Control systems for Wraspa

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Abstract--**The paper discusses the need for a wave energy converter (WEC) to sense and respond to its environment in order to survive and to produce its maximum useful output. Such systems are described for Wraspa, a WEC being developed at Lancaster University and first reported at ICCEP in 2007. The main control system that continually monitors and optimises the power-take-off is termed "Stepwise Control" and seeks to continually adjust the damping force applied to the collector to suit the wave force that drives it. The complete instrumentation and control system that will be needed is considered briefly, including the above PTO control system; direction sensing and heading control; tide level compensation; condition monitoring and provisions for access and maintenance.**

Index Terms-- **Control equipment, Control systems, Controllability, Energy conversion, Energy resources, Energy storage, Marine technology.**

I. INTRODUCTION

Wraspa, as its name is intended to imply, is a Wave-driven, Resonant, Arcuate-action, Surging Point Absorber and has its origins in the clear need for WECS to survive over long periods in a harsh natural environment [1]. The idea was taken forward as "Frond" [2] and as OWSC [3] which later became the Oyster device [4]. The two approaches are similar and both benefit from being in relatively shallow water [5]. Tests on collectors moving in surge [12] confirmed the findings of Evans [6,7] that, at resonance, Capture Width (CW) could exceed collector width and amplitude, un-damped, could be more than 5x wave amplitude. A pure surge WEC was seen as impractical and Wraspa – see Fig. 1A - was devised in 2006 as a possible, quasi-resonant-in-surge, collector pivoted at or near the seabed. The design mimics nature in being rooted to the seabed and able to move to and fro, so aiding its survival and keeping structural forces within limits [8,9,10].

The first version [11] showed full-scale CWs, in a 50 kW/m, regular wave of up to 10m and in a later version [12] these were increased to over 20m, both with fixed-value Coulomb damping.

Wraspa control – fast and slow tuning

The Coulomb damping, used initially, represented a type of latching control [13] in that it set a single torque - threshold that had to be exceeded before the collector moved and any power was absorbed and the resulting work loops were roughly rectangular. The stepwise damping concept was modelled and described [12] and is an extension of the latching idea in that it sets a number of thresholds at increasing levels of torque that make the

collector able to react proportionately to "small, medium and large" waves and so provide a better match to the variations in incoming power. The method can be said to maximise power transfer from sea to machine by matching impedances [14].
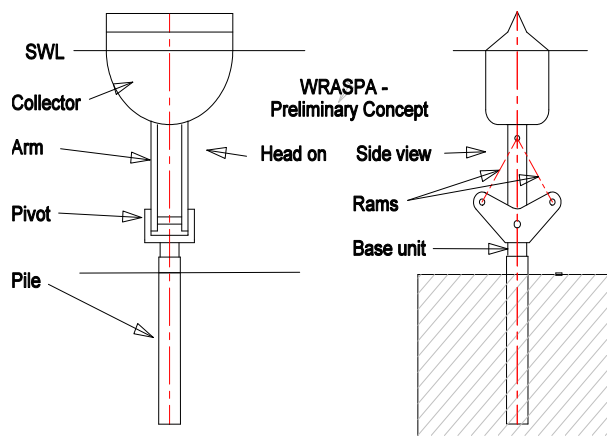

Fig.1A An initial sketch of the concept + key nomenclature

The system has similarities with the Pelamis PT0 described by Cruz [15] and in both systems the force on a particular damper would be almost constant at either a Max. or a Min. set by the system pressure. For the stepwise system to operate its algorithm will need an input signal related to the incident wave force. In this, and probably in any on-board systems that may be developed, Wraspa is a mechatronic device and benefits from design principles [16] that include the idea "keep complexity in the software". The input signal is provided in the laboratory by a wave probe and, in a sea-going device, would probably be given by a combination of pressure and motion signals and a wave sensor [17] located nearby at the seabed.

II. APPARATUS.

This is shown in Fig. 2 (photo). A lever, connected to the collector body under water, drives a light vertical pushrod acting on the top shaft via a crank, seen in the picture. This shaft mimics the action of the collector and to it are fitted the motion sensor and two bi-directional band-brakes. The brakes are activated by two solenoid-operated clutches. The frictional torque offered by brake 1 is half that of brake 2 so that, by binary combinations 0+0, 1+0, 0+2 and 1+2, a series of 3 steps plus zero are selectable by the control program.
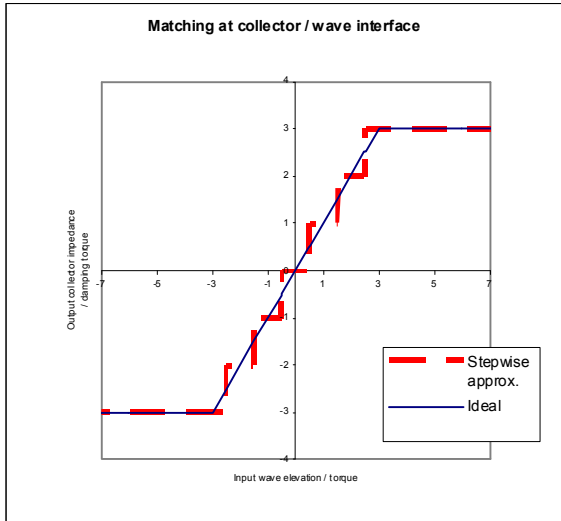
Fig.1B Stepwise control action - diagramatic

We were very pleased to be able to use Edinburgh University's Curved Tank [18] which has a depth of 1.2m and a nominal model scale of 1:100 when compared with typical N. Atlantic conditions. Its design comes from their original Wide Tank but is better than its predecessor
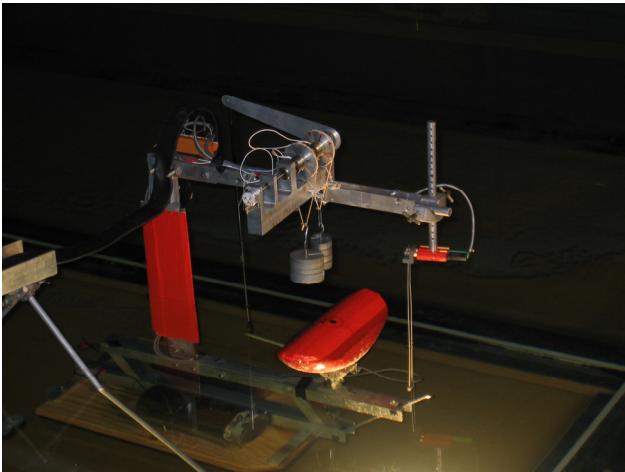

Fig.2 The rig showing collector body (red) with wave probe on seaward side and top shaft with brake loads

in minimising side wall reflections and is well suited to testing isolated WECs or small arrays. In tests the model was clipped to a tall 4 legged frame such that it could easily be removed & replaced. As part of the system we also used the Edinburgh Designs [19] sine wave and mixed wave generators. A Bretschneider spectrum with a Cosn spreading function was used except where, as noted, it was more convenient to use a PM spectrum.

III. EXPERIMENTAL RESULTS.

Most result are given in terms of Capture Width (CW) (being Absorbed Power (Watts) / Incident Wave Power (Watts/metre)) so, in each case, model power can be found from the product of Incident wave power(x) **x** CW (y)

Regular waves - Results in regular waves showed a clear trend of CW increasing in smaller waves. The curve in Fig.3 – below - was obtained by plotting CW vs. 1/Power and finding a least-squares best-fit line. The Point Absorber ideal CW of λ/π in surge [7] - occurs at 0.49 on the Y axis and fits well with the plotted line. These results, scaled up, correspond with absorbed powers of 1 MW in waves of 90 kW/m and 0.5 MW in 30 kW/m.
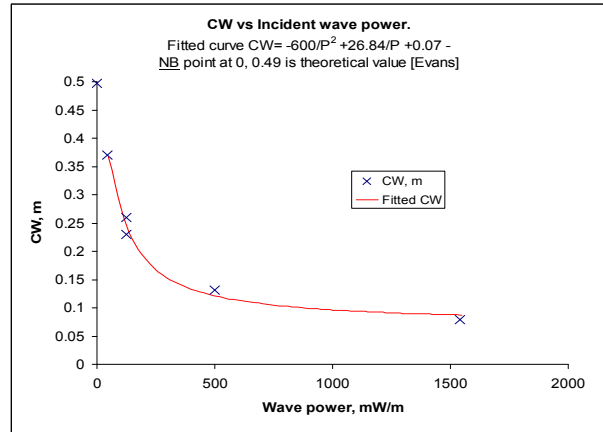

Fig.3 CW results in regular waves at T=1

Mixed Waves (2D) – Tuning - Fig. 5 shows the variation in CW with changes in the model's n while keeping the wave's fp at 1. A maximum is seen at n =1.06 fp.
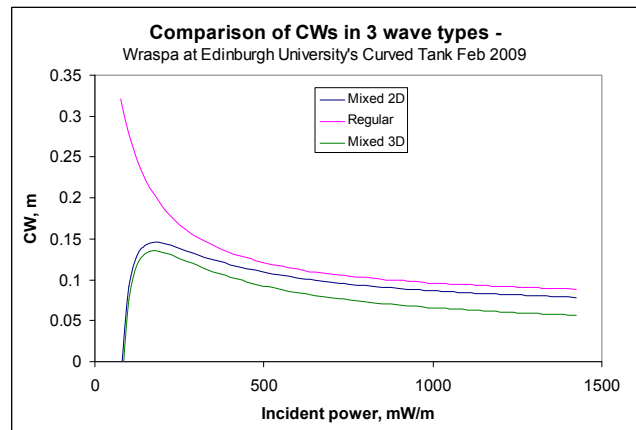

Fig.4 Comparing CW's in the 3 sea types (see text for notes re Mixed power results below 200 mW/m incident)

Mixed waves(2D) – power - The middle curve in Fig.4 shows the tuned and optimised CW vs. incident wave power. The plotted curve was again found by assuming an exponential variation and using the same method as above. The sharp turn-down at about 200 mW/m may be due to the model control system's inability to operate in very small waves.

Mixed - and Spread (3D) waves – Fig 6 examines the effect of spreading function on CW, with Cosn = 1 giving the widest spread of directions (centred around the head-on direction) and Cosn = 1000 giving almost 2D-like seas. In a fully developed sea state Cosn tends to increace

as the sea becomes more "focussed". Fig. 4 compares these "worst case" spread seas results with the powers recorded in 2D regular and mixed seas.
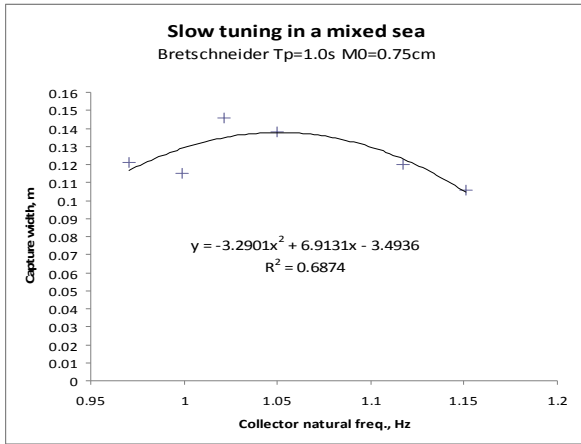

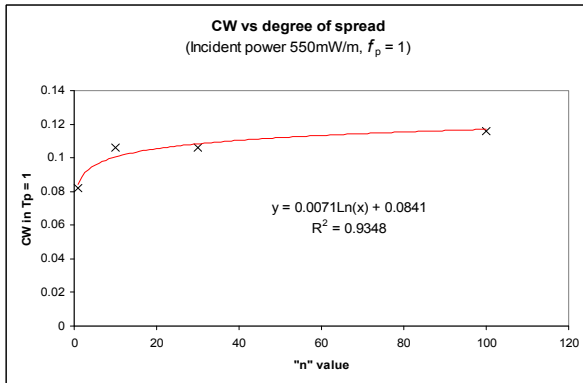Fig.5 Finding best tuning frequency in mixed seas

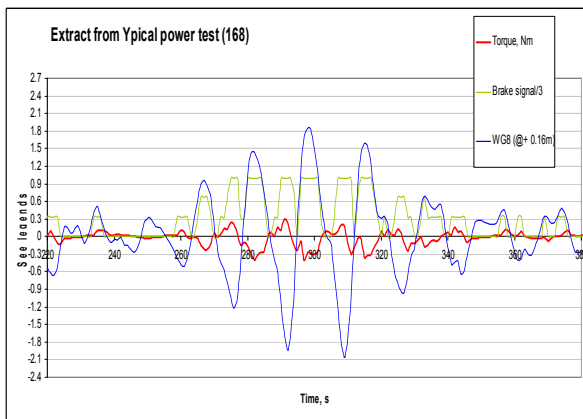Fig.6 Best-tuned power vs degree of spread in mixed-   and-spread seas

Fig.7 "Opportunistic" operation of control system

Control - Fig 1B showed the (idealised) logic of the control system and Fig.7 illustrates its typical behaviour in practice: the input signal from the wave gauge ahead of the collector; the step-changes in brake signal and the resulting collector torques. The input side of the system appears to work well, converting wave elevation to brake signal but the subsequent stage of torque vs. signal are

more inexact. Readings were separated into those for the different brake levels and, after removing cases where collector velocities were less than 0.1rad/s, results for one setting are shown in Fig.8. However, torques seem to be far from those expected even though the system appeared to be "working well".
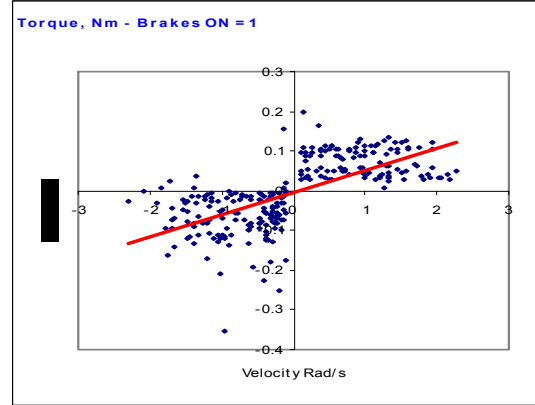

Fig.8 Second stage Torque vs velocity at brake = 1

IV. ANALYSIS AND DISCUSSION

A. Whole device systems

The stepwise method or any other system for matching wave and machine cannot operate alone. In a real WEC there will be a number of operational , diagnostic and safety systems that must all collaborate to make a WEC economic. These are indicated in Fig.9 and together they will strive to maximise:

Power output (P), Availability (A) and Longevity (L)

And overall lifetime economy can be said to be proportional to: P x A x L

B. Power

The equation of motion of this single-degree-of-freedom system has been given [18] as:-

$$F_1\alpha(p-q) = D^2\theta\ a_{55} + D\theta\ b_{55} + D\theta D|\theta|\ d_{55} + \theta\ c_{55} + (PTO\ torque) \qquad (1)$$

In a collector tuned to the prevailing swell frequency much of the energy circulates between Inertia and Spring and as drag is minimal [21] their terms can be omitted so equation 1 becomes:-

$$(PTO\ torque) = F_1\alpha(p-q) - D\theta\ b_{55} \qquad (2)$$

And it appears that the controller is, rather inexactly, following this equation.

In the above :-
F_1 = Wave torque coeff. Nm/m wave ampl.
α = surface elevation, m
(p-q) = lever arm from pivot to centre of pressure, m
θ = Collector pitch angle, rad
a_{55} = sum of added inertia and collector inertia kgm^2

b_{55} = radiation coeff. – Nms

c_{55} = pitch stiffness of collector Nm/rad

d_{55} = an assumed drag factor referred to the pivot as a torque Nms^2/rad^2

1. Airlocks for personnel and equipment
2. Air pump, snorkel and control
3. Bulkhead
4. Airtight hatch
5. Main PTO cylinders – 4 in number
6. Electrical alternator
7. Turbine
8. Directional valves for Stepwise control (Loop 1)
9. Flow control valves (Loop 2)
10. Low pressure reservoir
11. High pressure reservoir
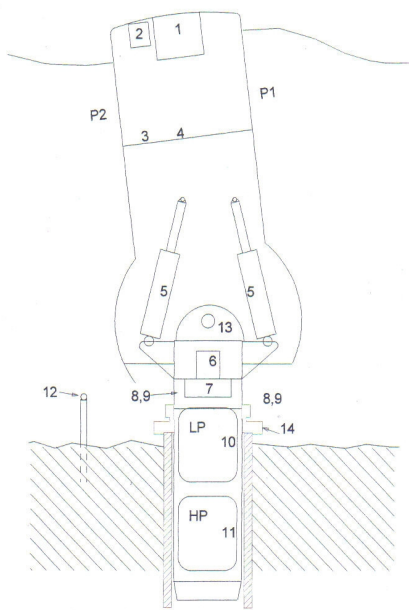12. Wave sensor (see Ref.)
13. Main pivot

Fig. 9. Simplified diagram of a Wraspa seen in side view section

C. Average power

Short term maximum wave power averaged over one or two wave periods is typically more than 10 x the concurrent long or medium term averages at the same site. In order to capture or "land" the maximum energy per year a WEC and its associated power systems will have to cope with this. In Wraspa, using hydraulics, this can be done by delivering oil from the Stepwise system into a High pressure reservoir and the feeding this out at a steady, but slowly varying rate to the prime-mover (assumed to be a high pressure Pelton-type turbine). A convenient control signal would be the fluid level in that reservoir: if the flow out is so controlled then the torque at the turbine would be varied and the correspondingly the current flowing into the electricity grid.

D. Availability and Longevity

These aspects can be greatly enhanced by on-board monitoring and control and in a wave farm of hundreds of WECs, operating in harsh conditions, such systems will have a huge economic impact. Fig. 9 shows some of the functions that might be needed (even on such a relatively simple device as Wraspa).

E. Condition monitoring

As with conventional power plant monitoring [23 - 26], monitoring and diagnostics of a wave farm and its

WECs would play an increasingly important role in the competitive operation of these devices. Consolidated knowledge about the past and current WEC condition can be used to improve performance, reliability and availability, thus enabling the optimal scheduling of maintenance activities and minimising the risk of costly, unexpected failure of the devices during the service life.

Condition monitoring of WECs would include the monitoring of wave condition as well as performance of devices. For example, by use of a wave sensor located nearby at the seabed, the oncoming wave and local waves surrounding the device can be measured. By fitting motion sensors, the motion of collector and arms that is driven to and fro by wave can be detected and further correlated to the wave condition.

Monitoring of WECs would concentrate on specific areas of the device. In the WRASPA, main pivot bearings are designed to oppose the sum of forces acting on the collector and arm which could be up to 10 MN at extreme load conditions whereas bearings for the ends of the four cylinders will have to withstand similar but smaller forces. The monitoring of bearing loads, stresses, temperatures and lubricating oil leakage will be essential. Pressure reservoirs also need to be constantly monitored to ensure that a steady outflow is maintained from the high pressure accumulator to the turbine. Monitoring of turbine vibrations and outputs from the alternator such as rotation speed, average power output would also be considered. Correlation analysis to wave condition is also applied to these key health data of the device being monitored.

Each WRASPA device essentially works as a small-scale off-shore power station. The monitoring and diagnostic system would consist of a modular system that can be configured to meet the individual WRASPA device's specific requirements in a wave farm. This would benefit from knowledge gained through the design and commissioning process as well as from managing and supporting installed fleets. Monitoring data stored on onsite system and other relevant data can be transmitted back to a remote support centre for further analysis. This analysis can be done to support an existing problem, to assess the current performance of the device and the overall performance of the wave farm, to assist maintenance and planning or to apply more advanced early warning techniques to mitigate failure risks.

V. CONCLUSIONS AND RECOMMENDATIONS

1. Wraspa, with the stepwise control system operating is able to give very good CWs in small regular waves and the loss in power in moving from regular to mixed-and-spread waves seems acceptably small.

2. The stepwise control system was used in all power tests and the method of changing the step-height allowed us to optimise power in each case. However, the controller as tested needs much improvement and development.

3. Further tests on slow tuning are needed to assess the best strategy over the whole annual spectrum. This might be done initially by simulation and then confirmed in tank tests – probably following further development of the collector's shape – see 4 below.

4. The collector body ("RHM2") used in these tests is large in volume and alternative shapes should be assessed. Those proposed at present are a set of ½ ellipses of the same frontal area and that will have differing added mass values which will allow volume to be reduced at the same resonant frequency.

5. As this and other WECs approach commercialisation ensuring availability and longevity will be needed and design and research effort will be needed in this regard to effectively target and refine systems for this purpose.

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