Challenges and Progress in Wave Energy Technologies

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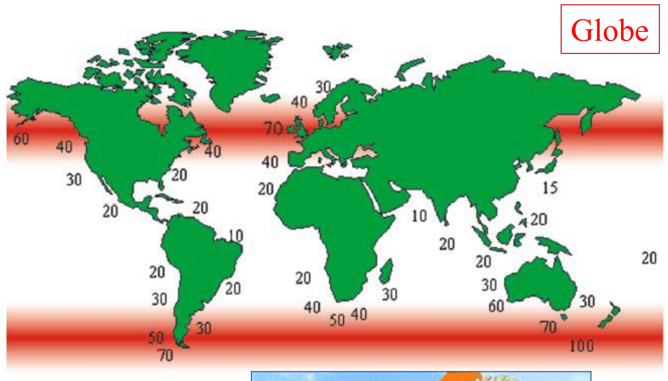
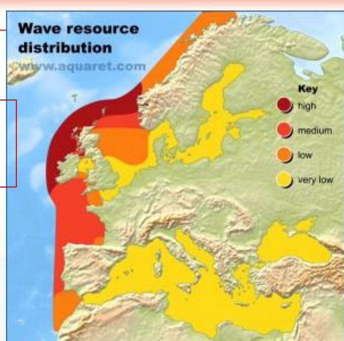
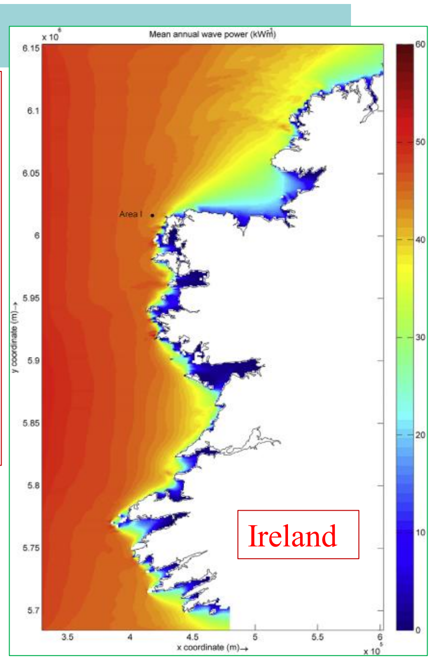
Wave energy Resources

Globe



Atlantic Arc





Ireland

- ~70kW/m annually
- 100km=demand of electricity in Ireland

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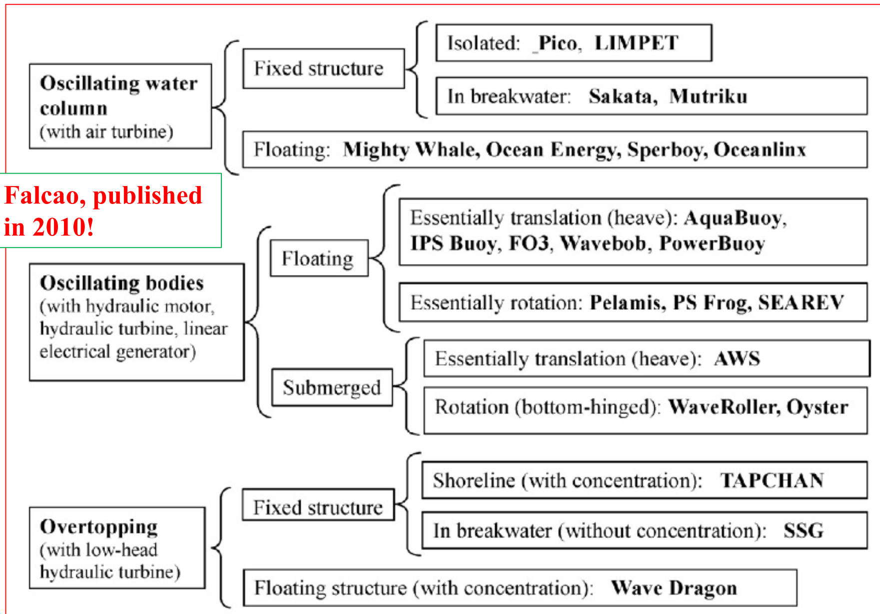
Wave energy converters: technology convergence?



Falcao, published in 2010!

- Efficiency?
- Initial cost?
- Reliability?

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Q: when will we see a 50MW wave farm? (ICOE 2012)

- For optimists (very soon?)
  - Pre-commercial full-scale grid connection or sea trials: Pelamis, Oyster, OWC plants…
  - MEA (Carbon Trust-Marine Energy Accelerator) baseline costs for current technologies, Wave: 38-48p/kWh, Tidal: 29-33p/kWh (JRC report 2014: €0.70-1.05/kWh for Wave; €0.50-0.65/kWh for Tidal).
  - MEA cost reduction strategies: 18-20p/kWh, i.e. ~ 39% reduction for tidal devices.
  - Cost reduction through technology innovations/massive production…

- For pessimists
  - A fear that all technologies may fail: too many failures and too few successes so far.
  - Real cost of wave energy still unknown for most developers and researchers.
  - Lack of assessment methods and standardizations.
  - Too many technical and non-technical barriers.
  - Theory development limited…

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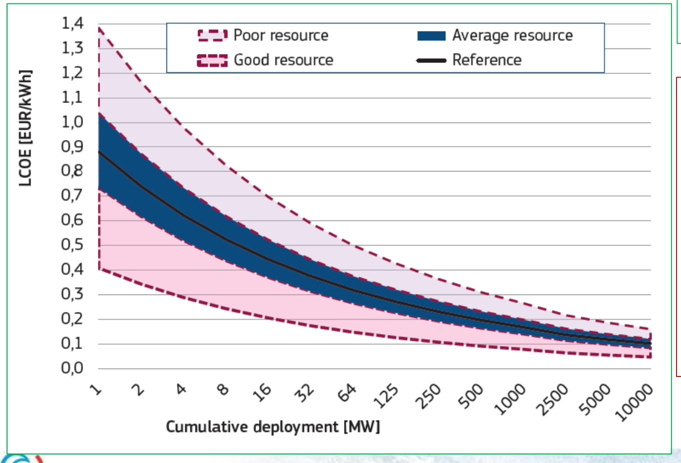
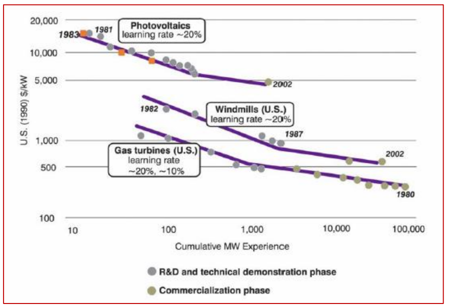
Pathways to reduce the cost of ocean energy

- **Targets (OEE 2016) on ocean energy costs:**
  - Tidal LCoE could reach €c10/kWh by 2030
  - Wave LCoE could reach €c10/kWh by 2035

– Large scale/volume production
– Experience (learning curves)
– Technology innovations





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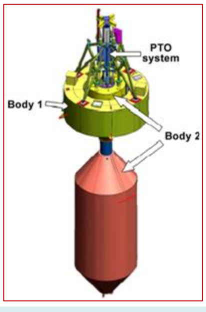
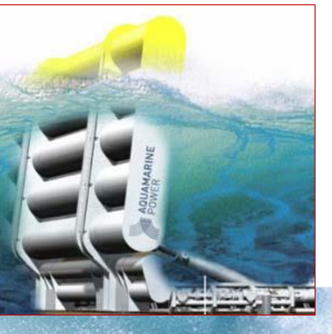
Reality: Failures



WaveBob (Ireland)
Bankrupt in 2013

Oceanlinx OWC (Australia)
Company bankrupt in 2010
Bought by a Taiwanese company

Pelamis (Scotland)
Bankrupt in 2014



Oyster (Scotland)
Bankrupt in 2015

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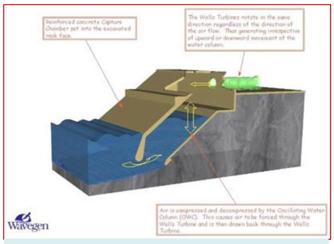
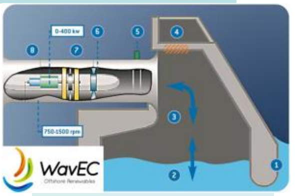
Reality: Successes (?)

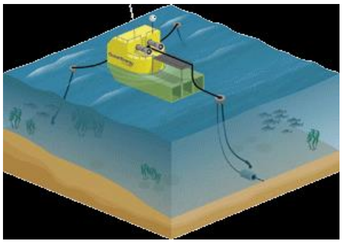


Scotland
LIMPET OWC plant in operation since 2000, generated power >60,000hrs in 10 years
Now in decommissioning



Portugal
PICO OWC plant, still operational

Spain
Mutriku OWC plant, still operational



Ireland
OE Buoy OWC device, ¼ scale sea trials in Galway Bay >3 years
Full commercial device in construction (will be a sea trial for one year in Hawaii in 2018).

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Technical challenges in wave energy conversions

Power conversion equation: $P = F \cdot V$

To generate a large power:
- with a very high speed in conventional power generation (e.g., steam turbines): high reliability and high energy conversion efficiency
- with a very large force (because of the small speed) for wind, tidal and wave energy: low reliability and low energy conversion efficiency

For wave energy (wave period: 6-11s):
- Large force and low speed for wave energy conversion (also with reciprocating motion/velocity and force):
  - fatigue problems: reliability problem
  - low conversion efficiency: high energy cost

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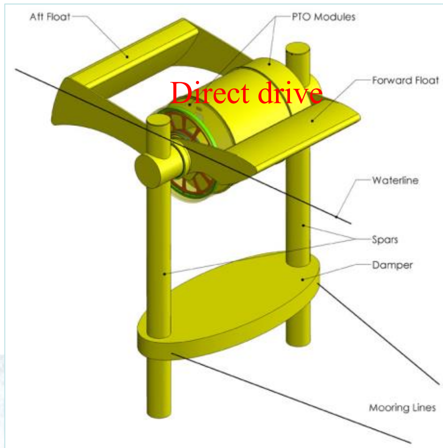
PTO reliability

PTO (power take-off)
- **Hydraulics/Ram**
- **Direct drive**
- **Air/water turbine**



Blue power energy PTO

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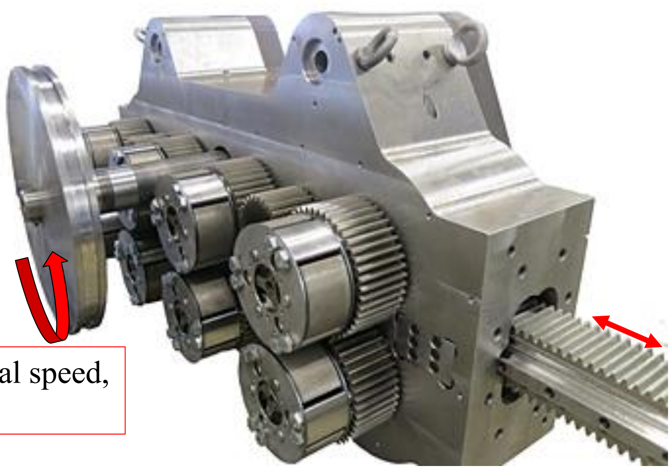
PTO reliability: specialized gear box

to generator



High rotational speed, low torque

to WEC

Large force
Low speed

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Dynamic systems: wave energy conversion

Newton's 2[nd] Law: $m\ddot{\mathbf{x}} = \mathbf{F}_{total}$

Generic dynamic equation for wave energy devices, with PTO, control and mooring systems:

$$[\mathbf{M} + \mathbf{A}(\infty)] \cdot \ddot{\mathbf{x}}(t) + \int_{-\infty}^{t} \mathbf{B}(t-\tau) \cdot \dot{\mathbf{x}}(\tau) d\tau + \mathbf{C} \cdot \mathbf{x}(t) = \mathbf{X}(t) + \mathbf{F}_{PTO} + \mathbf{F}_{mooring} + \mathbf{F}_{control}$$

Power extraction: $P(t) = \mathbf{F}'_{PTO}(t) \cdot \dot{\mathbf{x}}(t)$

Big question: how can we calculate or model these forces (each term) so that we can optimise the device or improve wave energy conversion efficiency?

- Physical modelling
- Numerical simulation

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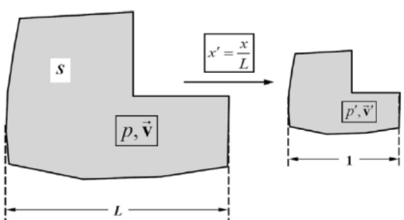
Physical modelling (1): Why and How

$$[\mathbf{M} + \mathbf{A}(\infty)] \cdot \ddot{\mathbf{x}}(t) + \int_{-\infty}^{t} \mathbf{B}(t-\tau) \cdot \dot{\mathbf{x}}(\tau) d\tau + \mathbf{C} \cdot \mathbf{x}(t) = \mathbf{X}(t) + \mathbf{F}_{PTO} + \mathbf{F}_{mooring} + \mathbf{F}_{control}$$

Fundamental requirements:
(1) Meaningful: geometrical similarity must be satisfied.

(2) Useful: kinematic and dynamic similarities must be partially or fully satisfied. For instance, the data from a scale model are used to predict the prototype/full scale.



$$\begin{cases} \frac{\partial u'}{\partial t'} + u'\frac{\partial u'}{\partial x'} + v'\frac{\partial u'}{\partial y'} + w'\frac{\partial u'}{\partial z'} = -\frac{1}{2}\frac{\partial p'}{\partial x'} + \frac{1}{R_e}\left(\frac{\partial^2 u'}{\partial x'^2} + \frac{\partial^2 u'}{\partial y'^2} + \frac{\partial^2 u'}{\partial z'^2}\right) \\ \frac{\partial v'}{\partial t'} + u'\frac{\partial v'}{\partial x'} + v'\frac{\partial v'}{\partial y'} + w'\frac{\partial v'}{\partial z'} = -\frac{1}{2}\frac{\partial p'}{\partial y'} + \frac{1}{R_e}\left(\frac{\partial^2 v'}{\partial x'^2} + \frac{\partial^2 v'}{\partial y'^2} + \frac{\partial^2 v'}{\partial z'^2}\right) \\ \frac{\partial w'}{\partial t'} + u'\frac{\partial w'}{\partial x'} + v'\frac{\partial w'}{\partial y'} + w'\frac{\partial w'}{\partial z'} = -\frac{1}{2}\frac{\partial p'}{\partial z'} - \frac{1}{F_r^2} + \frac{1}{R_e}\left(\frac{\partial^2 w'}{\partial x'^2} + \frac{\partial^2 w'}{\partial y'^2} + \frac{\partial^2 w'}{\partial z'^2}\right) \end{cases}$$

$$R_e = \frac{\rho L U}{\mu} > 10^5$$

Sheng, W., Alcorn, R., Lewis, T., "Physical modelling of wav energy converters," ***Ocean Engineering,*** Vol. 84, **(2014)**, pp.29-36.

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Physical modelling (2): Pros and Cons

Advantages:

- Full physical phenomena if modelling is appropriate.
- Controlled lab conditions to isolate dynamic effects (e.g. regular waves).
- Easy and accurate measurements.
- Fast optimisation process
- Installation and removal of device
- Cost: cheap, when compared to full scale sea trials .

Disadvantages:

- Scaling effects: how large the model is appropriate?
- Power take-off (PTO)/control system: is correctly modelled? Feasibility problem!
- Energy conversion system: can we do this? (~1W in model scale)
- Cost: expensive, when compared to numerical modelling.

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Dynamic systems: numerical simulation

Solution to the time domain equation

W=WAMIT

$$[\mathbf{M}+\mathbf{A}(\infty)]\cdot\ddot{\mathbf{x}}(t)+\int_{-\infty}^{t}\mathbf{B}(t-\tau)\cdot\dot{\mathbf{x}}(\tau)d\tau+\mathbf{C}\cdot\mathbf{x}(t)=\mathbf{X}(t)+\mathbf{F}_{PTO}+\mathbf{F}_{mooring}+\mathbf{F}_{control}$$

W W ? W ? ?

Device assessment and optimisation using WAMIT

How to optimise PTO and control the device for improving wave energy production?

How to solve the convolution term in the time-domain equation?

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Solution 1: Convolution calculation

Time domain equation

$$[\mathbf{M}+\mathbf{A}(\infty)]\ddot{\mathbf{x}}(t)+\int_{-\infty}^{t}K(t-\tau)\dot{\mathbf{x}}(\tau)d\tau+\mathbf{C}\cdot\mathbf{x}(t)=\mathbf{X}(t)+\mathbf{F}_{PTO}+\mathbf{F}_{mooring}+\mathbf{F}_{control}$$

Step 1: $K(t)\approx\sum_{k=1}^{N}\alpha_k e^{\beta_k t}$ — The Prony approximation to impulse function

Step 2: $I(t)=\int_0^t K(t-\tau)\dot{\zeta}(\tau)d\tau$ ⇨ $I(t)=\sum_{k=1}^{N}I_k(t)$ with $I_k(t)=\alpha_k e^{\beta_k t}\int_0^t e^{-\beta_k\tau}\dot{\zeta}(\tau)d\tau$

Step 3: $I_k(n+1)=I_k(n)e^{\beta_k\Delta t}+\dot{\zeta}(n)\Delta t\alpha_k e^{\beta_k\Delta t/2}$

Recursive!

W. Sheng, R. Alcorn, A. Lewis, 'A new method for radiation forces for floating platforms in waves', ***Ocean Engineering***, 105(2014)43–53

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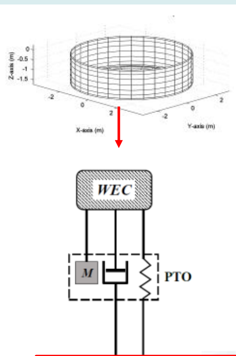
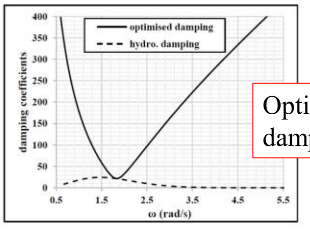
Solution 2: PTO Damping and device optimization (in regular waves)

$$[\mathbf{M}+\mathbf{A}(\infty)]\ddot{\mathbf{x}}(t)+\int_{-\infty}^{t}K(t-\tau)\dot{\mathbf{x}}(\tau)d\tau+\mathbf{C}\cdot\mathbf{x}(t)=\mathbf{X}(t)+\mathbf{F}_{PTO}+\mathbf{F}_{mooring}+\mathbf{F}_{control}$$

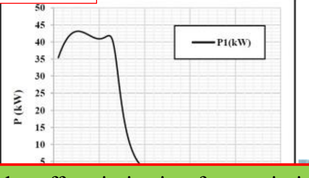
- **A point absorber: *D*=6m, draft=1.5m**
- **PTO optimal damping in regular waves**



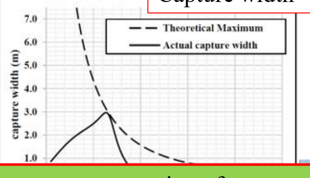


Optimised PTO damping

Maximal power (H=2m)



Capture width



<u>**Sheng, W.,**</u> R. Lewis, T., 'Power take-off optimisation for maximising energy conversion of wave activated bodies', ***IEEE Journal of Oceanic Engineering***, **2015. DOI:** 10.1109/JOE.2015.2489798.

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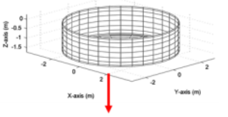
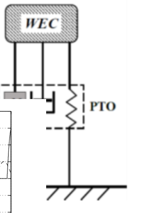
Solution 3: Control (latching control)

$$[\mathbf{M}+\mathbf{A}(\infty)]\ddot{\mathbf{x}}(t)+\int_{-\infty}^{t}K(t-\tau)\dot{\mathbf{x}}(\tau)d\tau+\mathbf{C}\cdot\mathbf{x}(t)=\mathbf{X}(t)+\mathbf{F}_{PTO}+\mathbf{F}_{mooring}+\mathbf{F}_{control}$$

A point absorber: *D*=6m, draft=1.5m





Fundamental challenges in active control:

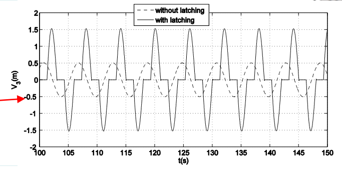
(1) Physical implementation: how to make the control.
(2) Time horizon into future (~10-20s).

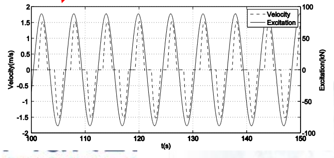
Latching for phase control

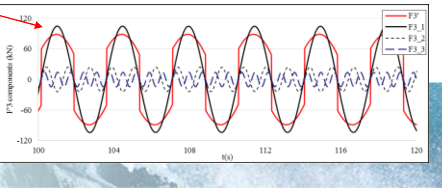
- Latching when velocity is zero or very small, for instance, use a clamp or breaking system.
- Latching duration T_{latch}

Improvement of wave energy conversion in terms of

- Phase control
- Motion acceleration
- Excitation increase







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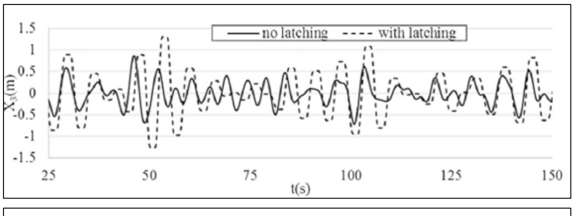
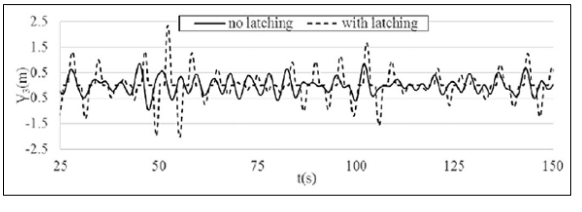
Solution 3: novel latching control

$$T_{\mathrm{latch}}=\frac{T_e-T_0}{2}$$

(Hs=1.0m,Te=6.0s)





Power conversion increase by 320%! (Hs=1.0m,Te=6.0s)

1. **Sheng, W.,** Alcorn, R., Lewis, T., "On improving wave energy conversion, Part I: optimal and control technologies", ***Renewable Energy*** **75 (2015)**, pp. 922-934. **doi:**10.1016/j.renene.2014.09.048.
2. **Sheng, W.,** Alcorn, R., Lewis, T., "On improving wave energy conversion, Part II: development of latching control technologies", ***Renewable Energy*** **75 (2015)**, pp. 935-944. **doi:**10.1016/j.renene.2014.09.049.

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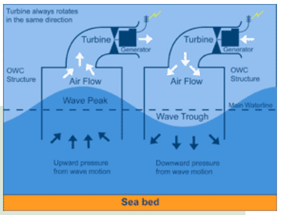
Why Oscillating Water Column (OWC)?



- **A very adaptive and well-proven concept**
  - Shoreline, nearshore or offshore: bottom-fixed and floating.
  - LIMPET plant: > 60,000 hours in 10 years; OE Buoy sea-trial > 3 years.
- **Structural reliability**
  - **No moving components**
  - **no joints/articulations, thus** no significant stress concentration
  - **no end-stop problem!**
- **High reliability for power take-off**
  - Small force for a certain power take-off due to high speed air flow and rotational speed.
  - Small size generator, probably off-the-shelf !

- **High primary/secondary wave energy conversion efficiency**
  - Novel turbines with very high energy conversion efficiency (~90%).
  - Novel OWC for good power performance.
- **Fewer engineering problems**
  - Power conversion is through a high speed air flow.
  - High speed rotary PTO machine for direct connection to generator and for reducing size of PTO.
  - No significant sealing and wearing issues.

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Understanding OWC wave energy converters

- **Hydrodynamics of OWCs**
  - Interaction of OWC and waves.
  - Internal water surface motions (or pressure distribution on IWS).
- **Air flow and compressibility (thermodynamics)**
  - “Spring effect” in full scale air chamber.
  - Difficulties in model test, hence a reliable numerical analysis is needed.
- **Time-domain analysis**
  - Numerical tool for primary wave energy conversion
  - Detailed validations using experimental data
  - Air compressibility included

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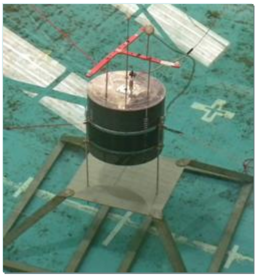
Time-Domain analysis: hydrodynamics and thermodynamics

$$[M_{99}+A_{99}(\infty)]\ddot{x}_9+C_{99}x_9+b_{99}\dot{x}_9+\int_0^t K_{99}(t-\tau)\dot{x}_9(\tau)d\tau$$
$$=F_9-A_0p$$

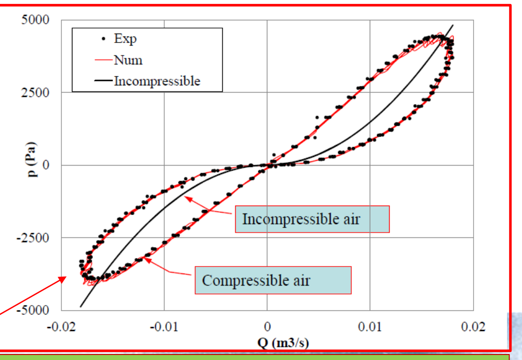
Chamber pressure



$$\frac{dV}{dt}+\frac{V}{\gamma p_0+p}\frac{dp}{dt}+\frac{-k_1+\sqrt{k_1^2+4k_2p}}{2k_2}=0$$

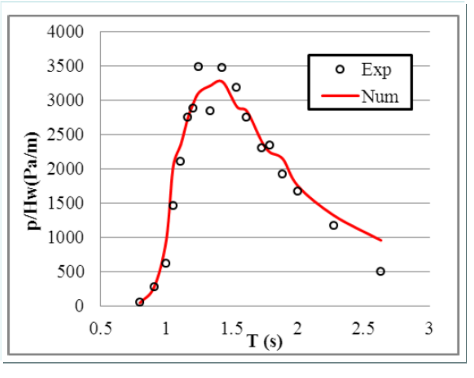
$$\left(1+\frac{p}{\gamma p_0}\right)\frac{dV}{dt}+\frac{V}{\gamma p_0}\frac{dp}{dt}+\frac{k_1-\sqrt{k_1^2-4k_2p}}{2k_2}=0$$

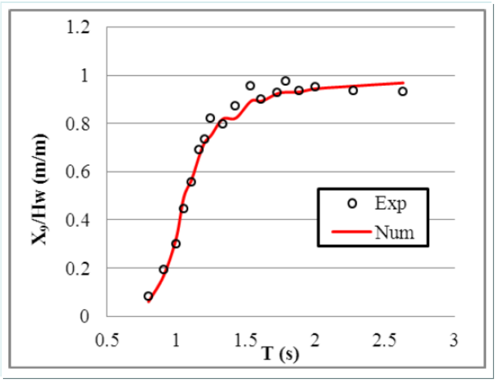
$$V=V_0-A_0x_9$$



Sheng, W., Alcorn, R. Lewis, T., **"On Thermodynamics of OWC Wave Energy Converters,"** ***Journal of Renewable and Sustainable Energy*** 5, 023105 (**2013**); doi: 10.1063/1.4794750

Comparison: OWC model





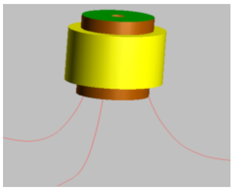
1. **Sheng, W.**, Alcorn, R., Lewis, T., "Assessment of primary energy conversions of oscillating water columns. I. hydrodynamic analysis," ***Journal of Renewable and Sustainable Energy*** **6**, 053113 (**2014**); **doi:** 10.1063/1.4896850.
2. **Sheng, W.,** Alcorn, R., Lewis, T., "Assessment of primary energy conversions of oscillating water columns. II. power take-off and validations," ***Journal of Renewable and Sustainable Energy*** **6**, 053114 (**2014**); **doi:** 10.1063/1.4896851.

OWC: novel development

IDF application: Efficient shallow water OWC wave energy converter
(IDF No. IDF 13-08)

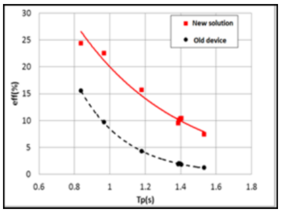
Advantages: **shallow water OWC**

- Fabricated and fully assembled in harbour/shipyards.
- Concrete structure for low cost and high reliability
- Towed to deployment site and a 'plug-in' type installation requiring a small weather window.



Problems addressed:

- **Significant increase in wave energy conversion efficiency**
- **Much improved performance of the device**
  - ✓ Beneficial for mooring and cable connections.
  - ✓ Beneficial to the accessibility for O&M.



What next?

1) contribution to MaREI fundamental research.
2) a novel device used for H2020 LCE proposal (2017), scored 8.5/10, missed the cut @9/10 (03/2017)…
3) Seeking funds for advancing the technology

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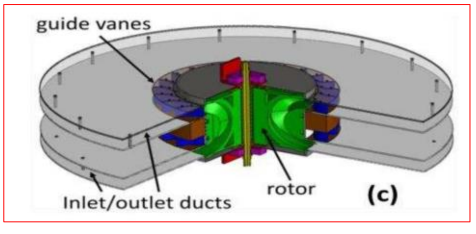
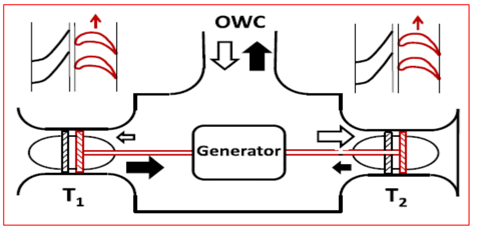
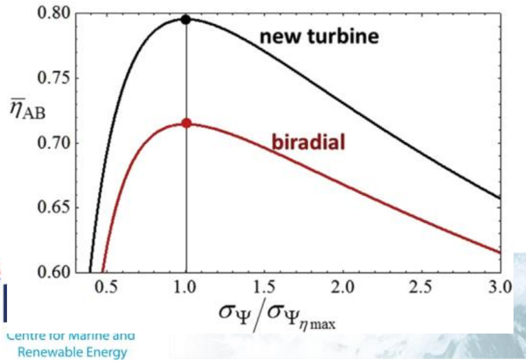
New air turbines for OWC devices

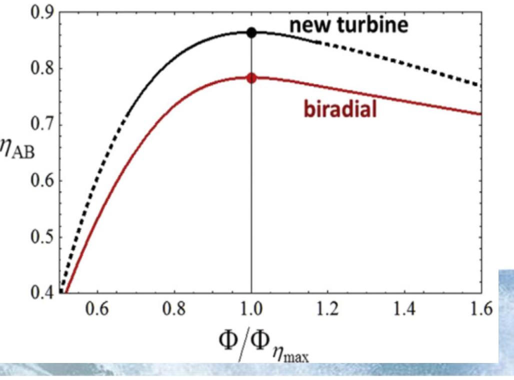
Bi-radial turbine



Twin-rotor turbine







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THANK YOU
Questions?