PHASE CONTROL BY LATCHING APPLIED TO THE ARCHIMEDES WAVE SWING

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Abstract: Absorption of wave energy by the Archimedes Wave Swing (a wave energy converter, of which a prototype has already been tested in Portugal) can be improved by latching its heaving motion in order to optimise its interaction with the incident waves. For regular and irregular waves (the later based on statistical data from the ONDATLAS software), time-domain simulations are presented and results obtained with several latching strategies are examined. It is seen that latching significantly improves the performance; power extracted by the AWS from waves with the best performing latching strategy is up to 27 times larger than that obtained without control.

Keywords: Marine control, Latching control, Wave energy converter, Archimedes Wave Swing

1. INTRODUCTION

Sea waves may become an important source of renewable energy if only economically viable devices can be developed to extract electricity therefrom. This paper is a step towards that objective, presenting preliminary results of the control of one such device, the Archimedes Wave Swing (AWS), a wave energy converter (WEC) of which a 2 MW prototype (Fig. 1) has already been built and tested at the Portuguese northern coast during 2004. Since this prototype has been decom-

Fig. 1. The AWS before submersion

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missioned, results presented were obtained with an accurate, non-linear *Simulink* model thereof (Pinto, 2004; Sá da Costa *et al.*, 2005). Several parameters and significant values of the model, however, have been altered, due to industrial secrecy reasons. Nevertheless, these results are expected to be of use during the development of a new, improved second-generation prototype.

The paper is organised as follows: section 2 briefly presents the AWS; section 3 introduces the idea of latching control and describes several latching strategies applied to the AWS; section 4 presents the results obtained; conclusions are drawn in section 5.

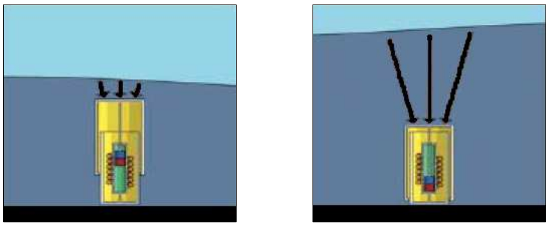

Fig. 2. AWS working principle

2. THE AWS

The AWS is an off-shore, fully-submerged (43 m deep underwater), point absorber (that is to say, of neglectable size compared to the wavelength) WEC consisting mainly in a bottom-fixed air-filled cylindrical chamber (the silo) and a movable upper cylinder (the floater) which heaves due to the changes in wave pressure (Fig. 2): under a wave top the floater moves down compressing the air inside the AWS; under a wave trough pressure decreases and consequently the air expands and the floater moves up (*Archimedes Wave Swing*, 2006). An electric linear generator (ELG) converts the floater's heave motion into electricity. The AWS can hence be expected to behave much like a mass–spring–damper system, though with relevant non-linearities.

In the dynamic behaviour of the AWS two motions can be modelled separately: the low frequency motion due to changes in tide, atmospheric pressure and/or temperature inside the AWS—slow dynamics—, and the high frequency motion due to sea waves—fast dynamics. In this paper simulations are brief enough to allow neglecting effects of slow dynamics. The control of the fast dynamics is provided to ensure that the amplitude of the floater heave motion is as large as possible to extract the maximum wave energy, but maintained within certain operational preset limits (±3.5 m). This is done varying the damping of the AWS, part of the damping being provided by the ELG and part by hydraulic damping devices, called water dampers. These are necessary when the damping force from the ELG is not enough.

The AWS time-domain model is based on Newton's law applied to the floater's vertical acceleration $\ddot{\xi}$. The equation of motion of the AWS is:

$$f_{tot} = m\ddot{\xi} \Leftrightarrow f_{pe} + f_{pi} + w_f + f_n + f_v + f_m + \\ + f_{wd} + f_{lg} = (m_f + m_{wt})\ddot{\xi} \qquad (1)$$

The total mass m comprises the mass of the floater m_f and the water trapped inside the floater m_{wt}. The total force f_{tot} acting on the floater is the sum of the forces due to external water pressure f_{pe}, to internal air pressure f_{pi}, to the weight of the floater w_f, to a nitrogen cylinder extant inside the AWS f_n, to the hydrodynamic viscous drag f_v, to mechanical friction f_m, to the water dampers f_{wd}, and to the ELG f_{lg}, the last two being damping forces. A detailed description and complete explicit expressions of all these terms cannot be given here for lack of space. They may be found for instance in (Pinto, 2004; Sá da Costa *et al.*, 2003; Sá da Costa *et al.*, 2005).

3. PHASE CONTROL BY LATCHING

It can be shown (Falnes, 2002) that, in order to maximise the power absorbed from the waves, the velocity of the floater should be in phase with the excitation force (this is the force that would act on the floater if it were fixed) acting thereupon. This, however, requires non-causal control actions (Falnes, 2002). A suboptimal alternative is to latch the floater during some periods of its oscillation and unlatch it so that it will be (as nearly as possible) in phase with the excitation force (Falnes, 1993; Falnes, 2002; Greenhow and White, 1997; Babarit *et al.*, 2004). This latching control is suboptimal since it can never achieve the energy extraction efficiency that the optimal, non-causal (and hence hardly feasible) control would achieve.

Latching is clearly a discrete, highly non-linear form of control. In what concerns the AWS, latching is achieved by actuating the water dampers so as to prevent (as much as possible) the floater from moving; unlatching means turning the water dampers off to let the floater go about (as much as possible) freely. The water dampers reference is thus a sequence of steps, but since they do not respond immediately they were assumed to be affected by a low-pass filter $F_{wd}(s)$:

$$F_{wd}(s) = \frac{3.5}{s + 3.5} \qquad (2)$$

In all that follows full knowledge of how the incident wave will behave in the future is assumed, as done for instance in (Falnes, 1997; Eidsmoen, 1998; Babarit *et al.*, 2004). This unreal assumption will have to be dropped in future research, but, for now, the independent problem of wave prediction, either from past data or from measurements done around the WEC (Naito and Nakamura, 1985), was not tackled, and is postponed to some later opportunity.

Table 1. Latching force in kN

wave	wave amplitude				
period	0.25 m	0.5 m	1.0 m	1.5 m	2.0 m
8 s	95	285	570	855	1425
10 s	95	285	760	1520	1995
12 s	190	380	1235	1900	2185
14 s	190	380	1520	2185	1995

Clearly, the best moment to latch the floater is when its velocity vanishes. The following unlatching strategies were implemented:

1. The latching time is constant. This is only reasonable when the incident wave is regular (sinusoidal). Hence this strategy was used for testing only, and will not be addressed further.
2. When the floater is latched, the duration of the last unlatched period is obtained. The next unlatched period is assumed to be going to last the same as the previous one. The floater's position is assumed to have its maximum (or minimum) precisely at the middle of that time interval. So the latching time is reckoned for that position maximum (or minimum) to coincide in time with the next maximum (or minimum) of the excitation force. The force required from the water dampers to latch the floater is constant.
3. The same as above, save that the force required from the water dampers to latch the floater depends on the amplitude and period of the incoming wave, larger waves requiring a larger force and smaller waves requiring a smaller force. The forces for each wave amplitude and period are those necessary to latch effectively the floater when the incident wave is regular and has the required amplitude and period. Values are given in Table 1 and are interpolated and extrapolated as needed.
4. The same as above, but the duration of the next unlatched period is assumed to be equal to the last one corrected according to the ratio between the next wave amplitude and the previous.
5. The same as above, but the duration of the next unlatched period is assumed to be equal to half of the floater's natural period of oscillation, which is 11 s. Thus, the floater is unlatched 2.75 s (one quarter of the natural period) before the next maximum (or minimum) of the excitation force (Falnes, 1993; Falnes, 1997; Eidsmoen, 1998).

4. RESULTS

4.1 Regular (sinusoidal) waves

Simulations of phase control by latching were first carried out for regular, sinusoidal incident waves. Some significant results for four different waves, with amplitudes and periods within the ranges expected, are given in Table 2. Fig. 3 illustrates the evolution of energy absorption during a 600 s (10 min) simulation for one of them.

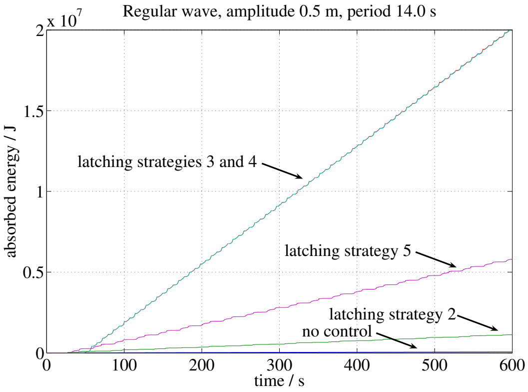

Fig. 3. Evolution of energy absorbed with time, for a regular wave *(figurative data)*

These results show that latching strategies 3 and 4 have nearly the same performance. This is no surprise: since the wave is regular, the duration of each heave motion is always the same, and there is no need to correct the duration of the last unlatched period. The usefulness of such a correction—if any—is to be assessed with irregular waves. Additionally, it is seen that strategies 2 and 5 perform quite poorly when compared with strategies 3 and 4. Yet, all strategies significantly improve the results obtained with no control at all.

Table 2. Power extracted by the AWS (in kW) for regular waves *(figurative data)*

amplitude	0.5 m	0.75 m	1.0 m	1.25 m
period	14.0 s	12.0 s	10.0 s	8.0 s
without control	0.1	0.4	3.8	5.7
latching strategy 2	1.9	7.8	7.3	70.6
latching strategy 3	36.5	53.0	119.6	153.9
latching strategy 4	36.5	53.0	119.6	153.3
latching strategy 5	10.1	40.1	71.5	56.3

In Fig. 4 the evolution of the position and the velocity of the floater is shown, together with the evolution of the excitation force. When there is no control, the position and the velocity are not far from sinusoids (the difference arises from the nonlinearities of the AWS), which are clearly not in

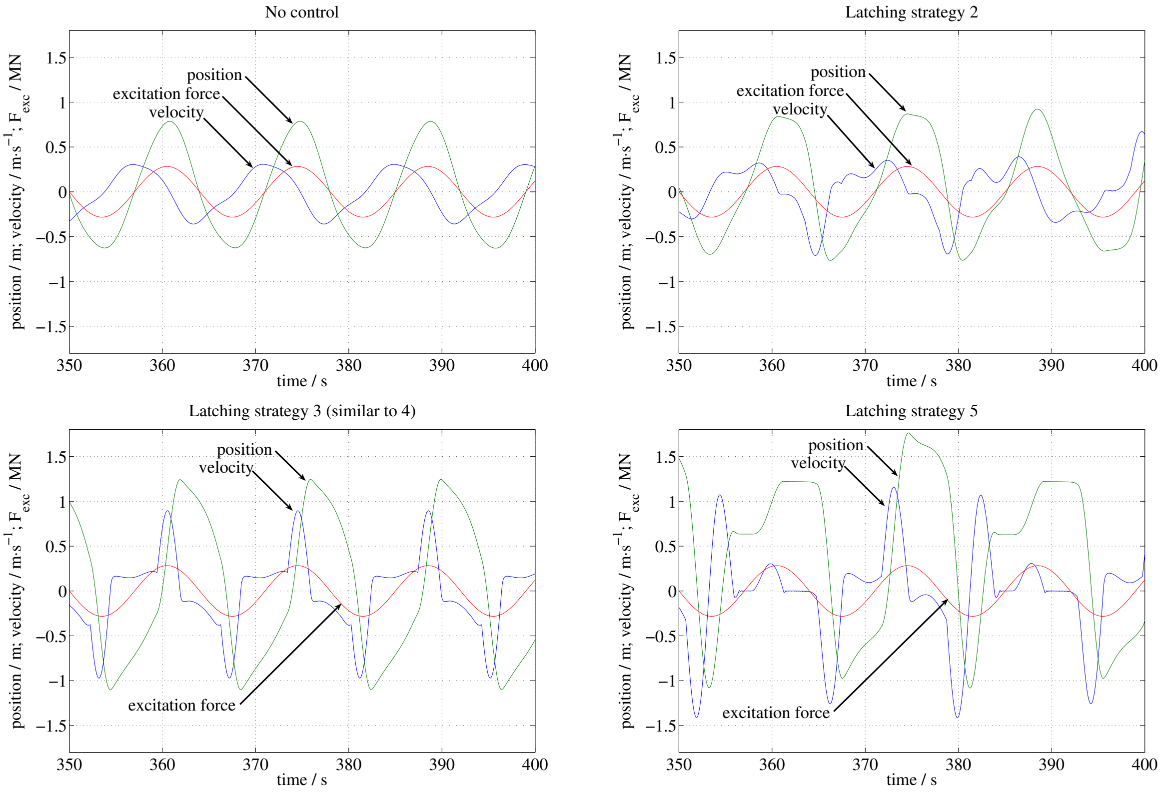

Fig. 4. Floater's position and velocity, together with the excitation force; 50 s long period from the simulation with a wave of 0.5 m of amplitude and 14.0 s of period

phase with the excitation force. Latching strategy 2 succeeds in slightly increasing the amplitude of the oscillations—hence the increase in energy extracted—, but the velocity is still not in phase with the excitation force. Strategies 3 and 4 (only the first is shown; results obtained are, as said above, the very same) manage to get velocity and excitation force in phase: that is why they perform best. Notice that latching is not perfect: the floater is never really stopped, it only slows down significantly. A perfect latching would often require a much more significant damping force, above the maximum water dampers can provide. Strategy 5 fails in putting velocity and excitation force in phase. Notice that sometimes, after unlatching, the floater begins its motion without inverting the direction of movement. This is a clear sign that the latching time was not appropriate. In spite of the wider oscillations, this strategy does not lead to a better energy absorption.

4.2 Irregular waves

Twelve further simulations (one for each month of the year) were then carried out with non-sinusoidal waves. Pierson-Moskowitz's spectrum, that accurately models the behaviour of real sea-waves (Falnes, 2002), was used. This is given by

$$S(\omega) = \frac{A}{\omega^5} e^{\frac{-B}{\omega^4}} \tag{3}$$

where S is the wave energy spectrum (a function such that $\int_0^{+\infty} S(\omega)d\omega$ is the mean-square value of the wave elevation). The numerical values $A = 0.780$ (SI) and $B = 3.11/H_s^2$ were used. Values for the significant wave height H_s and for the limits of the frequency range (corresponding to the maximum and minimum values of the wave energy period T_e) are given in Table 3 and are those provided by ONDATLAS software (Pontes *et al.*, 2005) for the Leixões–bóia site (41° 12.2′ N, 9° 5.3′ W), the closest, among those available, to the AWS deployment site. Since the power the AWS absorbs is no longer constant, 600 s (10 min) long simulations were carried out and the absorbed power averaged over that period, deemed significant.

Results are summed up in Table 4; some significant examples are given in Fig. 5. It is clear that winter and summer months are rather different. During summer (loosely defined as the May–September period), when there is less energy available in waves, strategies 2, 3 and 4 are comparable; 3 is always (with one single exception, and that by a narrow margin) the best. During the rest of the year (the October–April period), when there is more energy available, strategies 3 and 4 are clearly better than all others. Strategy 5, though improving energy absorption over the situation without control, never leads to acceptable results. It is clear that strategy 4 is not a

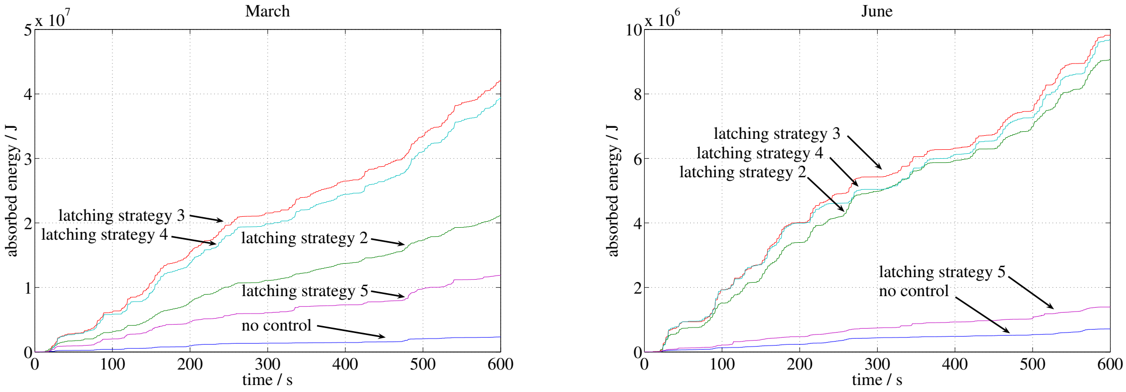

Fig. 5. Evolution of energy absorbed with time, for two significant months *(figurative data)*

Table 3. Average values for waves in Leixões–bóia, according to ONDATLAS

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
H_s / m	3.2	3.0	2.6	2.5	1.8	1.7	1.5	1.6	1.9	2.3	2.8	3.1
$T_{e,min}$ / s	5.8	5.8	5.2	5.5	5.0	4.7	4.6	5.0	5.2	5.3	5.5	5.3
$T_{e,max}$ / s	16.1	14.5	13.7	14.8	12.2	9.7	11.1	10.5	12.0	12.6	13.3	14.2

Table 4. Power extracted by the AWS (in kW) for irregular waves *(figurative data)*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
without control	6.9	5.9	3.4	2.6	1.2	1.0	0.7	0.7	1.0	2.1	4.5	7.5
latching strategy 2	42.3	41.0	33.5	32.7	17.2	14.5	11.0	13.9	19.8	27.3	37.7	42.2
latching strategy 3	108.5	87.9	67.6	64.0	22.6	15.7	10.4	15.6	26.9	48.5	76.8	87.7
latching strategy 4	91.4	85.2	62.7	61.4	22.1	15.2	9.6	15.2	26.0	45.7	72.8	85.9
latching strategy 5	50.8	35.0	18.7	15.3	3.3	2.4	1.5	1.7	4.0	10.2	25.3	39.6

good improvement over 3. Its more complicated algorithm seldom leads to a better performance. From this analysis, it is clear that strategy 3 is the one to choose.

Fig. 6 is a counterpart of Fig. 4. Strategies 3 and 4 are once more the ones that succeed in putting the floater velocity reasonably in phase with the excitation force. Strategies 2 and 5 are clearly less successful. Again, latching is sometimes not perfect; hence the floater moves in spite of the water dampers' effort.

5. CONCLUSIONS

In this paper phase control by latching has been successfully employed with a non-linear simulator of a real, prototype-tested WEC. Several different variations of the control strategy have been implemented and their performance evaluated for irregular waves, similar to those found at the real sea. Beyond assessing the strategies' relative merit, simulations have shown that control by latching significantly improves the performance of the AWS.

Strategy 3, clearly the one to choose, improves energy absorption from 12 times (in December) up to 27 times (in September) compared with the situation without control. These improvements take place all around the year, not only in summer or winter. In what concerns the figures given for energy extraction, two things must be noticed. Firstly, the AWS model has been modified, as stated above, for industrial secrecy reasons. Secondly, power extraction with irregular waves is very far from being constant with respect to time: to achieve the average values shown, it is necessary to be able to extract a much higher peak value.

The work reported is still preliminary. Three improvements are obvious and are being pursued. The first is the (both important and difficult) problem of wave prediction, since information on the incoming waves will not be so easily available as assumed here. The second is the comparison with other control alternatives, such as, for instance, reactive control or phase and amplitude control (Falnes, 2002). The third is the adaptation of these techniques to the real, improved AWS prototype expected to be available soon.

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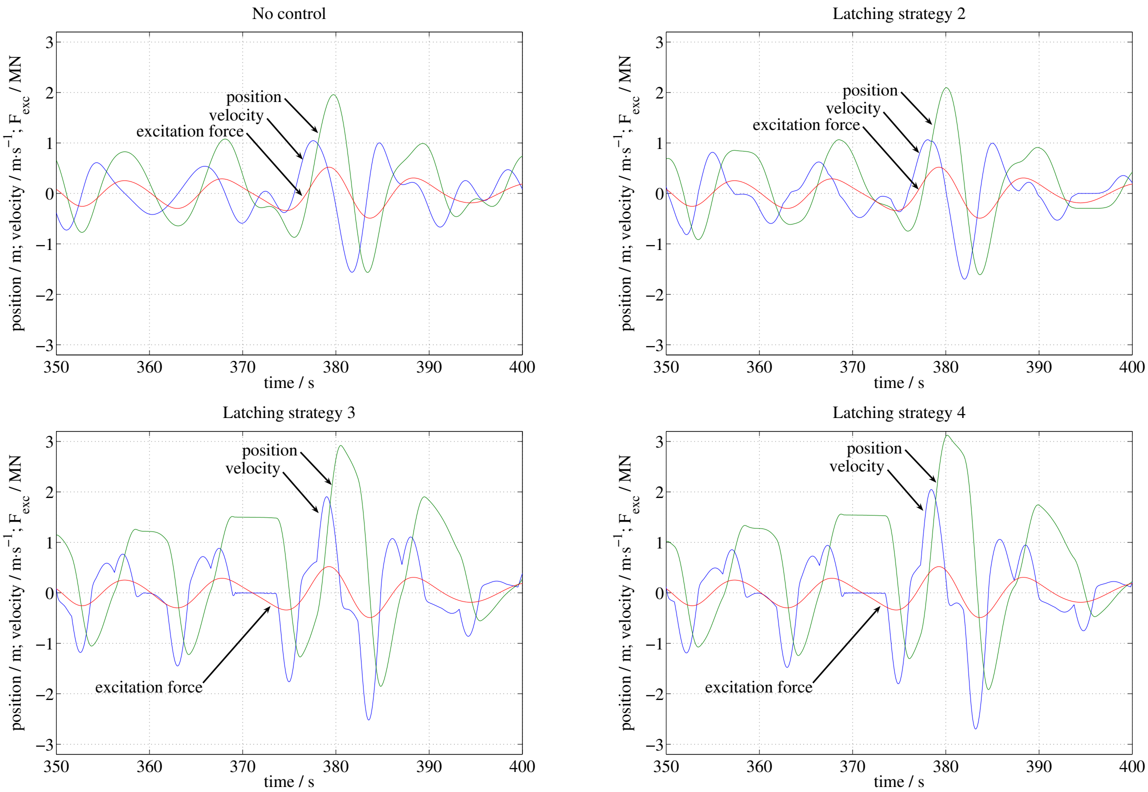

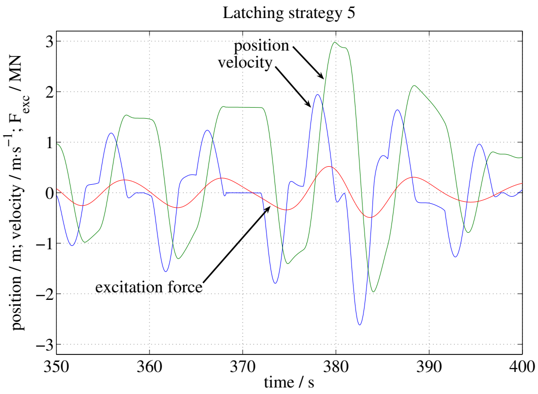

Fig. 6. Floater's position and velocity, together with the excitation force; 50 s long period from the February simulation

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