ACHIEVING A THREE-FOLD INCREASE IN PERFORMANCE FOR THE ARCHIMEDES WAVESWING™ WAVE ENERGY CONVERTER

Simon Grey[1]
AWS Ocean Energy Ltd
Inverness
Scotland, UK

Johannes Spinneken
Evergreen Innovations
2725 57th Street
Sacramento
95817 CA

[1]Corresponding author: simon.grey@awsocean.com

Abstract— **This paper will present the significant performance increases achieved with the Archimedes Waveswing wave energy converter technology since the conclusion of the Wave Energy Prize in 2016. The technology fundamentals are described, together with the advanced controls strategy, physical test results and the methods used to determine the optimum parameters to achieve best economic performance.**

INTRODUCTION

In November 2016, team Waveswing America won 3rd place in the Wave Energy Prize. Since that time, AWS Ocean Energy (AWS), owners of the Waveswing™ technology have tripled the performance of the device per unit volume, whilst at the same time have quadrupled the power rating and reduced mooring loads by a factor 5.

This remarkable performance boost confirms the Waveswing™ as a leading point-absorber technology and was achieved through a combination of control system improvement and hydrodynamic optimization guided by parametric modelling.

In recent testing at FloWave in Edinburgh, Scotland, the Waveswing™ has demonstrated power capture in excess of 40% of the theoretical point-absorber limit in almost all seas of interest and capture rates as high as 59% in the longer-period seas typically found off the US coastline. This remarkable result demonstrates the benefits of a submerged, self-reacting point-absorber as it has generally been held that the practical limit for floating point-absorbers is 50% of the theoretical maximum.

This paper describes the fundamental features of the Waveswing that underpin the excellent performance, the novel velocity-based control system which maximizes power capture and the parametric modelling techniques used to guide the optimization process.

WAVESWING FUNDAMENTALS

The Archimedes Waveswing is a submerged point-absorber comprising a vertically oriented telescopic structure that changes volume in response to the sub-sea pressure changes caused by passing waves (Figure 1).

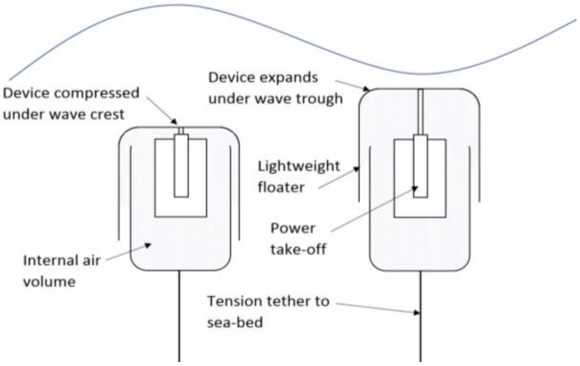

FIGURE 1: SCHEMATIC OF THE ARCHIMEDES WAVESWING

The relative motion of the two parts of the 'telescope' is resisted by a power take-off (PTO) which converts the absorbed wave power into useful electricity for export ashore via a sub-sea cable. The restoring (spring) force is provided by compression of internal air.

The current design of the Waveswing uses an 8.0m diameter floater with a mean submergence of 4.5m and stroke amplitude of +/- 1.5m. The device is rated at 180kW.

Performance drivers

The Waveswing design is characterized by several features which allow excellent performance namely:

- The restoring spring is much lower than the hydrostatic spring experienced by a surface-piercing body;
- The oscillating mass is relatively low;
- The device motion is in anti-phase with the wave which means that the wave excitation force is not reduced due to the device 'following the wave';
- The radiation damping forms a small part of the overall wave forcing.

The inherently low spring and mass values result in the Waveswing being a highly dynamic wave energy converter (WEC) able to achieve full-stroke for most waves of interest for power generation. The extremely broad-banded response as shown in Figure 2 is achieved before application of additional control of the PTO forcing. The narrow-banded response for surface piercing devices (shallow and deep cylinders shown in Figure 2) is due to their large hydrostatic stiffness, which in turn requires a large mass for device tuning. This is not the case for the Waveswing, which can be designed as a low-inertia system due to its soft spring characteristic.

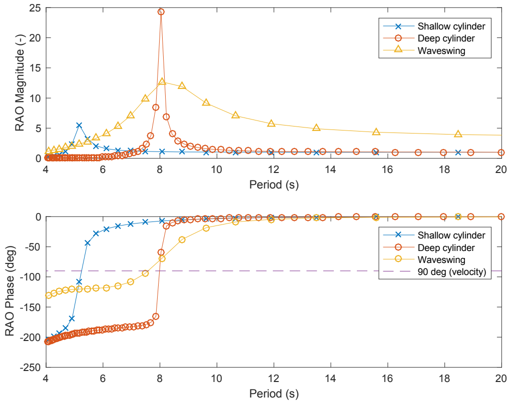

FIGURE 2: THEORETICAL RAO FOR SURFACE PIERCING CYLINDERS AND WAVESWING

The result of the third feature is that it is possible to achieve very high wave excitation forces per unit of active absorber area. The Wave excitation force for the Waveswing is a result of wave-induced pressure which is compounded by the device moving in anti-phase with the wave. In contrast, a surface-piercing device moves in phase with the wave, thus reducing the relative velocities and change in draft which produce the excitation forces. Accordingly, the wave excitation force is largely independent of the damping applied. Understanding this feature has allowed us to optimize geometry to achieve a significant increase in wave forcing per unit area.

The final important feature is that application of PTO damping equal to the radiation damping does not result in optimum power capture. This is due to the fact that radiation forms a relatively small proportion of the wave-forcing and hence application of radiation damping alone would result in un-feasibly large amplitudes of oscillation (Figure 3).

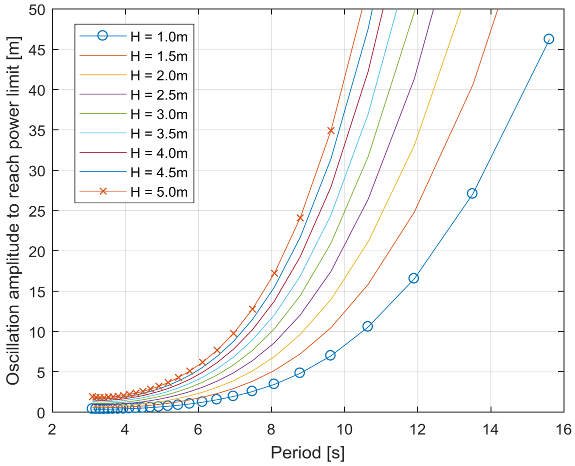

FIGURE 3: OSCILLATION AMPLITUDE REQUIRED TO REACH VOLUMETRIC POWER LIMIT FOR WAVE HEIGHTS FROM 1.5M TO 4.5M. ALL EXCEED THE 3M STROKE LIMIT OF THE WAVESWING BY A VERY SIGNIFICANT MARGIN WITH THE EXCEPTION OF SMALLER WAVES BELOW AROUND 7 SEC.

Requirements for optimal control

The conditions for a point absorber WEC capable of benefitting from optimal control are listed by Falnes in [1] and are:

a) The oscillating body is relatively small (V→0);

b) Most of the incident (free) wave power remains in the ocean;

c) Wave excitation force and velocity are in phase;

d) The oscillation amplitude equals the design amplitude;

e) The oscillation mode has a source-like wave radiation (e.g. a point-absorber in heave mode).

Conditions (a), (b) and (e) are a function of the WEC geometry (and are satisfied by the Waveswing design) and hence the control system challenge reduces to maximizing the oscillation amplitude whilst ensuring that wave excitation force and velocity remain in phase.

A consequence of the low radiation damping of the device is that to achieve meaningful power using radiation-matching, significant stroke is required (Figure 2). Accordingly, for almost all waves other than the shortest waves in the lowest operating sea-state, the device will be significantly over-damped (i.e. over-constrained in velocity) when compared to the radiation damping. Another way of stating this would be to say that for the Waveswing, power absorption will always be maximized by maximizing velocity, providing of course that the velocity is in phase with the excitation force.

Accordingly, rather than attempting to apply optimal damping on a wave-by-wave basis (as is necessary for optimal control of some WEC types), the challenge for the Waveswing control is to maximize velocity whilst simultaneously avoiding end-stop collisions and ensuring phase-matching with the wave excitation force.

VELOCITY BASED CONTROL

To meet this controls challenge, AWS have devised a control strategy whereby a position-based velocity limit is imposed on the oscillator. Determination of the velocity profile is made on the basis of two key assumptions:

1. That the velocity profile should be sinusoidal, at least as the floater approaches end of stroke, and;
2. That the average wave period changes only slowly over time.

The velocity profile is then easily determined from the control period and amplitude (Tc and Amax) with the peak velocity (Vmax) being limited to $Vmax=2\pi Amax/Tc$ and the allowable velocity (+ or -) at any point in the stroke being constrained to $Vlim=(2\pi/Tc)\sqrt{(Amax^2-z^2)}$ where z is the current position (measured from mid-stroke).

OPTIMISATION OF WAVE EXCITATION FORCE

As noted previously, the wave excitation force is independent of the applied PTO damping within the practical ranges of interest. Instead, the forcing is a function of nose-cone geometry, mean device submergence (which is also affected by stroke) and the area of the water-column between the floater and the inner cylinder which has a notable force-cancellation effect. Hydrodynamic improvements were achieved with the assistance of the radiation-diffraction solver NEMOH, and the parametric optimization described below.

Overall, the Waveswing team achieved an increase in wave forcing per unit area of 143% as compared with the design used during the WEP and this was a significant contributor to the overall power improvement. The key parameters varied were the nose cone shape (flat, radiused or domed), the device mean submergence and the floater to silo diameter ratio. An example of one of the floater geometries considered is shown in Figure 4.

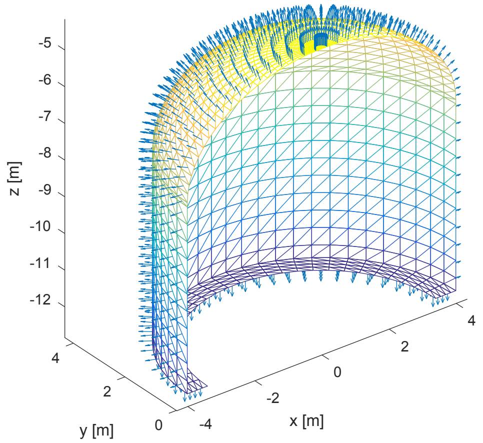

FIGURE 4: EXAMPLE NEMOH MESH FOR ONE OF THE NOSE-CONE GEOMETRIES CONSIDERED

DEVICE OPTIMISATION USING PARAMETRIC MODELLING

As part of a research project carried out under contract to Wave Energy Scotland (WES), AWS undertook a parametric modelling study in order to establish the likely optimum parameters for the Waveswing™.

The modelling process followed the methods recommended in [2] and required the development of a means of estimating the device performance and through-life cost for a range of device diameter and stroke combinations. Costs were relatively easy to determine from a parameterized bill of materials, however estimation of annual energy production (AEP) was more challenging. The usual approach would be to simulate performance in every sea-state on a resource scatter diagram using a time-domain model set up for the particular WEC parameter combination. This however was not practical for the 49 parameter combinations and 91 sea-states (=4459 simulations requiring some 2,200 hours of processor time) and hence AWS developed a new statistical model for energy production which was validated against both test results and the time-domain model. This model was able to complete the AEP estimations for all parameter sets in less than 5 minutes.

The statistical model is based on the recognition that individual wave heights in a real sea-state typically conform to a Rayleigh distribution. As noted earlier the broad-banded response of the Waveswing™ results in a very similar RAO across the range of frequencies predominant within a sea-state. Accordingly, it is possible to estimate both the amplitude of motion and the excitation force for each wave in the distribution, with the product of force and displacement being the work done. Dividing the total work done in the sea-state by the total time (given by the number of waves multiplied by the mean up-crossing period) provides an estimate of the total absorbed power. Losses due to friction and viscous effects can be estimated from the mean velocity. The model was calibrated against experimental data by adjusting RAO and loss parameters and was found to be capable of estimating power to within 10% across the range of sea-states tested experimentally.

The parametric model was then used to generate estimates of key values for each of the diameter and stroke combinations. These outputs included economic indicators, for example levelized cost of energy, and technical indicators such as total WEC displacement and mooring loads. Typical output from the parametric model is shown in Figure 5 below.

Inspection of the outputs allowed the team to select the parameter set which appeared to provide the best economic performance on a full through-life cost basis.

Annual Energy Production [MWh]		Diameter						
		6.0	7.0	8.0	9.0	10.0	11.0	12.0
Stroke	2.0	**283.7**	388.7	508.8	643.6	792.4	954.8	1130.0
	3.0	368.2	505.4	660.9	833.7	1022.5	1226.2	1443.5
	4.0	418.1	574.8	750.9	944.5	1153.8	1376.8	1611.7
	5.0	440.3	606.4	791.3	992.5	1207.5	1434.0	1669.6
	6.0	442.1	609.9	795.1	994.6	1205.6	1425.1	1650.8
	7.0	429.9	594.1	773.8	965.7	1166.4	1373.0	1583.3
	8.0	408.9	566.0	736.8	917.5	1104.7	1295.7	1488.4

FIGURE 5: TYPICAL OUTPUT FROM THE PARAMETRIC MODEL SHOWING AEP IN A MODERATE RESOURCE FOR A RANGE OF STROKE AND DIAMETER COMBINATIONS

PHYSICAL DEMONSTRATION

Initial physical demonstration of the Waveswing™ was provided during testing at University of Iowa and at the US Navy Maneuvering and Sea-keeping Basin (MASK) at Carderock, MA, during the 2016 Wave Energy Prize. Owing to the time-pressures of the prize programme, the Waveswing team did not have time to optimize either the model geometry or the control system. Accordingly, whilst the model performed well, the team could see that significant improvements were possible.

In September 2017, AWS undertook testing of an improved 1:20 scale model at the FloWave test facility in Edinburgh, Scotland. This model reflected a revised geometry and a significantly improved physical implementation of the controller which focused on sensor noise reduction to allow the high loop-gains required for effective operation. The test results confirmed the team's view that improvements were possible, with an average power increase in equivalent seas of 410% per unit volume, and as high as 720% for smaller short-period seas.

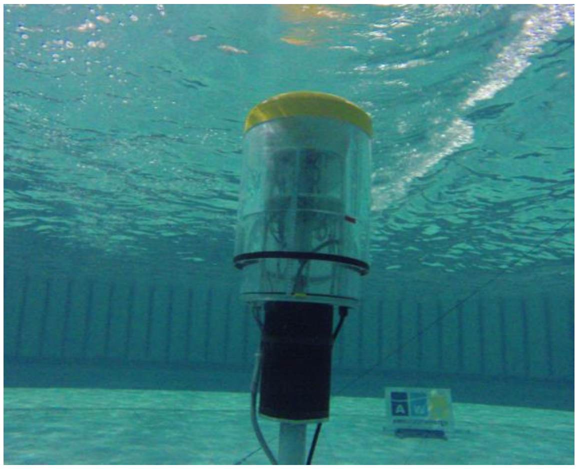

FIGURE 6: 1:20 SCALE MODEL WAVESWING UNDER TEST AT FLOWAVE IN SEPTEMBER 2017

The test campaign was highly successful and not only demonstrated the power potential of the Waveswing™ and the efficacy of the velocity control scheme, but also provided valuable data to allow validation of the numerical model of the WEC.

FUTURE DEVELOPMENTS

Work during the past year has delivered significant progress for the Waveswing team. Not only has the performance potential of the technology been demonstrated, but the team has also shown that the use of a range of modelling techniques, combined with a deep understanding of the technology fundamentals can deliver real benefits.

Next steps in terms of performance will be to use the newly-validated numerical models to explore further the effects of geometry and scale on device performance, whilst also exploring enhancements to the control strategy. Early indications are that larger scales of machine will be possible and that further relative improvements are possible.

In terms of engineering, AWS are currently completing a Novel Wave Energy Converter Stage 2 project with Wave Energy Scotland. This work includes the Front-end engineering design and permitting preparations for a partial-scale at-sea prototype.

REFERENCES

[1] Falnes, Johannes. "Optimum Control of Oscillating Wave Energy Converters." Part of "Annex Report B1: Device fundamentals/Hydrodynamics", an annex to the main report "Wave Energy Converters: Generic Technical Evaluation Study", final report for the B-study of the DG XII Joule Wave Energy Initiative, June 1993.
[2] Grey, Simon. "Report on Parametric Cost Modelling, AWS Report 15-011r3." Part of Wave Energy Scotland Knowledge Capture Project, February 2016.