OSCILLATING WAVE SURGE CONVERTERS

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Platform P1
Marine Renewable Energy Device Design, Innovation and Optimisation

Hydrodynamic modelling competition

Dias (UCD) Hydrodynamic modelling

Analysis of viscous effects

Ringwood (NUIM) Optimal control

Optimal control from wave to wire

Lewis (UCC) Cost reduction

Modeling different offshore wave energy generators

Lightbody (UCC) Predictive control

Toal (UL) Interconnection of devices

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from The challenging life of wave energy devices at sea: A few points to consider

R. Tiron, F. Mallon, F. Dias, E. G. Reynaud

OYSTER FOR DUMMIES

How does Oyster work? The simple interpretation of Oyster mathematics

E. Renzi\textsuperscript{a,*}, K. Doherty\textsuperscript{b}, A. Henry\textsuperscript{b}, F. Dias\textsuperscript{a,c}

Oyster is 3D, not 2D – capture factor > 1/2

Oyster is not tuned to resonance

Oyster is dominated by diffraction
POINT ABSORBER VS FLAP-TYPE WAVE ENERGY CONVERTER

**Point absorber**

- Froude-Krylov
- Inertial
- Drag

**Flap-type**

- Froude-Krylov
- Diffraction
The Oyster converter
3D analytical model
3D numerical model
Slamming
Conclusions
THE OYSTER CONVERTER

- Pitching flap type Wave Energy Converter (WEC)
- Shallow water (10 – 15m)
- Oyster 800 - 26 metres wide
- 1MWh generated in 5h on a single power cylinder

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OWSC – Bottom hinged buoyant flap-type wave energy converter (pitches as inverted pendulum)

OWSC – Bottom hinged buoyant flap-type wave energy converter (pitches as inverted pendulum)

Single degree of freedom $q(t)$ or $\theta(t)$: Newton’s second law

$T(t) = m\ddot{q}(t) + \ell \dot{q}(t) + kq(t)$

As the body oscillates, we need to consider other forces acting:
- radiation damping ($\nu$): The body emits a wave
- added mass ($\mu$): The body accelerates the fluid around it
- power take off torque ($\nu_{pto}$): We apply a generator torque

$\implies$ new equation of motion is

$T(t) = (I + \mu)\ddot{\theta}(t) + (\nu + \nu_{pto})\dot{\theta}(t) + k\theta(t)$
WHY DOES OYSTER PITCH?

- NON-point-absorber dynamics (in point-absorber dynamics, the diffracted wave field is neglected)
- Oyster pitches because of the strong exciting torque resulting from the pressure difference between its sides

Density plot of free-surface elevation around fixed flap (left) and contour plot of pressure difference (right)

- 1 – reflection zone
- 2 – refraction zone
- 3 – shading zone

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Governing Equations and Boundary Conditions (BC)

Laplace Equation

$$\nabla'^2 \Phi' = 0$$

Free Surface BC

$$\Phi'_{,tt'} + g\Phi'_{,z'} = 0, \quad z' = 0$$

Sea Bottom BC

$$\Phi'_{,z'} = 0, \quad z' = -h'$$

Kinematic BC on \(m^{th}\) flap

$$\Phi'_{,x'} = -\theta_{m,t'}(z' + h' - c_\beta')H(z' + h' - c_\beta'), \quad x' = x'_m \pm \varepsilon', \varepsilon' \to 0,$$

$$y_m^{A'} < y' < y_m^{B'}, \quad m = 1, \ldots, M.$$
MATHEMATICAL MODEL

Non-dimensional system

\[(x', y', z') = \left(\frac{x}{w'}, \frac{y}{w'}, \frac{z}{w'}\right), \quad t = \sqrt{g/w'} t', \quad \Phi = \Theta'(\sqrt{g w'} A_l')^{-1}, \quad \theta_m = \left(\frac{w'}{A_l'}\right) \theta_m'\]

Separate time dependence

\[\{\phi, \theta\} = Re[\{\phi, \Theta\} e^{-i\omega t}]\]

Decompose the potential

\[\phi = \phi^S + \phi^R\]

- Scattering Potential
- Radiation Potential

Separate vertical dependence

\[\phi(x, y, z) = \sum_{n=0}^{\infty} \varphi_n(x, y) Z_n(z)\]

where

\[Z_n(z) = \frac{\sqrt{2} \cosh \kappa_n(z + h)}{(h + \omega^{-2} \sinh^2 \kappa_n h)^{1/2}}\]

Procedure

1. Boundary Value Problem
2. Green's Integral Equation Formulation
3. Hypersingular Integrals
4. Chebyshev Polynomial
MATHEMATICAL MODEL

\[ G_n(x, y; \xi, \eta) = \frac{1}{4i} H_{0}^{(1)}(\kappa_n \sqrt{(x-\xi)^2 + (y-\eta)^2}) \]

→ Application of Green’s theorem to the 2D domain yields

\[ \varphi_n(x, y) = \sum_{m=1}^{M} \int_{y_m^A}^{y_m^B} \Delta \varphi_{nm} G_{n,\xi} \bigg|_{\xi=x_m} \, d\eta \]

→ Application of boundary conditions on the OWSC gives

\[ \left\{ \begin{array}{l}
\frac{1}{1} \{ P_{n\alpha}^{(\beta)}(u) \} \\
1 \cdot \{ Q_{n\alpha}(u) \}
\end{array} \right\} = \kappa_n du + \sum_{\gamma=1}^{M} \int_{-1}^{1} \left\{ \begin{array}{l}
P_{n\gamma}^{(\beta)}(u) \\
Q_{n\gamma}(u)
\end{array} \right\} L_{n\gamma}(u) \, du = 4i \left\{ \begin{array}{l}
A_{n}\beta \, d_n^{(\alpha)} e^{ik(\omega_\alpha w_\alpha/2 + y_\alpha^C) \sin \psi}
\end{array} \right\} \]

→ Expand the Hankel function as a series

\[ H_{1}^{(1)}(\kappa_n \frac{1}{2} w_\alpha |v_\alpha - u|) = \frac{4}{i\pi \kappa_n w_\alpha |v_\alpha - u|} + R_n(\kappa_n \frac{1}{2} w_\alpha |v_\alpha - u|) \]
MATHEMATICAL MODEL

→ Expand the unknown jumps in potential

\[
\begin{align*}
\begin{cases}
P_{nm}^{(\beta)}(u) \\
Q_{nm}(u)
\end{cases} = (1 - u^2)^{1/2} \sum_{p=0}^{+\infty} \begin{cases}
a_{pnm}^{(\beta)} \\
A_f b_{pnm}
\end{cases} U_p(u)
\end{align*}
\]

→ Chebyshev polynomials \( U_p \) satisfy the integral relationship

\[
\int_{-1}^{1} \frac{(1 - u^2)^{1/2} U_p(u)}{(v_\alpha - u)^2} \, du = -\pi (p + 1) U_p(v_\alpha), \quad v_\alpha \in (-1, 1)
\]

→ Linear System

\[
\begin{align*}
\sum_{p=0}^{\infty} \begin{cases}
a_{pn\alpha}^{(\beta)} \\
b_{pn\alpha}
\end{cases} C_{pn\alpha}(v_\alpha) + \sum_{\gamma=1}^{M} \begin{cases}
a_{p\gamma\alpha}^{(\beta)} \\
b_{p\gamma\alpha}
\end{cases} D_{p\alpha\gamma}(v_\alpha) &= -\pi w_\alpha \left\{ \begin{cases}
d_n^{(\alpha)} e^{ik(v_\alpha w_\alpha/2 + y_\alpha)} \sin \psi \\
f_n \delta_{\alpha\beta}
\end{cases} \right\}
\end{align*}
\]

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SOLUTION

**Diffraction Potential**

\[
\phi^D(x, y, z) = -\frac{i}{8} A_I k x Z_0(z) \sum_{m=1}^{M} w_m \sum_{p=0}^{P} b_{p0m} \int_{-1}^{1} (1 - u^2)^{1/2} U_p(u) 
\]

\[
H_1^{(1)} \left( \frac{k \sqrt{(x - x_m)^2 + (y - \frac{uw_m + 2y_m}{2})^2}}{\sqrt{(x - x_m)^2 + (y - \frac{uw_m + 2y_m}{2})^2}} \right) du
\]

**Radiation Potential (induced by motion of the \(\beta\)th flap while other flaps are held fixed)**

\[
\phi^{(\beta)}(x, y, z) = -\frac{i}{8} \sum_{n=0}^{\infty} \kappa_n x Z_n(z) \sum_{m=1}^{M} w_m \sum_{p=0}^{P} a_{pnm}^{(\beta)} \int_{-1}^{1} (1 - u^2)^{1/2} U_p(u) 
\]

\[
H_1^{(1)} \left( \kappa_n \sqrt{(x - x_m)^2 + (y - \frac{uw_m + 2y_m}{2})^2} \right) \frac{1}{\sqrt{(x - x_m)^2 + (y - \frac{uw_m + 2y_m}{2})^2}} du
\]

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Let us consider the $\alpha$–th OWSC

\[-\omega^2(I_\alpha + \mu_\alpha) + C_\alpha - i\omega(\nu_\alpha + \nu_{\alpha}^{pto})]\Theta_\alpha - \sum_{\beta=1, \beta \neq \alpha}^{M} [\omega^2 \mu_\beta + i\omega \nu_\beta] \Theta_\beta = F_\alpha\]
Interaction factor $q = \frac{P}{MP_{\text{single}}}$

- Value of $q > 1$ implies gain in net power output from an array because of constructive interaction amongst flaps
- Value of $q < 1$ indicates that mutual interactions have a cumulative destructive influence on the array efficiency
EXTENSIONS OF THE 3D ANALYTICAL MODEL

- Optimization of wave energy converter arrays using machine learning
- The modular concept of the Oscillating Wave Surge Converter
- Oscillating Wave Surge Converters near a straight coast
- Performance enhancement of the Oscillating Wave Surge Converter by a breakwater
- Interactions between an Oscillating Wave Surge Converter and a Heaving Wave Energy Converter
MODULAR OWSC CONCEPT

Rigid OWSC

Modular Concept

Fig. 2. Geometry of the physical system a) top view and b) cross-section of the j-th module.

\[ \nabla^2 \Phi' = 0 \]

\[ \Phi'_{tt'} + g \Phi'_{xx} = 0, \quad z' = 0 \]

\[ \Phi'_{x'} = 0, \quad z' = -h' \]

\[ \Phi'_{r_j} = -\theta_j r_j (z' + h' - c') H(z' + h' - c') \cos \xi_j, \quad r_j' = a_j, \quad 0 < \xi_j < 2\pi \]

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MODULAR FLAP – MAIN RESULTS

- Behaviour strongly depends on the applied power take-off mechanism

- When the magnitude of the applied PTO-damping is low, strong resonance effects are observed which are attributed to the closely packed nature of the system resulting in strong mutual interactions

- At lower periods, away from the resonant frequencies, similar levels of efficiency as that of a rigid flap are obtained using the optimized coefficients, while at higher periods, the occurrence of multiple resonances enables the modular system to capture more power than that of a rigid flap
In exceptionally energetic sea states, the analytical model is no longer valid.

Alternative techniques must be used to capture the more complex dynamics (viscous effects, vorticity, wave breaking, slamming).

- CFD models
- Visco-potential models (modify inviscid theory in regions of the fluid domain where the effects of viscous dissipation are non-negligible)
Recent theoretical and experimental testing have suggested that the standard treatment of viscous drag (e.g., Morison's equation) is not suitable when the effects of diffraction dominate the wave torque on the device.

We assess the effect that viscous dissipation has on an OWSC by modifying the semi-analytical theory to include the effects of viscous dissipation near the flap's edge.

We achieve this by applying an effective pressure discharge in the vicinity of the flap's tips.
VISCO-POTENTIAL MODEL (in progress)

dissipative surface $D'$
CFD MODEL

- CFD software package ANSYS FLUENT (solves conservation equations for mass and momentum using the finite volume method)
- Our CFD model mimics the experimental wave tank
- Waves generated by a piston-type wave-maker
- Free surface captured using the Volume of Fluid (VOF) method
- Built-in dynamic mesh method is used to deal with the large amplitude rotations of the flap
Vortex generation and shedding on the free surface in both numerical simulation and experiment (H = 1.25 m, T = 12.5 s, undamped)
Vortices are generated and shed at each half wave period at the edge of the flap locally.

The flow field is significantly different for the fixed, damped and undamped flaps (result of the competition between the inertial force of the flap and the wave force acting on the flap)

Slight differences in the flow around the flap are found by scaling the model, but the difference on the device performance is negligible for the OWSC with a 26 m wide flap.

Viscous scaling effects are not an important issue for OWSCs. In normal wave condition, Froude scaling can be adopted for scaling up the model test results with any flap width.

Diffraction/radiation effects dominate the OWSC with 26 m width flap. Viscous effects are insignificant for such devices. Hence, simply adding a drag term in the equation of motion is not recommended to describe the effects of viscous loss of OWSC.
THE SLAMMING PROBLEM

- Load data from 3D small scale experiments revealed high magnitude, short duration, ‘impulsive’ loads
- These were linked to impact events

Objectives
- Develop understanding of the slam loading process
- This knowledge feeds into the extreme load case for Oyster design, i.e. pressure scaling methodology
2D TESTS AT ECOLE CENTRALE MARSEILLE

- 40\textsuperscript{th} scale model of generic Oyster
- Spans the width of the flume

**Sensors**
- Flap rotation
- High speed camera
- Wave gauges
- Immersion gauges on the flap
- **Array of pressure transducers**
  (17 on the centerline)
DESCRIPTION OF THE SLAMMING EVENT

1 – Wave crest pushes flap landward

Wave propagation
DESCRIPTION OF THE SLAMMING EVENT
2 – Flap moves up due to buoyancy, after crest passes

Wave propagation
DESCRIPTION OF THE SLAMMING EVENT
3 – Water rushes down the face, creating dip in water level
DESCRIPTION OF THE SLAMMING EVENT
4 – Start of slamming phase, as flap re-enters the water
DESCRIPTION OF THE SLAMMING EVENT

5 – Water jet travels up the flap face
DESCRIPTION OF THE SLAMMING EVENT

6 – Water is ejected in front of the flap

Wave propagation
EARLY STAGE OF SLAMMING
Wave impact

- Two loading processes involved
  - Pressure peak similar to a breaking wave or flip-through impact
  - Building of jet and propagation

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\[ y = \text{distance from hinge} \]
EARLY STAGE OF SLAMMING
Wave impact (a soft one and a strong one)

SOFT

STRONG

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- Impact rises along the flap
- Longer impacts near the hinge of the flap
- Stronger impacts close to the hinge of the flap
- Impact pressure decreases slightly with time as the impact propagates
OTHER CHARACTERISTICS
CFD results

Velocity magnitude

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Pressure starts rising as the extremity of the jet approaches.

Maximal pressure under the jet root.

Slamming duration ~ 200ms (i.e. ~ T/10)

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Similarities between Oyster slamming and water entry problem

Wagner theory (1932)
- Impact of a wedge in water at rest
- Constant velocity \(V\)
- Potential flow theory
- Uprise of the free surface

Maximum impact pressure

\[ p_{\text{max}} = 0.5 \rho V^2 C_{p,\text{max}} \]

with
\[ C_{p,\text{max}} = \frac{\pi^2}{4\tan^2(\beta)} \]
Good agreement between measured pressures and dynamic ones
Pressures at the early stage are underestimated
- Characteristic oscillations of compressible air pocket
- No big air pocket but bubble swarms as the water rushes down and breaks the surface

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BACK TO OYSTER
OYSTER IN ROUGH SEAS
The 3D semi-analytical model has been very useful to understand the subtleties of OWSCs.

Recent 2D experiments allow a better description of pressure distribution on the OWSC.

Slamming of Oyster and maximum pressure well described by dynamic pressure once the jet is built (Wagner impact).

Early stage of slamming requires further understanding:
- Breaking wave impact as water rushes down - reproducibility
- Compressible effects?
THEN CAME THE SETBACKS OF 2014 AND 2015

- Pelamis Wave Power went into administration on 21 November 2014, with the subsequent loss of 40 jobs

- Aquamarine Power went into administration on 27 October 2015

- Most companies stopped investing in wave energy
WHAT WENT WRONG?

- We were doing the technology at full scale too soon
- We should have built at a small scale and built up to it
- Venture capital financing usually means that one should not spend too long in a test tank – one wants to see something credible out there bobbing around in the ocean delivering energy
- We want wave devices that are sensitive enough to capture the energy from a 1 m wave, but also robust enough to survive 20 m waves

(Ref: Breaking the waves from Herald Scotland, 6 September 2015)
More research needed on **power take-off systems**

More research needed on **corrosion** (for example, *in the nearshore environment, high levels of oxygenation in the water due to turbulence can lead to premature corrosion failure of components*).

Sites might have been overlooked in terms of **potential for wave energy installations** (sites with lower energy resource but sheltered from extreme wave climate) – see *recent study by Gallagher et al. to appear in Renewable Energy*. 
The nearshore wind and wave energy potential of Ireland: A high resolution assessment of availability and accessibility

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