Locally-resonant wave energy converter

Fabien Montiel & Ben Wilks

Department of Mathematics & Statistics, University of Otago

OERC Symposium 2018
What is wave energy?

- A form of marine renewable energy (MRE)
What is wave energy?

- A form of marine renewable energy (MRE)

MRE

- Tides
- Currents
- Heat
- Salinity
- Waves
What is wave energy?

- A form of marine renewable energy (MRE)

Converting ocean wave mechanical energy to electrical energy, e.g. with a turbine.

A device extracting wave energy is called a wave energy converter (WEC).
WEC technology

- Point absorber
WEC technology

- Point absorber
- Attenuator
WEC technology

- Point absorber
- Wave surge converter
- Attenuator
WEC technology

- Point absorber
- Attenuator
- Wave surge converter
- Oscillating water column (OWC)
WEC technology

- Point absorber
- Attenuator
- Wave surge converter
- Oscillating water column (OWC)

and more ...
Wave energy resources

International

- ~20,000 TW h/yr on world’s coastline\(^1\).

\(^1\)Reguero et al., 2015, *Applied Energy*.

Wave energy resources

International

- $\sim 20,000$ TW h/yr on world’s coastline\(^1\).

- Intensification of winds is expected to further increase available wave power, especially in the Southern Ocean.

---

\(^1\)Reguero et al., 2015, *Applied Energy.*

Wave energy resources

International

- ~20,000 TW h/yr on world’s coastline\(^1\).

- Intensification of winds is expected to further increase available wave power, especially in the Southern Ocean.

---

1 Reguero et al., 2015, *Applied Energy*.

NZ

- 25 kW per metre of coastline\(^2\).

---

Wave energy farms

- Capacity of individual WECs currently limited (∼O(100–1000) kW).
- Commercial developments looking at large scale farms (100–1000 MW) composed of hundreds of WECs.

\[ q(\omega) = \frac{P_{\text{array}}(\omega)}{N \times P_{\text{single}}(\omega)}. \]

\(^3\text{Babarit, 2013, Renewable Energy.}\)
Wave energy farms

- Capacity of individual WECs currently limited (\(\sim O(100–1000) \text{ kW}\)).
- Commercial developments looking at large scale farms (100–1000 MW) composed of hundreds of WECs.
- **Goal**: Maximise power absorption through wave interference (park effect\(^3\))

\[ q(\omega) = \frac{P_{\text{array}}(\omega)}{N} \times P_{\text{single}}(\omega). \]

Wave energy farms

- Capacity of individual WECs currently limited ($\sim O(100–1000)$ kW).
- Commercial developments looking at large scale farms (100–1000 MW) composed of hundreds of WECs.

**Goal**: Maximise power absorption through wave interference (park effect$^3$)

Wave energy farms

- Capacity of individual WECs currently limited (∼O(100–1000) kW).
- Commercial developments looking at large scale farms (100–1000 MW) composed of hundreds of WECs.
- **Goal**: Maximise power absorption through wave interference (park effect\(^3\) with \(q > 1\)).

\[
q_{\text{factor}}(\omega) = \frac{P_{\text{array}}(\omega)}{N \times P_{\text{single}}(\omega)}.
\]

\(^3\)Babarit, 2013, *Renewable Energy*.
Motivation: sonic crystals

Hard cylinders

Split-ring resonators

incident waves
transmitted waves
incident waves
transmitted waves

F. Montiel
Motivation: band gaps

Simulation parameters

- $5 \times 51$ array
- radius 0.2 m
- angle 45°
- spacing 0.6 m
- frequency sweep: $f = 10–450$ Hz

Motivation: band gaps

Simulation parameters

- 5 × 51 array
- radius 0.2 m
- angle 45°
- spacing 0.6 m
- frequency sweep: \( f = 10–450 \) Hz

Band gaps

- Gap 1: Helmholtz resonance (split-ring geometry)
- Gap 2: Bragg resonance (periodic arrangement)

A new concept of OWC

**Features**

- Fixed, rigid cylindrical shell
- Bottom-mounted and surface-piercing structure
- Opening connecting interior and exterior domains

Pressurised internal chamber

Low-frequency resonance (Helmholtz)

Wave interaction problem can be solved using semi-analytical mathematical techniques!
A new concept of OWC

Features

- Fixed, rigid cylindrical shell
- Bottom-mounted and surface-piercing structure
- Opening connecting interior and exterior domains
- Pressurised internal chamber
A new concept of OWC

Features

- Fixed, rigid cylindrical shell
- Bottom-mounted and surface-piercing structure
- Opening connecting interior and exterior domains
- Pressurised internal chamber
- Low-frequency resonance (Helmholtz)
A new concept of OWC

Features

- Fixed, rigid cylindrical shell
- Bottom-mounted and surface-piercing structure
- Opening connecting interior and exterior domains
- Pressurised internal chamber
- Low-frequency resonance (Helmholtz)
- Wave interaction problem can be solved using semi-analytical mathematical techniques!
Oscillating water column (OWC) models

**Uniform pressure model**

- **Internal surface condition**: free surface
- **Power take-off (PTO)**: through turbine motion
- **Tuning**: air pressure in chamber
Simulation — example without PTO

Parameters

- \( h = 10 \text{ m} \), \( a = 1 \text{ m} \),
- \( d = 5 \text{ m} \), \( \alpha = \pi/8 \)
- \( f = 0.38 \text{ Hz} \) (\( \lambda \approx 10 \text{ m} \))
Simulation — example without PTO

Parameters

- $h = 10 \text{ m}$, $a = 1 \text{ m}$,
- $d = 5 \text{ m}$, $\alpha = \pi/8$
- $f = 0.38 \text{ Hz} \ (\lambda \approx 10 \text{ m})$

Incident wave with unit amplitude
Simulation — example without PTO

Parameters
- $h = 10\, m$, $a = 1\, m$, $d = 5\, m$, $\alpha = \pi/8$
- $f = 0.38\, Hz$ ($\lambda \approx 10\, m$)

Incident wave with unit amplitude

Link to animation
Our WEC — $d = 5\, \text{m}$ (no PTO)

Parameters
- $h = 10\, \text{m}$, $a = 1\, \text{m}$, $d = 5\, \text{m}$
- $\alpha$ varies
- $f = 0.01$–$1\, \text{Hz}$

Output
- Scattering cross-section $\sigma$ measures magnitude of resonance.
Our WEC — $d = 5 \text{ m} \text{ (no PTO)}$

**Parameters**
- $h = 10 \text{ m}$, $a = 1 \text{ m}$, $d = 5 \text{ m}$
- $\alpha$ varies
- $f = 0.01–1 \text{ Hz}$

**Output**
- Scattering cross-section $\sigma$ measures magnitude of resonance.
Our WEC — $d = 3 \text{ m (no PTO)}$

**Parameters**
- $h = 10 \text{ m}$, $a = 1 \text{ m}$, $d = 3 \text{ m}$
- $\alpha$ varies
- $f = 0.01$–$1 \text{ Hz}$

**Output**
- Scattering cross-section $\sigma$ measures magnitude of resonance.
Our WEC — $d = 1\,\text{m}$ (no PTO)

**Parameters**
- $h = 10\,\text{m}$, $a = 1\,\text{m}$, $d = 1\,\text{m}$
- $\alpha$ varies
- $f = 0.01$–$1\,\text{Hz}$

**Output**
- Scattering cross-section $\sigma$ measures magnitude of resonance.
Our WEC — \( d = 0.5 \) m (no PTO)

**Parameters**
- \( h = 10 \) m, \( a = 1 \) m, \( d = 0.5 \) m
- \( \alpha \) varies
- \( f = 0.01-1 \) Hz

**Output**
- Scattering cross-section \( \sigma \) measures magnitude of resonance.
Future research

- Resonance analysis
- Couple to PTO
- WEC farms
- More realistic geometry/fluid
- Experiments in wave basin
Wrap-up

Future research

- Resonance analysis
- Couple to PTO
- WEC farms
- More realistic geometry/fluid
- Experiments in wave basin

THANK YOU!