FPM Liquid for Fluid Structure Interaction in Aeronautics: Ditching, Floatation, Fuel Sloshing

Dieter Kohlgrüber, Christian Leon-Munoz, DLR-BT,

VPS Conference, Prag, 20.06.2024

esi 2024
VPS User Conference

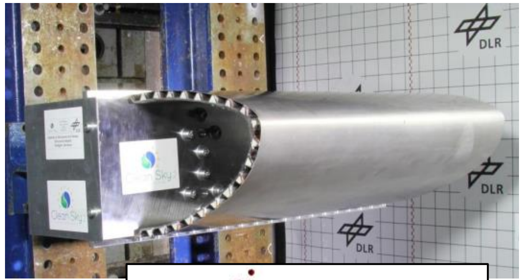
DLR

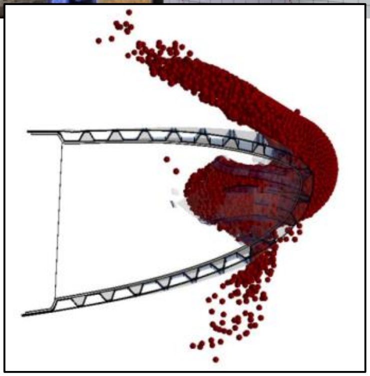
German Aerospace Center (DLR)
Institute of Structures and Design, Stuttgart

Department: Structural Integrity

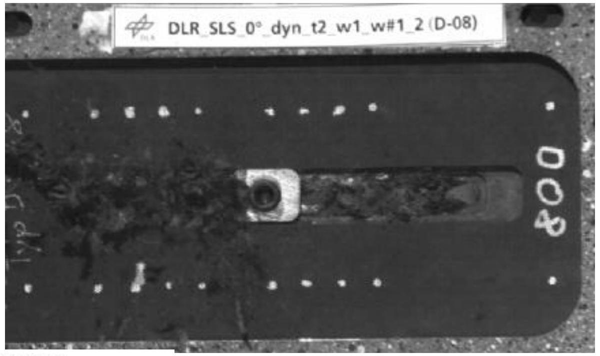
Mission

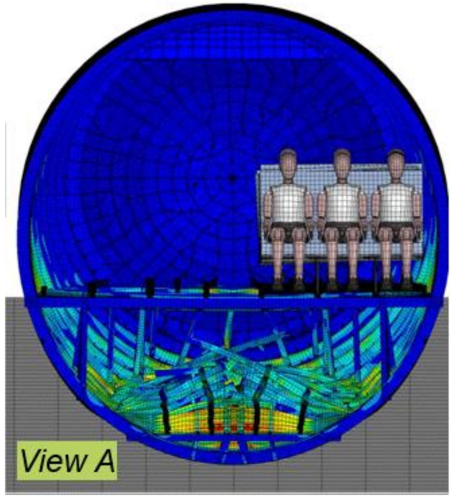
- Development of structural concepts to improve passive safety in aeronautical structures (incl. testing)
- Modelling and simulation of structures under stat. und dyn. loads



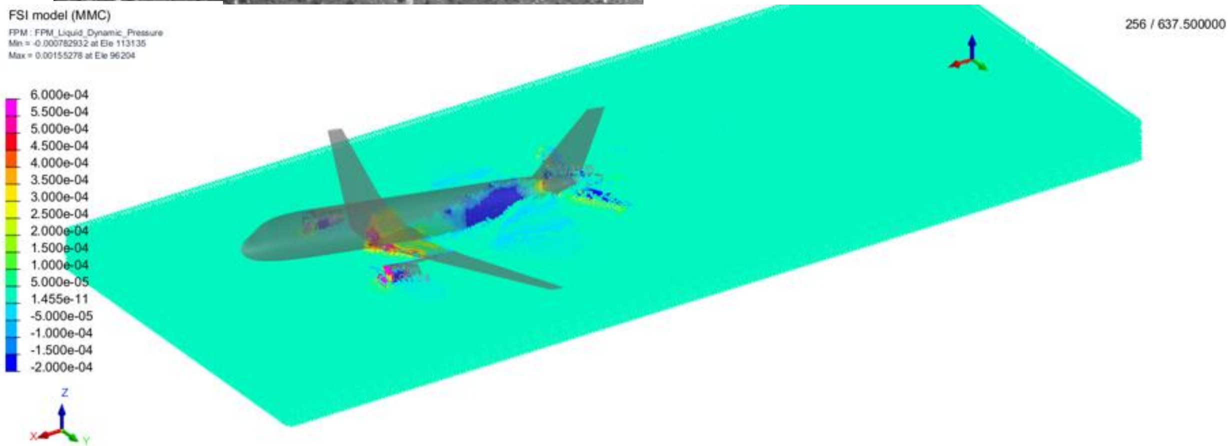


Bird strike research





Crash simulation



DLR, Institute of Structures and Design
Short History with VPS (PAM-CRASH)

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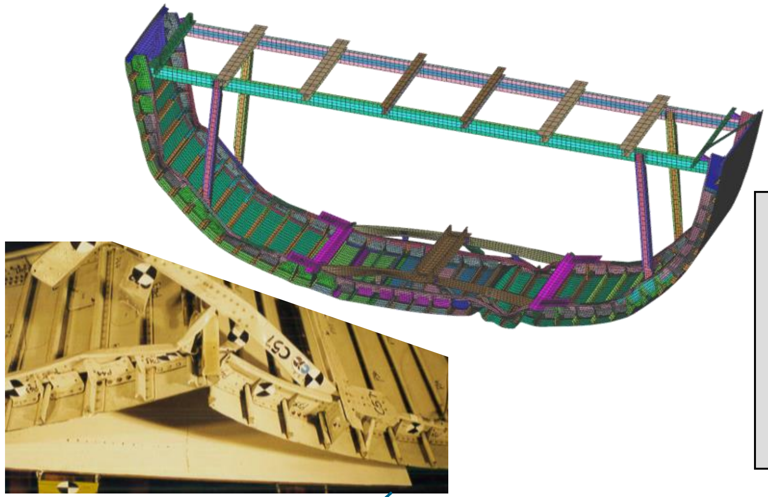
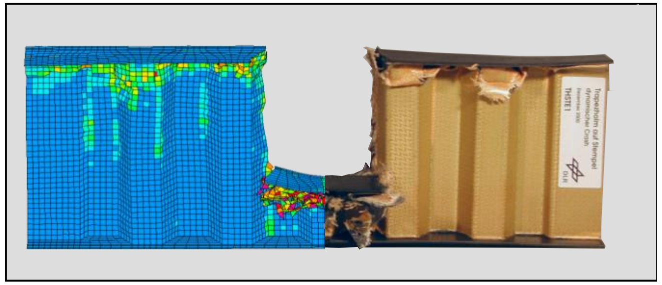
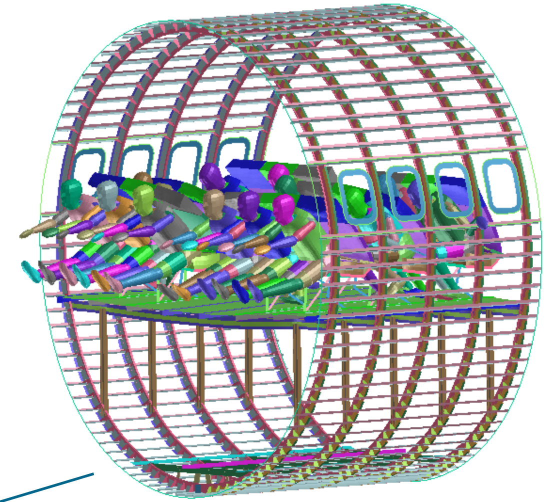




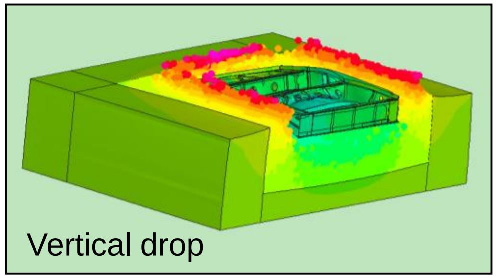


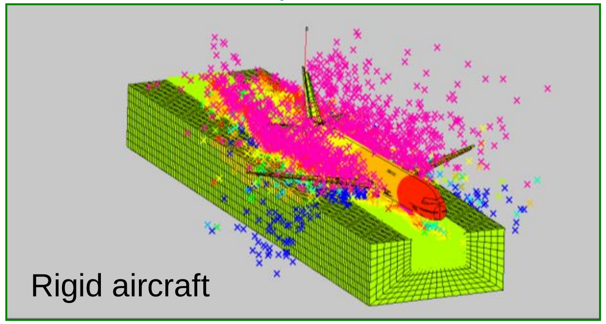
1993 1995 2001 2004 2010 2019 2020 2024

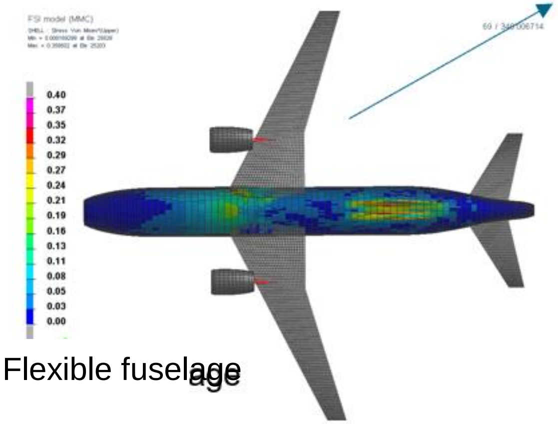
VPS (PAM-CRASH, VPS)

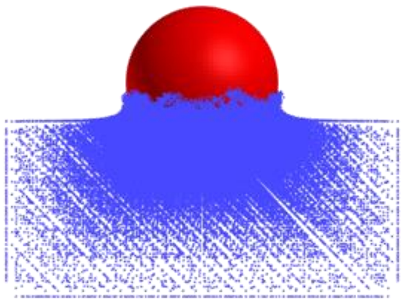
FSI (SPH)

FSI (FPM)


Vertical drop


Rigid aircraft


Flexible fuselage



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Motivation of todays talk (FSI challenges)

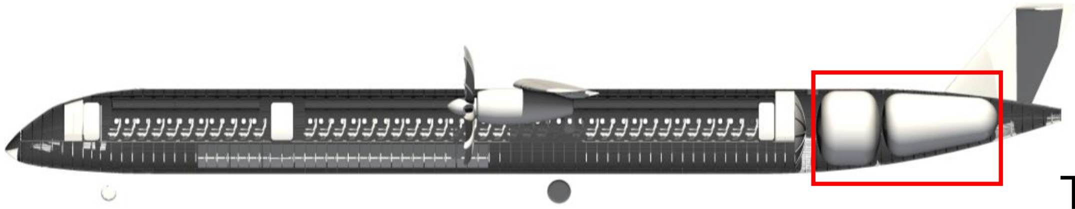
Target: Operation of aircraft has to be safe (even in emergency situations!)

- Ditching (CS 25.801, prepared landing on water)

1944 Source: Ditching of a B-24 Airplane into the James River https://www.youtube.com/watch?v=WjadMxpXprk

2009 US Airways A320, Januar 2009, Hudson River, New Jersey, USA

- Fuel sloshing (fuselage tanks for LH2)



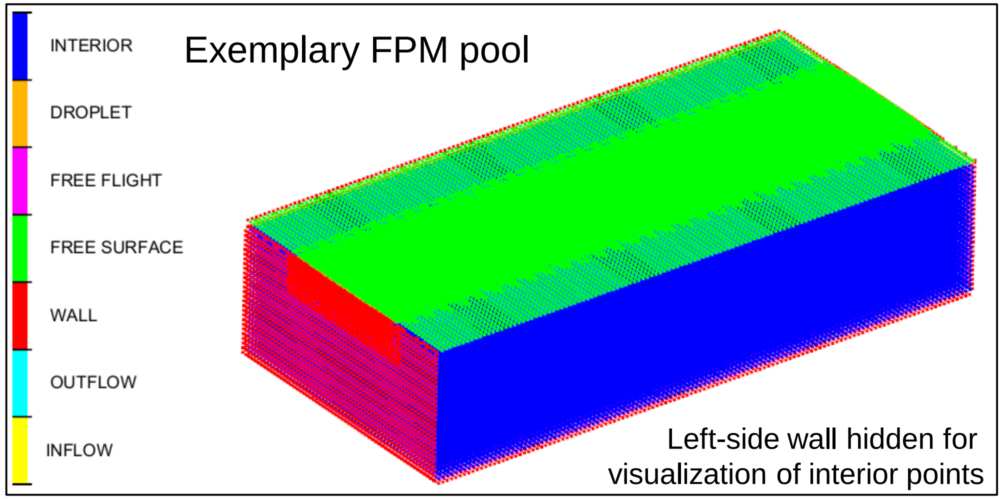
2022 DLR Climate Neutral Aircraft configuration (LH2 based)

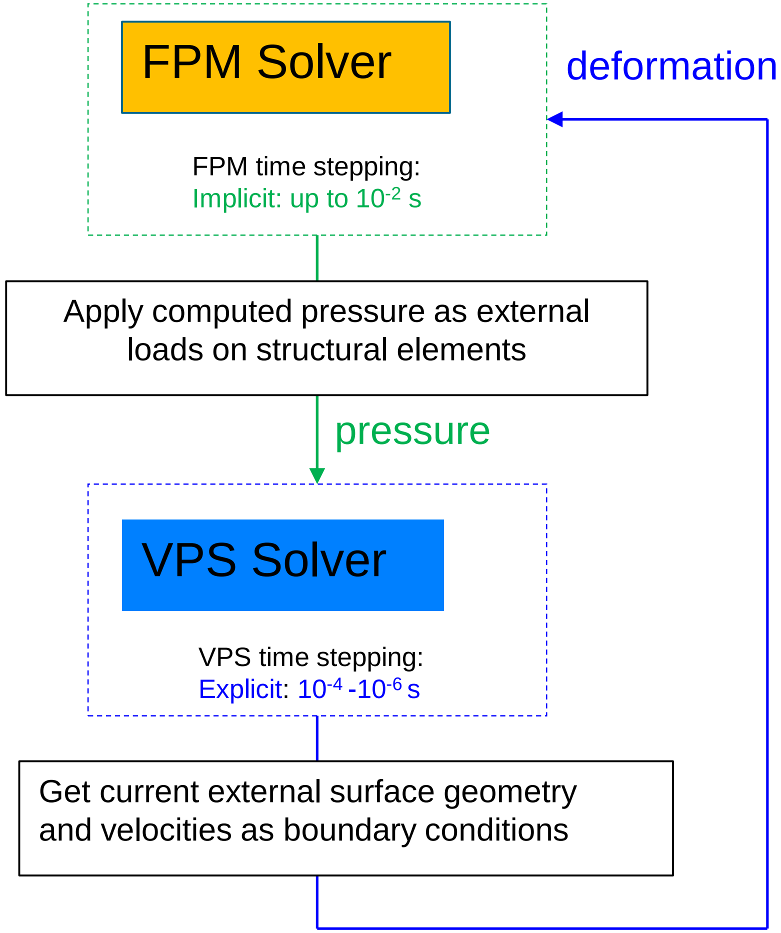
Tank volume: 2 x 25m³
LH2 mass: 2-3 t

Source: https://youtu.be/56cxOzgl-mc

Few words on FPM Liquid in VPS

- Fundamentals of FPM (FPMIN /)
  - Meshfree approach for fluid discretization (point cloud)
  - Solves the Navier-Stokes equations for incompressible fluid
  - Adaptive point clout refinement (smoothing length)
  - Implicit time integration schema ➔ larger timesteps possible!
  - Easy model generation by definition of the free surface and the pool (tank) walls. Interior points generated automatically ➔ small and easily adaptable input cards





Schema of 2 way coupling VPS and FPM

1. Ditching research (since ~ 2000 at DLR)

Phases of Ditching ➔ impact on FSI methods

Impact / Landing:

- Short Impact phase (<100 ms)
  Moderate landing phase (~ 1 s)
- High forward velocity (~70m/s)
- FSI with complex hydrodyn. phenomena
- Nonlinear structural response
- Potential Influence of sea state

Floatation:

- Long physical time (>30 s)
- Potential influence of sea state
- Potential sinking

FSI methods in VPS considerd at DLR

Impact / Landing:

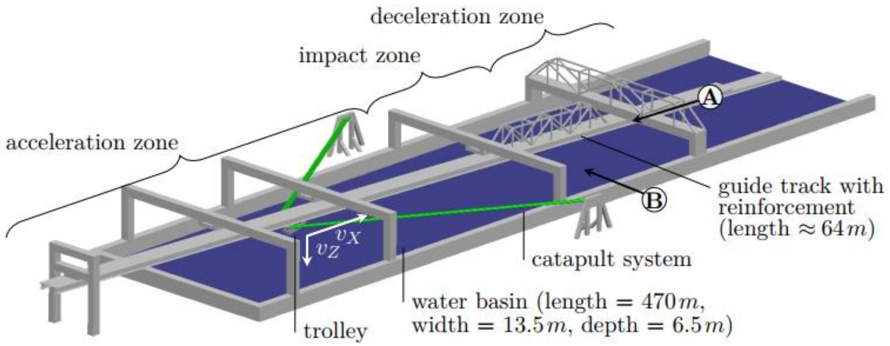
- SPH Method partly applicable and proved (challenges due to short timestep)
- High potential for FPM (time step, hydrodynamic phenomena, …)

Floatation:

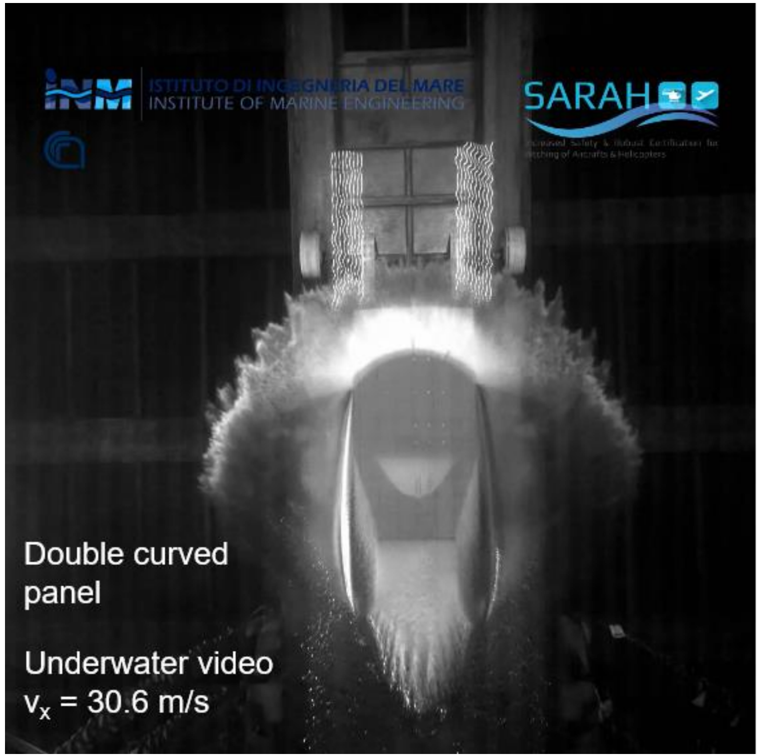
- SPH not / barely feasible (time step)
- High potential for FPM (time step, …)

1. Ditching research (Impact phase)

- Short period of time (<100 ms)
- Characterized by high forces and structural deformation
- Detailed knowledge of local load transfer required
- Guided ditching tests on aeronautical panels at real velocity in EC Project SMAES (2011-2014) and SARAH (2016-2020)
  - Pressure, strain, global forces, High speed video (incl. underwater view)



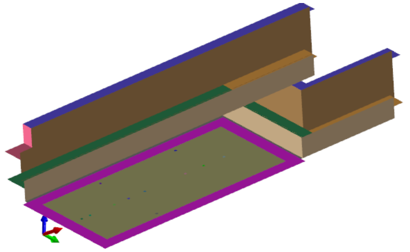
Real time camera (slow motion), v = 40 m/s

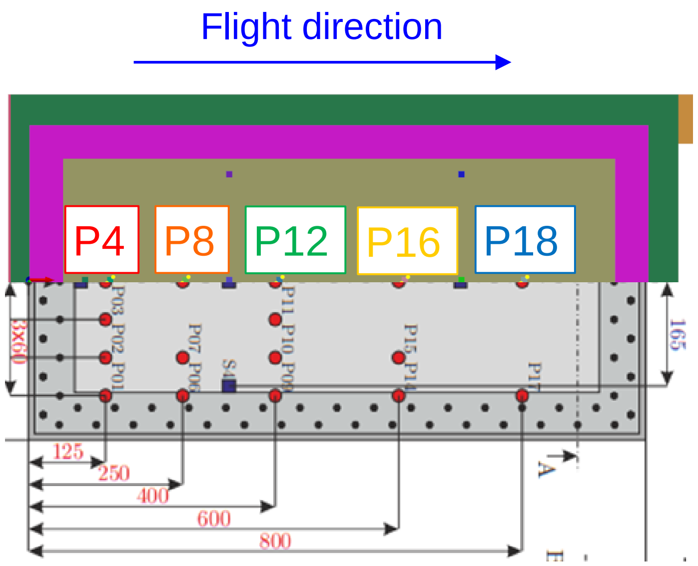


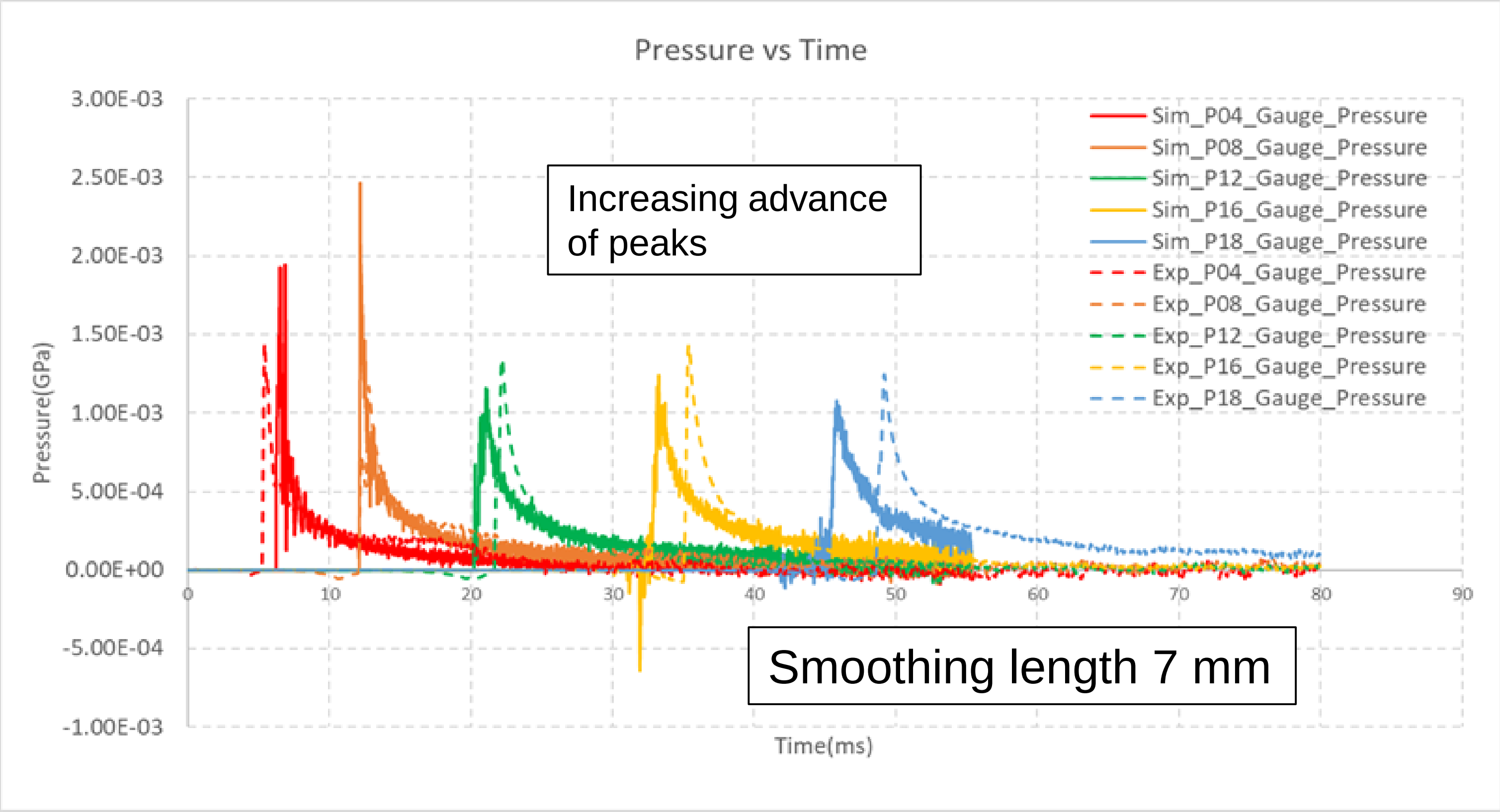
1. Ditching research (Impact phase)

Impact phase (flat panel, FPM simulation)

- Good correlation for rigid specimen
- Good pressure gauge results / slightly too early compared to test
- Still challenges with flexible structure (deformations too large, failure)







Aluminium panel, t = 15 mm, α = 6°, $v_{X,0}$ = 40 m/s

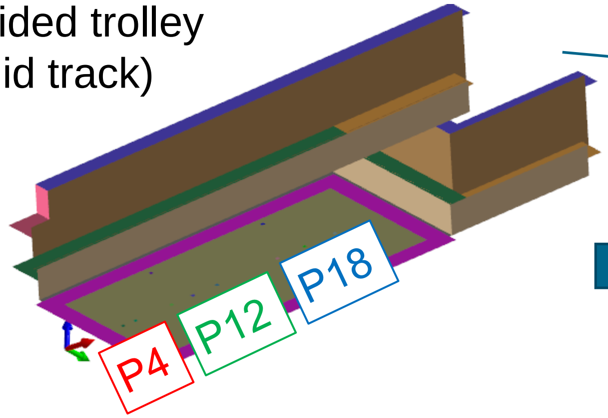
1. Ditching research (Impact phase)

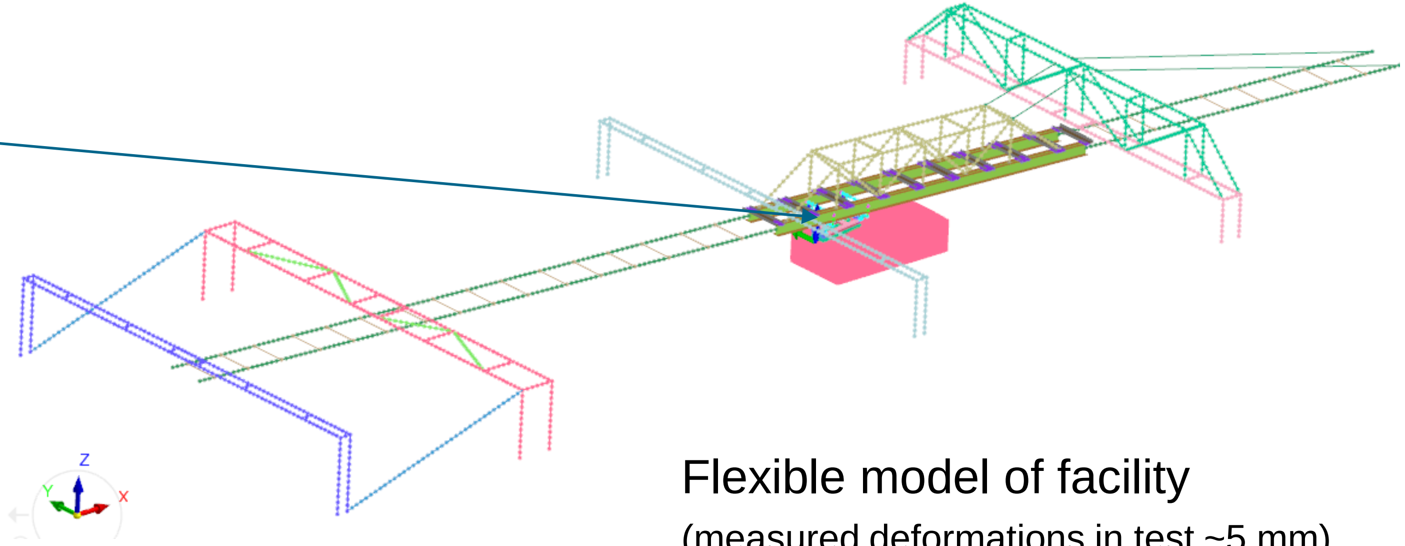
Impact phase (flat panel, FPM simulation)

- Good correlation for rigid specimen
- Good pressure gauge results / slightly too early compared to test

  ➔ Adaptation of model to consider flexibility of facility (current student project)

Guided trolley
(rigid track)

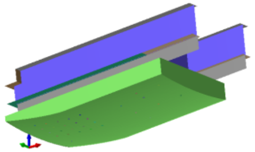




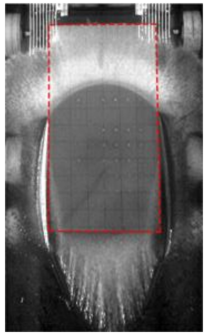
Flexible model of facility
(measured deformations in test ~5 mm)

1. Ditching research (Impact phase)

Impact / Landing phase (Double curved panel, FPM simulation)

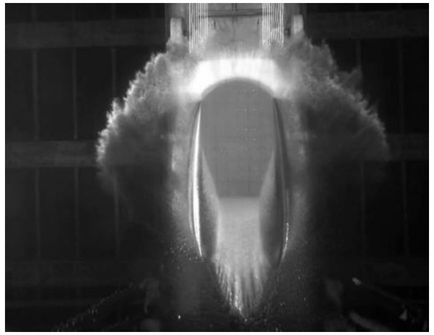


- Cavitation observed in guided impact tests



Bottom view (underwater video)

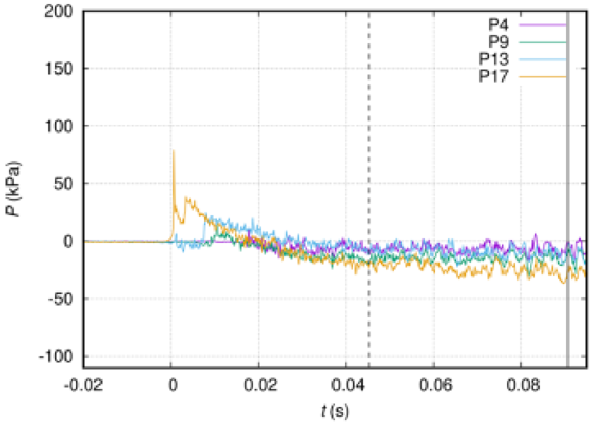
V = 21.0 m/s (no cavitation)

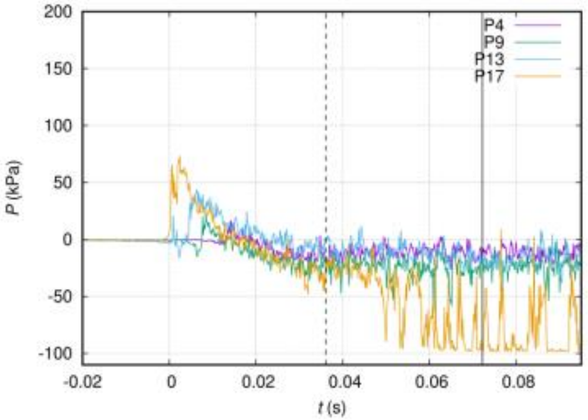


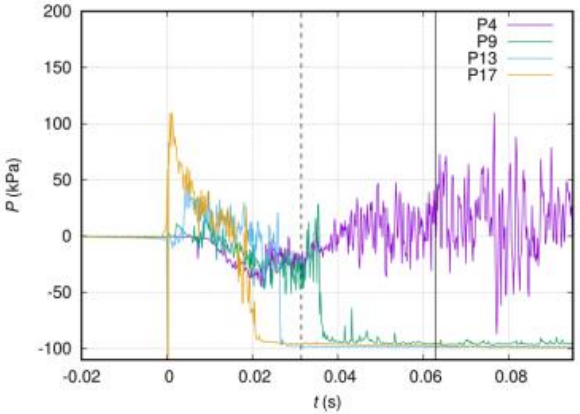
V = 26.8 m/s (almost no cavitation)

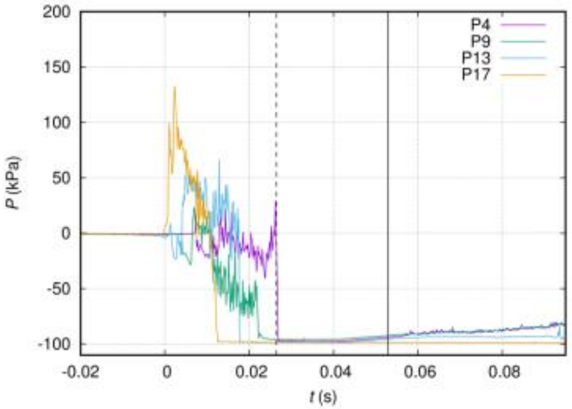
V = 30.6 m/s (**cavitation**)

V = 35.7 m/s (**cavitation + ventilation**)



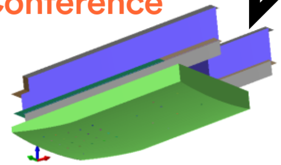






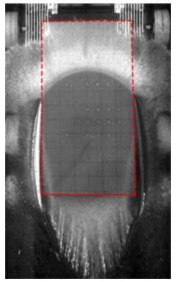
A. Iafrati, S. Grizzi; *Cavitation and ventilation modalities during ditching*, Physics of Fluids 31, 052101 (2019); https://doi.org/10.1063/1.5092559

1. Ditching research (Impact phase)

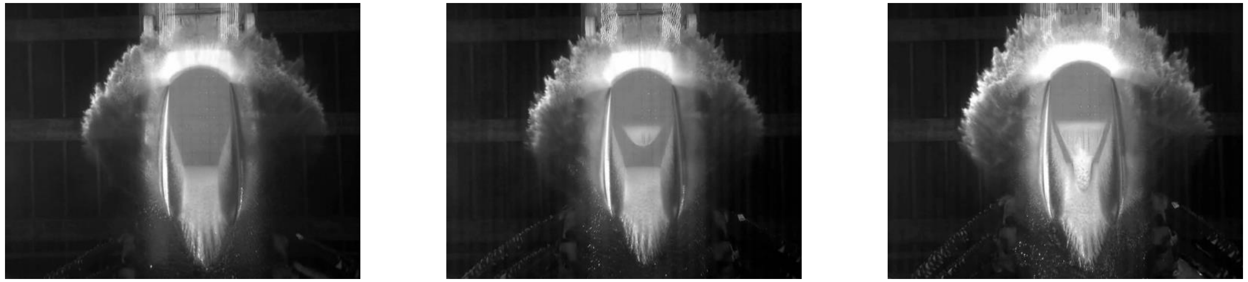


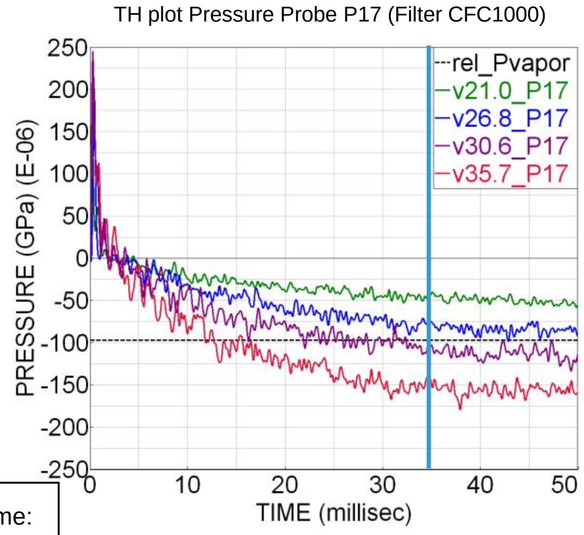
Impact / Landing phase (Double curved panel, FPM simulation)

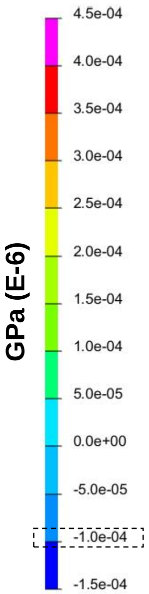
- FPM results with different speeds: gauge pressure at t = 35 ms

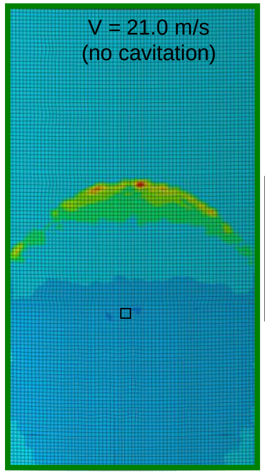


Bottom view

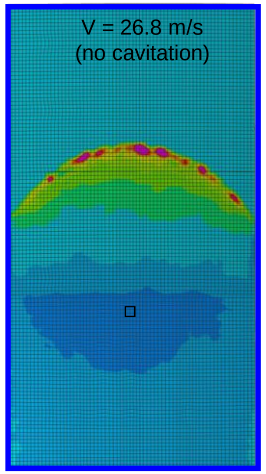




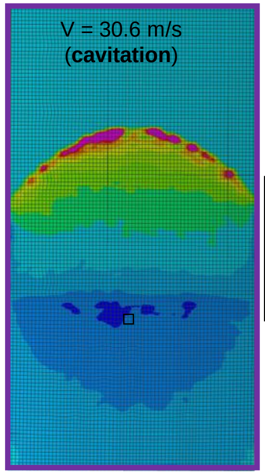




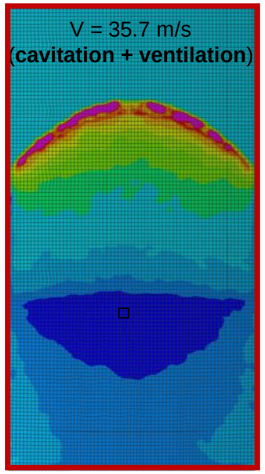
PC Time: ~39h with 16 Cores



PC Time: ~42h with 16 Cores



PC Time: ~31h with 24 Cores



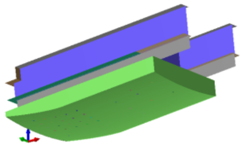
PC Time: ~61h with 16 Cores

➔ Calculated pressure in water drops below vapor pressure (~100kPa) ➔ cavitation to occur

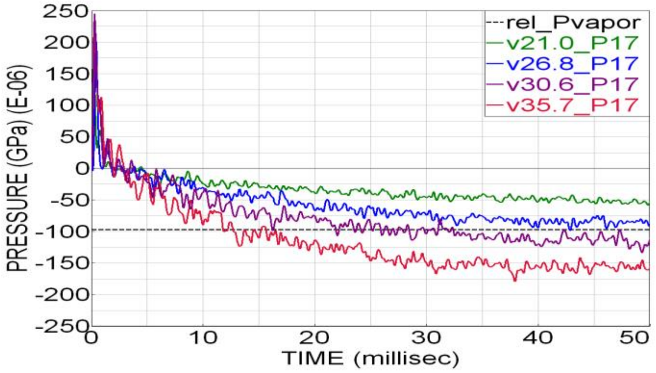
➔ pressure cut-off in UCV Append

1. Ditching research (Impact phase)

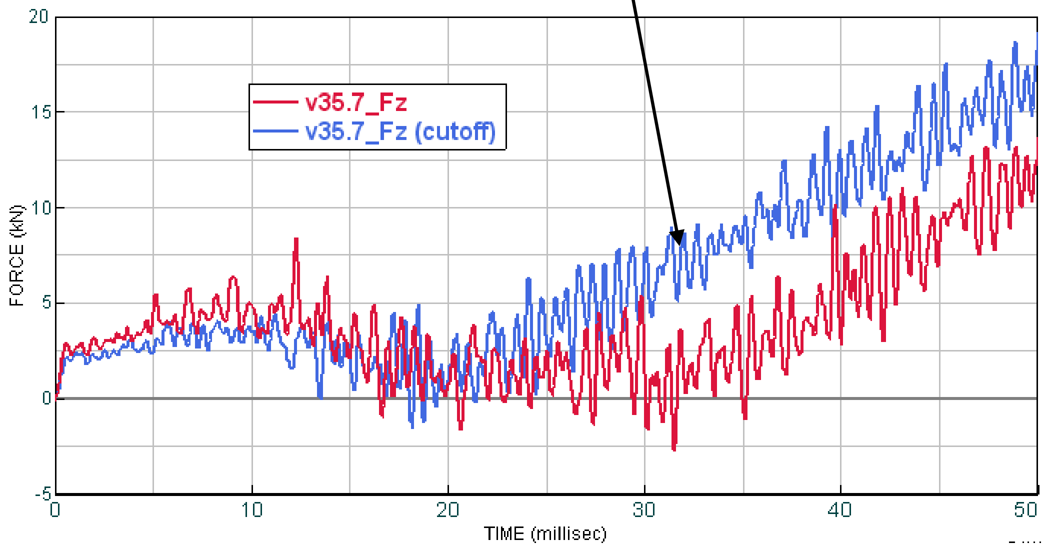
Impact / Landing phase (Double curved panel, FPM simulation)

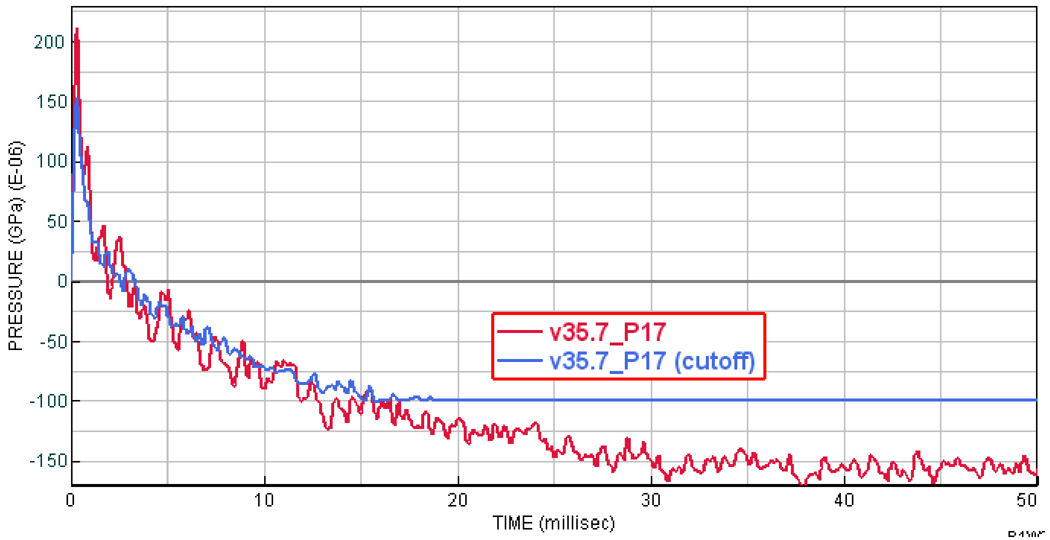


- FPM results with activated asymmetrical pressure cutoff
  - Min dynamic pressure limited to -100kPa (vapor pressure)



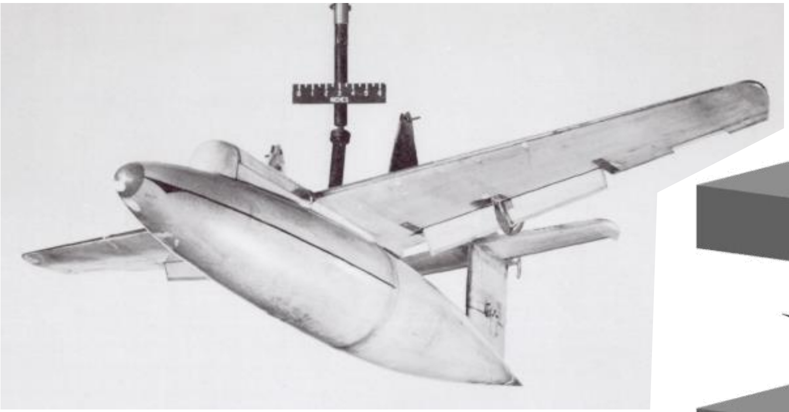
Reduced suction



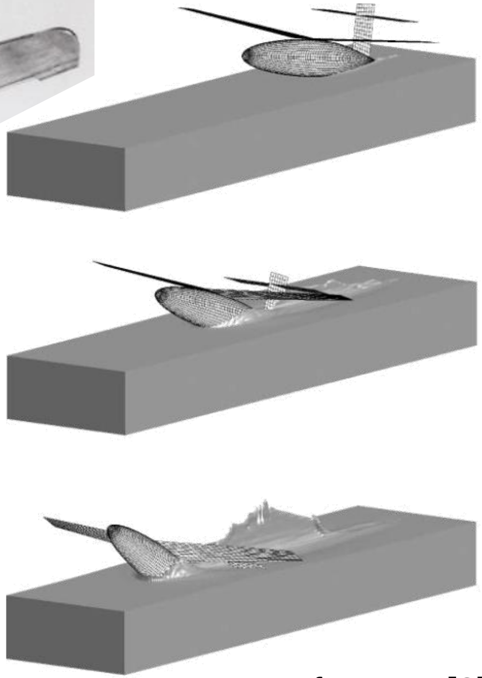


1. Ditching research (landing phase)

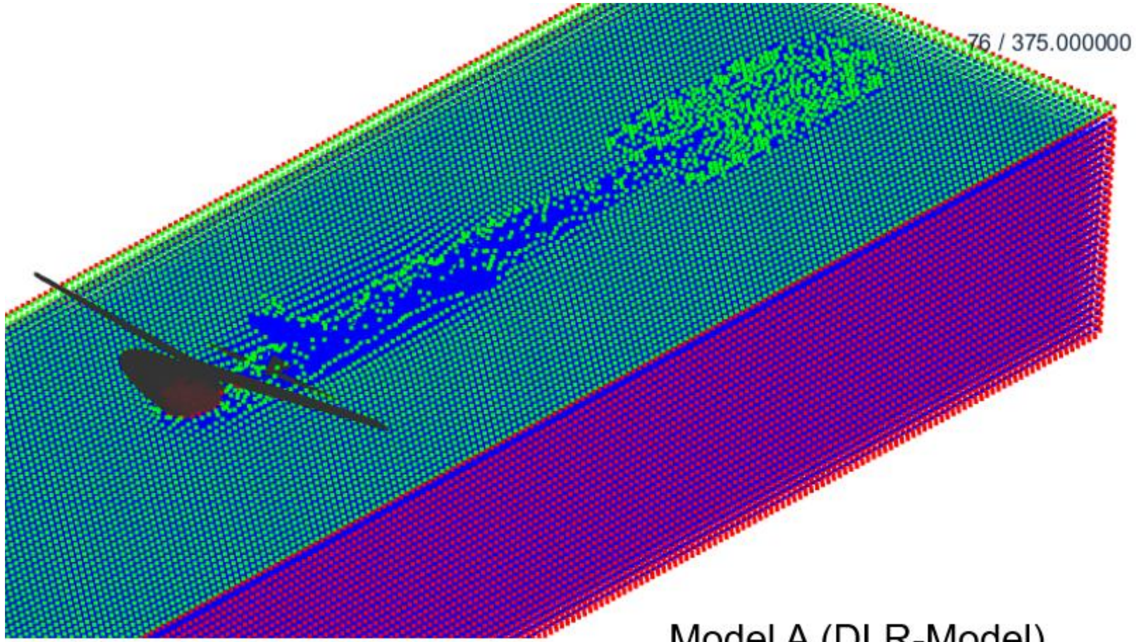
- Moderate period of time (~ 1 s) following the impact phase
- Characterized by free motion of aircraft under acting hydrodynamic forces
- Limited test data (on model tests) available for comparison with simulation results



NACA TN 2929 [1]



ALE reference [2]



Model A (DLR-Model)

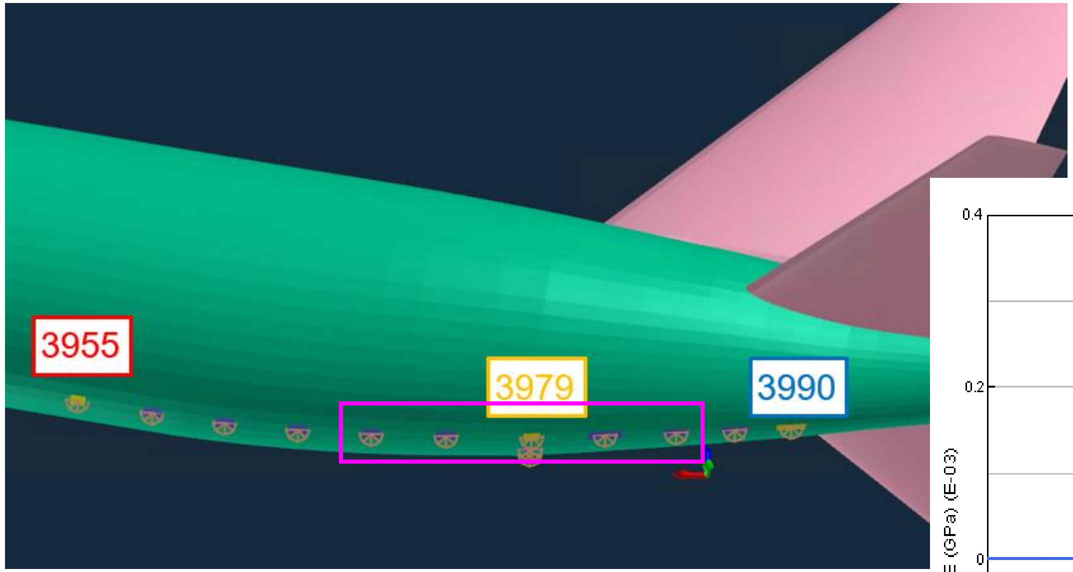
➔ Student internship ongoing

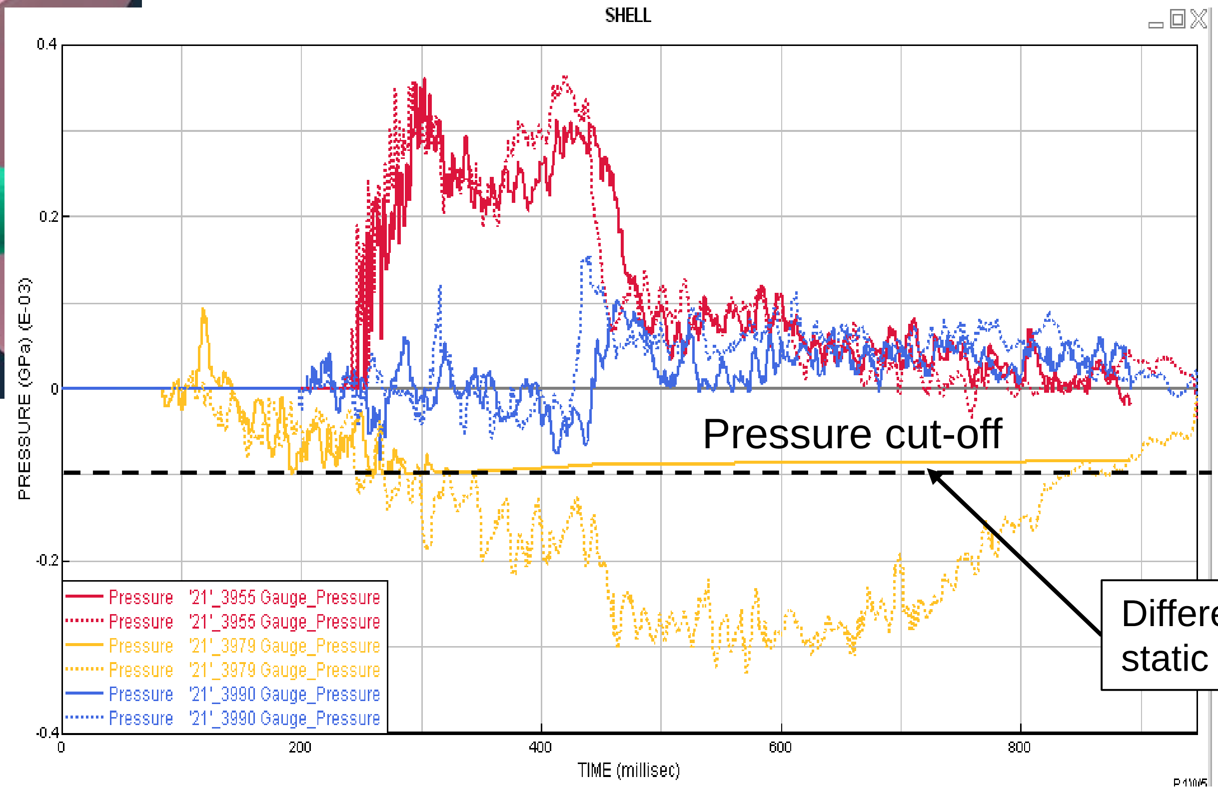
[1] E.E. McBride, L.J. Fischer, NACA TN 2929, 1953
[2] C. Bisagni & M.S. Pigazzini (2017): Modelling strategies for numerical simulation of aircraft ditching, International Journal of Crashworthiness, DOI: 10.1080/13588265.2017.1328957

1. Ditching research (Impact / landing phase)

Impact / landing phase (Full aircraft)

- Influence of gauge pressure cut-off at -100kPa (cavitation pressure)

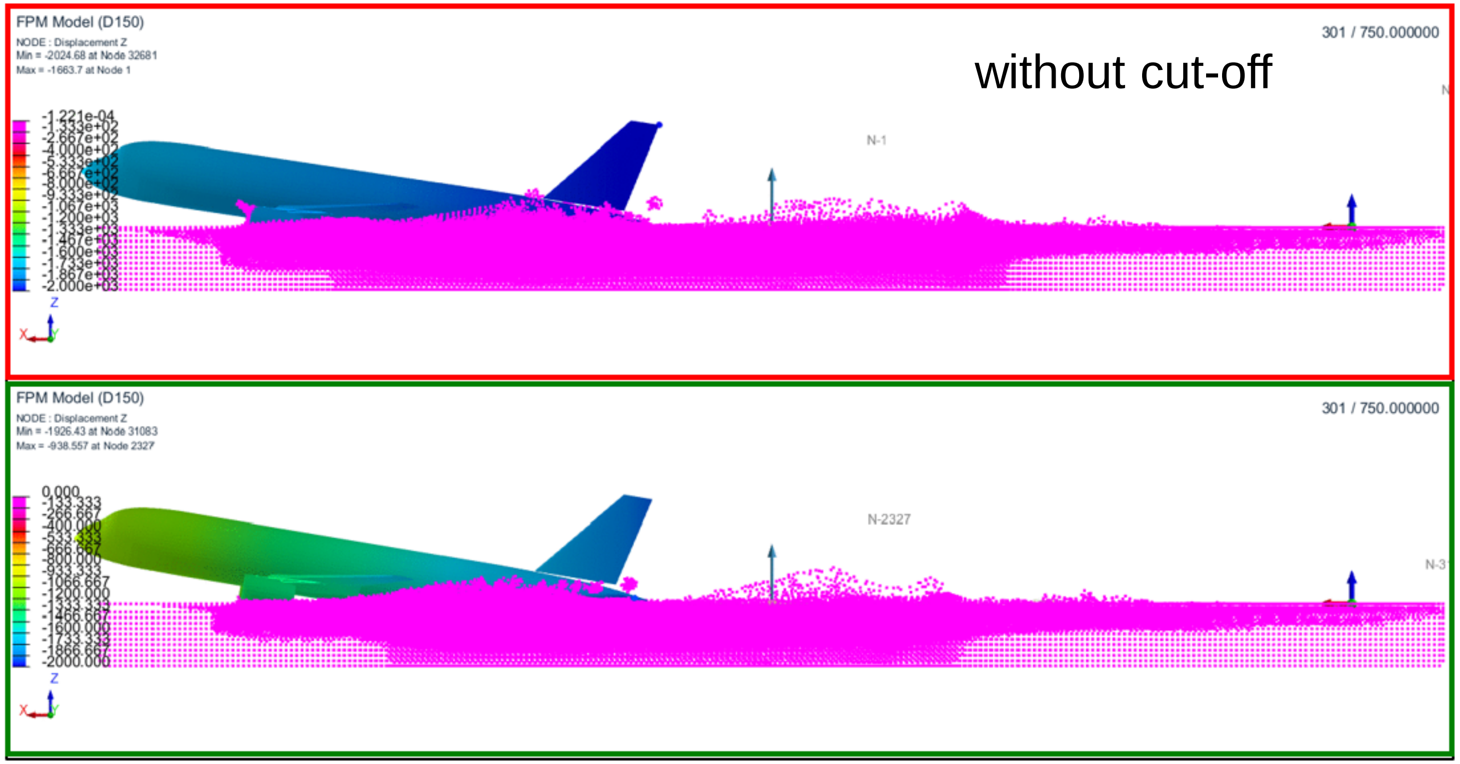


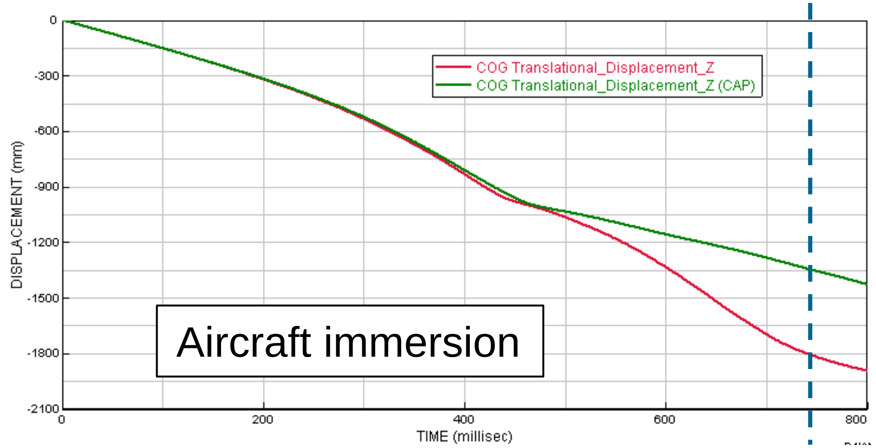


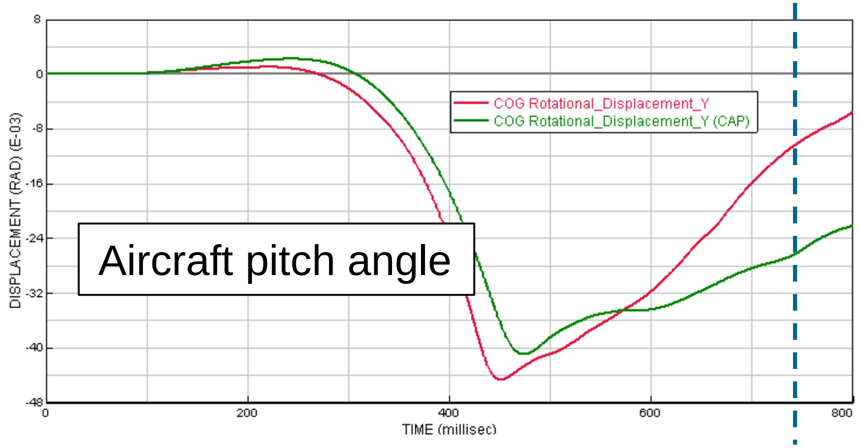
1. Ditching research (Impact / landing phase)

Impact / landing phase (Full aircraft)

- Influence of gauge pressure cut-off at -100kPa (CAP)



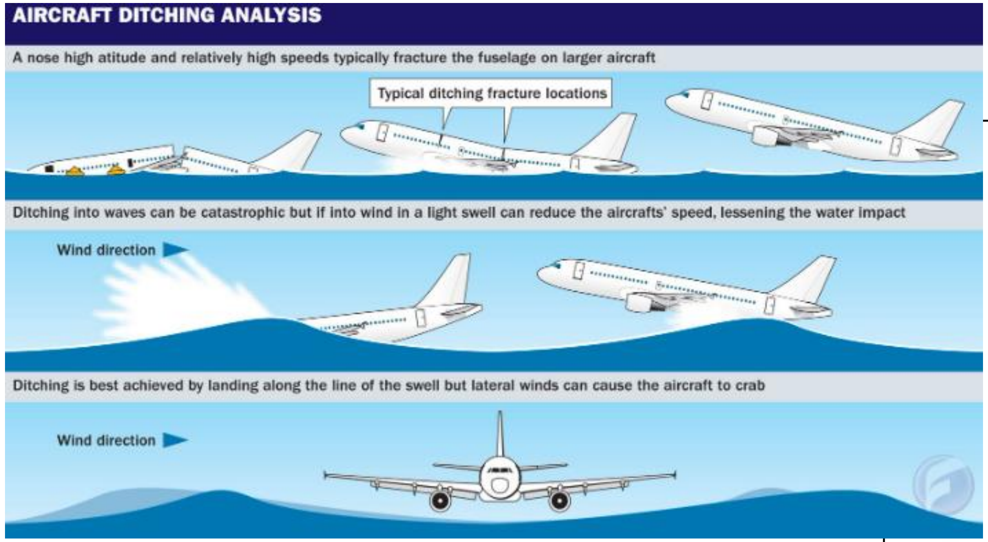




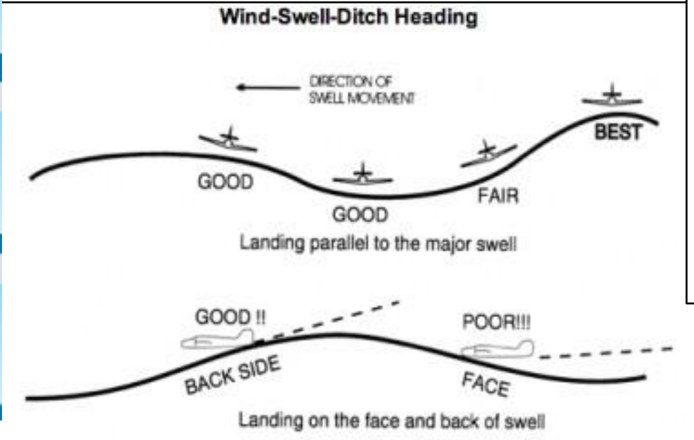
Influence of pressure cut-off on aircraft kinematics

1. Ditching research (Influence of rough water)

- With the potential of FPM (implicit flow solver, large timesteps) studies on Influence of rough water on ditching behavior seem feasible (not performed with HiFi methods until now)
- Different scenarios may be analyzed and evaluated (future work)
  - Wave characteristics, relative motion, shift of impact point



[1]



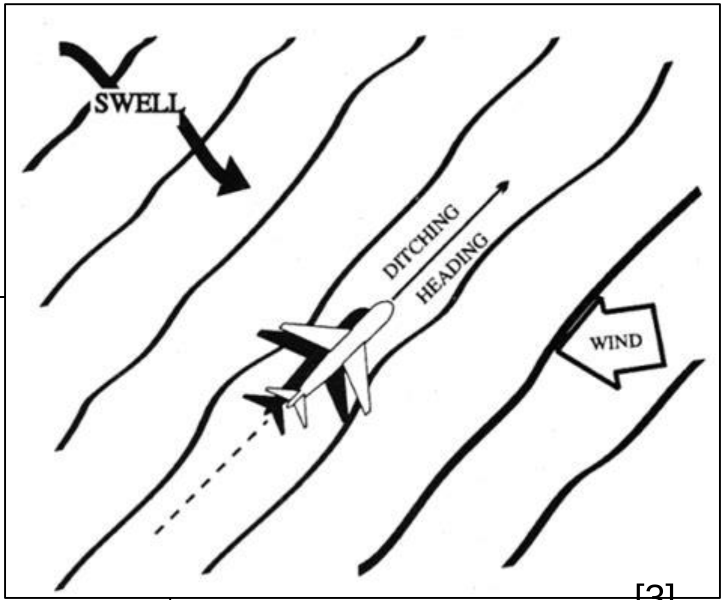
a. A successful aircraft ditching is dependent on three primary factors. In order of importance they are:

1. Sea conditions and wind.

2. Type of aircraft.

3. Skill and technique of pilot.

[2]



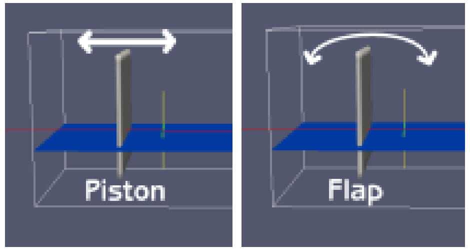
[3]

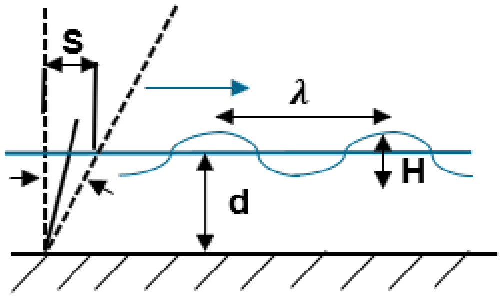
[1] Widhigenzo.blogspot.com
[2] https://hubpages.com/travel/How-To-Ditch-An-Airplane
[3] avstop.com/ac/aim/chap6/aim0603.html

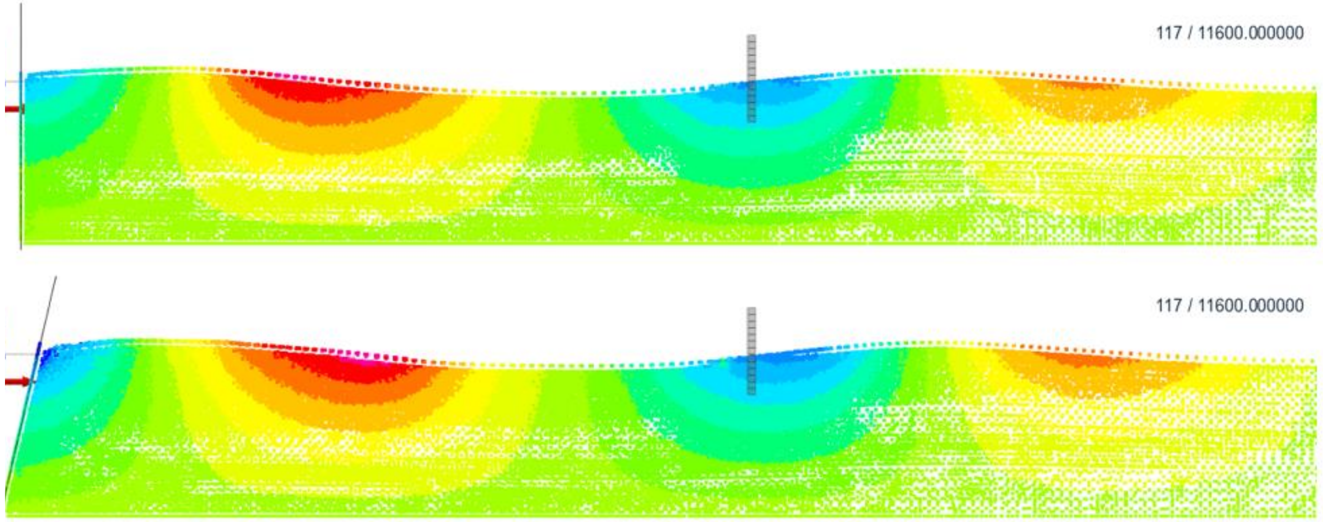
1. Ditching research (Influence of rough water)

Wave generation in a water domain

- Different wave generation methods tested (e.g. piston vs. flap)
- Size and kinematics of the waves validated against wavemaker theory
- Process established in DLR process tool PANDORA







Step 1: Desired waves characteristics (Airy wave theory):

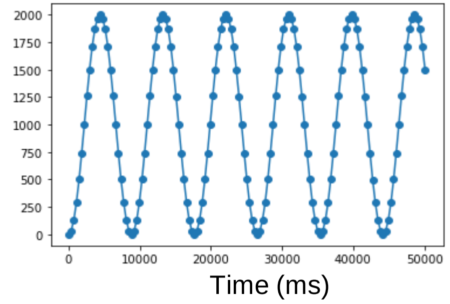
- Wavelength λ
- Wave height H
- Water depth d

Wavemaker theory

Step 2: Calculation of stimulator inputs:

- Frequency
- Amplitude:
  - Piston: distance (s)
  - Flap: angle (α)

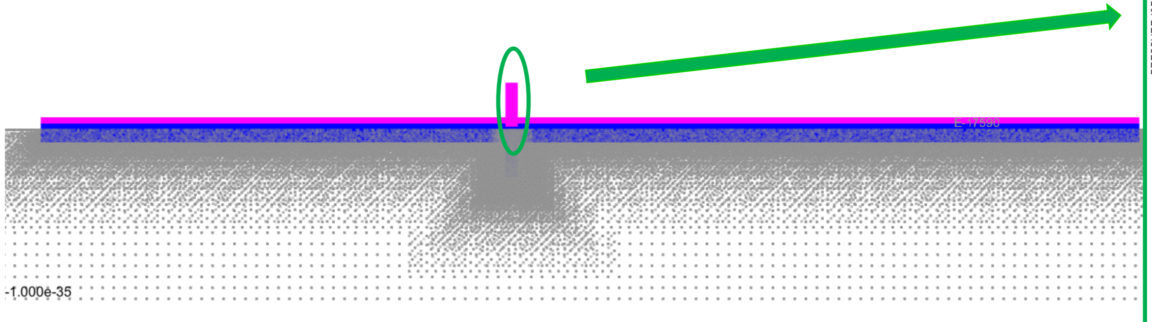
Step 3: stimulator definition (in VPS)



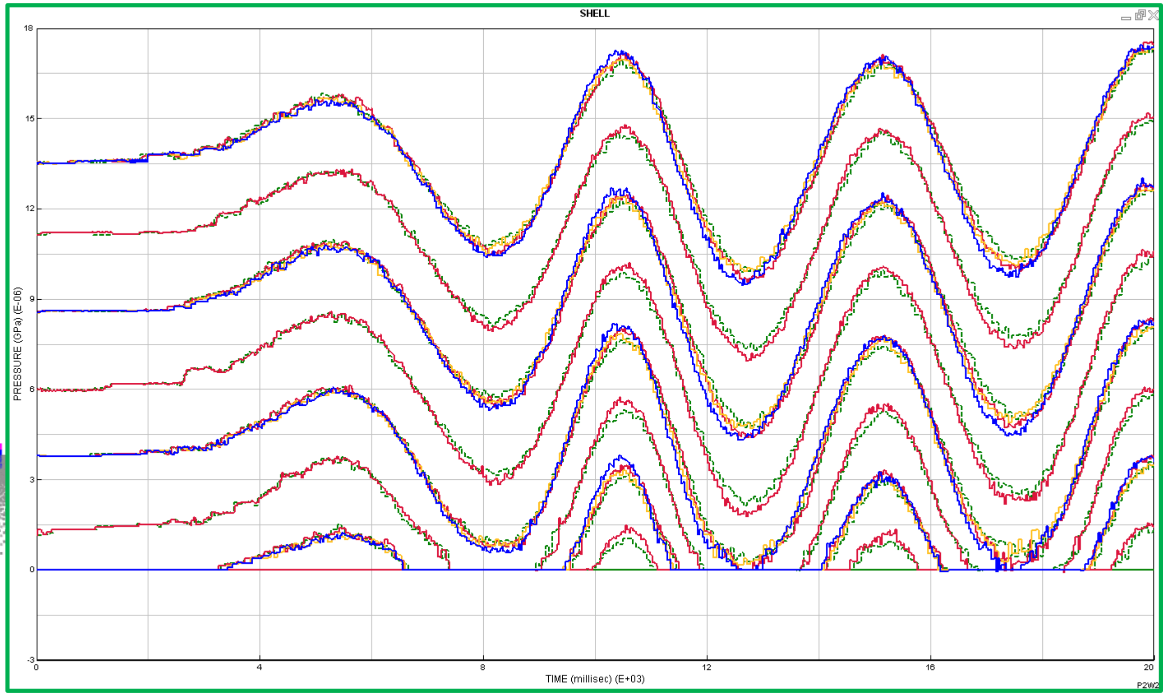
1. Ditching research (Influence of rough water)

Wave generation in a water domain ➔ validation

- Target: Calculation of input parameters to achieve waves with 30m length and 1.0m height
- Run piston and flap simulations with different FPM timestep parameter FPMDTMAX (30-60 ms!)
- Detailed analyses of wave pattern
  - Wave length between 29 and 30 m ✔
  - Wave height between 0.9 and 1.0 m ✔
  - Almost no influence of FPMDTMAX (just computing time) ✔



Piston: FPMDTMAX 30
Piston: FPMDTMAX 60
Flap: FPMDTMAX 30
Flap: FPMDTMAX 60



Pressure on the side wall / prop. to water height

1. Ditching research (Influence of rough water)

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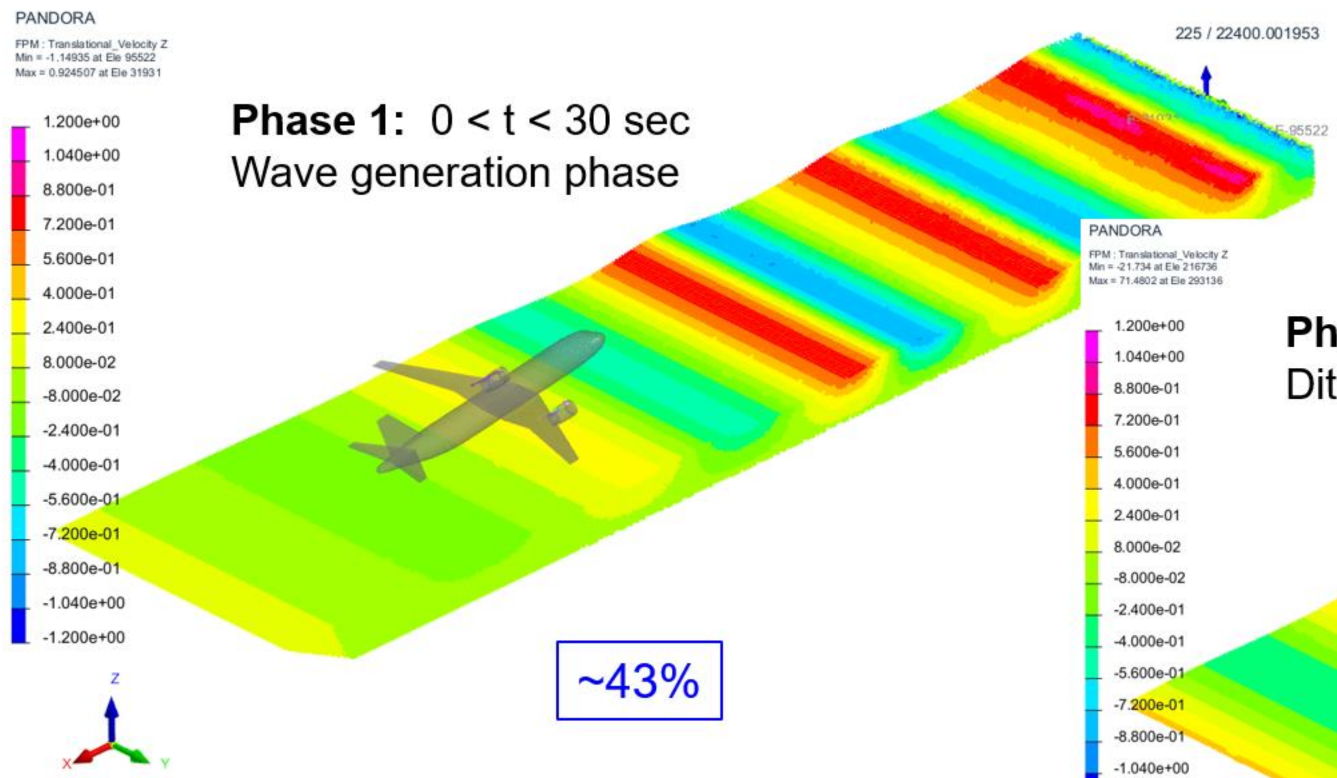
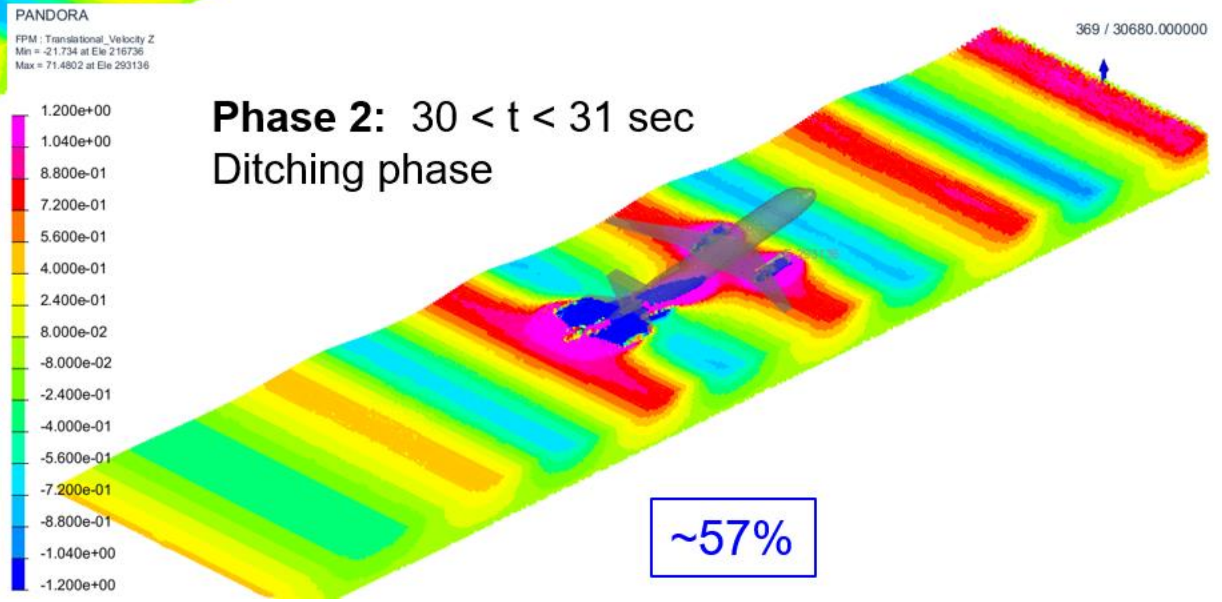
Exemplary application of FPM for ditching, Landing phase (1/3)

Transfer to aircraft ditching on waves: 2 stage approach with adapted runtime parameters (e.g. timestep)



Timestep: 30 ms (1000 Iterations)
0:55 h (64 Cores)

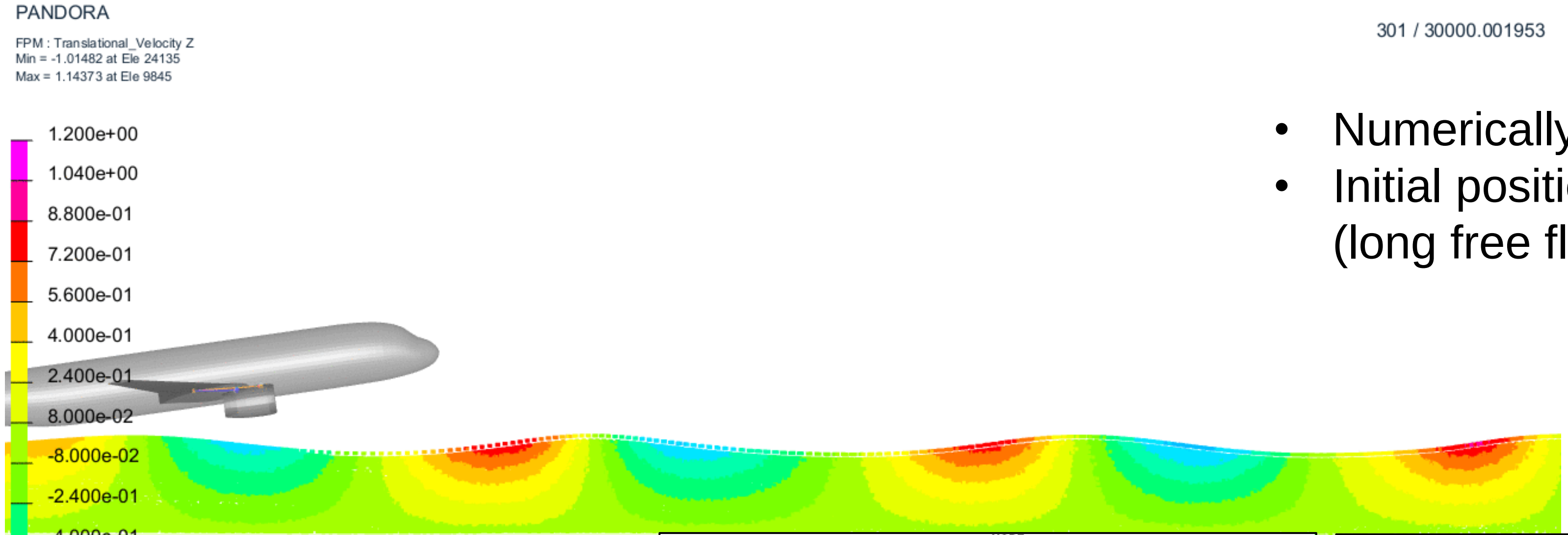


Timestep: ~ 0.8 ms (1058 Iterations)
1:13 h (64 cores)

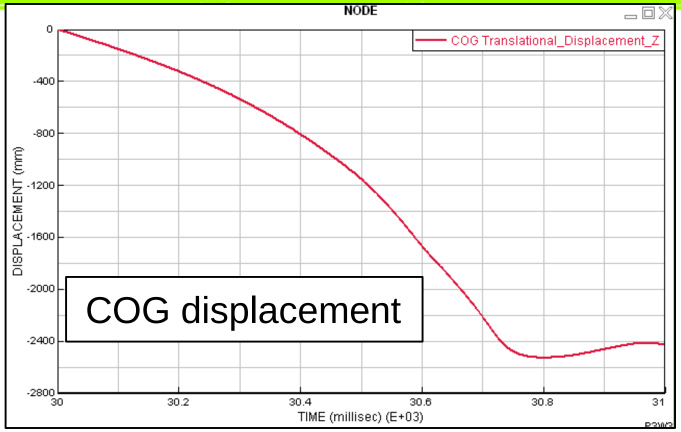
1. Ditching research (Influence of rough water)

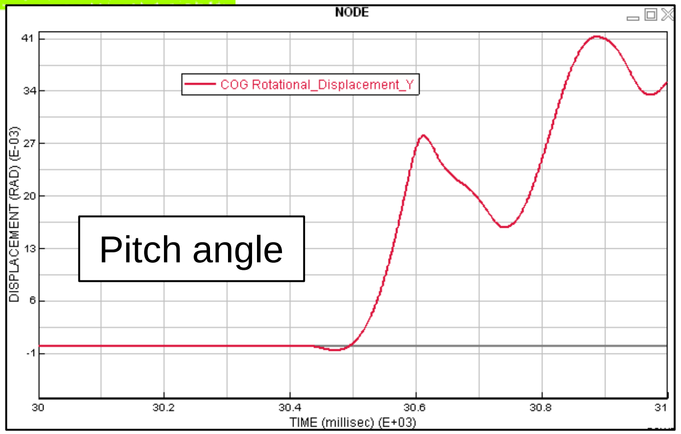
Exemplary application of FPM for ditching / landing phase (2/3)

Evaluation of 2nd stage (ditching)



- Numerically stable solution
- Initial position slightly too high (long free flight period)

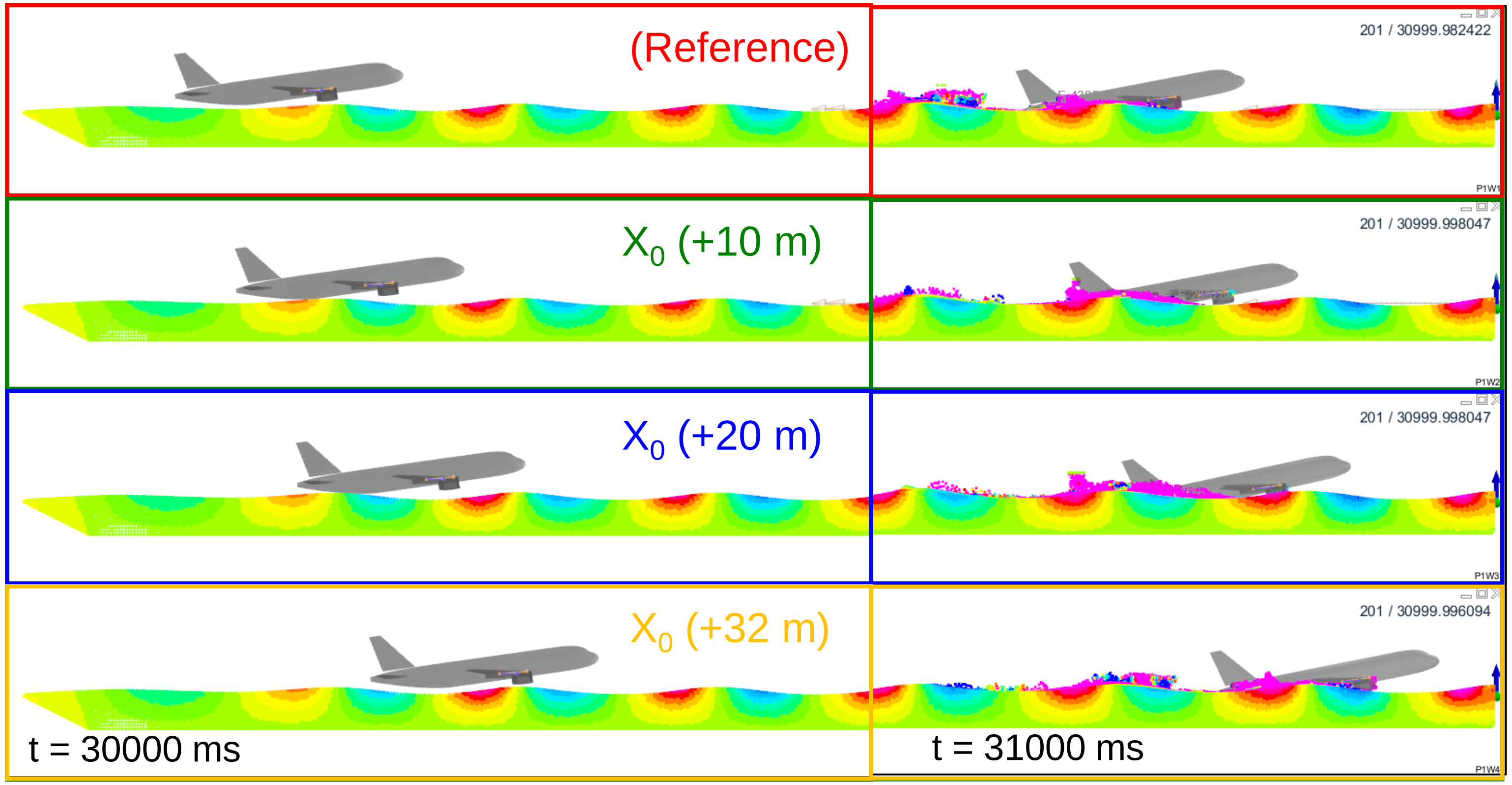


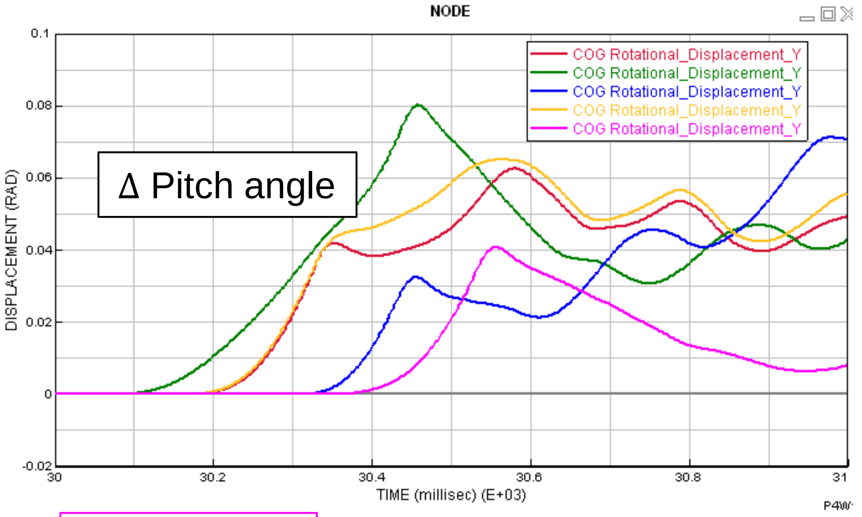


1. Ditching research (Influence of rough water)

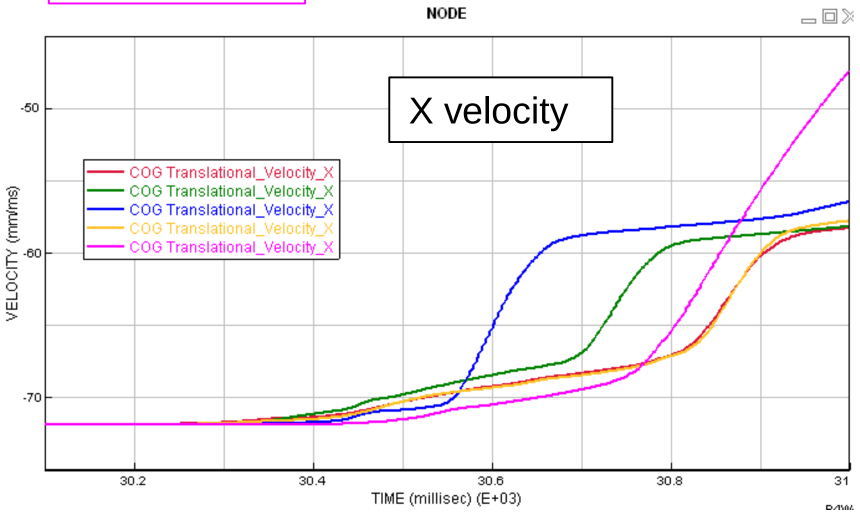
Exemplary application of FPM for ditching / landing phase (3/3)

Evaluation of 2nd stage (ditching) with variation of initial position





Calm water

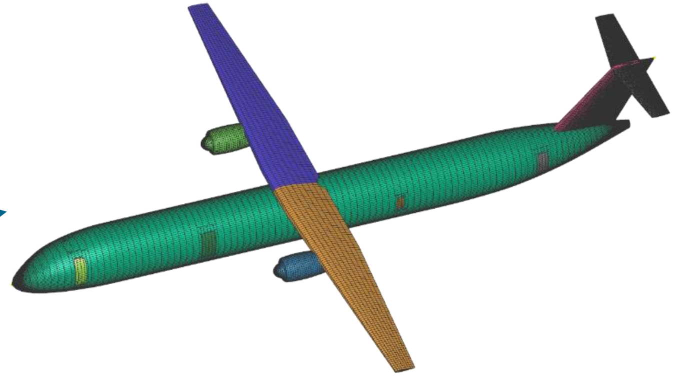


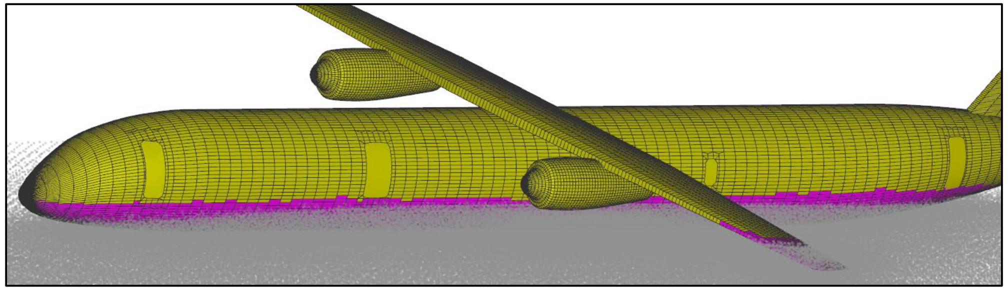
1. Ditching research (Influence of rough water)

Exemplary application of FPM for ditching / floatation phase

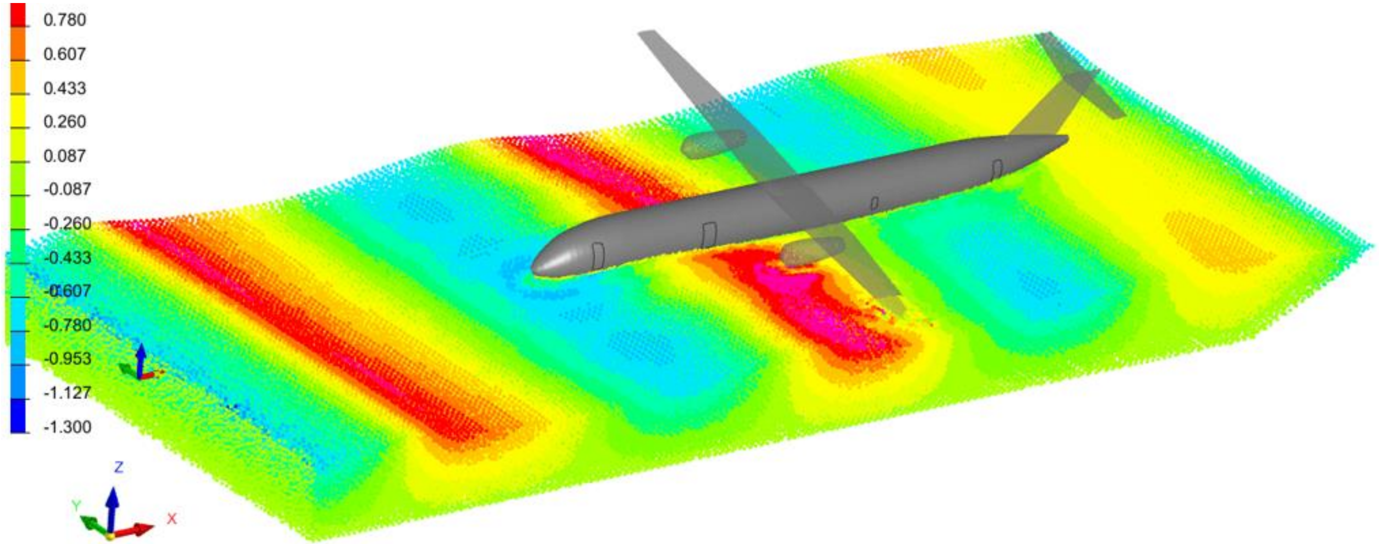
Investigation of the static floatation characteristics of generic aircraft model

- Development of an automated process for fixed wing aircraft
  - Automatic generation of aircraft surface
    (based on common aircraft description format CPACS (www.cpacs.com))
  - Positioning almost in equilibrium using analytical approach in inhouse tool PANDORA
  - Prediction of the waterline state compared to the door sills
- Influence of different type of waves and wave heights on dynamic waterline





Evaluation of waterline (calm water)
(heavy electric aircraft configuration)



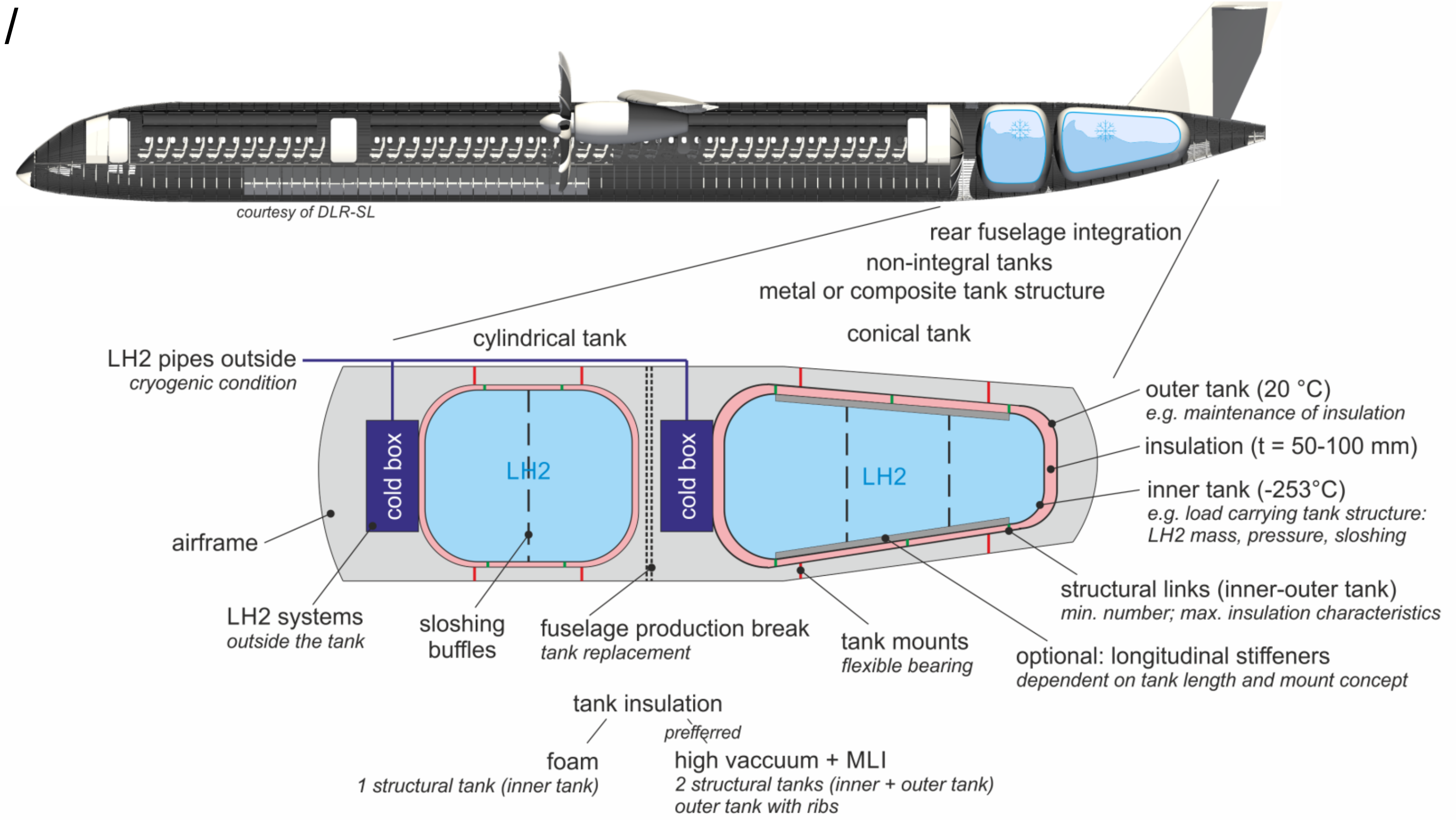
Floatation analysis including waves

2. Sloshing in LH2 tanks (since 2023)

- 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
- Therefore, special tanks have to be integrated in the fuselage (or in specific wing pylons)
- LH2 tanks will consist of inner / outer tank with isolation

Challenges

- LH2 tanks shall not bear flight loads (design question)
- 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



2. Sloshing in LH2 tanks

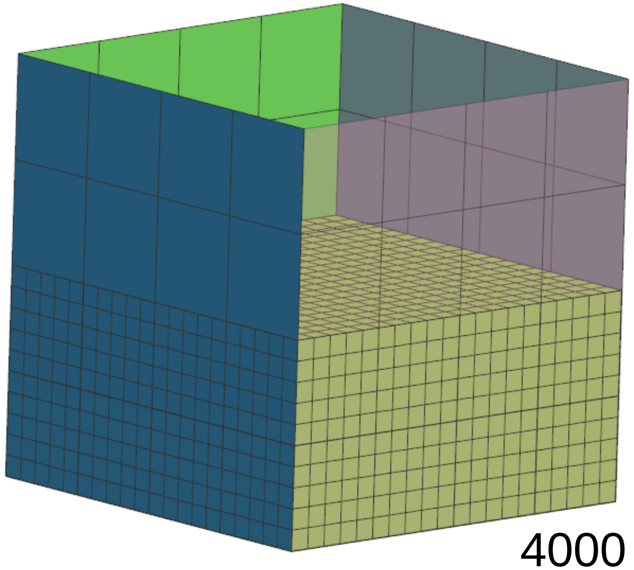
Purpose of first feasibility study (in progress)

- Evaluation of structural loads on realistic tank structure (at the tank attachments)
- Focus on <u>structural loads</u> / not on details of flow physics
- Consideration of different load cases (e.g. rejected take-off (~40 s), crash loads (later stage))
- Studies shall include:
  - Evaluation of numerical methods to model FSI phenomena (SPH vs. FPM)
  - Modelling of loading conditions
    - rotated acceleration vector (commonly used)
    - real tank movement (required for crash)
  - Influence of baffles in the tanks
  - Evaluation of exemplary tank attachments
  - …

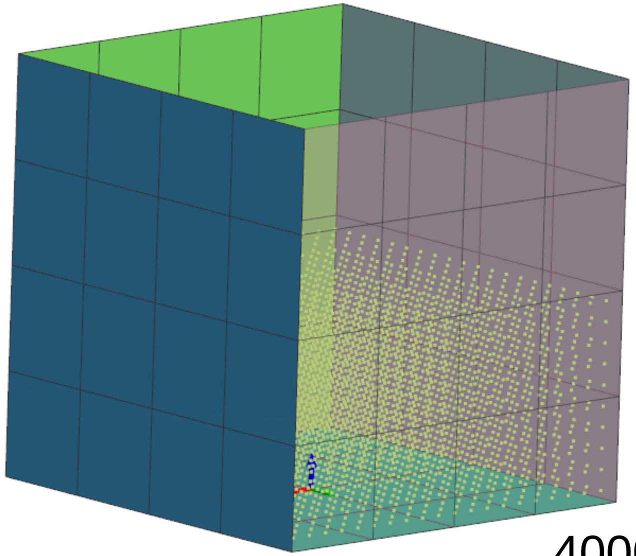
2. Sloshing in LH2 tanks

Basic comparison of FPM with alternative approaches

- Box (rigid) of 1 x 1 x 1 m in shells (coarse mesh)
- Fluid representation
  - FPM:
    - Just free surface definition at z = 500 mm, Smoothing length 100
    - Predefined water properties in VPS
    - Cube as wall definition
  - Hydrodynamic solids (HS):
    - Mesh of solid elements generated within tank (~50 mm edges)
    - distance to tank 1 mm in all directions ➔ 124.251 g per element
    - Water properties : Hydrodynamic solid (MAT7) with polynomial EOS
    - Contact (type 34) thickness: 1mm
  - SPH:
    - Positioned at COG of all hydrodynamic elements (identical density) ➔ 124.251 g per particle
    - Identical water properties with material type 7 and polynomial EOS
    - Contact (type 34) between tank and particles, contact Thickness 25.9 mm
    - Additional SPH CONTROLS card



4000 solids



4000 particles

2. Sloshing in LH2 tanks

Basic comparison of FPM with alternative approaches

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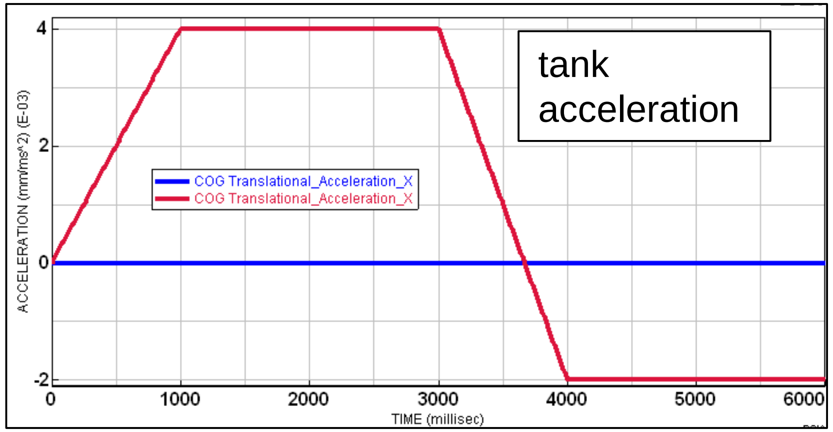
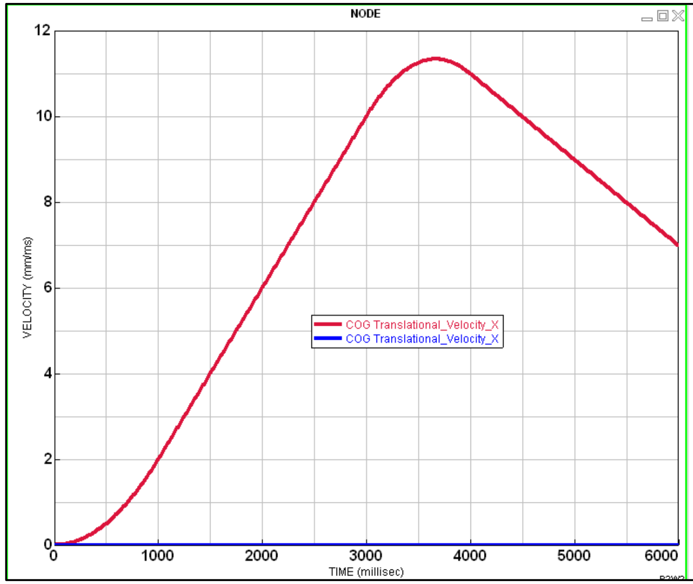
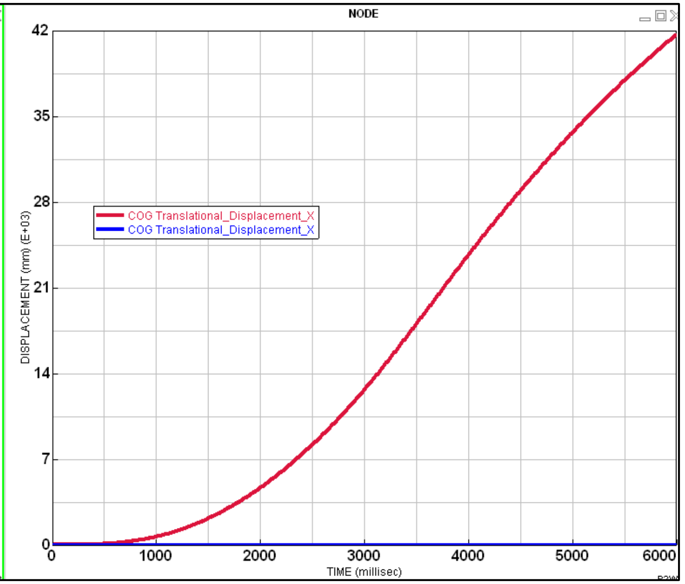
- For the three alternative fluid modelling option the following two loading conditions have been analyzed ➔ total of six variations!
- Loading 1: similar to rejected take-off (tank moves)
  - Total time: 6 s
  - Acceleration +0.4 g for 3 s (linear increase over first second)
  - Deceleration of -0.2 g 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





2. Sloshing in LH2 tanks (comparison of FSI methods)

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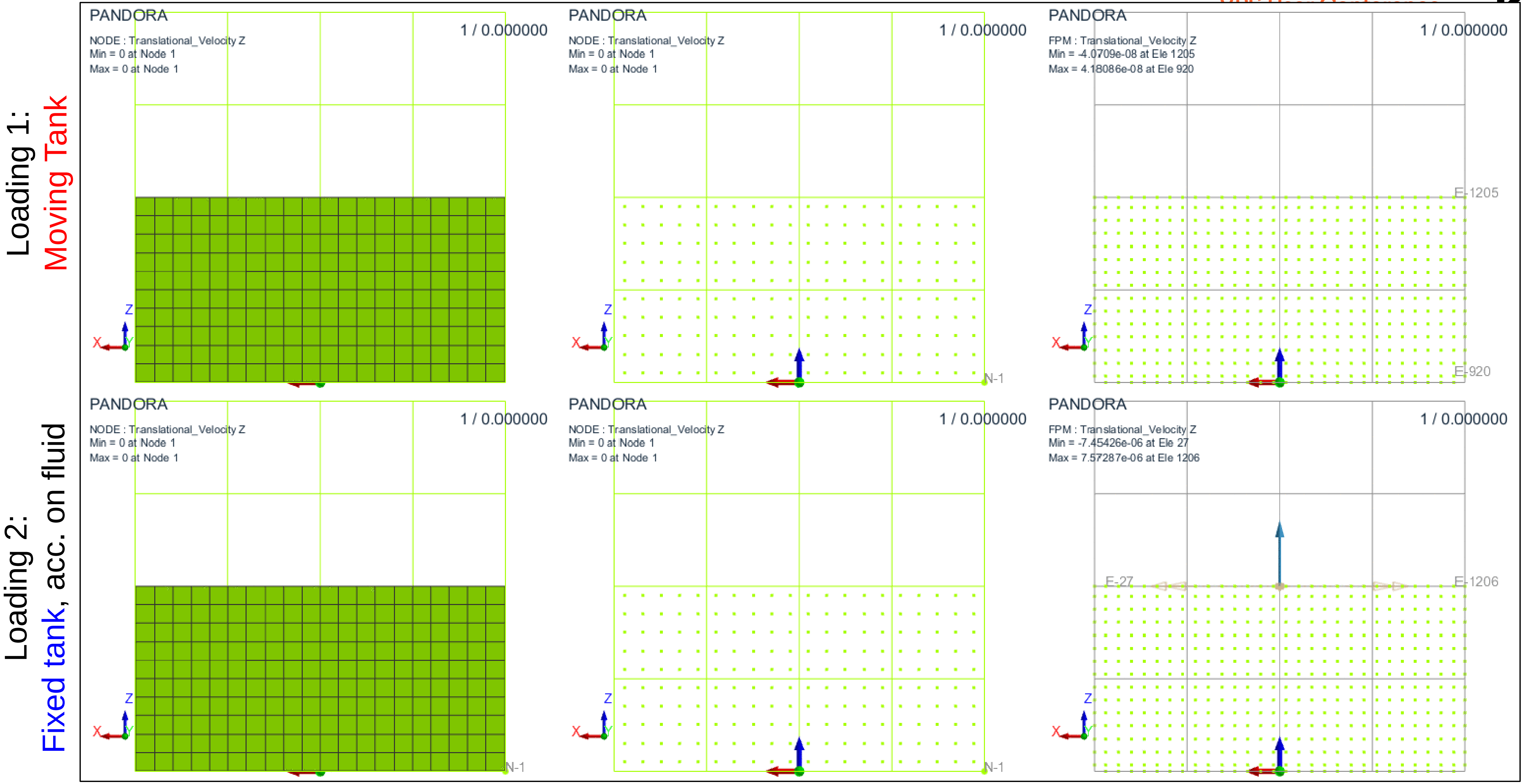
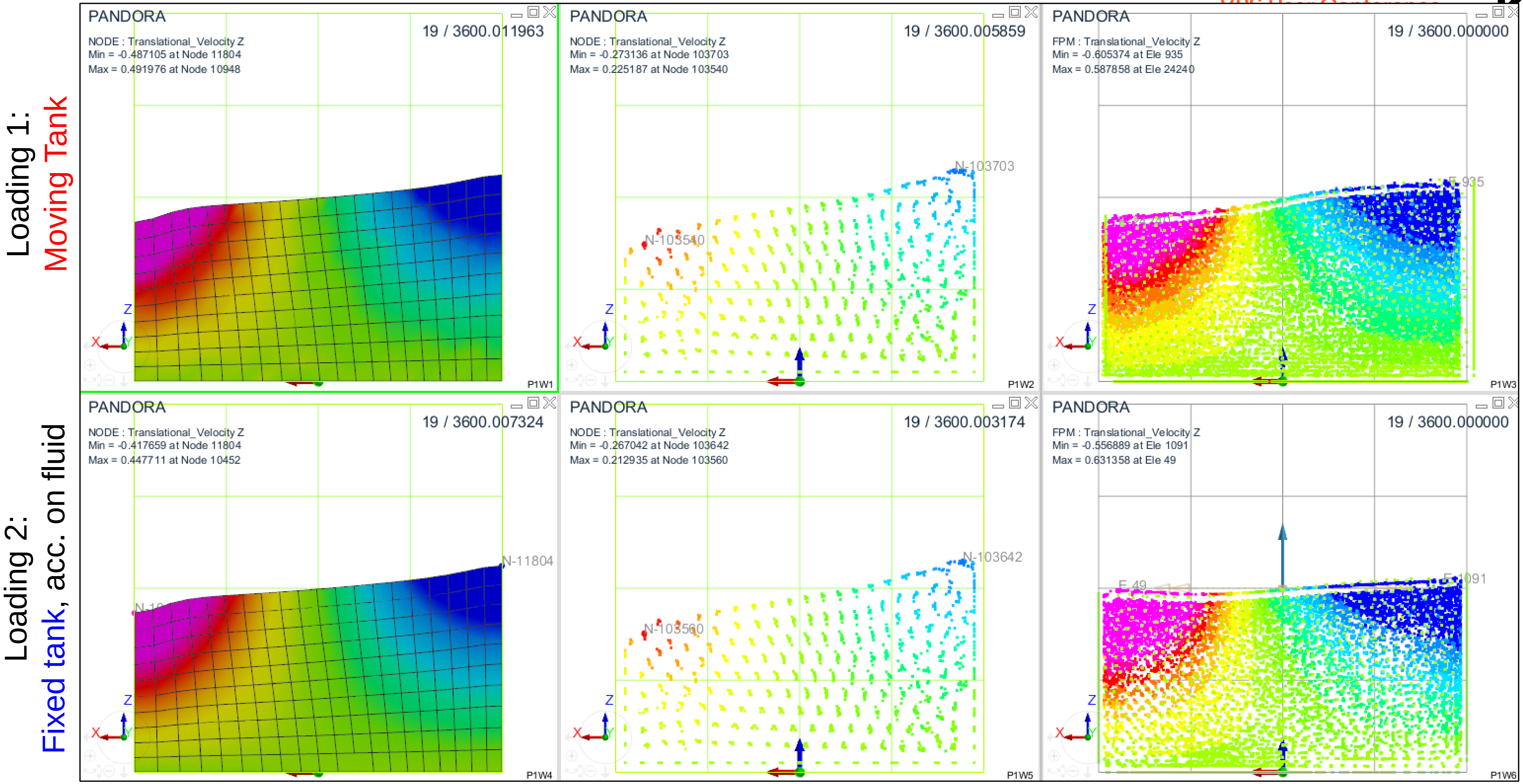


➔ Similar behavior in all simulations

2. Sloshing in LH2 tanks (comparison of FSI methods)

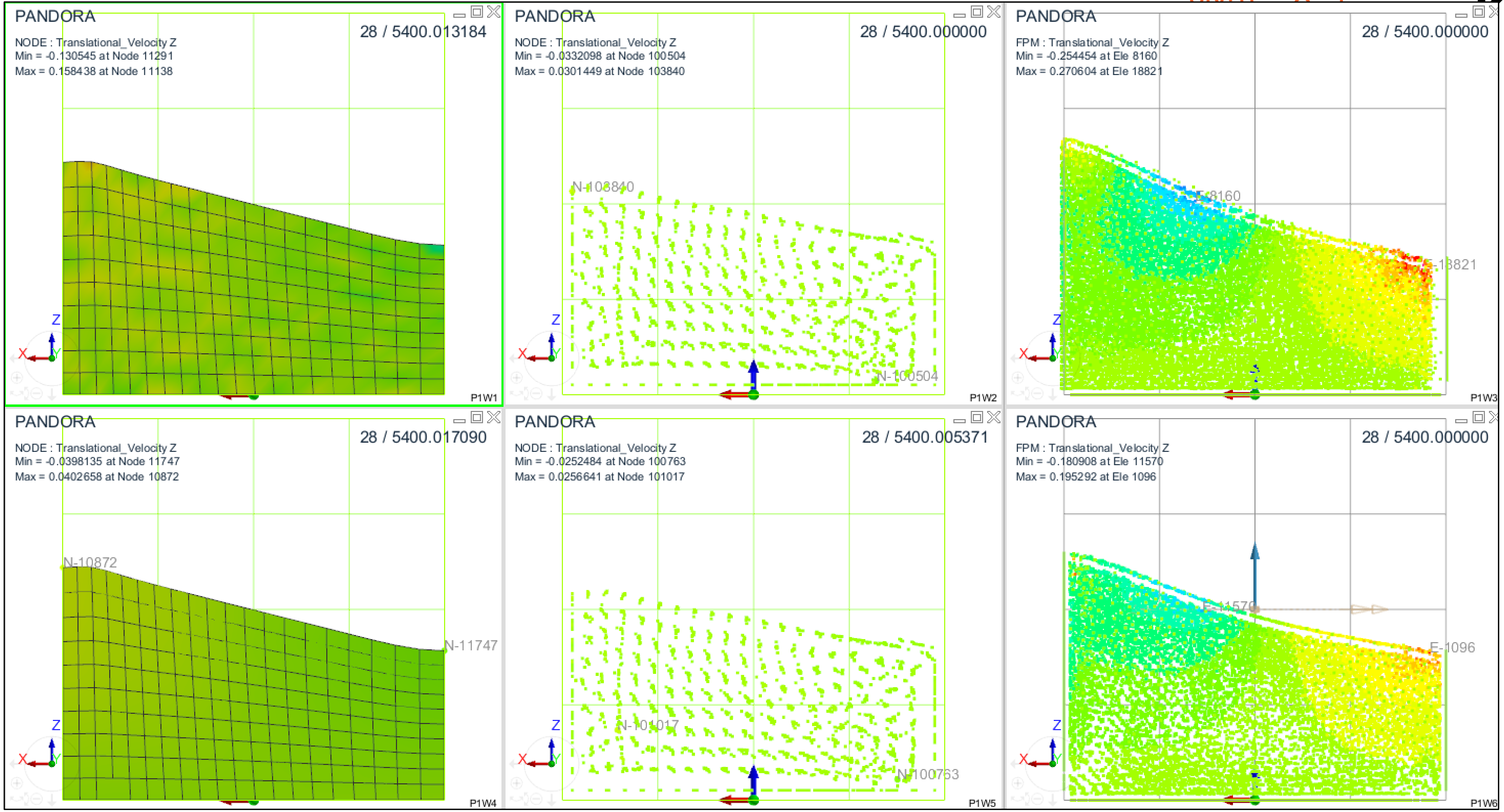


➔ Similar behavior in all simulations

2. Sloshing in LH2 tanks (comparison of FSI methods)

Loading 1: Moving Tank

Loading 2: Fixed tank, acc. on fluid



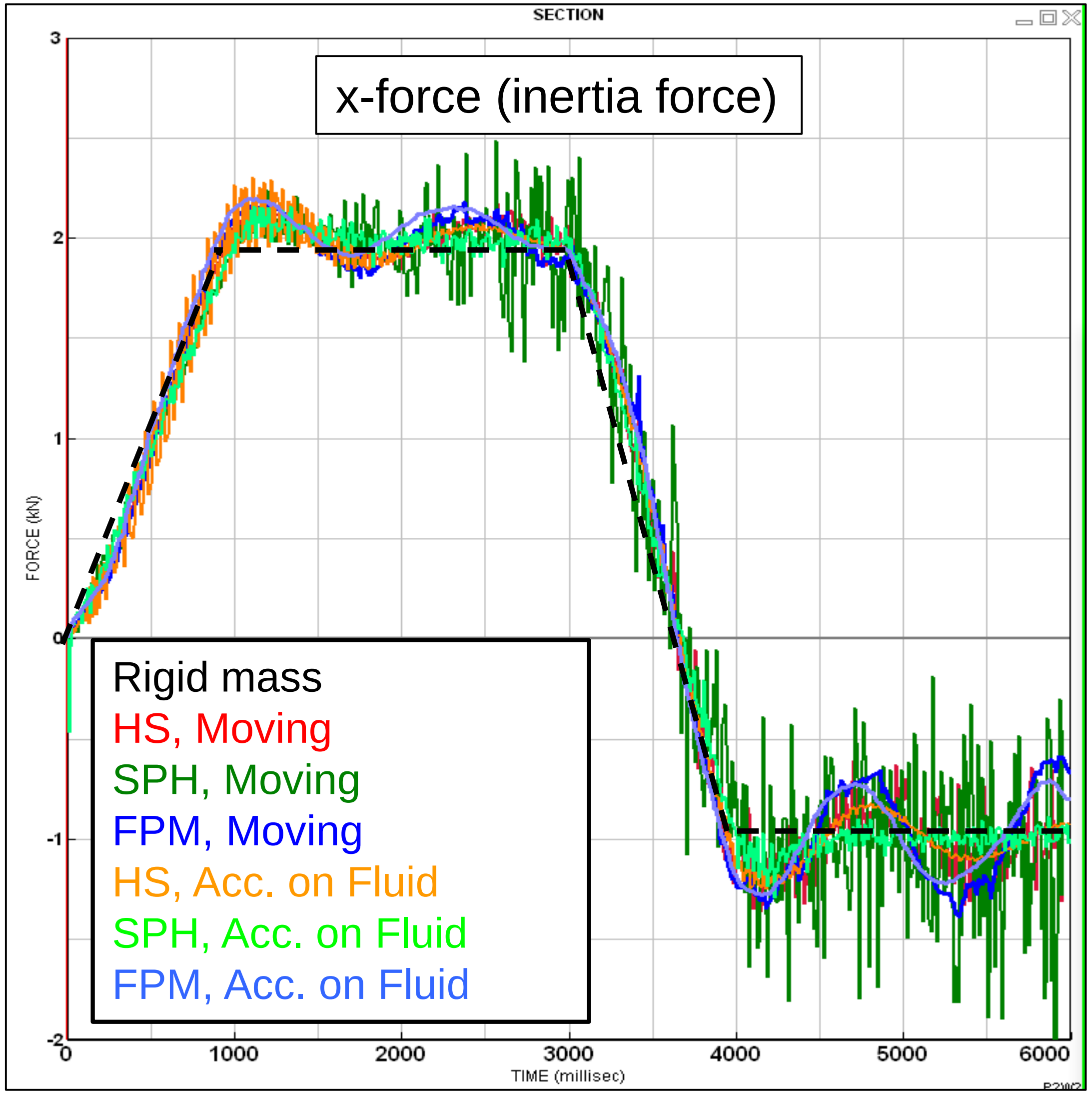
➔ Similar behavior in all simulations

2. Sloshing in LH2 tanks

Comparison of reaction forces / computing costs

Method	loading	Iterations	Elements /points	Computing time (laptop)
HS	Moving	344609	4000	00:01:57
HS	Acc. on H2O	347129	4000	00:02:11
SPH	Moving	819654	4000	01:10:19
SPH	Acc. on H2O	833582	4000	01:11:02
FPM	Moving	1736	26174	00:16:25
FPM	Acc. on H2O	306	23344	00:02:59

- HS are cheap, but considered limited to moderate flow (finally not usable in general)
- SPH is very expensive compared to FPM (due to small timestep / many iterations)
- FPM is the easiest method to set-up the model (just definition of free surface plane)

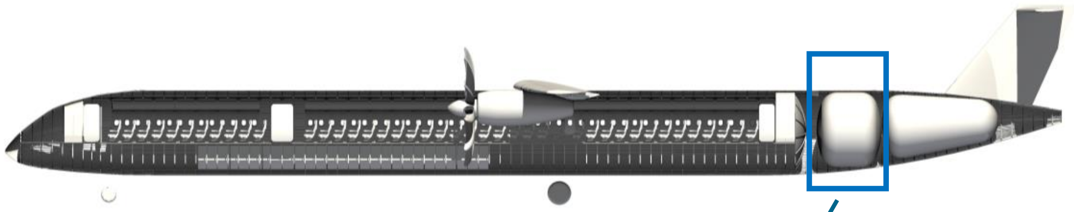


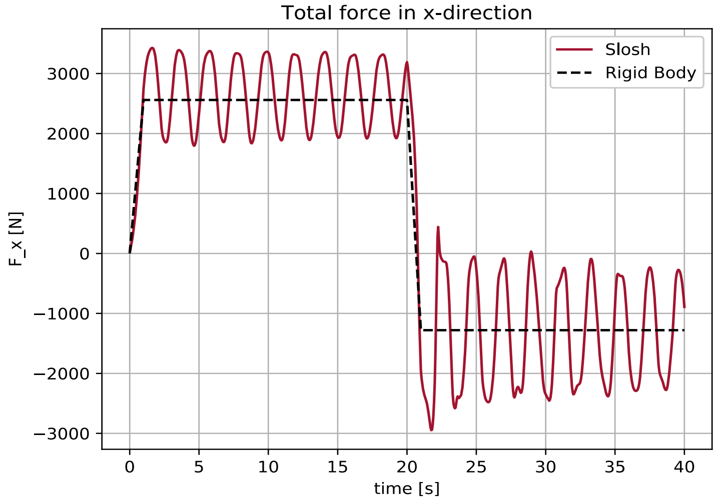
➔ FPM shows highest potential (will be used for tank sloshing)

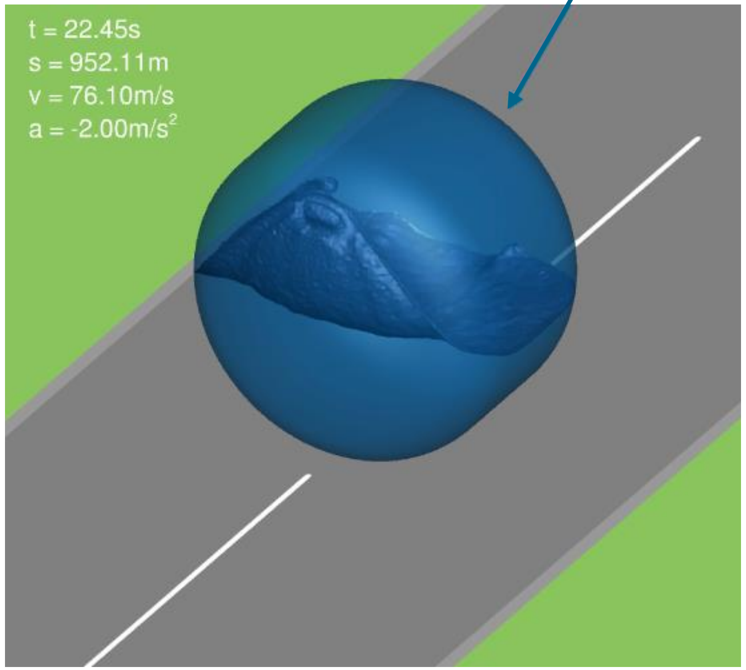
2. Sloshing in LH2 tanks
Reference simulation for LH2 fuel sloshing

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 +0.4g for 20s
  - Deceleration of -0.2g for 20s
  - ➔ Max. speed: ~79.3m/s
  - ➔ Total distance: ~2000m



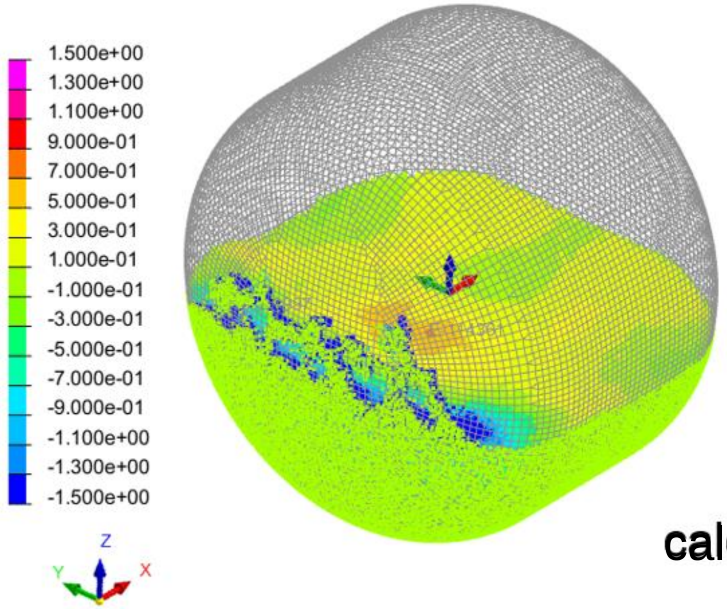


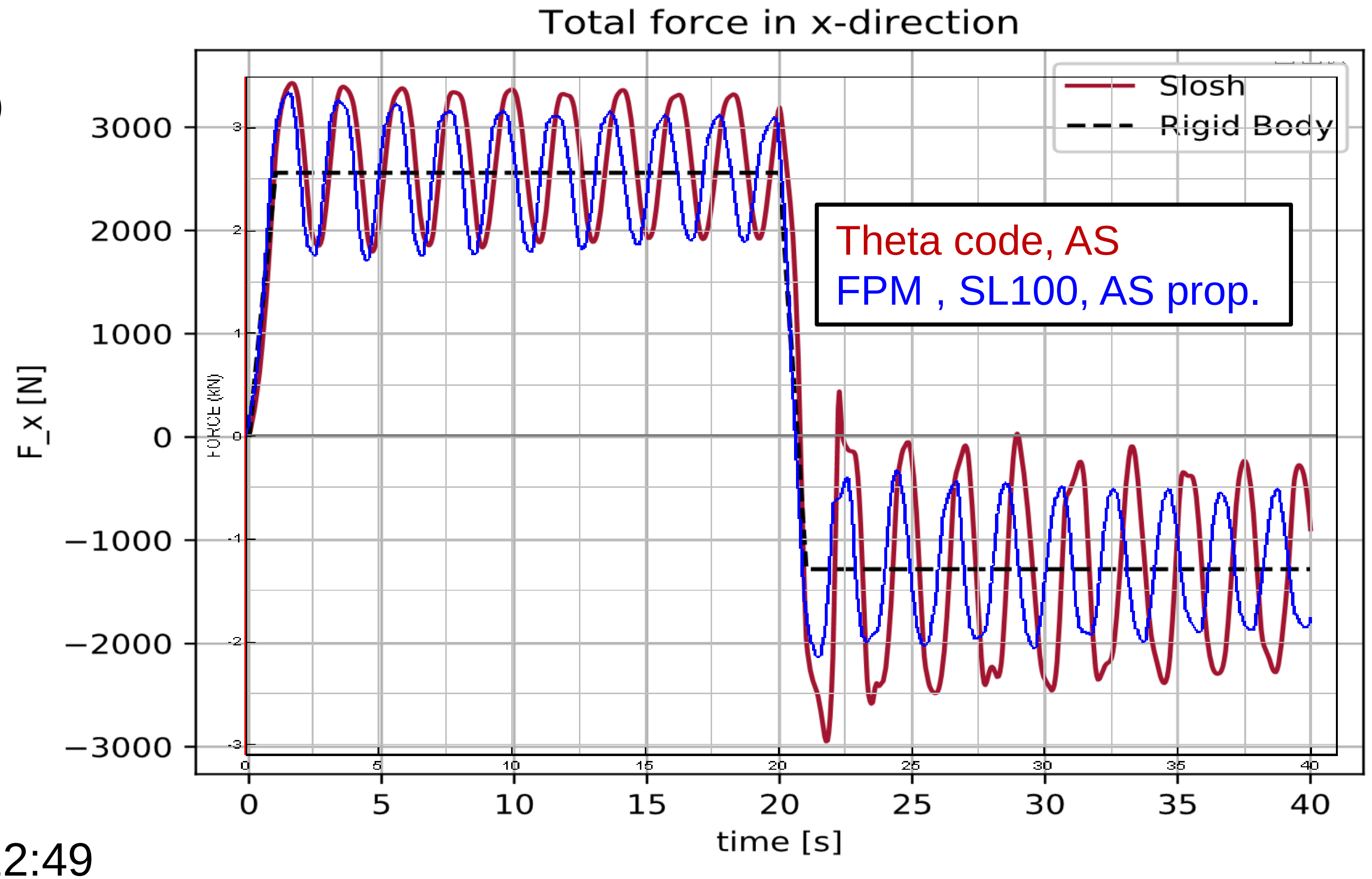


Source: HYTAZER Meeting in spring 2023 (DLR-AS)

2. Sloshing in LH2 tanks
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)





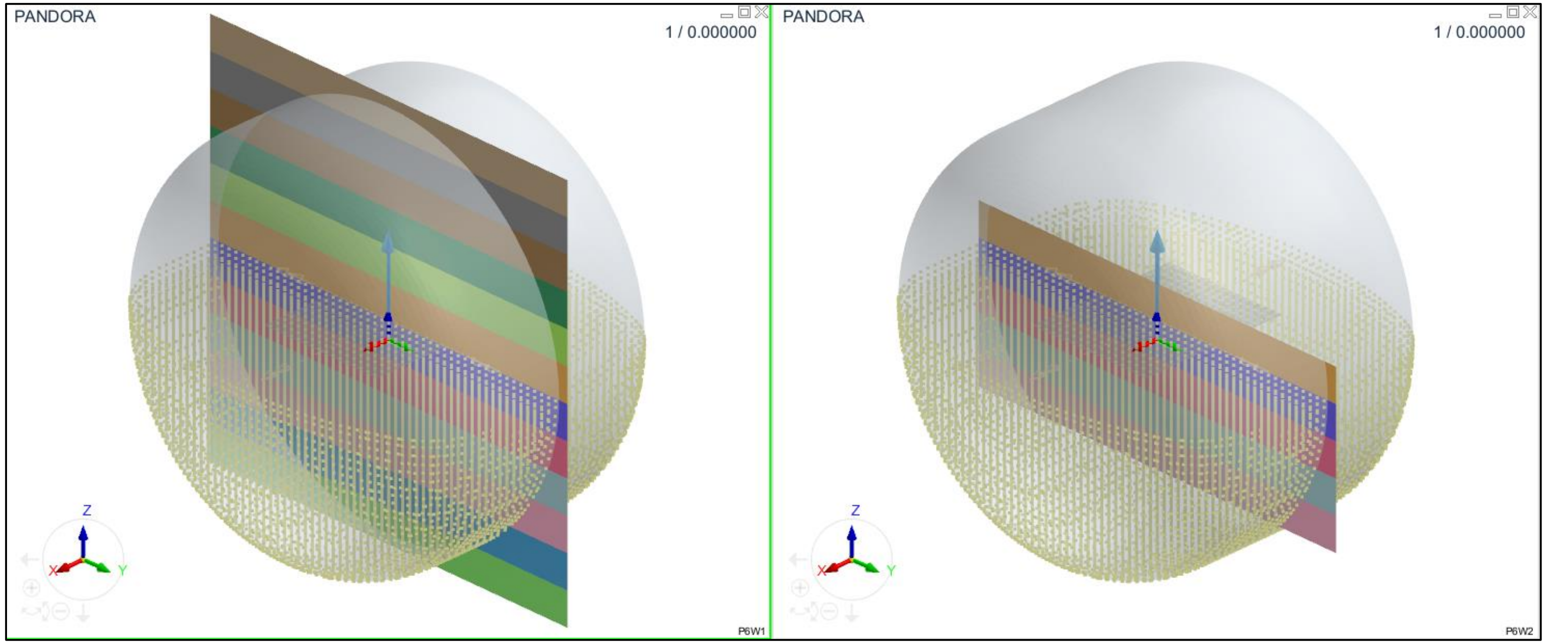
calc. time: 03:22:49
(128 cores)

2. Sloshing in LH2 tanks
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 has been added to the tank
- Simulations were performed with smoothing length 100 / 200 and some volume correction

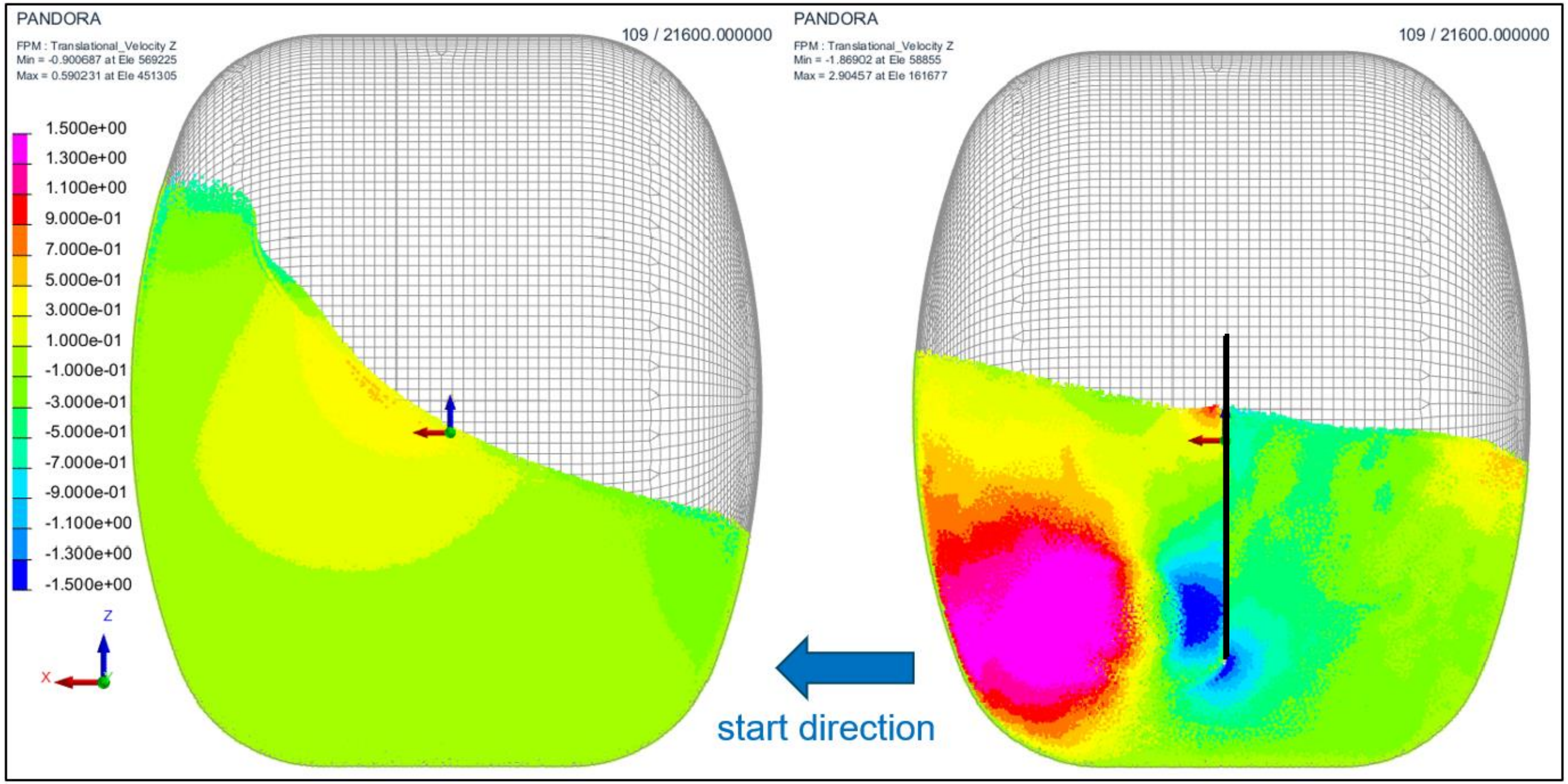
- Very simple wall with 12 segments of 300mm height have been added
- Only segments 3 to 7 have been selected for FSI contact
- Wall is not considered in FPM initialization (INIT_WET NO)!



Segments in WALL definition

2. Sloshing in LH2 tanks
Influence of baffles

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



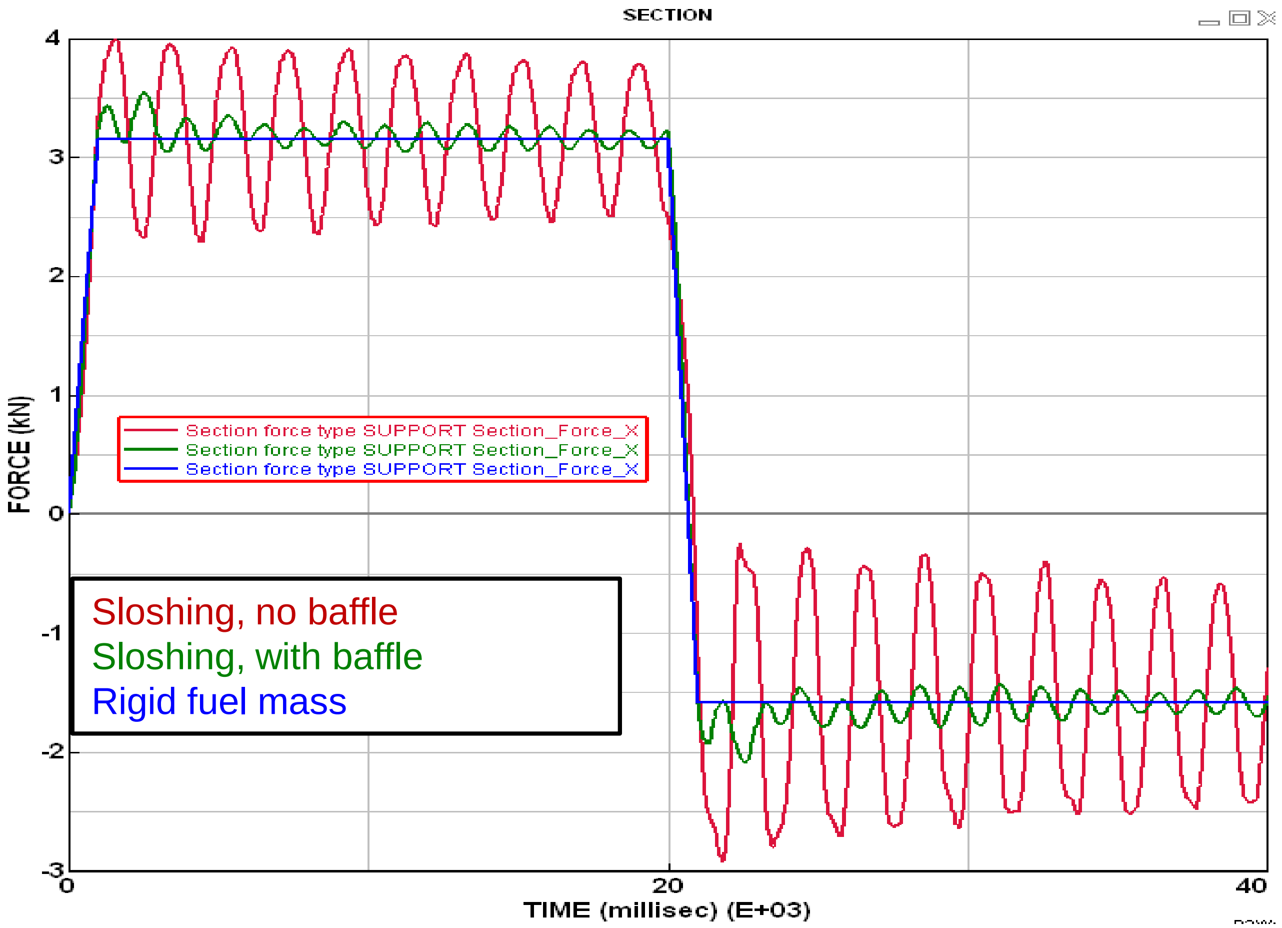
Significant reduction of flow in tank ☺ (SL100, Acc. Loading)

2. Sloshing in LH2 tanks

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% (SL100 and SL200)

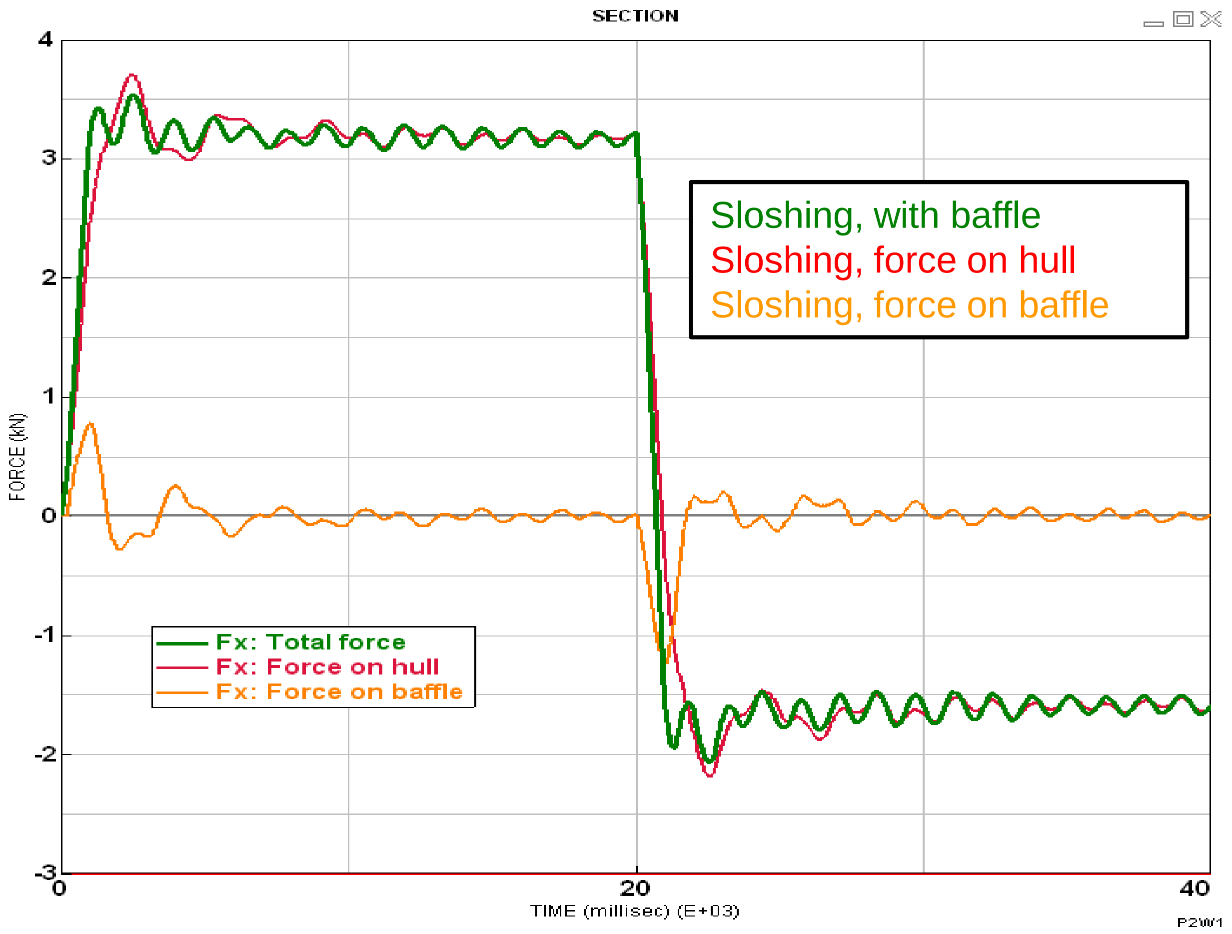


2. Sloshing in LH2 tanks

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% (SL100 and SL200)
- Loads introduced by baffle can be analyzed in detail

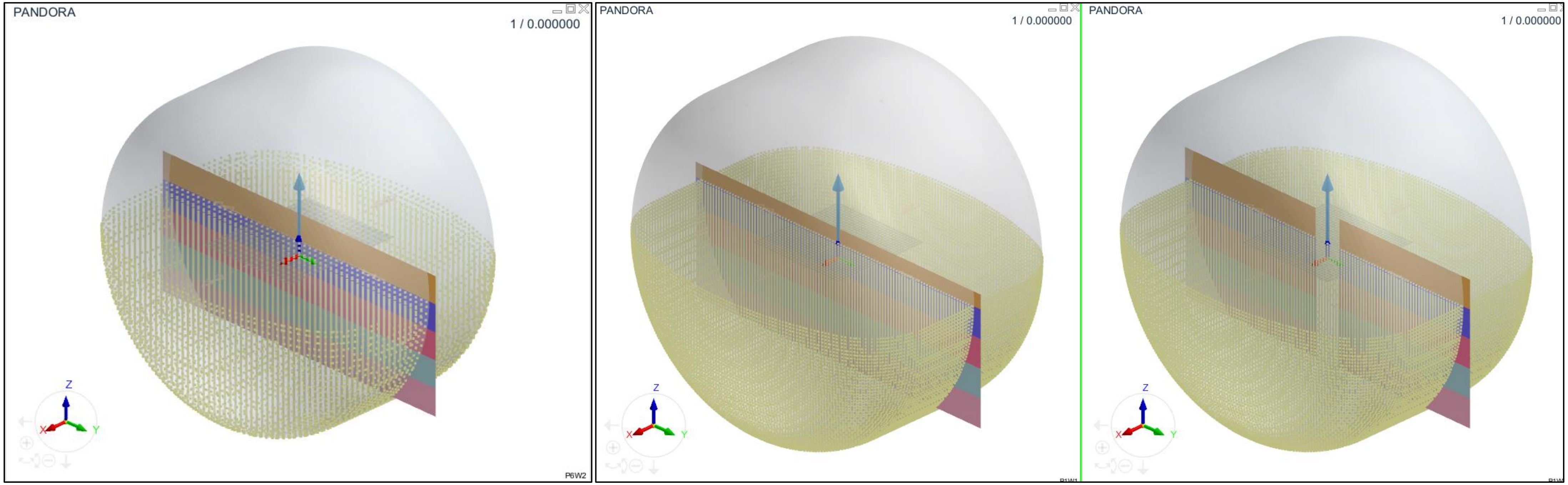


2. Sloshing in LH2 tanks
Influence of baffles (alternative designs)

Reference model from previous study (baff = reference)

Modelling of flow over baffle possible / feasible ➔ change of baffle height (baff2 = lower)

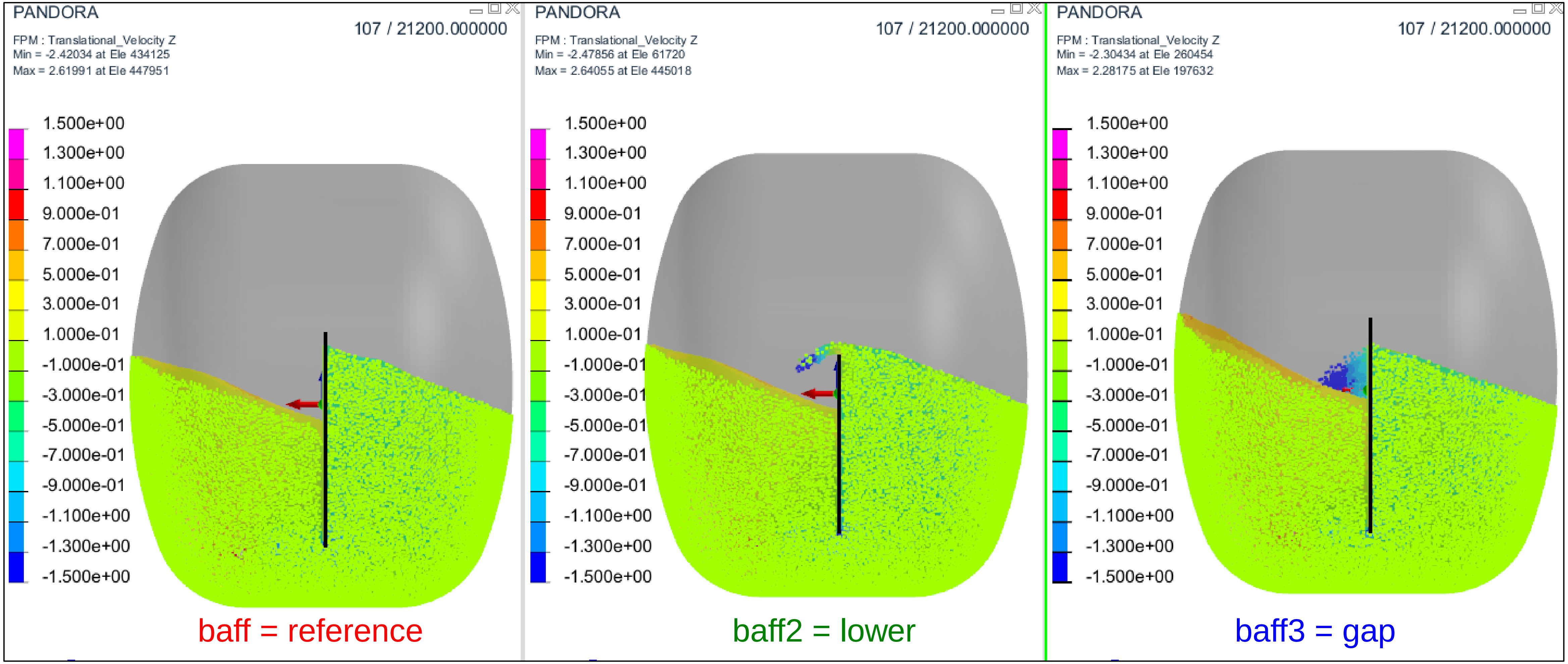
Alternative baffle design with cut over height ➔ baff3 = gap



Finally Smoothing length 100 has been used for all simulations

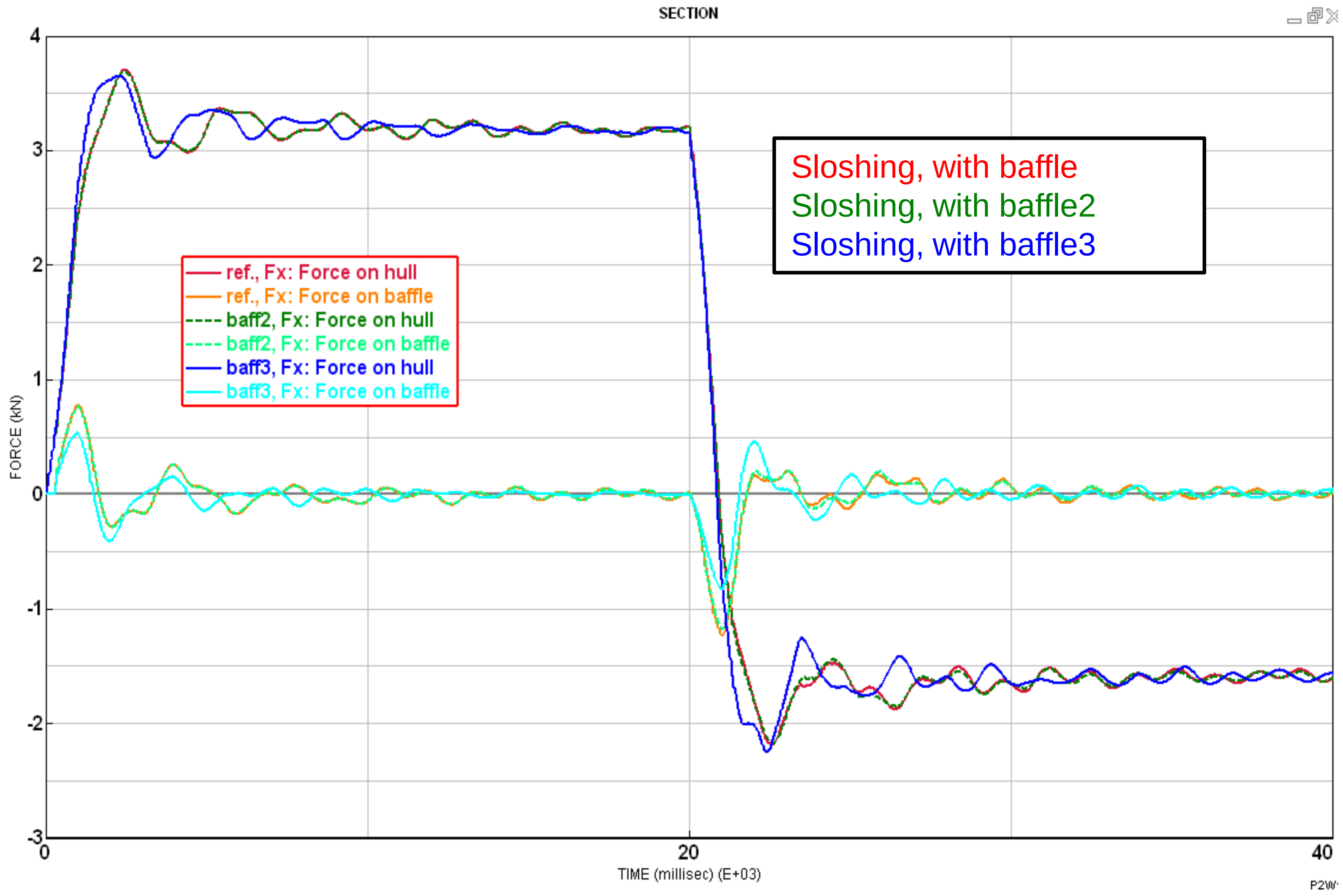
2. Sloshing in LH2 tanks
Influence of baffles (alternative designs)

Flow in Tank after change of acceleration vector (t = 21.2 s)



2. Sloshing in LH2 tanks
Influence of baffles (alternative designs)

- Different baffle designs can be modelled
- Loads acting on single baffle can be analyzed easily
- Flow over baffle can be modelled without causing num. trouble



Summary / Outlook

- FPM incompressible flow solver could be used in several applications in Aeronautics
- The application delivers feasible results on almost all these fields
- However, further validation is ongoing for ditching and sloshing applications (especially in Combination with thin flexible structures)
- Scientific papers are planned to be published in near future
- Next presentation with application of FPM method
  D. Kohlgrüber, M. Petsch, C. Leon-Munoz, P. Schatrow, M. Waimer:
  '*A Process to evaluate fuselage structural loads caused by sloshing in liquid hydrogen tanks*'**,**
  Deutscher Luft- und Raumfahrtkongress', 30.09 – 02.10.2024, Hamburg

Thanks for your attention

Questions? ➔ dieter.kohlgrueber@dlr.de