Numerical modelling of Wave Energy Converters

at LHEEA Lab

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The Ocean Energy and Waves group @ LHEEA Lab.

LHEEA Lab. : Hydrodynamics, Energetics and Atmospheric Environment

Staff : 100, Director : Prof. Pierre Ferrant

Ocean Energy and Ocean Waves Group Staff : 18, Head : Aurélien Babarit	**DyRAC**	**DSPM**	**DSSM**	**DAUC**	**TSM**

Research topics :

1. Ocean wave propagation and complex sea states

Deterministic wave propragation, wave breaking, wind/wave coupling, freak wave statistics, wave propagation over complex bathymetry

2. Hydrodynamic peculiarities of MRE applications

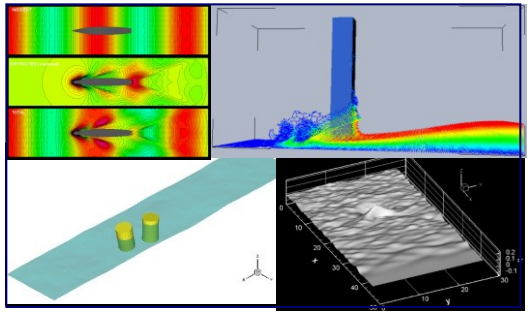
Large amplitude motion of Wave Energy Converters, wave interactions in arrays, aero-hydrodynamic coupling in seakeeping of offshore wind turbine

3. Control and optimisation of MRE systems

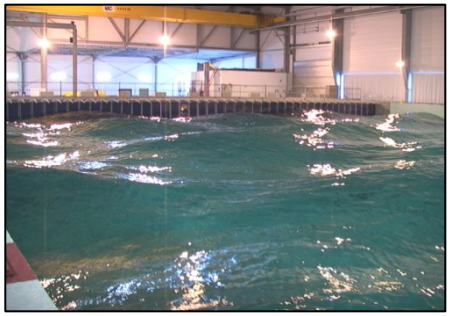
Development and validation of control algorithms for isolated and arrays of MRE systems.

Tools :

Numerical wave tanks



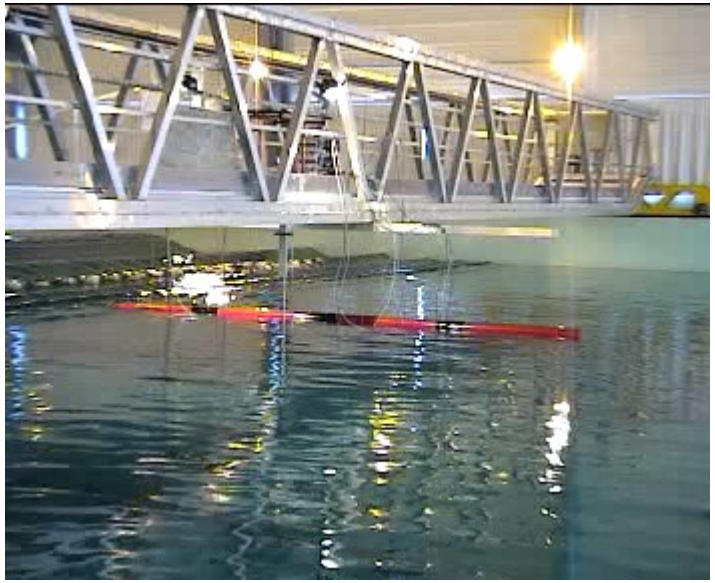
Large scale facilities



Full scale test site SEM-REV

Experiments: wave + wind large tank

LHEEA Lab. : Hydrodynamics, Energetics and Atmospheric Environment



1/20th scaled PELAMIS WEC tested at ECN

1/50th offshore wind turbine in waves

A floating multiple OWC device in waves

Numerical WEC modeling: the ultimate goal

Long term simulation of large arrays of WECs in conditions as close as possible from real exploitation and/or survival conditions.

- detailed engineering of the device (computation of maximum forces, loads, stresses, motions, deformations , etc..)
- assessing the energy production in any given sea state
- assessment of physical impact on the environment
- optimizing the device, optimizing the farm

Complete WEC modeling: the ultimate goal

Simulation of large arrays of WECS in conditions as close as possible from real exploitation and/or survival conditions.

➡ **Time domain** rather frequency domain ; **CPU time << real physical time**

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- **100+ machines** on sea surface area > 100+ km^2
- comput. domain from **local to regional**
- accounting for **hydrodynamic interaction** beween devices
- Device/device , farm/grid **electrical interaction** (PTO), farm management softw.

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- **Viscous fluid** hydrodynamics, **wind-wave-current interaction**
- **Normal to severe** sea state energy levels, nonlinear hydrod. modeling
- real (variable) **bathymetry** resulting in
- space **modification of incident sea state** (energy losses, refraction, diffraction, etc..)

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  - space **modification of incident sea state** (energy losses, refraction, diffraction, etc..)

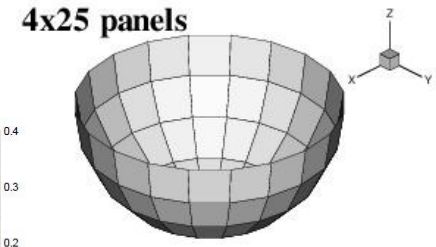
- **past breaking wave models** and algorithms (SPH) & fluid structure interaction
  - **Fail-soft** simulation mode

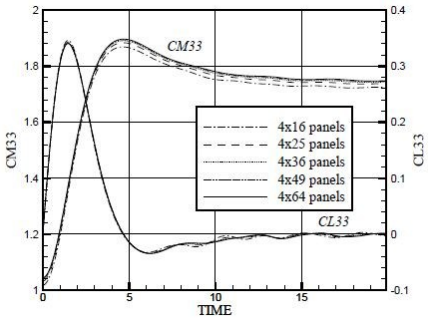
WEC modeling: available LHEEA softwares

	time variable	fluid model	N-Body	hydro model	PTO model	Accura	CPU time	special
AQUAPLUS	frequency domain	perfect fluid	< 10	Linear BEM (Kelvin CPM)	Linear damping	+	++	+ OWC Special version
ACHIL-3D	time domain	perfect fluid	<10	Linear BEM (Kelvin CPM)	Linear + nonlinear	+	++	Several control strategies
LAMSWEC	time domain	perfect fluid	1	BEM Exact FK + Kelvin	nonlinear	++	+	Moving body + Moving FS
ICARE-SWENSE	time domain	viscous fluid	1	RANSE (finite diff.) + SWENSE	N/A	++	-	SWENSE decomposition + HOS
SPH-FLOW	time-domain		1	SPH	N/A	+++	- -	Violent flows breaking

AQUAPLUS

- Frequency domain
- Linear potential flow (solve for velocity potential)
- Boundary element method (BEM)
- Kelvin Green function for sources & dipoles
- (CPM-low order WAMIT equivalent)
- 0th order sources distribution over each panel
- Multiple independent interacting bodies (<10)
- Calculation of drift forces





Solve in parallel for elementary potentials Φ_j. provided $\phi_j = \Re_e\left[\Phi_j e^{i\omega t}\right]$

$$\begin{aligned} \Delta\Phi_j &= 0 && \text{in the fluid domain } z<0 \text{ outside body surface} \\ \frac{\partial\Phi_j}{\partial z} - k_0\Phi_j &= 0 && \text{on the mean free surface } z=0 \text{ outside body surface} \\ \frac{\partial\Phi_j}{\partial n} &= n_j && \text{on the wetted surface of the WEC} \end{aligned}$$

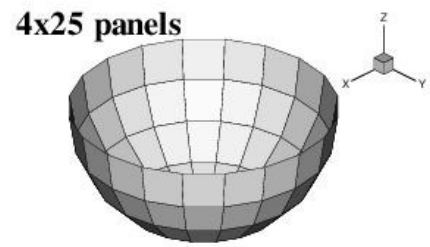
Then potentials → velocity → pressure → Hydro.forces : C_M and C_A

$$\left[-\omega^2\left(\mathbf{M}+\mathbf{C}_M(\omega)\right)+i\omega\mathbf{C}_A(\omega)+\mathbf{K}_H\right]\mathbf{X}=\mathbf{F}_{ex}+\mathbf{F}_{PTO}+\mathbf{F}_{mooring}$$

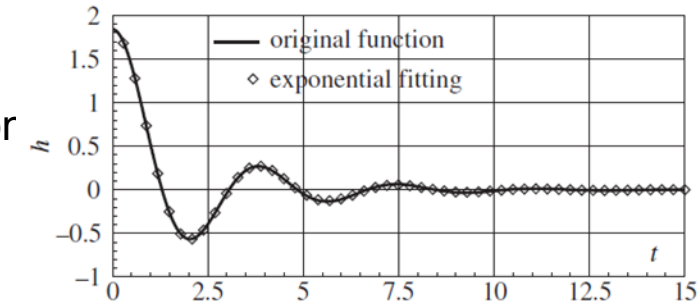
Finaly motions (velocity) X PTO forces → absorbed power

$$\mathbf{X}=X.e^{i\omega t} \qquad \mathbf{F}=F.e^{i\omega t}$$

ACHIL3D



- Time domain.
- Linear potential flow (solve for velocity potential)
- Generalized deformation (1 potential solution/panel)
- Boundary element method (BEM)
- Kelvin sources & dipoles
- Clement's 4th order ODE for Green function calculatior
- 0th order sources distribution over each panel
- Multiple independent interacting bodies (<10)



Solve for $\Phi_j(t)$ after a velocity impulse of panel j

$$
\begin{aligned}
\Delta\Phi_j &= 0 && \text{in the fluid domain } z<0 \text{ outside body surface}\\
\frac{\partial^2\Phi_j}{\partial t^2}+g\frac{\partial\Phi_j}{\partial z} &= 0 && \text{on the mean free surface } z=0 \text{ outside body surface}\\
\frac{\partial\Phi_j}{\partial n} &= \delta(t).n_j && \text{on panel } j \text{ of the WEC,}\\
\frac{\partial\Phi_j}{\partial n} &= 0 && \text{on other panels}
\end{aligned}
$$

Then $\Phi_j(t)$ ➡ radiation and wave excitation IR by integrating over the body $\sum_j$

$$(\mathbf{M}+\mu_\infty)\,\ddot{\mathbf{X}}+\int_0^t \mathbf{H}(t-\tau)\dot{\mathbf{X}}(\tau)d\tau+(\mathbf{K}+\mathbf{K}_H)\,\mathbf{X}=\int_0^t \mathbf{H}_{ex}(t-\tau)\boldsymbol{\eta}(\tau)d\tau+\mathbf{F}_{PTO}+\mathbf{F}_{mooring}$$

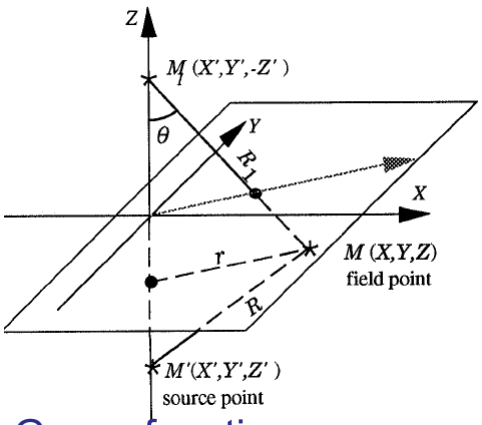
ACHIL3D …/…

The time domain Green function

$$F(r,Z;t) = 2\int_0^\infty J_0(Kr)\,e^{KZ}\sqrt{K}\,\sin[\sqrt{K}t]\,dK,$$

solution of a 4th order ODE

$$R_1^{\,2}\frac{\partial^4 F}{\partial t^4} + \mu R_1 t\frac{\partial^3 F}{\partial t^3} + \left(\frac{t^2}{4} + 4\mu R_1\right)\frac{\partial^2 F}{\partial t^2} + \frac{7t}{4}\frac{\partial F}{\partial t} + \frac{9}{4}F = 0$$



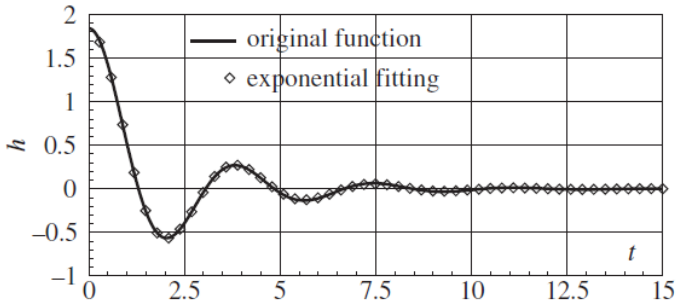
RK4 scheme → fast and accurate on-line evaluation of the Green function

A.H. CLÉMENT (1998), *An ordinary differential equation for the Green function of time-domain free-surface hydrodynamics*. Journal of Engineering Mathematics, 33 (2), pp.201-217

$$(\mathbf{M}+\mu_\infty)\,\ddot{\mathbf{X}} = \mathbf{F}_{ex} - \mathbf{B}\dot{\mathbf{X}} - \int_0^t \mathbf{H}(t-\tau)\dot{\mathbf{X}}(\tau)d\tau - (\mathbf{K}+\mathbf{K}_H)\,\mathbf{X}$$

Prony's method $h(t) \simeq \sum_{r=1}^{N} \alpha_r e^{\beta_r(t)}$

$$\mathbf{S}(t) = \int_0^t \mathbf{H}(t-\tau)\dot{\mathbf{X}}(\tau)d\tau \;\rightarrow\; \begin{cases} \mathbf{S}(t) = \begin{pmatrix} \sum_{j=1}^{3}\sum_{r=1}^{N_{1j}} S_{1jr}(t) \\ \sum_{j=1}^{3}\sum_{r=1}^{N_{2j}} S_{1jr}(t) \\ \sum_{j=1}^{3}\sum_{r=1}^{N_{3j}} S_{1jr}(t) \\ 0 \end{pmatrix} \\ \dot{S}_{ijr}(t) = \beta_{ijr}S_{ijr} + \alpha_{ijr}\dot{\mathbf{X}}_j(t) \end{cases}$$



G. DUCLOS, A.H. CLÉMENT, G. CHATRY (2001) : *Absorption of outgoing waves in a numerical wave tank using a self-adaptive boundary condition* . Int. Journal of Offshore and Polar Engineering, Vol11, n°3, pp.168-175

ICARE-SWENSE (CFD for wave problems)

SWENSE = Spectral Wave Explicit Navier-Stokes Equation

Functional decomposition of primitive variables in Navier-Stokes eq.

$$\begin{cases} U^{\alpha} = U_I^{\alpha} + U_D^{\alpha} \\ p = p_I + p_D \\ h = h_I + h_D \end{cases} \qquad \alpha \in \{1,2,3\}$$

Explicit incident flow: nonlinear potential model (HOS method)

Diffracted flow: Solved by a modified RANSE solver

$$\frac{\partial U_D^i}{\partial t} + \left(U_I^j + U_D^j - \frac{\partial \upsilon_t}{\partial x^j} \right) \frac{\partial U_D^{\alpha}}{\partial x_j} - (\upsilon + \upsilon_t) \frac{\partial^2 U_D^{\alpha}}{\partial x_j^{\,2}} + \frac{1}{\rho} \frac{\partial P_D}{\partial x_{\alpha}} = -U_D^j \frac{\partial U_I^{\alpha}}{\partial x_j} + (\upsilon + \upsilon_t) \frac{\partial^2 U_I^{\alpha}}{\partial x_j^{\,2}} + \frac{\partial \upsilon_t}{\partial x^j} \frac{\partial}{\partial x_{\alpha}} \left(U_I^j + U_D^j \right)$$

Example of the modified momentum equation

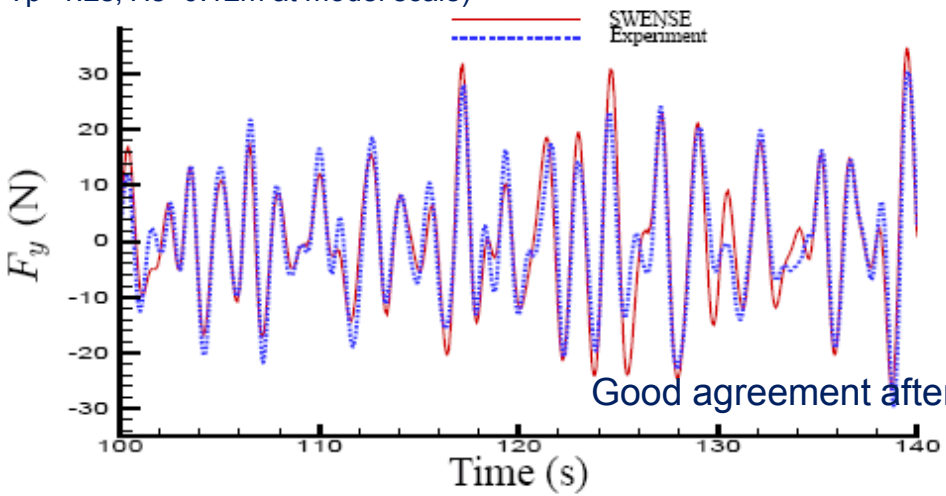
C. Monroy, G. Ducrozet, F. Bonnefoy, A. Babarit, L. Gentaz and P. Ferrant (2011) RANS Simulations of CALM Buoy in Regular and Irregular Seas Using SWENSE Method , International Journal of Offshore and Polar Engineering, Vol. 21, No. 4, pp. 264–271

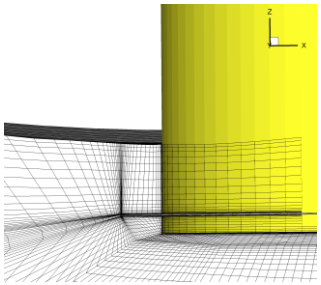
ICARE-SWENSE

courtesy of Principia RD

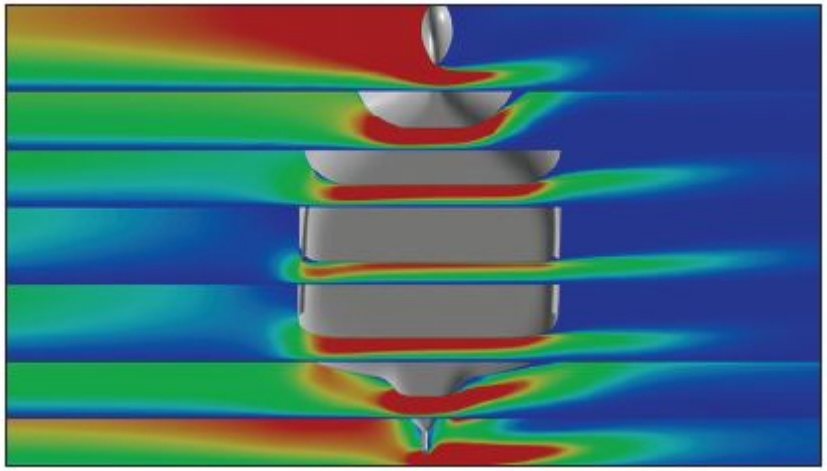
Comparisons experiments/numerics

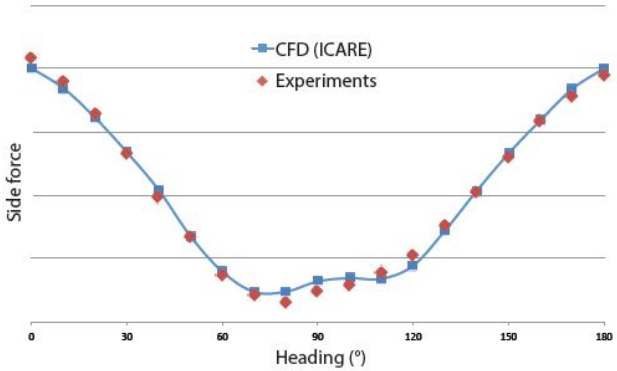
JIP CALM buoy in 3D irregular waves (Jonswap spectrum, Tp=1.2s, Hs=0.12m at model scale)





Good agreement after 115 wave periods !





Example of current coefficient calculation (side force)
Comparisons CFD / experiments

LAMSWEC

Large Amplitude Motion Simulation of Wave Energy Converters (~LAMP2 ?)

- Time domain. potential flow
- Panels over the full body
- Body and free surface moving at each time step
- Froude-Krylov forces= integration of pressure over the wetted surface of the displaced body
- Radiation problem = linearized around mean position (1st +2nd order)
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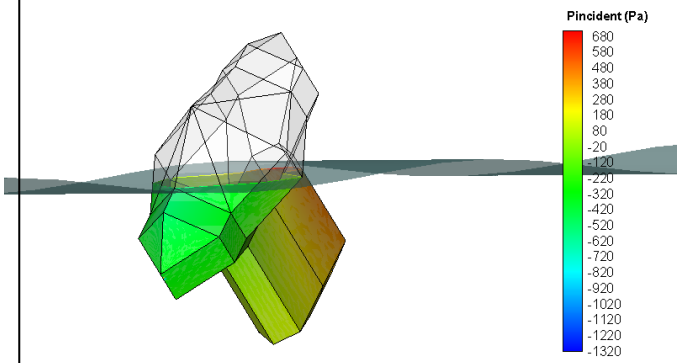
- Boundary element method (BEM) (like ACHIL3D)
- CPM - Kelvin sources & dipoles (like ACHIL3D)



Static and dynamic pressures

$$\begin{cases} p_S = p_0 - \rho g z, \ -\infty < z < \eta(t) \\ p_D = -\rho\left(\dfrac{\partial \phi_0}{\partial t} + \dfrac{1}{2}\nabla\left|\phi_0\right|^2\right) \end{cases}$$

Integrated over the wetted hull

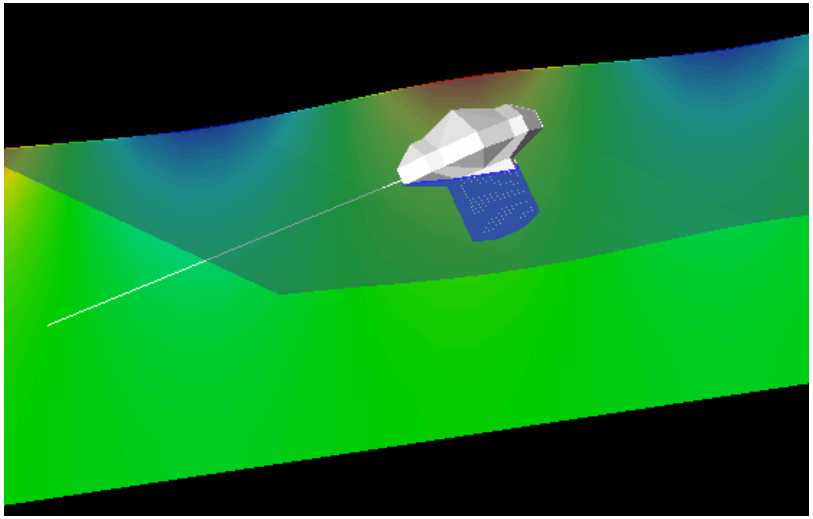
$$\begin{cases} \vec{F}_{FK,O}(G,t) = \iint_{C(t)} (p_S + p_D)\vec{n}dS \\ \overrightarrow{M}_{mt\,FK,O}(G,t) = \iint_{C(t)} (p_S + p_D)\left(\overrightarrow{GM} \times \vec{n}\right)dS \end{cases}$$

Nonlinear incident wave model : Fenton-Rienecker (regular waves)
HOS (irregular waves)

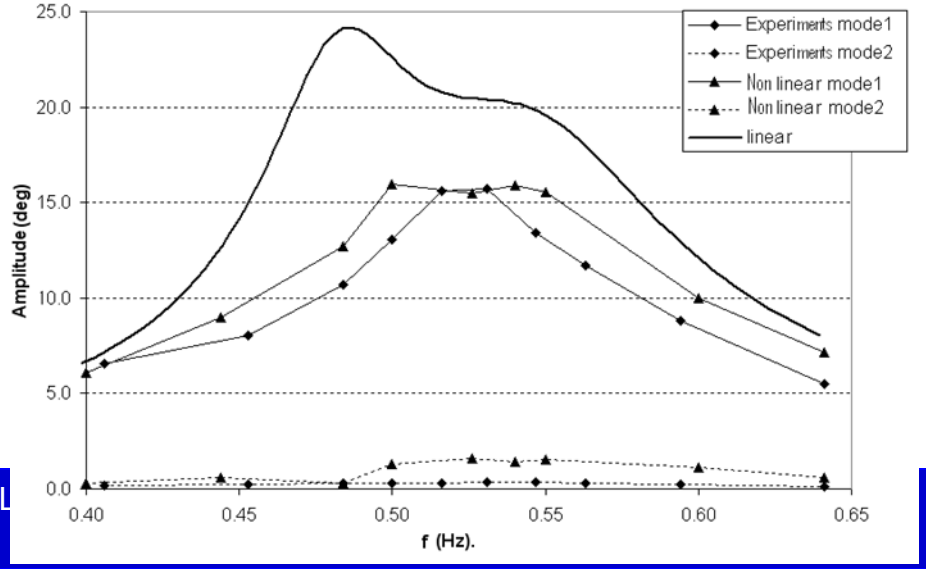
J.C. GILLOTEAUX, A BABARIT, G. DUCROZET, M. DURAND, AH. CLÉMENT (2007) Non-linear potential model to predict large amplitude motions: application to the SEAREV wave energy converter. Proceedings OMAE2007 Conference. San Diego (USA).

LAMSWEC: Comparison numerical / experimental modeling

1/12 scale model of the SEAREV Wave Energy Converter in the LHEEA wave tank

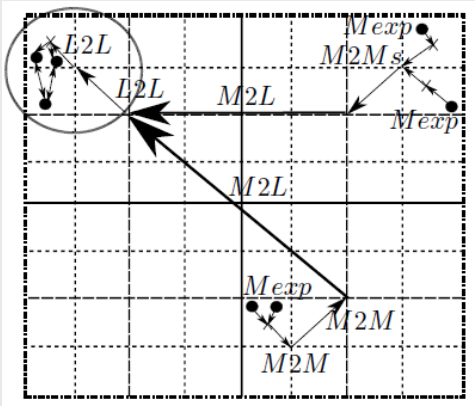


LAMSWEC was able to predict parametric roll instabilities



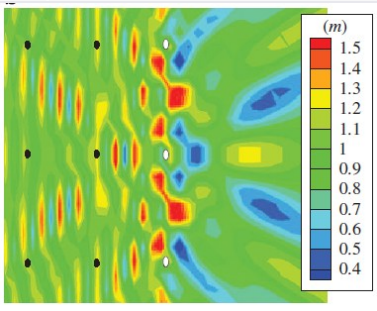
WEC modeling softwares: current developments

	time variable	fluid model	N-Body	hydro model	PTO model	Accura	CPU time	comment
AQUAPLUS + multipole	frequency domain	perfect fluid	> 20	Linear BEM (Kelvin CPM) + multipole	Linear damping	+	++	toward large arrays



$$\tilde{M}_n^m = \sum_{t=0}^{n} \sum_{s=-t}^{t} M_{n-t}^{m-s} \epsilon_{m-s} \epsilon_m \underbrace{\epsilon_s r_{x_M}^t \frac{P_t^{|s|}(cos\theta_{x_M})}{(t+|s|)!} e^{-\mathrm{i}s\alpha_{x_M}}}_{Coeff_{M2M_t^s}}$$

$$\tilde{L}_u^v = \sum_{t=v}^{\infty} \sum_{s=-t}^{t} \frac{\epsilon_u}{\epsilon_s} L_t^s \underbrace{\epsilon_{u-s}(-1)^{(t-v)+(u-s)} r_{x_L}^{t-v} \frac{P_{t-v}^{|u-s|}(cos\theta_{x_L})}{[(t-v)-|u-s|]!} e^{-\mathrm{i}(u-s)\alpha_{x_L}}}_{Coeff_{L2L_{t-v}^{u-s}}}$$

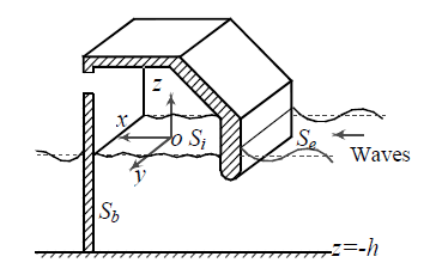


B. BORGARINO, A .BABARIT, P; FERRANT (2012) Impact of wave interaction effects on energy absorption in large arrays of wave energy converters Ocean Engng , Vol41.

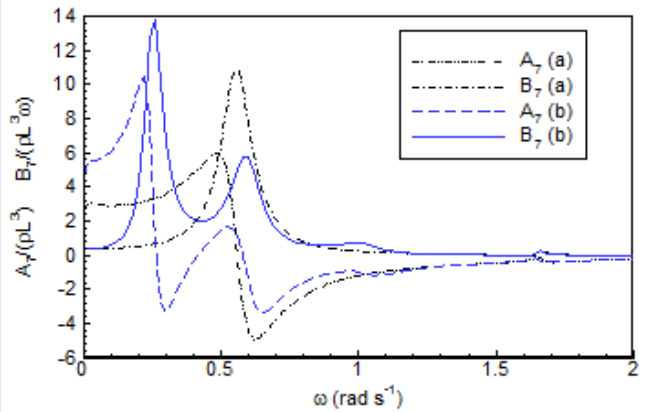
B. BORGARINO, A .BABARIT, P; FERRANT (2011) an implementation of the fast multipole algorithm for wave interaction problem on sparse arrays of floating bodies. J.Engng.Math.

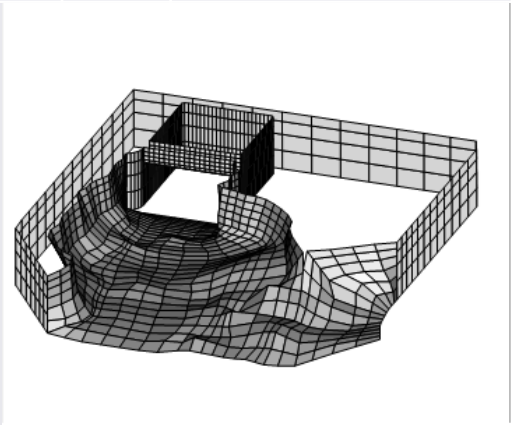
WEC modeling softwares: current developments

	time variable	fluid model	N-Body	hydro model	PTO model	Accura	CPU time	comment
AQUAPLUS + OWC	frequency domain	perfect fluid	> 20	Linear BEM (Kelvin CPM)	Linear damping	+	++	For coastal OWC



$$\frac{\partial \phi}{\partial z} - \frac{\omega^2}{g}\phi = \begin{cases} \dfrac{i\omega p}{\rho g} & \text{on } S_i \\ 0 & \text{on } S_e \end{cases}$$

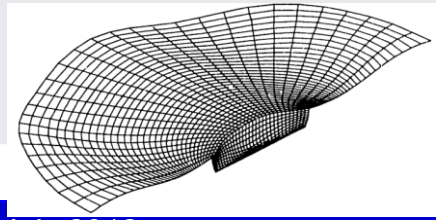




A. BRITO-MELO, T. HOFMANN, A.J.N.A SARMENTO, A.H. CLÉMENT, G. DELHOMMEAU (2001): Numerical Modelling of OWC-Shoreline Devices Including the Effects of Surrounding Coastline and Non-flat Bottom ; Int Journal of Offshore and Polar Engineering, Vol11, n°2, pp.147-154

LAMSWEC + weak scatterer	time domain	perfect fluid	1	RANSE (finite diff.) + SWENSE	nonlinear	++	+	SWENSE decomposition + HOS

- linearization around the exact position of the undisturbed free-surface flow
- discretization of body + free-surface around it.

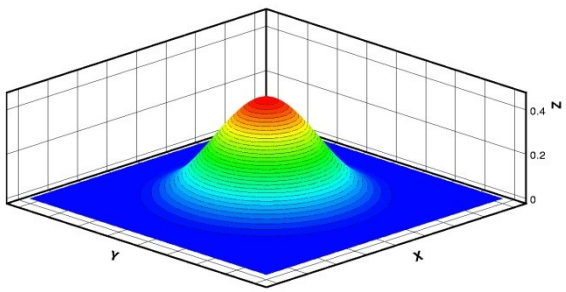


SPH methods (violent flows, wave breaking, etc..)

- Meshless methods ; variables represented by space convolutions integrals over a neighbouring of the current point

$$f(\vec{r}) \approx \int_D f(\vec{x}) W(\vec{r}-\vec{x}, h)\, \mathrm{d}\vec{x},$$

$$\vec{\nabla} f(\vec{r}) \approx \int_D f(\vec{x}) \vec{\nabla} W(\vec{r}-\vec{x})\, \mathrm{d}\vec{x},$$



- no linear system to solve
- implementable on parallel computers
- allow for numerical modelling of wave breaking
- adapted to overtopping WECs
- allow for hydroelasticity and multiphase simulations

Oger M., Doring M., Alessandrini B., Ferrant P. (2006) Two dimensional SPH simulations of wedge water entries. *J. Comp. Physics*. 213-2,pp.803-822

Thank you for your attention