The OPD Pelamis WEC: Current Status and Onward Programme

R W Yemm, R M Henderson, C A E Taylor
Ocean Power Delivery Ltd., Edinburgh, UK.

ABSTRACT

Ocean Power Delivery Ltd is developing an offshore Wave Energy Converter concept known as Pelamis for immediate commercial application within the Third Scottish Renewables Order. The device is a free-floating articulated cylinder, with hydraulic power take-off, suitable for general deployment in water depths over 20 metres. Survivability is the core theme but various techniques are employed to enhance power capture. The device is an assembly of 'available' technology reducing the required development time. The first prototype is due to be launched in early 2002. This paper describes the Pelamis development programme up to the present date.

1. INTRODUCTION

Ocean Power Delivery has a drawn on the collective experience of many years in wave power research by its founding members. Preliminary studies were carried out on a number of novel concepts in addition to studying existing proposals for offshore Wave Energy Converters (WEC's). The lessons learnt have resulted in a set of conceptual criteria that are thought to be necessary characteristics of a promising offshore WEC concept.

1. Survivability before Power Capture Efficiency - The device must be designed with survivability as the key objective, then effective ways of improving power capture must be found. These two essentially conflicting aspects are often approached from the other direction.
2. Choice of source of reference - The device must react against itself, rather than against a fixed reference frame such as the sea bed. The preferred source of reaction is 'length-down-wave' as this allows significant de-referencing in the long wavelengths associated with storm waves and presents the minimal cross-sectional area to the passage of extreme waves in which drag loads become significant.
3. Inherent load shedding - The device must incorporate features that inherently limit loads and motions once the rated-power wave amplitude has been reached.
4. Resonant motion - A degree of resonant response is essential to improve power capture in small waves. However, the device must be capable of de-tuning in large waves to prevent excessive loads and motions.
5. Hydrodynamic added damping - The device must have a significant amount of added damping in relation to its displacement. Put another way, the device must be capable (when compared to its displacement) of being an effective wave-maker if run 'in reverse'.
6. Non site specific - The device must be able to be installed in a range of water depths and sea bed conditions
7. Minimum on-site work - The complete device must be constructed, assembled and tested off-site with a minimum of installation work required on-site.
8. Prototypes and initial production devices must use 100% 'available' technology

The Pelamis, or ‘sea-snake’, concept was conceived to embrace all of these criteria and provisional calculations showed that the concept was sound. The inclusion of wave energy as a technology band within Third Scottish Renewables Order (SRO3) (1) provided the required catalyst and Ocean Power Delivery Ltd (OPD) was formed in January 1998 to develop, demonstrate and commercialise the Pelamis concept. OPD has assembled a strong development team with the requisite skills in theoretical and experimental hydrodynamics, conceptual and practical engineering design and offshore technology. The company is now working towards demonstration of the technology by early 2002 and initial commercial application under SRO3 by mid-2002.

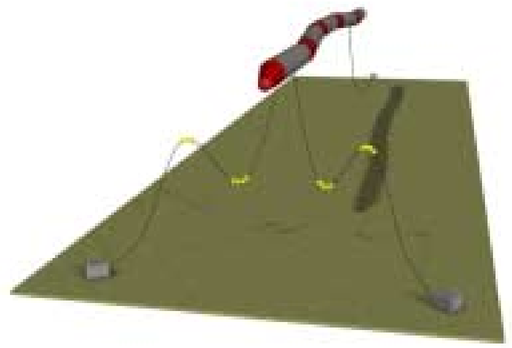
2. DEVELOPMENT PROGRAMME

2.1 Design Summary

The Pelamis device is a semi-submerged, articulated structure composed of cylindrical sections linked by hinged joints, Figure 1. The wave-induced motion of these joints is resisted by hydraulic rams which pump high pressure oil through hydraulic motors via smoothing accumulators. The hydraulic motors drive electrical generators to produce electricity. A 650kW device will be of the order of 130metres long and 3.5metres in diameter. Power from all the joints is fed down a single umbilical cable to a junction on the seabed. Several devices can be connected together and linked to shore through a single seabed cable. Prototypes and initial series-production devices will use 100% available technology

A novel joint configuration is used to induce a tuneable cross-coupled resonant response that greatly increases power capture in small seas. Control of the restraint applied to the joints allows the resonant response to be 'turned-up' in small seas where capture efficiency must be maximised or 'turned-down' to limit loads and motions in survival conditions. The complete device is flexibly moored so as to swing head-on to the incoming waves and derives its 'reference' from spanning successive wave crests.

The device is designed to be manufactured, assembled and tested at a suitable facility such as a shipyard. Installation and commissioning involves an absolute minimum of on-site work.



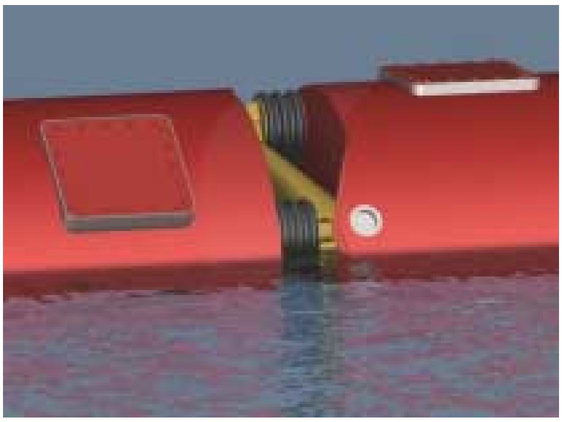


Figure 1: View of the Pelamis WEC with a close-up of one of the joints.

2.2 Numerical Modelling

The Pelamis concept has been extensively modelled using various numerical techniques. Wherever possible these numerical predictions have been validated using tank test experiments or published results.

The main power prediction programme is a linear, frequency-domain code using a ‘strip-theory’ approach to evaluate hydrodynamic forces and moments. The frequency dependent excitation, added mass and damping coefficients are calculated using the 3-D wave diffraction programme described by Pizer (2),(3). The programme output includes motions, loads and power capture. An extension to the code uses normalised Response Amplitude Operators and joint Power Operators to predict performance in site-specific wave spectra. This allows optimisation of the system in terms of: overall size and geometry, joint number and configuration, bending moment and joint angle limits and the required annual capacity factor. The numerical code has been validated using a 35th scale tank model, agreement was found to be good across the range of wavelengths and amplitudes of interest.

A non-linear time-domain simulation program was subsequently developed and allows power enhancing non-linear power take-off strategies to be examined in addition to analysis of the onset of non-linear hydrodynamic effects. It was successfully validated with reference to tank tests at 20th scale (4). Continued development of the time-domain simulation is underway and includes power take-off systems, non-linear dynamics and hydrodynamics, and mooring systems. The time-domain program is a key design tool and will allow efficient device optimisation.

Additional numerical work has focussed on the linear and non-linear response of the mooring system, calculations of re-entrant and engulfment slamming pressures, inertial loading during extreme motions, provisional time-domain models of non-linear power take-off strategies and of other aspects of the power conversion system.

2.3 Experimental Testing

To date, six experimental programmes have been conducted using three tank models, Figure 2.

1. 80th scale survivability tests, University of Edinburgh (UoE) Wide Tank, May 1998
2. 35th scale numerical code validation tests, UoE, July 1998
3. Further tests using the 35th scale model to examine alternative configurations, UoE, Feb 1999
4. 20th scale survivability tests, City University 55m wave flume, Sept 1999
5. 20th scale numerical simulation validation tests, Glasgow University 77m flume, Aug 2000
6. 20th scale tests in directional waves, Marinteck 3-D ocean wave basin, Oct 2000

Tank testing is central to the development of the Pelamis WEC concept and will continue at regular intervals throughout the development process. Numerical predictions used in isolation can be misleading.

Two new model programmes are planned. A new 35th scale model incorporating electronic power take-off is currently under construction. A 7th scale model incorporating hydraulic systems functionally identical to those proposed for use at full scale is planned for construction in January 2001. The 7th scale model will allow the development and rigorous testing of control systems hardware and software prior to full scale deployment. The hydraulic and control systems for the 7th scale model have already been tested using a specially constructed rig.

OPD is committed to an on-going tank test program with the 35th and 20th scale models to validate new configurations and prediction codes even after moving to 7th scale for systems development.

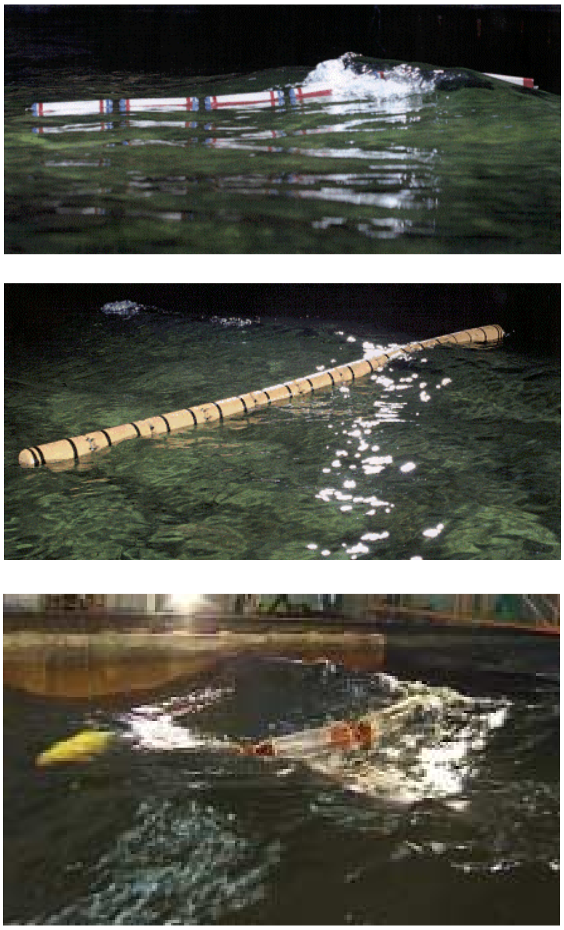


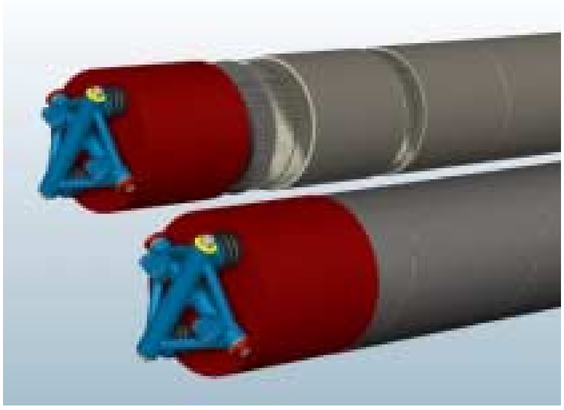
Figure 2: Tank test experiments at (from top to bottom) 80th, 35th, and 20th scales.

2.4 Full Scale Design

The Pelamis WEC was conceived from the outset to use entirely 'available' equipment and structural techniques. Figures 3 shows some aspects of the full-scale design. The prototype device will be composed of five segments linked by four 2 degree-of-freedom joints. The motion of these joints is controlled by sets of hydraulic rams. All rams are in a sealed, dry compartment at the end of the device segment, sealing is achieved using reinforced rubber bellows units normally used as air springs. All power conversion equipment is in a fully sealed modular power-pack within the ram bay so that in the event of bellows failure only the hydraulic rams are immersed. Access to all system components is via a hatchway in the top of the power conversion bay. Maximum individual component weight is less than 1.5tonnes to allow replacement on-site using light lifting equipment, for example a Hiab from a trawler deck.

Detailed design has begun on the power take-off systems for use in the full-scale prototype. Flow and machinery efficiency calculations based on output from the device simulation give an expected overall power take-off system efficiency in excess of 80% for the prototype design.

The prototype will be constructed entirely of steel using conservative factors of safety. Steel has been chosen to simplify structural analysis, design and instrumentation and to ensure that modification and repair are straightforward. It is anticipated that subsequent series-production devices will make use of post-tensioned concrete tube elements to reduce capital costs, Figure 3. A prototype design has been fully costed using firm quotes for all system components and established costing rules for the structure itself.



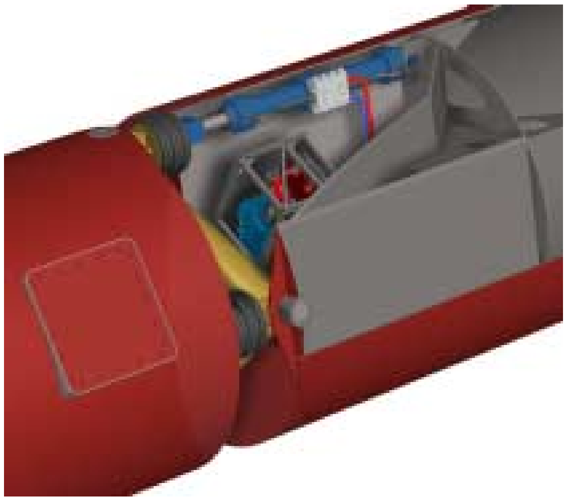


Figure 3: Steel and post-tensioned concrete construction options.
Cut-away view of a joint showing internal structure and power-pack.

3. PERFORMANCE CHARACTERISTICS

3.1 Survivability

A core theme of the Pelamis concept is survivability. The fundamental survivability mechanisms are the use of length as the source of reaction to allow the system to de-reference in long storm waves in conjunction with a finite diameter to induce full submergence and emergence (hydrostatic-clipping) in large, steep waves. The moorings offer little restraint and have a motion envelope large enough to accommodate extreme wave motions in addition to the low frequency wave-group induced response.

The hydraulic rams restraining the joints can generate sufficient moments to induce hydrostatic-clipping and therefore should never reach their end-stops. If however a system failure or unforeseen load condition results in an end-stop being reached the cylinder rod end bearings are designed to successively break away to prevent damage to the cylinders or extreme moments in the main tube structures. The 'free' joint then has an angular range of motion large enough to prevent contact between critical structural elements. Wave slamming loads are not extreme due to the small diameter and absence of flat panels.

Survivability in limiting height and steepness waves has been demonstrated by the 80th and 20th scale tank experiments, Figure 2.

3.2 Power capture, Conversion and Transmission

The wave-induced motion of each joint is resisted by sets of hydraulic rams configured as pumps. The rams pump oil into smoothing accumulators which then drain at a constant rate through a hydraulic motor coupled to an electrical generator. The accumulators are sized to allow continuous, smooth output across wave groups. Output smoothness from the complete device will be comparable with that of a diesel generator set. Both synchronous, constant speed, variable displacement hydraulic motor systems and asynchronous, variable speed, fixed displacement motor systems are currently being considered. A simple oil-to-water heat exchanger is included to dump excess power in large seas and to provide the necessary thermal load in the event of loss of the grid.

Each joint has an independent power conversion system to provide redundancy and to avoid large flow losses through long hydraulic manifolds. The generator sets are linked by a common 415V, 3-phase bus running the length of the device. A single transformer is used to step-up the voltage to an appropriate level for transmission to shore, HV power is fed to the sea bed by a single flexible umbilical cable than then to shore via a conventional sub-sea cable.

3.3 Installation, Operation, Maintenance and Service life

Installation of the Pelamis WEC involves an absolute minimum of on-site work. The moorings, seabed power cable and flexible umbilical are pre-placed in advance of the arrival of the device itself. Installation only involves connection of mooring lines and the power umbilical and thus requires the shortest possible weather window. The system is 100% removable at the end of its service life.

The device is autonomous in operation and includes all supervisory control and protection systems required to 'cut-in' as wave power levels rise, match captured and output power in operation and 'cut-out' under fault conditions and when wave power levels fall below the required minimum. Operation is similar to that of a modern wind-turbine in most respects.

The structure and power conversion systems are designed or selected to minimise in-service maintenance. Estimates of service requirements have been derived through discussion with component suppliers and it is currently envisaged that maintenance required will be limited to a 'levels and pressures' check once per year with a mid-life partial refit to replace hoses and seals. Actual maintenance requirements will only be determined through close monitoring of the initial prototype and production devices.

The device structure and all major components are designed to give the system a service life in excess of 15 years.

4. ONWARD DEVELOPMENT

4.1 Onward Programme

The staged development programme to commercialisation is summarised below:

1. Conclusion of Primary R&D Mar 2000 - Sept 2000
2. Core technology R&D Programme (including 7th and new 35th scale models) Oct 2000 - June 2001
3. Full-scale technology R&D Programme May 2001 – Mar 2002
4. Full-scale Demonstration Mar 2002

5. SRO3 system commissioned August 2002
6. Orders for further commercial systems. August 2002 onwards

OPD is committed to a responsible, staged development path towards full-scale demonstration of the technology by early 2002. As described in Section 2.3 three tank test models have been built to date at 80th, 35th and 20th scales. The 9 month Main R&D phase will take the Pelamis to 7th scale for systems development. The 7th scale model will be used to develop and test all aspects of the full-scale hydraulic and control systems on a cheap, rugged platform. The 7th scale model will allow extensive testing in extreme conditions and will allow simulations of partial and full system failures that would be impossible to conduct safely at full-scale.

The new 35th scale model will continue to provide a test bed for new control developments after full-scale deployment.

4.2 Future Development

Once the technology has been successfully demonstrated at full-scale, onward development will focus on driving down the cost-of-energy of the system to make the Pelamis WEC fully competitive with wind energy and other renewable technologies by 2010. Key areas for development will include:

- Optimisation of the device configuration, joint geometry and joint restraint envelopes
- Reduction of capital cost by using concrete as the main structural material and by improving structural efficiency
- Development of structures and systems suitable for volume production
- Development of control algorithms to maximise energy capture
- Improving the whole cycle efficiency of the power conversion system, particularly at low-power levels
- Development of low-cost high-voltage links to shore

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