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Optimising power take-offs for maximizing wave energy conversions

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1 Introduction

The paper presents a study on the different power take-off (PTO) dampers (linear and nonlinear) and their optimizations for maximising wave energy conversions on a point absorber wave energy converter.

To simplify the problem, a bottom-fixed point absorber and the single heave motion is considered for power conversion and analysis. For such a system, theoretical work has been widely carried out in optimising the damping levels in maximising wave power conversion if the power take-off is linear and under the assumption of the linear hydrodynamics of wave energy conversion. It has been shown that the relevant optimised damping can be easily obtained analytically in regular waves [1, 2]. However, when it comes to the nonlinear power take-off, the problem becomes more complicated, and much less research work has been conducted and optimised for nonlinear power take-offs.

It has been wondered, however, whether the nonlinear power take-offs are better than the linear ones, because some claims have been made that the nonlinear power take-offs can convert more power than those of linear power take-offs. Though there is limited evidence for the claims, it is not evident whether it is coincident or not. For instance, if these PTOs are not optimised, then the comparison among the different PTO damping coefficients may be meaningless and even unfair in some cases. In this research work, the power conversions from the linear and nonlinear PTOs will be conducted appropriately. More importantly, the comparisons will be made for the optimised damping coefficients for both linear and nonlinear PTO damping coefficients so that the maximum power conversions from different PTOs are comparable.

From the study, it is shown that the averaged power conversion from the optimised linear damper and nonlinear dampers can be very similar. The maximum power conversion using the nonlinear PTOs may be marginally higher than that of the optimised linear PTO, both in regular waves and in irregular waves. That is, the maximised power conversion using a nonlinear PTO may exceed theoretical maximum from the linear analysis, but it must be noted that the exceedance is only marginal.

One difference in optimizing the linear and nonlinear PTOs is that the optimised nonlinear damping coefficient is both wave period and height dependent, whilst the optimised linear damping coefficient is only wave period dependent.

2 Dynamic equations

Figure 1 shows a schematic drawing of the wave energy converter. Under the wave excitation, the buoy is supposed to move up and down (heave motion). When a PTO is applied to connect the buoy and the fixed reference (for example, the seabed), the heave motion of the buoy can drive the PTO to convert the mechanical power into useful energy. The generic dynamic equation can be expressed as

$$\begin{aligned}&[M + A_{33}(\infty)]\ddot{x}_3(t) + \int_0^t K_{33}(t-\tau)\dot{x}_3(\tau)d\tau + C_{33}x_3(t) \\ &= F_3(t) - F_{pto}(t)\end{aligned} \qquad (1)$$

where M is the mass of the device; A_{33} the added mass at infinite frequency for heave motion; K_{33} the impulse function; C_{33} the restoring coefficient; F_3 the excitation; F_{pto} the power take-off (PTO) force due to the power conversion; x_3 the heave motion; v_3 the heave velocity ($v_3 = \dot{x}_3$). All parameters in eq. (1) except F_{pto} can be assessed using the boundary element method for potential flow theory (in this case, WAMIT), in which the hydrodynamics of the float has been taken as a linear dynamic system, thus a frequency domain can be conducted, and the relevant time-dependent parameters can be also easily obtained using a Fourier transform.

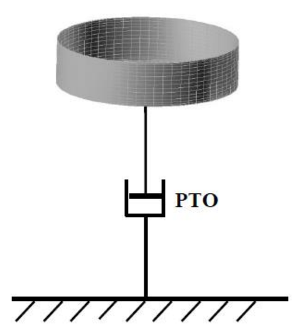

Figure 1 Seabed referenced point absorber

If nonlinear effects are considered, for instance, a nonlinear power take-off, they are only external forces, rather than the hydrodynamic forces. When we consider the wave energy conversion, the wave heights may be medium, hence the nonlinear hydrodynamic effects may not be evident. Hence in this research, linear hydrodynamics is assumed. Under the assumption of the linear hydrodynamics, the dynamic equation (1) is correct whilst the PTO force can be considered to be nonlinear or even piecewise type, like in latching control (see Sheng et al. [3]). Overall, this convention will be applied throughout this research.

For a linear PTO, a pure damper PTO can be simply expressed as a linear relation between the PTO force and the motion velocity as

$$F_{pto}(t) = b_0 v_3(t) \tag{2}$$

where b_0 is the constant damping coefficient of the PTO, and v_3 the velocity of the device in heave (i.e., $v_3 = \dot{x}_3$).

For the nonlinear PTOs, we will examine different types of PTO. The first type is inspired by the nonlinear air turbine, for example, the impulse turbine (see Falcao et al.[4]), in which the PTO force can be expressed as a nonlinear function of the velocity as,

$$F_{pto}(t) = b_1 |v_3(t)|^2 sign(v_3(t)) \tag{3}$$

where b_1 is the nonlinear damping coefficient, and the PTO force is proportional to the velocity squared, |*| means an absolute value.

The second type of nonlinear PTO is inspired by the relation of the newly invented bi-radical turbine (see Falcao et al. [5]), in which the PTO force can be expressed as

$$F_{pto}(t) = b_2 \sqrt{|v_3(t)|} sign(v_3(t)) \tag{4}$$

where b_2 is the nonlinear damping coefficient, and the PTO force is proportional to the velocity square root.

Once the dynamic equation (1) is solved, the power conversion is simply calculated as

$$P(t) = |F_{pto}(t) * v_3(t)| \tag{5}$$

the corresponding average power is given by

$$\overline{P} = \frac{1}{T}\int_0^T P(t)dt \tag{6}$$

where T is the time interval for calculating the average power.

3 Results and analysis

3.1 Power conversion in regular waves

Figure 2 shows the averaged power conversions using linear and nonlinear PTOs in the regular waves of a height H=2m and a period T_w=8s. In the calculations, time-domain simulations and averaged power conversion have been conducted using the procedure shown in the previous section. It can be seen that the linear PTO has an averaged power conversion close to (never larger than) the theoretical maximum in the frequency domain analysis, i.e., 40.77 kW. Using the optimized damping coefficient, the linear PTO could extract the maximal power close to the theoretical maximum. It can be seen that away from the optimised damping coefficient, the captured power is decreased when the damping coefficient is either increased or decreased ('solid line' in Figure 2). When the nonlinear PTOs are considered in the forms of Eqs. (3) and (4), the maximised power conversions can be slightly larger than that of the linear PTO.

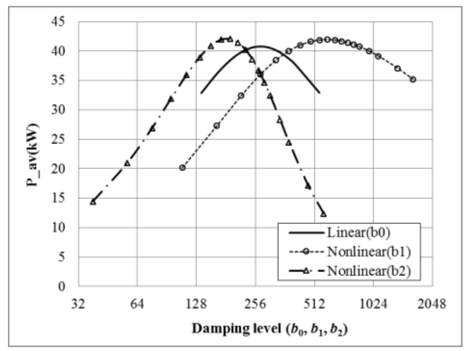

Figure 2 Damping level for regular waves (*H*=2m and T_w=8s)

The optimised damping coefficients are b_0=271.14 kN*s/m, b_1=596.5 kN*s^2/m^2 and b_2=189.8 kN*s$^{1/2}$/m$^{1/2}$ for the respective linear and nonlinear PTOs. It must be noted that the optimised nonlinear PTO coefficients given above are based on both the specific wave height H=2m and period, T_w=8s, whilst for the linear PTO, the optimised damping coefficient is only decided by the wave period.

Figure 3 to Figure 6 show the time series of the simulations in the specific regular wave. It can be seen that the motions for different optimised PTOs are very similar, only small differences can be discerned in the peaks and troughs (Figure 3). Relatively, the velocities of the heave motions for different PTOs are quite different in amplitude (Figure 4).

The PTO forces are very close again in the magnitudes, and no large difference can be seen (Figure 5), whilst as a combination of the PTO force and the velocity, the power conversions are quite different in peaks. It must be noticed that though the difference in peaks in the power conversion, their average power conversions are very similar, 40.77kW, 41.92kW and 42.01kW for b_0, b_1 and b_2 respectively. The nonlinear PTO could exceed the maximal power conversion given by the linear PTO by 2.82% and 3.04% respectively.

For a reference, the ratio of the maximal power over the average power is 2.284 for the nonlinear PTO (b_2), 1.806 for the nonlinear PTO (b_1), compared to the case with a linear PTO, which is a constant of 2 (Figure 6).

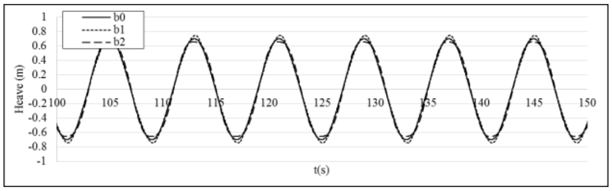

Figure 3 Motion (H=2m &T_w=8s)

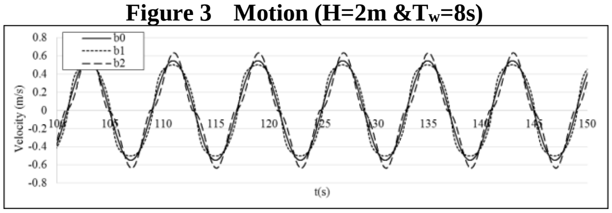

Figure 4 Velocity (*H*=2m & T_w=8s)

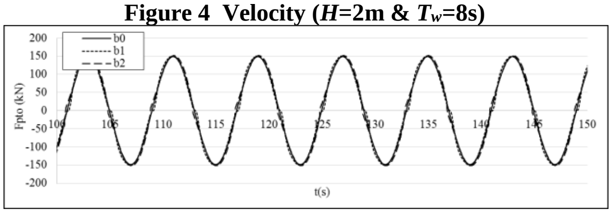

Figure 5 PTO force (*H*=2m & T_w=8s)

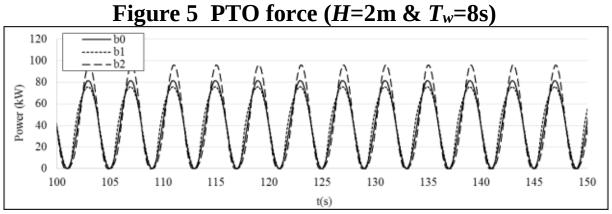

Figure 6 Power conversion (*H*=2m & T_w=8s)

3.2 Power conversion in irregular waves

Figure 7 shows the averaged power conversions using linear and nonlinear PTOs in the irregular wave of a significant height H_s=2m and a peak period T_p=8s (for a Bretschneider spectrum). From the calculations, it can be seen that the linear PTO has a maximal averaged power conversion for the optimised damping coefficient based on the wave energy period, T_e=6.86s, that is, b_0=210.77 kN*s/m in this case. The corresponding maximal power conversion for the linear PTO is 17.76 kW. Away from the optimised damping coefficient, the captured power decreases whenever the damping coefficient is either increased or decreased (‘solid line’ in Figure 7). When the nonlinear PTOs are used, the maximised power conversions can be slightly larger than that of the linear PTO.

Based on the simulations, the optimised damping coefficients for the irregular waves are b_0=210.77 kN*s/m, b_1=505.5 kN*s^2/m^2 and b_2=132.79 kN*s$^{1/2}$/m$^{1/2}$ for the respective linear and nonlinear PTOs. And all optimised linear and nonlinear PTO coefficients given above are based on the wave condition of a significant height H_s=2m and a peak period, T_p=8s.

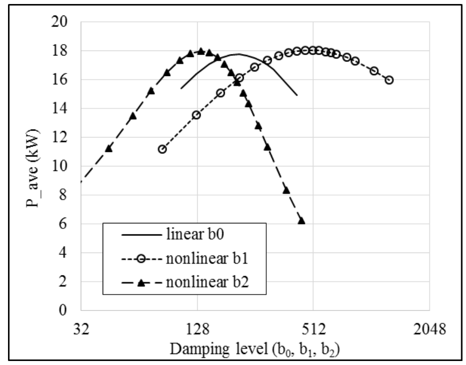

Figure 7 Damping level for irregular waves (*H_s*=2m & *T_p*=8s)

Figure 8 to Figure 11 show the time series of the simulations for the specific irregular waves. It can be seen that the motions in different optimised PTOs are very similar, though some differences can be seen in the peaks and troughs (Figure 8). Similarly, the velocities of the heave motions for different PTOs are different, again in peaks and troughs (Figure 9).

Figure 10 shows the differences of the PTO forces in the magnitudes (Figure 10).

Though the power conversions in time series are quite different in peaks, but the averaged power conversion are very similar, 17.76 kW, 18.05kW and 17.98 kW respectively. The nonlinear PTOs may increase power output by 1.63 % and 1.24% for b_1 and b_2 respectively. Again, a very small increase of the power conversion can be only possible using the optimized nonlinear PTOs. For this particular case, the ratio of the maximal power over the average power is 10.09 with the nonlinear PTO (b_2), 9.12 with the nonlinear PTO (b_1), compared to the linear PTO, which is 10.29 (Figure 11). These statistic values are based on the simulations for about 150 wave cycles.

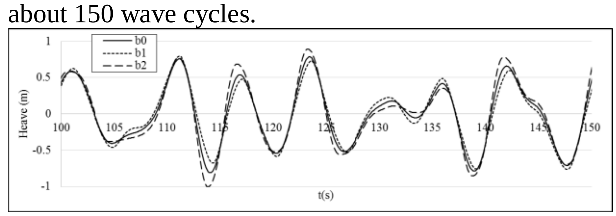

Figure 8 Motion (*H_s*=2m & *T_p*=8s)

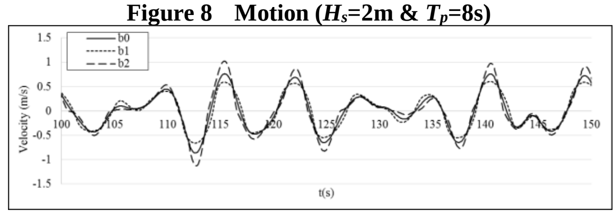

Figure 9 Velocity (*H_s*=2m & *T_p*=8s)

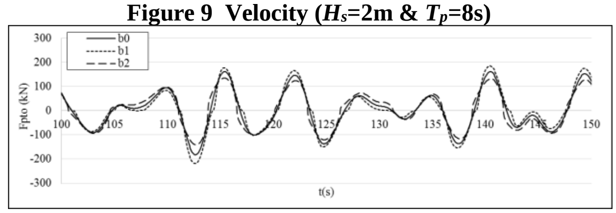

Figure 10 PTO force (*H_s*=2m & *T_p*=8s)

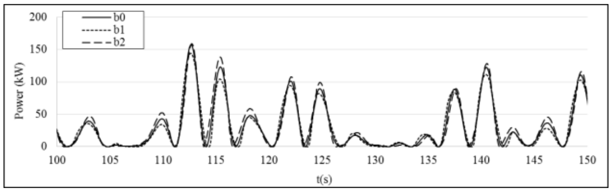

Figure 11 Power conversion (H_s=2m & T_p=8s)

3.3 Maximised power conversion in irregular waves

Figure 12 shows the maximised power conversions for different significant wave heights in irregular waves (peak period T_p=8s). It can be seen that if the damping coefficients are optimised, the linear and nonlinear PTOs can extract very similar maximised powers from waves. The maximised power conversions are generally proportional to the wave height squared with slightly different coefficients for each PTO. From Figure 13, it is interesting to note that for the linear PTO, for the specific wave period, T_p=8s, the optimised damping coefficient is a constant, regardless of the wave heights. But for the nonlinear PTOs, the optimised damping coefficients are both wave period and height dependent. To reach optimised power conversions for different wave heights, the optimised damping coefficient b_1 decreases with the increase of the wave height, whilst the optimised damping coefficient b_2 increases with the increase of the wave height.

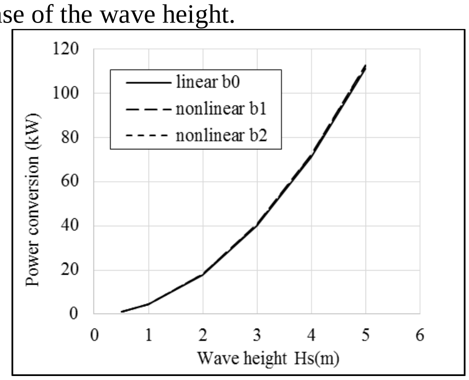

Figure 12 Optimised damping levels with the wave height in irregular waves (T_p=8s)

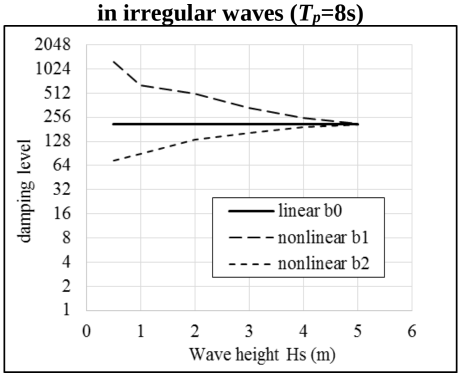

Figure 13 Power conversion with the optimised damping levels for irregular waves (T_p=8s)

4 Conclusions

In this investigation, some comparisons have been made for the linear and nonlinear PTOs in converting wave power into useful energy in which the nonlinear power take-offs are inspired by the practical PTOs. From the investigation, the following conclusions can be drawn:

- For maximising power conversion for the linear and nonlinear PTOs, the damping coefficients must be optimised. Under the optimised damping coefficients (b_0, b_1 and b_2), the averaged power conversions are very similar for the linear and nonlinear PTO dampers. The nonlinear PTOs may extract the maximised power more than that of the linear PTO, by 2-4% in regular waves, and 1-2% in irregular waves, respectively.
- For linear PTOs, the optimisation of the damping coefficient is only based on the wave period in regular waves and in irregular waves, regardless of the wave height. For the nonlinear PTOs, the optimised damping coefficients are based both on the wave period and wave height. For a specific wave period, the optimised damping coefficient decreases with the increase of the wave height for the nonlinear PTO (b_1), and the nonlinear PTO (b_2) has an opposite trend with regard to the nonlinear PTO (b_1).

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