A process to evaluate fuselage structural loads caused by sloshing in liquid hydrogen tanks

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DLRK 2024
DEUTSCHER LUFT- UND RAUMFAHRTKONGRESS
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Motivation: Aspects of LH2 tank integration

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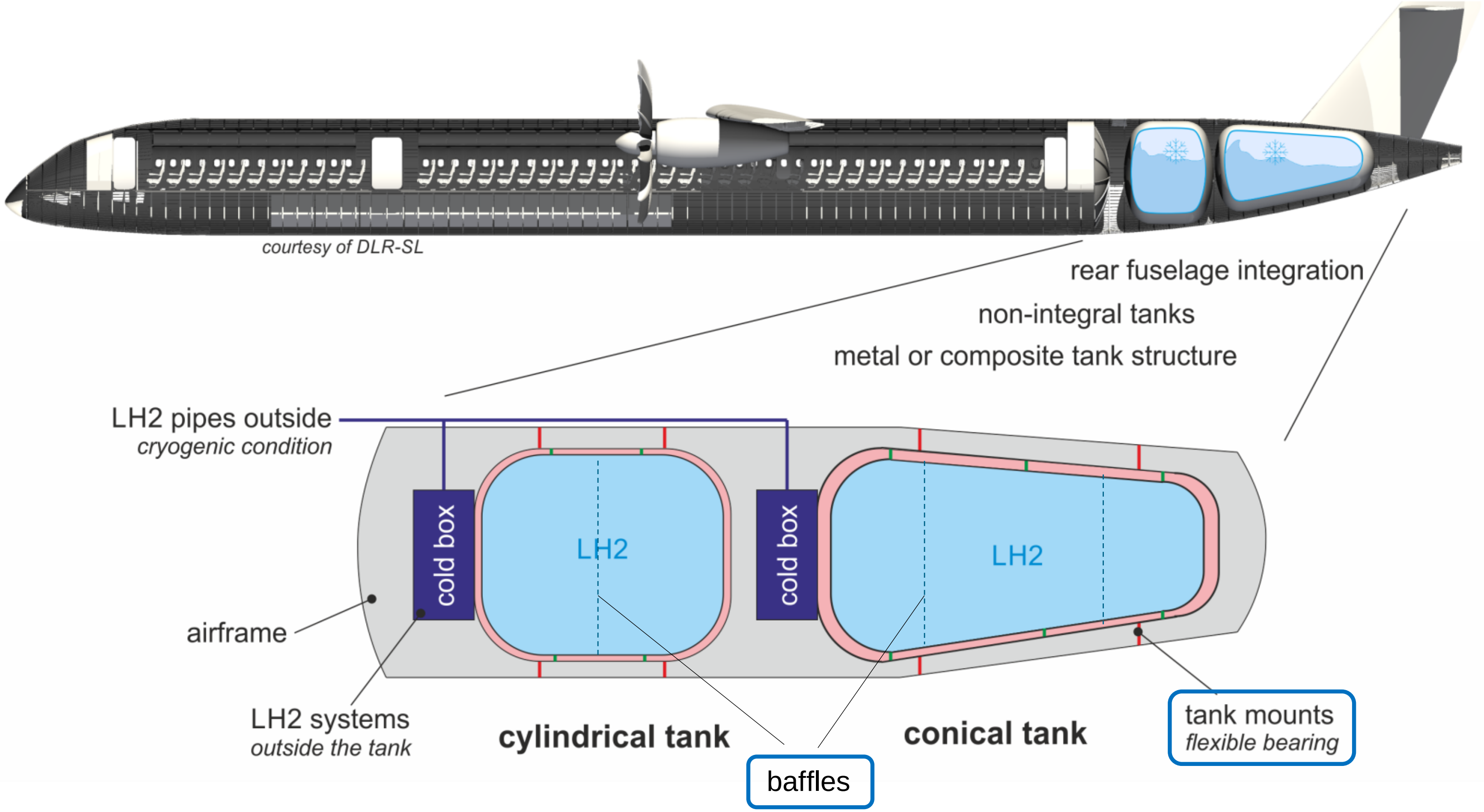
- LH2 can be an alternative to fossil fuels to achieve a climate-neutral aviation
- LH2 for aviation has to be stored at cryogenic temperature (~-250°C) at pressures of 2-4 bar
- One option are special tanks to be integrated in the fuselage
- LH2 tanks will consist of inner / outer tank with insulation

Challenges

- LH2 tanks shall not bear flight loads (isostatic support)
- LH2 tanks have to be save in emergency situations (e.g. crash landing)
- Sloshing of the LH2 may be a challenge for tank design and especially its attachments



Motivation: Process chain development

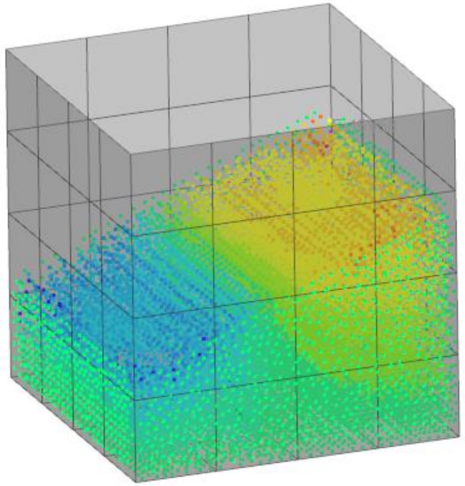
- Tank integration has to be investigated under different loading scenarios
  - Quasi-static flight loads
  - Dynamic loads (e.g. rejected take-off) ➔ more than 30 s
  - Transient dynamic loads ➔ less than 0.5 s
    (e.g. emergency Landing, survivable crash)
- Expected certification requirement
  - Aircraft with integrated LH2 tanks have to be as save as current fuel powered aircraft
- Modelling approach (LH2)
  - LH2 mass may be distributed over the tank hull (1st approach)
  - Despite the low density, loads may be significantly higher when sloshing is considered
  - Different design aspects may be investigated to reduce load transfer to primary structure
    (Tank design (e.g. baffles) and tank integration)

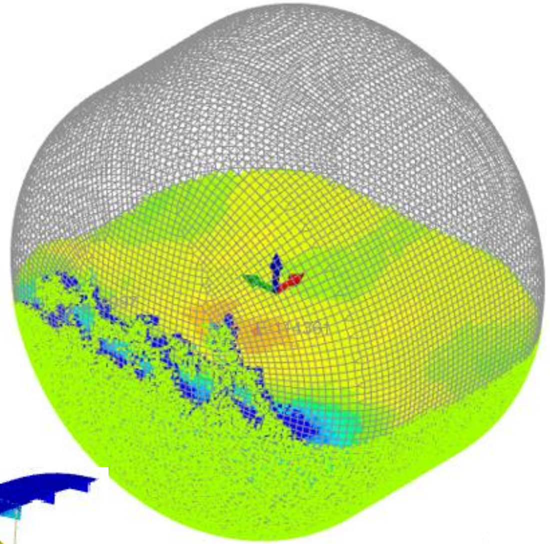
Turkish Airlines 1951, Amsterdam, 2009 [1]

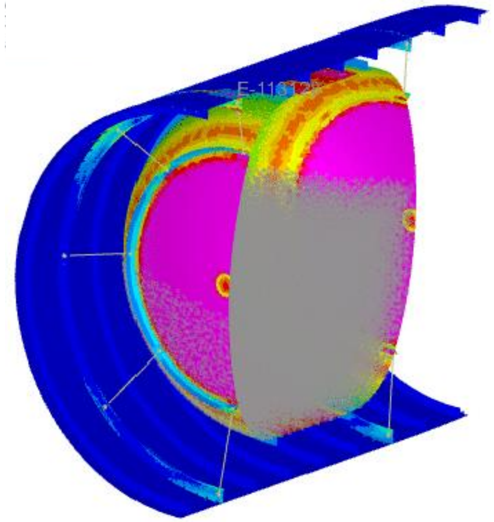
➔ Target: Development of a process chain to evaluate different tanks integration concepts

Overview

- Motivation ✓
- Numerical process development
  1. Evaluation of Fluid Structure Interaction (FSI) modelling methods (water)
  2. Validation of most suitable method (LH2)
  3. Automatic model generation (fuselage structure, tank structure, attachments, …)
  4. Initial integrated simulation (LH2, in progress)
- Summary / outlook
- Acknowledgements







1. Sloshing in tanks (comparison of FSI methods)
Available approaches for FSI modelling

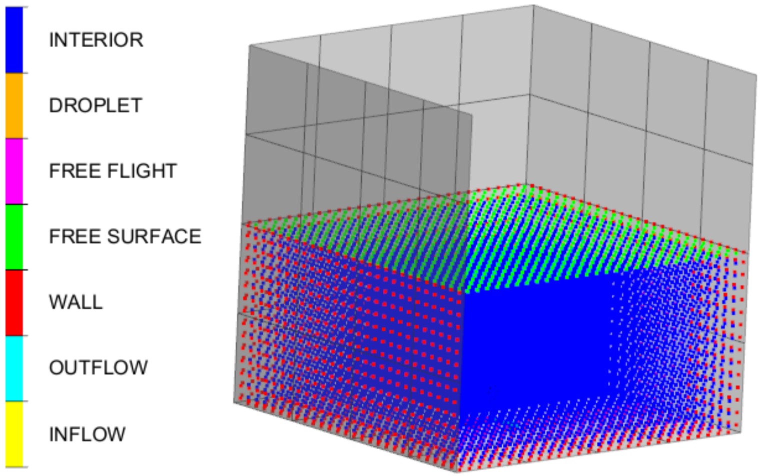
- Focus here on load transfer to the tank, not the flow physics ➔ focus on CSM codes!
- CSM codes with explicit time integration are commonly used for transient dynamic simulations (e.g. LS-DYNA, Abaqus Explicit, VPS (ex. Pamcrash), …)
- The following methods to calculate FSI are available

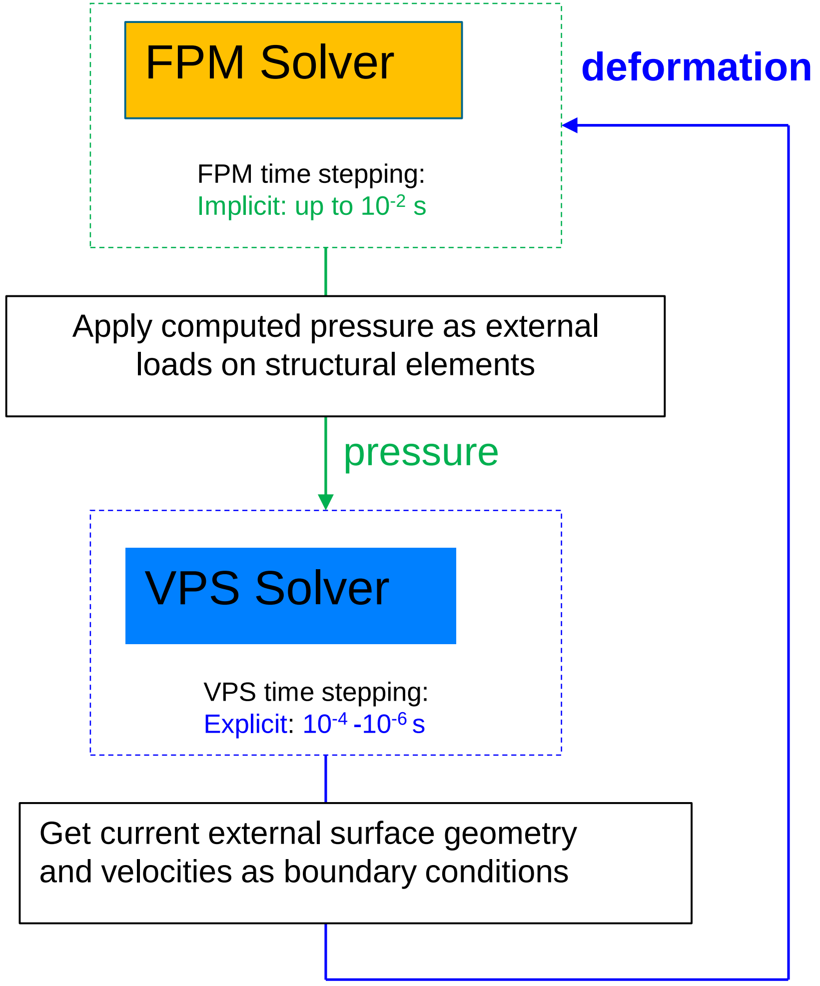
FSI method	Solver	Fluid mesh	Integr. schema	Typ. Timestep [s]	Remarks
HS (hydrod. Solid)	CSM	Lagrangian	Explicit	$10^{-7} – 10^{-5}$	Mesh distortion limiting
SPH (Smoothed Particle hydrodynamics)	CSM	Lagr. meshfree	Explicit	$10^{-7} – 10^{-5}$	Large experience on ditching at DLR
ALE (Arbitrary Lagrangian –Eulerian)	CSM	Eulerian	Explicit	$10^{-7} – 10^{-5}$	Very little experience at DLR
FPM (Finite Pointset Method)	CSM + NS solver	Lagrangian Lagr. meshfree	Explicit Implicit	$10^{-7} – 10^{-5}$ $10^{-4} – 10^{-2}$	2 way coupling of two solvers (promising)

➔ In first evaluation, only method available in VPS software [2] are considered

1. Sloshing in tanks (comparison of FSI methods)
Few word on FPM

- Fundamentals of FPM (Finite Pointset Methods)
  - Meshfree approach for fluid discretization (point cloud)
  - Solves the Navier-Stokes equations for incompressible fluid
  - Adaptive point clout refinement (Parameter: smoothing length)
  - Implicit time integration schema ➔ larger timesteps possible!
  - Easy model generation by definition of the free surface and the tank walls.

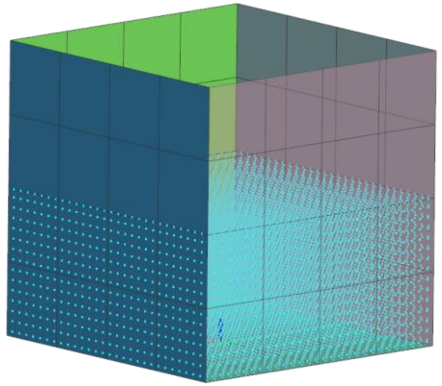




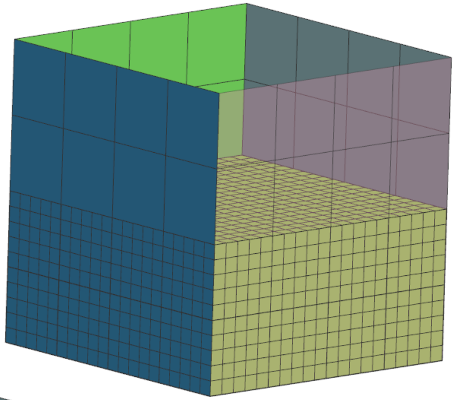
Schema of 2 way coupling VPS and FPM

1. Sloshing in tanks (comparison of FSI methods)
Basic comparison alternative FSI approaches

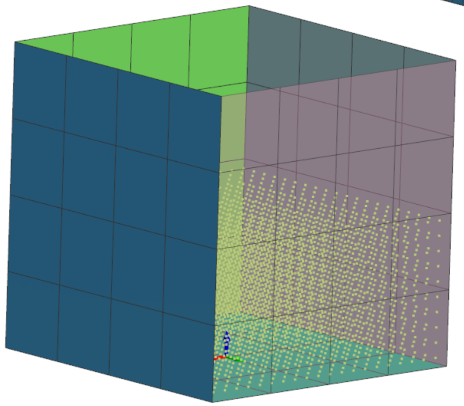
- Box (rigid) of 1 x 1 x 1 m in shells (coarse mesh)
- Fluid representation (water)
  - FPM (Finite Pointset Method):
    - Just free surface definition at z = 500 mm, Smoothing length 100
    - Predefined water properties in VPS (density, viscosity)
  - HS (Hydrodynamic solids):
    - Mesh of solid elements generated within tank (~50 mm edges)
    - Water properties : Polynomial EOS of Hydrodynamic solid (MAT7)
  - SPH (Smoothed Particle Hydrodynamics):
    - Positioned at COG of all hydrodynamic elements (identical number of elements)
    - Identical water properties (polynomial EOS, MAT7)



>14000 solids



4000 solids



4000 particles

1. Sloshing in tanks (comparison of FSI methods)
Basic loading conditions to stimulate sloshing

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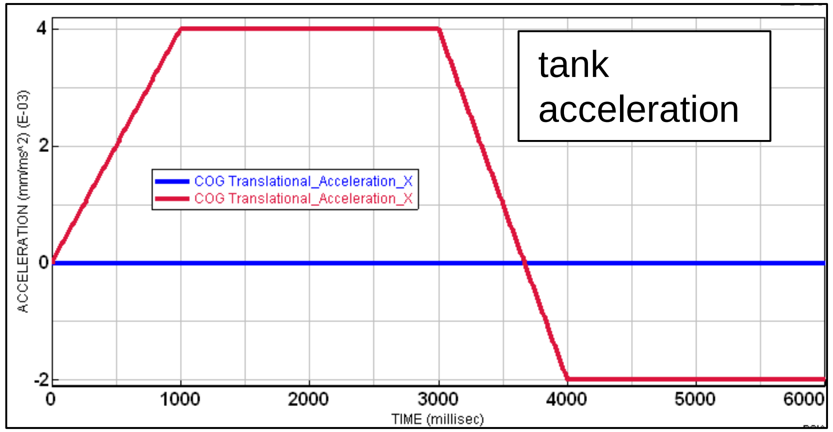
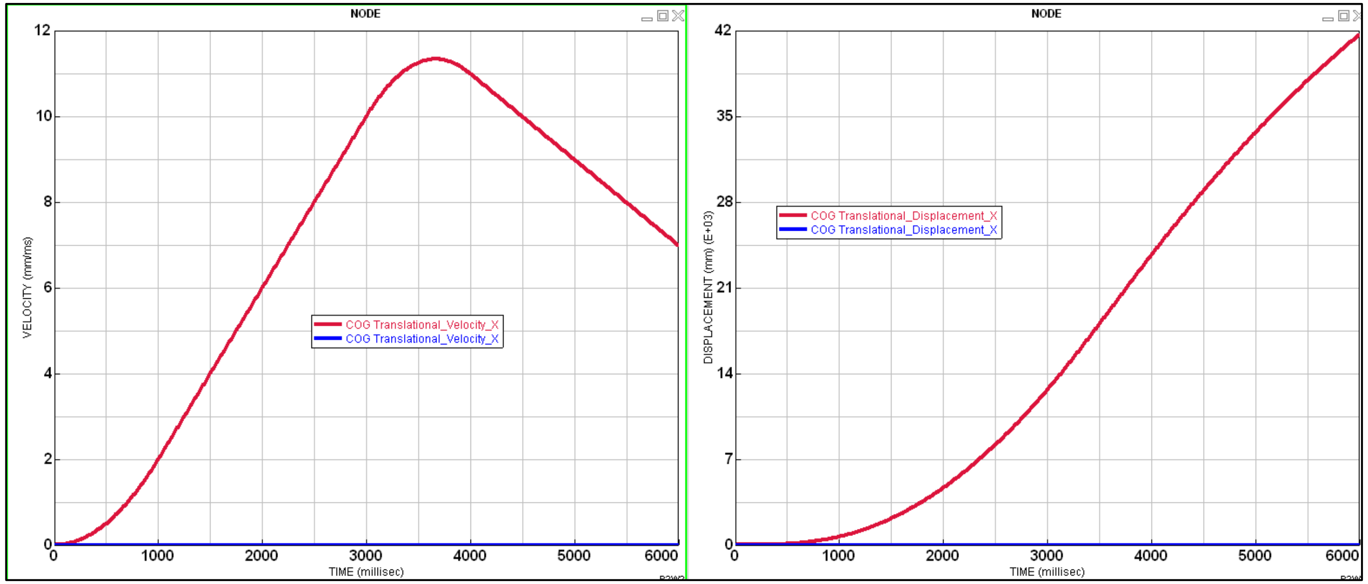
Two loading conditions considered with 3 FSI approaches ➔ total of six variations!

- Loading 1: similar to rejected take-off (tank moves)
  - Total time: 6 s
  - Acceleration +4 m/s² for 3 s (linear increase over first second)
  - Deceleration of -2 m/s² for 3 s (linear change over 1 second)
  - ➔ max. velocity: ~11.4 m/s
  - ➔ total distance: ~42 m
  - ➔ mandatory for final crash simulations!



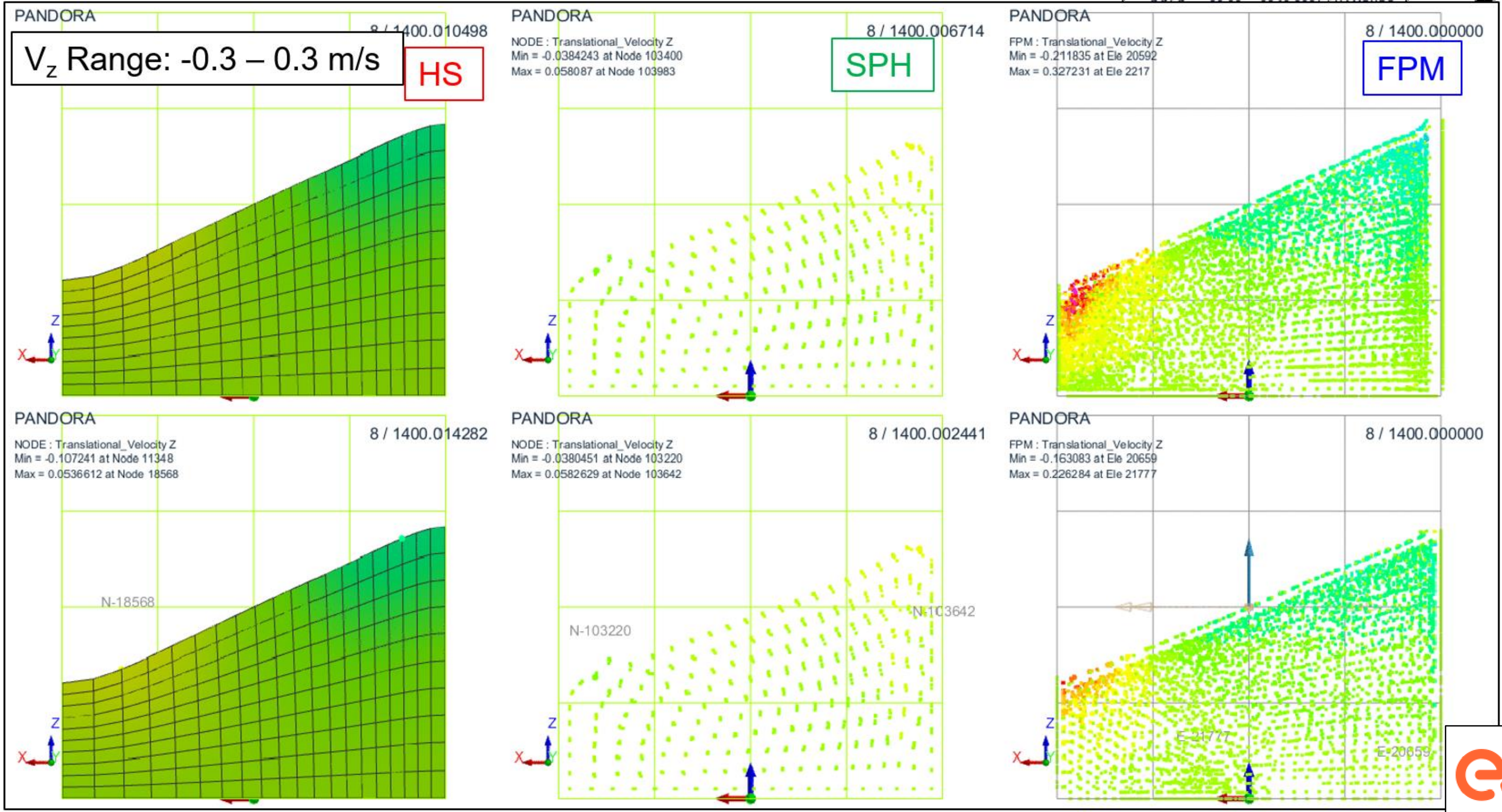
- Loading 2: acceleration purely on fluid (tank fixed)
  - Total time: 6s
  - Identical acceleration pulse



1. Sloshing in tanks (comparison of FSI methods)

Loading 1: Moving Tank

Loading 2: Fixed tank, acc. on fluid



➔ Similar behavior in all simulations

1. Sloshing in tanks (comparison of FSI methods)

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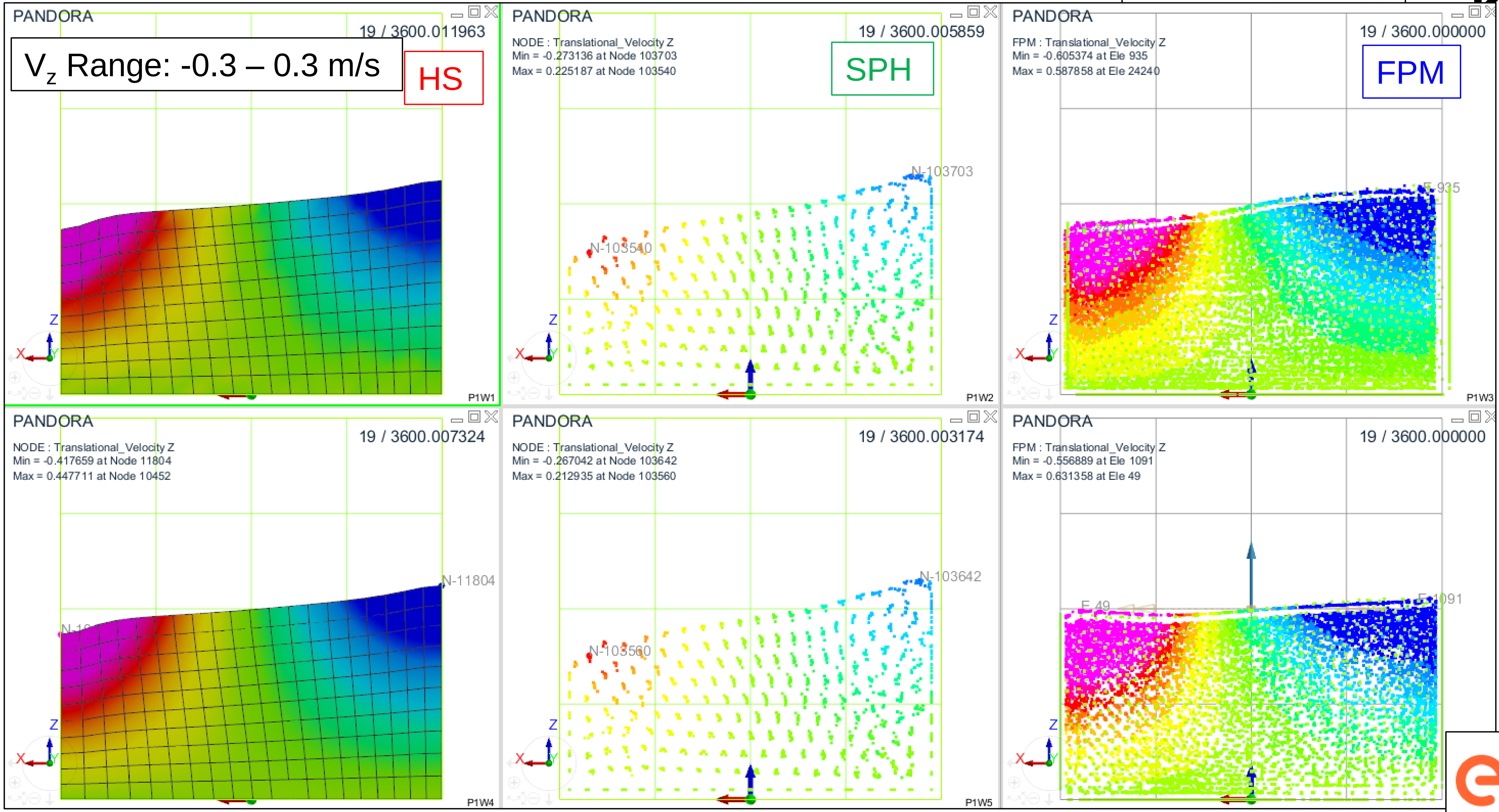
Loading 1: Moving Tank

Loading 2: Fixed tank, acc. on fluid



➔ Similar behavior in all simulations

esi get it right

1. Sloshing in tanks (comparison of FSI methods)

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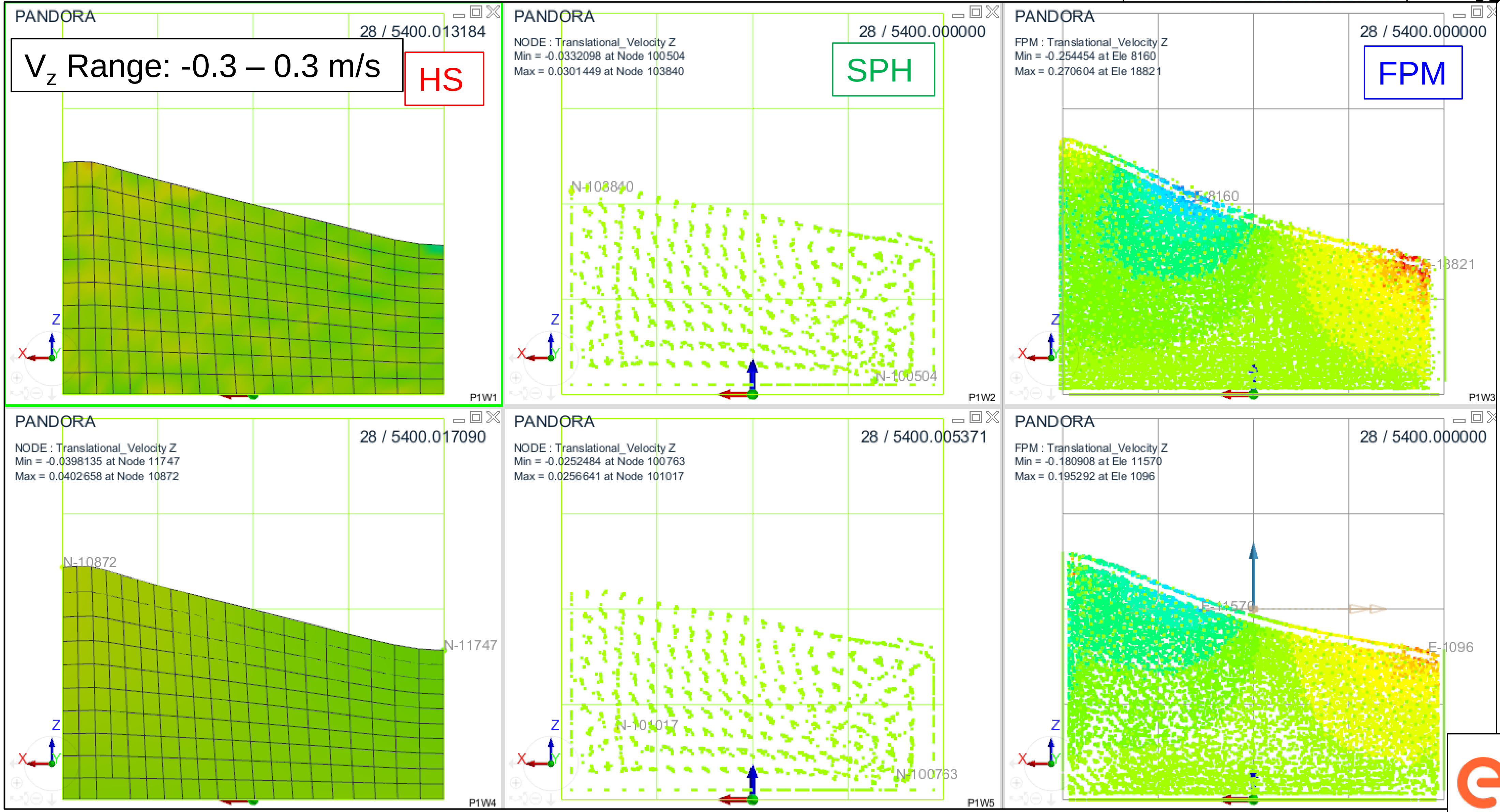
Loading 1: Moving Tank

Loading 2: Fixed tank, acc. on fluid



➔ Similar behavior in all simulations

esi get it right

2. Sloshing in tanks (comparison of FSI methods)

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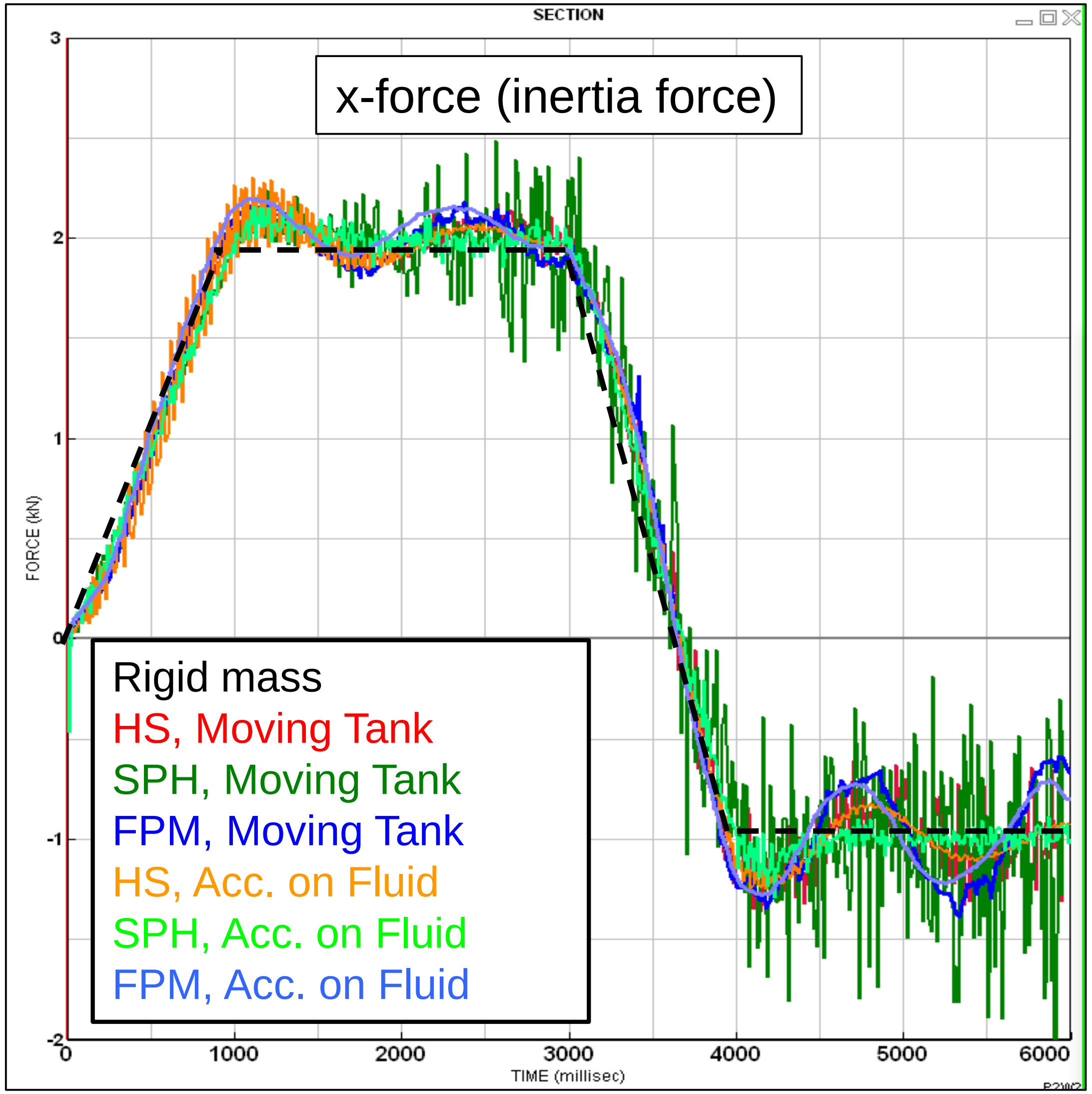
Comparison of reaction forces / computing costs

Method	loading	Iterations (Fluid)	Elements /points	Computing time (8 cores)
HS	Moving Tank	344609	4000	1:57
HS	Acc. on H2O	347129	4000	2:11
SPH	Moving Tank	819654	4000	1:10:19
SPH	Acc. on H2O	833582	4000	1:11:02
FPM	Moving Tank	1736	26174	16:25
FPM	Acc. on H2O	306	23344	2:59

- HS are cheap, but considered limited to moderate flow
- SPH is very expensive compared to other methods (due to small timestep / many iterations)
- FPM is the easiest method to set-up the model



➔ Further investigation with higher acceleration /stimulation

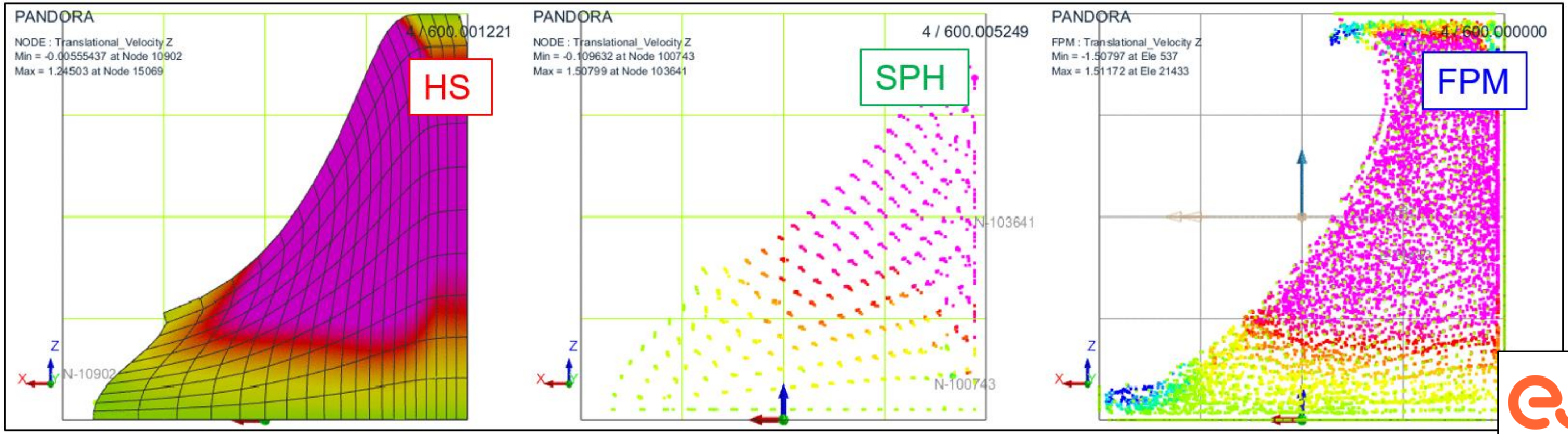
1. Sloshing in tanks (comparison of FSI methods)

- Sloshing simulation test tests with more severe acceleration pulse
  - Acceleration increased to 25 m/s² - 12 m/s² (Factor ~6, compared to initial test)
  - Simulation time increased to 10 s

- Only Loading 2 considered here

V_z Range: -0,5 – 0.5 m/s

Loading 2:
Fixed tank, acc. on fluid



1. Sloshing in tanks (comparison of FSI methods)

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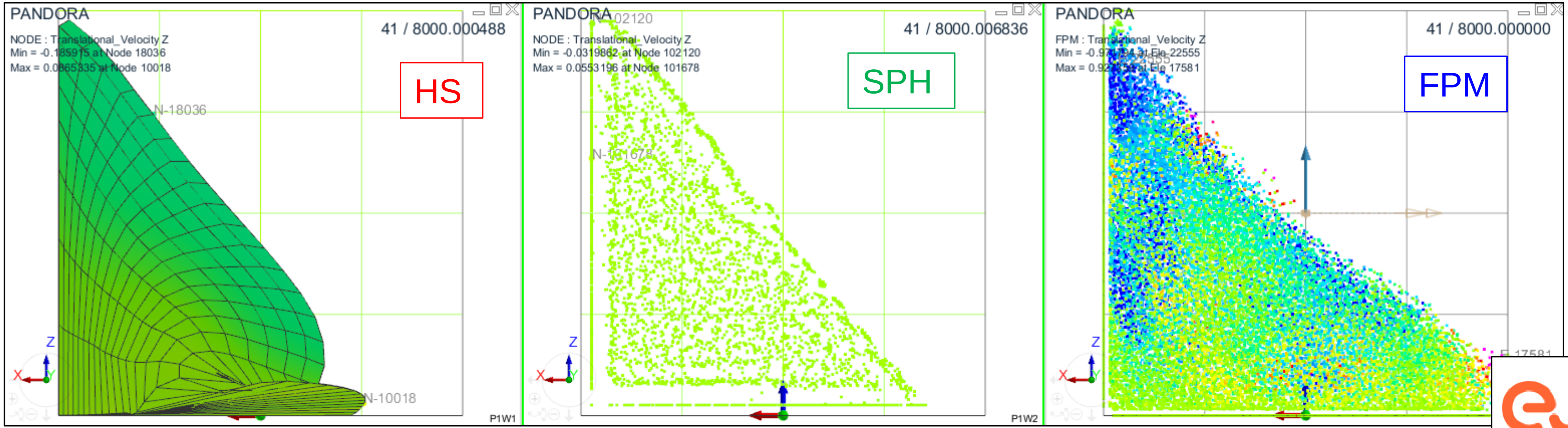
- Sloshing simulation test tests with more severe acceleration pulse
  - Acceleration increased to 2.5g / -1.2 g (Factor ~6)
  - Simulation time increased to 10 s
- Only Loading 2 considered here

V_z Range: -0,5 – 0.5 m/s

Loading 2:
Fixed tank, acc. on fluid



esi get it right

1. Sloshing in tanks (comparison of FSI methods)

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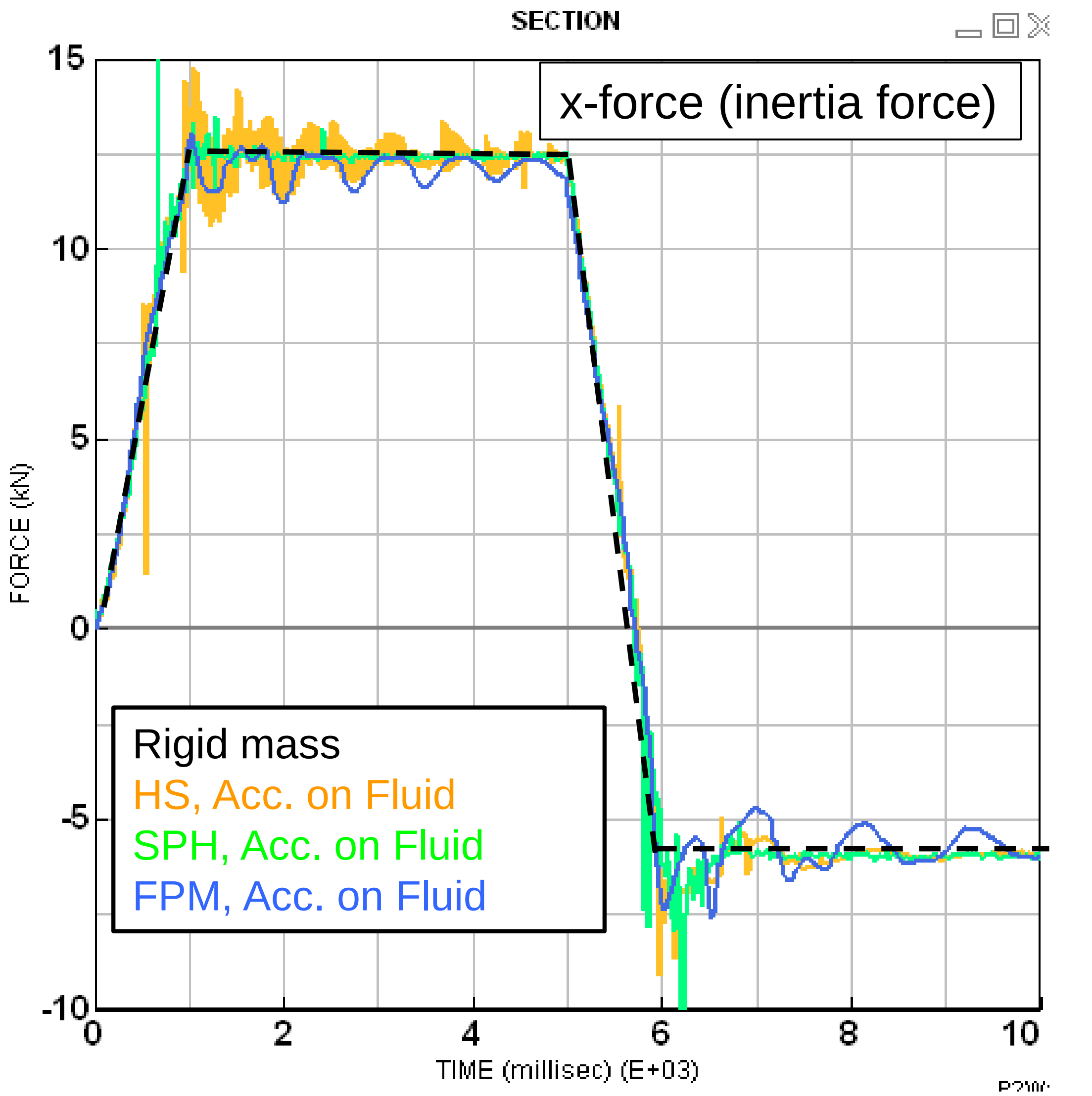
Comparison of reaction forces / computing costs

Method	loading	Iterations (Fluid)	Elements /points	Computing time (laptop)
HS	Acc. on H2O	347129	4000	18:13 (8 cores)
SPH	Acc. on H2O	833582	4000	34:19 (64 cores)
FPM	Acc. on H2O	306	23344	12:33 (8 cores)

- HS show severe deformation of the mesh with corresponding drop of stable timestep (finally not usable for even higher accelerations)
- SPH is very expensive compared to HS, FPM (alternative workstation used)
- FPM delivered the most feasible results at lowest cost

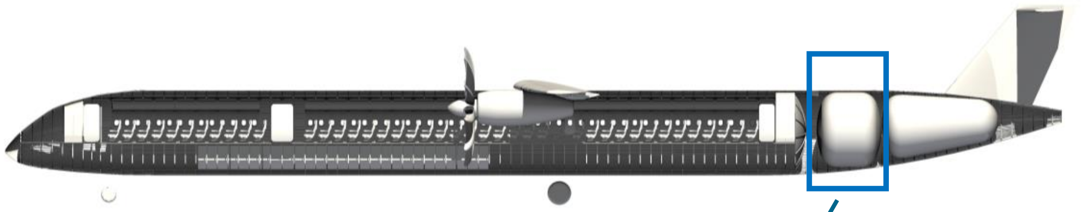


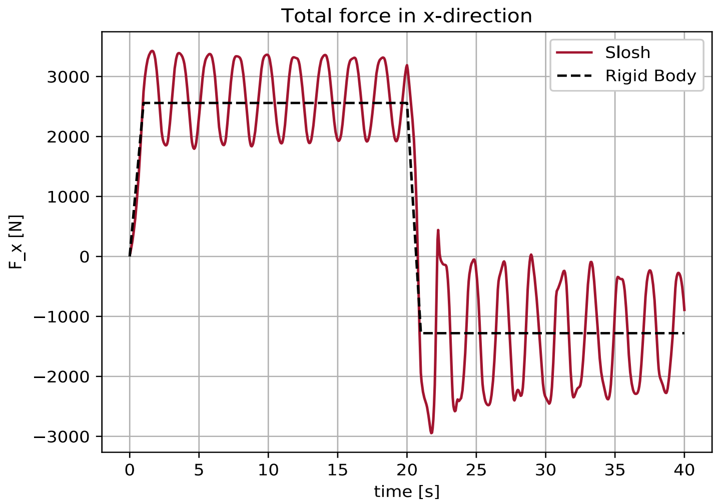
➔ FPM shows highest potential (will be used for tank sloshing)

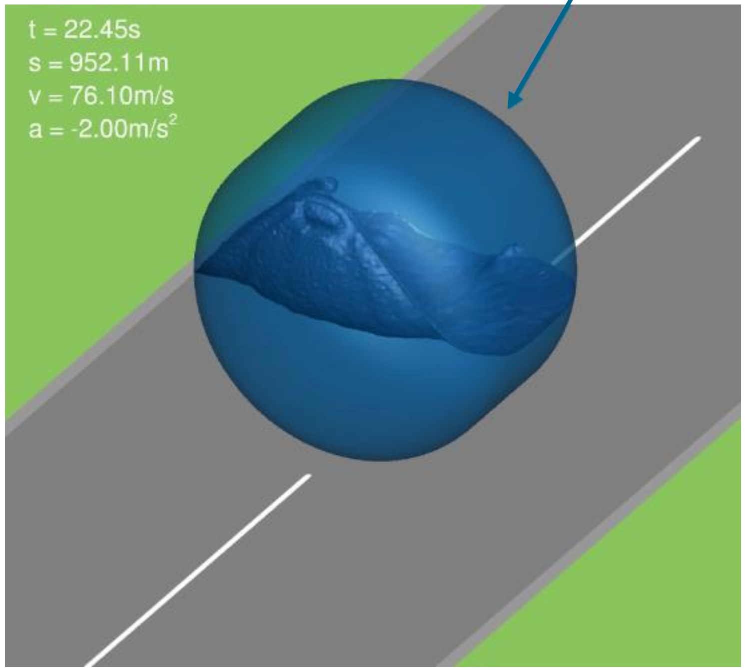
2. Validation of FPM Method for sloshing
Reference simulation for LH2 fuel sloshing

Loads during LH2 sloshing at rejected take-off (DLR-AS)

- Volume of Fluid (VoF) Method
  (DLR inhouse incompressible flow solver)
- Tank filled up to ~half of volume with LH2
- Considered load case
  - Total time: 40s
  - Acceleration +4 m/s² for 20s
  - Deceleration of -2 m/s² for 20s
  - ➔ Max. speed: ~79.3m/s
  - ➔ Total distance: ~2000m





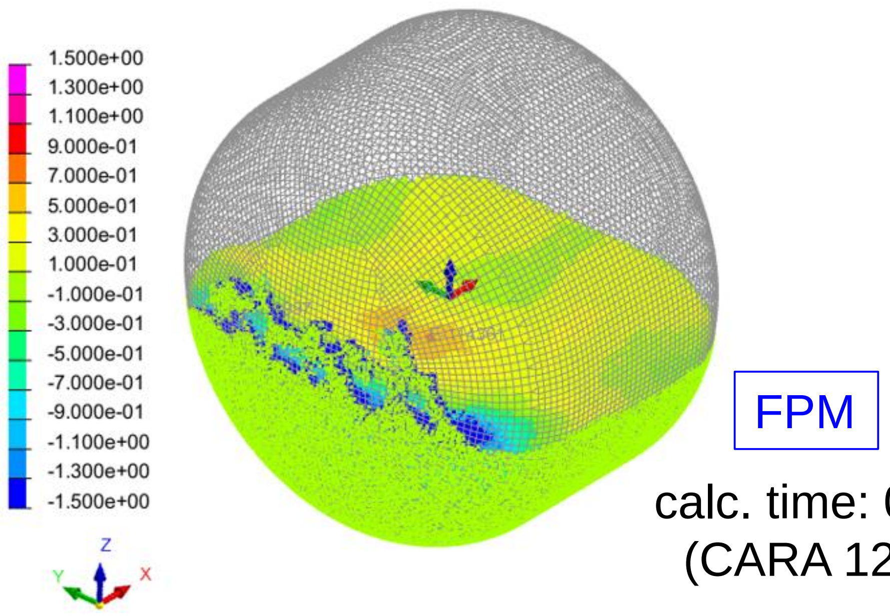


Source: HYTAZER Meeting in spring 2023 (DLR-AS)

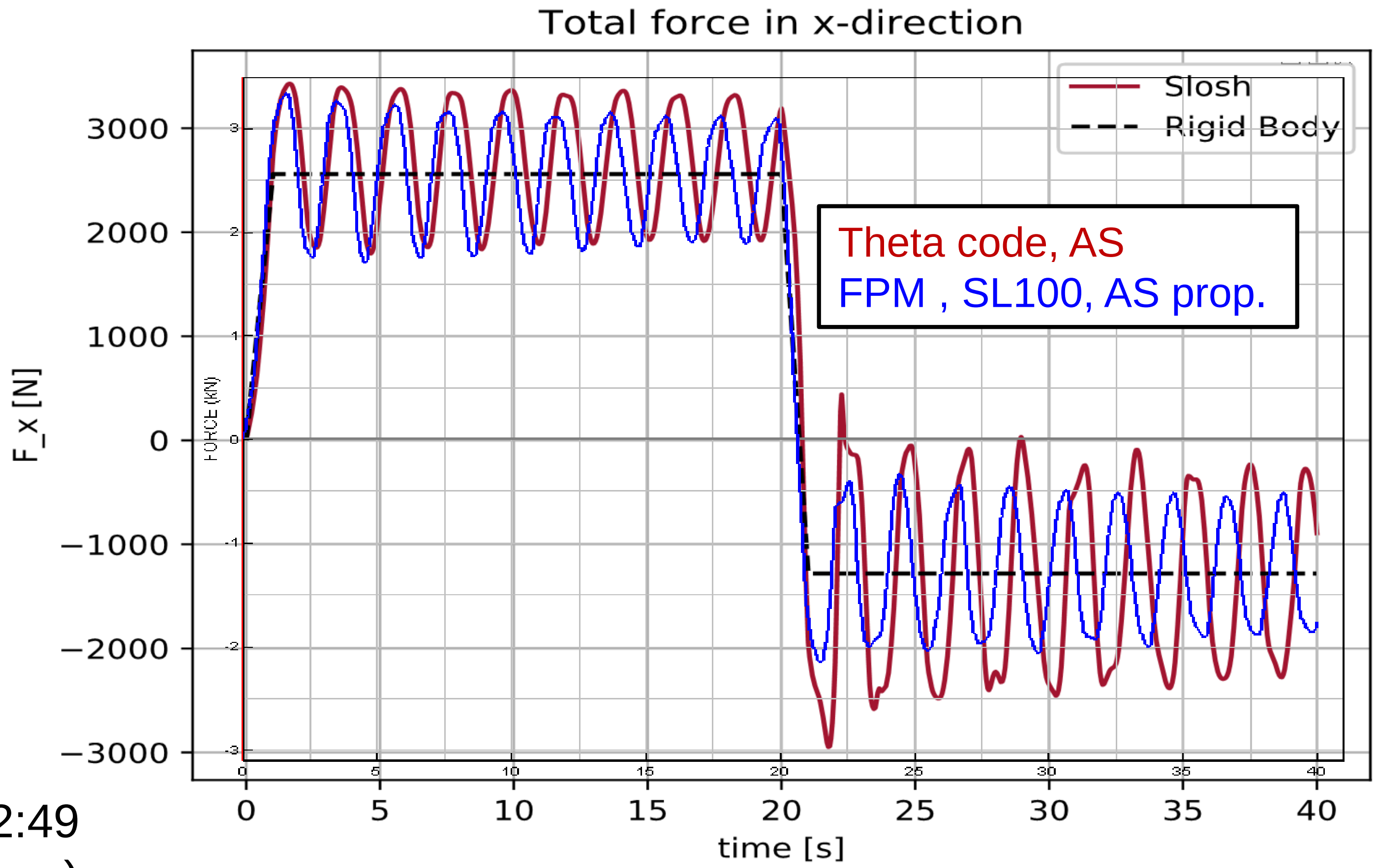
2. Validation of FPM Method for Sloshing

Comparison with reference simulation

- LH2 density and viscosity as used by DLR Colleague AS
  - Density: 72.20E-09 kg/mm³
  - Dynamic Viscosity: 1.48E-11 GPa ms [1]
    (other literature quotes: 1.14E-11)
  - Surface Tension: 0 (default, recommended)
- Loading by rotation of acc. vector
  (tank fixed in all DOFs)



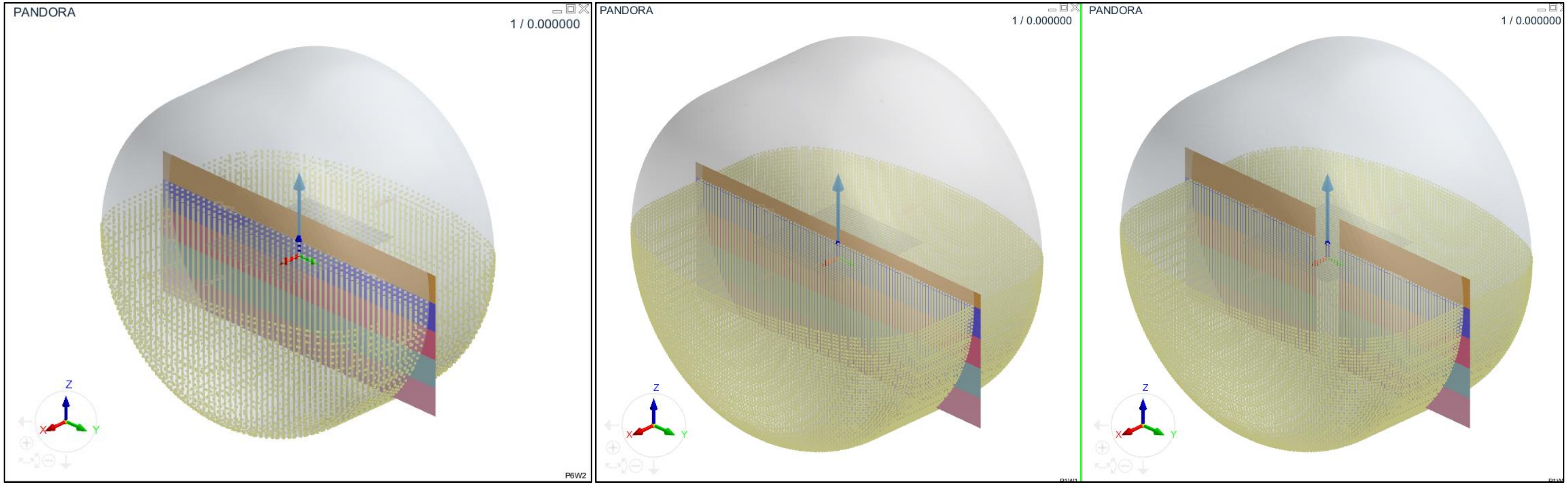
calc. time: 03:22:49
(CARA 128 cores)



2. Validation of FPM Method for Sloshing
Influence of baffles

Question: how can a baffle in the tank be modelled and what is the influence on the loads?

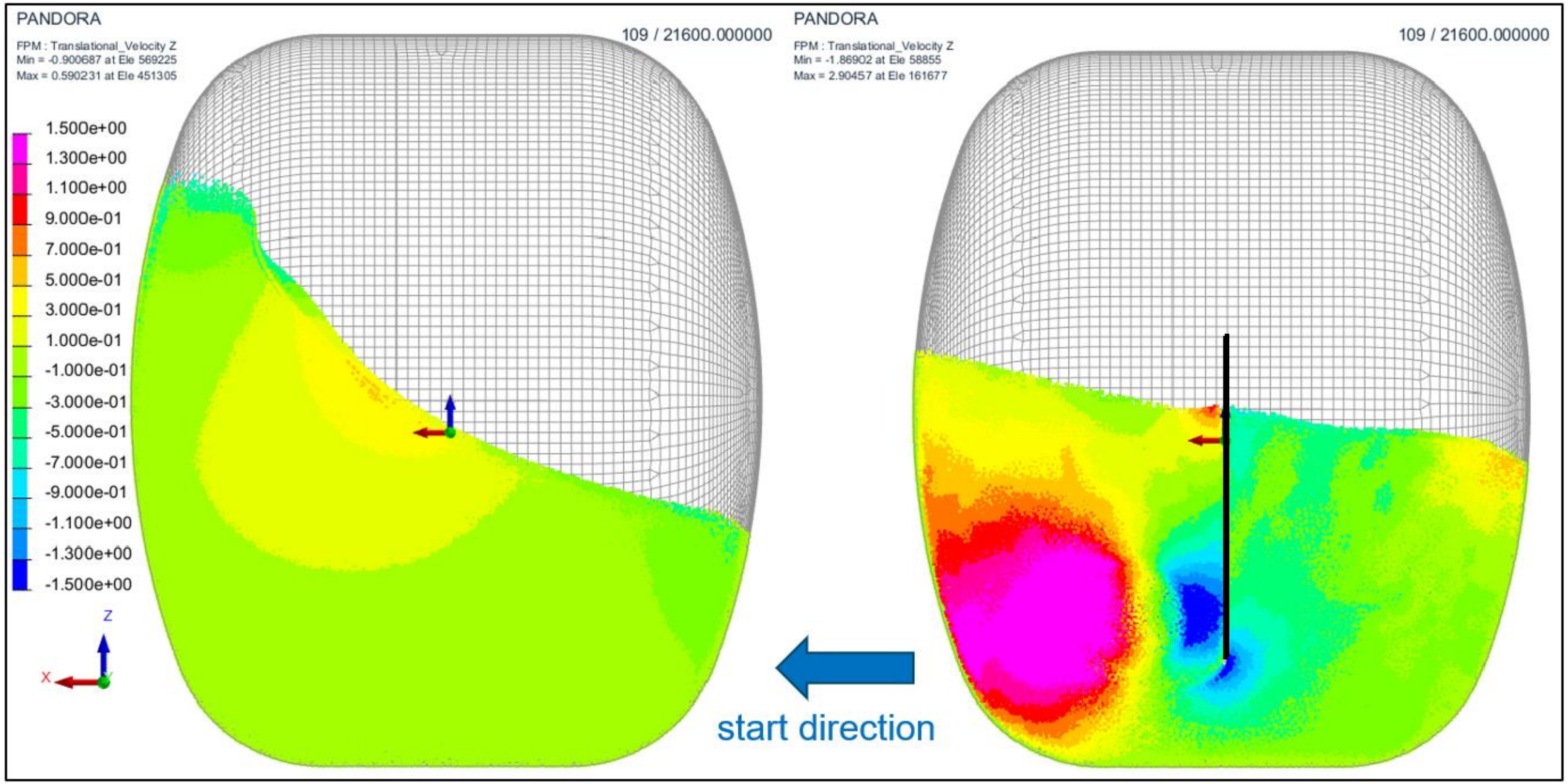
- A baffle is an additional wall inside the tank that suppresses the sloshing
- A very simple model (segmented wall) has been added to the rigid tank model



Reference model (baff) | Lower baffle (overflow, baff2) | Baffle with cut over high (baff3)

2. Validation of FPM Method for Sloshing
Influence of baffles

Question: how can a baffle in the tank be modelled and what is the influence on the loads?



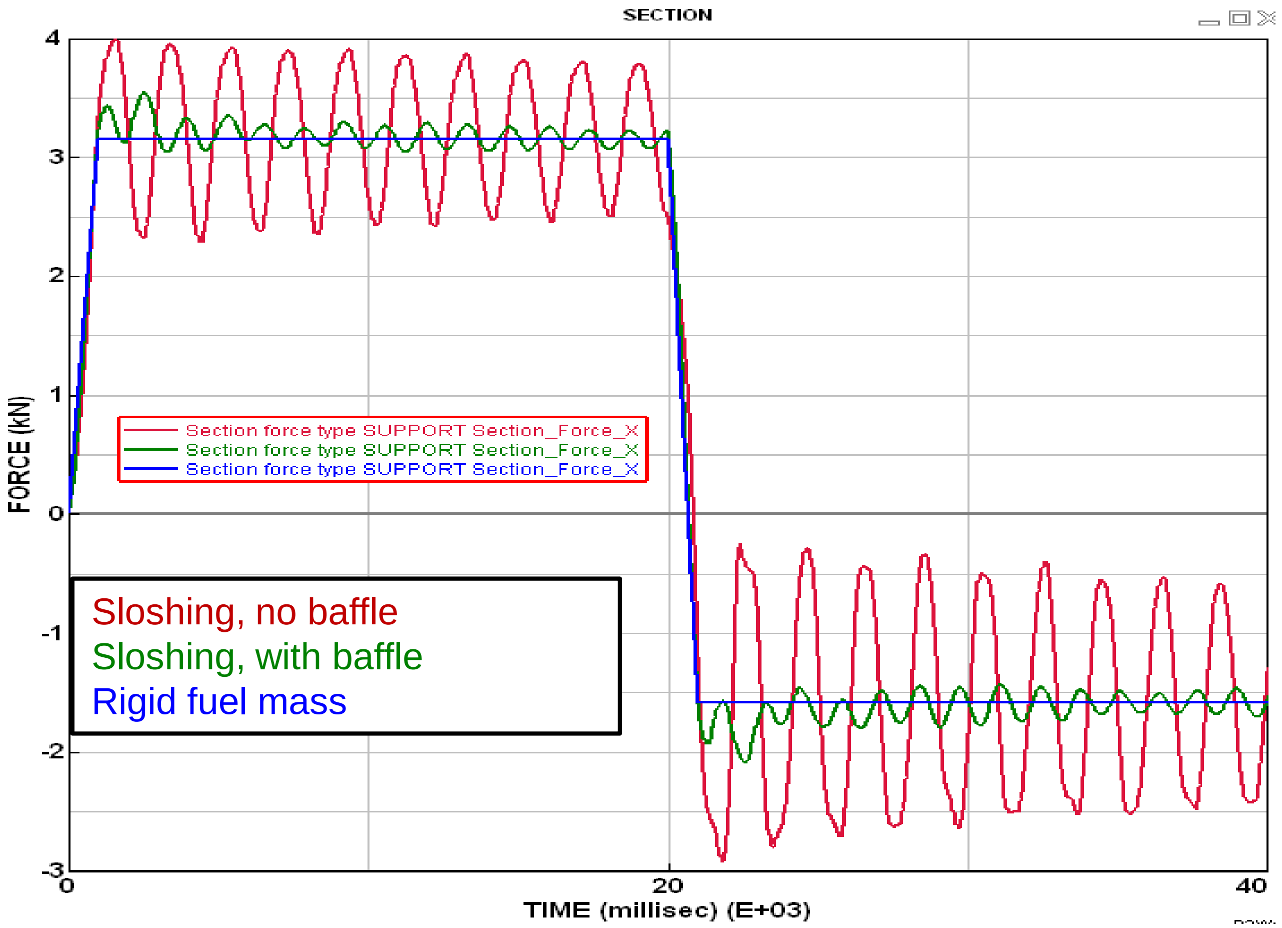
Significant reduction of flow in tank ☺ (SL100, Acc. Loading, baff = reference)

2. Validation of FPM Method for Sloshing
Influence of baffles

Question: how can a baffle in the tank be modelled and what is the influence on the loads?

- Significant reduction of the loads on the tank can be achieved with the baffle

- Simulation time increased by about 15-20%



3. Automatic model generation (process chain)

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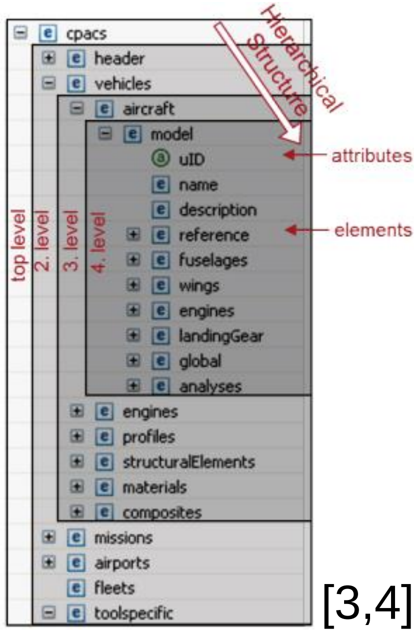
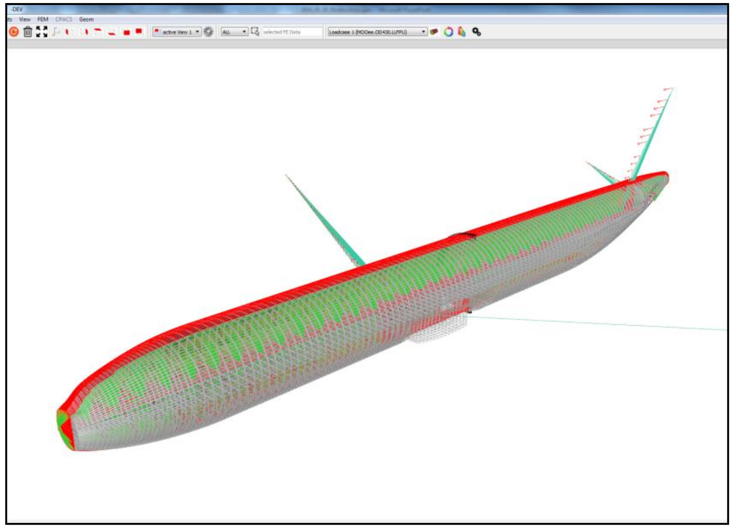
Final process chain will include following steps

cpacs
A Common Language for Aircraft Design

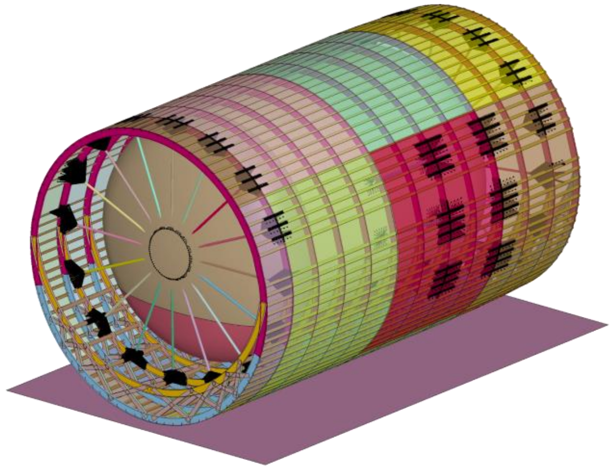


[3,4]

DLR design environment
PANDORA   [5]



CSM Solver
(VPS, LS-DYNA, …)



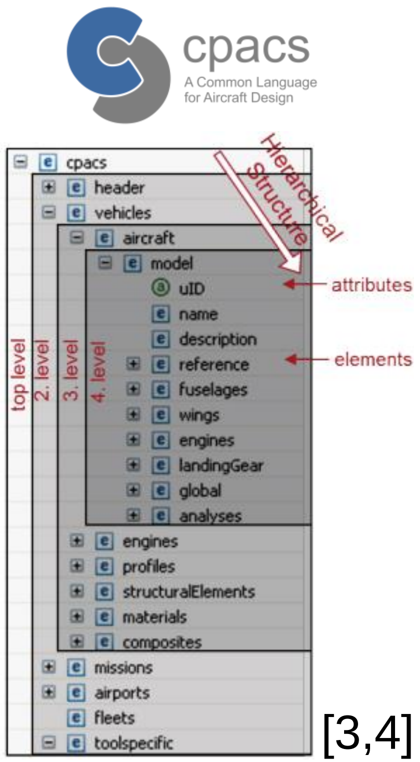
Aircraft description
incl. tank and mount points

Aircraft / tank model generation
incl. conversion to solver format

Appropriate FE model
(here: manually adapted
 model for crash analyses) [6]

3. Automatic Model generation (process chain)

CPACS status



[3,4]

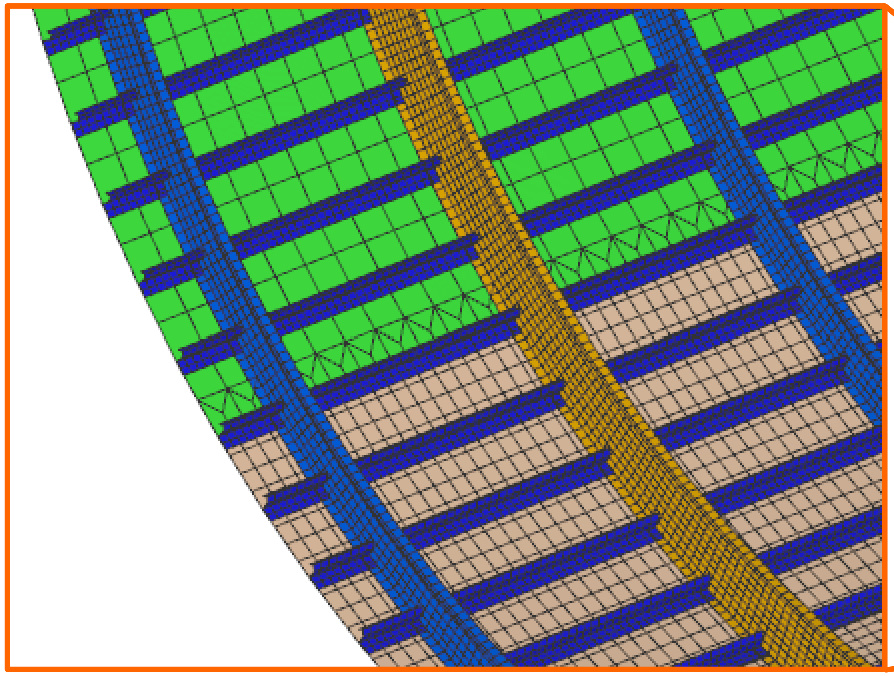
Aircraft description
incl. tank and mount points

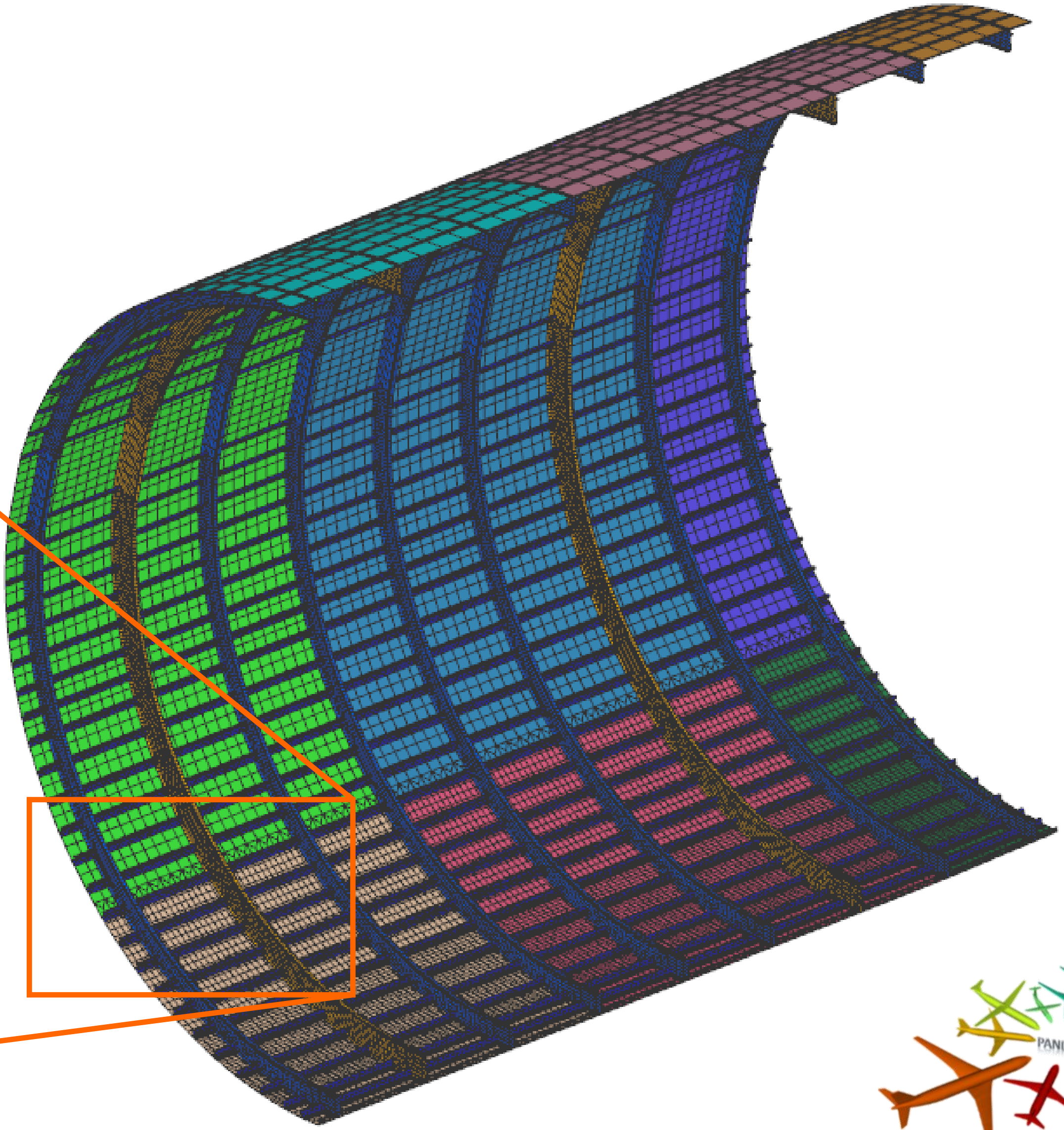
- Branches for detailed structural description of fuselage available (SoA)
- Hulls of fuselage tanks can be defined (incl. reinforcements) (V3.5)
- More general description of the tanks under discussion (V3.6+)
  - Tanks independent from fuselage (finally reference to fuselage)
  - Tank baffles to be included (first proposal)
  - Tank mounts to primary structure (initial ideas)

3. Automatic Model generation

Model generation in PANDORA environment

- Fuselage model generation is SoA
  - Extruded frames and stringers
  - Local mesh refinement
  - …

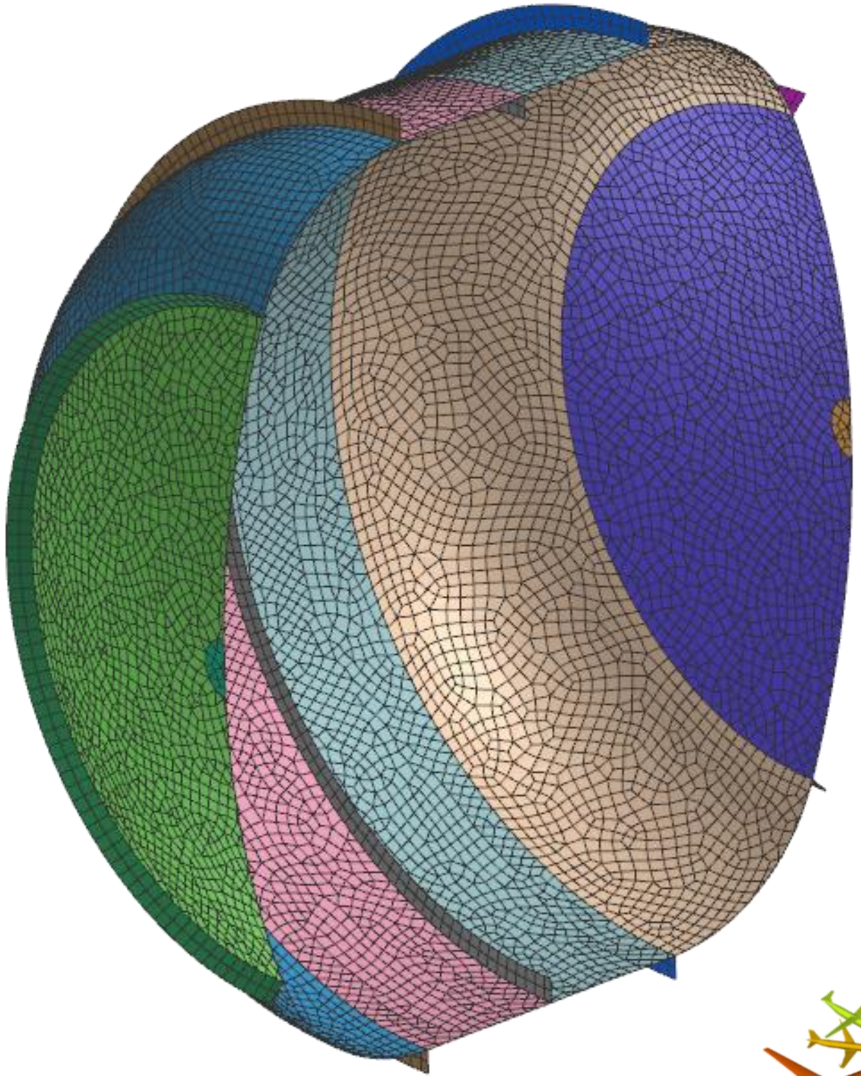




3. Automatic Model generation

Model generation in PANDORA environment

- Fuselage model generation is SoA
  - Extruded frames and stringers
  - Local mesh refinement
  - …
- Initial tank modelling implemented (CPACS based)
  - Hull with different segments to adapt wall thickness
  - Arbitrary hull reinforcements (inside /outside)



3. Automatic Model generation

Model generation in PANDORA environment

- Fuselage model generation is SoA
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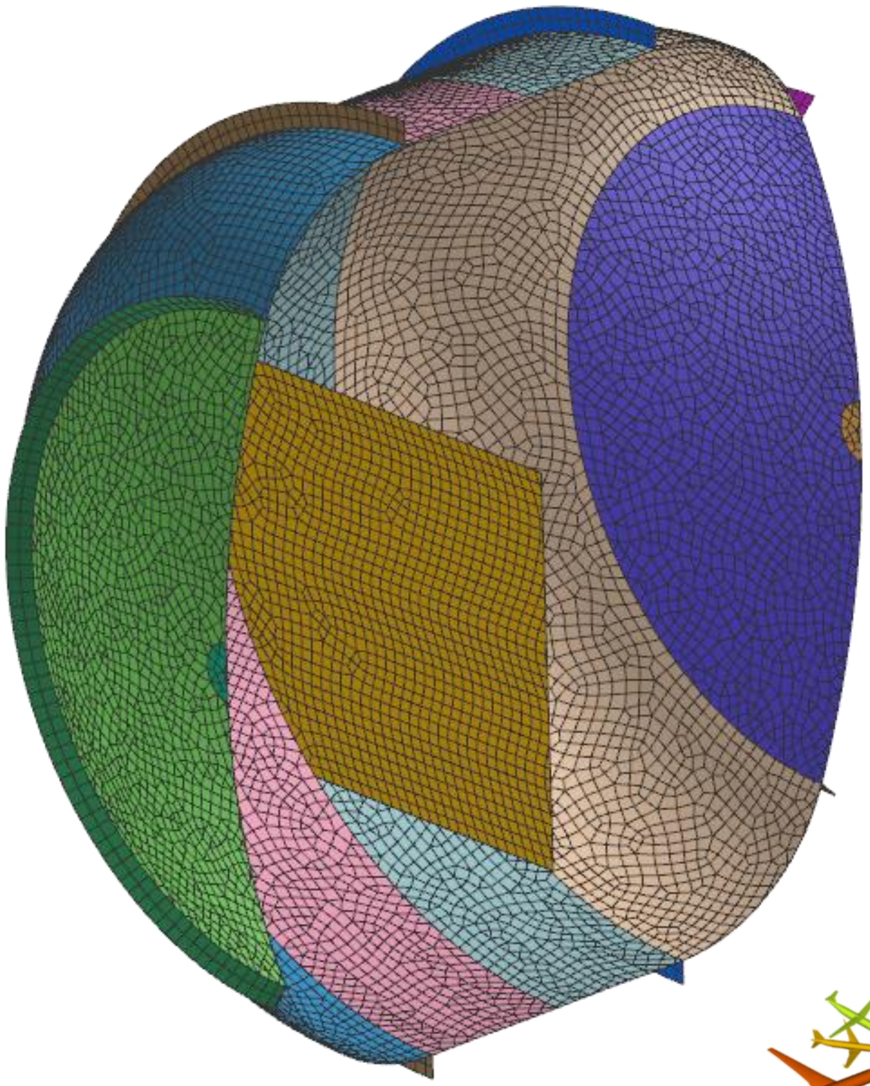
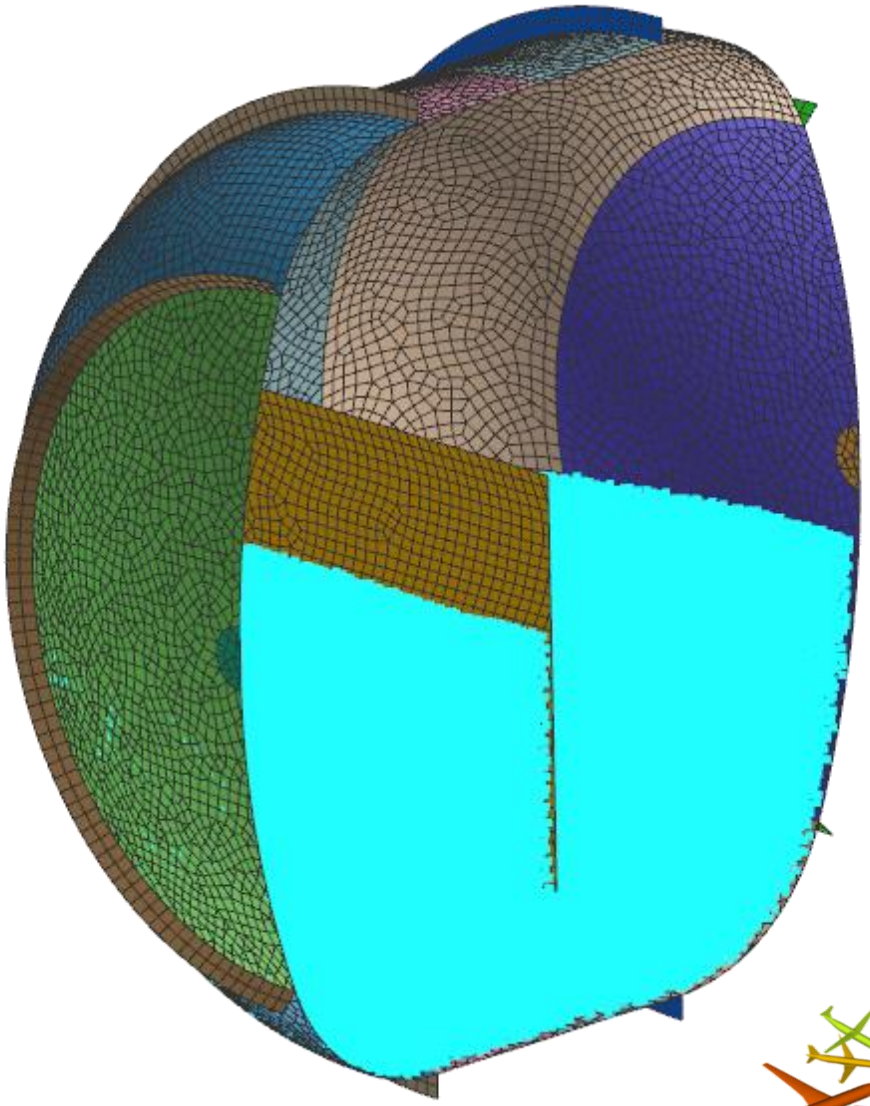
  - Local mesh refinement
  - …
- Initial tank modelling implemented (CPACS based)
  - Hull with different segments to adapt wall thickness
  - Arbitrary hull reinforcements (inside /outside)
  - Optional modelling of baffles
  - Open Source geometry and meshing tools



3. Automatic Model generation

Model generation in PANDORA environment

- Fuselage model generation is SoA
  - Extruded frames and stringers
  - Local mesh refinement
  - …
- Initial tank modelling implemented (CPACS based)
  - Hull with different segments to adapt wall thickness
  - Arbitrary hull reinforcements (inside /outside)
  - Optional modelling of baffles
- Automatic filling of tank cavity with particles (SPH) ongoing (several approaches)
- Tank mounts not implemented, yet



SPH

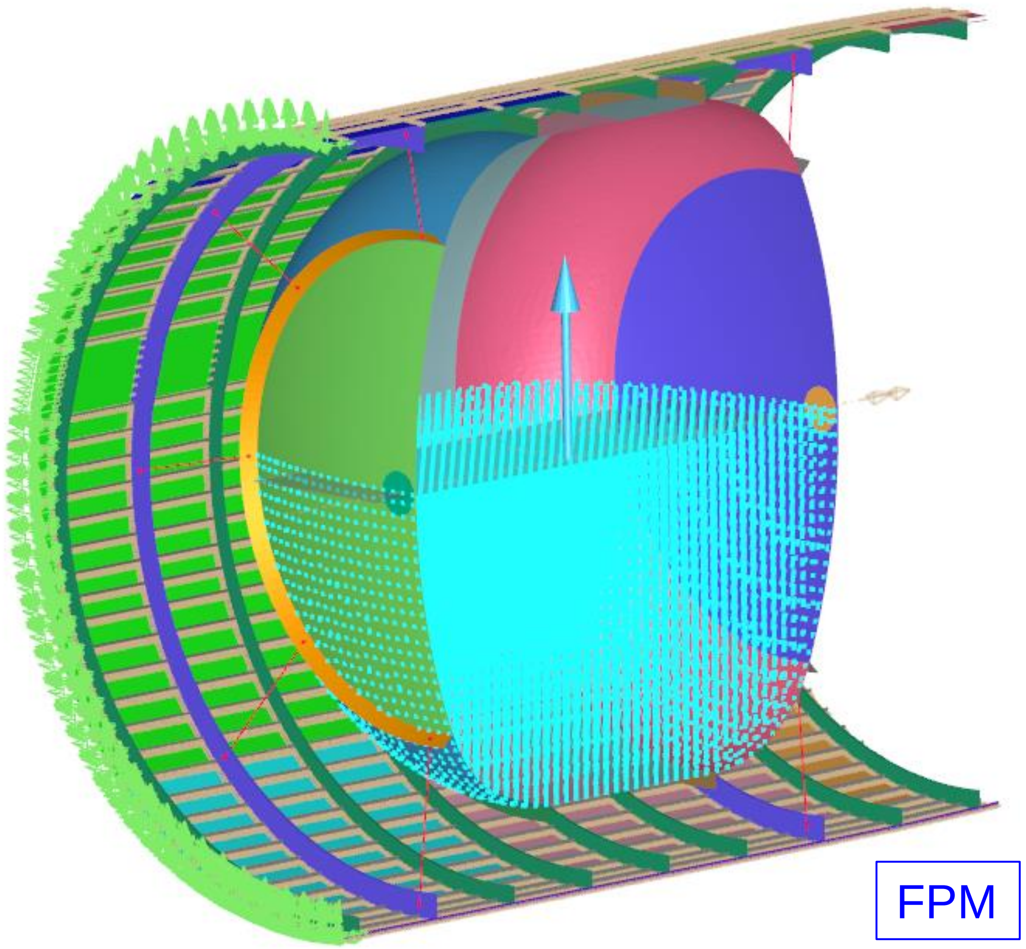
4. Initial integrated simulation

First simulation combines fuselage, tank and fluid

- Classical aluminium fuselage design
- Simplified LH2 tank
  - Single hull without insulation
  - Wall thickness increased in double curved sections
  - Exemplary reinforcements considered

- Tank attachment added to connect fuselage and tank
  - 8 spokes on either side of the tank to reinforced frames
  - Connection via interpolation elements (RBE3 like)

- LH2 modelled using FPM method

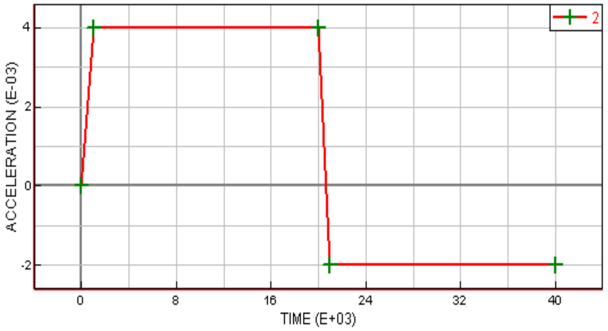


FPM

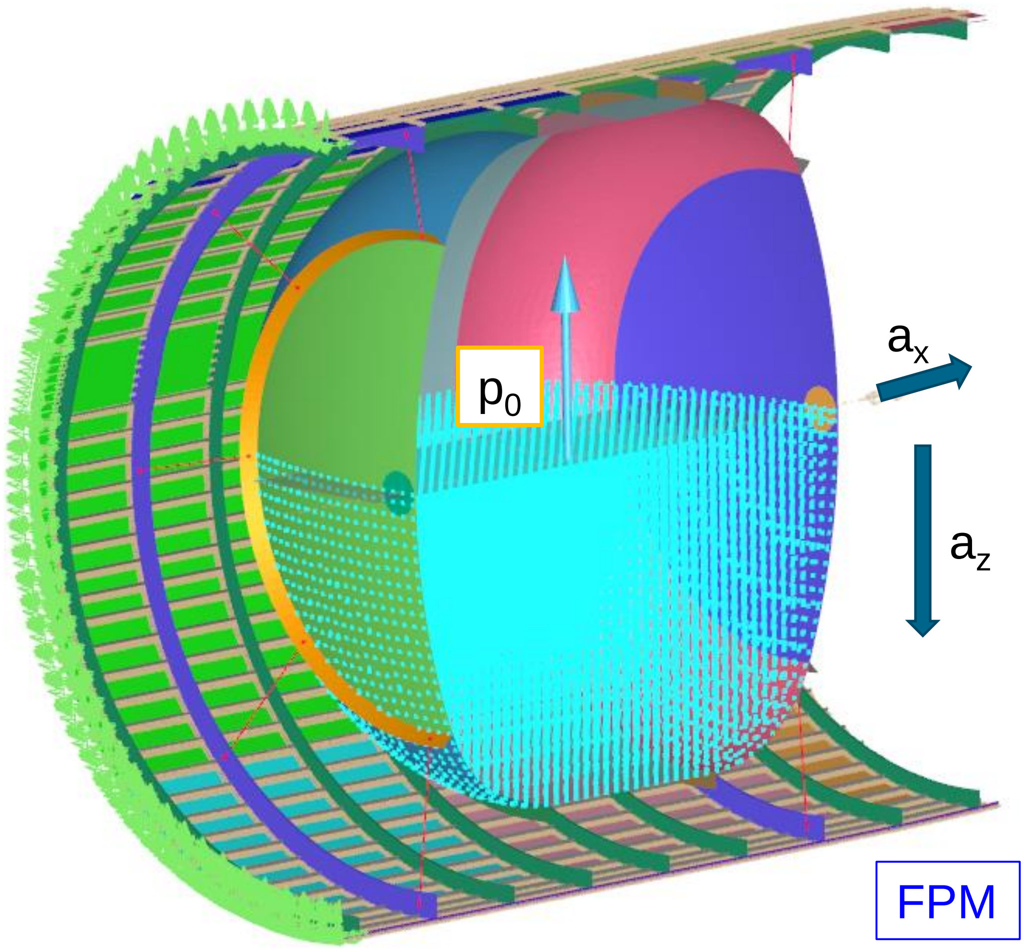
4. Initial integrated simulation

First simulation combines fuselage, tank and fluid

- Loading conditions
  - Fuselage section clamped at forward edge
  - Tank mass increased by 500 kg to assume 2nd hull and isolation
  - Tank filled up to 50% with LH2 (795 kg LH2)
  - Gravity (a_z = 1 g) acting on fuselage, tank and LH2
  - Acceleration a_x according to rejected take-off load case above (40 sec)
    - +4,0 m/s^2 up to 20 s (with 1 s ramp up)
    - -2.0 m/s^2 g from 21-40 s (with 1 s for transition)

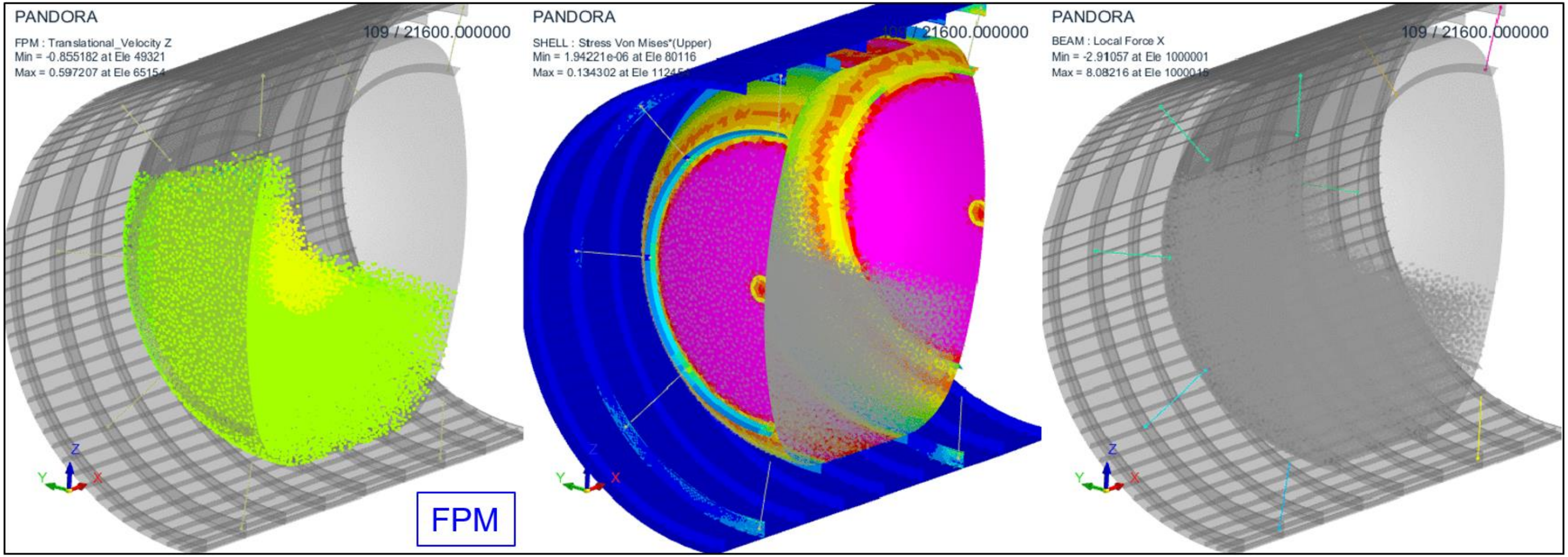


  - Addition internal pressure p_0 = 2 bar within the tank (ramp up over 1 s)



4. Initial integrated simulation

Preliminary results of initial integrated simulation



- V_z of fluid
- Range: -3 - +3 m/s
- Similar behavior compared to rigid tank

- Von Mises stress
- Range: -0 – 120 MPa
- High stress level in tank due to internal pressure

- Load in rods
- Range: -5 - +10 kN
- Realistic load transfer during rejected take-off

4. Initial integrated simulation

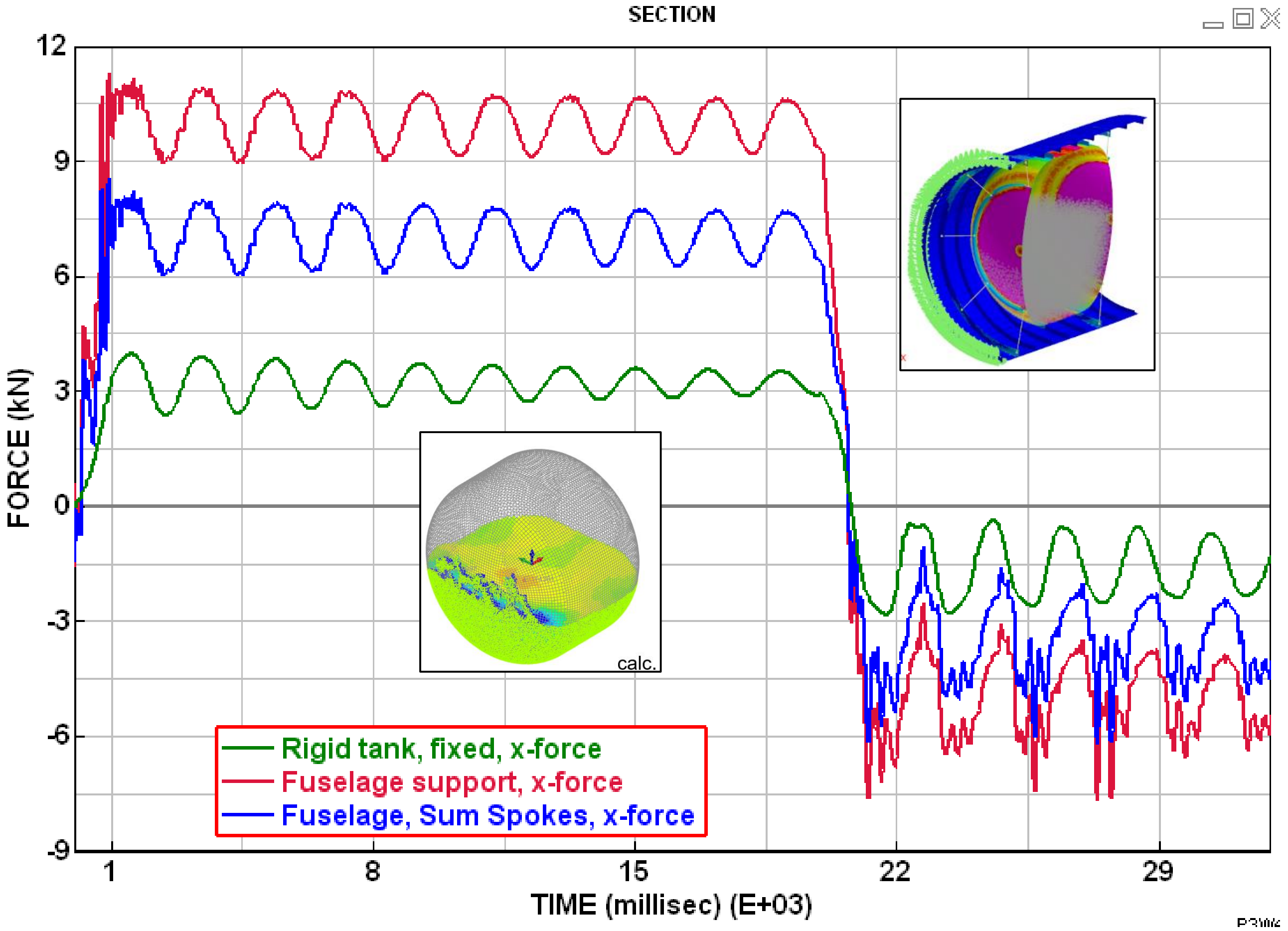
Comparison of calculated section forces

Mass summary:

LH2:	795 kg	➔ 3.18 kN
Tank:	977 kg	
Fuselage :	733 kg	
LH2+ Tank:	1772 kg	➔ 7.09 kN
Full model:	2504 kg	➔ 10,0 kN

➔ Feasible load transfer calculated

➔ disturbance of system after deceleration starts, vibration of tank mass



Summary / Outlook

Achievements

- Assessment of different numerical methods to model fluel sloshing
- FPM successfully used for LH2 sloshing (validation with alternative CFD solution)
- First integration into fuselage model leads to feasible results

Next steps

- Extension of process chain development
  - CPACS description for baffles and tank mounts
  - Completion of automatic modelling in PANDORA
- Assessment of more realistic tank integration concepts under sloshing loads
- Provision of inputs for dedicated crash analyses (e.g. alternative code, SPH method, …)

➔ full aircraft crash analyses with correct LH2 dynamics

Questions? ➔ dieter.kohlgrueber@dlr.de

Acknowledgment

Contribution of Co-Authors

Michael Petsch: PANDORA development / model generation

Christian Leon Munoz: Contribution to FSI evaluation, expert in SPH modelling

Paul Schatrow:
Matthias Waimer:
} Contribution to LH2 tank integration concepts (crashworthiness)

More details in further presentation at DLRK:

Crashworthiness demonstration strategy for LH2 tank integration
P. Schatrow, M. Petsch, M. Waimer, E. Wegener, L. Marconi,
N. Wegener, D. Kohlgrüber [6]

Session 5.5
Di. 01.10.24
Hörsaal C
15:25 – 15:50

Questions? ➔ dieter.kohlgrueber@dlr.de

D&C – Acknowledgment & Disclaimer

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Contribution of Projects

EXACT	HYTAZER	FASTER H2
DLR project	DLR project	Clean Aviation project

Parts of the presented research were performed in the scope of the project FASTER-H2.

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Disclaimer

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CLEAN AVIATION

Co-funded by the European Union

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