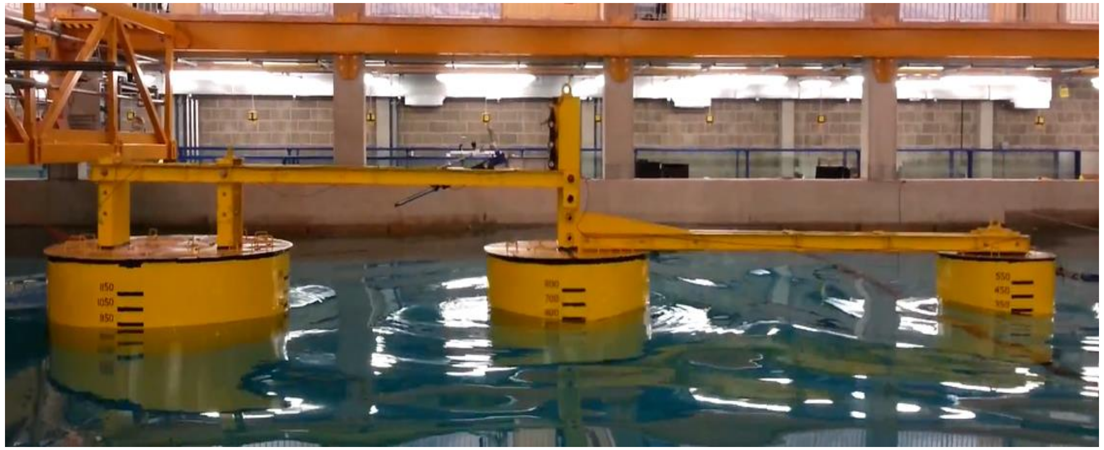
A scalable multi-body wave energy converter (for offshore aquaculture)



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UiB EnergyLab, 13th April 2021

Høgskulen på Vestlandet

Content

Wave energy

– status today

- some basic principles

The M4 device

Linear modelling using the Moving frame method

Results of power capture and energy yield

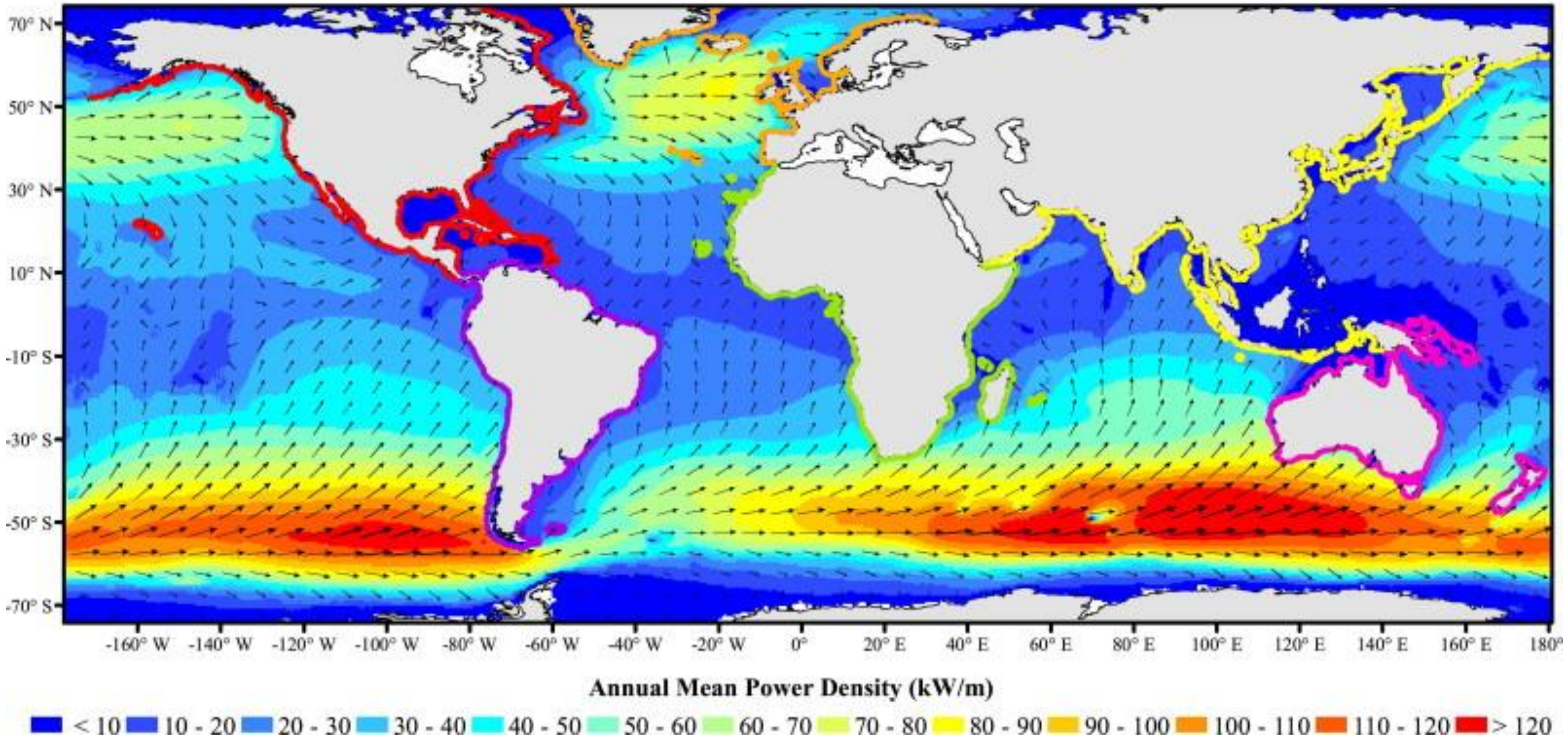
Analysis for an offshore fish farm

Conclusions

Future work

Høgskulen på Vestlandet

Energy in waves



$$P_{wav} = \frac{\rho g^2 H_S^2 T}{64\pi}$$ **[W/m]**

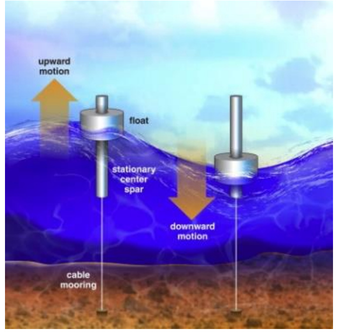
→ ~ 0.5 $H_S^2 T$ kW/m of crest

Høgskulen på Vestlandet

Types of WECs

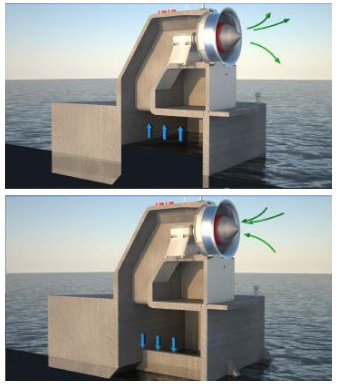
Point Absorbers

- Operate in heave, pitch or a combination
- Small compared to wavelength

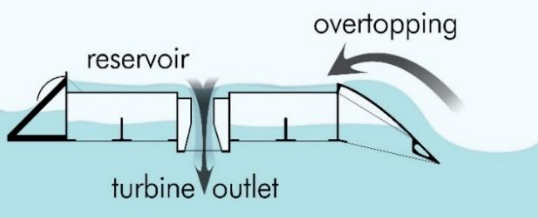


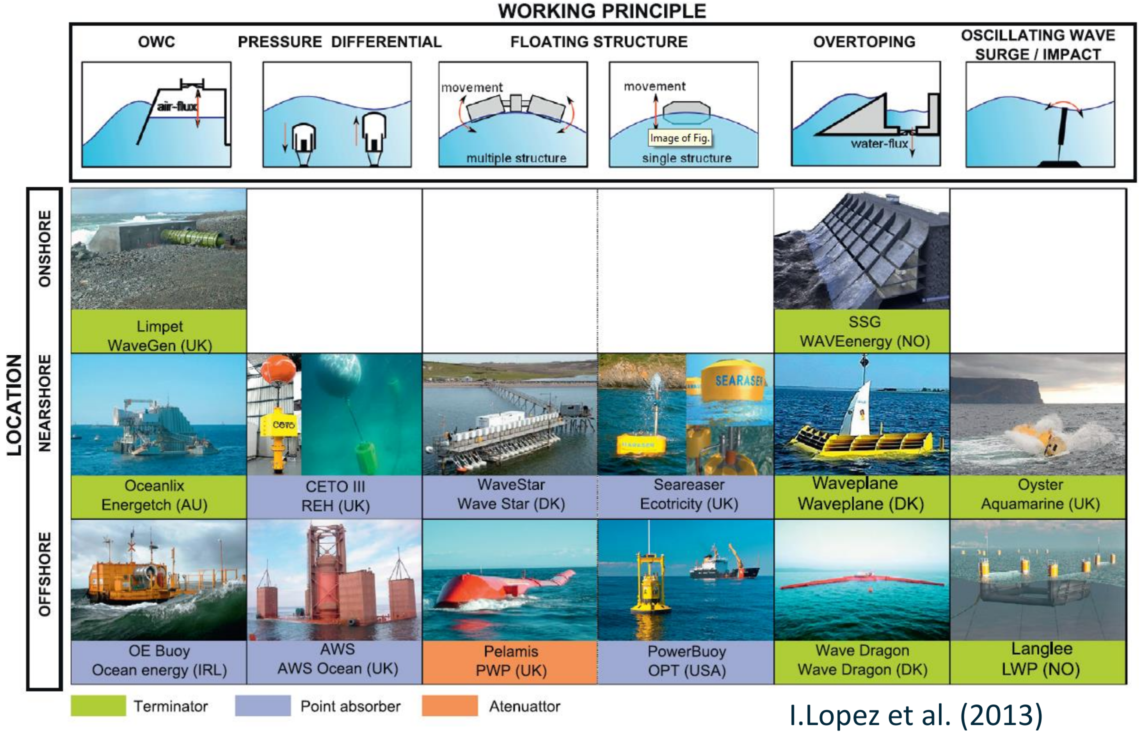
Terminator device

- 'Terminates' the wave motion
- E.g. OWC - wave in, air out/ Wave out, air in
- Wells turbine turns in same direction, irrespective of air flow



- E.g. Overtopping device
- Device increases potential energy in wave and forces water through turbines

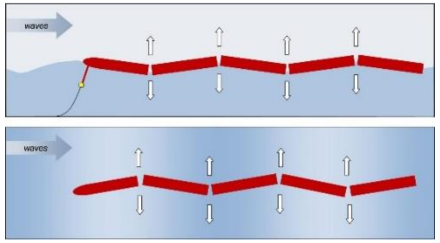




I.Lopez et al. (2013)

Attenuator device

- Long structure compared to wavelength.
- Direction dependent
- 'Attenuate' the wave amplitude



Høgskulen på Vestlandet

Wave Energy: Future Challenges

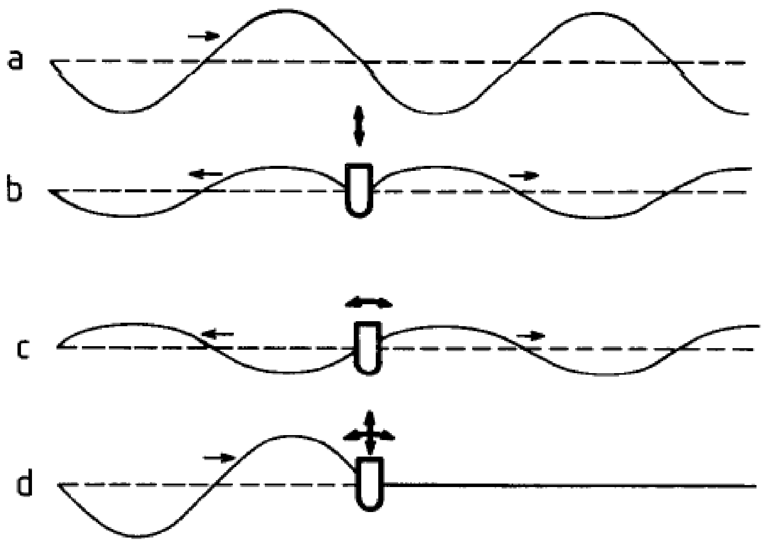
- Reasons for failure:
  - Technical – structural, mooring lines, extreme loads, wear and corrosion
  - Financial – difficulty to provide match funding to public grants, or increase private equity due to late delivery of milestones.
- But failures provide learning!
- Need for continued technological innovation:
  - Support for diverse designs to encourage competitiveness
  - Co-ordinated development, knowledge-sharing and standardisation
  - Moorings for highly dynamic systems
  - Power take off design and control
- Need for specialised supply chains
- Niche markets – integrated breakwaters, desalination, aquaculture, oil & gas platforms (ENI/ISWEC), island microgrids, hybrid energy systems, etc.
- LCOE should be integral to design, but minimised over time.
- Specific financial support mechanisms

Jin and Greaves (2021) [1]
EC (2017) [2]

Høgskulen på Vestlandet

How to absorb 2D waves?

"To destroy a wave means to create a wave", Falnes.

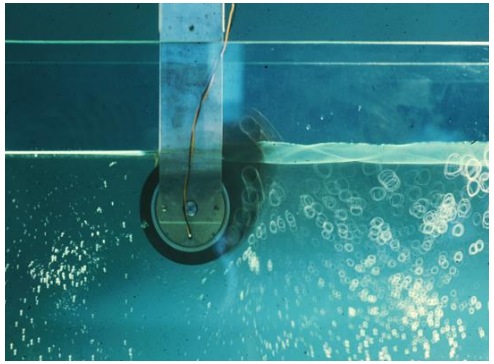


Incident wave

Symmetric wave < 50%

Non-symmetric wave < 50%

Superposition < 100%

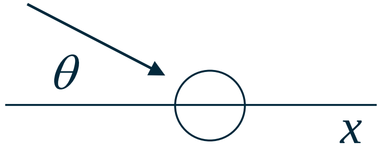


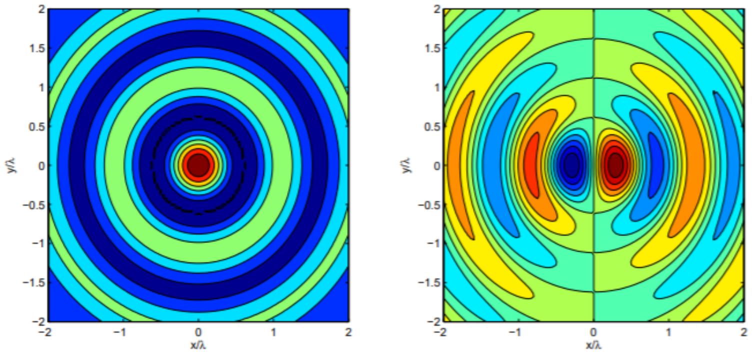
100% absorption also possible with asymmetric body oscillating in one mode:
e.g. Duck

Optimal 3D wave absorption

Evans (1979):

$$R = \frac{1}{8LP_{wav}} \int_0^{2\pi} F_0^2(\theta)d\theta$$





Force to generate radiated wave is of equal magnitude and opposite sign to the incident force on the same geometry due to the same crest pattern

Optimal power is given as $P_{opt} = \frac{F_0^2}{8R}$,
such that on substitution:

$$\boxed{P_{opt} = P_{wav}\varepsilon\frac{L}{2\pi}}$$ **[W]**

Real devices absorb less than optimal.
Define a capture width ratio:

$$CWR = \frac{P_{abs}}{P_{wav}L}$$

Multi-Mode Moored Multibody (M4) - Strategy

Høgskulen på Vestlandet

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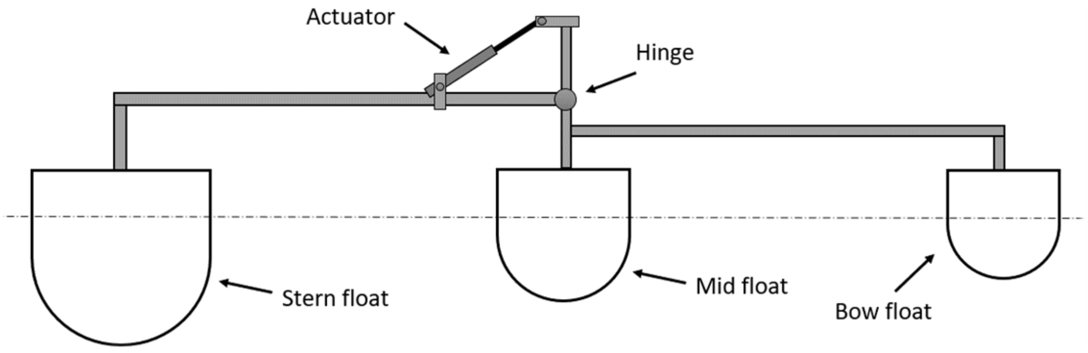
- Target LCOE 10p/kWh or less through device with high energy capture
- Multi-bodies for high wave energy capture across range of real wave conditions through streamlined floats with multi-mode hydrodynamic interactions
- Moored floating device for easy deployment and long-term maintenance in port
- Survivable in extreme waves
- Scalable to several power take offs for high capacity as offshore wind
- Power take off at each hinge accessible above deck for maintenance
- Environmentally non-intrusive



Laboratory testing

Manchester 2015

Stansby et al. (2015) [3]

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Laboratory testing

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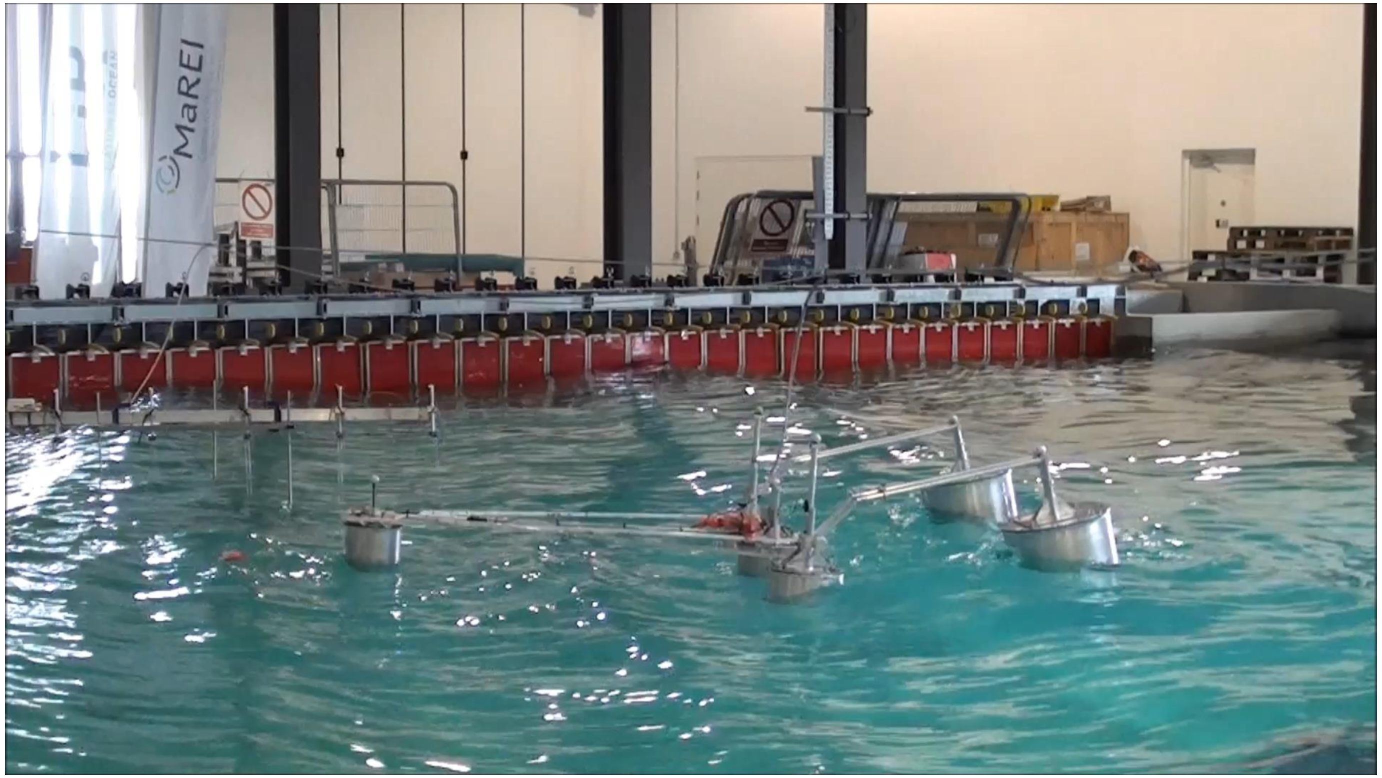
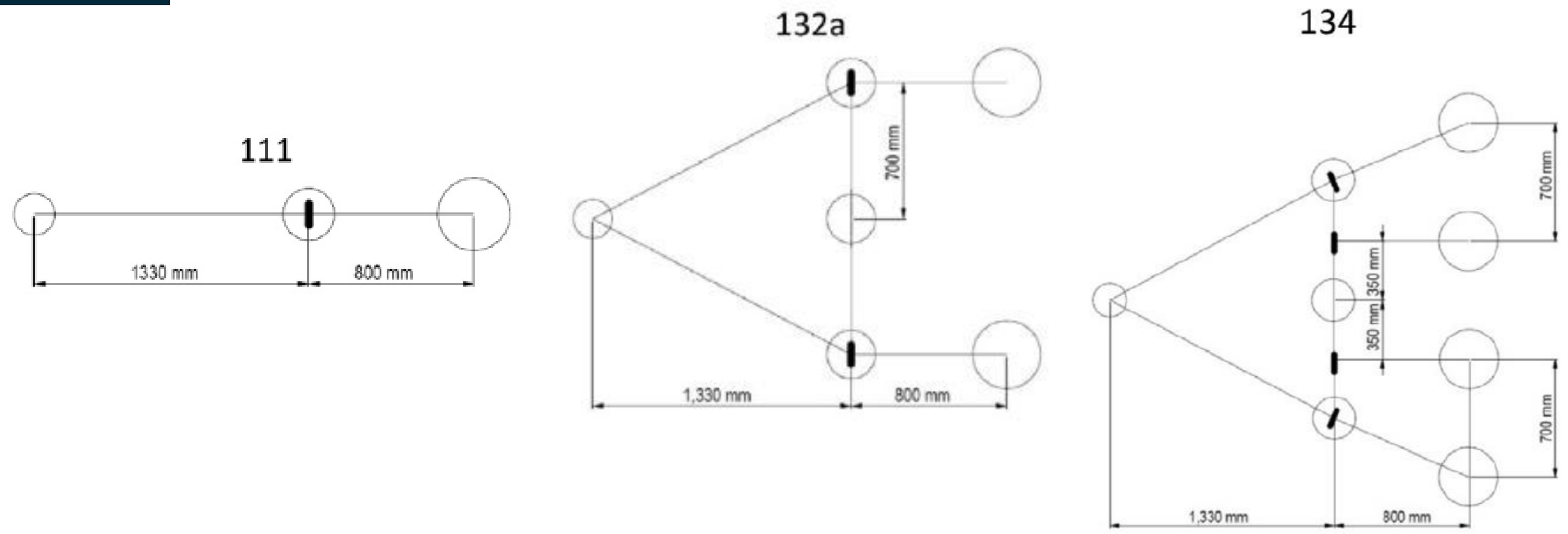
Cork 2018 (Marinet2)



Moreno and Stansby (2019) [4]

Modelling M4



- Existing analysis of several float configurations by [5] uses a vectorial mechanics model
- Model validated for 111 and 132a configurations against experimental tests
- Vectorial mechanics becomes more complex the more floats. This makes it cumbersome to implement for structural modelling and prone to human error.
  - → The MFM [6] may solve this issue

Høgskulen på Vestlandet

Tenets of Moving Frame Method

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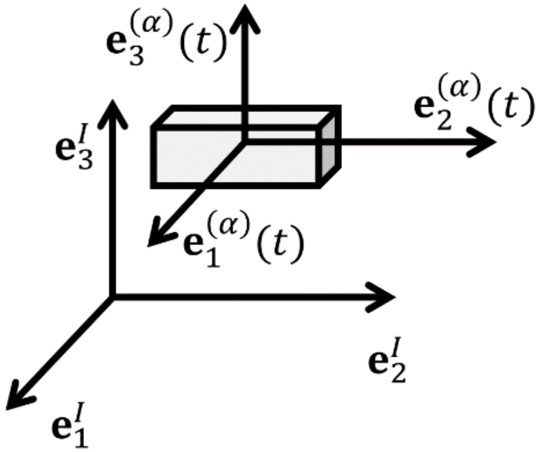
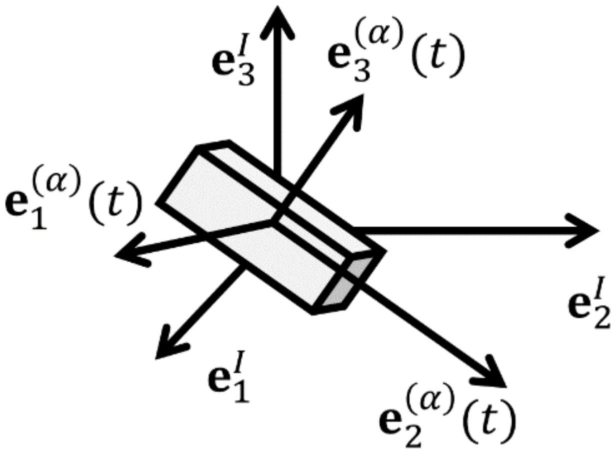
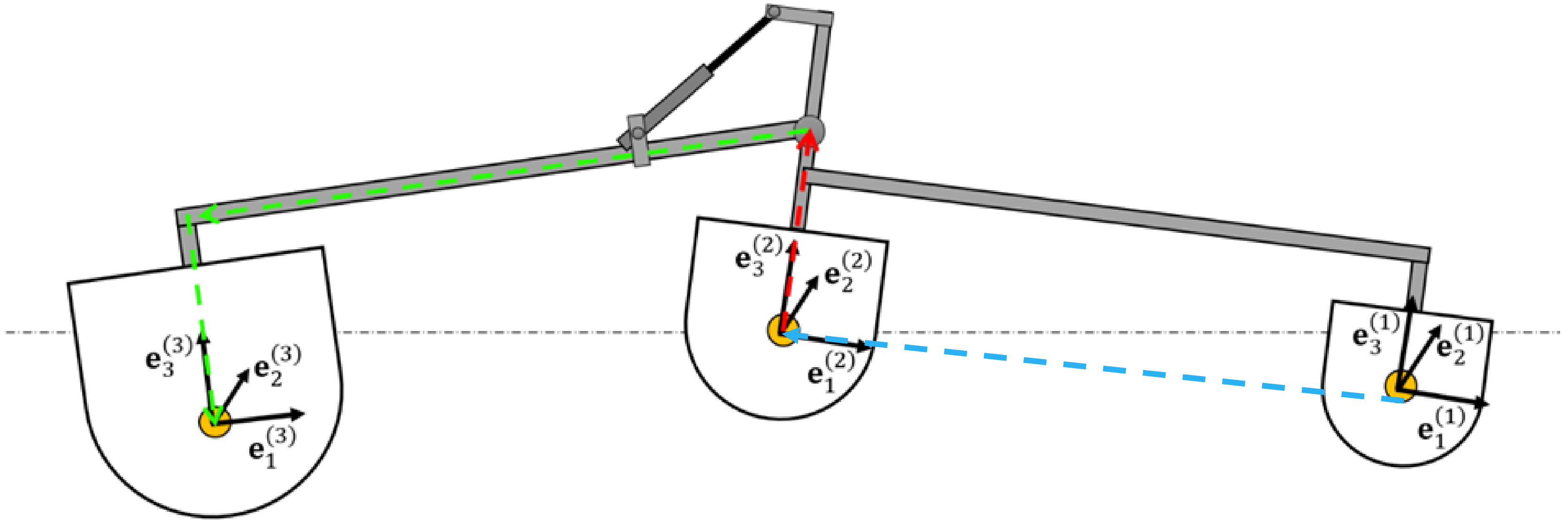
- At the center of mass of each moving body (α) a time-dependent (moving) frame is attached
- An inertial frame $\boldsymbol{e}^I$ is defined at t=0
- SE(3) - combine the rotational and translational data of a frame in one structure:

$$E^{(\alpha)}(t) = \begin{bmatrix} R^{(\alpha)}(t) & x^{(\alpha)}(t) \\ 0_3^T & 1 \end{bmatrix}$$





M4 with Moving Frames



1) Frames placed at COG of each float.

$$E^{(1)}(t) = \begin{bmatrix} R^{(1)}(t) & x^{(1)}(t) \\ 0_3^T & 1 \end{bmatrix}$$

2) Absolute frame connection for float 1:

$$E^{(2)}(t) = \begin{bmatrix} R^{(1)}(t) & R^{(1)}(t)s^{(2/1)} + x^{(1)}(t) \\ 0_3^T & 1 \end{bmatrix}$$

3) Absolute frame connection for float 2:

$$E^{(3)}(t) = \begin{bmatrix} R^{(1)}(t)R^{(3/2)}(t) & R^{(1)}(t)\left(R^{(3/2)}(t)s^{(3/h)} + s^{(h/2)}\right) + \left\{R^{(1)}(t)s^{(2/1)} + x^{(1)}(t)\right\} \\ 0_3^T & 1 \end{bmatrix}$$

4) Absolute frame connection matrix for float 3:

Equations of motion

Traditionally, equations of motion can be derived based on principles of Variation of Kinetic Energy and Work for float position, x, as:

$$[M+A]\ddot{x}+[R+B_m]\dot{x}+[S]x=\{F\}$$

Alternatively, via the MFM using minimal set of generalised co-ordinates, q, as:

$$\{\ddot{q}\}=[M^*]^{-1}\left(\{F^*\}-[N^*]\{\dot{q}\}\right)$$

- Coupled ODE's can be solved using any 2nd order (or higher) time-stepping method, e.g. Midpoint method, Beeman's method, Runge-Kutta, etc.

Generalised coordinates

- A minimal set of *generalised velocities,* $\{\dot{q}(t)\}$, are needed to model the system.

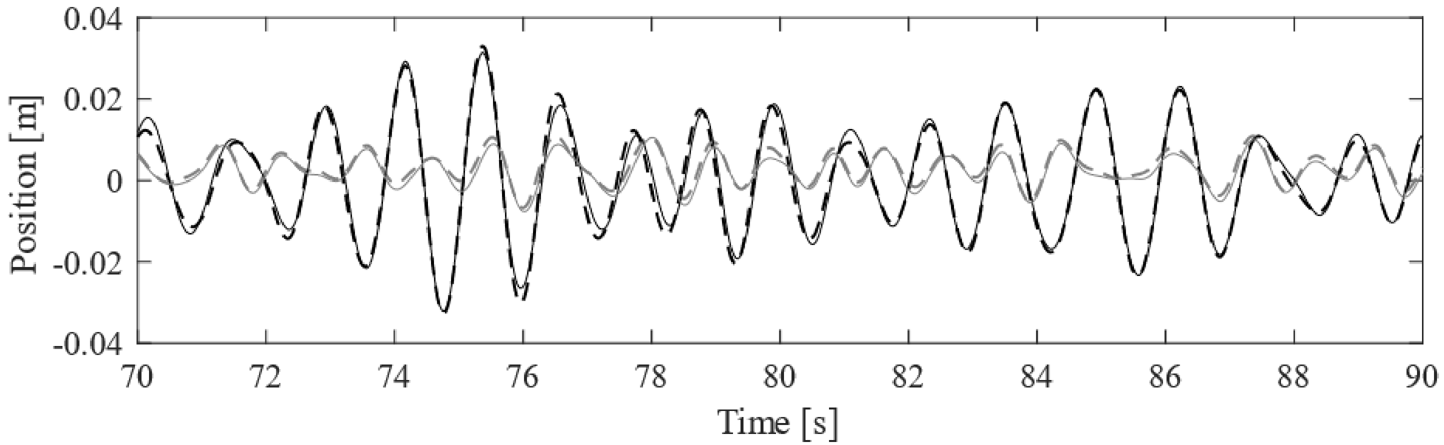
- The cartesian velocities, $\{\dot{X}(t)\}$ relates to the generalised velocities by a B-matrix:

$$\{\dot{X}(t)\} = [B(t)]\{\dot{q}(t)\}$$

$$\{\dot{X}(t)\} \equiv \begin{pmatrix} \dot{x}_1^{(1)}(t) \\ \dot{x}_2^{(1)}(t) \\ \dot{x}_3^{(1)}(t) \\ \omega_1^{(1)}(t) \\ \omega_2^{(1)}(t) \\ \omega_3^{(1)}(t) \\ \dot{x}_1^{(2)}(t) \\ \dot{x}_2^{(2)}(t) \\ \dot{x}_3^{(2)}(t) \\ \omega_1^{(2)}(t) \\ \omega_2^{(2)}(t) \\ \omega_3^{(2)}(t) \\ \dot{x}_1^{(3)}(t) \\ \dot{x}_2^{(3)}(t) \\ \dot{x}_3^{(3)}(t) \\ \omega_1^{(3)}(t) \\ \omega_2^{(3)}(t) \\ \omega_3^{(3)}(t) \end{pmatrix} \equiv \begin{pmatrix} \dot{x}^{(1)}(t) \\ \omega^{(1)}(t) \\ \dot{x}^{(2)}(t) \\ \omega^{(2)}(t) \\ \dot{x}^{(3)}(t) \\ \omega^{(3)}(t) \end{pmatrix}, \quad \{\dot{q}(t)\} \equiv \begin{Bmatrix} \dot{x}_1^{(1)}(t) \\ \dot{x}_3^{(1)}(t) \\ \dot{\theta}^{(1)}(t) \\ \dot{\varphi}^{(3/2)}(t) \end{Bmatrix}$$

<u>3 float system:</u>
18 Cartesian co-ordinates reduce to 4 generalised co-ordinates.

Results - time-series response



Nyland et al. (2020) [7]

Heave (black) and surge (grey) position for $T_p = 1.2$ s as calculated by the vectorial model (dashed) and MFM (solid).

- Heave and surge response RMSE: less than 3×10^{-3} m and 4×10^{-3} m

Small discrepancies due to:

1) RK4 vs Beeman

2) Hydrodynamic coefficients about centre of buoyancy

The hydrodynamic forces are correctly implemented into the MFM.

Computational run-time

- Original vectorial model written in Fortran 95 – migrated here into Matlab
- Both models using midpoint method.
- Computer: Laptop with dual-core 2.4GHz processor and 16 GB RAM.

Computation time per iteration:

- Vectorial model: 0.018 s
- MFM: 0.076 s

No parallel processing in either code.

MFM used symbolic toolbox in Matlab.

Notation in MFM is consistent for 2D, 3D, single and multi-bodies.

Høgskulen på Vestlandet

Capture Width Ratio

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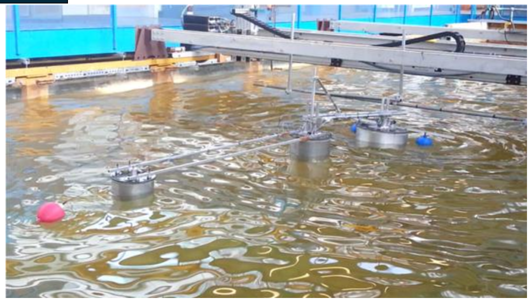
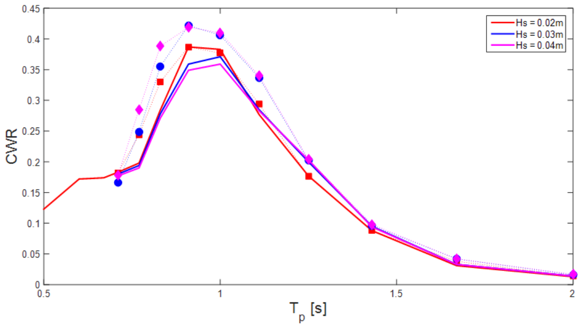
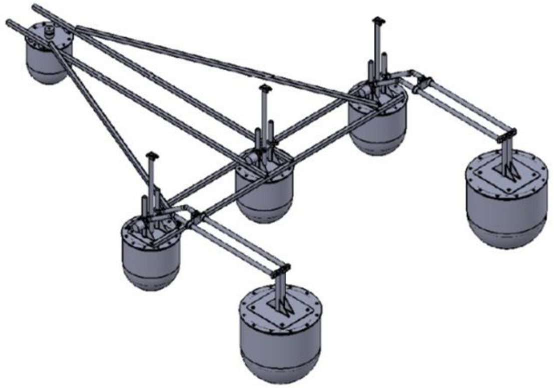
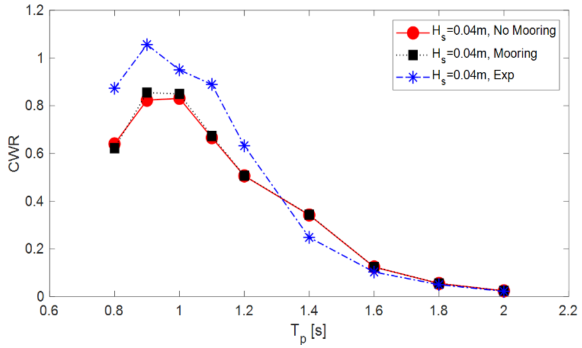


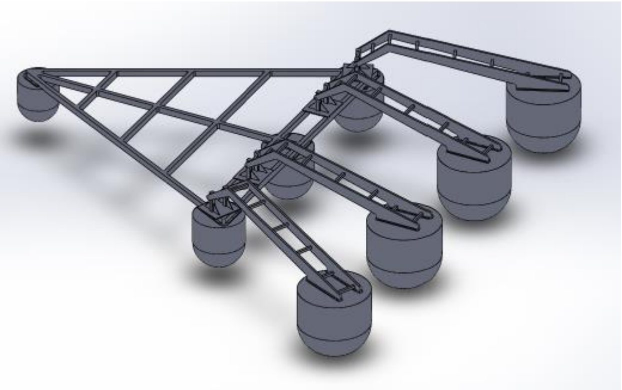


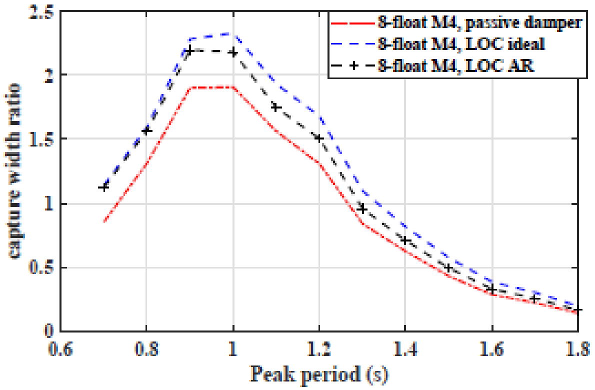
111 , 1 PTO
Max capture width
0.4 wavelength





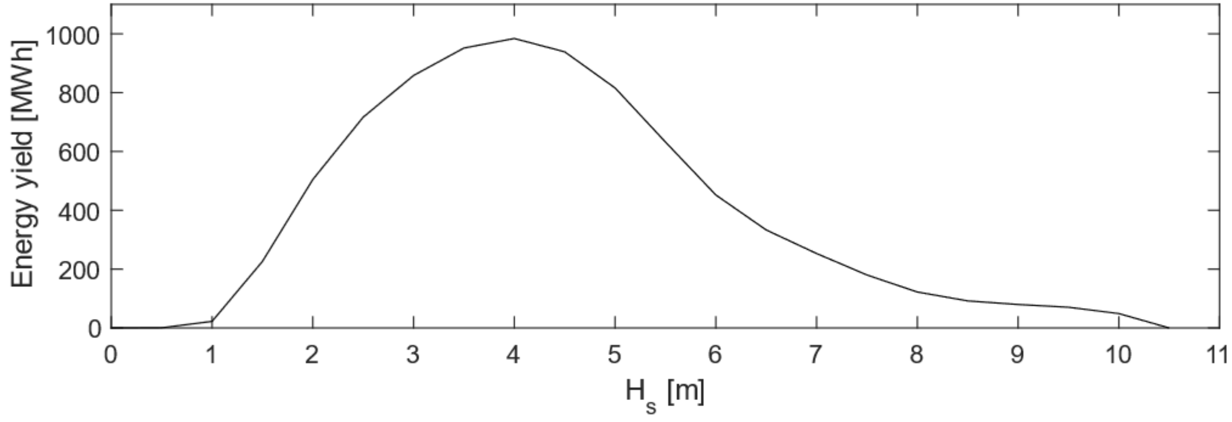
132 , 2 PTOs
Max capture width
1 wavelength





134 , 4 PTOs
Max capture width
2 wavelengths

Full-scale Energy Yield



Energy yield at Belmullet [7] as a function of significant wave height

Configuration	Average power [kW]	Annual energy yield [MWh]	Rated power [MW]
3fl_111 (MFM)	945	8282	2.84
3fl_111 (from [3])	970	8505	2.91
8fl_134 (from [3])	2998	26264	8.99

- Full-scale analysis run for Belmullet, Ireland.
- Discrepancies between MFM and vectorial model result in just 2.5% reduction on predicted energy yield.
- Previous analysis by [5] has shown M4 with rated power up to 17.8 MW for the Death Coast, Spain.
- Useful to find optimal device arrangements and float sizes relative to the site-specific resource

Offshore Aquaculture?

Photo: salmar.no

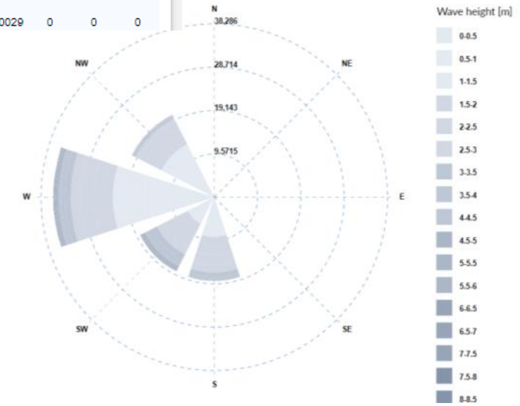
- LCOE study by Wiken, L. (2018)[8]:
  - Avg. power needed: 10-50kW
  - Diesel: 15-26p/kWh
  - 50-150kW Offshore Wind: 20-50p/kWh*
    - D=40 m rotor
- M4 study:
  - Avg. power 47 kW
  - LCOE⁺:

    32 p/kWh (avg. Hs=1 m) +6 floats ~50x40 m area

    8p/kWh (avg. Hs=2 m) + smaller system
- Karmøy case-study
  - avg. Hs=1.7 m & Tp=8.5 s

Peak period [s]

	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20
0-0.5	0	0	0.0418	0.1216	0.3022	0.3877	0.3763	1.1622	0.9788	0.3108	0.2832	0.1216	0.1017	0.0998	0.0418	0.0323	0.0133	0.0076	0.0029	0.001
0.5-1	0	0	0.0048	0.5873	2.4015	3.9163	3.0543	4.478[illegible]	5.9234	2.1078	1.7419	1.2896	0.6795	0.6728	0.3013	0.1834	0.0855	0.0238	0.0076	0.0048
1-1.5	0	0	0	0.0029	1.3666	4.6129	4.6148	3.7262	2.411	1.7134	1.5519	1.1223	0.6823	0.7479	0.2195	0.1444	0.039	0.0219	0.0057	0.0019
1.5-2	0	0	0	0	0.0067	1.5281	3.7272	4.4[illegible]75	2.5[illegible]98	1.205	0.8905	0.5103	0.4029	0.5075	0.2062	0.1435	0.0276	0.0048	0.001	0
2-2.5	0	0	0	0	0	0.0247	1.3761	3.0059	3.1883	1.2791	0.6177	0.3032	0.1502	0.2746	0.1112	0.1055	0.0285	0.0067	0.001	0
2.5-3	0	0	0	0	0	0	0.0912	1.511	2.5231	1.7134	0.555	0.191	0.0988	0.0798	0.0627	0.0665	0.0304	0.0114	0.0019	0
3-3.5	0	0	0	0	0	0	0	0.2537	1.32	1.8332	0.6225	0.1625	0.0523	0.0361	0.0181	0.0276	0.0162	0.0057	0.001	0
3.5-4	0	0	0	0	0	0	0	0.0133	0.4391	1.3571	0.7584	0.1359	0.0485	0.0276	0.0057	0.0057	0.0067	0.0029	0	0
4-4.5	0	0	0	0	0	0	0	0	0.0513	0.669	0.7945	0.1768	0.039	0.0133	0.0029	0	0.0029	0	0	0
4.5-5	0	0	0	0	0	0	0	0	0.0019	0.2262	0.6453	0.1692	0.0295	0.0076	0.001	0.001	0.0029	0	0	0



- LCOE similar to diesel/wind
- Similar dimensions as fish cages – small visual intrusion

Høgskulen på Vestlandet

Conclusions

- M4 demonstrates high power capture and survivability in modelling and experimental testing at range of Froude scales.
- M4 has been modelled using vectorial mechanics and MFM, with excellent agreement.
- The MFM allows for analysis of more complex wave energy converters in all six degrees of freedom, *but hydrodynamic modelling is main limitation*.
- In the context of offshore aquaculture, M4 looks to be an economically competitive option of power generation.

Høgskulen på Vestlandet

Future work

- Several projects on-going with M4:
  - Half-scale ocean testing in China, Australia and Mexico.
  - Further PTO design and control
  - Design of moorings
- Improvements are being made to MFM - Numerical computation and sparse matrices.
- MFM is being implemented for modal analysis of floating wind turbines.
- Mooring line loads (generally for ORE applications) need higher-order hydrodynamic modelling – HYDROMORE NFR application

Høgskulen på Vestlandet

Thank you

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Questions?

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- [5] Stansby, P., Moreno, E. and Stallard, T. (2017), Large capacity multi-float configurations for the wave energy converter M4 using a time-domain linear diffraction model. In: Appl. Ocean Res. 68 (2017) 53-64.
- [6] H. Murakami, "A Moving Frame Method for Multi-Body Dynamcis Using SE(3)," Proceedings of the ASME 2015 International Mechanical Engineering Congress & Exposition IMECE2015, November 13-19, Houston, Texas, 2015.
- [7] Nyland, J. et al. (2020) A hydrodynamic model of the M4 wave energy converter using the Moving Frame Method. In Proc. 4th International Conference on Renewable Energies Offshore (RENEW2020), Lisbon.
- [8] Wiken, L.S. (2018) Akvakultur og Små Vindturbinar: Eit moglegheitsstudie av i kva grad små vindturbinar kan dekkje energiforbruket ved norske oppdrettsanlegg. Master thesis, University of Bergen.