Coupling DualSPHysics and Project Chrono: towards large scale HPC multiphysics simulations

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General motivation

Mechanical contacts and constrains are ubiquitous in natural and industrial processes, ranging from simple linear mechanisms to intricate highly non-linear problems.

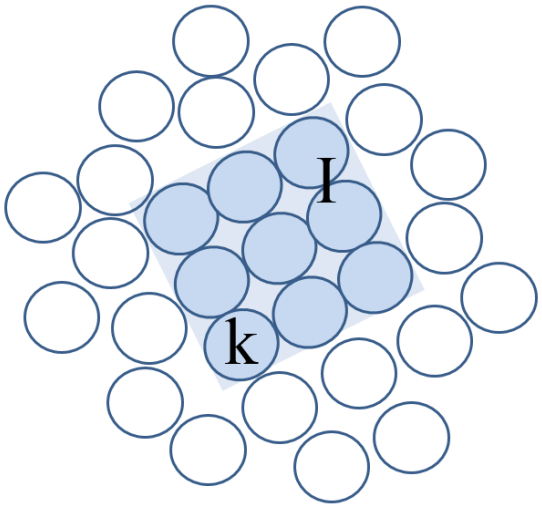
Unfinished business from our solid-solid work:

- Not unconditionally stable solids description (far from it);
- Difficult to model intricate mechanisms;
- Complex friction models hurt performance unacceptably for HPC code

General motivation - why this wasn't important until now

Rigid bodies in DualSPHysics

Conserving the **relative positions** of a group of particles, these can be made to describe a solid body.



$$M_I \frac{d\boldsymbol{V}_I}{dt} = \sum_{k \in I} m_k \frac{d\boldsymbol{v}_k}{dt}$$

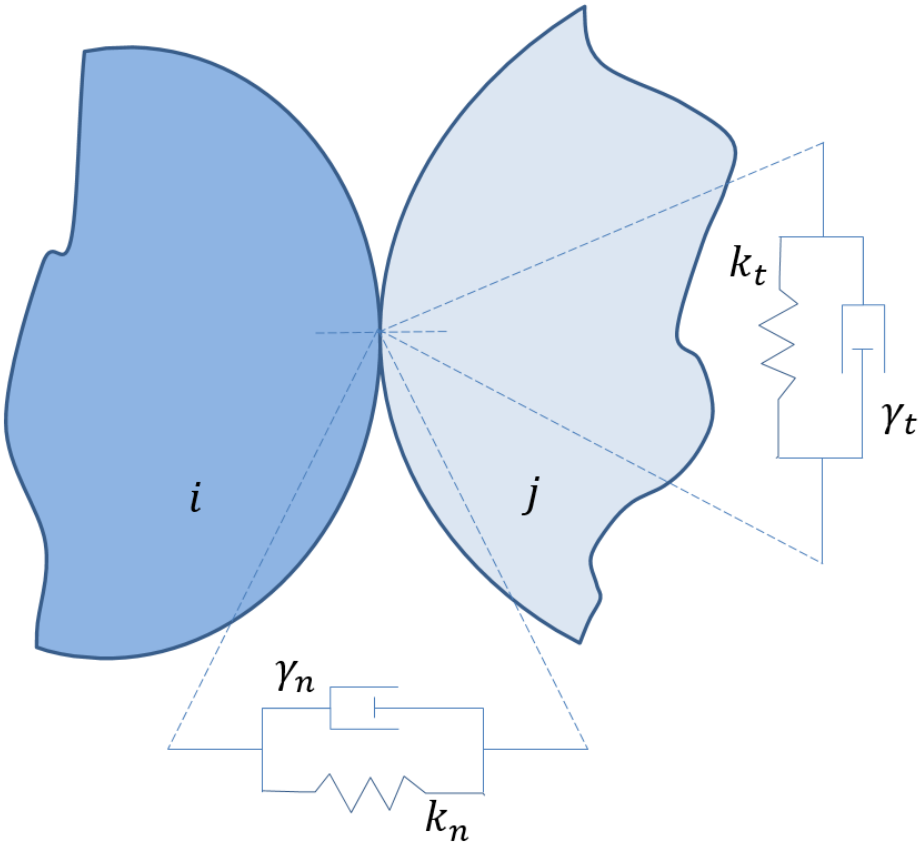
$$I_I \frac{d\boldsymbol{\Omega}_I}{dt} = \sum_{k \in I} m_k (\boldsymbol{r}_k - \boldsymbol{R}_I) \times \frac{d\boldsymbol{v}_k}{dt}$$

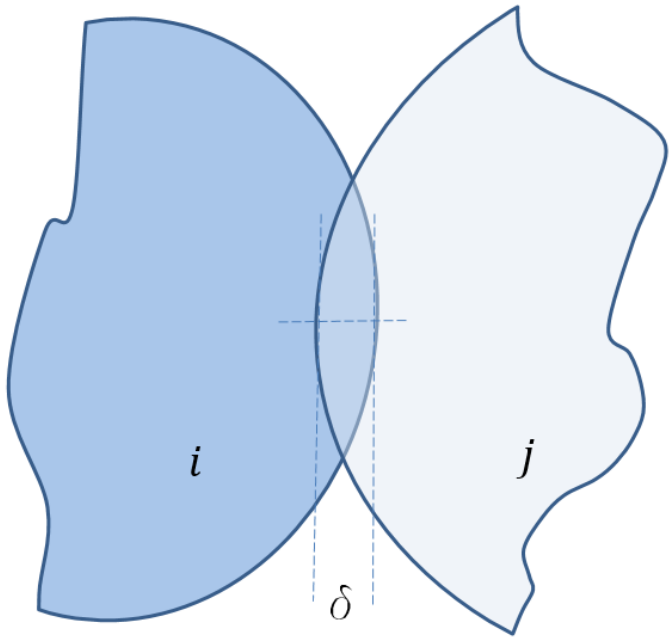
$$\boldsymbol{v}_k = \boldsymbol{V}_I + \boldsymbol{\Omega}_I \times (\boldsymbol{r}_k - \boldsymbol{R}_I)$$

The **inertia tensor** is computed for the fly for the system of material points, making no assumptions on shape, i.e. it **is exact for the discretized system**.

DEM - Soft body model

Approximate contacts with a **spring-dashpot model**:





Spring displacement is given by body overlap, δ, hence 'soft' body. This translates into a **penalty method**, solved with the same explicit schemes as the SPH equations.

DEM - Soft body model

Very useful, but laden with issues for generic contact modeling:

- Very stiff contacts induce very narrow stability regions;
- Full, long term frictional contacts are prohibitively expensive to model;
- Bodies made of a collection of spheres induce geometrical effects - locking, aliasing effects on relative motions...

An explicit penalty method is just too limited for our goals with DualSPHysics!

DVI - Hard body model

Approximate *everything* with a **Differential Variational Inequality**:

$$\dot{\mathbf{q}} = \mathbf{T}(\mathbf{q})\mathbf{v}$$

$$\mathbf{M}(\mathbf{q})\dot{\mathbf{v}} = \mathbf{f}(t,\mathbf{q},\mathbf{v}) - \mathbf{g}_{\mathbf{q}}^{\mathrm{T}}(\mathbf{q},t)\boldsymbol{\lambda} + \sum_{i=1}^{N_c}(\gamma_n^i \mathbf{D}_n^{T,i} + \gamma_u^i \mathbf{D}_u^{T,i} + \gamma_w^i \mathbf{D}_w^{T,i})$$

$$\mathbf{g}(\mathbf{q},t) = \mathbf{0}$$

$$0 \le \Phi^i(\mathbf{q},t) \quad \perp \quad \gamma_n^i \ge 0 \qquad i = 1,2,\ldots,N_c$$

$$(\gamma_u^i, \gamma_w^i) = \underset{\mu^i \gamma_n^i \ge \sqrt{(\gamma_u^i)^2 + (\gamma_w^i)^2}}{\arg\min} \; (\gamma_u^i \mathbf{v}^T \mathbf{D}_u^i + \gamma_w^i \mathbf{v}^T \mathbf{D}_w^i)$$

DVI - Hard body model

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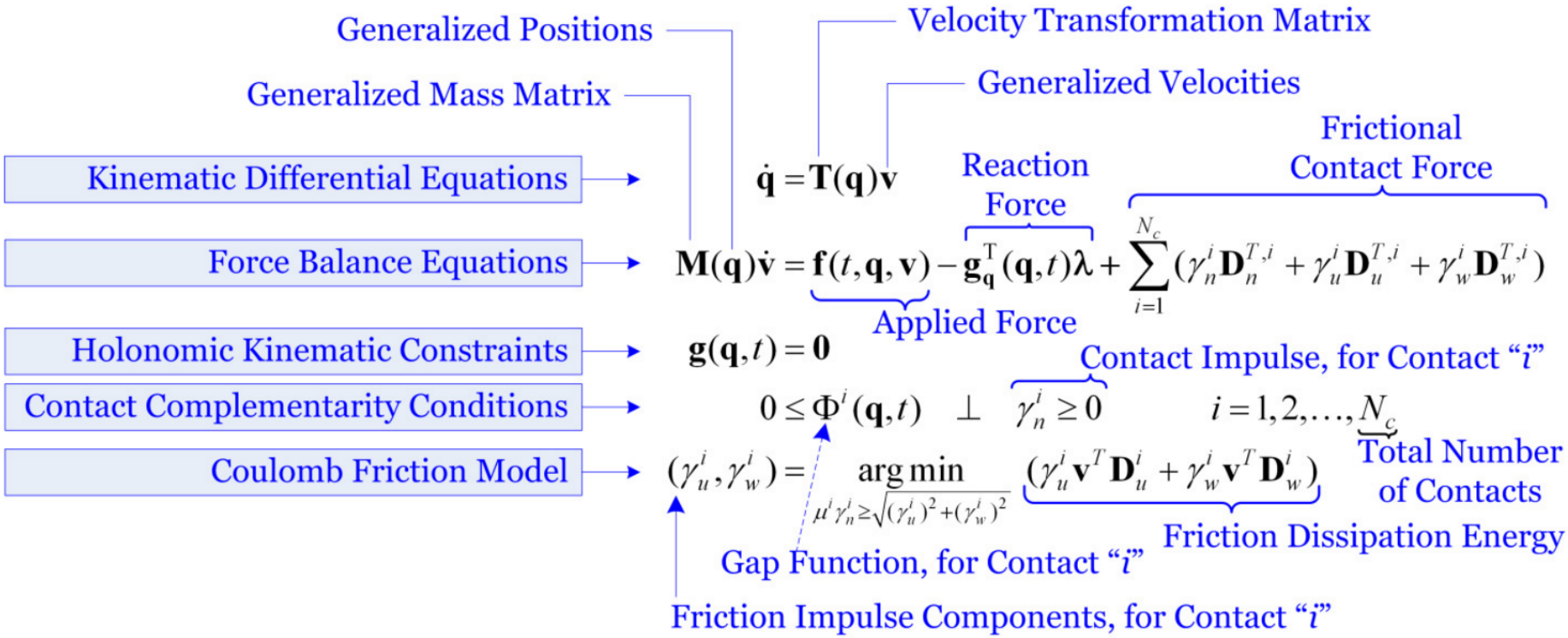


Chrono Project

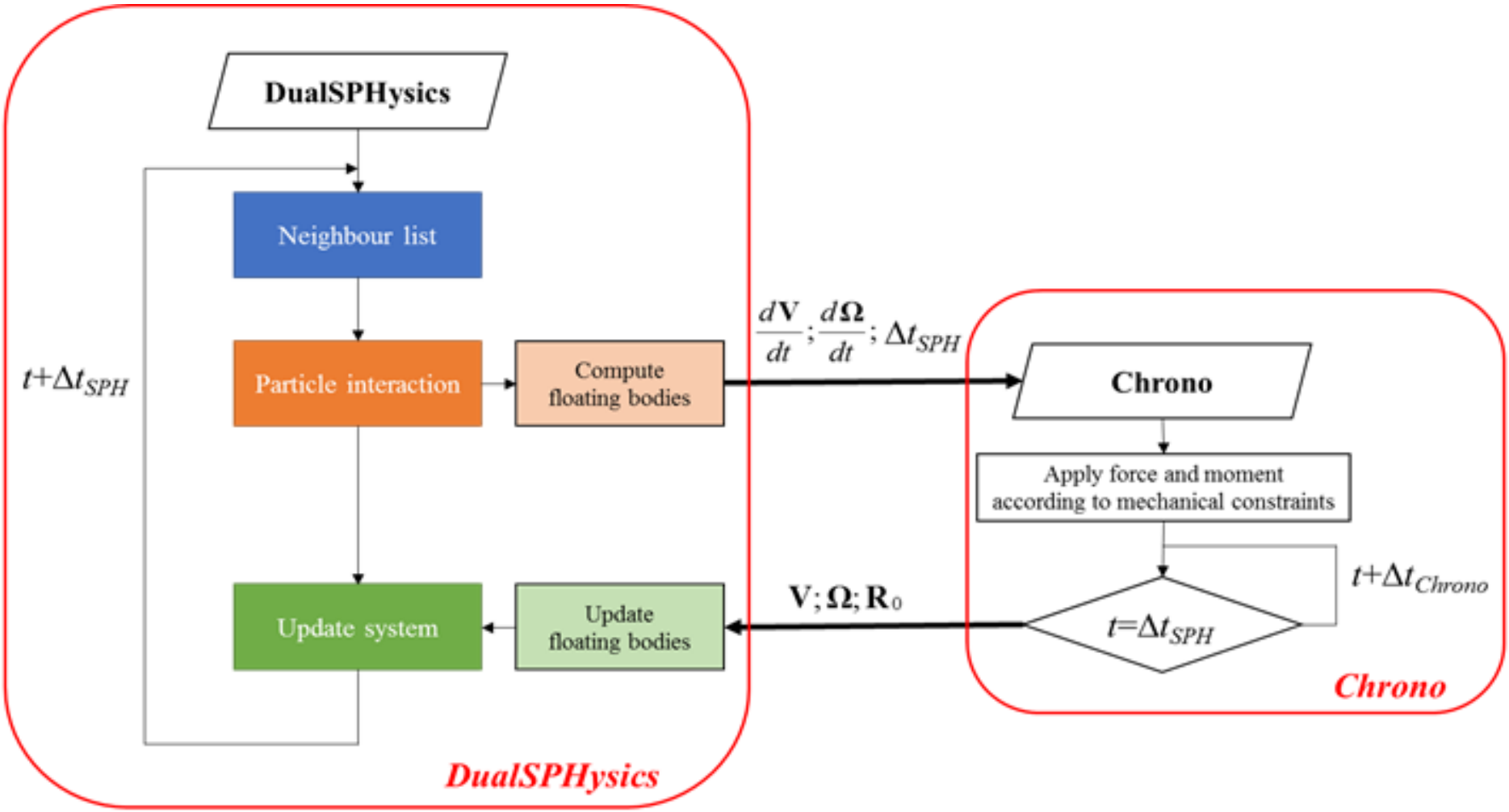
Project Chrono is a physics-based modeling and simulation infrastructure based on a platform-independent, open-source design - much like DualSPHsysics

- Wide set of joints (spherical, revolute joint, prismatic, universal joint, glyph, with limits, etc.);
- Unilateral constraints;
- Exact Coloumb friction model, for precise stick-slip of bodies;
- Springs and dampers, even with non-linear features;
- Recent support for linear and nonlinear Finite Element Analysis - Euler-Bernoulli beams, bars, shells, cables.

Implementation

- Problem is cast in CCP form and solved with a novel fixed point iteration method;
- GPU implementation allows for million+ bodies in Chrono-side to be simulated orders of magnitude faster than DEM;
- Geometries are represented by meshes;
- Mesh is overlaid over the particle distribution - done automatically by GenCase;
- For simple non-contact problems mesh is not required;

Project Chrono and DualSPHysics



Current advances and the future

- Generalized restrictions (revolute and spherical joints);
- Uses the same material parameters and structure as the DEM formulation;
- Simple pre-processing visual aids;
- Initials conditions are synchronous and compatible across both scenes.

- Maximum number of bodies superior to current 2048;
- Periodic conditions;
- Run-time contact and joint force reports;
- Deformable bodies support in DualSPHysics.

Frictional interactions

Plane at 20º, critical $\mu \approx 0.36$.

Restrictions and joints

Ever heard of a chaotic pendulum?

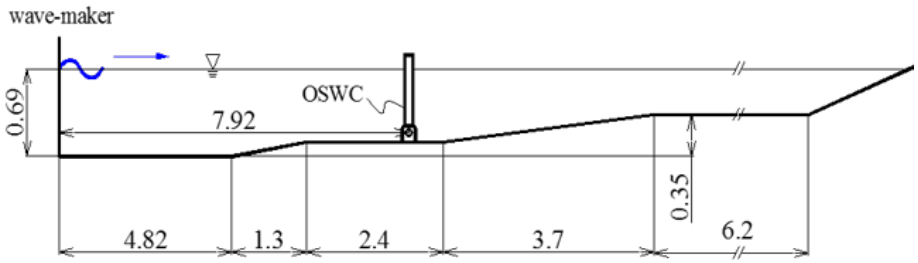
Formulation is robust.

Gluing everything, kind of a water mill

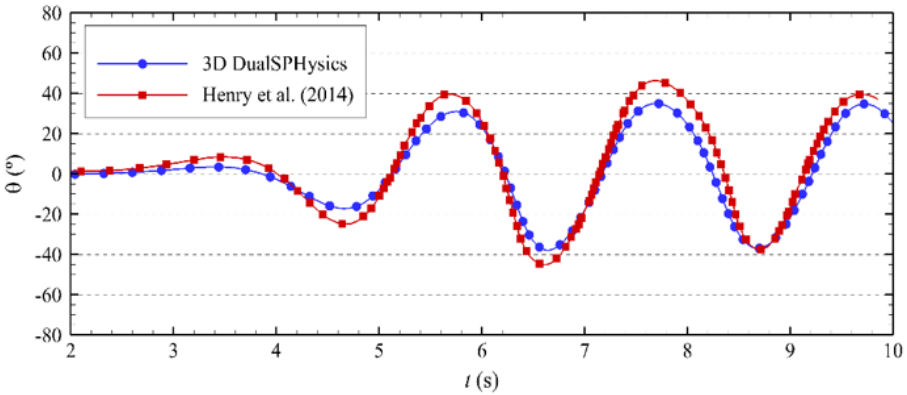
No imposed motions, periodic conditions on the fluid

Officially the worst mill designer ever, but the model makes up for it.

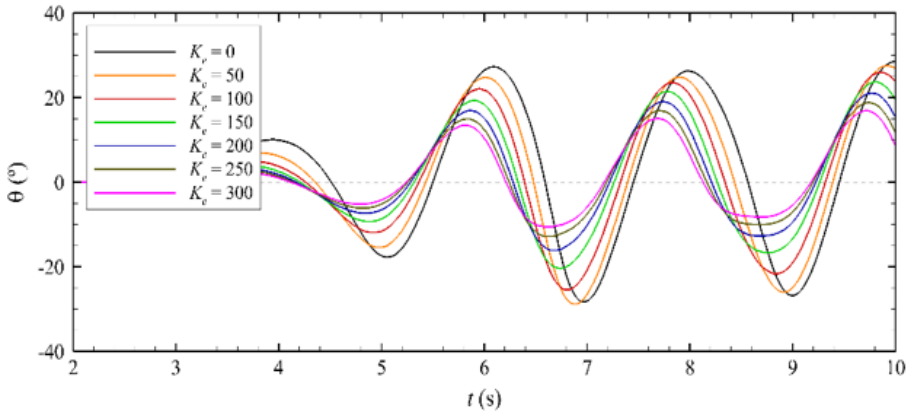
Application to Wave Energy Converters - Flaps

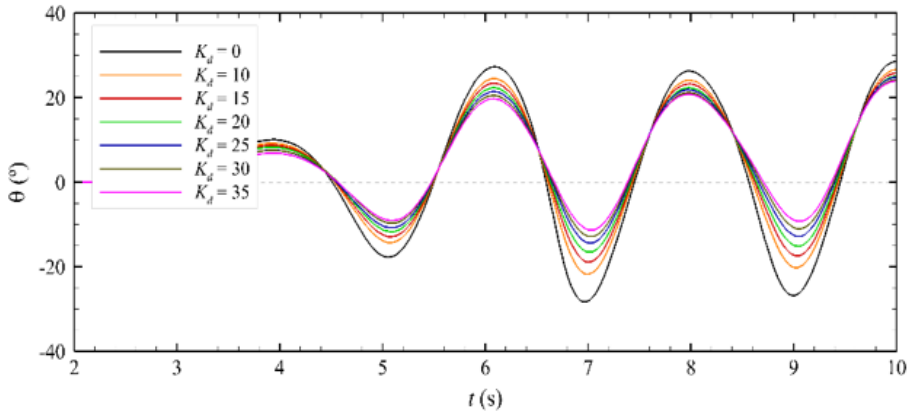


Experimental set up at the Marine Research Group's hydraulics laboratory at Queen's University Belfast.

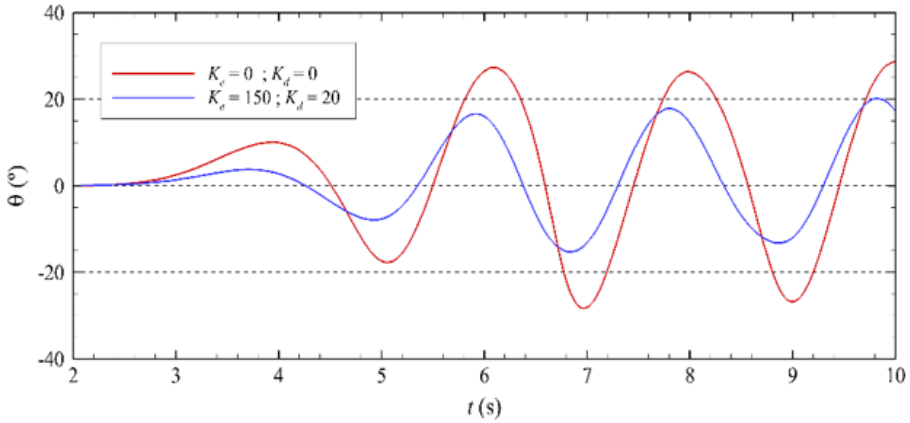


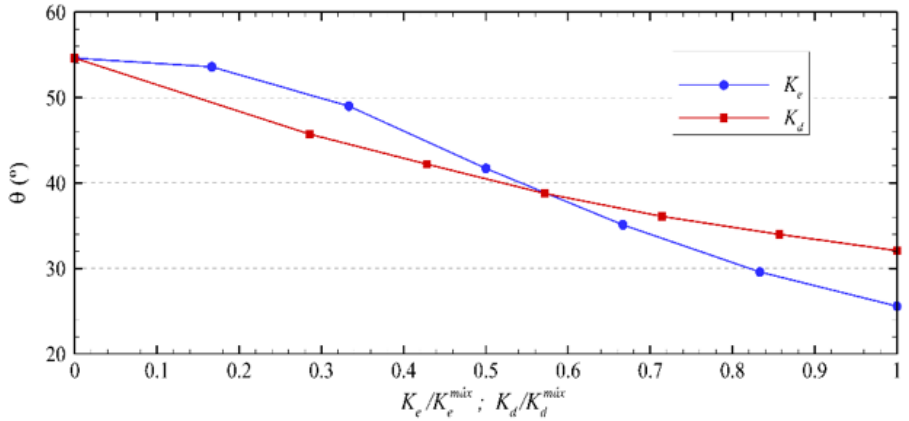
WECs - Flaps





Introducing different values of the elastic coefficient (K_e) and the damping coefficient (K_d), we can go beyond the current experiments.





WECs graveyard - Pelamis

6 linked bodies with free revolute joints.

WECs graveyard? - Wavestar

Revolute and spherical joints on the articulated arms and buoys.

Conclusions and future work

- A fully coupled and robust multi-physics oriented DualSPHysics version was presented;
- Simple set-up of large numbers of mechanical constraints;
- Complex mechanisms such as most WECs, control structures and multi-body floating structures can now be efficiently modeled and pre-designed;

- Implement deformable particle cluster for FEM use;
- Test GPU concurrent runs for large scale granular dynamics studies;