Obtaining Greater Average Power Output from Wave Energy Converters:

An Introduction
OPT Power Buoy

Typical Wave Energy Converter “WEC”

Simple Model of WEC

Figure 2. Isotropic WEC
OPT Wave device (OPT Power Buoy)
Typical Current Investment

• Considerable financial and intellectual investment has taken place in wave energy capture systems.

• Despite this energy costs are far higher than existing alternatives even with substantial carbon taxes. Why?

• To date most effort has gone into the wave energy converting devices and not into the most effective way to operate them.
Improving WEC Returns

• What is required is to get the biggest possible return on the investment made already.

• Achieving this goal is the main driver for the Device Operations
The Marine Environment

• The Marine Environment is very hostile
• Most Wave Energy capture devices have a maximum safe operating wave height
• Above this maximum the devices must be shut down
• Shutting down for too long wastes potential power output
Device Shut-down

Wave induced motion

Typical Large Swell Sea

Maximum limits for given Operation

Significant periods within Operating limits

tens of seconds
Wave by Wave Issues

Viewed on a short time-scale wave properties are very variable.
Wave by Wave Tuning

Response of wave absorber
Design for the average wave effect
Wave by Wave Tuning

Effect of individual waves
Adapt the Wave Absorber Response on a Wave by Wave Basis
Focus Upon
Quiescent Period Operation
Quiescent Period Prediction

Wave induced motion

Maximum limits for given Operation

Typical Large Swell Sea

Significant periods within Operating limits

Prediction Method

Classical Sea State (Statistical Data)

Outcome

Never Execute Operation

Deterministic Look Ahead Prediction for tens of seconds

Often Execute Operation in safe prediction window

tens of seconds

Exeter Marine Dynamics
Simple Device Model

\[ m_1 \frac{d^2 y_1(t)}{dt^2} + C_1 \frac{dy_1(t)}{dt} + C(t) \frac{d\{y_1(t) - y_2(t)\}}{dt} + k_1 y_1(t) = u(t). \]
The non-dimensionalised isotropic WEC model where only the float moves is

\[
\frac{d^2 \theta_1(\tau)}{d\tau^2} + \left\{ C_1' + C'(\tau) \right\} \frac{d\theta_1(\tau)}{d\tau} + \theta_1(\tau) = w'(\tau)
\]
Approximate Response

- Full numerical solutions can be computationally demanding and limit the prediction time available.
- An analytic approximation is based upon:

\[
\theta_{1,2}(\tau) = \exp \left\{ -\frac{C'_1 \tau}{2} \right\} \exp \left\{ -\frac{1}{2} \int_0^\tau C'(\beta) d\beta \right\} \sin \left\{ \omega_0 \tau - \frac{C'_1}{2 \sqrt{4 - (C'_1)^2}} \int_0^\zeta C'(\beta) d\beta \right\}
\]

\[
\theta(\tau) = R_1 \theta_{1,1}(\tau) + R_2 \theta_{1,2}(\tau)
\]

\[
+ \int_0^\tau w'(s) \exp \left\{ \int_0^s [C'(\beta) d\beta] \right\} \left[ \theta_{1,1}(s) \theta_{1,2}(\tau) - \theta_{1,2}(s) \theta_{1,1}(\tau) \right] ds
\]
Some nice problems in time varying systems
Adapting WEC Response on a Wave By Wave Basis

HOW?

- Changing the WEC parameters induces transients
- Transients can be many seconds in duration
- Requires forward prediction of waves arriving at WEC
- Involves changing WEC operating parameters
Wave and Vessel Motion Forward Prediction

The prediction of the motion of a vessel some tens of seconds ahead utilising deterministic sea surface shape prediction.
Elements Needed for a Wave Energy Converter Motion Estimator

1. Measure
2. Wave Model
3. Predict Sea Surface At WEC Location
4. WEC Model
5. Predict WEC Motion

Wave Fronts from Remote Storms

Operation site. e.g. Shuttle tanker berthing on FPSO
Some nice problems in infinite dimensional system prediction
Wave Limited Critical Stage Task
Pipe connector attachment on an LNG barge

Courtesy of Shell and Single Buoy Moorings
Wave and Vessel Motion Forward Prediction
Non-military applications
Wave Measurements
Using Wave Buoys

Price approx £1M for buoys

Km Size Scale
South West Wave Buoy Array

The buoy array will also be an important part of the Wave Hub's infrastructure, capable of feeding wave information to the WEC devices. In one mode of operation the buoys will be able to deliver synchronized live and continuous data streams that will allow PRIMaRE to explore new deterministic and statistical descriptions of a spatially local sea wave system.

Specific tasks:
- To characterize the spatial variation of sea state measures across the area.
- To measure more local sea state measures for each WEC berth.
- To measure 'wave power' from the WECs to evaluate wave energy depletion.
- To facilitate phase coherent, time series measurement, allowing a more spatially local sea wave system description, and deterministic sea wave prediction.

Wave Data

The buoy array will also be an important part of the Wave Hub's infrastructure, capable of feeding wave information to the WEC devices. In one mode of operation the buoys will be able to deliver synchronized live and continuous data streams that will allow PRIMaRE to explore new deterministic and statistical descriptions of a spatially local sea wave system.

Support from the South West regional Development Agency and the European Union is gratefully acknowledged

Contact: Richard Thurley
Email: r.w.f.thurley@ex.ac.uk
www.primare.org
enquiries@primare.org

Support from the South West regional Development Agency and the European Union is gratefully acknowledged

Exeter Marine Dynamics

£750,000 for an array of 10 wave buoys
Figure 1. Schematic of a vessel mounted remote sensing beam scanning over the surface of a wave profile.
Some nice problems in non-uniform sampling
Current Development Of Wave LIDAR

The first shallow angle wave profiling LIDAR has been developed by the Exeter Marine Dynamics group at Exeter University, UK.
WAVE PROFILE 0 SEC
WAVE PROFILE 0.4 SEC
WAVE PROFILE 0.8 SEC
WAVE PROFILE 1.2 SEC
WAVE PROFILE MOVIE

Sea Surface Profile

Surface Elevation (cm)

Horizontal Range From Scanner (m)

88 90 92 94 96 98 100 102 104 106 108 110

Exeter Marine Dynamics
Multiple long crested swell sea model and two LIDAR scans lines
Effects of Measurement Window Size and Range on Prediction Period

- $f_1$ represents the low frequency waves (High phase velocity)
- $f_h$ represents the high frequency waves (Low phase velocity)
Some nice problems in non-causal filters
\[ I(x, y, t) \leftrightarrow FT \Rightarrow e^{-i \left( \frac{\omega^2 y \sin \theta}{g} \frac{\omega^2 y \cos \theta}{g} \right)} \]

Hence the impulse response is non-causal, is not an L2 function and has an unbounded derivative at large time.
Temporal Impulse Response of Wave Prediction Filter
Prediction Using a Sea Model:

Time domain filter based prediction. The blue line is wave model, black line is the prediction. The figure shows how prediction begins when measured wave arrive and ceases when measured waves have passed.
A space time prediction error surface for 1000 individual waves from a Pierson-Moskowitz sea model measuring the waves over 1000 m. Black denotes zero error.
Thresholded Prediction Error Surface:

Re-plotting of the data in previous slide to show the regions where the prediction error exceeds a given threshold.
Temporal Wave Filter Prediction from Measurements

Time series at the prediction site

Wave prediction filter output using up-wave input data
Getting the Most Energy from Existing Wave Energy Converters

Summary:

• Turn the converter OFF at just the right time, otherwise leave it ON.

• Tune its response to waves on a Wave by Wave basis.

• Both of these depend upon Look Ahead Prediction of Wave Shapes.

• PRIMaRE has a World Leading Wave measurement facility for capturing the data needed to do this prediction and it has the staff who developed the subject of Look Ahead Wave Prediction to do the Research.
Case Study of Quiescent Period Operation
Twelve months of wave data measured in m from the Cefas data-base.
Comparison of Control Approaches:

Weekly normalised comparison between QPPC and SPC for a WEC operating limit of a significant wave height of 10m.

\[ H_c = 10m \]
Realisation of Aim:

- Normalised yearly output comparisons between QPPC and SPC as a function of WEC operating limit.
Results of WEC Simulation using Wave Predictive Control
Realisation of Specific Aims:

Effects of Measurement Window Size and Range on Prediction Period

- $f_1$ represents the low frequency waves (High phase velocity)
- $f_h$ represents the high frequency waves (Low phase velocity)
Realisation of Specific Aims:

- The existing prediction methods have been considerably improved upon, these are:
  - Frequency domain based prediction which now incorporates multiple data sets to improve prediction.
  - The development of time domain filter based prediction techniques.
Realisation of Specific Aims:

Generator Module

Floating element

Waves decay to negligible by this depth

Figure 2. Isotropic WEC

\[ m_1 \frac{d^2 y_1(t)}{dt^2} + C_1 \frac{dy_1(t)}{dt} + C(t) \frac{d\{y_1(t) - y_2(t)\}}{dt} + k_1 y_1(t) = u(t). \]
Realisation of Specific Aims:

The non-dimensionalised isotropic WEC model is

$$\frac{d^2 \theta_1(\tau)}{d\tau^2} + \left\{ C' + C'(\tau) \right\} \frac{d\theta_1(\tau)}{d\tau} + \theta_1(\tau) = w'(\tau)$$
Realisation of Specific Aims:

- Full numerical solutions can be computationally demanding and limit the prediction time available.
- An analytic approximation is based upon:

\[
\theta_{1,2}(\tau) = \exp\left\{ -\frac{C_1'\tau}{2} \right\} \exp\left\{ -\frac{1}{2} \int_0^\tau C'(\beta) d\beta \right\} \sin\left\{ \omega_0\tau - \frac{C_1'}{2\sqrt{4 - (C_1')^2}} \int_0^\tau C'(\beta) d\beta \right\}
\]

\[
\theta(\tau) = R_1\theta_{1,1}(\tau) + R_2\theta_{1,2}(\tau)
\]

\[
+ \int_0^\tau w'(s) \exp\left\{ \int_0^s [C'(\beta) d\beta] \right\} \left[ \theta_{1,1}(s)\theta_{1,2}(\tau) - \theta_{1,2}(s)\theta_{1,1}(\tau) \right] ds
\]
Realisation of Specific Aims:

WEC motion computed numerically
Remaining Work to complete Contract

Run numerical models over a set of sea conditions and compared against conventional control methods.
Concrete Outcomes of the 18 month Feasibility Study

- Five journal publications, two already submitted
- A 7M Euro FP7 bid with OPT to implement Predictive WEC Control in a full scale demonstrator on their Power Buoy device. Results on Jan 28th.
Future Work

- Very strong relationships have been established with the WEC developers who now have considerable confidence in the ability of the wave by wave predictive technology to reduce installed capacity costs, as evidenced by the FP7 bid.

- Whether the bid with OPT succeeds or not there is little doubt that the technology will be implemented in the very near future in wave energy farms.
A Tool for Enhancing Vessel Operations

• Extends the viable range of sea states of a given operation

• Makes wave climate dominated fields viable

• Increases safety within existing sea state ranges

• Increases return on investment
A Tool for Releasing Resources

- Makes wave climate dominated fields viable

- For some gas resources facing oceanic wave fields, connection for transfer is impossible for up to 40% of the time
Wave and Vessel Motion Forward Prediction For Transfer Operations

- Moving into position and hauling the pipe system up to the shuttle tanker takes a long time
- The final CRITICAL matting of pipe to spigot should take at most tens of seconds
Wave Limited Critical Stage Task
Pipe connector attachment on an LNG barge

Courtesy of Shell and Single Buoy Moorings
Wave Limited Critical Tasks

Up to 60 seconds is a good time scale for many wave limited critical Tasks.

The Royal Navy require only 20 seconds from final hover to helicopter recovery.
Wave Limited Critical Stage Task
Helicopter recovery on a vessel
Wave Limited Critical Stage Task
Critical Cargo lift from supply vessel onto a rig
Wave Limited Critical Stage Task
Handling a ROV in the Splash Zone
Military Tasks Benefiting from >5 seconds Prediction

- Manned and unmanned aircraft/heli launch & recovery
- Launch & recovery of landing craft
- Rescue vessel launch/recovery
- Rassing
- Launch and recovery of rescue craft including NSRS
- Towed array launch and recovery
Present Methods for Negotiating the Wave Climate

- Met-Ocean Systems
- Local Sea-State Sensors
- Met-ocean and ship borne radar wave data

These methods all produce statistical information.
What can be done without wave Prediction?

Statistical information can tell a helicopter pilot landing on a vessel the following:

"Under prevailing conditions on average you will crash once every 10 landings"

This is not comforting to the pilot or useful.
It would be more comforting and useful to say:

"6...5...4...3...2...1... you now have 20 seconds for a safe landing"

But without Wave Induced Vessel Motion we can’t say this.
Vessel Motion Prediction

What can we do now?

Using only the actual vessel motions and the instantaneous wave elevation at the bow we can predict one cycle (5-10 seconds) ahead
What can be done without Wave Prediction?
The Landing Period Designator (LPD) 
<5 sec prediction

 Courtesy of QinetiQ
How do we do Wave Induced Vessel Motion Prediction?

Measure wave profiles, typically 0.5 – 1km upwave

Use these as input to a wave prediction model

Use the predicted waves in a vessel motion model
Accuracy and Cost

How accurate do we have to Predict the Sea Shape, eg 50% error?

Even Relatively Poor Systems Provide Considerable Benefits
Key issues

Time is of the essence

Prediction Time = Wave arrival time - Measurement + Processing + Prediction

<table>
<thead>
<tr>
<th>TASK</th>
<th>Time Scale</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement</td>
<td>&lt;1 second</td>
<td>Done</td>
</tr>
<tr>
<td>Processing: Shallow angle</td>
<td>~ 1 second</td>
<td>Done</td>
</tr>
<tr>
<td>Data i non uniform samples</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prediction: Fast Spatial and Temporal</td>
<td>~ 1 second</td>
<td>Done</td>
</tr>
<tr>
<td>Prediction filter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>~ 3 seconds</td>
<td>OK</td>
</tr>
</tbody>
</table>
What Type of System Will Measure Waves?

- Buoys (inconvenient)
- Satellite (insufficient resolution/availability)
- Radar (?)
- Lidar - optical radar (?)
Radar or Lidar (optical radar)?

- Measurement angles are very shallow
- Critical parameter is $\frac{wavelength}{aperture}$
- Critical parameter for Lidar is 100 times better than Radar

MARIN radar trials show radar is not viable.
Consequences for wave measurement

footprint

footprint
A LIDAR scan and the inevitable Non-uniform sampling

Figure 1. Schematic of a vessel mounted remote sensing beam scanning over the surface of a wave profile.
Current Development Of Wave LIDAR

The first shallow angle wave profiling LIDAR has been developed by the Exeter Marine Dynamics group at Exeter University, UK.
WAVE PROFILE 0 SEC
WAVE PROFILE 0.4 SEC
WAVE PROFILE 0.8 SEC
WAVE PROFILE 1.2 SEC
WAVE PROFILE MOVIE

Sea Surface Profile

Surface Elevation (cm) vs Horizontal Range From Scanner (m)
Temporal Wave Filter Prediction from Measurements

Time series at the prediction site

Wave prediction filter output using up-wave input data
The Floating body Motion Prediction Cycle

- Make statistical measurements of the surrounding sea (valid for a few minutes)
- Compute the optimum values of the prediction system operating parameters and the short term stationary parts of the prediction models
- Assess the likely quality of prediction achievable in relation to the needs and manner of implementing the proposed operation
The Vessel Motion Prediction Cycle

- Acquire sea surface profile data needed for building the prediction model corrected for vessel motion
- Assess the computational cost/model quality of the current dataset
- Either build the prediction model or reject the data and examine the next acquired dataset
- Predict wave and vessel motion
The Vessel Motion Prediction Cycle

- Measure the actual arrived waves and the vessel motion
- Adapt the operating parameters and prediction quality assessment
Predictable Sea Types

• Only linear wave models can be reliably built in the time between wave measurement and wave arrival

• Wind waves cannot be predicted

• Only multi-directional swells can be predicted

• For moderate to large vessels when local wind waves are large enough to control an operation the wind speed alone would often prohibit activities
Multiple long crested swell sea model and two LIDAR scans lines.
Space Time Prediction Diagram

Effects of Measurement Window Size and Range on Prediction Period

- $f_1$ represents the low frequency waves (High phase velocity)
- $f_h$ represents the high frequency waves (Low phase velocity)
Types of Prediction Model

- Frequency Domain: DFT + Phase Shifting
- Time Domain: Convolve with Impulse Response of Linear Gravity Waves
Spectral Wave Prediction from Measurements

LEGEND

- Actual Wave
- 'Raw' Prediction
- 'Improved' Prediction

Wave Elevation

Time, s
Spectral Wave Prediction from Measurements
Temporal Impulse Response of Wave Prediction Filter
JIP Proposal

Where is OWME Technology?

- Researching the Concepts ✓
- Developing the Sensor Technology ✓
- Engineering Trials
JIP Proposal

Phases of Engineering Trials

• Vessel Motion Compensated Measurements
• System Design and Production
• Shore Based Trials
• Fitting Out
• Sea Trials
JIP Proposal

Vessel Motion Compensation?

- Remote wave profile measurement are key to OWME
- Knowing the locations of measurement points is vital
- Measurements are inevitably made at Shallow Angles
- Vessel motion affects the measurement locations
JIP Proposal

- It will deliver the key vessel based hardware component required for OWME without commitment to full scale costs.
- It will deliver the design information needed for OWME without the risks inherent in a large innovative project.
- It will deliver the one remaining element needed to enable new generation of vessel mounted wave sensors independently from other aspects of OWME.
JIP Proposal

Engineering Tasks

• Design and build an instrumented single axis motion platform
• Mount existing LIDAR transmitter/collector head
• Develop LIDAR data motion compensation algorithms
• Laboratory validation using surveyed ground profiles
• Shore based field trials on inshore waves