}$, the IM-based control law must respect

$$I(j\omega) = \frac{1}{G^\star(j\omega)}, \quad (21)$$

evaluated at every $\omega \in \mathbb{R}^+$, and where $G^\star(j\omega)$ denotes the complex conjugate of the function evaluated at the specific frequency. Nonetheless, the condition in (21) gives origin to a non-causal law, which is intrinsically non-implementable (see *e.g.* [16]). A practical solution for this problem is to implement a mapping which satisfies (21) in a narrowbanded sense, *e.g.* for the energetic wave period (T_e) of the characteristic sea state, *i.e.* is respected in correspondence of $\omega = \omega_p = \frac{2\pi}{T_e}$.

Considering a PI control structure

$$I(s) = \theta_p + \frac{\theta_i}{s}, \quad (22)$$

the parameters are chosen according with

$$\theta_p = \Re(I(j\omega_p)), \quad \theta_i = -\omega_p \Im(I(j\omega_p)) \quad (23)$$

where $\Re(\cdot)$ and $\Im(\cdot)$ denote the real and imaginary part operators.

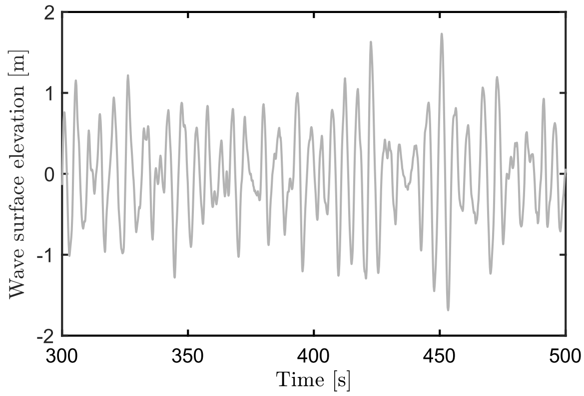

Fig. 2. Partial timetrace of the wave elevation employed for simulation.

V. Results

This section presents an account of the main results of this paper, providing an appraisal of the FDI system fault estimation characteristics, in the presence of other component damages, both in case of isolated and simultaneous faults. Within this study, the geometrical and physical parameters of the device are based on [18].

To evaluate the performance of the proposed FDI strategy, an irregular wave scenario based on a JONSWAP spectrum [19] description, with a fixed peak-enhancement factor of 3.3, energetic period $T_e = 6.4$ [s] and significant height $H_s = 2.1$ [m], obtained from the scatter data of the Pantelleria site [20], is considered. Figure 2 shows a snippet of the time trace of the employed wave elevation signal.

The system is affected both by velocity sensor and actuator faults, in an additive fashion. Formally,

$$\begin{cases} u = u + u_f, \\ y = y + y_f, \end{cases} \quad (24)$$

where

$$u_f = \begin{cases} 0, & 0 \le t \le t_2, \\ -u, & t_2 \le t \le t_3, \\ 0, & t_3 \le t \le t_4, \\ 60t - 24000, & t_4 \le t \le t_5, \\ 0, & t_5 \le t \le t_7, \\ 4000\sin(t), & t_7 \le t \le t_{end}, \end{cases} \quad (25)$$

and

$$y_f = \begin{cases} 0, & 0 \le t \le t_1, \\ -y, & t_1 \le t \le t_2, \\ 0, & t_2 \le t \le t_3, \\ -0.025t + 7.5, & t_3 \le t \le t_4, \\ 0, & t_4 \le t \le t_6, \\ \sin(t), & t_6 \le t \le t_8, \\ 0, & t_8 \le t \le t_{end}, \end{cases} \quad (26)$$

with $[t_1, t_2, t_3, t_4, t_5, t_6, t_7, t_8, t_{end}] = [100, 200, 300, 400, 500, 600, 700, 800, 1000]$ [s]. The residual vector is then generated by comparing the

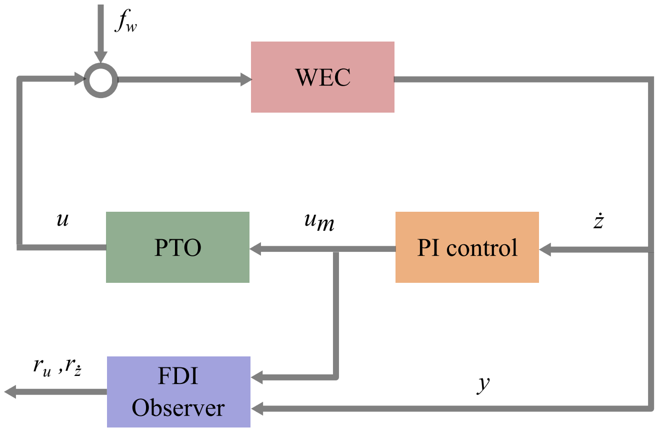

Fig. 3. Architecture of the system under consideration, comprising the WEC, the PTO, the PI impedance matching-based controller, and the FDI block.

actual measurement of the signal in consideration and is defined as $r_{\dot{z}} = \dot{z} - \hat{\dot{z}}$ and $r_u = u - \hat{u}$.

Remark 3. *The construction of a robust residual $r_{\dot{z}}$ relies on the displacement measurement (z) availability. As a matter of fact, if the observer does not estimate the velocity output by employing a measurement which is not connected with the fault itself, it is impossible to reconstruct the proper behaviour of $\dot{z}$. The same applies for r_u, which also considers the nominal control action u_m to converge at consistent estimates for u.*

An appraisal of the actuator fault estimate is given in Fig. 4, where the observer proves its efficiency in tracking the fault signal affecting the actuation dynamics.

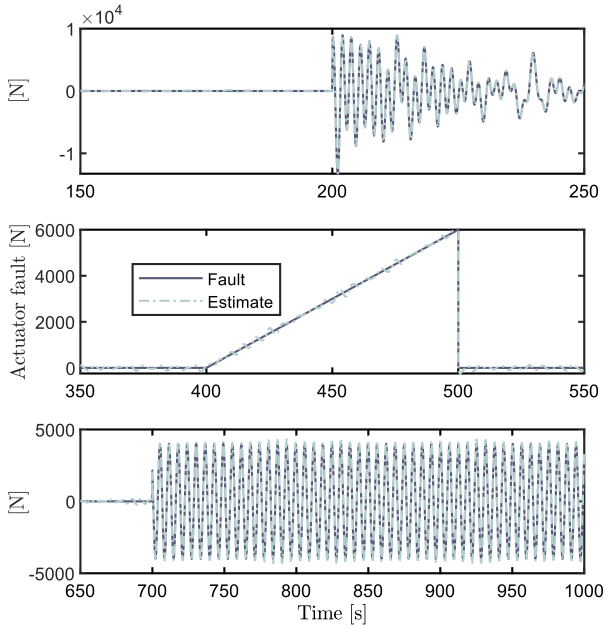

Fig. 4. Actuator fault: real signal (continuous line) and estimate (dashed line). Input wave energetic period $T_e = 6.4$ [s] and significant height $H_s = 2.1$ [m]. The x axis indicates the time (in seconds), while the y axis is the timetrace of each actuator fault condition.

The counterpart relative to $\dot{z}$ sensor fault estimate is in Fig. 5

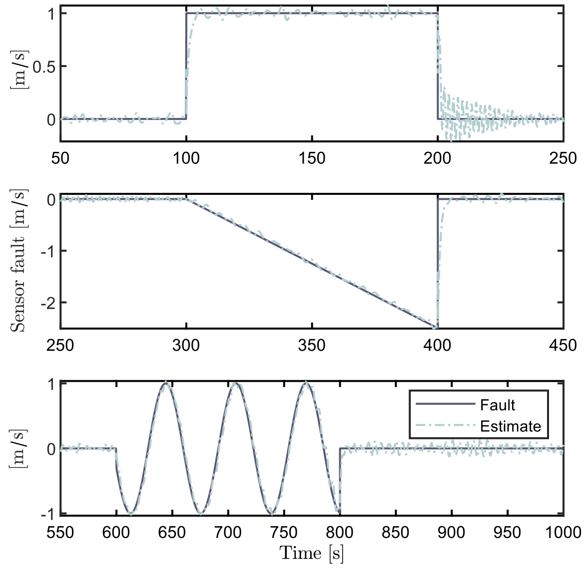

Fig. 5. Sensor fault: real signal (continuous line) and estimate (dashed line). Input wave energetic period $T_e = 6.4$ [s] and significant height $H_s = 2.1$ [m]. The x axis indicates the time (in seconds), while the y axis is the timetrace of each sensor fault condition.

The observer is also effective in distinguishing between actuator and sensor faults when they are occurring simultaneously. In fact, from t_7 and t_8, both of the considered faults are present in the system, as detected from Fig. 4 and Fig. 5. Nonetheless, after t_8, the FDI block recognises that a malfunction is acting on the sensor subsystem only, while actuation is working properly. This can also be appreciated between t_6 and t_7 time periods, over which only the actuator presents faulty behaviour.

In the case of sensor fault detection, the observer is affected by an appreciable estimation error, even if effective fault behaviour tracking is obtained. This phenomenon is connected with the reasoning in Remark 1: the uncontrollable modes of the observer dynamics introduce a system response which is characterised by an oscillatory behaviour in transient periods. Furthermore, from the analysis of the observer dynamics in 6, it appears clear that high-frequency components cannot be reconstructed properly, thus evidencing a structural limit of the proposed UIO in this particular application.

To test the observer robustness, a different wave scenario is considered. In particular, the wave spectrum is a JONSWAP with a different energetic period and wave significant height, *i.e.* $T_e = 4.6$ [s] and $H_s = 1.5$ [m], while the faults are the same as in (25) and (26). In Fig. 7 it is showed the consistency of the sensor fault estimate with Fig. 5: even though the input wave force is changed, both from the time trace and the process spectrum perspective, the fault estimate is unchanged, remarking that the observer is working properly (reminding that it is not provided of any information about the wave excitation force).

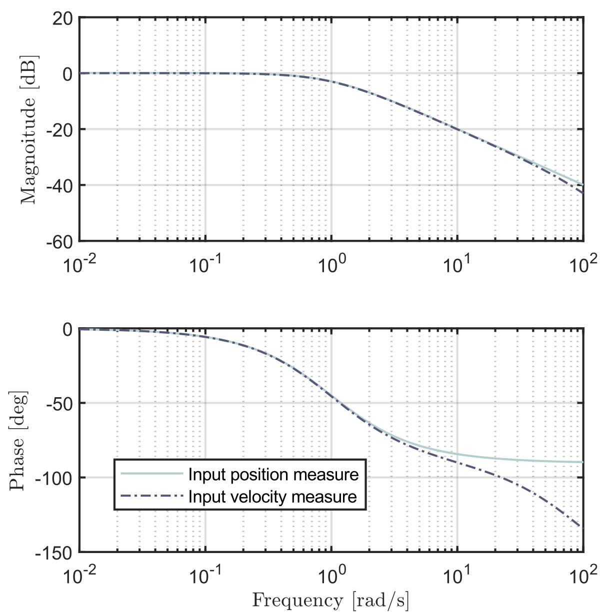

Fig. 6. Frequency response of the UIO in (10): measurement input channel.

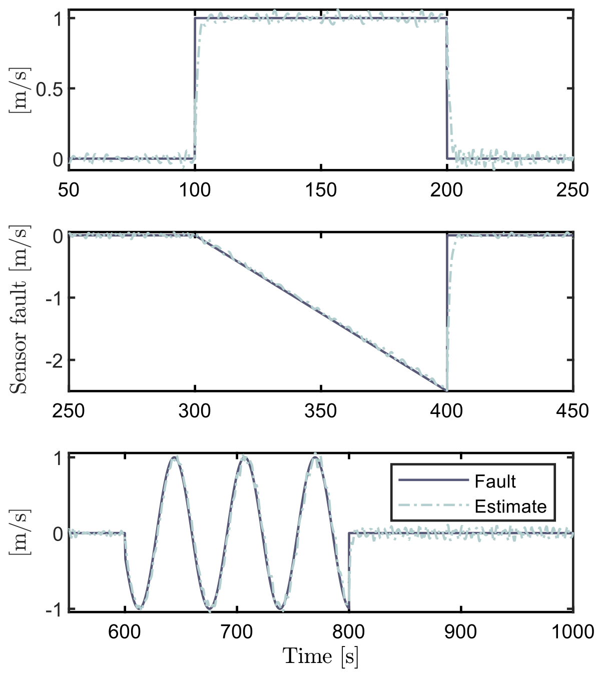

Fig. 7. Sensor fault: real signal (continuous line) and estimate (dashed line). Input wave energetic period $T_e = 4.6$ [s] and significant height $H_s = 1.5$ [m]. The x axis indicates the time (in seconds), while the y axis is the timetrace of each sensor fault condition.

VI. Conclusions

Driven by the increasing necessity to guarantee reliability in wave energy systems, this study proposes the implementation of an unknown input observer (UIO) for sensor and fault detection applied to wave energy converters. The observer is designed so that the estimation error convergence does not depend on the wave excitation force affecting the WEC, bringing the advantage of avoiding the design of auxiliary wave estimators. The paper also describes the design procedure of such a UIO in details, even in the case of non-detectability of matrices pairs.

The UIO, designed for FDI of a heaving cylindrical point absorber operating in irregular wave conditions, under a PI-parameterised energy-maximisation control law, consistently estimates the occurring faults both in the actuation and velocity measurement units, even in the presence of simultaneous fault conditions. The estimation performances are retained with different wave scenarios, showing that the observer structure is effective in estimating the fault effects while being insensitive to the wave component. Nonetheless, the observer presents some dynamics that cannot be altered, especially leading to a limited bandwidth for what concerns a reliable estimate of faults occurring on velocity measurements.

Future work will concern a deeper analysis of such undesired observer dynamics, and a more detailed analysis of the consequences brought by the proposed wave insensitivity properties on the actuator fault detection, identification and resilient fault-tolerant control stage, which is, as a matter of fact, the main motivation behind FDI implementation.

References

[1] R. Novo, P. Marocco, G. Giorgi, A. Lanzini, M. Santarelli, and G. Mattiazzo, "Planning the decarbonisation of energy systems: The importance of applying time series clustering to long-term models," *Energy Conversion and Management: X*, vol. 15, p. 100274, 2022.

[2] G. Mattiazzo, "State of the art and perspectives of wave energy in the mediterranean sea: Backstage of iswec," *Frontiers in Energy Research*, vol. 7, p. 114, 2019.

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

[4] G. Papini, E. Pasta, F. Carapellese, and M. Bonfanti, "Energy-maximising model predictive control for a multi degree-of-freedom pendulum-based wave energy system," *IFAC-PapersOnLine*, vol. 55, no. 31, pp. 433–438, 2022.

[5] N. Faedo, G. Giorgi, J. Ringwood, and G. Mattiazzo, "Optimal control of wave energy systems considering nonlinear froude–krylov effects: control-oriented modelling and moment-based control," *Nonlinear Dynamics*, vol. 109, no. 3, pp. 1777–1804, 2022.

[6] M. Penalba and J. V. Ringwood, "A review of wave-to-wire models for wave energy converters," *Energies*, vol. 9, no. 7, p. 506, 2016.

[7] S. Ambühl, L. Marquis, J. P. Kofoed, and J. Dalsgaard Sørensen, "Operation and maintenance strategies for wave energy converters," *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, vol. 229, no. 5, pp. 417–441, 2015.

[8] A. G. González E., C. Verde, and P. Maya-Ortiz, "Fdi study for a wave energy converter by structural analysis," *IFAC-PapersOnLine*, vol. 53, no. 2, pp. 13 721–13 726, 2020, 21st IFAC World Congress. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2405896320312143

[9] Y. Zhang, T. Zeng, and Z. Gao, "Fault diagnosis and fault-tolerant control of energy maximization for wave energy converters," *IEEE Transactions on Sustainable Energy*, vol. 13, no. 3, pp. 1771–1778, 2022.

[10] M. Blanke, M. Kinnaert, J. Lunze, M. Staroswiecki, and J. Schröder, *Diagnosis and fault-tolerant control*. Springer, 2006, vol. 2.

[11] Y. Peña-Sanchez, C. Windt, J. Davidson, and J. V. Ringwood, "A critical comparison of excitation force estimators for wave-energy devices," *IEEE Transactions on Control Systems Technology*, vol. 28, no. 6, pp. 2263–2275, 2019.

[12] J. Chen and R. J. Patton, *Robust model-based fault diagnosis for dynamic systems*. Springer Science & Business Media, 2012, vol. 3.

[13] W. Cummins, “The impulse response function and ship motions,” David Taylor Model Basin Washington DC, Tech. Rep., 1962.
[14] A. Babarit and G. Delhommeau, “Theoretical and numerical aspects of the open source bem solver nemoh,” in *11th European wave and tidal energy conference (EWTEC2015)*, 2015.
[15] “Orcawave user guide,” https://www.orcina.com/webhelp/OrcaWave/, accessed: 2023-05-23.
[16] F. Carapellese, E. Pasta, B. Paduano, N. Faedo, and G. Mattiazzo, “Intuitive lti energy-maximising control for multi-degree of freedom wave energy converters: the pewec case,” *Ocean Engineering*, vol. 256, p. 111444, 2022.
[17] N. Faedo, U. Bussi, Y. Peña-Sanchez, C. Windt, and J. V. Ringwood, “A simple and effective excitation force estimator for wave energy systems,” *IEEE Transactions on Sustainable Energy*, vol. 13, no. 1, pp. 241–250, 2021.
[18] Z. Yu and J. Falnes, “State-space modelling of a vertical cylinder in heave,” *Applied Ocean Research*, vol. 17, no. 5, pp. 265–275, 1995.
[19] M. Ryabkova, V. Karaev, J. Guo, and Y. Titchenko, “A review of wave spectrum models as applied to the problem of radar probing of the sea surface,” *Journal of Geophysical Research: Oceans*, vol. 124, no. 10, pp. 7104–7134, 2019.
[20] L. Liberti, A. Carillo, and G. Sannino, “Wave energy resource assessment in the mediterranean, the italian perspective,” *Renewable Energy*, vol. 50, pp. 938–949, 2013.