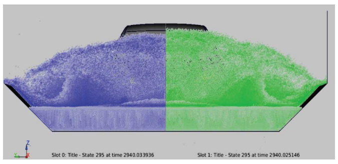
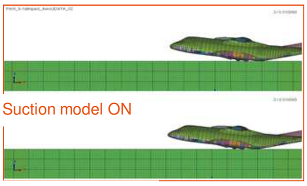
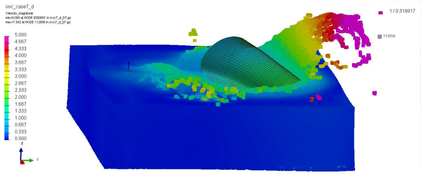


Industrial simulation of fluid flow and fluid-structure interaction with SPH from the VPS software

ESI-Group Netherlands
Paul Groenenboom



Suction model OFF



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Introduction

ESI-Group is a world-leading engineering software company

VIRTUAL PRODUCT ENGINEERING

Recent applications involving SPH have been requested for or conducted for:

- Maritime field
- Automotive sector
- Power generation
- Aeronautics
- Other

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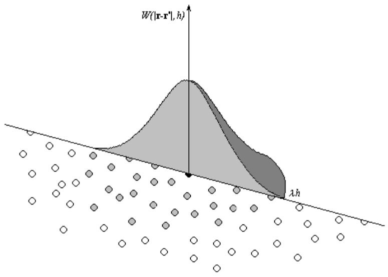
2

Particle Method SPH

- Smoothed Particle Hydrodynamics
- Meshless method for continuum mechanics
- Origins in modelling of cosmic physics
- Significantly enhanced for fluid-flow
- Handles free-surface and other interfaces
- SPH is available for fluid flow and structural dynamics.



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SPH basic boncept

✓ **Kernel approximation**

$$f(x) = \int f(x')W(x-x',h)dx'$$

$$\nabla f(x) = \int f(x')\nabla W(x-x',h)dx'$$

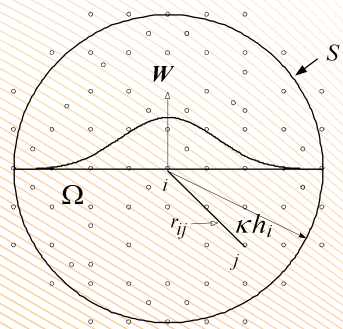
h – Smoothing length

W – Smoothing function

✓ **Particle approximation**

$$f_i = \sum_{j=1}^{N} \left(\frac{m_j}{\rho_j}\right) f_j W(x_i - x_j, h)$$

$$\nabla f_i = \sum_{j=1}^{N} \left(\frac{m_j}{\rho_j}\right) f_j \nabla_i W(x_i - x_j, h)$$



Properties smoothing function

- ✓ **Normalization:**

$$\int W(\boldsymbol{x} - \boldsymbol{x}', h) d\boldsymbol{x}' = 1$$

- ✓ **Compactly supported**

$$W(\boldsymbol{x} - \boldsymbol{x}') = 0 \quad |\boldsymbol{x} - \boldsymbol{x}'| > \kappa h$$

- ✓ **Delta function property**

$$\lim_{h \to 0} W(\boldsymbol{x} - \boldsymbol{x}', h) = \delta(\boldsymbol{x} - \boldsymbol{x}')$$

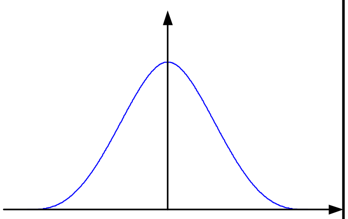


Illustration of a smoothing function

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Fluid Flow Equations

- Conservation of Mass

$$\frac{\mathrm{d}\rho_i}{\mathrm{d}t} = \sum_j m_j (\mathbf{v}_i - \mathbf{v}_j) \cdot \nabla_i W_{ij}$$

- Conservation of Momentum

$$\frac{\mathrm{d}\mathbf{v}_i}{\mathrm{d}t} = -\sum_j m_j \left(\frac{p_j}{\rho_j^2} + \frac{p_i}{\rho_i^2} \right) \nabla_i W_{ij}$$

- Conservation of Energy

$$\frac{\mathrm{d}u_i}{\mathrm{d}t} = \frac{1}{2} \sum_j m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} \right) (\mathbf{v}_i - \mathbf{v}_j) \nabla_i W_{ij}$$

- Equation of State

$$p_i = {}^0p_i + K \left[\left(\frac{\rho_i}{{}^0\rho_i} \right)^\gamma - 1 \right]$$

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Momentum Equations

Momentum formalism

- the expressions including the pressure to be used in the momentum and energy equations are not unique. The default is:

$$\frac{P_i}{\rho_i^2} + \frac{P_j}{\rho_j^2}$$

The alternative is:

$$\frac{P_i + P_j}{\rho_i \cdot \rho_j}$$

It is better to select this alternative for simulations involving materials with widely different densities but similar pressures i.e. water and air.

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Treatment of Shocks

Dissipation term:

$$\frac{d\mathbf{v}_i}{dt} = -\sum_j m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} + \Pi_{ij}\right) \nabla_i W_{ij}$$

$$\frac{du_i}{dt} = \frac{1}{2}\sum_j m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} + \Pi_{ij}\right) (\mathbf{v}_i - \mathbf{v}_j) \cdot \nabla_i W_{ij}$$

Artificial Viscosity:

$$\Pi_{ij} = \frac{2}{\rho_i + \rho_j}\left(-\alpha \frac{c_i + c_j}{2}\mu_{ij} + \beta \mu_{ij}^2\right)$$

$$\mu_{ij} = \begin{cases} \frac{1}{2}(h_i + h_j)\frac{(\mathbf{v}_i - \mathbf{v}_j)\cdot(\mathbf{r}_i - \mathbf{r}_j)}{|\mathbf{r}_i - \mathbf{r}_j|^2 + \eta^2} & (\mathbf{v}_i - \mathbf{v}_j)\cdot(\mathbf{r}_i - \mathbf{r}_j) < 0 \\ 0 & (\mathbf{v}_i - \mathbf{v}_j)\cdot(\mathbf{r}_i - \mathbf{r}_j) \geq 0 \end{cases}$$

Artificial viscosity:

- Required to make stable simulation involving pressure waves. For shock type of phenomena, parameter values of **1 to 1.5** are recommended. **For (relatively slow) fluid flow simulations, the first parameter may be orders of magnitude smaller.**

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Material with strength (SPH)

- ✓ **Constitutive modeling (Jaumann rate)**

$$\dot{\tau}^{\alpha\beta} - \tau^{\alpha\gamma}R^{\beta\gamma} - \tau^{\gamma\beta}R^{\alpha\gamma} = G\bar{\varepsilon}^{\alpha\beta}$$

- ✓ **Strain rate and Rotation rate**

$$\varepsilon^{\alpha\beta} = \frac{1}{2}\left(\frac{\partial v^{\alpha}}{\partial x^{\beta}} + \frac{\partial v^{\beta}}{\partial x^{\alpha}}\right)$$

$$R^{\alpha\beta} = \frac{1}{2}\left(\frac{\partial v^{\alpha}}{\partial x^{\beta}} - \frac{\partial v^{\beta}}{\partial x^{\alpha}}\right)$$

- ✓ **von Mises flow stress and von Mises rule**

$$J = \sqrt{\tau^{\alpha\beta}\tau^{\alpha\beta}}$$

$$\tau^{\alpha\beta} = \tau^{\alpha\beta}\sqrt{J_0/3J^2}$$

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SPH – Selected features

- The SPH method is fully integrated in the finite element code VPS (explicit version: PAM-CRASH).
- Standard Monaghan formulation incl. deviatoric strength
- Multi-material in SPH
- Pressure correction (similar to delta-SPH)
- Displacement corrections
- Variable smoothing length.
- Symmetry planes & periodic boundaries
- Special filling option (EWVT)
- Material models: JWL(detonation), Hydrodynamic-EP, Johnson-Cook, Murnaghan (Tait) EOS, elastic-plastic with damage, viscous fluids
- Coupling to VPS FE through contact algorithms.

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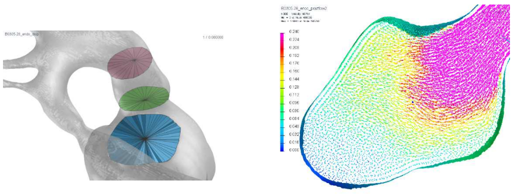
European Projects

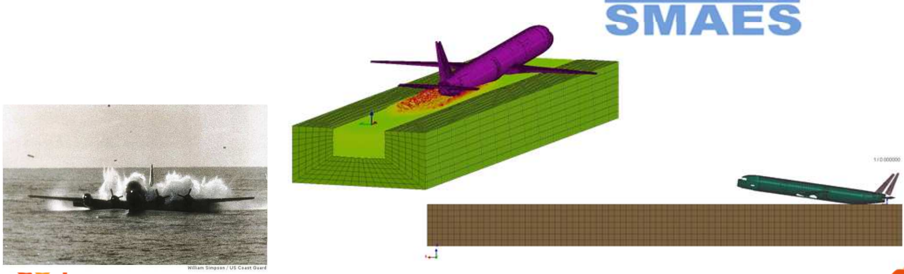
CARDIOPROOF



Anatomical model of the left ventricle and aorta of a patient and velocity vectors of the blood in a partial section (slice) of an SPH simulation when the valve has opened

Smart **A**ircraft in **E**mergency **S**ituations

SMAES



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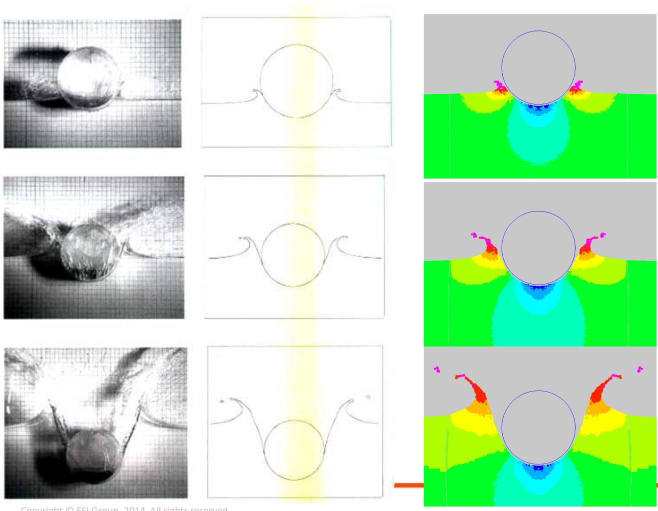
Test case: Cylinder at constant speed

Free-surface deformation from Fekken (left) and for the PAM-CRASH SPH/FE simulation with the contours of the velocity



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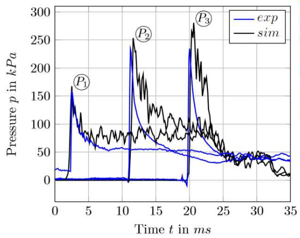
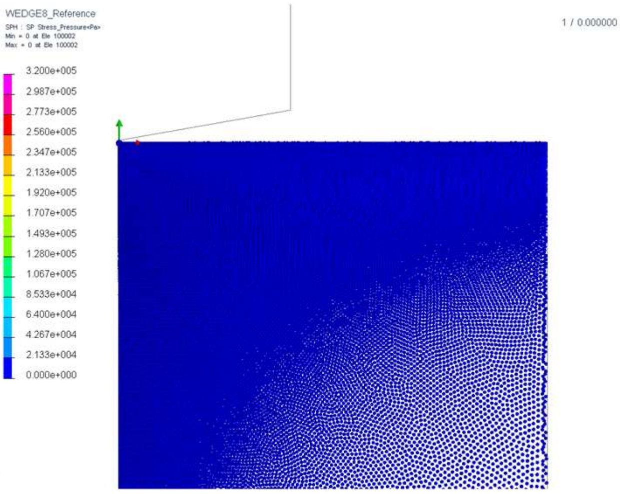
Test case: wedge impact on water

Rigid shell structure on SPH (2D)





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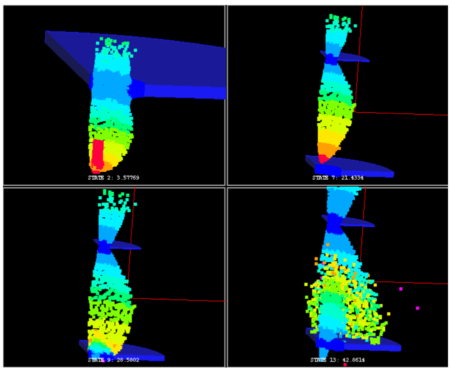
Aerospace applications

Assessment of Whipple shield for hyper-velocity impact

The **Whipple shield** hypervelocity impact shield is used to protect spacecraft from collisions with micrometeoroids and orbital debris whose velocities range between 3 and 18 kilometres per second (*Wikipedia*)



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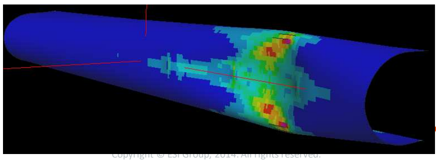
Aerospace applications

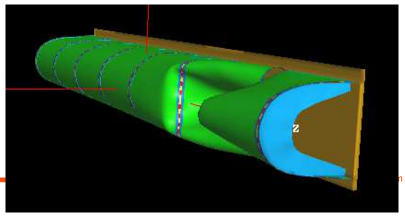
Crashworthiness of Aircraft for High Velocity Impact (CRAHVI)

AEROSPATIALE EADS 2001-2004

DLR NLR

FOD : foreign object damage
Birdstrike, Hail, Rubber
SPH validation for bird + water





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Maritime applications

Ship Studies – Interaction of Waves and Structures

Image from http://www.austal.com/

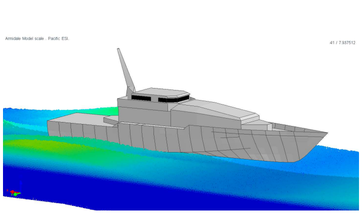

Image from simulation by Pacific ESI

Essential to the study of ship behaviours are waves, the ship structures, and their interaction. ESI Group has developed techniques within the VPS software suite to achieve this in a commercially robust package.

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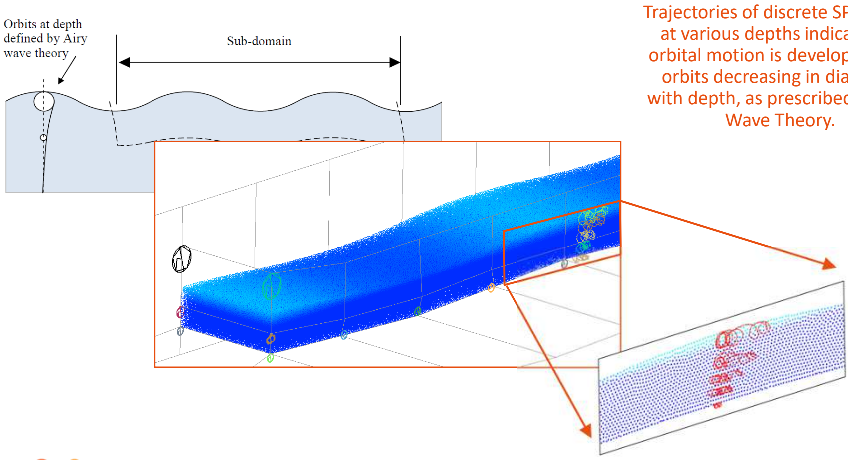
Maritime applications

Regular Wave Development - Moving Floor Pacific ESI has developed a novel technique to allow continuous waves to be developed, over many wavelengths.



Trajectories of discrete SPH nodes at various depths indicate the orbital motion is developed with orbits decreasing in diameter with depth, as prescribed by Airy Wave Theory.

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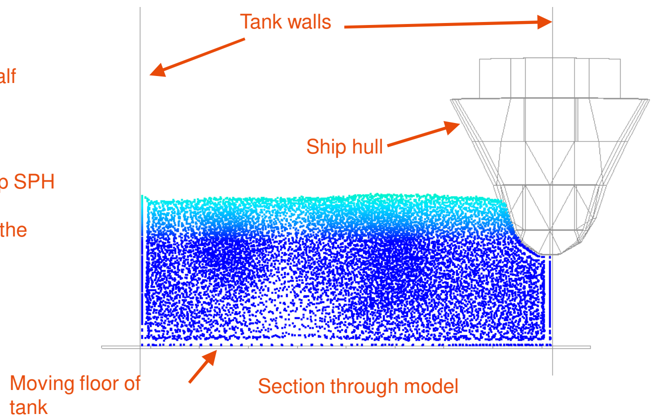
Maritime applications

FE-SPH : Fluid Structure Interaction

The image at right shows a section through the ship (half model) and the tank.

Industrially robust “Contact Interfaces” are used to keep SPH from passing through shell elements – of the ship and the “tanks”.



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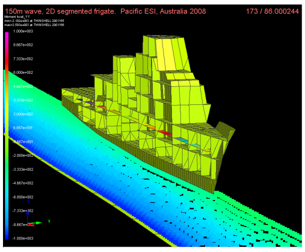
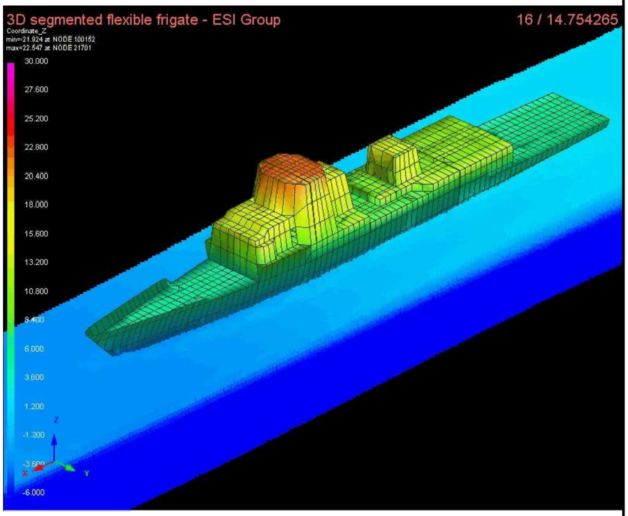
Fluid dynamics - maritime

Generic Frigate Model

Vertical/bending moment/velocity for flexible model





animation will be at the end of the presentation

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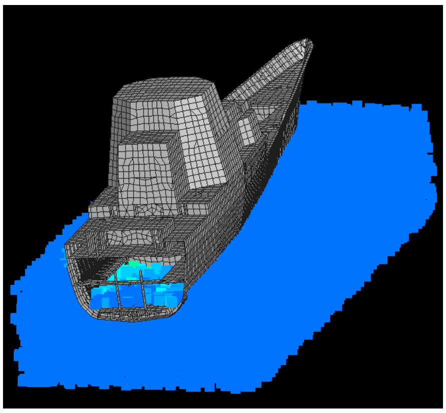
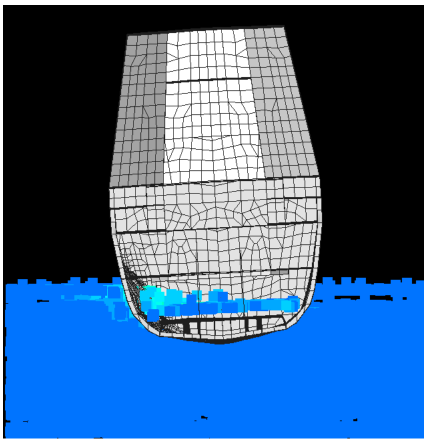
Fluid dynamics - maritime

FLOODING





Section through the vessel as the flooding proceeds

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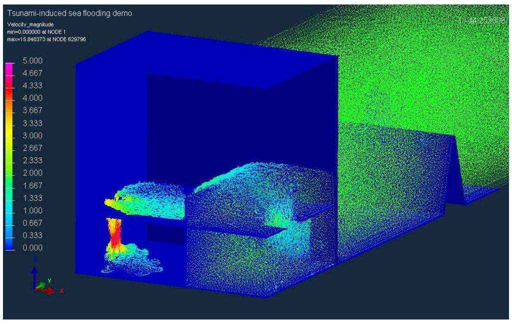
Fluid dynamics - maritime

Tsunami



Animation of Tsunami-like wave entering a building
will be a the end of the presentation

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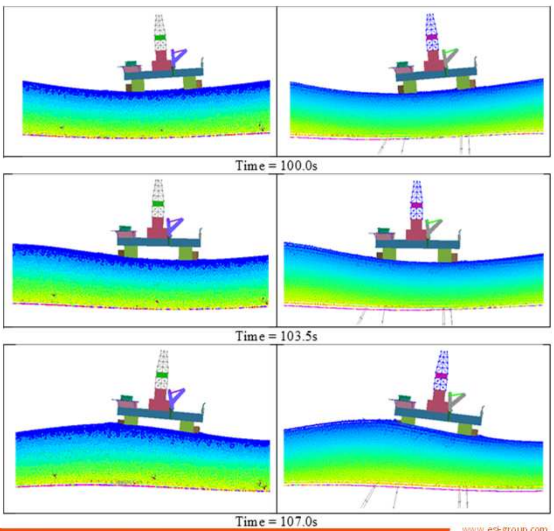
Offshore applications

Dynamic Response of Platform in Waves

The platform is tethered with flexible cables; the cranes are also deformable.



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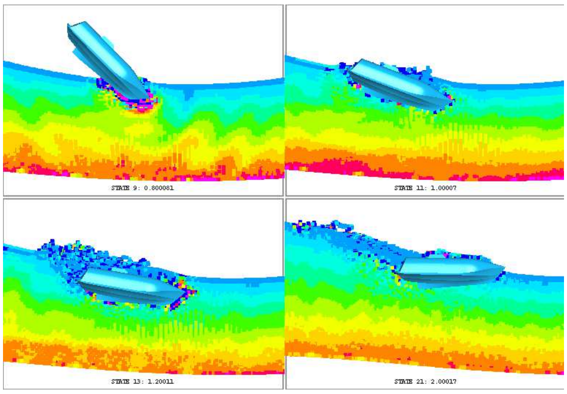
Offshore applications

Life Boat Water Entry

- A 'blind' benchmark study was of the impact of a life boat on water, conducted for LB water entry into waves



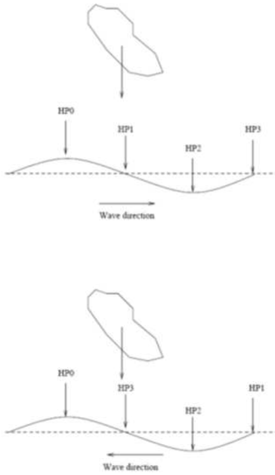


Figure 1.1: Hip point definition.

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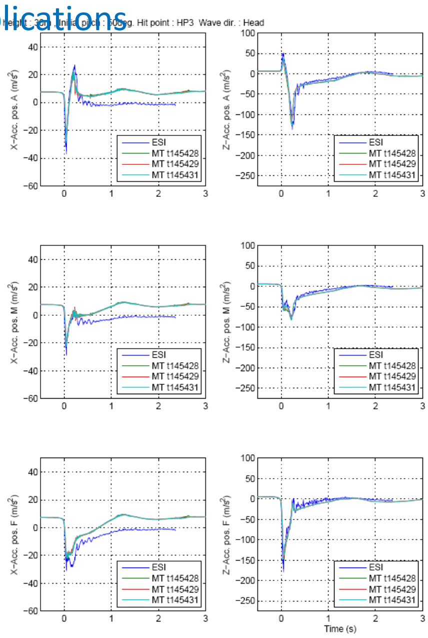
Offshore applications

Life Boat Water Entry

- The (x- and z-) accelerations from the PAM-CRASH simulations at 3 different locations at the hull of the LB have been compared to the results from 3 scale tests.



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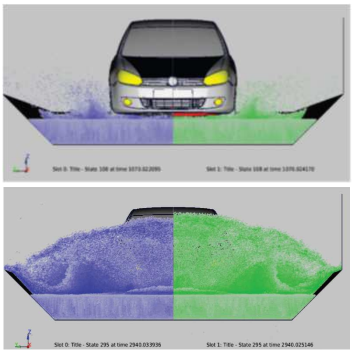
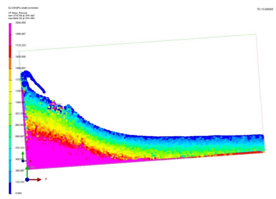
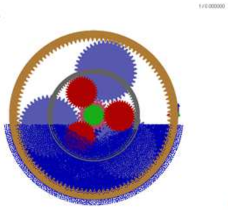
Automotive applications



Applications in which SPH comprise:

- Airbag inflation (not by SPH but by FPM)
- Water management
- Sloshing in fuel tanks
- Oil flow in bearings and oil churning
- dipping into the paint tank

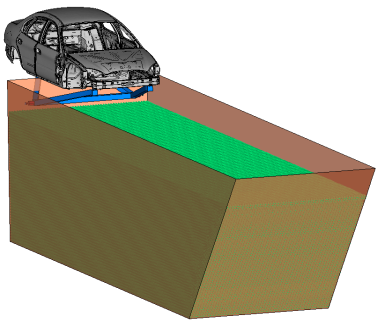




Automotive applications

Simulation of painting using the SPH elements.
Two ways of motion BIW in paint tank (Translation, Rotation).
Simulation of BIW kinematics in a paint tank.

- Maximal force and moment in drive engine and joints.
- Flow in BIW structure.



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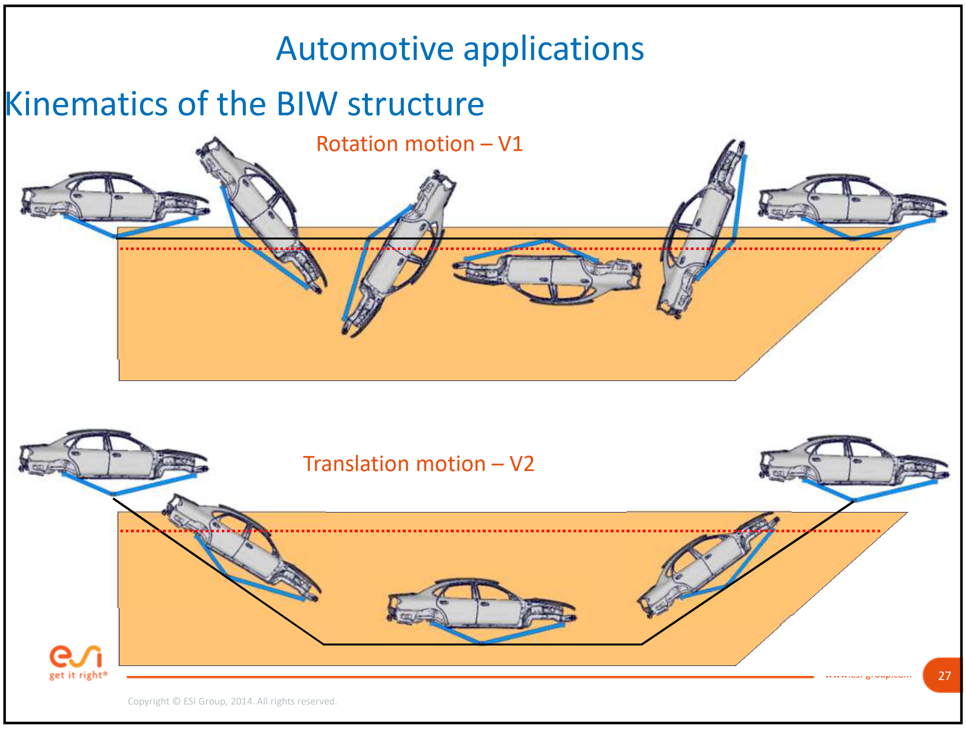
Automotive applications
Kinematics of the BIW structure
Rotation motion – V1
Translation motion – V2
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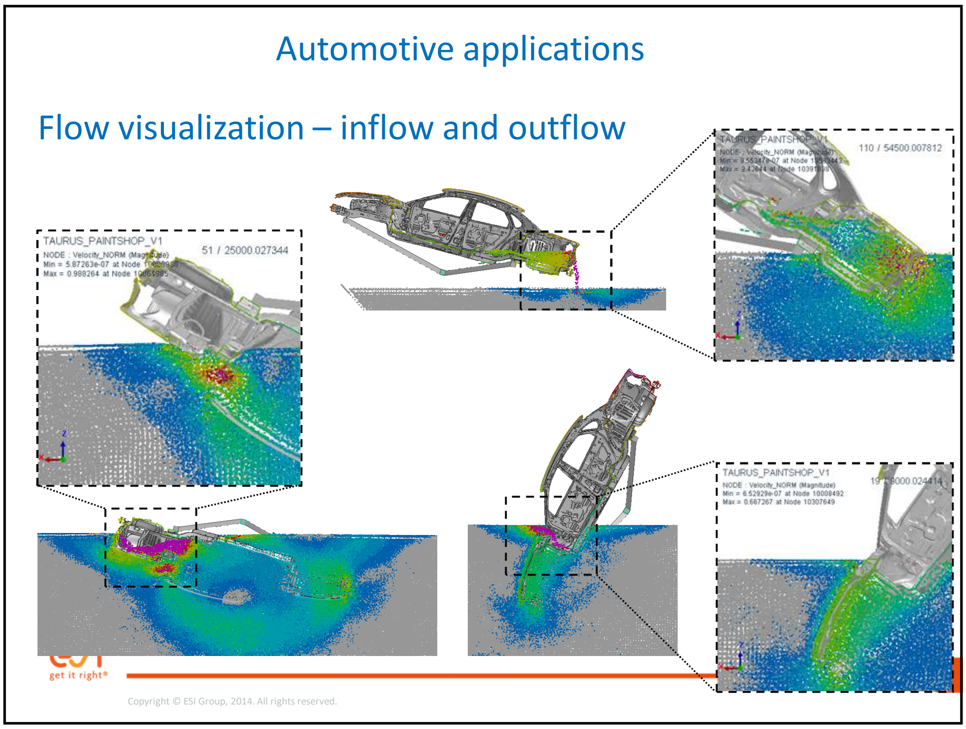
Automotive applications
Flow visualization – inflow and outflow
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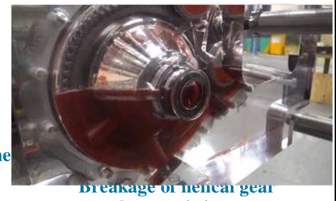
Rotating machinery

Lubrication in gear systems: Industrial need

- Gear systems are key mechanical components used to transmit power.
- Gear systems must be well lubı
  - Ensure minimal mechanica
  - Prevent the rupture of ırough accelerated wear.
  - Reduce heat production.
- Splash lubrication is a common lubrication method.
- Oil churning is considered as a major source of power loss in gear systems.
- **Industrial need:** Maintain structural integrity of the system with minimal oil volume .
- Problem: splash lubrication properties are hardly predictable.

Planetary gearbox used in wind turbine



Breakage of helical gear due to pitting

Splash lubrication

Wind energy sector

Aeronautical sector

Automotive industry

There is a need to get reliable insight on the oil churning pattern to drive an optimization process.

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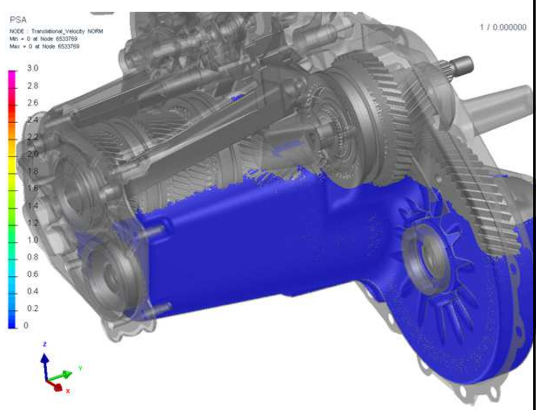
Rotating machinery

Lubrication in gear systems: industrial case: 5th gear ratio with 2000 rpm

Computing Time

Simulation conditions	Numerical value
Number of particles	500000
Particle diameter (mm)	1,6
Simulation time (s)	2
computing time (days)	15
Number of processors	12



Simulation result

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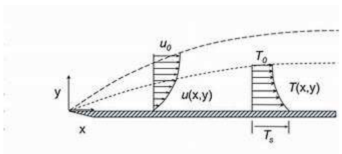
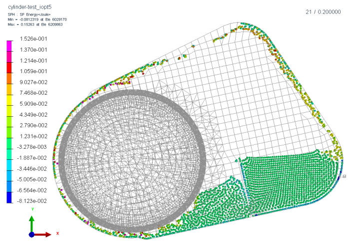
Rotating machinery

Lubrication in gear systems: Inclusion of heat transfer

Requirements for SPH software simuation tool:

1. WC-SPH including energy equation
2. Interaction with fast-moving structures
3. Viscosity model (Non-Newtonian, temperature dependent)
4. Heat conduction between particles
5. Heat transport with surface

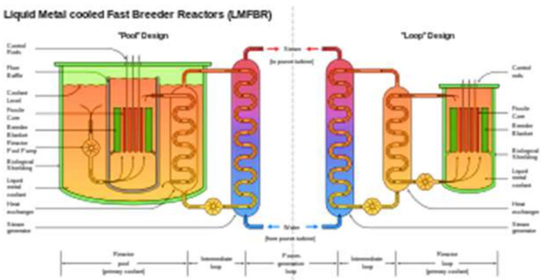


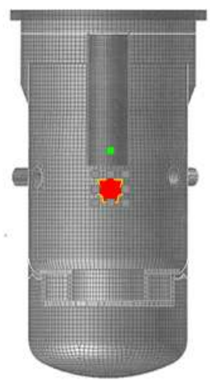


Particle distribution with the internal energy at 0.2 seconds

Nuclear Reactor Safety

Hypothetical Core Disruptive Accident in a fast breeder reactor

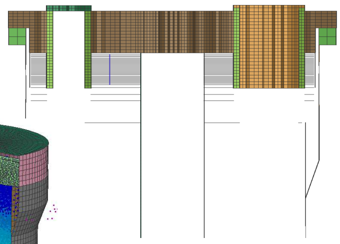


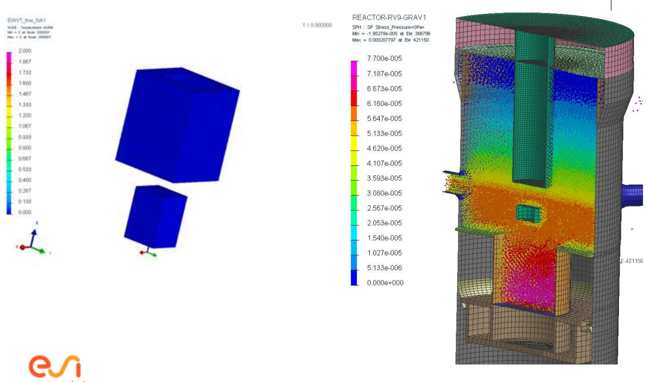


Nuclear Reactor Safety

Highly complex model: geometry, liquid sodium, argon gas, deformable structure, bubble dynamics, leakage

Generation of suitable distribution of (sodium) particles by the EWVT method.





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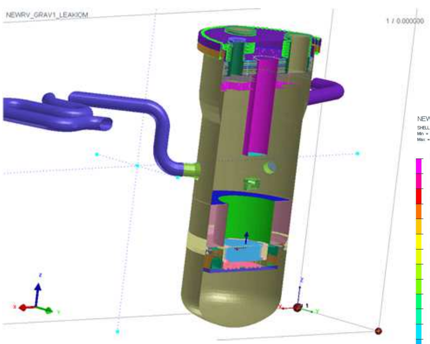
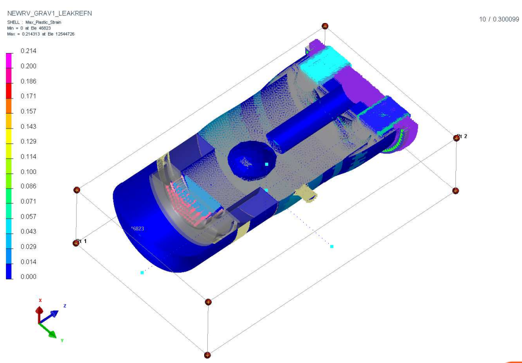
SPH-FE Analysis of Reactor Safety

Nuclear Reactor Safety

Hypothetical Core Disruptive Accident in a fast breeder reactor



Contour plot of the maximum equivalent plastic strain in the RV structure at the final time of 300 ms.



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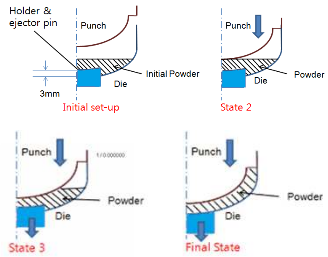
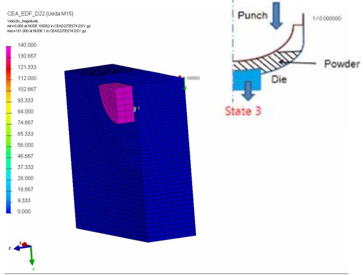
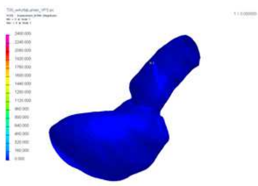
Miscellaneous applications

- Resin molding
- Powder compaction
- Impact on concrete & composites
- Cardiac flow







Industrial simulation of fluid flow and fluid-structure interaction with SPH from the VPS software

Thanks for your attention

paul.groenenboom@esi-group.com