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Title	Latching control theory for wave energy conversion
Authors	Sheng, Wanan;Alcorn, Raymond;Lewis, Anthony
Publication date	2014-03-01
Original Citation	Sheng, W., Alcorn, R., and Lewis, A. (2014) 'Latching control theory for wave energy conversion,' 29th International Workshop on Water Waves and Floating Bodies, Osaka, Japan, 30 March- 2 April.
Type of publication	Conference item
Link to publisher's version	http://www.iwwwfb.org/, http://www.iwwwfb.org/Workshops/29.htm
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Download date	2026-10-31 21:21:33
Item downloaded from	https://hdl.handle.net/10468/2690

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Paper for the 29th International Workshop on Water Waves and Floating Bodies, Osaka, Japan, 30 Mar-2Apr. 2014

Latching control theory for wave energy conversion

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1 Introduction

Control technologies have been proposed and widely studied for improving wave energy conversion efficiency since 1970s (see Falnes [1] and Salter et al. [2]), and it has been proven that control technologies could significantly improve the wave energy conversion efficiency if a phase optimum or an amplitude optimum or both can be implemented. Among the control technologies, the full reactive control technologies have fulfilled both the phase and amplitude optima completely, so they are most efficient. However, it is very difficult to implement the full control technologies in practical applications because they apply too strict constraints in the implementations and because the control parameters are mostly frequency dependent. To fulfill the full phase control, the control system must have a capacity to change its mass or spring coefficient or both from wave to wave. Alternatively, more practical control technologies, most of which are sub-optimal because they can only reach part of the full optimal requirements, have been proposed and studied (see Hals et al. [3]). Hals et al. [3] have extensively compared 8 control technologies, and it is shown that among the 8 proposed control technologies, latching control technologies are very effective.

To decide the de-latching instant, Babarit et al.[4] have compared three different latching control technologies, namely the peak absorbed-energy matching, the peak-amplitude matching and the peak-velocity-excitation matching. It has been shown that all these implementations can significantly improve wave energy conversion. For overcoming the drawback, Falcao [5] proposed a latching control strategy, which can be realised in a wave energy converters using hydraulic PTOs. In this latching control, the instant for delatching is only decided when the PTO force exceeds the given thresholds, thus the requirement for the future information has been discarded. Falcao has furthered the latching control application with the detailed control algorithm (see [6]), and the method has been employed by Lopes et al.[7] in developing a control strategy for oscillating water column wave energy converter.

In this paper, we explore the fundamentals of the dynamics of the latching controlled device. A "timing-out" strategy is employed following the development by Sheng et al. [8] in which when the device is latched/halted and the corresponding time during latching has been taken out. As a result of this, the dynamic system of the "time-out" system is still linear, only the excitation is no longer single-frequency dependent even in regular waves. A further analysis has been revealed that the 'time-out' excitation contains a component of base frequency, and higher frequency (e.g., triple frequency), but the dynamic system is insensitive to those components of high frequencies, but to the base frequencies. In this regard, the dynamic system is equivalent to a system under the excitation of single-frequency (time-out frequency) and hence, frequency domain analysis is possible in such a manner that the dynamic problem is much simplified. Based on the new methodology, we could clearly illustrate how the latching duration can be decided, in which the latching duration can be calculated simply based on the wave period for regular waves.

2 Dynamic equations for latching control

A point absorber is used for illustrating the dynamics for wave energy conversion in this research. The wave energy converter is a generic point absorber of a cylinder with a radius R=3.0m and a draft D=1.5m and its wetted surfaces have been paneled for hydrodynamic analysis, shown in Figure 1.

In the point absorber wave energy converter, like in many other practical point absorber wave energy devices, its heave motion is taken as the primary mover for wave energy conversion. For converting the mechanical energy into useful energy, a power take off (PTO) is connected to the cylinder and to a fixed reference, for instance, the seabed. The PTO unit considered here is generic, but it could provide the required inertia, damping and/or spring effects (see Babarit et al. [9]). Falnes [10] has shown how to optimize the PTO so to improve wave energy conversion, and a more detailed latching control technology has been developed by Sheng et al.[8], including the methodology of the 'time-out' scheme which is adopted in this paper.

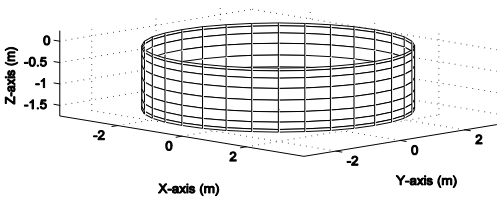


Figure 1 Panels on the wet body of the wave energy converter

As it is shown by Sheng et al.[8], the dynamics of the latching controlled device is nonlinear and hence its solution is normally studied in time domain, even the actual power take-off is linear (i.e., proportional to the velocity). However, it is possible to employ a method termed as the "time-out" method (see Sheng et al.[8]). Because during latching, the device is essentially doing nothing, but locked at a certain position. Hence it is practical to take the latching duration out of the dynamic system, i.e., 'time-out' the period during which the device is locked. It must be noted that during latching, the device does not radiate any waves, but due to the memory effect the radiated effect can be still present.

The time-out equation can be simply expressed

$$[M + A_{33}(\infty)]\ddot{X}_3(t) + \int_0^t K_{33}(t-\tau)\dot{X}_3(\tau)d\tau + b_{PTO} \times \dot{X}_3(t) + C_{33}X_3(t) = F_3'(t) \quad (1)$$

where the new excitation force F_3' is the excitation force after time-out (see Figure 2).

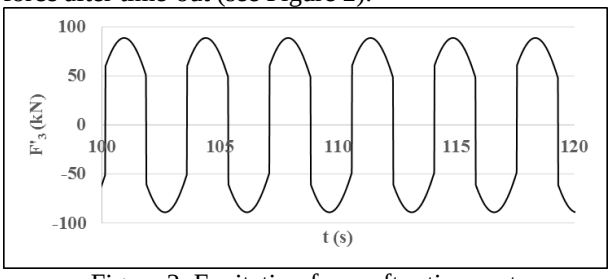


Figure 2 Excitation force after time-out

The equation (1) is a linear dynamic equation. However, even for the case of regular waves, F_3' is no longer single-frequency dependent (see Figure 2). A spectral analysis to the time-out excitation reveals that there is a dominant component at the resonance frequency ω_0=1.8 rad/s, but there are some high frequency components of ω=5.4 rad/s (triple frequency) and ω=9.0 rad/s and so on (Figure 3). Decomposition of the time-out excitation shows the first three components in Figure 4 against the excitation force after time-out. Obviously, the first component (at ω_0=1.8rad/s) is dominant, with an amplitude of 103.53kN (compared to the amplitude of the original excitation of 88.67kN), and amplitudes of 23.0kN and 13.08kN for the second and third components. It is interesting to note that the latching control not only changes the excitation period (from 6s to 3.49 s) so that the time-out system is resonant with the latched excitation (for phase control), but increases the excitation amplitude (the first component) from 88.67kN to 103.53kN, which is another important factor for improving wave power conversion, because the power conversion is normally proportional to the square of the amplitude of the excitation.

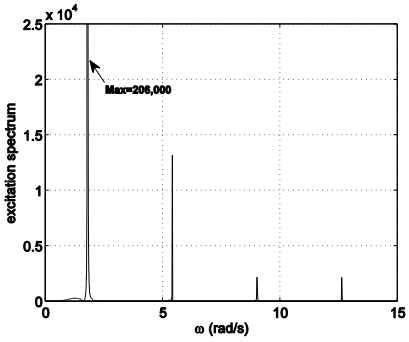


Figure 3 Spectrum of the excitation after time-out

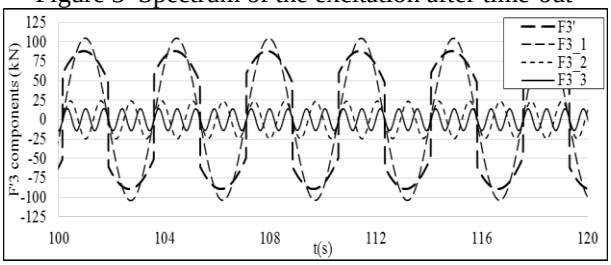


Figure 4 Excitation after time-out and its first three components

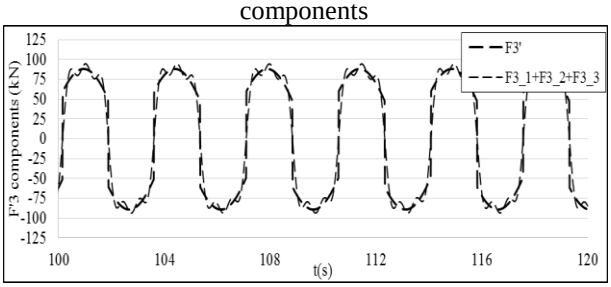


Figure 5 Comparison of excitation after time-out and the sum of the first three components

3 Latching theory

It is noted that the motion responses to the excitations of high frequencies will be small due to the facts that the motion response to unit excitation at high frequencies are much smaller than that at the resonance frequency and the fact that the excitations at high frequencies have much smaller amplitude (see Figure 4). It implies that the device will perform like a low-pass filter. The excitations of high frequencies will be simply filtered out. Therefore, the motion response under the time-out excitation could be actually same as that under the excitation of its first component. Figure 6 shows the comparison of the motion predictions of two methods: one method is solve the latching dynamics directly, and then the latched periods are timed out; and the other one times out the excitation first and then solve the linear latching equation in which the component of the base

frequency is only considered. From Figure 6, one can see that the two solutions are identical. In these two calculations, there is difference in their excitations. In the direct calculation, all excitation components should be included, while in the linearised latching dynamics, the time-out excitation is replaced by its first component. This example further confirms the dynamic system is very insensitive to the excitation of higher frequencies.

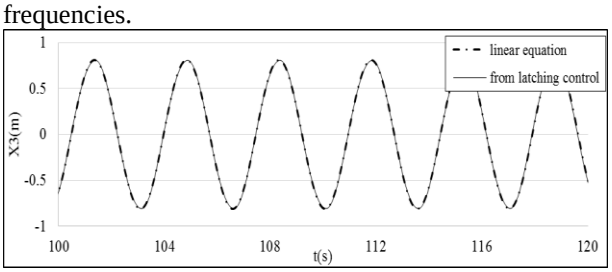


Figure 6 Comparison of the solutions from the linear equation and the latching control

As proven, the time-out dynamic system can be considered as a linear dynamic equation under a single frequency excitation, i.e.,

$$[M + A_{33}(\infty)]\ddot{X}_3(t) + \int_0^t K_{33}(t-\tau)\dot{X}_3(\tau)d\tau + b_{PTO} \times \dot{X}_3(t) + C_{33}X_3(t) = F_{3_1}(t) \quad (2)$$

The linearised time-domain equation can be now transformed back into a frequency-domain equation as

$$\left\{-\omega^2\left[M + a_{33}(\omega)\right] + i\omega(b_{33} + b_{PTO}) + c_{33}\right\}x_3 = f_{3_1} \quad (3)$$

or the frequency domain equation for the complex velocity is

$$\left\{i\omega\left[M + a_{33}(\omega)\right] + (b_{33} + b_{PTO}) + \frac{c_{33}}{i\omega}\right\}v_3 = f_{3_1} \quad (4)$$

where the frequency ω is that of the first component of the time-out excitation, f_{3_1} the complex amplitude of the first component of the time-out excitation, and x_3 and v_3 are the complex amplitude of $X_3(t)$ and $V_3(t)$, respectively.

The solution to eq. (4) is

$$v_3 = \frac{f_{3_1}}{i\omega\left[M + a_{33}(\omega)\right] + (b_{33} + b_{PTO}) + \frac{c_{33}}{i\omega}} \quad (5)$$

Obviously, to satisfy the requirement of phase control, the following condition must be fulfilled

$$\omega_1 = \sqrt{\frac{c_{33}}{M + a_{33}(\omega)}} \quad (6)$$

which is exactly same as that of the resonance frequency of the device (i.e., $\omega_1=\omega_0$), and the corresponding solution is

$$v_3 = \frac{f_{3_1}}{b_{33} + b_{PTO}} \quad (7)$$

If the time-out excitation has been made to have a first component of the resonance frequency, the time out excitation must have a resonance period, hence,

$$T_0 = T_w - 2 * T_{latch} \quad (8)$$

i.e. the latching duration is calculated as

$$T_{latch} = \frac{T_w - T_0}{2} \quad (9)$$

where T_w is the wave period, T_0 the resonance period of the device heave motion.

It must be noted that the simplification of the dynamic equation for latching control is approximated by assuming the memory effect is small or unchanged during the latching. This assumption may be justified due to the fact that the latching happens at the instant when the velocity becomes zero or very small. In this sense, the memory effect may not be very large or important, especially when the latching duration is small. Due to this approximation, the actual latching duration may be slightly different from that given by eq.(9). Nonetheless, the proposed latching duration is a very good approximation, and this will be studied in the following sections. The details can be found in Sheng et al. [8].

4 Results and Analysis

Calculation of latching duration has been formulated above under an assumption that the memory effect during latching is small or kept constant. This assumption may be justified due to the fact that before latching the velocity is already small, hence the latching effect to the memory effect may be small, or if the latching duration is small so that the memory effect has not been significantly influenced by latching.

To study the influence of the latching duration, we vary the latching duration by a small values of ±0.5s, ±0.3s, ±0.2, ±0.1s, and ±0.05s to demonstrate the influence of underlatching and overlatching ("underlatching" is defined as the latching duration given by Eq.(9) minus a small time and "overlatching" as the latching duration plus a small time). Figure 7 shows the influence of the latching durations (both underlatching and overlatching) for the optimal damping b_{PTO}=21.8 kN/(m/s). It can be seen that a slight underlatching by 0.05s is beneficial for a better wave energy conversion.

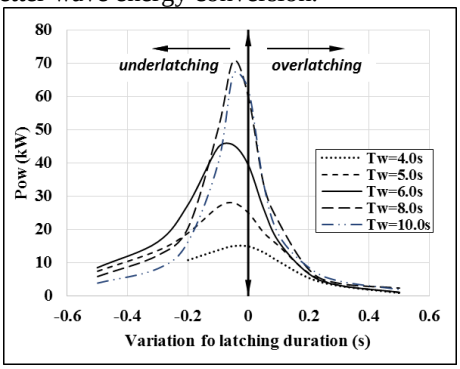


Figure 7 Latching duration on power extraction

5 Conclusions

This research is focused on how the latching duration can be easily calculated and the reasons why latching control can so much improve wave energy conversion. For these targets, a simplified mathematical equation has been established based on the proposed "time-out" method which has changed the actual nonlinear dynamics into a linear dynamics so that a frequency-domain analysis is possible. Based on the simplification, the fundamentals behind the latching control can be studied and the indications become more obvious. The in-depth studies why latching control can improve power extraction become possible as shown in the context.

In the study, the decision of the latching duration can be simply made and then justified, though a slight adjustment in the latching duration is a necessary in some cases. Nonetheless, this proposal gives a very good indicator. From the research, the following conclusions can be drawn:

1) A simple way in determining the latching duration in regular waves has been illustrated, in which the latching duration can be simply calculated by eq.(9).
2) A 'time-out' procedure has been proposed in this research, and based on the methodology, the complicated nonlinear problem can be simplified into a linear problem and a frequency-domain analysis can be possible.
3) It has been shown that by applying latching control, the wave energy conversion can be increased due to three major improvements, namely the phase optimum, the motion acceleration and the increase of the excitation amplitude.
4) Frequency domain analysis made in the research shows the fundamentals behind the latching control technologies, such as, how the phase optimum can be achieved, and therefore, how the latching duration can be chosen, though a better power conversion can be obtained by a slight underlatching, which may mainly be caused by the simplification in the analysis.
5) By using latching, the device can extract more energy from longer waves up to a certain wave period. In the example, the significant increase of wave energy conversion can be seen from 3.49s to 6.0s.

Acknowledgements

This material is based upon works supported by the Science Foundation Ireland (SFI) under the Charles Parsons Award at Beaufort Research-Hydraulics and Maritime Research Centre (HMRC). Statistics and data were correct at the time of writing the article; however the authors wish to disclaim any responsibility for any inaccuracies that may arise.

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