Tunable Control Strategy for Wave Energy Converters With Limited Power Takeoff Rating

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Abstract—In wave energy converters (WECs), the maximum power extraction would be achievable at the expense of a very high rating of the electric and power electronics equipment. The goal of this paper is to show how a convenient tradeoff between high-power extraction and viable electrical device rating can be achieved by a proper choice of the WEC control strategy. Referring to a direct coupled point absorber in heave operating in regular waves, it will be analytically shown how most common control techniques impact on both the power performance and the power takeoff (PTO) rating. Thus, a tool that can assist in the preliminary PTO sizing by taking into account the main constraints imposed by the application is obtained. Following, an adaptive control strategy including a reactive component is proposed, whose goal is to improve the overall system performance when the WEC is already operative in the sea. Its effectiveness in increasing the average power extraction while respecting the PTO peak power constraint is proved by computer simulations in both regular and irregular waves, and specific analyses also including the PTO force/torque limitation are finally developed.

Index Terms—Control strategies, irregular waves, point absorber, power takeoff (PTO), wave energy.

I. INTRODUCTION

IN THE FIELD of renewable energies, increasing attention is paid to the possibilities offered by ocean resources. According to the estimation contained in [1], about 2000-TWh/year can be obtained by the exploitation of the wave energy potential, corresponding to 10% of the world electrical energy consumption. Moreover, wave energy shows some advantages compared to other renewables: It has a higher energy density than solar energy, and it is more predictable and constant than wind energy [2]. In spite of this high potential, however, wave energy technology is still in its infancy. Several different aspects, from concept design and control to issues related to the power takeoff (PTO) system and grid connection, are still under investigation to find a leading solution being both technically and economically viable [3], [4].

In the past decades, most of the attention was focused on the primary takeoff mechanism [5], the goal being both to ensure its own survival in the harsh sea environment and to maximize its efficiency. As a consequence, mechanical and hydraulic optimization studies prevailed, while little attention was generally paid to the electric PTO. The drawback of this approach is that, in many cases [6], [7], the maximization of extracted power will require power electronics equipment being highly oversized with respect to the average power extraction.

It has already been recognized [8] that one of the reasons for the slow development of wave energy converters (WECs) is the fact that the ultimate goal of maximum power extraction often penalized the economic feasibility of the whole system. Now, with the increasing level of development and the need to enter the market in a near future, it is crucial to analyze also the electric PTO with a higher level of detail. Exploiting the lesson learned from other renewables, while recognizing the peculiarities of wave energy applications, can help in improving the PTO design, increase the overall system efficiency [9], [10], and achieve a reliable grid connection [11], [12]. To attain an electric device optimization, it is necessary to deal with the problem at the design stage, so that an integrated approach [13], [11] involving hydraulics, mechanics, and power electronics can be implemented.

Recent studies [15], [16] have underlined the primary importance of limiting the value of peak power, while maximizing the average extracted power, thus aiming at a tradeoff between two potentially conflicting requirements. They as well recognized how the elaboration of suitable control techniques is a key point in order to achieve such goal. The contributions in this field, however, mainly dealt with very specific applications; in most cases, they did not provide a theoretical framework to evaluate the impact of control on PTO rating in a generalized way. Moreover, with few exceptions [17], they only focused on techniques where a pure damping was applied to the WEC system [15], [16], without exploring the chance to employ also a reactive control component.

The specific goal of this paper is twofold. At first, it analytically evaluates, under sinusoidal conditions, the impact of linear control strategies including also a reactive component on the WEC peak-to-average power ratio [18]. The targeted application of such analysis is to provide a preliminary rating evaluation at the design stage of the PTO and to offer a unifying perspective on the several rating examples reported in the literature [6], [19]–[21]. As a following step, it will be shown how the provided tool can be useful when the system is already operative in the sea. In this case, the selection of the electric generator and power electronics interface has already been performed, and a specific constraint on the maximum power (and force) that the system can handle follows. Thus, the control strategy becomes fundamental in order to efficiently exploit the device. So, in the second part of this paper, an analysis to find a leading solution being both technically and economically viable [3], [4].

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A WEC with fixed mass and geometry is characterized by a specific natural (or eigen) period. When the incident wave period matches the WEC natural period, resonance condition occurs, and the maximum possible power is extracted.

In practical applications, it is desirable to have this WEC natural resonance frequency tuned according to the incident wave frequency. It is worth noting that, when considering devices that are small compared to the waves' wavelength (i.e., point absorbers), active control is even more crucial, since their resonance bandwidth is inherently very small.

The main goal of WEC control is to use the PTO to change the amplitude and/or the phase of the motion to make it close to the optimum condition.

The research of the most suitable control strategies is a very challenging issue for energy developers. Up to now, the most commonly adopted techniques are as follows.

1) Complex-conjugate control: It controls both the amplitude and phase of the WEC motion so that resonance condition is achieved. This generally requires the PTO to apply a force having a component which is proportional to the WEC velocity and another which is proportional to the WEC acceleration.

2) Passive loading: It only controls the amplitude of the motion, by modifying the WEC dynamical resistance (or damping) in order to maximize the extracted power. This is obtained by applying a force proportional to the buoy velocity, by the PTO.

3) Latching control: It is a suboptimal control where the point-absorber velocity is forced to be in phase with the excitation force by holding the device in the upper and/or lower position. The value of dynamic resistance is defined in the same way as in passive loading. The analysis of this intrinsically nonlinear control strategy is, however, beyond the scope of this paper, and it will not be further deepened.

III. PTO DESIGN STAGE

This section focuses on the mathematical analysis of the effect that different WEC control strategies have on the rating of the PTO. The study is developed under the hypothesis of monochromatic incident waves. Its goal is to offer a preliminary evaluation of the achievable tradeoff between average extracted power and required PTO oversizing, for each specific WEC and sea condition.

A. System Model Under Regular Waves

Under the assumption of regular waves, the hydrodynamic forces acting on the point absorber can be analyzed, and the following fundamental equation can be derived [25]:

\[-\omega^2 (M + A(\omega)) \mathbf{\ddot{S}} + j\omega B(\omega) \mathbf{\dot{S}} + K \mathbf{S} = \mathbf{F}_E + \mathbf{F}_L. \tag{1}\]

In (1), \(\omega\) is the angular frequency of the incident wave, \(S\) is the buoy position, and \(\mathbf{\ddot{S}}\) indicates complex operators.
The equivalent reactance is represented by the series between an equivalent resistance and capacitance, which can be both tuned, can be exploited in the optimization perspective.

In regular waves, the average power in steady state is given by the mean value of the sinusoidal power waveform, having an angular frequency that is equal to \( \omega \).

\[
F_L = -B_L(\omega)j\omega S + M_L(\omega)\omega^2 S \tag{2}
\]

where \( B_L \) and \( M_L \) are the damping and added mass applied by the PTO, respectively.

**B. Electric Analog of the System**

To gain a better understanding of WEC control and power transfer issues, it is worth representing the point absorber as a mass–spring–damper system and to introduce the corresponding electric analog, which is shown in Fig. 2. The correspondence between mechanical and electrical quantities is summarized in Table I, where lowercase variables and forces are considered as time-varying quantities and it is assumed that \( u = \dot{s} \).

As specifically regards the PTO control action, it is represented by the series between an equivalent resistance and an equivalent reactance. Such reactance is inductive (i.e., equivalent to a spring component) when the device reactance is negative and capacitive (i.e., equivalent to a spring component) when the device reactance is positive. The equivalent resistance always accounts for the damping force.

It is worth noting that passive loading corresponds to a null reactive component and that complex-conjugate control denotes the case when load reactance cancels the reactance given by inductance and capacitance (resonance condition), and load resistance \( R_L \) is selected to maximize the power transfer.

**C. Basic Approach to the Analysis**

When considering the PTO design and performance evaluation, the average power extraction is the main reference parameter. In order to achieve feasible solutions, however, also the electromechanical constraints imposed by the PTO itself must be carefully considered. In wave energy applications, the most important of such constraints is the peak power reached in the system. This is because it affects the rating of both the electrical machine and the power electronics interface: Peak power is a fundamental parameter to choose an appropriate electrical generator, and the corresponding current limit for the power electronics converters can be easily derived. The relevance of this parameter is clearly explained in [16]. It is worth to underline that the evaluation of WEC performance has been traditionally based on the peak-to-average power ratio, particularly for point-absorber direct-driven applications [15], [16], [26]. This parameter is suitable to cope with systems of different types [20], [27], and it represents an effective indicator for several issues, from the PTO design to the WEC grid connection [28], [29]. Thus, its already widespread use is further encouraged due to its relevance for device comparison.

**D. Control Strategy Impact on Peak-to-Average Power Ratio**

Once the load damping is assumed to be fixed, passive loading and complex-conjugate control represent somehow the two extreme conditions, corresponding to a zero load reactance and to the load reactance that maximizes average power extraction. It is evident, however, that phase and amplitude reactive solutions for the choice of load parameters, which can be exploited in the optimization perspective. More specifically, the two degrees of freedom offered by the control strategy can be exploited to control not only the average power extraction but also the peak power value. Thus, the power electronics equipment selection is also favored.

In other words, the choice of a control strategy that is suboptimal from the average power extraction standpoint can instead be extremely advantageous in the perspective of the power electronics ratings, and thus, it can be preferred [18].

As the first step, it is possible to express the average extracted power \( P_{\text{avg}} \), corresponding to the power dissipated on the load resistance \( R_L \), as a function of the load resistance itself and load power factor, which is

\[
\cos \varphi_L = \cos \left( \tan^{-1} \left( \frac{X_L}{R_L} \right) \right) \tag{3}
\]

In regular waves, the average power in steady state is given by the mean value of the sinusoidal power waveform, having an angular frequency that is equal to \( 2\omega \). It results to

\[
P_{\text{avg}} = \frac{E^2 R_L}{(R + R_L)^2 + \left( \omega L - \frac{1}{\omega C} \pm \frac{R_L \sqrt{1 - \cos^2 \varphi_L}}{\cos \varphi_L} \right)^2} \tag{4}
\]
where the \( \pm \) sign depends on the inductive or capacitive nature of the equivalent load.

Then, also the maximum instantaneous power transferred to the load, which is obtained when

\[
2(\omega t + \beta_L) = \pi - \phi_L
\]

(5)

can be expressed as a function of load resistance and power factor

\[
P_{\text{max}} = \frac{E^2 R_L}{(R + R_L)^2 + \left(\omega L - \frac{1}{\omega C} \pm R_L \sqrt{1 - \cos^2 \phi_L} \cos \phi_L\right)^2}
\]

(6)

At this point, it is straightforward to analytically evaluate the ratio between peak power and average power, which is a key factor for the correct sizing of the electric PTO components. It results to

\[
\frac{P_{\text{max}}}{P_{\text{avg}}} = 1 + \frac{1}{\cos \phi_L}.
\]

(7)

This simple formula shows how the ratio is only driven by the value of the load power factor and that it has potentially very large excursions when \( \phi_L \) varies.

E. Simulation Results

To prove the validity and usefulness of the theoretical analysis developed in the previous section, suitable Matlab/Simulink simulations were carried out. The parameters of the point absorber are in accordance with the device described in [20] and are reported in Table II.

![Fig. 3. Average extracted power as a function of the load power factor \( \cos \phi_L \) for several values of the load resistance \( R_L \).](image1)

![Fig. 4. Peak-to-average extracted power ratio as a function of the average extracted power, for several values of the load resistance \( R_L \).](image2)

Then, each of these choices immediately determines the peak-to-average power ratio, i.e., PTO rating.

The first important information that can be obtained from the graph regards the value of the absolute maximum average power that can be extracted from the device, if the control parameters are selected to reach the resonance condition (point A). In the considered case, it is \( P_{\text{avg}} = 175 \) kW. However, it can also be noted that, to reach such power absorption, an oversizing of the electric and electronic equipment by a factor 14.5 would be required, resulting in a rather antieconomical choice. From the same figure, however, it can be observed that, if a reduced absorbed power of around 140 kW (point B) is accepted, the power electronics rating can be more than halved (being \( P_{\text{max}} \) lower than 840 kW).

This kind of graph can be used as a design tool for evaluating the minimal PTO rating that is required to ensure a certain amount of average extracted power for a specific considered control strategy. Obviously, since Figs. 3 and 4 are referred to a defined incident wave, their usefulness in the design stage is subject to a suitable choice of the “design wave” that best represents the dominant wave at the considered location.
IV. WEC ORDINARY FUNCTIONING IMPROVEMENT

When the PTO for the WEC has already been selected, a specific constraint on the maximum power and on the torque/force that can be handled by the whole system must be respected. The WEC control strategy can be adapted in order to always respect at first the peak power constraint, whose relevance has already been clarified in the previous section, while maximizing the average extracted power \([22]\). To complete the analysis, also the force/torque constraints will be analyzed \([30]\), but it will be shown how, in the present application, they are less critical than the peak power limit.

A. Mathematical Analysis

The goal of this section is to outline, through a mathematical approach, how the control problem can be dealt with and optimally solved in the described perspective, with reference to sinusoidal waves of different amplitudes and frequencies.

At first, it must be considered that, for some values of the period and height of the incident waves (i.e., when they are “small” and having “relatively high frequency”), it is possible that, even when applying complex-conjugate control, the maximum allowed value for the peak power is never reached. This corresponds to an unconstrained case, and it is well known that, under such circumstances, the maximum extraction of average power is obtained in resonance. After defining the input conditions making complex-conjugate control advisable, the choice of the best control strategy for the remaining conditions can be operated.

It is theoretically possible to determine the values of \(R_L\) and \(X_L\) (or, equivalently, \(R_L\) and \(\cos \phi_L\)) that maximize the power \(P_{\text{avg}}\), while imposing a constraint on \(P_{\text{max}}\) (e.g., with the Lagrange multiplier approach), but due to the complexity of the analytical expressions, a numerical approach would be required. In the following, a simpler alternative strategy is proposed and adopted, which is exemplified in the flow chart in Fig. 5.

Once stated, the peak power limit \(P_{\text{lim}}\) (= \(P_{\text{max}}\)), a second-order equation in the unknown \(R_L\), can be derived from (4) and (7), having \(\cos \phi_L\) as a parameter

\[
R_L^2 \left( \frac{P_{\text{max}}}{\cos \phi_L} \right) + R_L \left[ 2P_{\text{max}}R + 2P_{\text{max}}X \sqrt{\frac{1}{\cos^2 \phi_L} - 1} - E^2 \left( \frac{1}{\cos \phi_L} + 1 \right) \right] + P_{\text{max}}(R^2 + X^2) = 0. \tag{8}
\]

In order to guarantee that the equation admits at least a 352 positive solution for \(R_L\), it is necessary that there is at least one 353 variation in the signs of the equation coefficients. Since it can be easily seen that, under reasonable operating conditions, both 355
the first and third coefficients are never negative, it is necessary to ensure the negativity of the second one, i.e.,

\[ 2P_{\text{max}} R + 2P_{\text{max}} X \sqrt{\frac{1}{\cos^2 \varphi_L} - 1 - E^2 \left( \frac{1}{\cos \varphi_L} + 1 \right)} < 0. \]

(9)

It can be shown, by a proper analytical analysis, that this can be obtained for different values of \( \cos \varphi_L \), depending on the input wave and on the buoy parameters. In order to select the best control strategy, once the range of possible \( \cos \varphi_L \) is defined, the highest of them must be selected. This choice can be explained with reference to (7) since, once \( P_{\text{max}} = P_{\text{lim}} \) is fixed, the higher is \( \cos \varphi_L \), the higher is the average power that can be extracted. It is also worth noting that, when defining the optimum value of the power factor, it is necessary that it guarantees also that the determinant of the second-order equation in \( R_L \) (8) is not negative.

Once the optimal \( \cos \varphi_L \) has been identified, (8) is solved to find the optimal value of \( R_L \). Then, the corresponding value of \( X_L \) can be easily derived from the knowledge of the load power factor (3).

Even if mathematically possible, conditions where the proposed method fails in providing the optimal control parameters have not been found for reasonable ranges of the incident wave amplitudes and frequencies, as shown in the following section.

According to this “multimonochromatic” approach, a sort of map of the advisable control strategies can be drawn for each WEC, which is shown in Fig. 6 for the considered test case. As expected, when high waves are considered, a pure damping suitably tuned on the incident waves must be preferred in order not to exceed the peak power limit. On the other hand, traditional complex-conjugate control is chosen in small and high-frequency waves, whose lower energy content can be fully exploited, without risks for the power electronics equipment. In between, intermediate reactive control can be applied, where the ideal control parameters can be derived according to the described method.

![Fig. 6. Map of the advisable control strategies according to changes in the sinusoidal incident wave amplitude and frequency.](image)

![Fig. 7. Peak extracted power with three different control techniques, for incident waves having \( T = 9 \) s.](image)

![Fig. 8. Average extracted power with three different control techniques, for sinusoidal waves having \( T = 9 \) s.](image)

**B. Simulation Results in Regular Waves**

The first set of simulations was aimed to prove how different sinusoidal incident waves influence the power performance of the point absorber, when it is controlled in order to never exceed the peak power limit. Reference is made to the same system considered in the previous sections, and it is here assumed that the PTO actually imposes on the system a power limit of \( P_{\text{lim}} = 840 \) kW. It is at first useful to analyze the difference in the application of the proposed tunable control strategy with respect to the more traditional passive loading and complex-conjugate control employing constant parameters. In order to do this, it is assumed that the sinusoidal incident waves have a fixed period of \( T = 9 \) s and the parameters of passive loading and complex-conjugate control are kept constant at their correspondent optimal value for sinusoidal conditions. On the other hand, the proposed intermediate reactive control is tuned as previously described. Under such conditions, the effect of the wave amplitude variations on the peak (Fig. 7) and average (Fig. 8) power absorption is considered.

From Fig. 7, it can be seen that, in case of high waves (\( A > 4 \) m), both constant passive loading and complex-conjugate control overpass the stated limit for the peak power. Moreover, 411
complex-conjugate control works above such limit for many of the considered wave amplitudes. It can be noted, instead, how the proposed strategy respects the constraint imposed on the peak power. Fig. 8 shows how this different behavior reflects on the average power extraction. It can be clearly seen that the proposed control strategy shows an evident advantage with respect to traditional passive loading for the majority of the operating conditions, while it is still competitive with complex-conjugate control in low waves.

V. PERFORMANCE UNDER IRREGULAR WAVES

In order to verify the potential advantages of the proposed adaptive control techniques with respect to traditional passive loading and complex-conjugate control also when applied in irregular waves, specific time-domain analyses must be performed.

A. System Model in the Time Domain

The system behavior can be modeled in the time domain by the Cummins equation [31], resulting in

\[
(M + A_\infty)\ddot{s}(t) + \int_{-\infty}^{t} K_{\text{rad}}(t - \tau)\dot{s}(\tau)d\tau + Ks(t) = F_E(t) + F_L(t), \tag{10}
\]

In (10) "\(\cdot\)" is the time derivation operation, \(K_{\text{rad}}\) is the radiation impulse response, and \(A_\infty\) represents the value of the added mass at infinite frequency. From (10), the time-domain model of the WEC has been built, as shown in Fig. 9.

Additional details on the time-domain modeling of the system can be found in [32].

B. Proposed Technique Performance in Irregular Waves

Accordingly to the previously presented control analysis, it is here assumed that the considered system is equipped with a squirrel-cage induction machine, whose rated power is 850 kW. Its rated speed is 2985 \(t/min\). Assuming for the point absorber a reference velocity of 3 m/s and a pinion radius of 0.1 m, a gear ratio of 10 is required to couple the point absorber to the PTO. For the considered electrical machine, the rated torque is 2716 N \(\cdot\) m, but a peak torque of 7333 N \(\cdot\) m can be sustained. In terms of force, this corresponds to a rated force of 271.6 kN and a peak force of 733.3 kN.

To test the performance of the proposed control technique, irregular waves were generated from a Bretschneider spectrum [33], [34] having significant wave height \(H_s = 2.12\) m and energy period \(T_e = 9\) s. This is the same period of the sinusoidal wave used for the analyses of Figs. 7 and 8. The 20-min incident wave profile is shown in Fig. 10. At first, constant passive loading is applied under irregular waves, using the \(R_L = 802.5\) k\(\Omega\) that is optimal for a sinusoidal wave having \(T = 9\) s. Under this condition, the average power extraction, calculated as the average value of the instantaneous power along the entire 1200-s simulation, is \(P_{\text{avg}} = 43\) kW, and the peak power reached 458 kW for a few seconds is \(P_{\text{max}} = 602\) kW [Fig. 11(a)]. In this 459 case, the rms value of the force is \(F_{\text{rms}} = 185.7\) kN, which is below the rated force of the machine. The peak value of 460 the force is \(F_{\text{max}} = +696.5\) kN, also below the peak force 462 limit. If complex-conjugate control with constant parameters \(R_L = 63\) k\(\Omega\) and \(X_L = 1145.9\) k\(\Omega\) is applied, while keeping 464 the power saturation at 840 kW, under the same sea condition, 465 the peak power limit would be repeatedly reached and hold for 466 tens of seconds every time. However, a reduced average power 467 absorption of 41.6 kW would be obtained, due to the reverse 468 power flow required during the large part of the operation 469 [Fig. 11(b)]. Furthermore, complex-conjugate control would 470 be completely unsustainable from the mechanical standpoint, 471 requiring the electrical generator to apply an rms force of 472 621.4 kN, with a peak power of 7600 kW. The proposed adap- 473 tive control strategy is then applied in real time as follows. The 474 peak amplitude of incident waves is measured, and \(R_L\) and \(X_L\) 475 are selected according to the previously described algorithm, 476 based on the measured amplitude of the waves (updated twice 477 per period) and under the simplifying assumption of constant 478 wave period \(T = 9\) s. This leads to an average extracted power 479 of \(P_{\text{avg}} = 62.7\) kW with a peak power of \(P_{\text{max}} = 719.17\) kW 480 [Fig. 11(c)]. The advantage with respect to traditional passive 481 loading is apparent: The average power extraction is improved by 482 46%, and the ratio between peak and average extracted 483 powers is lower with the proposed control strategy, resulting 484 in a better exploitation of the PTO. From Fig. 11(c), it can be also noted that, in some parts of the period (corresponding 486
...to small waves), a reactive control component is applied and...the extracted power is therefore bidirectional, while, in the part corresponding to high waves, a pure damping is used, leading to unidirectional power.

As regards the mechanical force required to the PTO, it can be noted that its rms value is $F_{\text{rms}} = 267.4$ kN, leading to a better use of the PTO, compared to passive loading. Also, the peak value of the force ($F_{\text{max}} = -689.8$ kN) is still below the allowed limit for the considered machine.

It is important to underline that the here presented approach to a constrained maximization of the average power extraction can be also extended to directly include additional constraints (as the PTO force/torque limit and/or the maximum stroke of the point absorber), whenever they should result predominant compared to the peak power limit [35].

Finally, it is worth noting how these tests under irregular waves also provide an order of magnitude of the PTO oversizing needed to specifically account for the stochastic nature of real sea waves. This does not restrict the importance of preliminary analyses developed under sinusoidal conditions [6], [7], [17], [19]–[21] but underlines that they need to be considered as best case guidelines, to be following deepened by more realistic tests.

VI. DISCUSSION

It is important to underline that the proposed optimization of the system control strategy under sinusoidal conditions is based on the assumption that a linear approach is to be maintained also when a constraint on the power absorption is introduced. This means that the control parameters that guarantee the maximum average power extraction while respecting the peak power limit are found by a linear analysis. It should be pointed out, however, that the application of nonlinear control techniques [15], [19], [32], which can equivalently ensure that the peak power limit is not exceeded, can potentially allow higher average power absorption with respect to linear ones. However, the analytical approach to such techniques is much more complex and generally avoided: Numerical and simulative analyses are preferred in that case. It must be also observed that, when the considered optimized control parameters are applied in irregular waves, the stated limit on peak power is not automatically respected anymore, but specific power saturation must be imposed by the PTO. It has been verified that, even when such saturation intervenes in limiting the instantaneous power, the proposed adaptive technique is still extremely convenient in increasing the average extracted power.

VII. CONCLUSION

In this paper, the problem of the optimization of the control strategy for a point absorber in heave is dealt with, taking into specific consideration the power and torque limitations imposed by the rating of the electrical machine and power electronics equipment. As the first step, a theoretical framework to study in a systematic way the impact of control on the PTO rating was built, whose goal is to provide preliminary performance information already at the PTO selection stage. From such design tool, a specific tuning of control parameters, aimed at maximizing the average power extraction while respecting peak power and torque limitations, was derived. It considers sinusoidal incident waves of different amplitudes and frequencies in a “multimonochromatic” approach. It has been finally shown how such technique can be applied in irregular waves as well, being the core of an adaptive control technique based on the measure of incident waves’ amplitude. The advantage of such strategy with respect to traditional constant passive loading and considering the complex-conjugate control has been finally proved by computer simulations performed also in irregular waves.

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