Some Fundamental Results for Cyclorotor Wave Energy Converters for Optimum Power Capture

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***Abstract*—Cyclorotor-based wave energy converters (WECs) present a relatively new and innovative paradigm for wave energy harvesting. Their operational principle is based on the generation of lift forces on the rotating hydrofoils due to their interaction with wave-induced circulation of water particles. As a result, relatively little is known about their optimal operation. To date, cyclorotor device performance has been measured by the power of waves radiated by the WEC, while a constant rotational velocity, consistent with the wave frequency, is employed. In this note we show (a) that variation of the cyclorotor velocity within the incoming monochromatic wave period significantly increases the generated mechanical power, while (b) optimising wave cancellation is at odds with the maximisation of shaft power. To optimise shaft power, the letter adopts a multi-harmonic solution for variable cyclorotor rotation rate, inspired by methods developed in other WEC domains.**

***Index Terms*—Cyclorotor, optimal control, performance metrics, velocity profile, wave energy converter.**

I. Introduction

Though research into lift-based cyclorotor-based wave energy converters (WECs) began over 40 years ago, development in the interim has been sporadic and slow [1]. Much of the recent progress has been documented in the PhD thesis of Scharmann [2] and the work of Hermans [3] and Siegel [4], [5]. While not explicitly stated or proven, the lack of any analysis for cyclorotors, where the rotational speed is adjusted in real time, leads to the implicit conclusion that cyclorotors should be operated at constant rotational velocity, in both monochromatic and panchromatic seas. This note clearly demonstrates that, for optimum power capture, a variable rotation rate should be used, even in monochromatic seas.

In addition, much of the performance assessment for cyclorotors has relied on the ability of cyclorotors to perform wave cancellation [6], [7], as a surrogate measure for converted power. Indeed, the required phenomenon of waves radiated from the WEC cancelling the down-wave wave field is well accepted as a condition for optimal device behaviour [8]. Nevertheless, the ultimate performance metric is the amount of energy usefully converted in mechanical or electrical form. To this end, this study shows that, under (optimal) rotational speed modulation, there is a significant inconsistency between the conditions for optimum wave cancellation, and converted shaft energy.

In this note, we demonstrate the case for monochromatic waves, for clarity of exposition. The key results also apply to the panchromatic case, where a fuller treatment is required.

The remainder of the note is organised as follows: Section II shows the basic formulation for calculation of the optimal velocity modulation, while Section III demonstrates the key results relating to the optimal velocity modulation and the disparity between performance metrics. Conclusions are drawn in Section IV.

II. Optimum Rotational Rate Modulation

In this study, a cyclorotor-based WEC is simulated with the use of point-source model presented and validated in [9]–[11]. In order to provide some indication of the connection between cyclorotor rotational velocity and tangential force, the principal model equations are briefly presented. The model [9] essentially considers rotation in two-dimensional potential flow, and includes radiation effects and viscous losses. Linear monochromatic Airy waves are used as input to the cyclorotor.

It is assumed that the lift F_T, drag F_D and tangential F_T forces are caused by the interaction of the rotating of hydrofoil i with a relative foil/fluid velocity $\mathbf{\hat{V}_i}$, which can be presented as a combination of the wave induced fluid velocity $\mathbf{V_W}$, the instantaneous foil velocity $\mathbf{V_R}$ and the waves radiated by the moving foils $\mathbf{V_H}$:

$$\mathbf{\hat{V}_i} = \mathbf{V_W} - \mathbf{V_R} + \mathbf{V_H} \tag{1}$$

The generated on the hydrofoil forces depend on the lift $C_L(\alpha)$ and drag $C_D(\alpha)$ coefficients [12], the chord length of the hydrofoil C, the water density ρ, and the hydrofoil/fluid relative velocity $\mathbf{\hat{V}}$:

$$F_L = \frac{1}{2}\,\rho\, C_L(\alpha)|\hat{V}|^2\, C, \quad F_D = \frac{1}{2}\,\rho\, C_D(\alpha)|\hat{V}|^2\, C,$$
$$F_T = F_L \sin(\alpha - \gamma) - F_D \cos(\alpha - \gamma) \tag{2}$$

where α is the attack angle, and γ the hydrofoil pitch angle.

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The instantaneous foil velocity $\mathbf{V_R}$, for foil i, can be found as the partial time derivatives of the hydrofoil position:

$$\begin{aligned} x_i(t) &= -R\cos(\theta(t) + \pi i) \\ y_i(t) &= y_0 + R\sin(\theta(t) + \pi i) \end{aligned} \tag{3}$$

$$\mathbf{V_{R_i}} = R\dot{\theta}(t)\left\{\sin(\theta(t) + \pi i), \cos(\theta(t) + \pi i)\right\} \tag{4}$$

where R is the cyclorotor radius, y_0 is the submergence depth, and $\theta(t)$ is the angular position of the hydrofoil. Thus, the instantaneous foil velocity $\mathbf{V_R}$ and relative foil/fluid velocity $\hat{\mathbf{V}}$ are linear functions of the rotational rate $\dot{\theta}(t)$.

Then, it can be seen from (2) that, for an optimal stall angle of attack $\alpha = 15^\circ$ [5], all forces are proportional to the square of the rotational rate $F_L, F_D, F_T \sim \dot{\theta}^2$. However, any increase in rotational rate $\dot{\theta}(t)$ also significantly increases structural loads [13]. In contrast, the angle of attack α is inversely proportional to the rotational rate $\dot{\theta}$ (if $\dot{\theta}$ is infinite, α, C_L and F_L are zero).

Given the harmonic nature of the wave excitation, it is reasonable to parameterise the rotational rate profile $\dot{\theta}(t)$ as a Fourier series [14], [15], with the wave frequency, $\omega = 2\pi/T$, as the fundamental:

$$\dot{\theta}(t) = \sum_{i=1}^{m} a_i sin(i\omega t) + b_i cos(i\omega t) \tag{5}$$

since we are predominantly interested in the steady-state behaviour of the system and the parameterisation naturally contains the default case where the (constant) rotation rate equals the wave frequency. In (5), m is the number of Fourier coefficients (frequencies) employed, and the coefficients a_i and b_i are the solution of the optimal rotation rate problem, for a given value of m. We note that this formulation is in the spirit of the more general pseudospectral WEC control solution framework pioneered in [16], with a performance function:

$$\text{Max } P_{Shaft} = \frac{1}{T}\int_{kT}^{(k+1)T} \dot{\theta}(t)\mathcal{T}(t)dt \tag{6}$$

where P_{Shaft} corresponds to the mechanical shaft energy converted over the kth wave period, where $\mathcal{T}(t) = (F_{T_1} + F_{T_2})R$ is the resisting torque of the system power take off (PTO), which is an electrical generator in the case where conversion to electrical energy is required, for example. While (1)–(4) give some impression of the connection between foil velocity and tangential force (directly connected to shaft power), it is not possible to solve analytically for the optimum rotational speed profile; rather a numerical solution is required.

For comparative purposes, we study the influence of the implemented control strategy on the 2D power of the incoming, transmitted, and radiated waves (evaluated from the free surface elevation using spectral analysis) within the period of the incoming monochromatic wave T at the gauge points located at $\pm\lambda$, where λ is the length of the incoming wave (see Fig. 2).

We consider the optimisation problem after $k \sim 8$ wave periods (Fig. 2) when the rotor rotation has synchronised with the incoming waves, radiation of waves from the hydrofoils become periodic, and we maximise the functional (6) on the interval $[T_k, T_{k+1}]$.

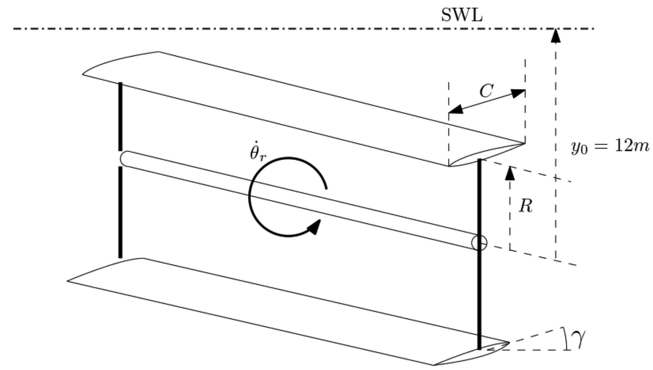

Fig. 1. A 2-foil cyclorotor wave energy device. SWL denotes the still water level.

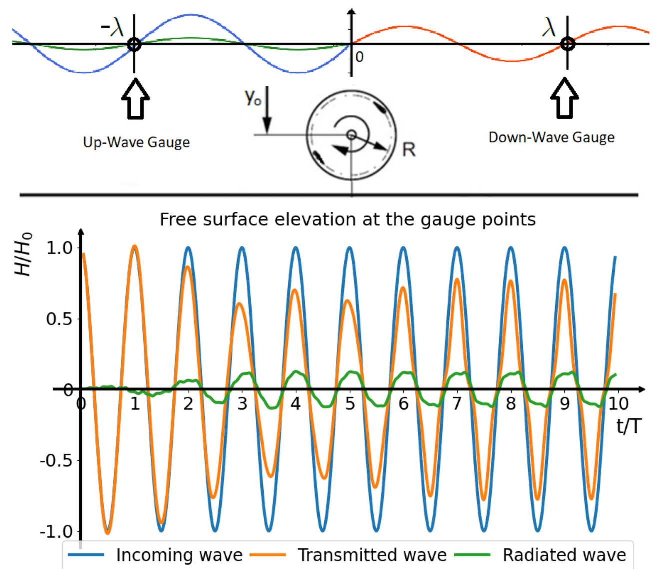

Fig. 2. Synchronisation of the CycWEC cyclorotor [5] with incoming waves for the case when T = 10 s, $H_0 = 2$ m and $\gamma = 0$.

The power available for absorption by the WEC can be obtained as:

$$P_{Wave} = P_{Incident} - P_{Transmitted} - P_{Radiated} \tag{7}$$

where power of the incident $P_{Incident}$, transmitted $P_{Transmitted}$, and radiated $P_{Radiated}$ waves can be estimated using spectral analysis [5] of the free surface elevation at the gauge points within the wave period. $[T_k, T_{k+1}]$, as shown in Fig. 2

The wave cancellation metric may include power losses due to drag P_{Drag} [5], which can be evaluated using equations (2, 6), in which only drag forces are taken into account.

$$P_{Cancelled} = P_{Wave} - P_{Drag} \tag{8}$$

The optimal wave cancellation effect [5] requires rotation with a constant rate $\omega = \dot{\theta}$, 90° phase angle between the first hydrofoil and the incoming wave crest, and generation of the maximal circulation Γ, by tuning hydrofoil pitch angles γ. The circulation parameter Γ is proportional to the lift force F_L and responsible for the amplitude of the generated wave, which should cancel

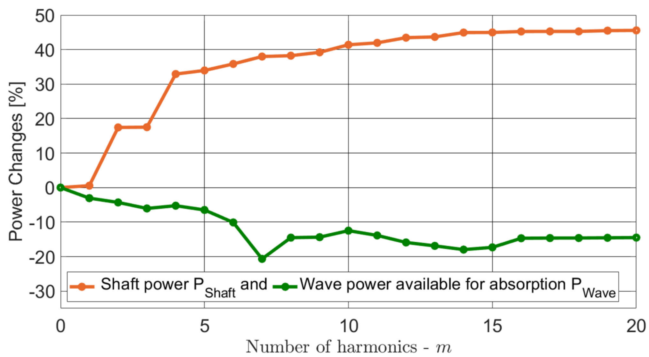

Fig. 3. Performance metrics for various number of harmonics m: Additional power (ΔP) captured over the constant rotational velocity ($\dot{\theta}_r(t) = \omega_w$) case, and corresponding *decrease* in wave cancellation power.

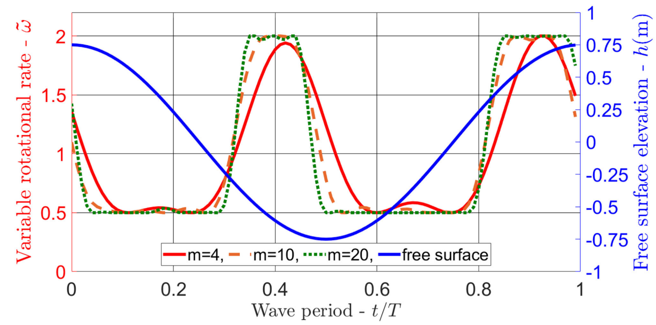

Fig. 4. Time domain solution for velocity profile for $m = 4$, 10, 20. Note that a value for $\tilde{\omega} = \dot{\theta}/\omega$ of unity corresponds to a case of a (constant) rotational rate equal to the monochromatic wave frequency.

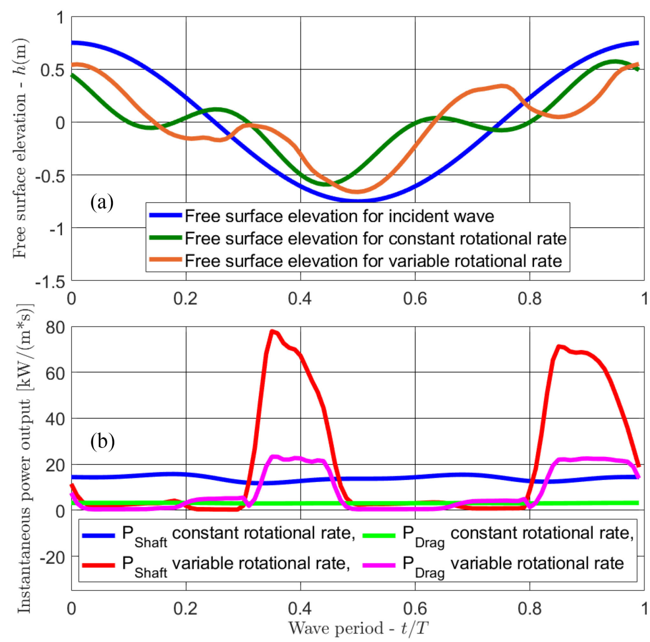

Fig. 5. (a) The free surface elevation H(m) measured at the up-wave gauge point for the cases of a motionless rotor (blue line), a rotor which rotates with a constant rate (green line), and a rotor rotating with a variable rate (orange line). (b) Instantaneous shaft power generation P_{Shaft} and viscous losses P_{Drag} for the cases of constant and variable rotational rate $m = 20$.

the incoming wave:

$$\Gamma = F_L/(\rho|\hat{V}|) = \frac{1}{2} C_L(\alpha) |\hat{V}| C \tag{9}$$

III. Key Results

In order to compute the optimal rotational rate profile, we use the validated model [9]–[11] of a cyclorotor, with the following specifications, proposed in [5]: two hydrofoils NACA0015 [12] with chord length $C = 5$ m, operational radius $R = 6$ m, and a distance $y_0 = -12$ m between the still water level (SWL) and rotor centre (see Fig. 1). Different monochromatic waves require the optimisation of the constant pitch angle value to ensure maximum wave energy extraction. Thus, for the case T = 11 s and H = 1.5 m, the optimal constant pitch angle values $\gamma_1 = 11^\circ$ and $\gamma_2 = -11^\circ$, were obtained for a constant rotational rate by solving a global optimisation problem using the same functional (6). We use the obtained constant velocity configuration and results as a reference for the variable rotational rate case. Variations in the rotation rate $\tilde{\omega} = \dot{\theta}/\omega$ are limited to $1/2 < \tilde{\omega} < 2$, to satisfy realistic electrical machine capabilities.

For a variety of m values, the optimal a_i and b_i in (5) are determined, with the captured energy plotted against m in Fig. 3, demonstrating that the bulk (approx. 30%) of the power increment (over the constant rotational velocity case) is achieved with just 4 additional harmonics, with 8–9 harmonics sufficient so that the inclusion of the next harmonics does not increase the captured power by more than 2–3%. It may be noted that the shaft power increase *is not matched by a corresponding increase in wave cancellation resulting from wave radiation.* In fact, less waves are cancelled with the variable rotational rate protocol (see Fig. 5(a)). The variation in rotational rate also significantly increases the viscous losses P_{Drag} (see Fig. 5(b)). The difference in the shaft power and wave cancellation metric values is primarily due to the fact that, when maximising shaft power, tangential force needs to be maximised (2) (with attack angle optimised at 15°) while, for wave cancellation, circulation needs to be optimised (9). In addition, the use of a variable rotational rate is also detrimental to wave cancellation.

While the use of a greater number of harmonics captures more power, the computational load for the solution is significantly greater, which may be an issue for a panchromatic controller operating in real time. In addition, the relatively smooth control signals for $m = 4$ are attractive in providing less stress to system components.

By way of example, the time domain solution for the rotor velocity (normalised by the wave velocity) is shown in Fig. 4 for m values of 4, 10, and 20. It is clear that the solution practically converges to a switching protocol between rotational rates corresponding to half and double the wave frequency, at different segments of the passing wave.

Clearly, modulation of the cyclorotor velocity has significant benefit, resulting, for the case shown, in a maximum energy increase of 46%.

The consistency of the presented effect has been also confirmed for cyclorotors with different submergence depth y_0, operational radius R, chord length $C = 0.8 * R$ and pitch angle

TABLE I
SHAFT POWER P_{Shaft} INCREASES AFTER IMPLEMENTATION OF A VARIABLE ROTATIONAL RATE (CORRESPONDING REDUCTIONS IN CANCELLED WAVE POWER P_{Wave} ARE IN BRACKETS)

y_0	R=3.75m $\gamma = 8^o$	R=4.5m $\gamma = 9^o$	R=5.25m $\gamma = 10^o$	R=6m $\gamma = 11^o$
10.5m	23% (-8%)	19% (-16%)	31% (-15%)	47% (-7%)
12m	18% (-2%)	11% (-10%)	29% (-11%)	43% (-13%)
13.5m	17% (-6%)	16% (-6%)	29% (-10%)	42% (-10%)
15m	16% (-5%)	18% (-6%)	27% (-9%)	54% (-15%)

γ values, for the same monochromatic wave with $T = 10$ s and $H = 2$ m, as shown in Table I.

IV. CONCLUSION

This note provides, within the fidelity of the model [9] employed, conclusive evidence that a time-varying rotational rate profile for a cyclorotor optimally captures wave power and that it is important to focus on the converted (shaft) energy metric, rather than using wave cancellation as a surrogate measure. However, the results presented are calculated by the model in [9], which has some approximations in relation to the potential (theory) wave model employed, using a representation of the foil as the point source and use of the approximate lift and drag coefficients from [12]. These approximations may affect the relative balance between shaft power and wave cancellation, since the model does not consider complex hydrodynamic effects such as added mass, dynamic drag losses and generation of the vortices caused by the rapid changes in rotational speed.

However, ultimately, shaft power is the most important metric in the commercial viability of a wave energy device, directly affecting the economic output performance of a device.

While only the ideal monochromatic case is dealt with here, for clarity of exposition, the panchromatic case can be addressed in a similar fashion, where a receding horizon control solution would need to be employed, in the spirit of [17]. While a potential increase of 46% in captured energy was demonstrated for the monochromatic case shown, the energy gain may be more moderate in panchromatic waves, though initial panchromatic results are quite promising. Nevertheless, given the challenges for wave energy to become economic, these energy gains are significant, since the associated costs are minimal; in any case, the torque on the shaft needs to be modulated to maintain a constant velocity, so little additional cost is incurred in generating a torque signal which gives an optimum, rather than a constant, velocity profile.

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REFERENCES

[1] A. Ermakov and J. V. Ringwood, "Rotors for wave energy conversion-practice and possibilities," *IET Renewable Power Gener.*, vol. 15, pp. 3091–3108, 2021.
[2] N. Scharmann, "Ocean energy conversion systems: The wave hydro-mechanical rotary energy converter," PhD dissertation, Inst. Fluid Dyn. Ship Theory, TUHH, Hamburg, Germany, 2014.
[3] A. Hermans, E. Van Sabben, and J. Pinkster, "A device to extract energy from water waves," *Appl. Ocean Res.*, vol. 12, no. 4, pp. 175–179, 1990.
[4] S. Siegel, "Wave climate scatter performance of a cycloidal wave energy converter," *Appl. Ocean Res.*, vol. 48, pp. 331–343, 2014.
[5] S. G. Siegel, "Numerical benchmarking study of a cycloidal wave energy converter," *Renewable Energy*, vol. 134, pp. 390–405, 2019.
[6] S. G. Siegel, C. Fagley, M. Römer, and T. McLaughlin, "Experimental investigation of irregular wave cancellation using a cycloidal wave energy converter," in *Proc. 31st Int. Conf. Ocean, Offshore Arctic Eng.*, 2012, pp. 309–320.
[7] C. P. Fagley, J. J. Seidel, and S. G. Siegel, "Computational investigation of irregular wave cancellation using a cycloidal wave energy converter," in *Proc. 31st Int. Conf. Ocean, Offshore Arctic Eng.*, 2012, pp. 351–358.
[8] K. Budar and J. Falnes, "A resonant point absorber of ocean-wave power," *Nature*, vol. 256, no. 5517, pp. 478–479, 1975.
[9] A. Ermakov and J. V. Ringwood, "A control-orientated analytical model for a cyclorotor wave energy device with n hydrofoils," *J. Ocean Eng. Mar. Energy*, vol. 7, pp. 201–210, 2021.
[10] A. M. Ermakov and J. V. Ringwood, "Erratum to: A control-orientated analytical model for a cyclorotor wave energy device with n hydrofoils," *J. Ocean Eng. Mar. Energy*, vol. 7, pp. 493–494, 2021.
[11] A. Ermakov and J. V. Ringwood, "Development of an analytical model for a cyclorotor wave energy device," in *Proc. 14th Eur. Wave Tidal Energy Conf.*, 2021, Art. no. 1885.
[12] R. Sheldahl and P. Klimas, "Aerodynamic characteristics of seven symmetrical airfoil sections through 180-degree angle of attack for use in aerodynamic analysis of vertical axis wind turbines," Sandia Nat. Labs., Albuquerque, NM, USA, Tech. Rep., SAND-80-2114, 1981.
[13] A. Arredondo-Galeana *et al.*, "A methodology for the structural design of liftwec: A wave-bladed cyclorotor," in *Proc. 14th Eur. Wave Tidal Energy Conf.*, 2021, Art. no. 1967.
[14] A. Ermakov, A. Marie, and J. V. Ringwood, "Optimal control of pitch and rotational velocity for a cyclorotor wave energy device," *IEEE Trans. Sustain. Energy*, Accessed: Apr. 5, 2022, doi: 10.1109/TSTE.2022.3168508.
[15] A. Ermakov and J. V. Ringwood, "Energy-maximising control philosophy for a cyclorotor wave energy device," in *Proc. 41st Int. Conf. Ocean, Offshore Arctic Eng.*, 2022, Art. no. 80990.
[16] G. Bacelli, J. V. Ringwood, and J.-C. Gilloteaux, "A control system for a self-reacting point absorber wave energy converter subject to constraints," *IFAC Proc. Volumes*, vol. 44, no. 1, pp. 11 387–11 392, 2011.
[17] R. Genest and J. V. Ringwood, "Receding horizon pseudospectral control for energy maximization with application to wave energy devices," *IEEE Trans. Control Syst. Technol.*, vol. 25, no. 1, pp. 29–38, Jan. 2017.