Xenon Sloshing in Microgravity

Meng Technical Exam

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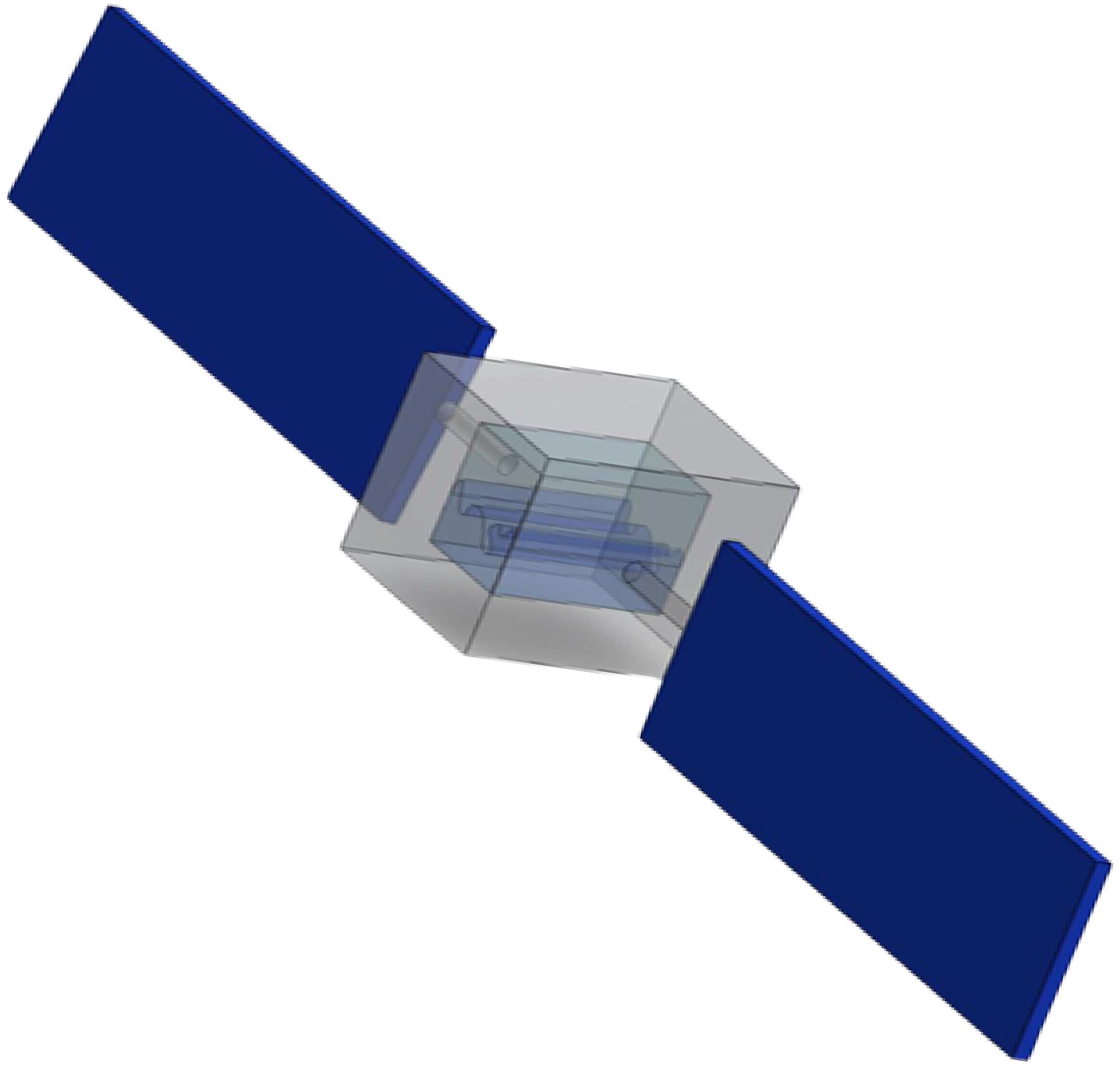
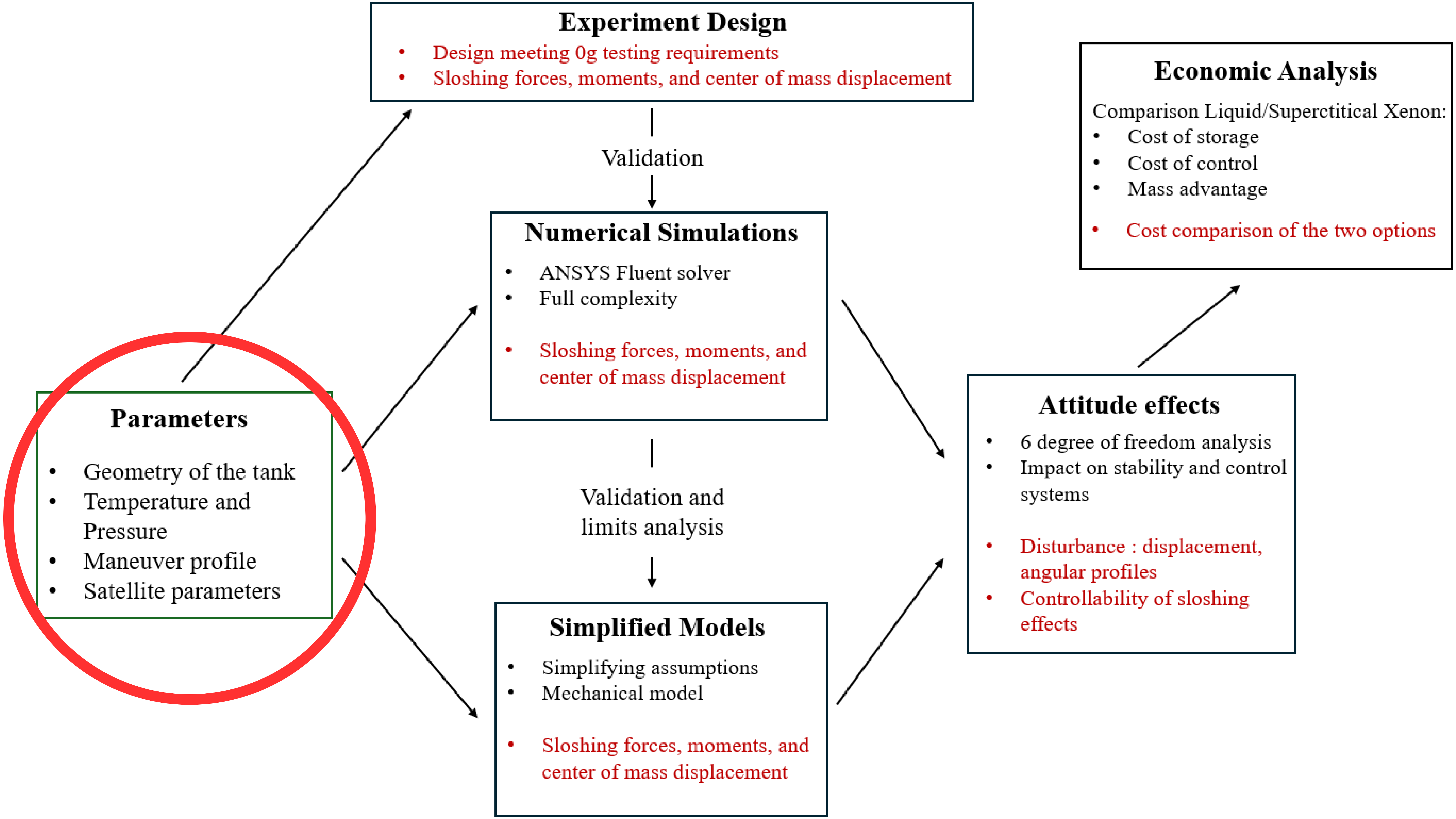
Introduction & Problem Statement



Determine the feasibility of liquid xenon storage in microgravity by:

- Quantifying slosh-induced forces and moments caused by sloshing
- Analyzing their impact on satellite dynamics and trajectory control



Experiment Design

- Design meeting 0g testing requirements
- Sloshing forces, moments, and center of mass displacement

Validation

Numerical Simulations

- ANSYS Fluent solver
- Full complexity

- Sloshing forces, moments, and center of mass displacement

Validation and limits analysis

Simplified Models

- Simplifying assumptions
- Mechanical model

- Sloshing forces, moments, and center of mass displacement

Parameters

- Geometry of the tank
- Temperature and Pressure
- Maneuver profile
- Satellite parameters

Attitude effects

- 6 degree of freedom analysis
- Impact on stability and control systems

- Disturbance : displacement, angular profiles
- Controllability of sloshing effects

Economic Analysis

Comparison Liquid/Superctitical Xenon:

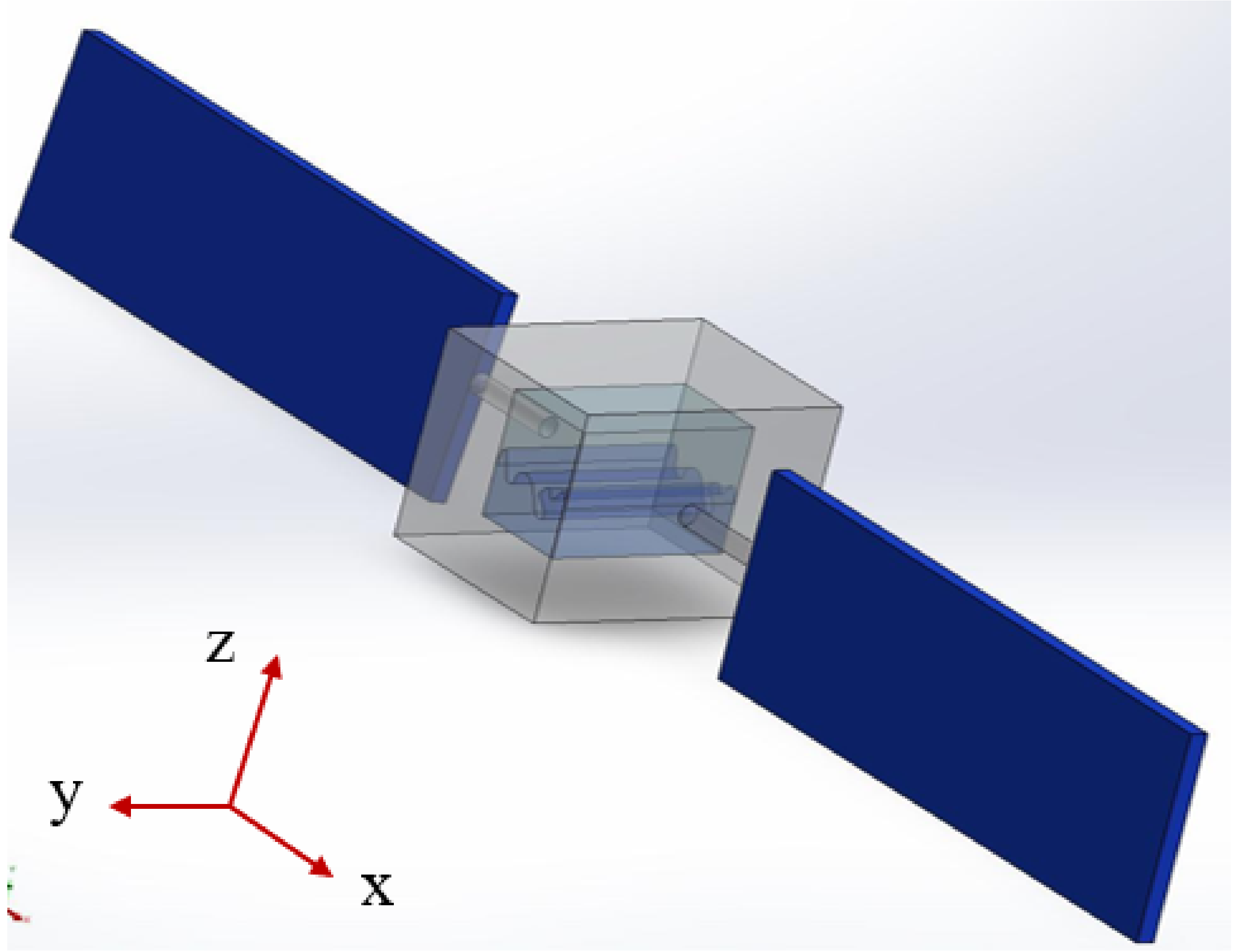
- Cost of storage
- Cost of control
- Mass advantage

- Cost comparison of the two options

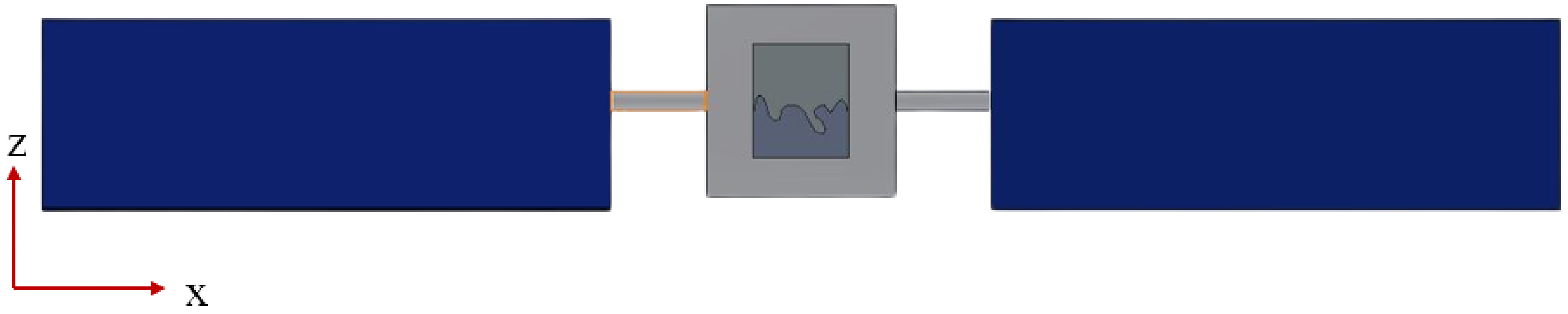
Parameters and Hypotheses

Satellite Properties:

- ARROW150 from Airbus US Space
- LEO range : 500 to 1500km (Earth Observation/ satellite constellation)
- 1mx1mx1.3m
- Total mass : 205 kg
- Estimated Inertia Properties



$$I = \begin{bmatrix} 36.25 & 0 & 0 \\ 0 & 29.7478 & 0 \\ 0 & 0 & 44.8639 \end{bmatrix} \mathrm{kg} \cdot \mathrm{m}^2$$

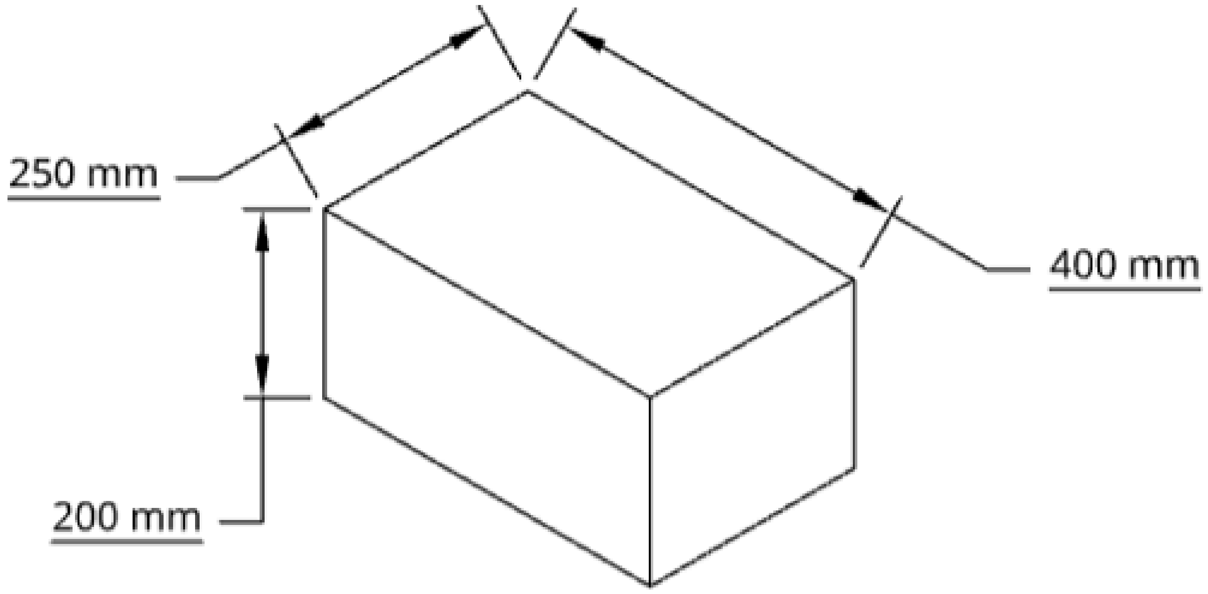


Important for Attitude Analysis later on

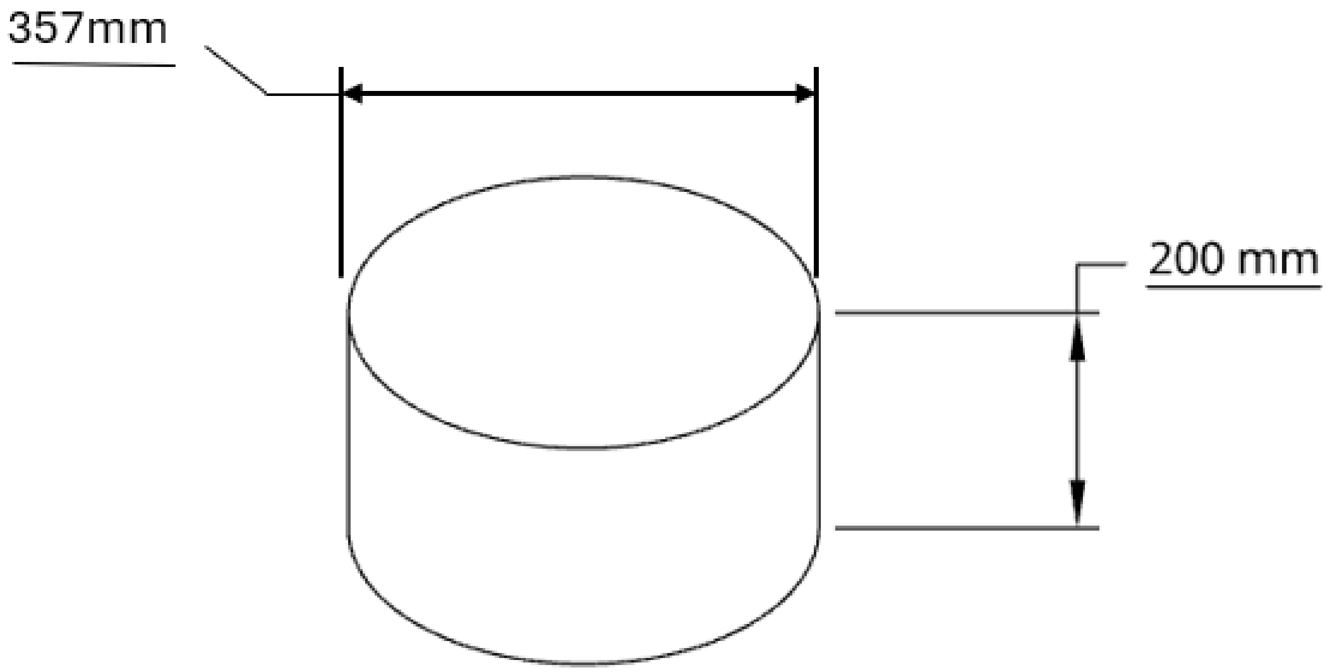
Tank Geometry

- Impacts sloshing exact behaviour
- Most commonly spherical or cylindrical (ellipsoidal caps)

To simplify things (modelling) two geometries selected :



Rectangular configuration, $V = 20L$



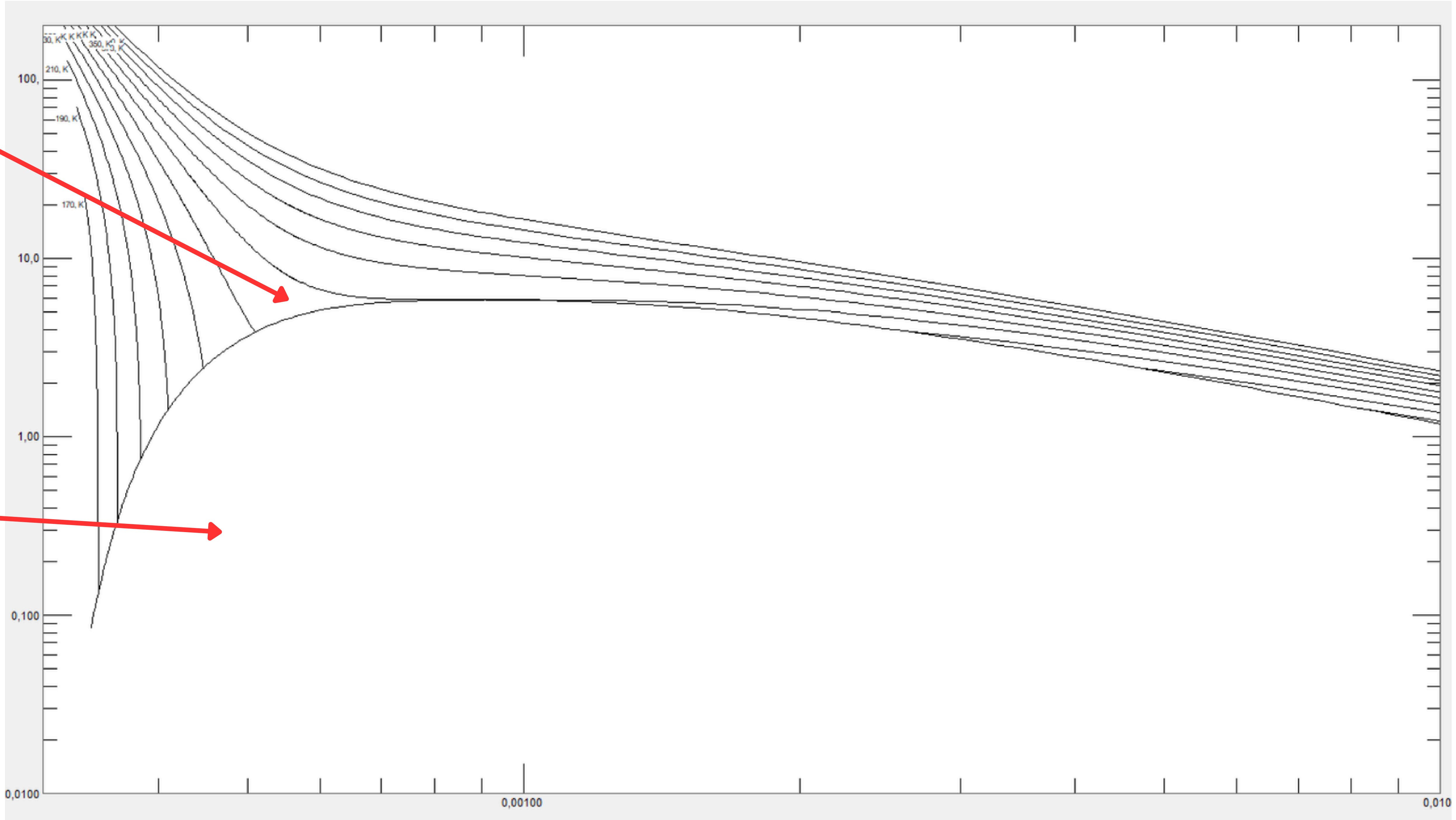
Cylindrical configuration $V = 20L$

State of the Xenon

Pressure-Volume diagram for Xenon (NIST)

Critical Point : Tc=289.8K

Goal : Operate somewhere here



State of the Xenon

Two parameters need to be defined : **Xenon mass** and **Temperature**

$$v = \frac{V_{tank}}{m_{Xe}} \qquad x = \frac{v - v_l}{v_v - v_l}$$

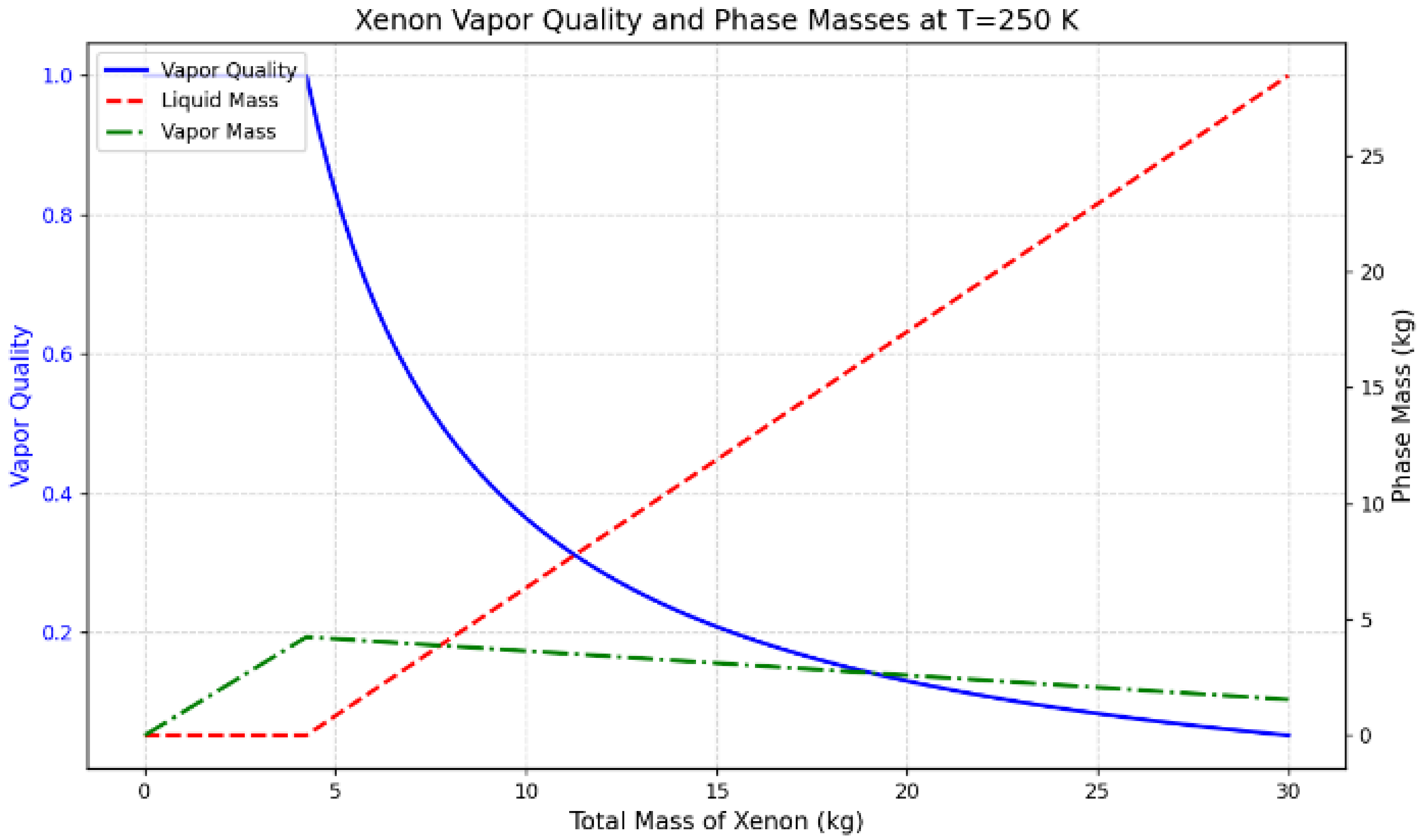
Parameters chosen for a half fill

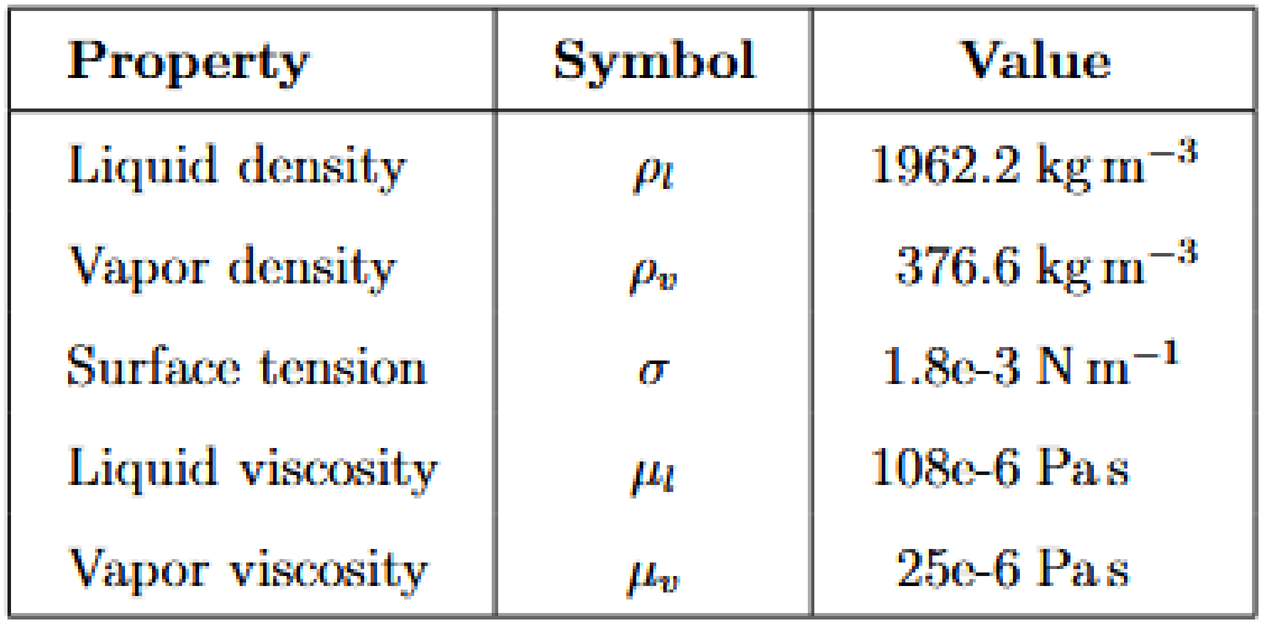
$$T = 270K \qquad m_{Xe} = 23.38kg$$

↓

$$Fill\% = \frac{V_l}{V_{tank}} = 0.5$$

Xenon Vapor Quality and Phase Masses at T=250 K





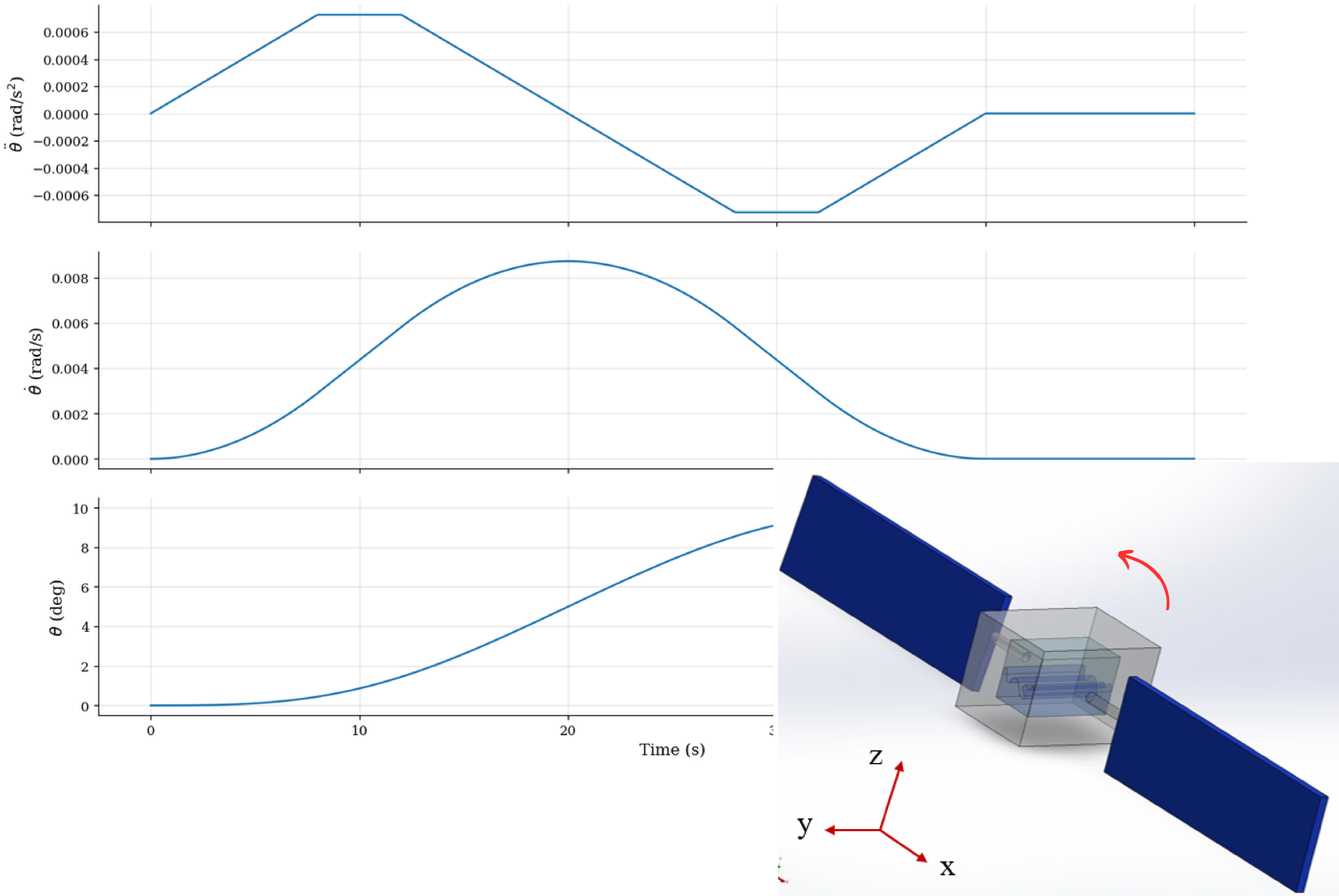
Property	Symbol	Value
Liquid density	ρ_l	1962.2 $\mathrm{kg\,m^{-3}}$
Vapor density	ρ_v	376.6 $\mathrm{kg\,m^{-3}}$
Surface tension	σ	1.8e-3 $\mathrm{N\,m^{-1}}$
Liquid viscosity	μ_l	108e-6 Pa s
Vapor viscosity	μ_v	25e-6 Pa s

Maneuvers considered

- Conditions Sloshing
- Needs to be **realistic** and **possible to simulate** (not too long)

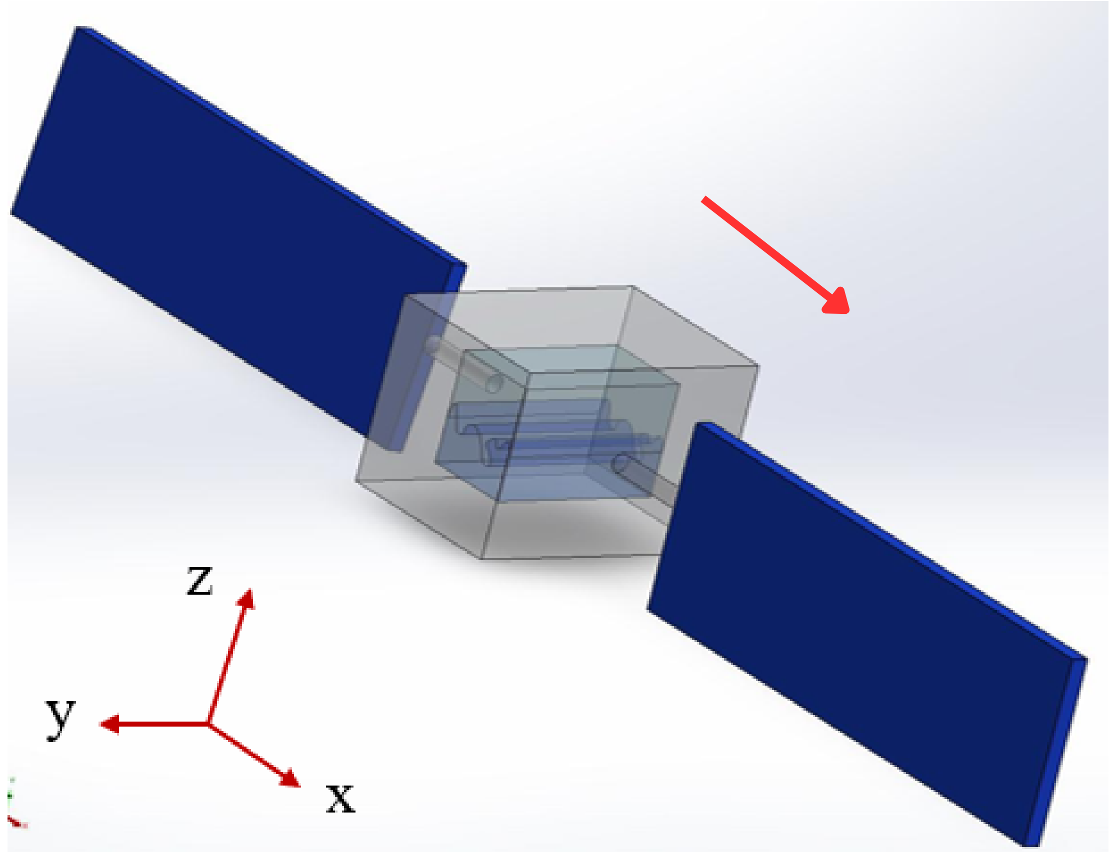
Reorientation Maneuver

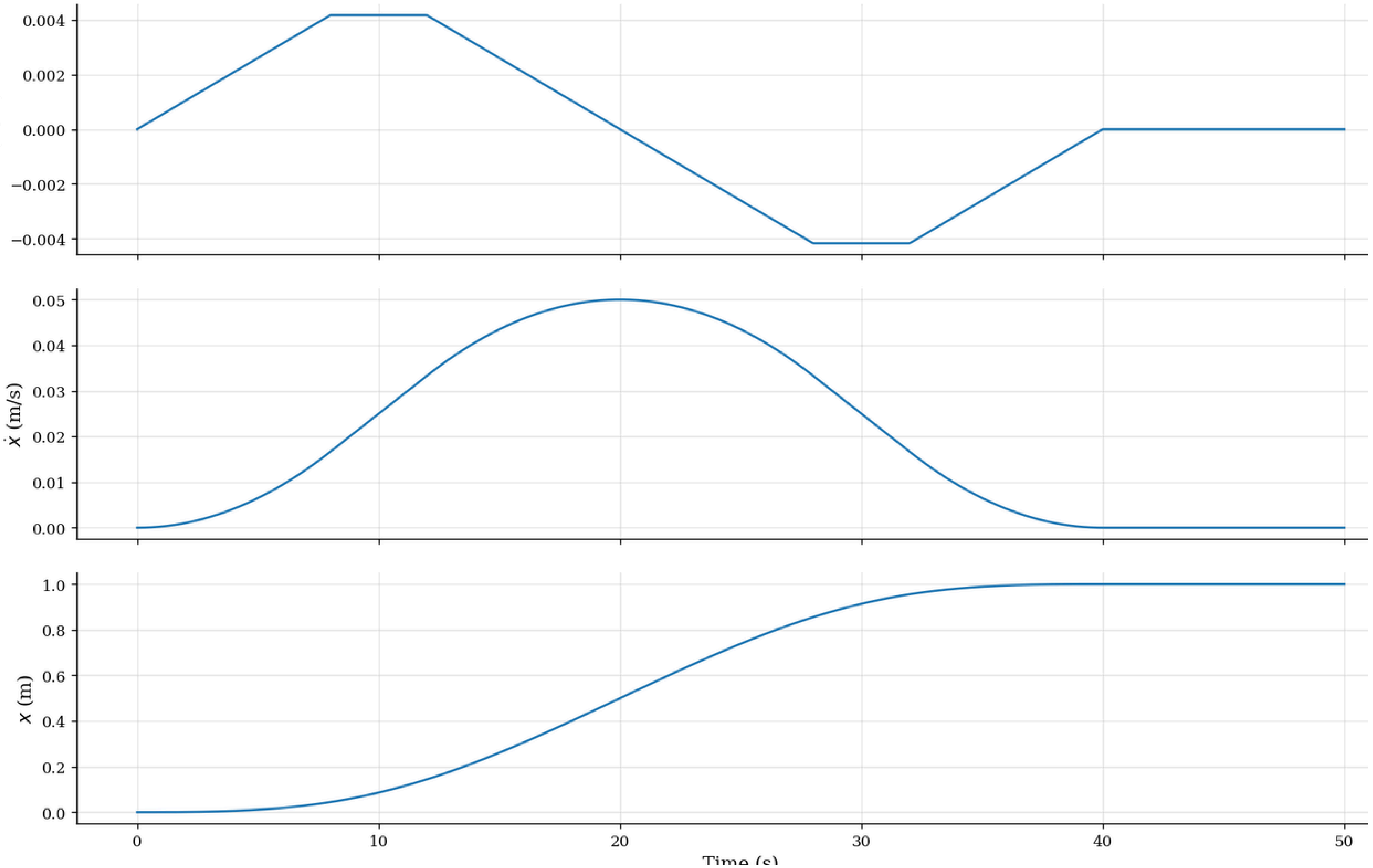
- Typical purpose: Pointing at a specific area of earth
- **Dynamic similarity** with real maneuvers (non dimensional numbers conserved)
- Rotation of 10° along the y axis

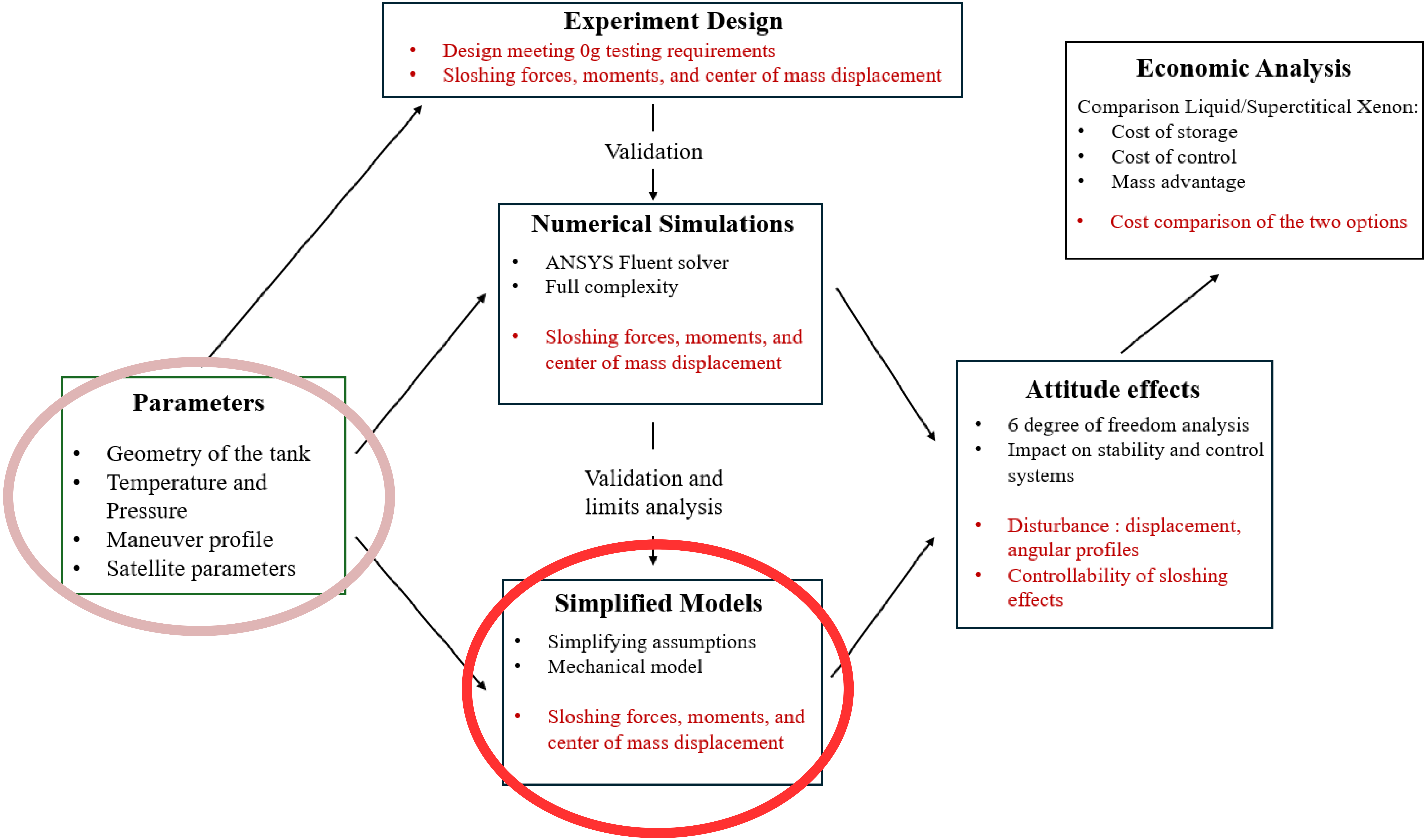


Translation Maneuver

- Typical purpose: Position hold / formation orbit
- **Dynamic similarity** with real maneuvers (non dimensional numbers conserved)
- Translation of 1m along the x axis







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Modelling Sloshing in Microgravity

Forces at play : **inertia**, **viscous**, **gravitational**, and **capillary**.

Can we neglect any ?

$$We = \frac{\rho v^2 L}{\sigma}$$

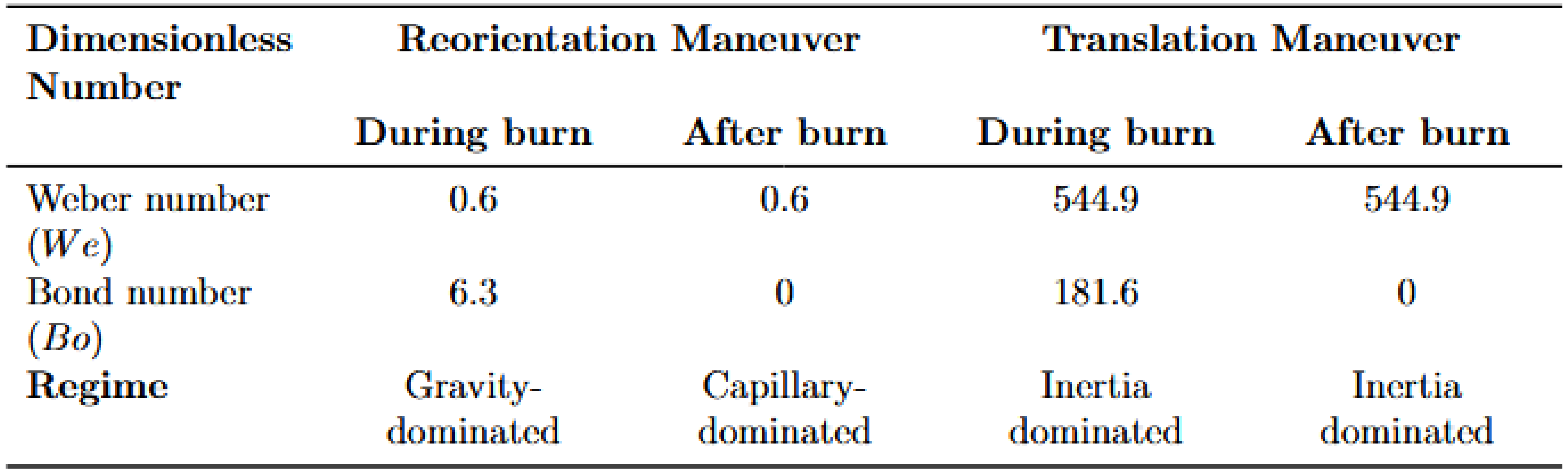
inertial

capillary

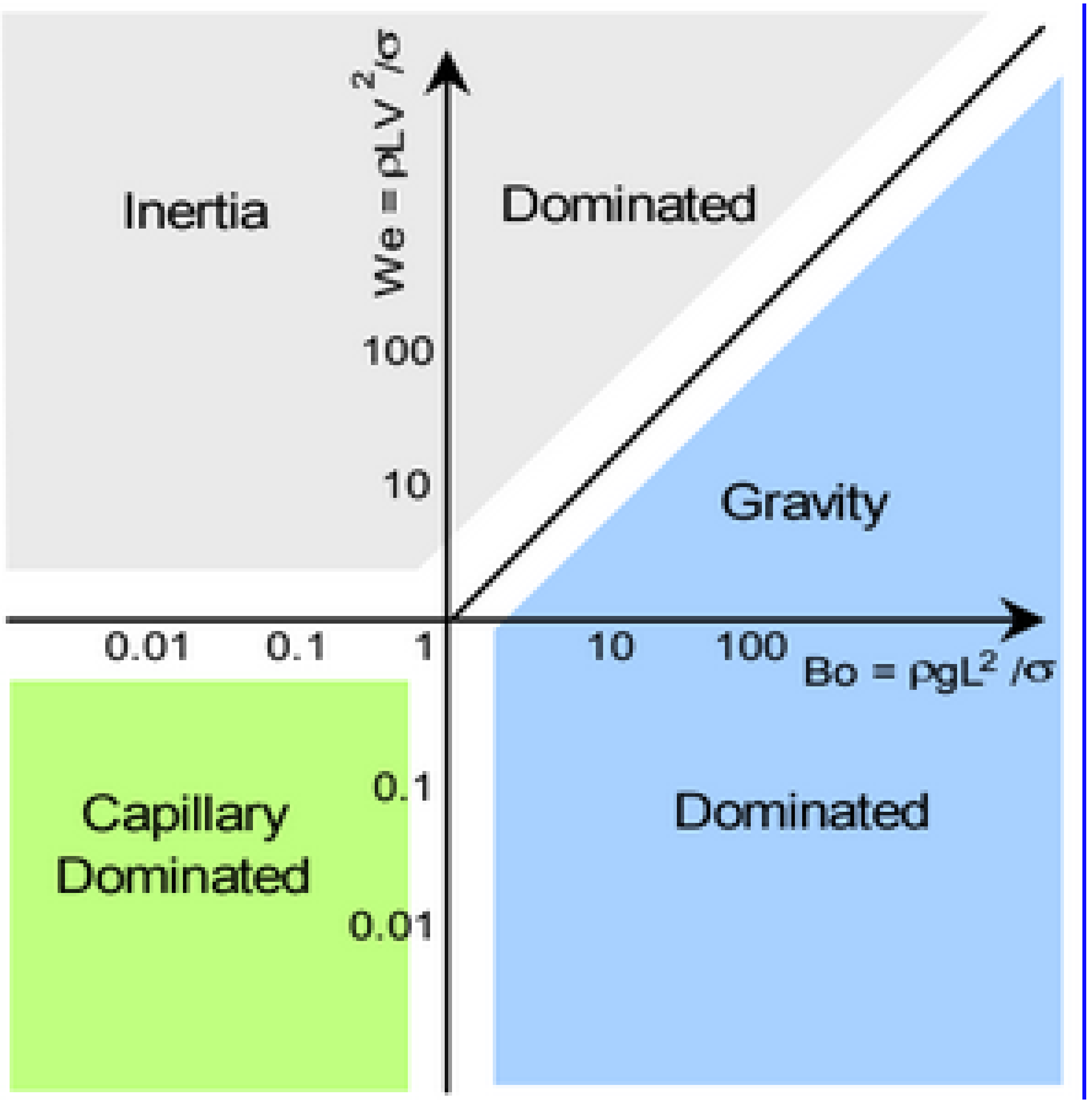
$$Bo = \frac{\rho g L^2}{\sigma}$$

gravitational

capillary



Dimensionless Number	Reorientation Maneuver		Translation Maneuver	
	During burn	After burn	During burn	After burn
Weber number (We)	0.6	0.6	544.9	544.9
Bond number (Bo)	6.3	0	181.6	0
Regime	Gravity-dominated	Capillary-dominated	Inertia dominated	Inertia dominated



Linear Sloshing

Establishing the fundamental equations of linear sloshing

Hypothesis to simplify the problem:

- Displacements small enough to linearize equations around equilibrium interface
- Flat equilibrium interface (contact angle of 90 degrees)
- Inviscid and incompressible flow
- Irrotational flow → velocity potential ϕ

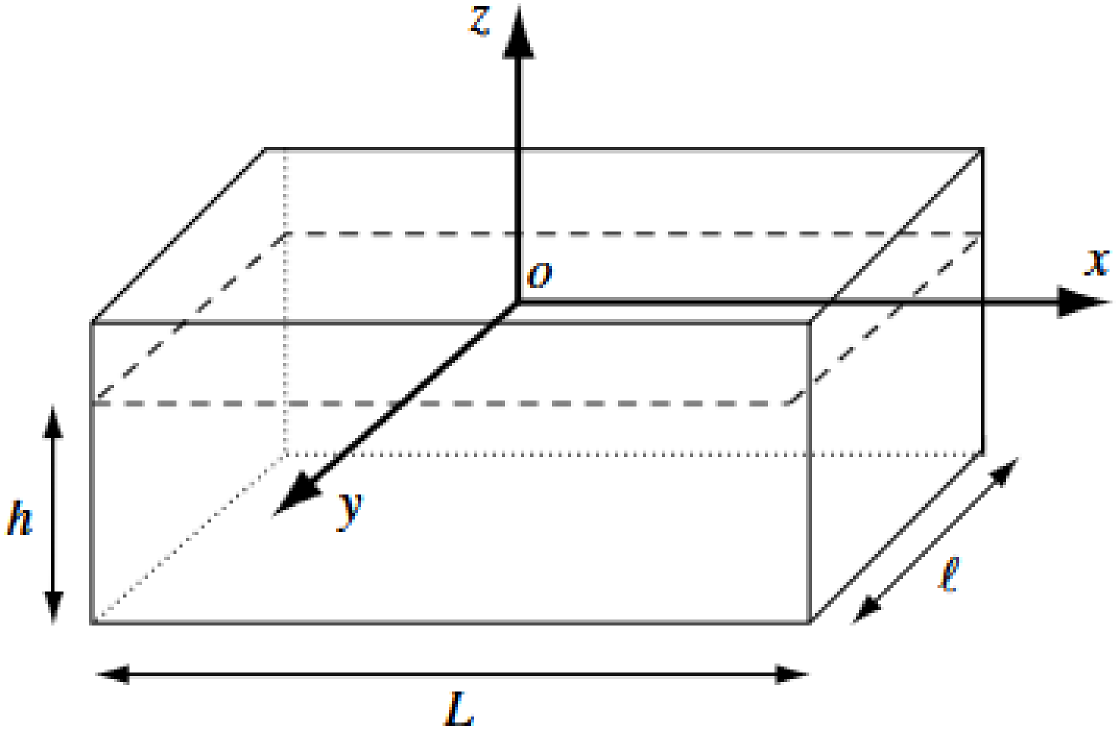
Boundary conditions

$$\frac{\partial \phi}{\partial n} = \mathbf{V}_{wall} \cdot \mathbf{n}$$

$$\frac{\partial \eta}{\partial t} = \frac{\partial \phi}{\partial z} \quad \text{at } z = 0$$

$$\boxed{\frac{\partial \phi}{\partial t} + g\eta - \frac{\sigma}{\rho}\nabla^2 \eta = 0 \quad \text{at } z = 0}$$

Linearized Bernoulli equation



Laplace equation $\nabla^2 \phi = 0$

$$\phi(x, z, t) = \sum_{n=1}^{\infty} q_n(t) \frac{\cosh k_n(z+h)}{\cosh k_n h} \cos(k_n x)$$

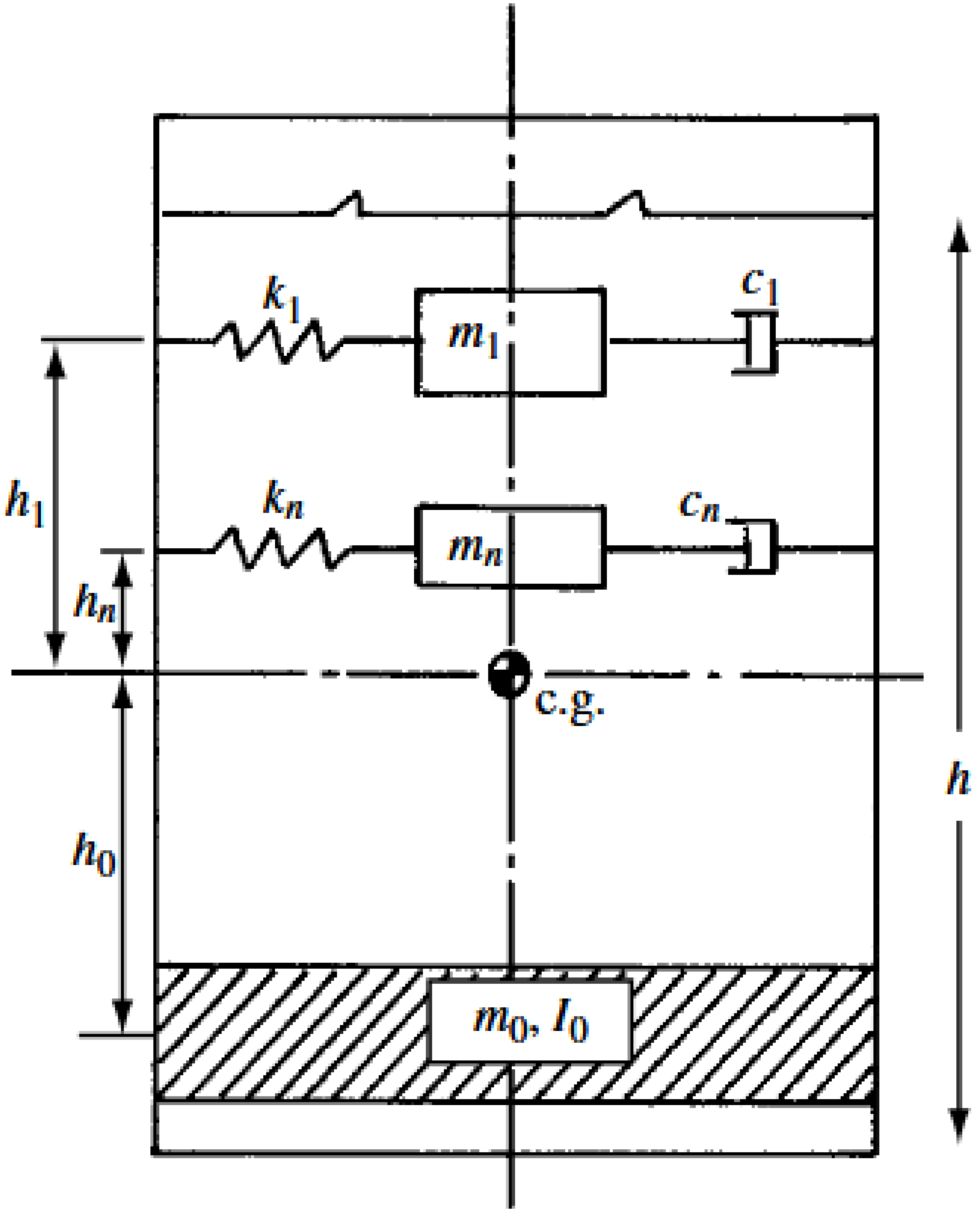
$$\ddot{q}_n + \omega_n^2 q_n = f_n(t), \qquad k_n = \frac{n\pi}{L}$$

Oscillator for modal amplitudes

$$\boxed{\omega_n^2 = \left(g k_n + \frac{\sigma}{\rho} k_n^3\right) \tanh(k_n h)}$$

Mechanical Model

Simulating sloshing effects with a mechanical equivalent model



- Parameters (modal masses, heights and spring constants) derived from linear sloshing theory
- Dashpots are not taken into account yet (inviscid)
- **Limits :** linear sloshing, vertical center of mass displacement

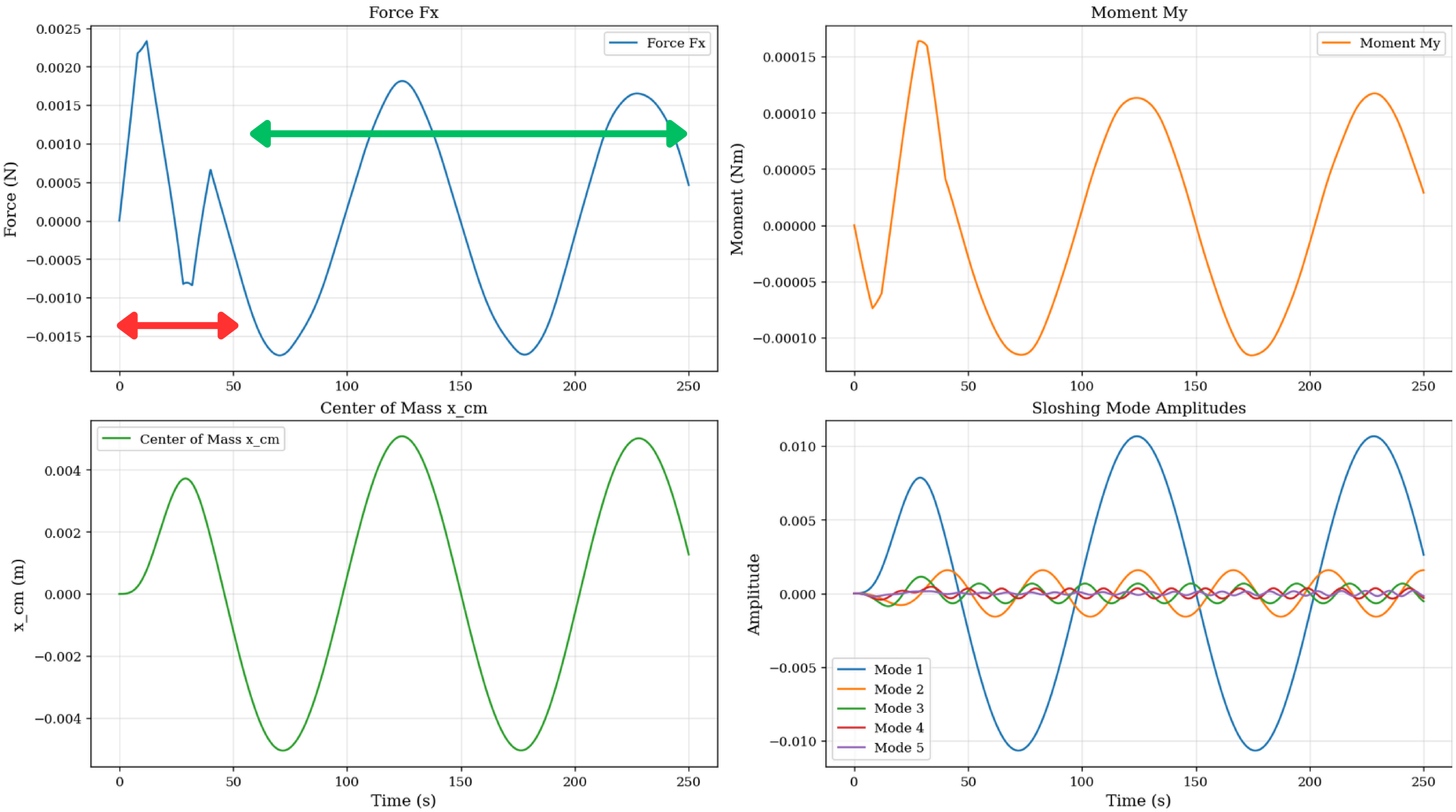
$$\mathbf{M}\,\ddot{\mathbf{q}}(t) + \mathbf{C}\,\dot{\mathbf{q}}(t) + \mathbf{K}\,\mathbf{q}(t) = \mathbf{F}(t)$$

$$\mathbf{q} = \begin{bmatrix} x & \psi & x_1 & \cdots & x_n \end{bmatrix}^T$$

→ python™

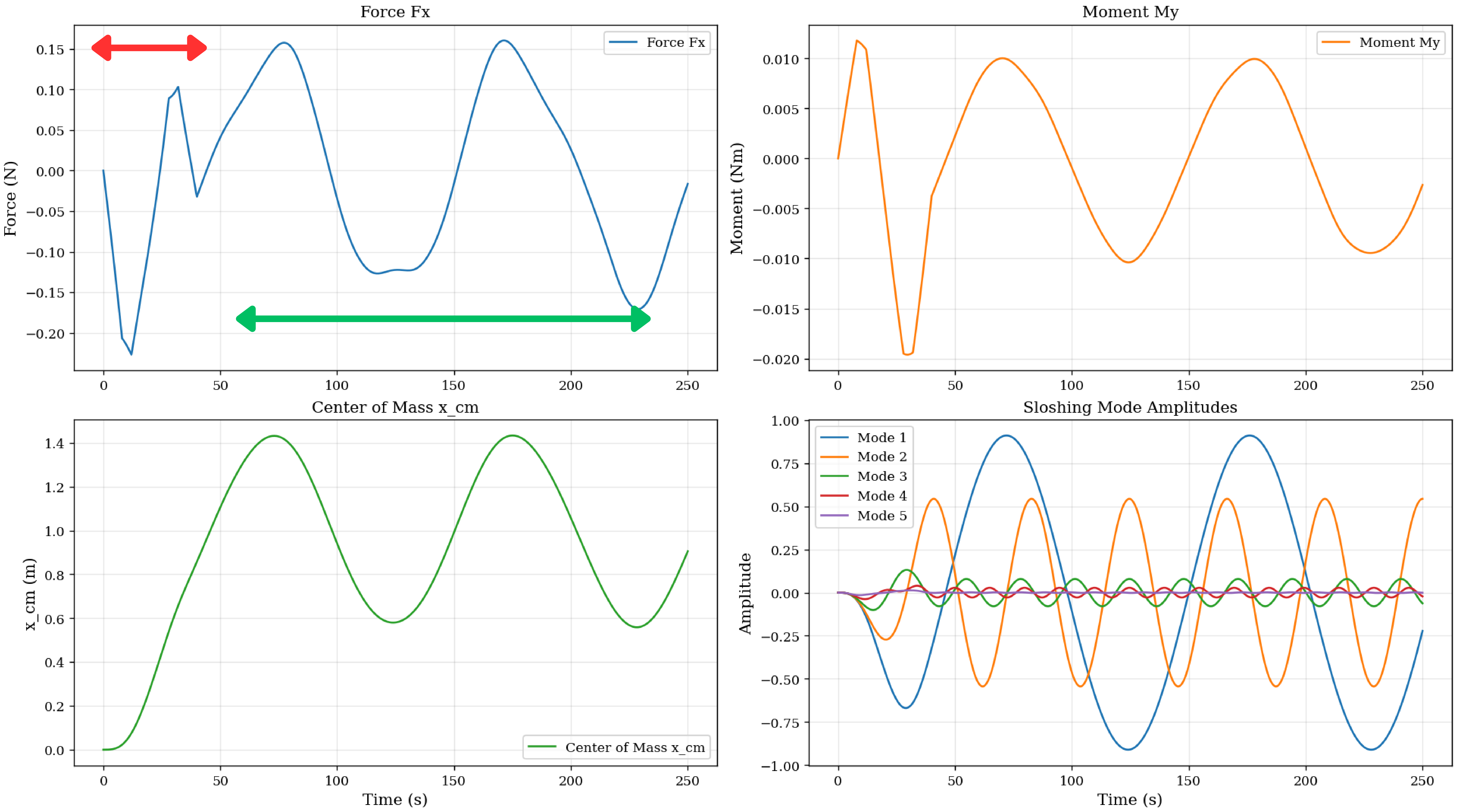
Reorientation Maneuver

Results given by the model for the reorientation maneuver



Translation Maneuver

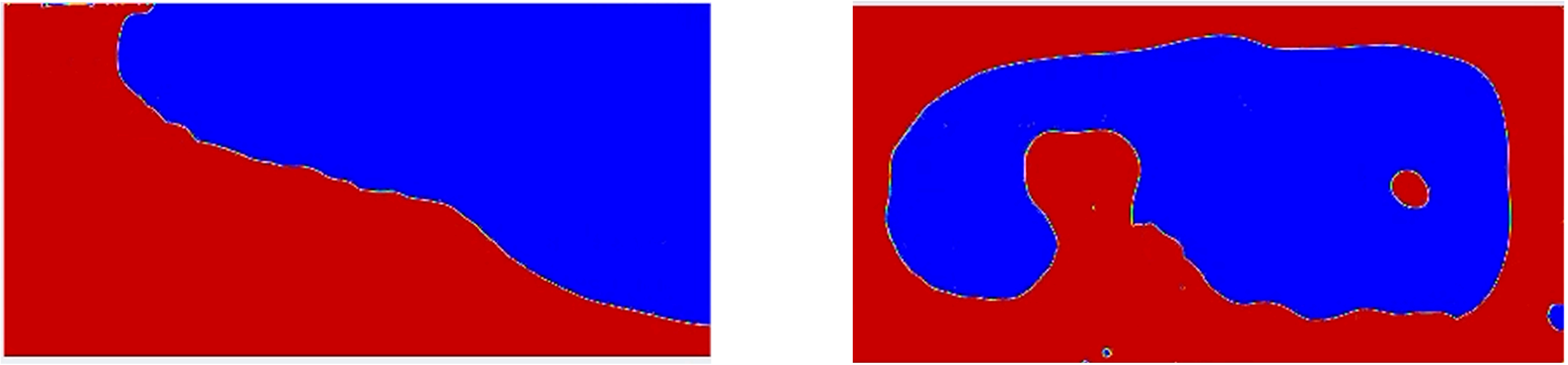
Results given by the model for the reorientation maneuver



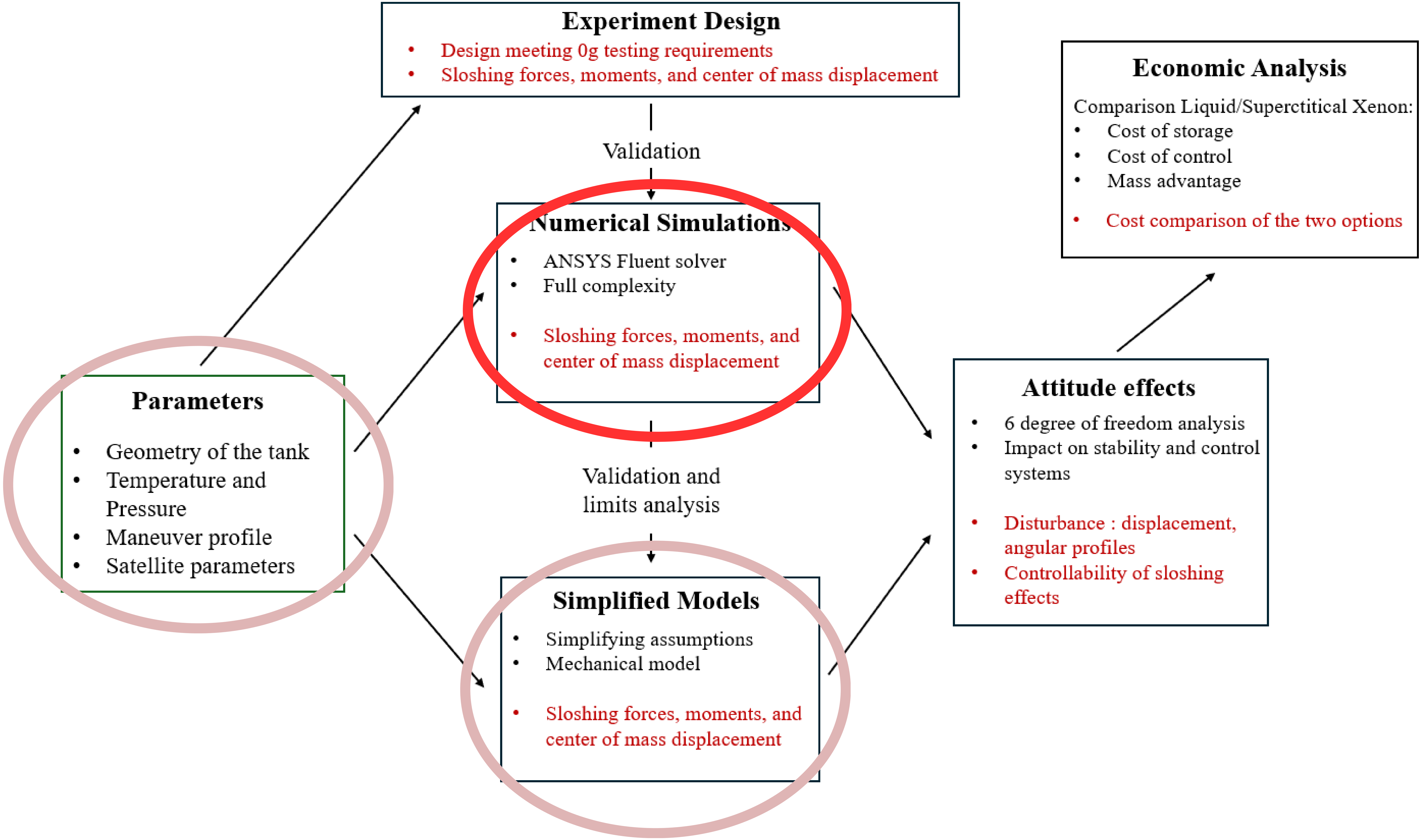
Non Linear Sloshing

What is non linear sloshing ?

- Large **geometric deformations** of the interface
- **Two main causes :** initial configuration (bubbles), high acceleration maneuvers
- Models are primarly descriptive (optimization methods to fit parameters)



Volume fraction for a case of non linear sloshing



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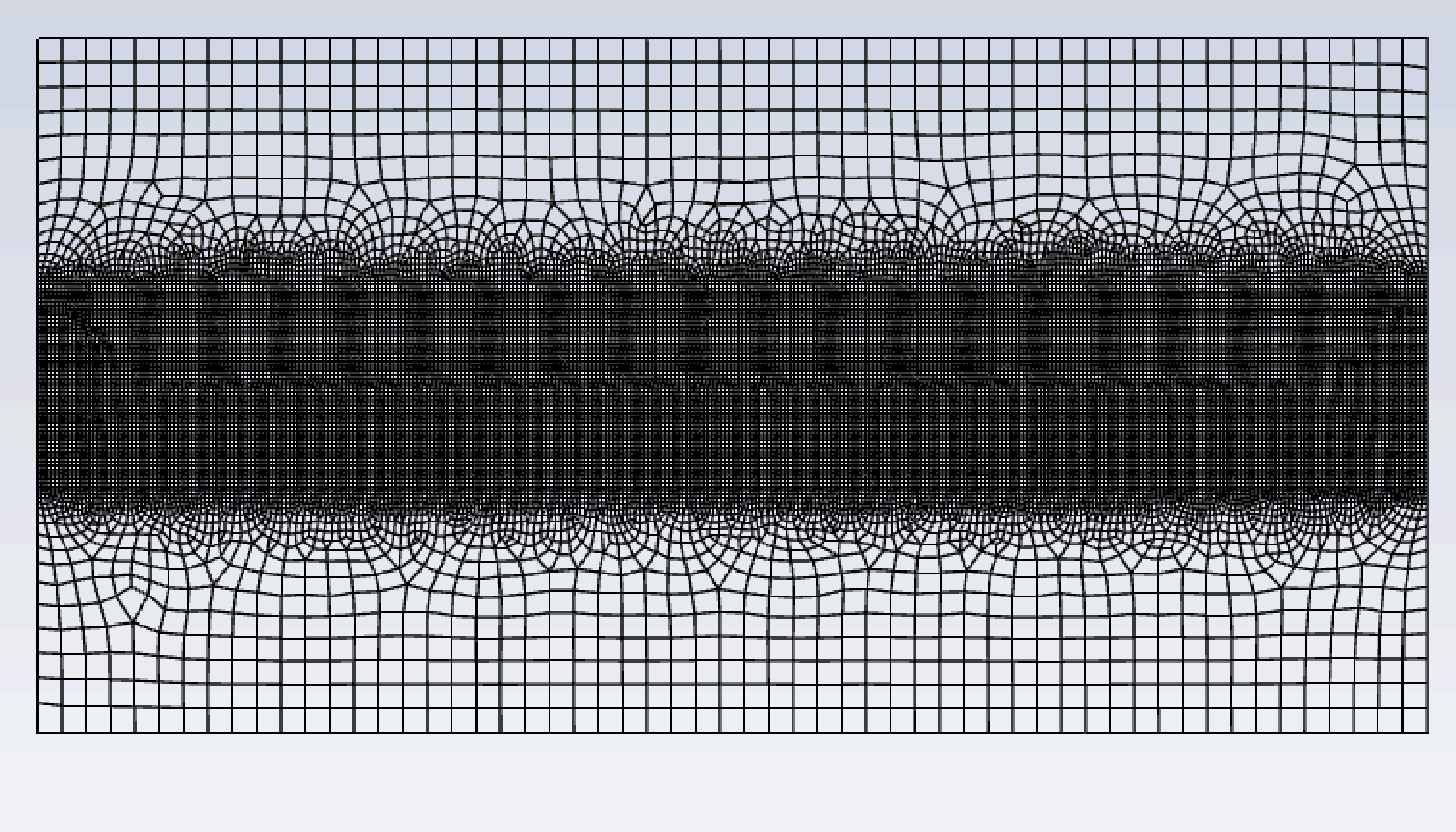
Numerical Simulations

Methods and parameters used:

- **Volume of Fluid** : two phase flow (volume fraction transport)
- **Dynamic mesh** to simulate maneuvers (UDF)
- **Mesh refinement** at the interface (gradient)
- Contact angle of 90 degrees
- Xenon parameters
- Flat interface at t=0

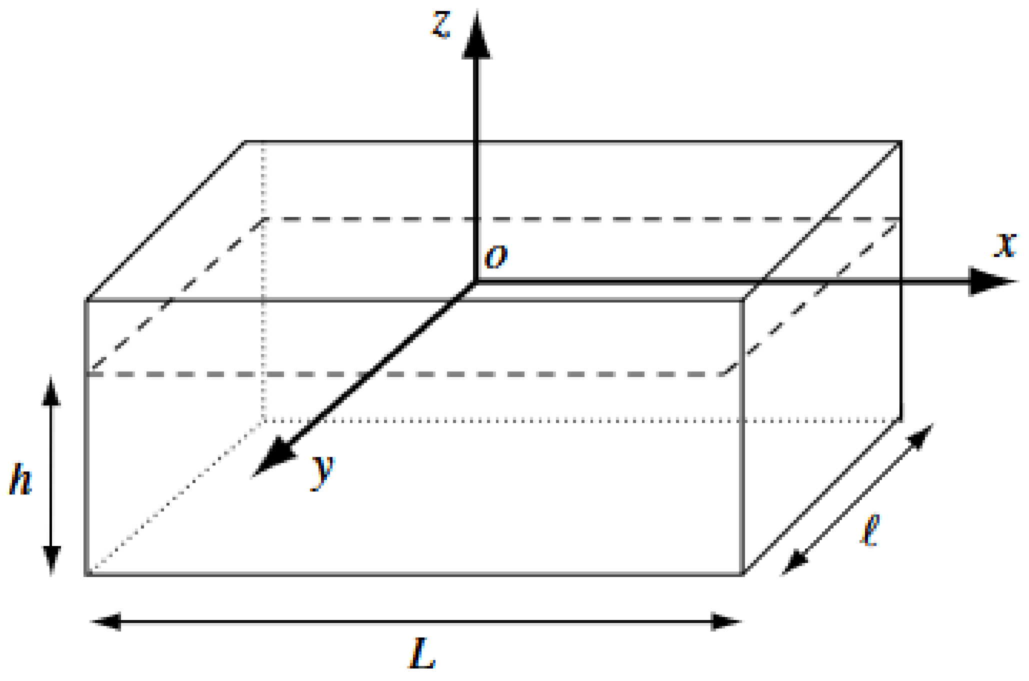


Mesh at t=0

2D rectangular Simulations

Presentation of the work done for 2D simulations

Important assumption: 2D simulations results can be extended to 3D assuming invariance in the direction normal to sloshing



Validating the linear model

Idea : compare modal frequencies

FFT of interface height

$$\hat{\eta}(\omega, x) = \sum_{n=1}^{\infty} \cos(k_n x) \int_0^T A_n \cos(\omega_n t + \phi_n)\, e^{-i\omega t}\, dt$$

→ **Peaks**

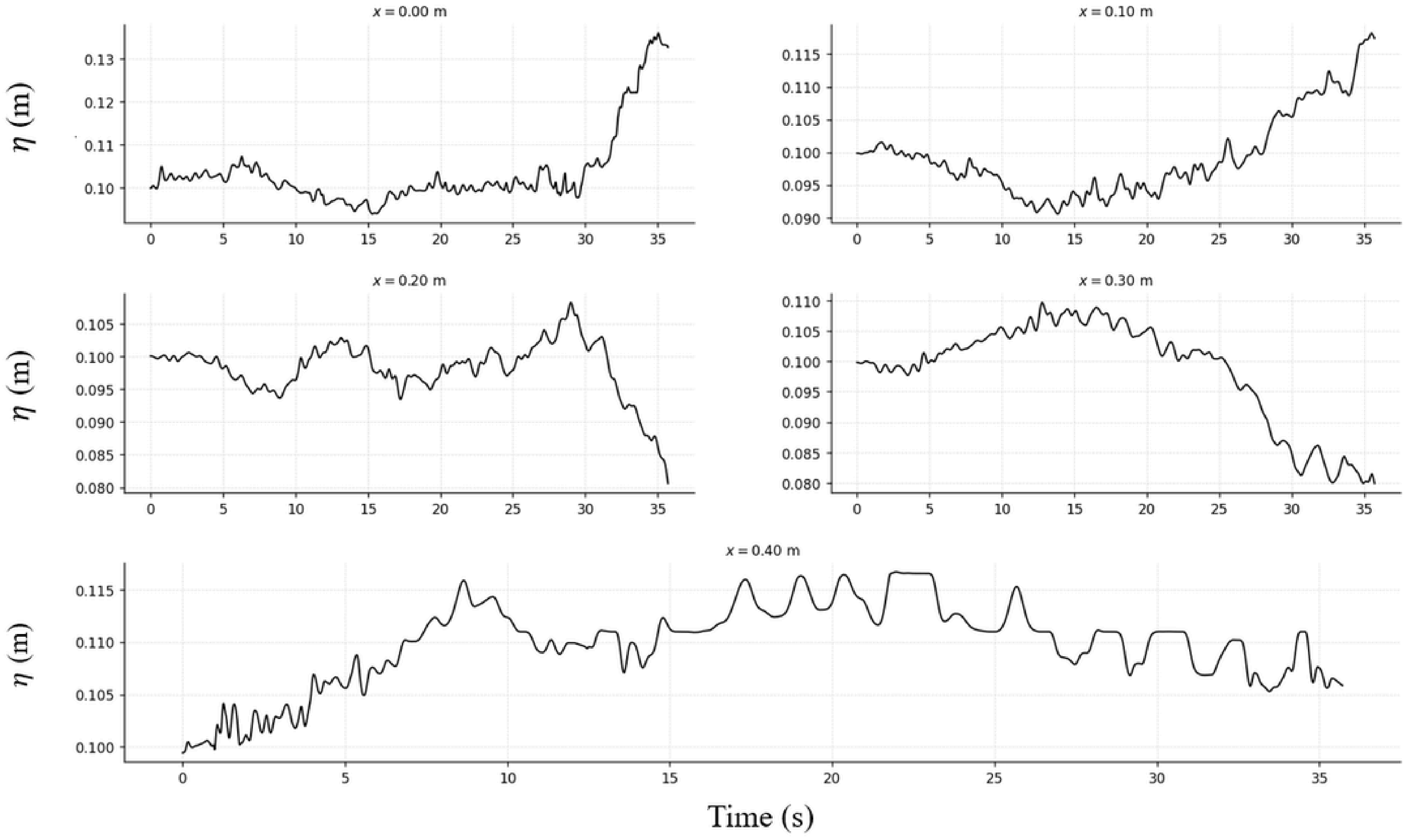
Simulation:

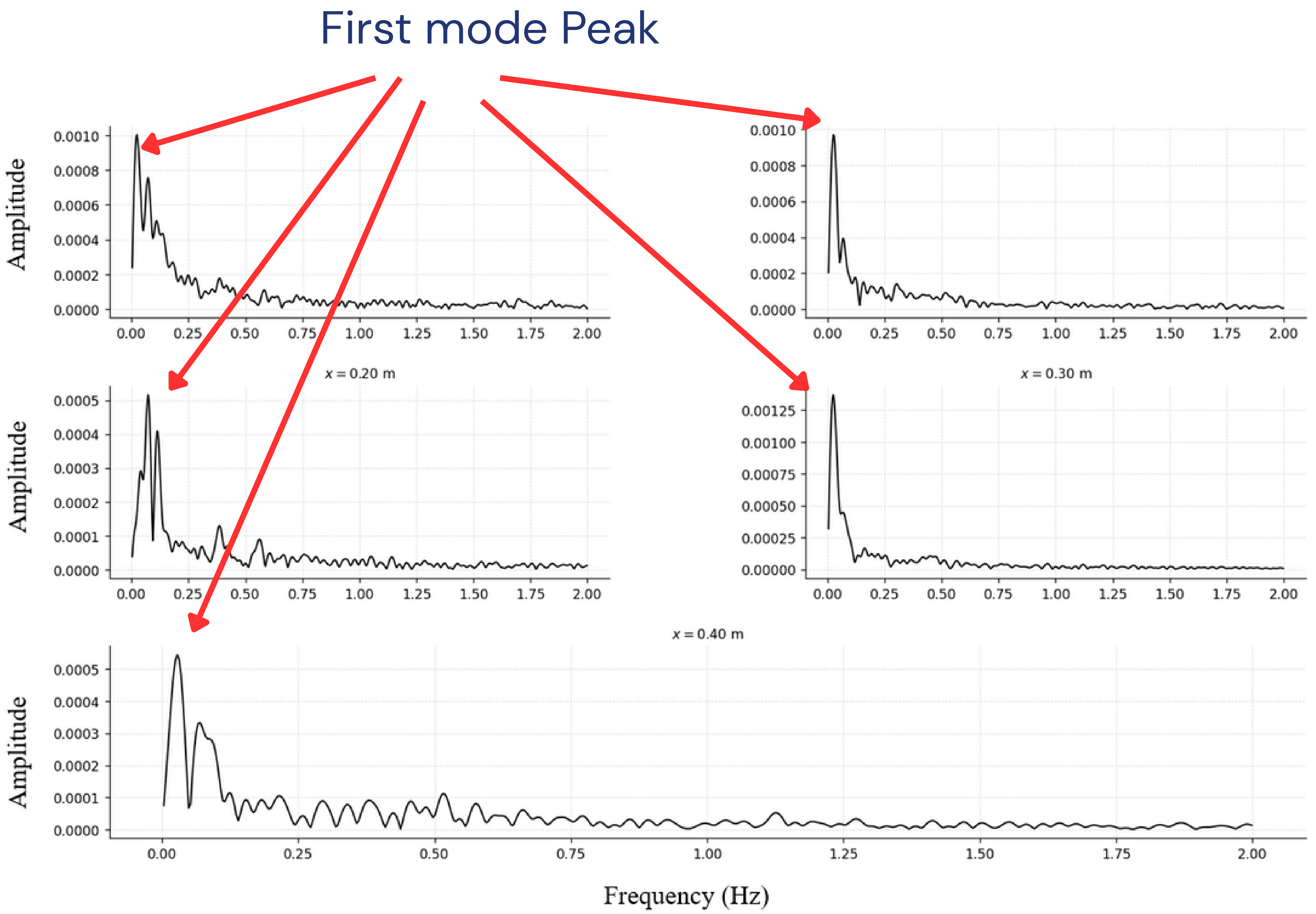
$$a_{\text{input}}(t) = \begin{cases} 0.0005\,\mathrm{m/s^2}, & 0 \le t \le T_i \\ 0, & t > T_i \end{cases}$$

→ Initial excitation (along x)

→ Free sloshing

Results





First mode Peak

Mode Number	Linear Model frequency (rad/s)	CFD frequency (rad/s)	Relative error (%)
1	0.07	0.072	2.86
2	0.19	0.2	5
3	0.35	0.36	2.86
4	0.50	0.58	16
5	0.75	0.82	9.33

First modes well represented, satisfactory predictions

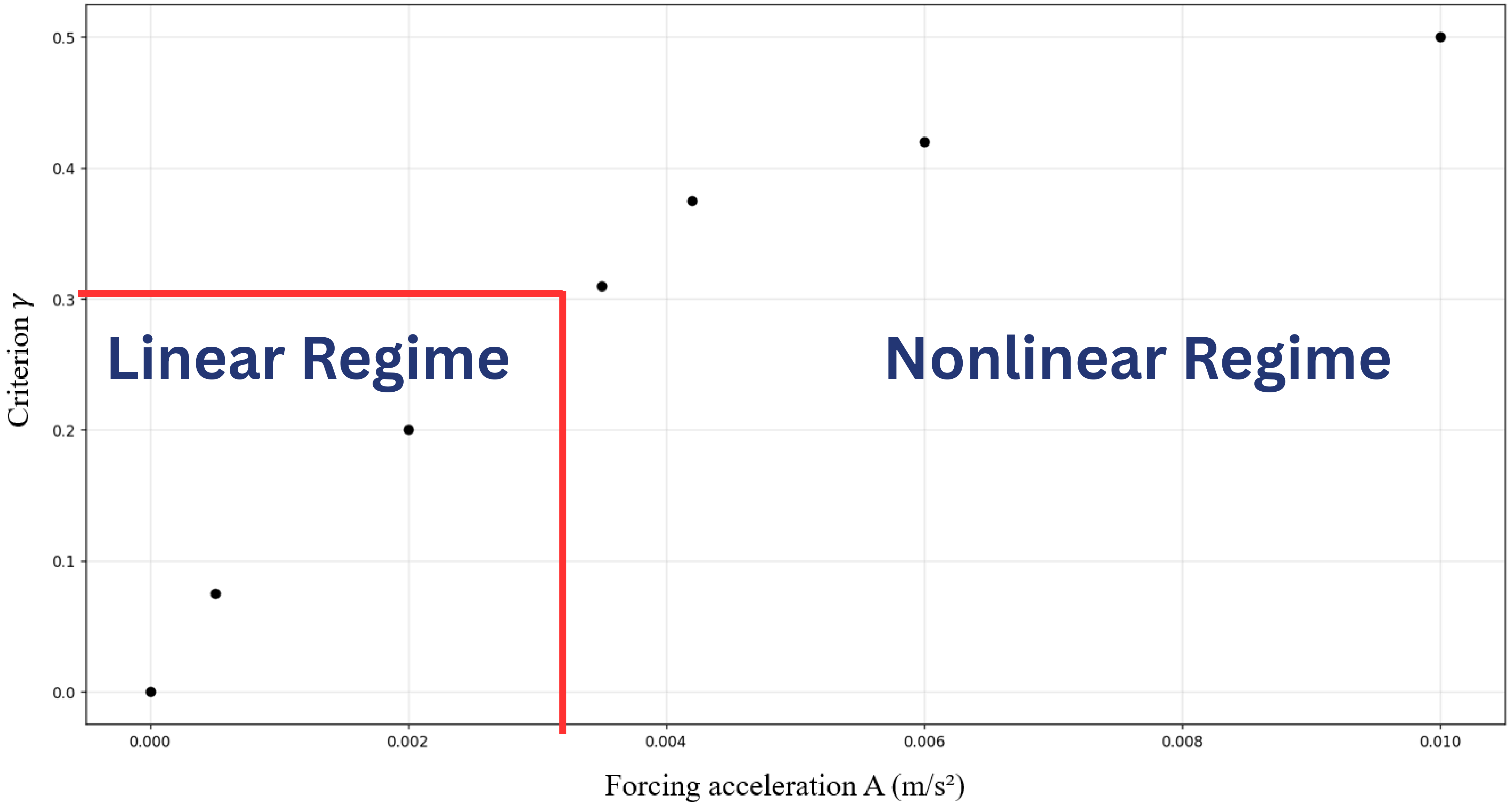
Non linear Sloshing :

Can we establish the validity limit of the linear model ?

Conditions:

- Flat initial interface
- Sinusoidal lateral acceleration with variable amplitude: $a = A\cos(\omega t)$

Criterion $\gamma = \dfrac{\max|\eta(x,t)|}{H}$ $\gamma \leq \gamma_c \;\Rightarrow\;$ linear regime, $\gamma > \gamma_c \;\Rightarrow\;$ non-linear regime.



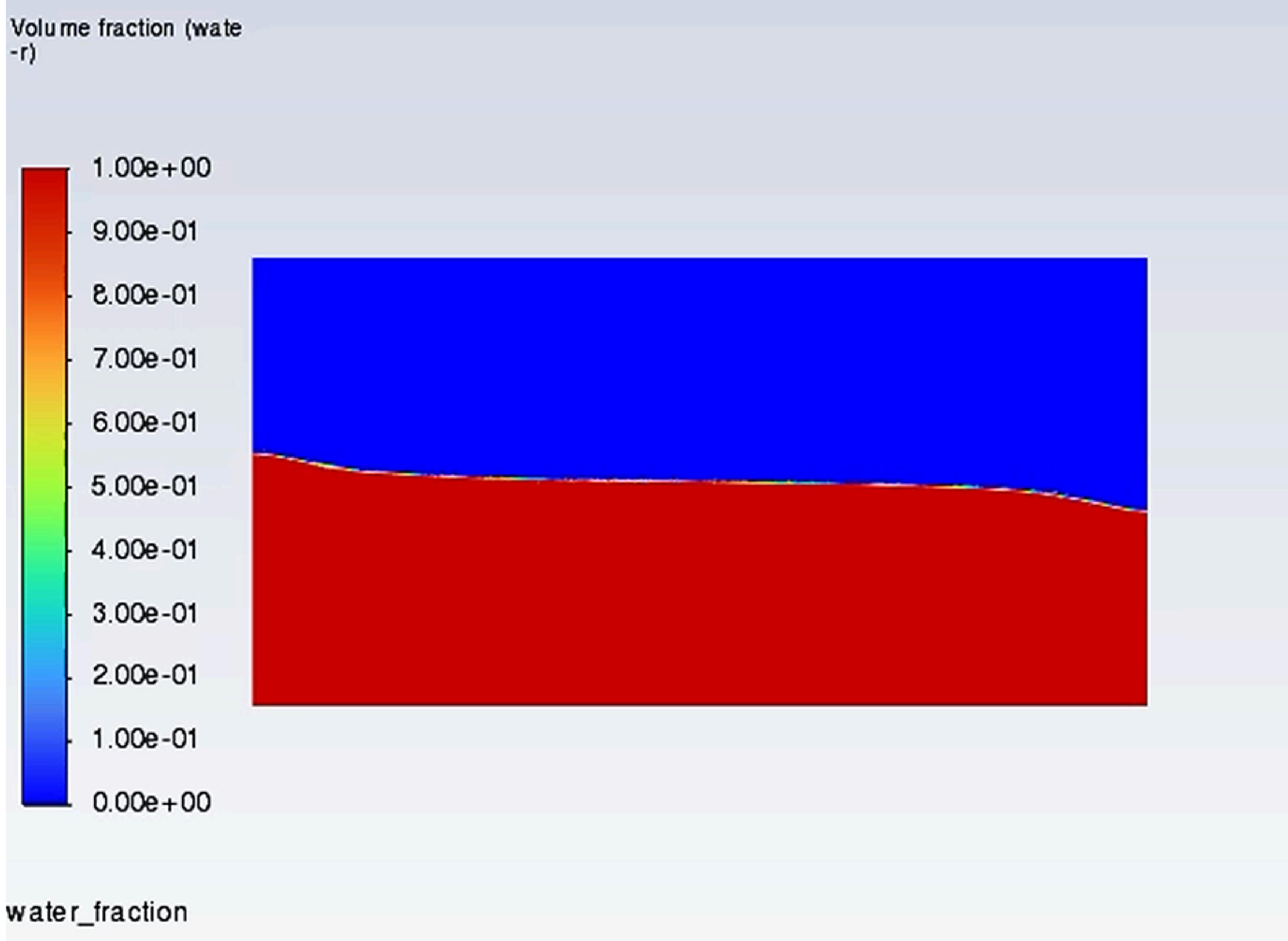
γc corresponds to : NMRSE=15% for the force

$$\mathrm{NRMSE} = \frac{\|F_{\mathrm{CFD}} - F_{\mathrm{model}}\|_2}{\|F_{\mathrm{CFD}} - \bar{F}_{\mathrm{CFD}}\|_2}$$

Critical value : For a criterion γ=0.3, a=0.003 m/s²

Linear sloshing breaks down for anything above

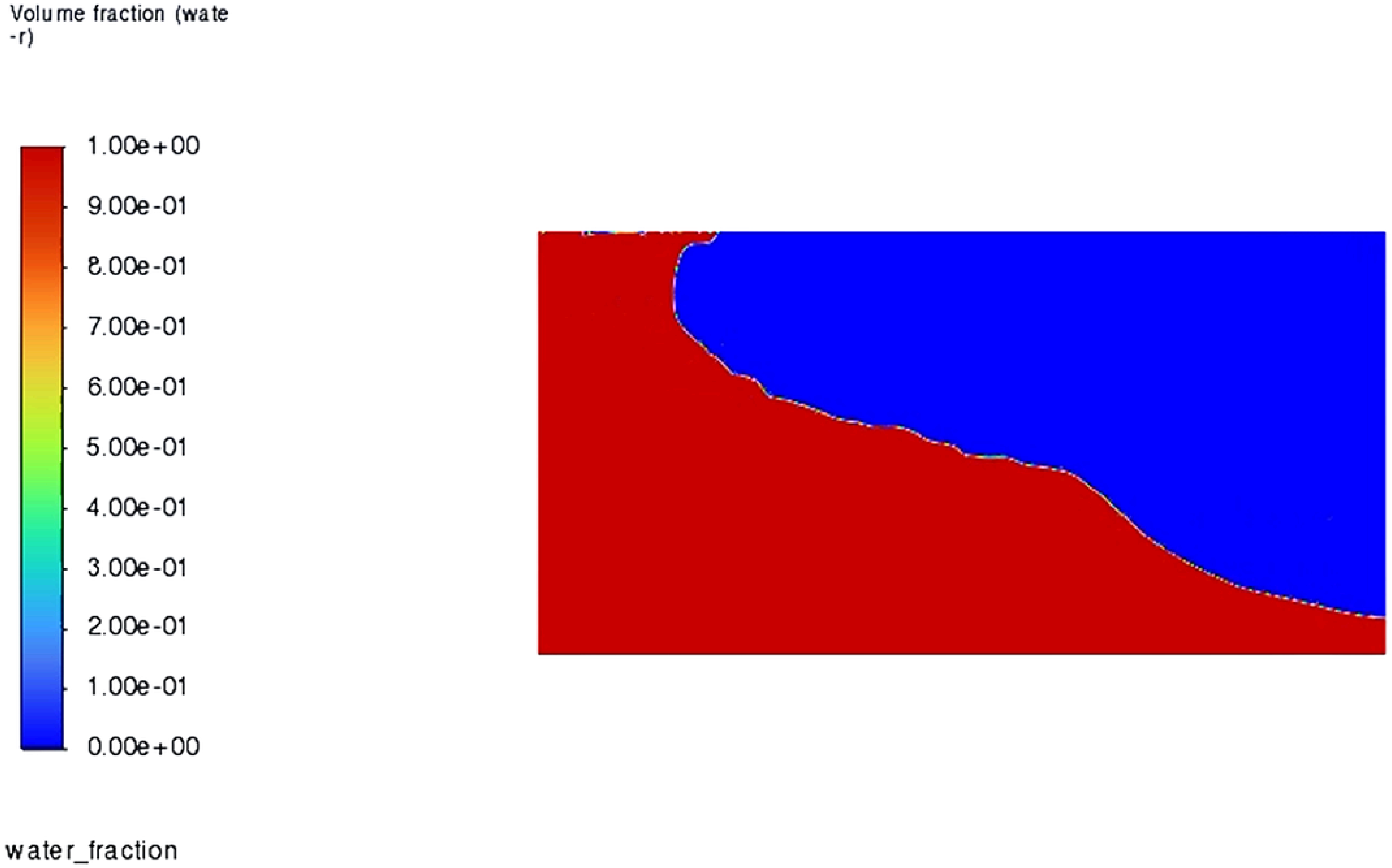
Illustration of the two regimes



‘Linear’ geometric deformations

$A=0.001\ \mathrm{m/s^2}$

$t=5\mathrm{s}$



‘Non linear’ geometric deformations

$A=0.01\ \mathrm{m/s^2}$

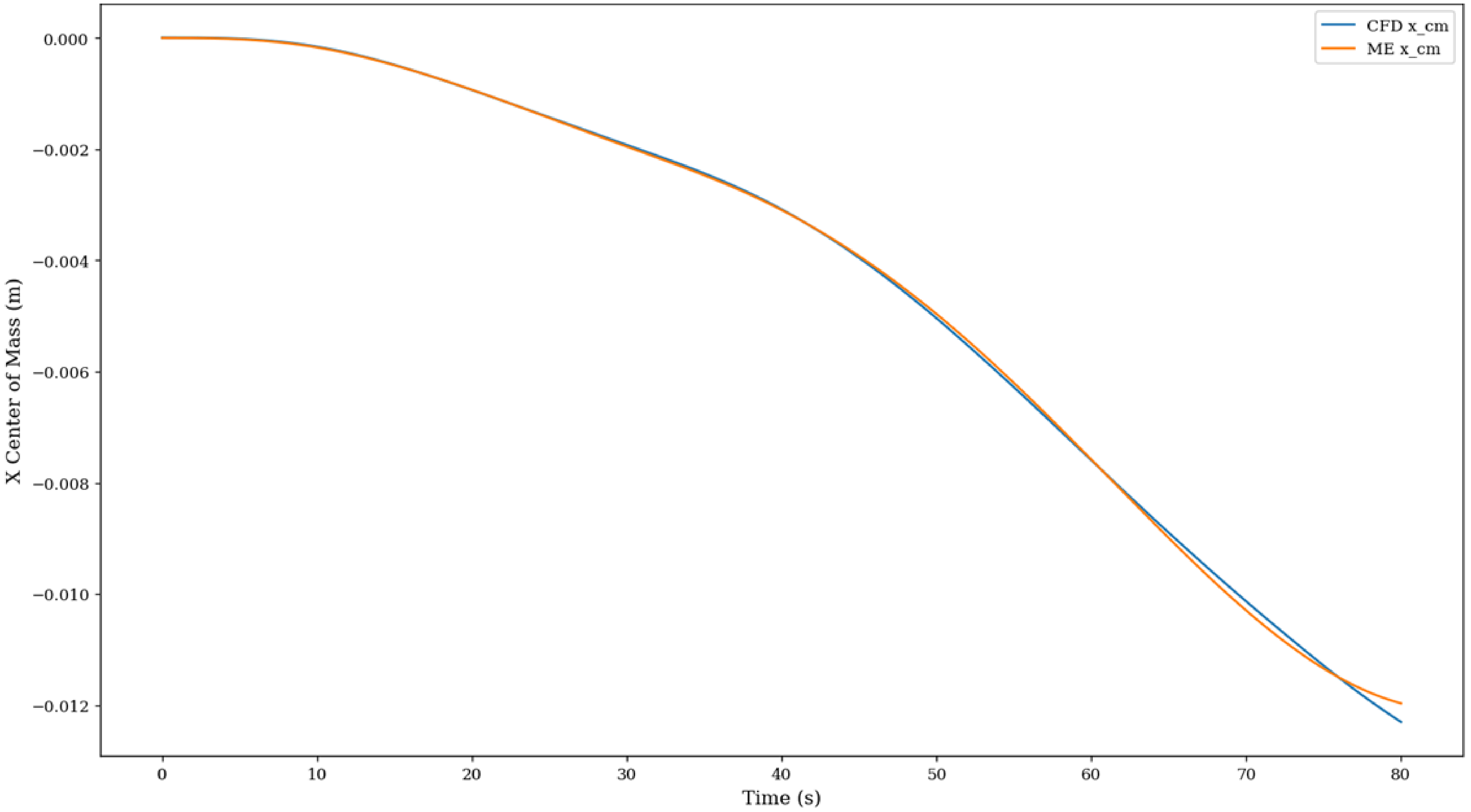
$t=7\mathrm{s}$

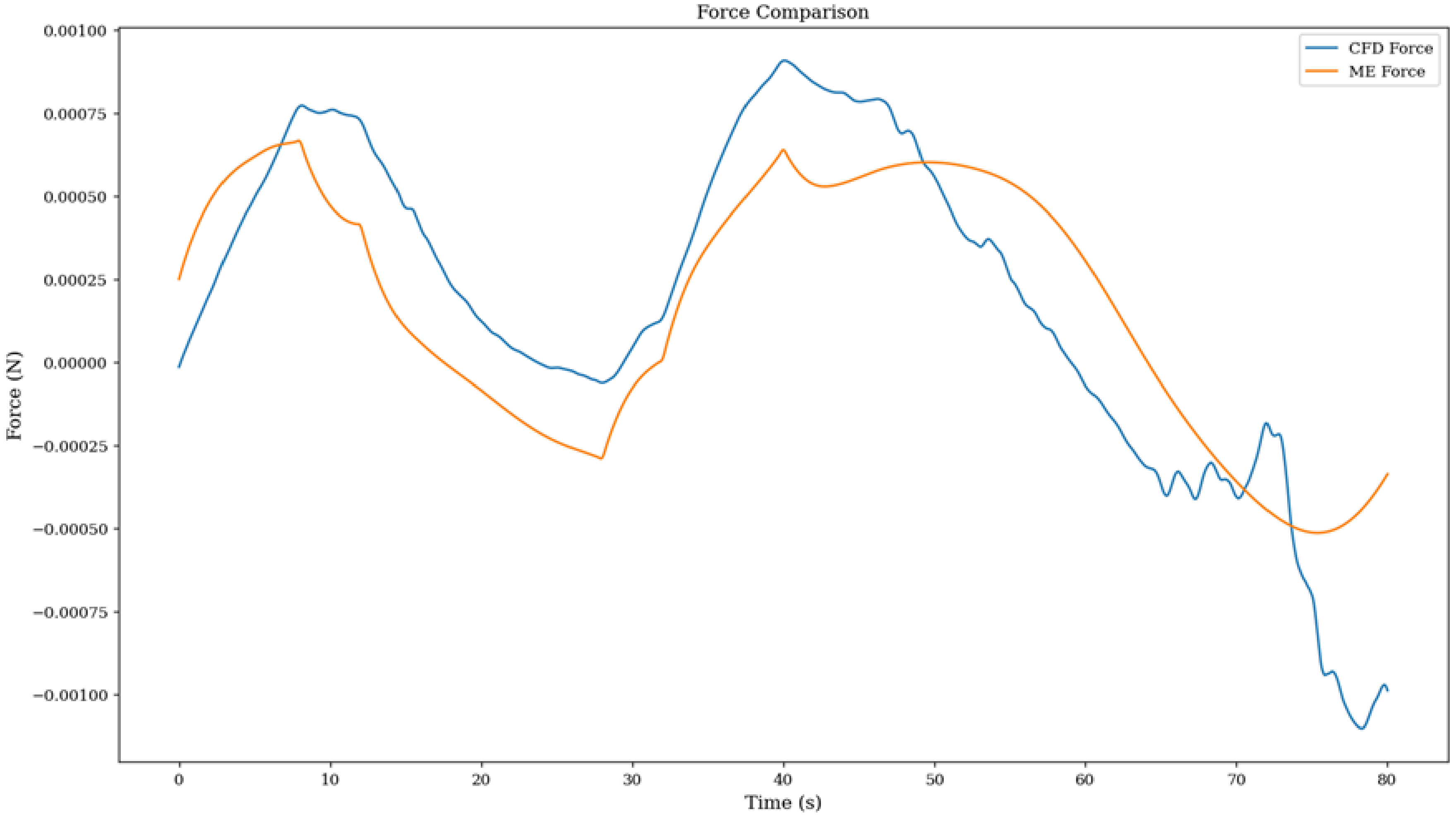
Simulation of the maneuvers

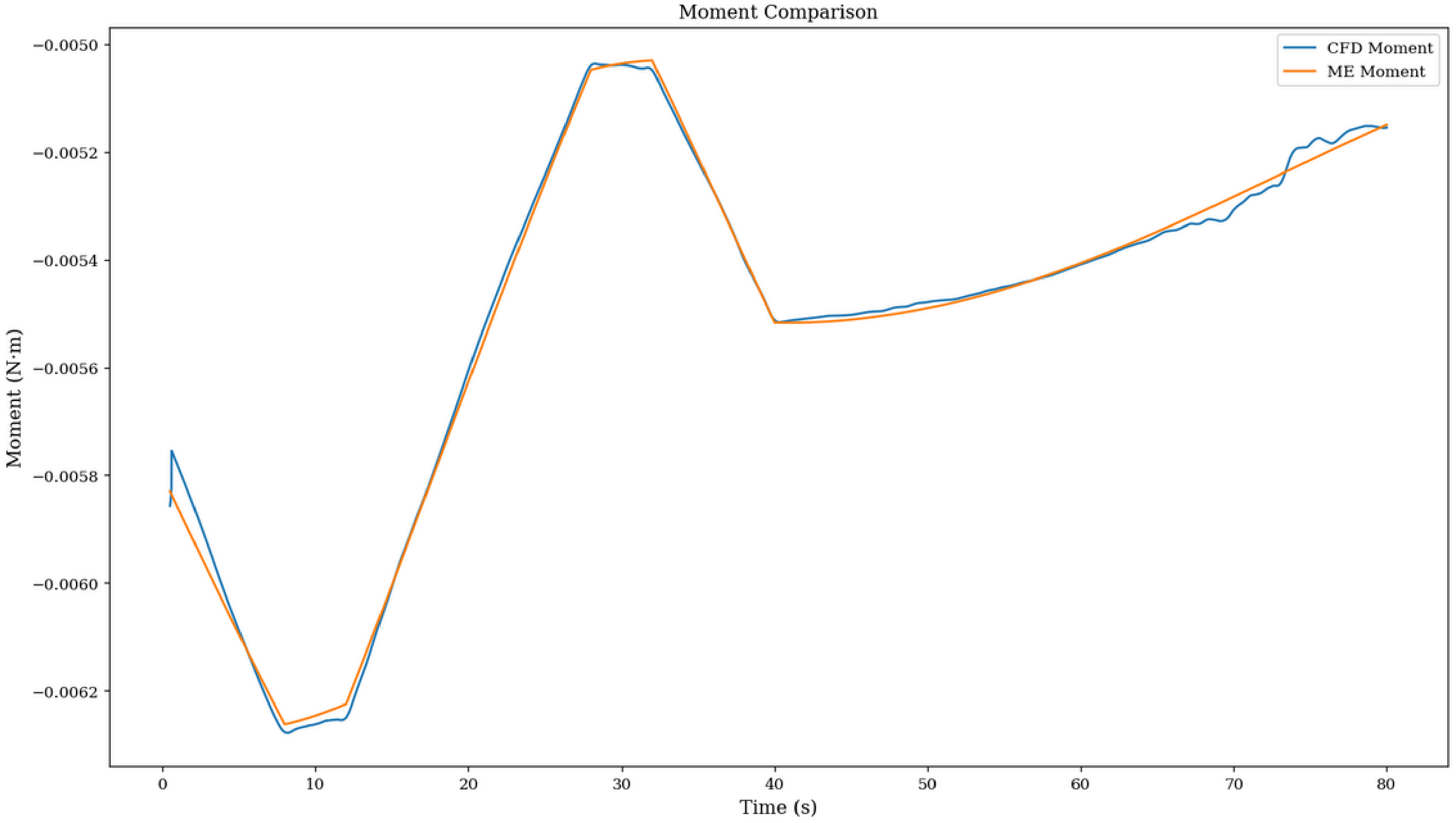
Reorientation Maneuver

$$a_{max} = 2.8\times10^{-4} m.s^{-2}$$

Linear behavior expected







$$NMRSE_{Force} = 9\%$$

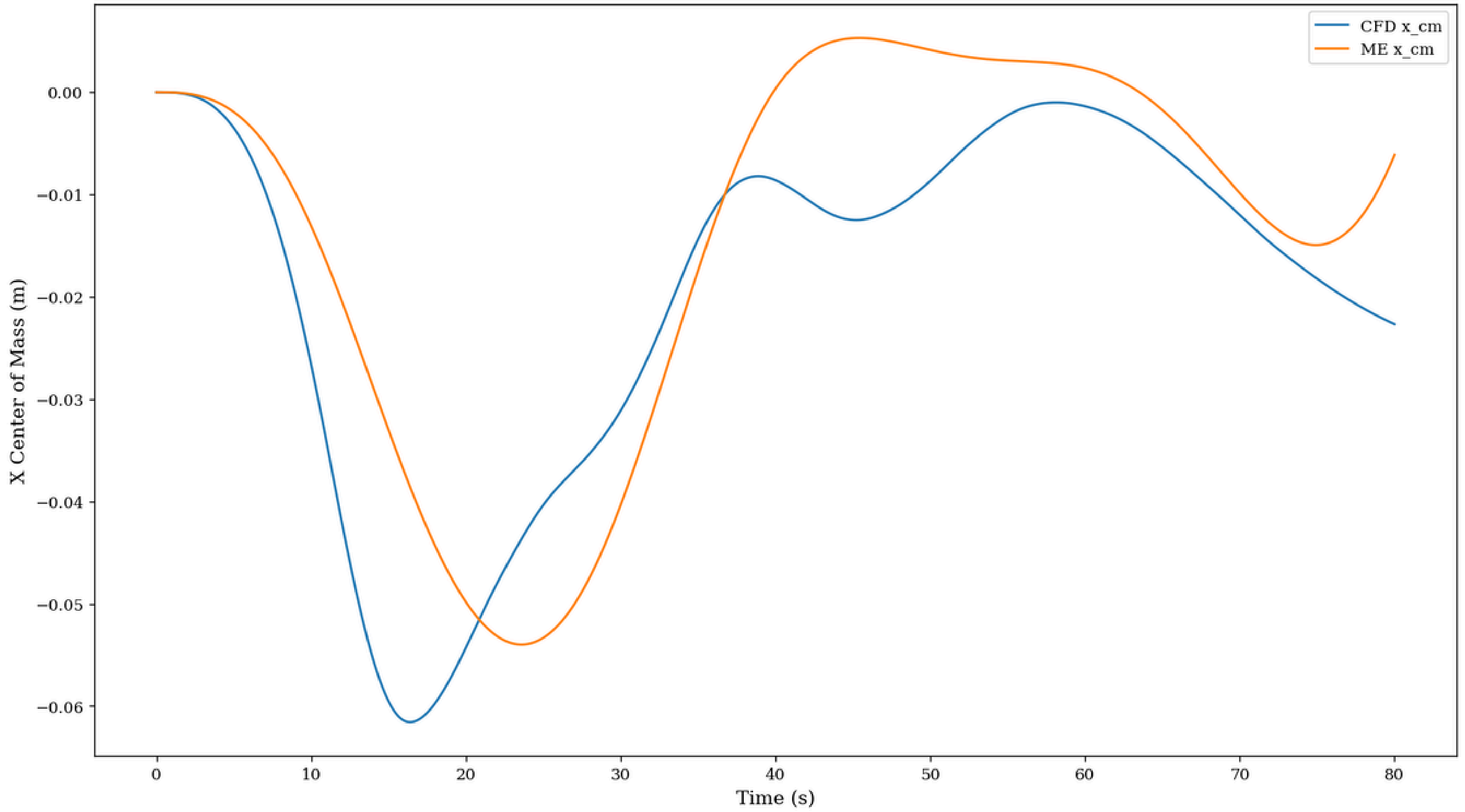
$$NMRSE_{Moment} = 1\%$$

$$NMRSE_{CM} = 1.5\%$$

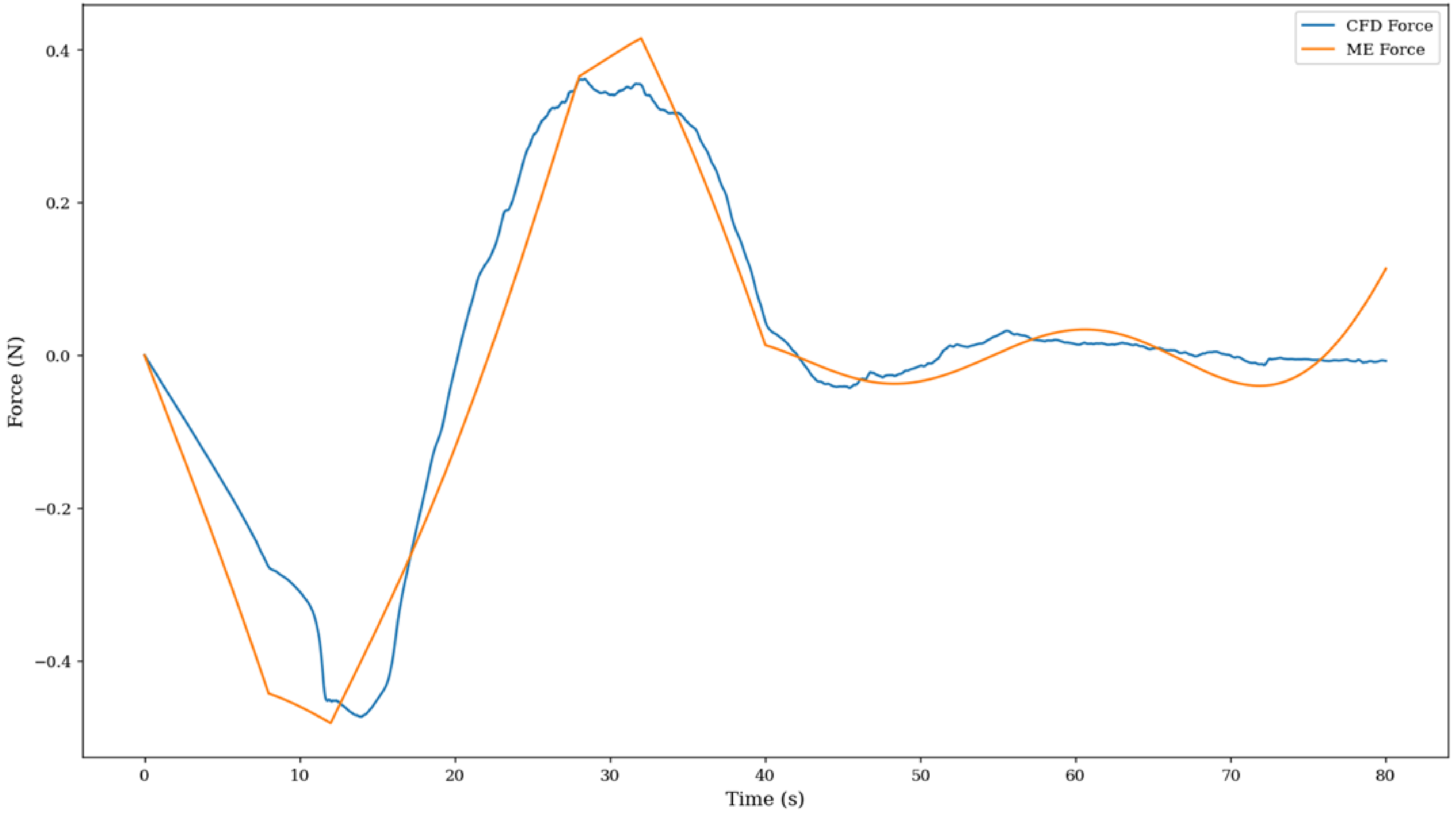
Translation Maneuver

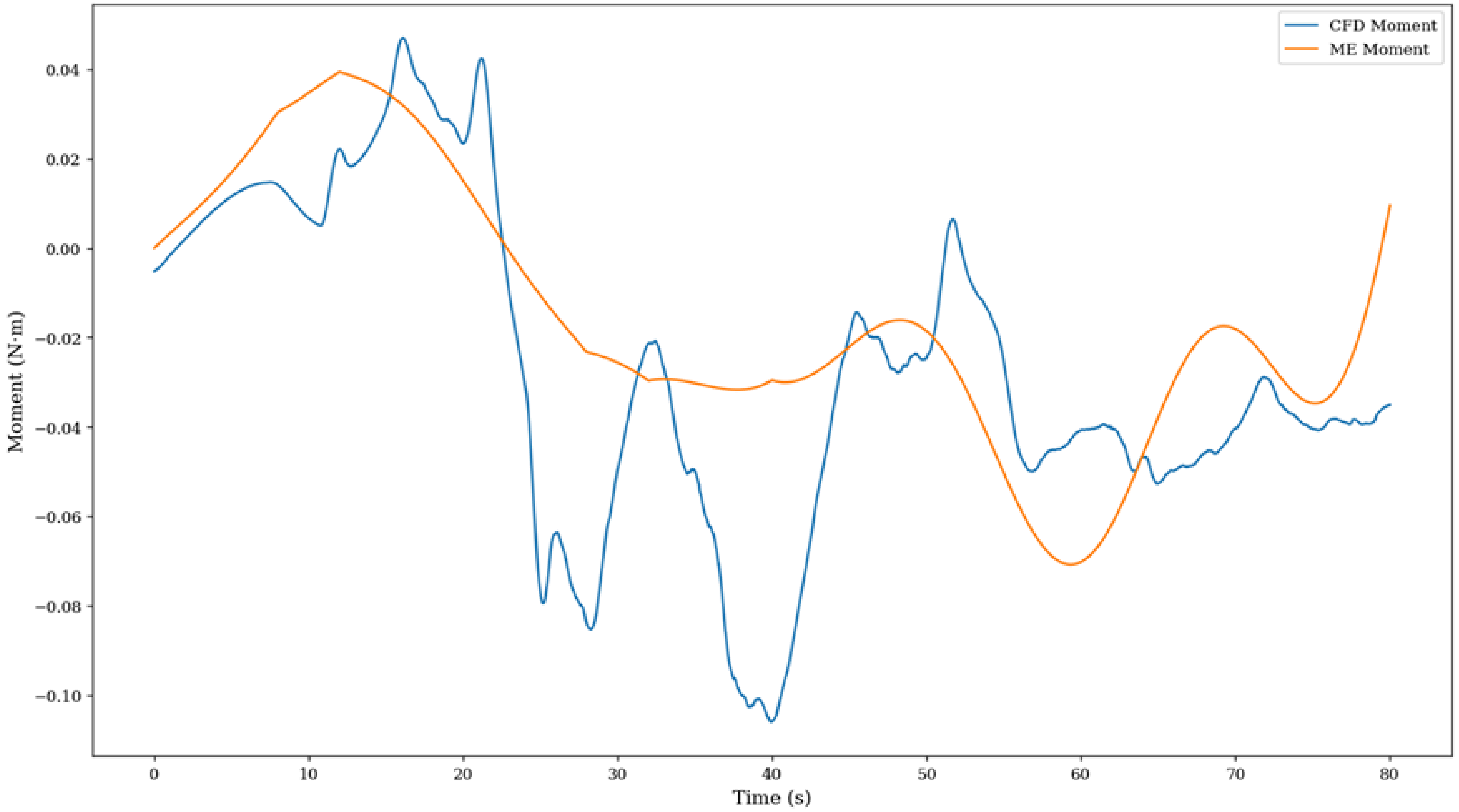
$$a_{max} = 0.004 m. s^{-2}$$

Non linear behavior expected: poor model predictions



$$NMRSE_{Force} = 14\%$$
$$NMRSE_{Moment} = 28\%$$
$$NMRSE_{CM} = 17\%$$

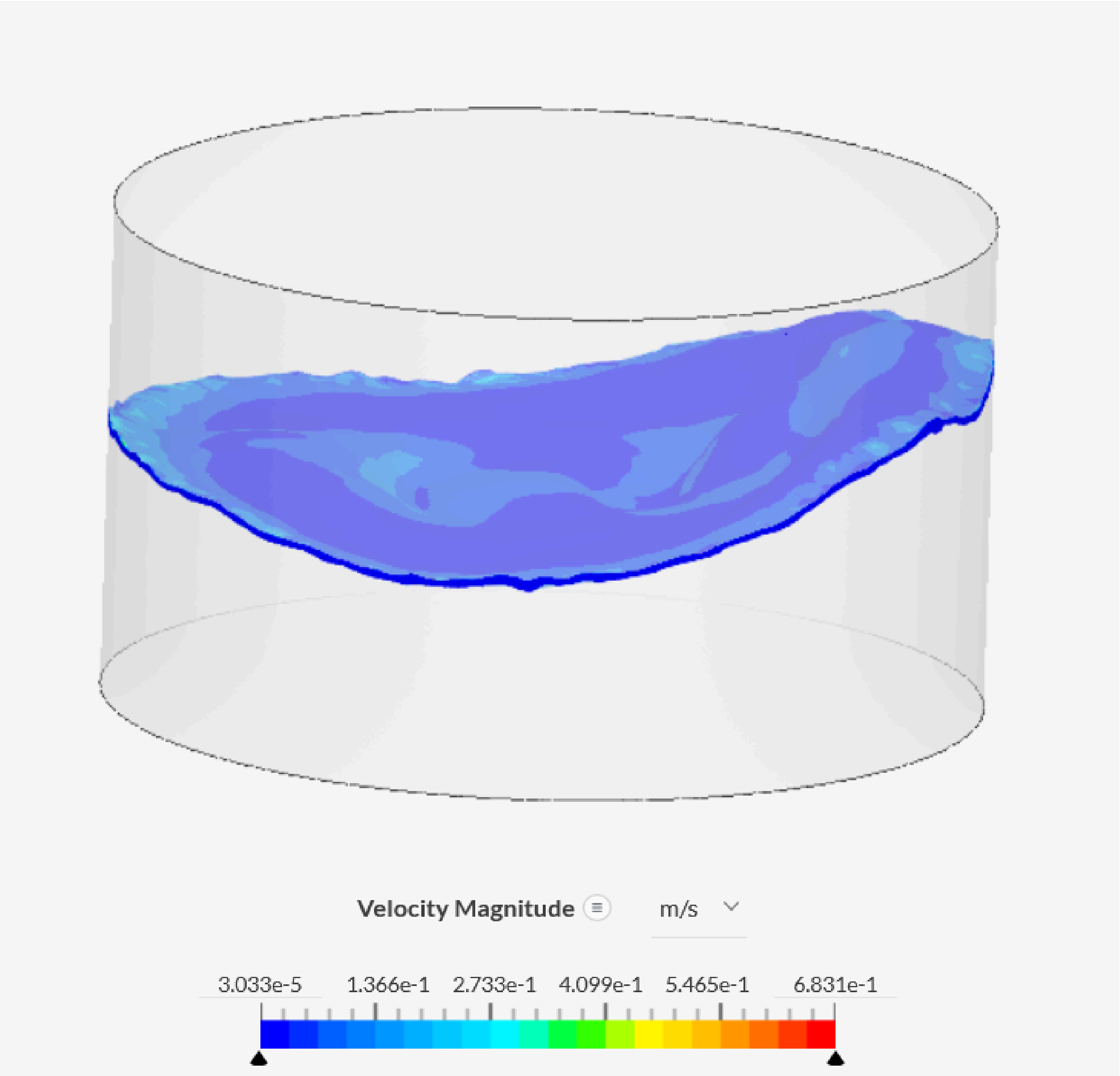


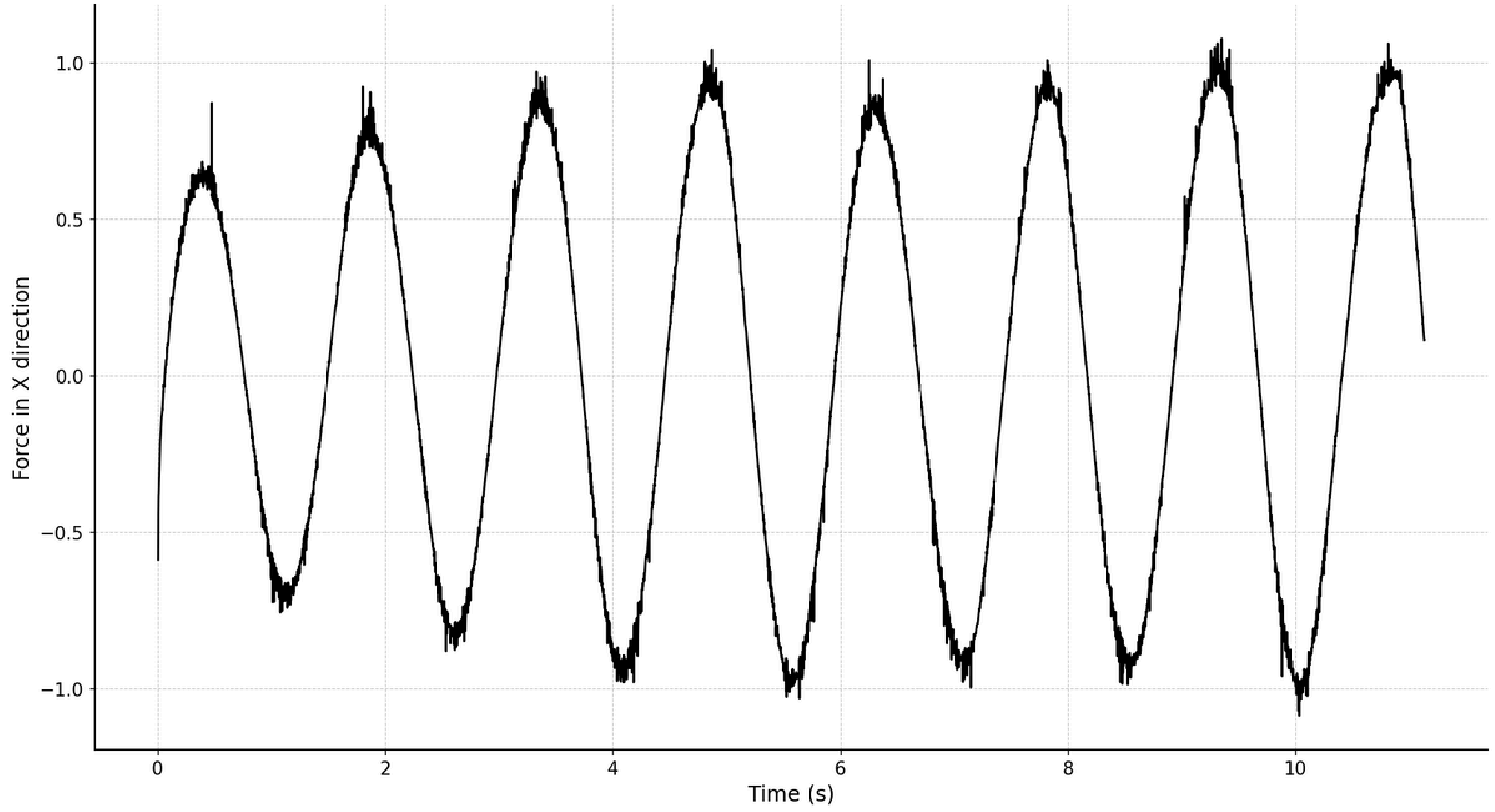


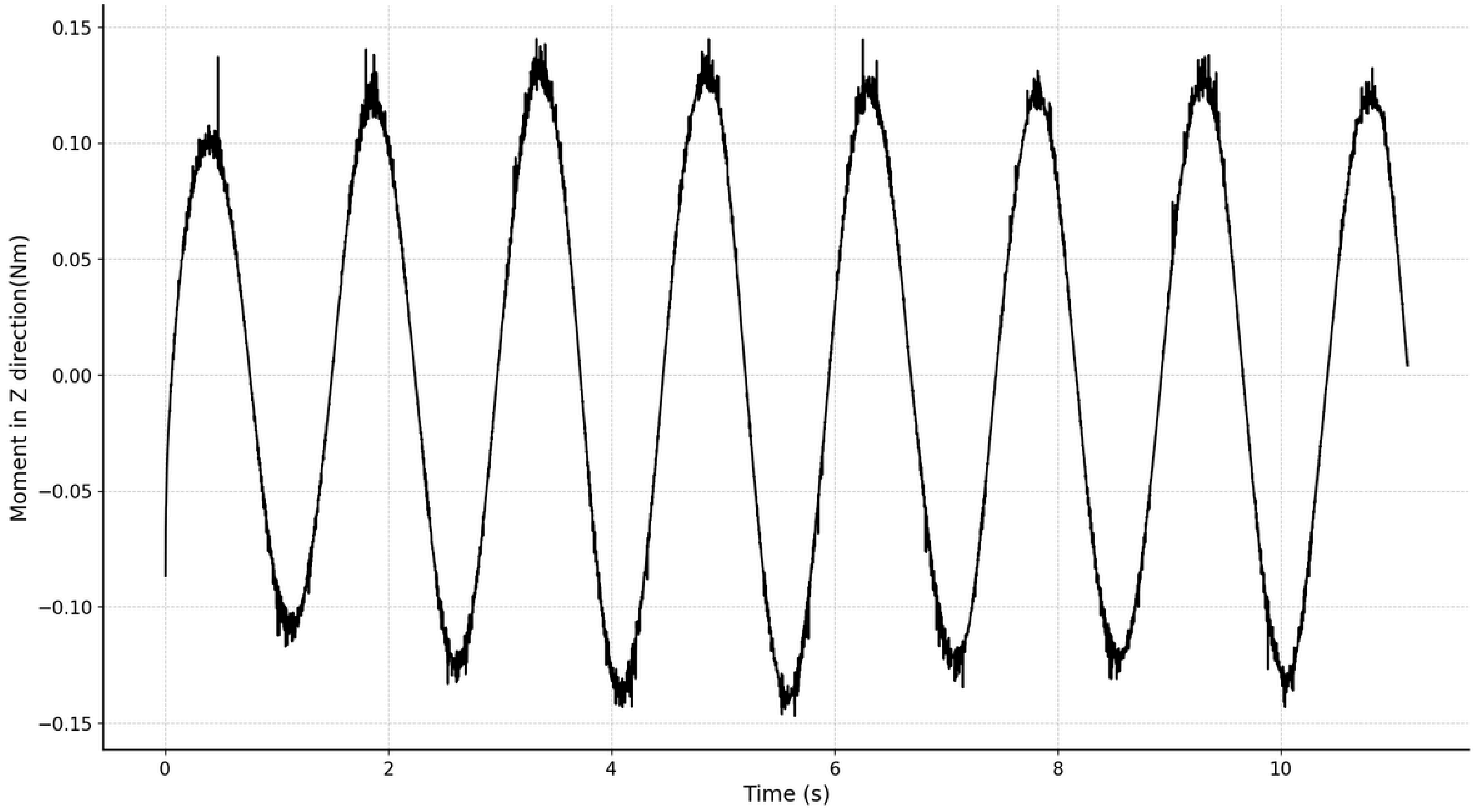
3D Simulations

- Computational challenge linked to the mesh sizes required
- First tests using cloud computing

SIMSCALE





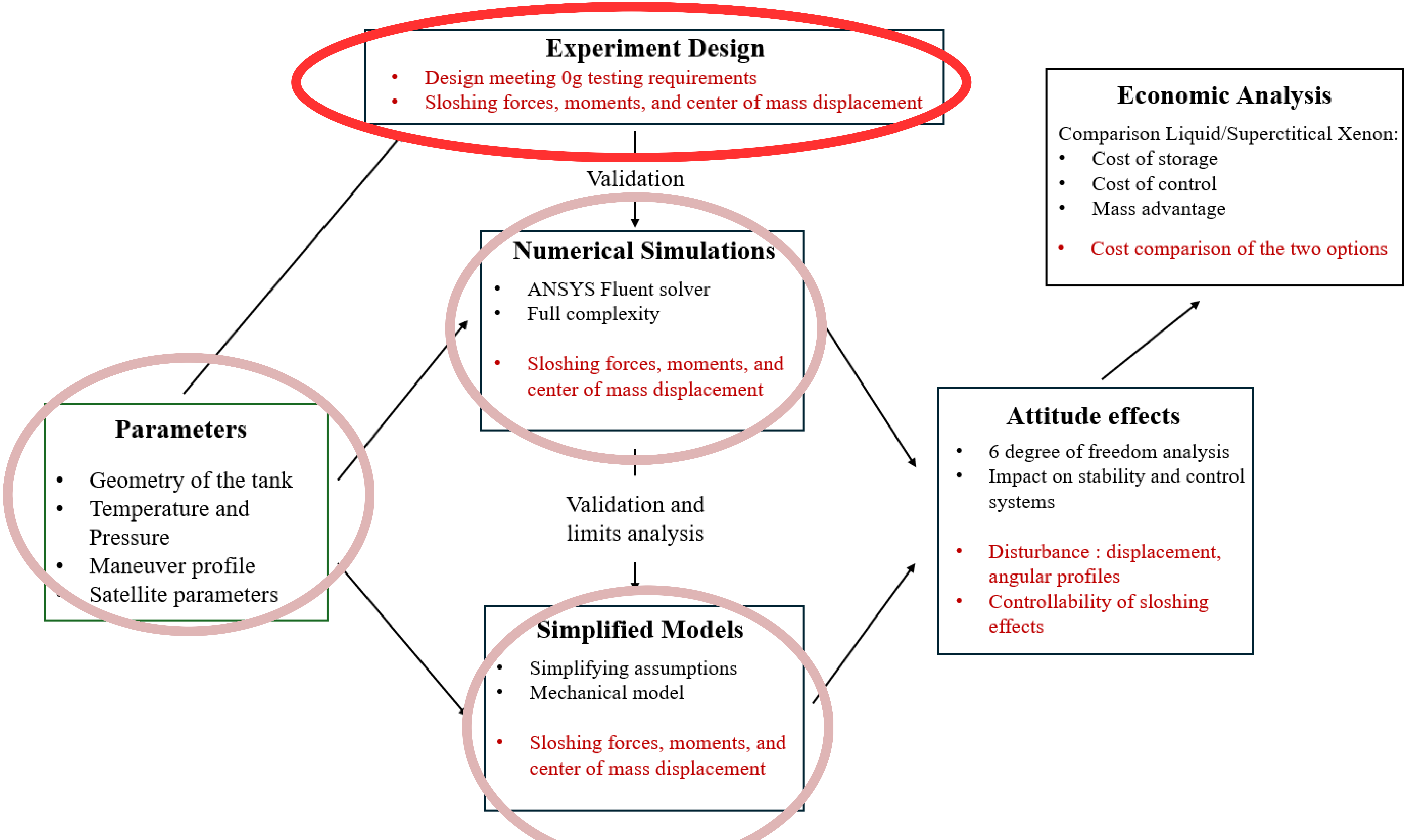


Finally we have…

- A linear sloshing model verified through simulation
- An idea of when it breaks down (empirical criterion)
- Simulations of the different maneuvers in 2D (parametric)
- Incomplete simulations in 3D

Future work should …

- Try to implement descriptive models for non linear sloshing (LPVs)
- Concentrate on 3D simulations (cylindrical/rectangular)



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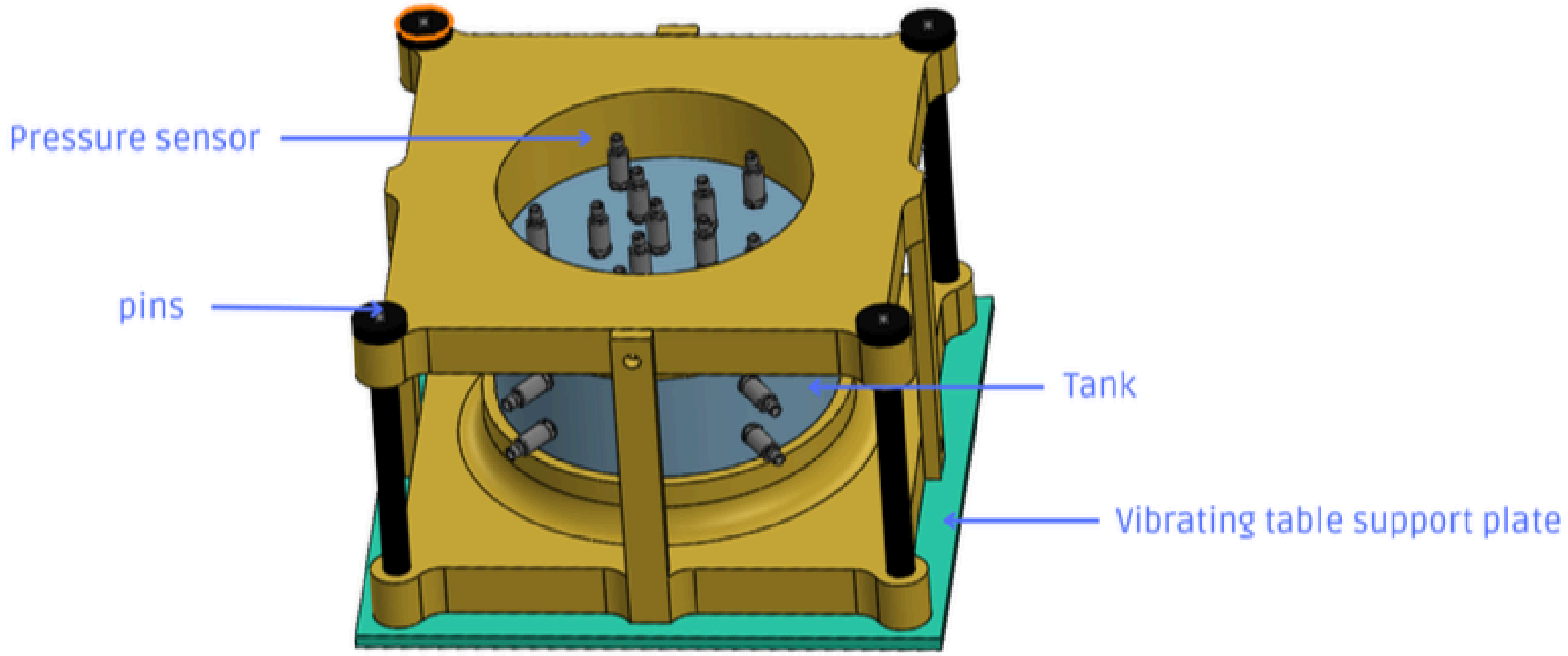
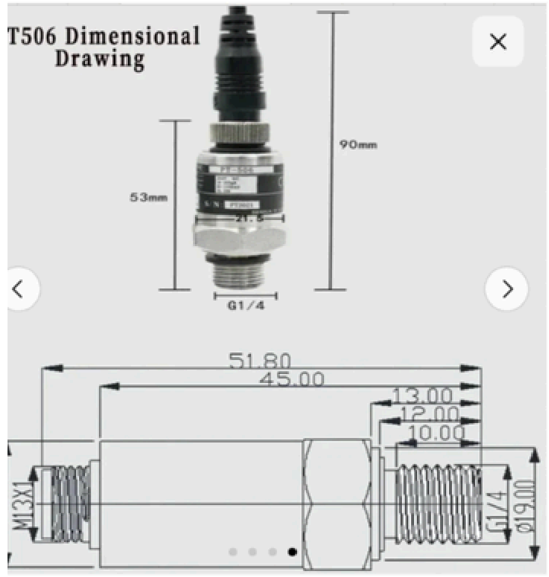
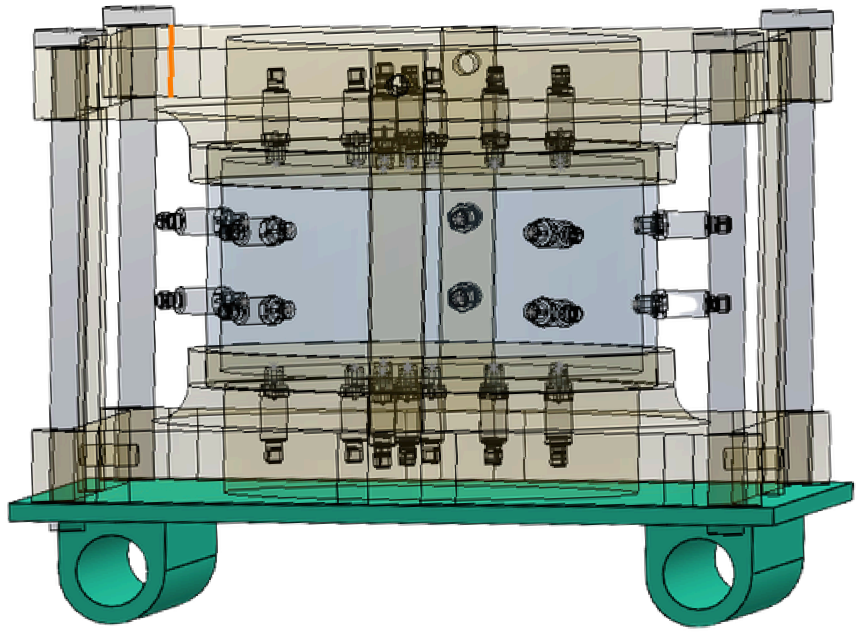
Experiment

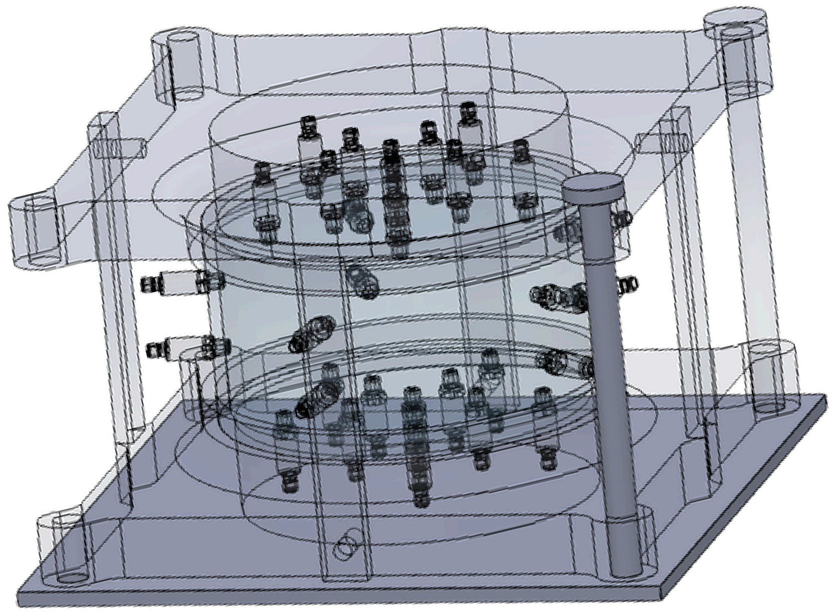
Objective: Measure sloshing forces via wall pressure





Pressure sensor
IP68 waterproof





Experimental Design for CFD Validation

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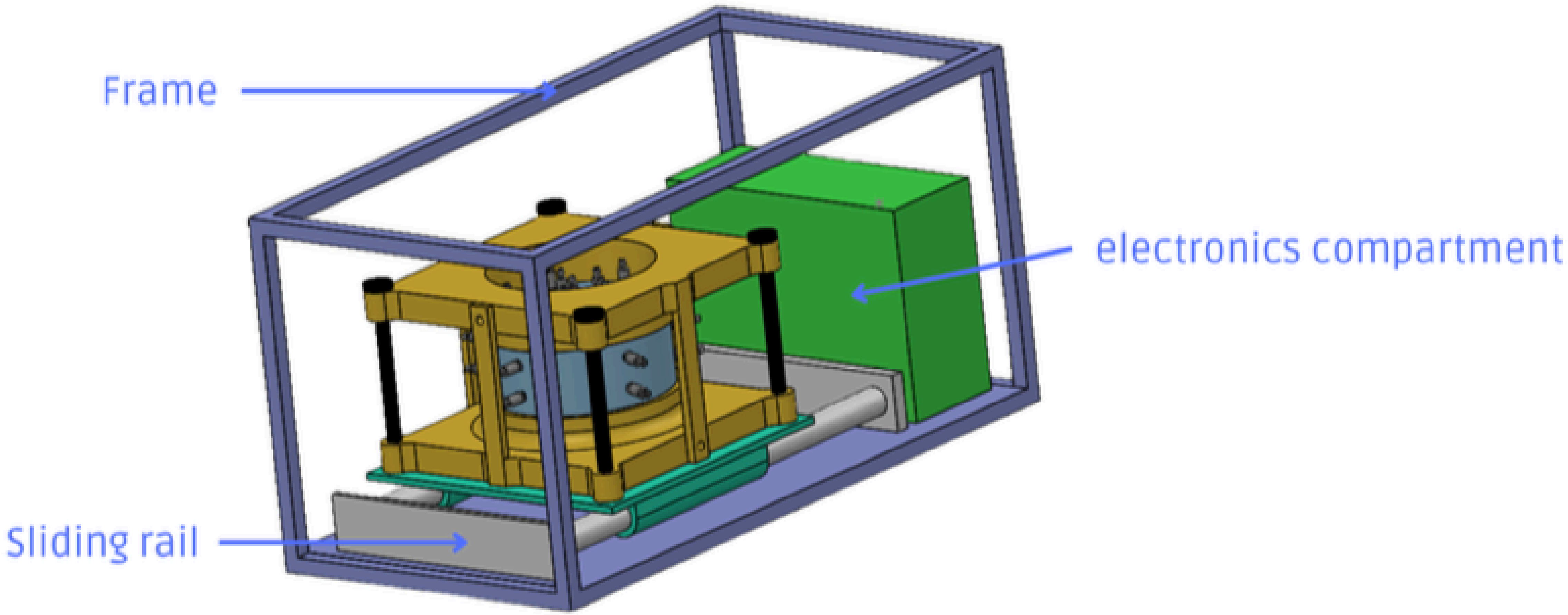
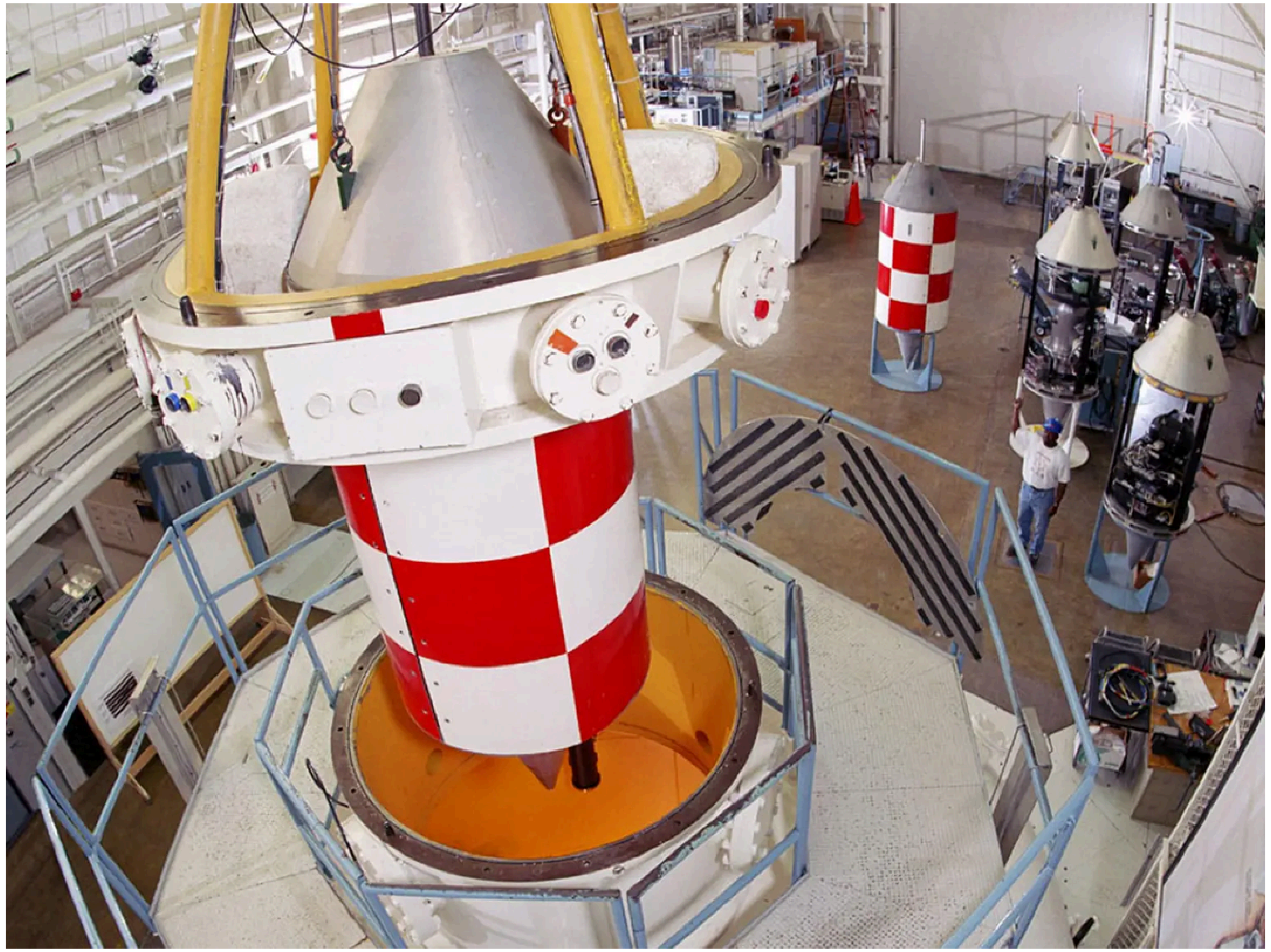


The vibrating plate is used to replicate lateral accelerations, with pressure sensors to measure the fluid sloshing dynamics.

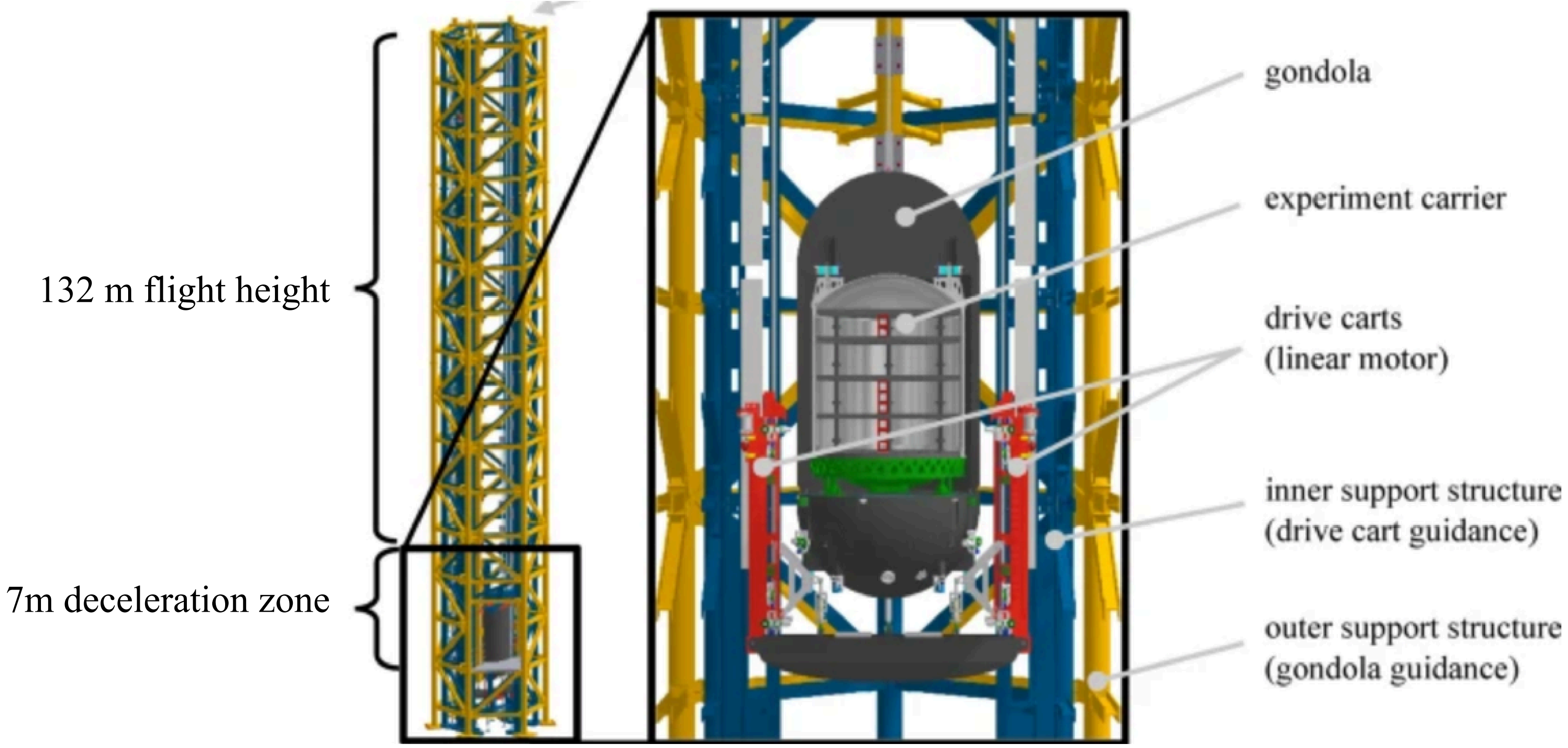
Experimental Design for CFD Validation

A drop tower to achieve gravity conditions



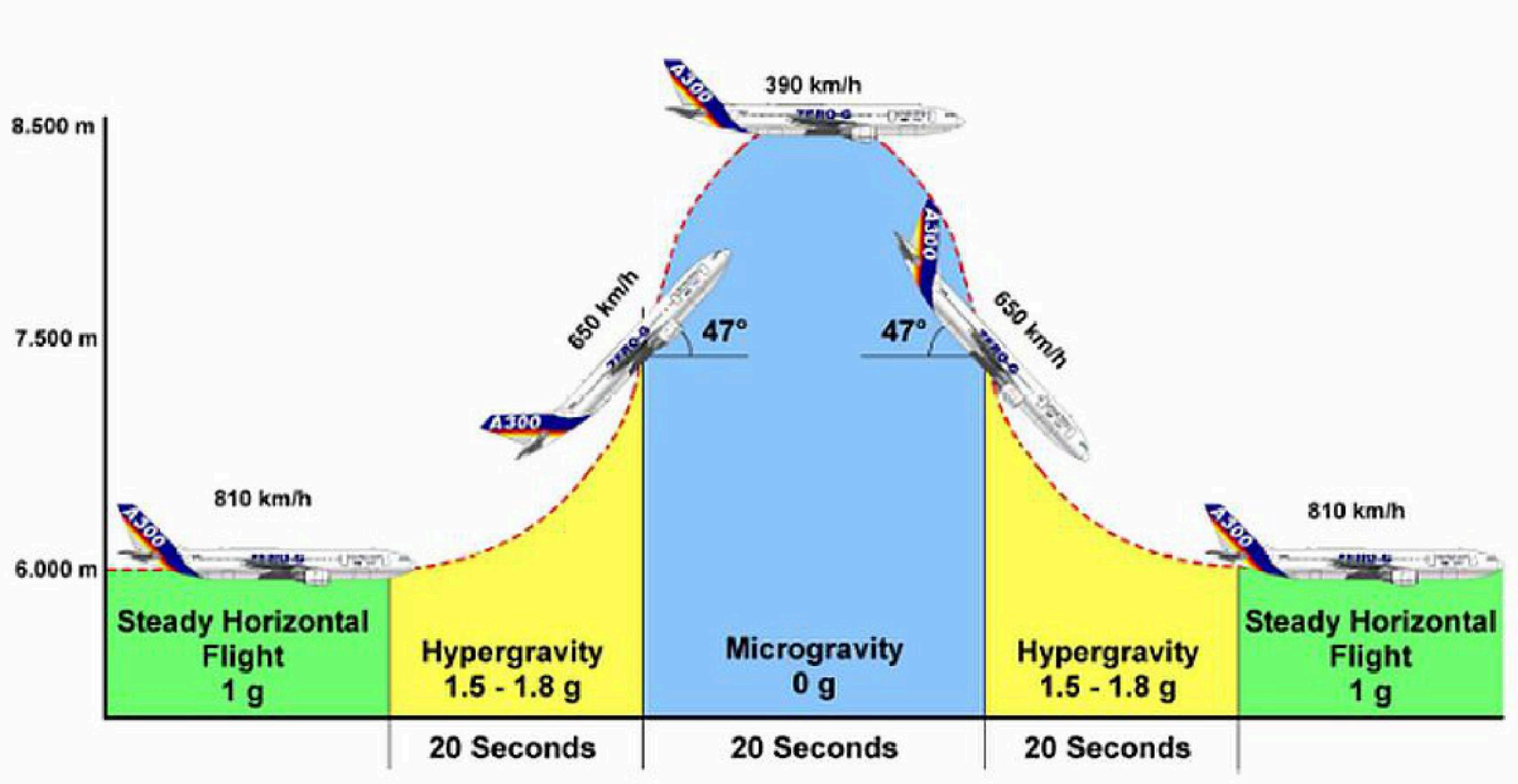
NASA Glenn Drop Tower (Cleveland, Ohio)

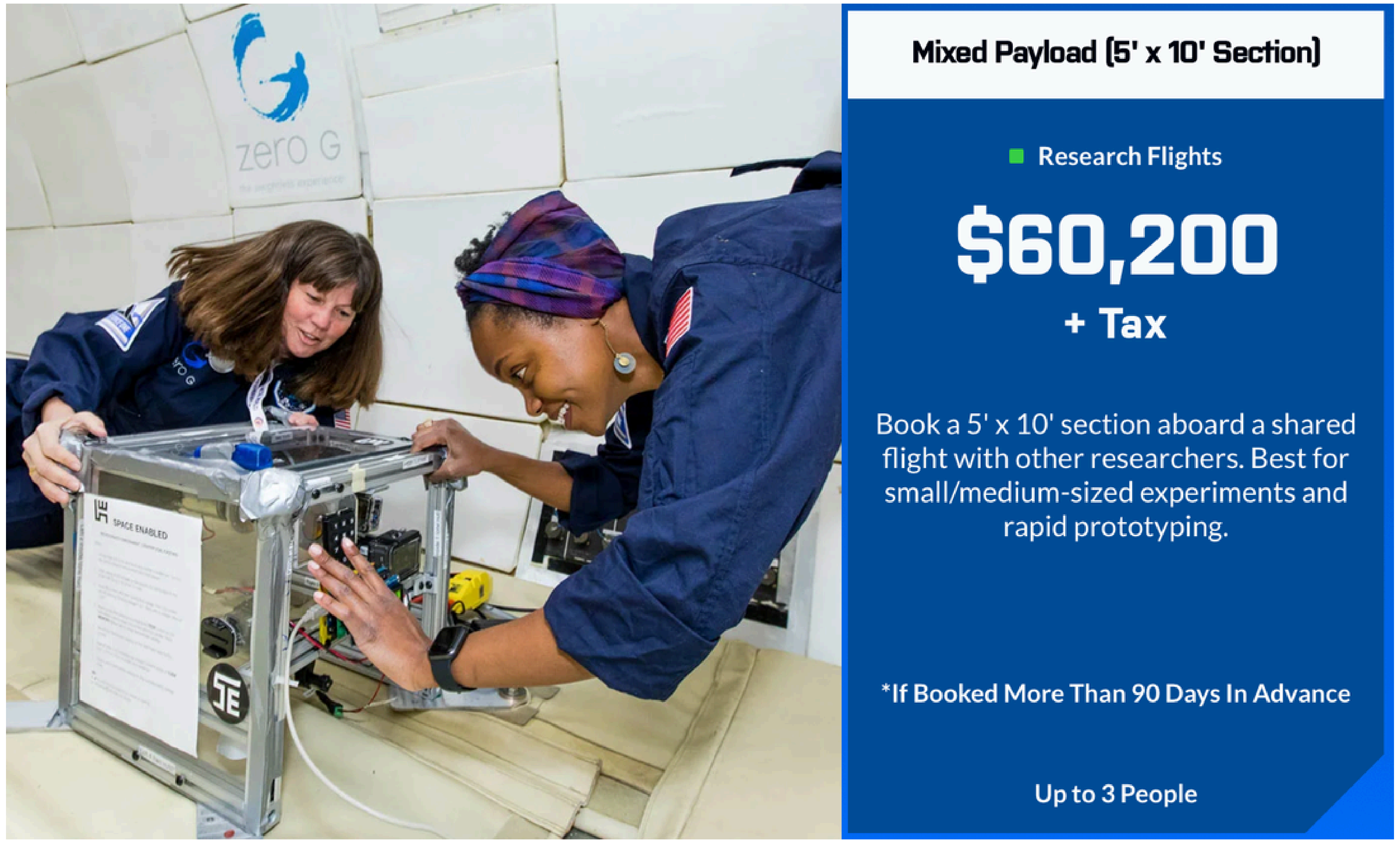
Height: 132 m
Free-fall height: 132 m → 5.18 s microgravity
Peak deceleration: up to 65 g



Experimental Design for CFD Validation

A parabolic flight (Zero-G flight) to achieve gravity conditions





Mixed Payload (5' x 10' Section)

🟩 Research Flights

$60,200

+ Tax

Book a 5' x 10' section aboard a shared flight with other researchers. Best for small/medium-sized experiments and rapid prototyping.

*If Booked More Than 90 Days In Advance

Up to 3 People

Experimental Design for CFD Validation

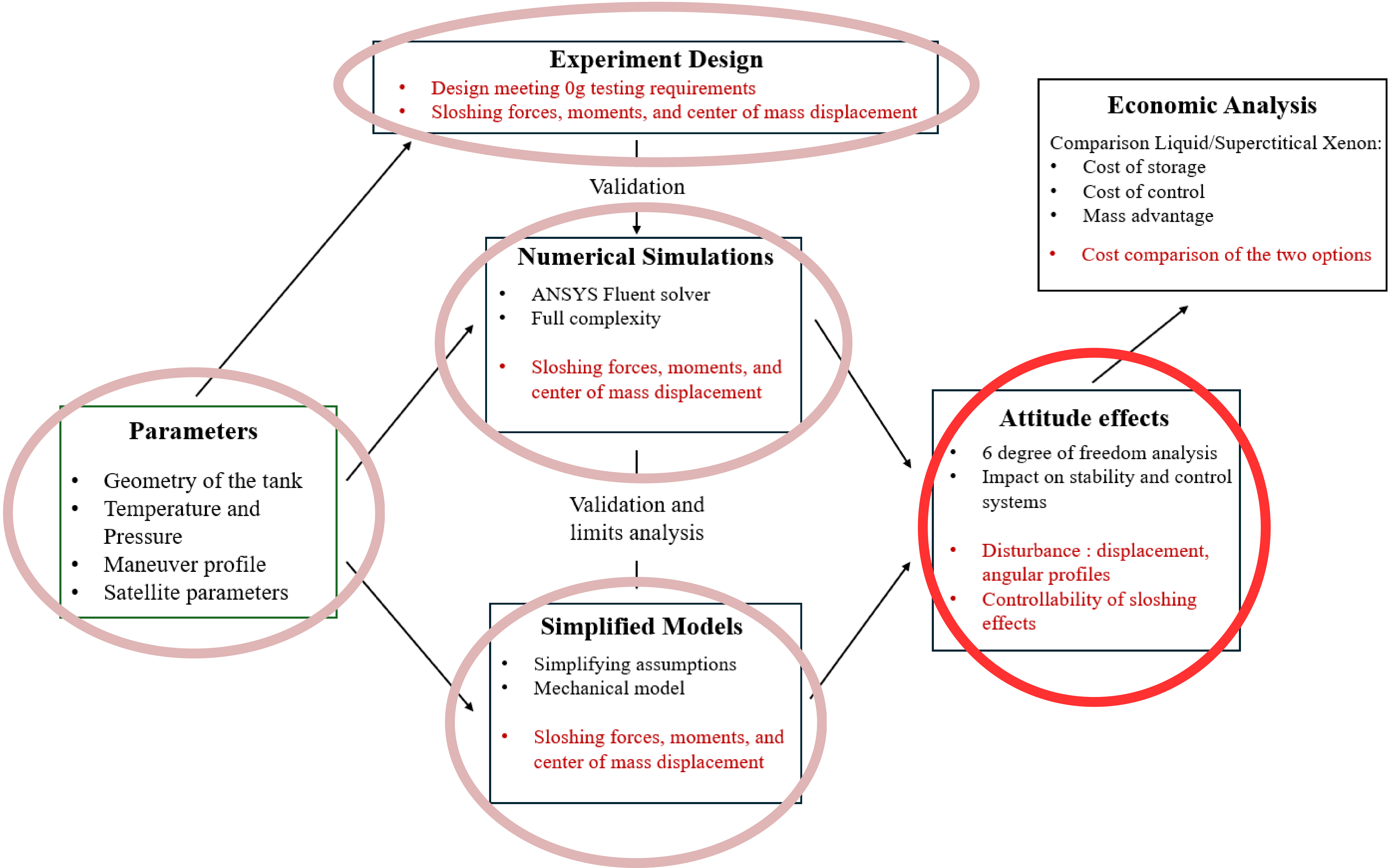
Comparaison of the two experimental conditions are considered to achieve microgravity:

Parabolic flight (Zero-G flight)

- 22 s of microgravity per parabola, with 25 repetitions per flight
- Payload must be fully integrated, flight-certified, and safely secured in a crewed aircraft environment
- System can be reset and adjusted between parabolas (allowing iterative testing and parameter tuning)
- Budget : ~$70k → $2,8k per parabola

Drop tower

- 5 s of microgravity through free fall, ideal for capturing early transient fluid dynamics
- Each drop allows only a single run
- Payload must be fully autonomous
- System must withstand high deceleration loads (~65g) during recovery, imposing strong structural constraints
- Budget: $6k / drop



Experiment Design

- Design meeting 0g testing requirements
- Sloshing forces, moments, and center of mass displacement

Validation

Numerical Simulations

- ANSYS Fluent solver
- Full complexity

- Sloshing forces, moments, and center of mass displacement

Validation and limits analysis

Simplified Models

- Simplifying assumptions
- Mechanical model

- Sloshing forces, moments, and center of mass displacement

Parameters

- Geometry of the tank
- Temperature and Pressure
- Maneuver profile
- Satellite parameters

Attitude effects

- 6 degree of freedom analysis
- Impact on stability and control systems

- Disturbance : displacement, angular profiles
- Controllability of sloshing effects

Economic Analysis

Comparison Liquid/Superctitical Xenon:

- Cost of storage
- Cost of control
- Mass advantage

- Cost comparison of the two options

Attitude Analysis

CFD Outputs

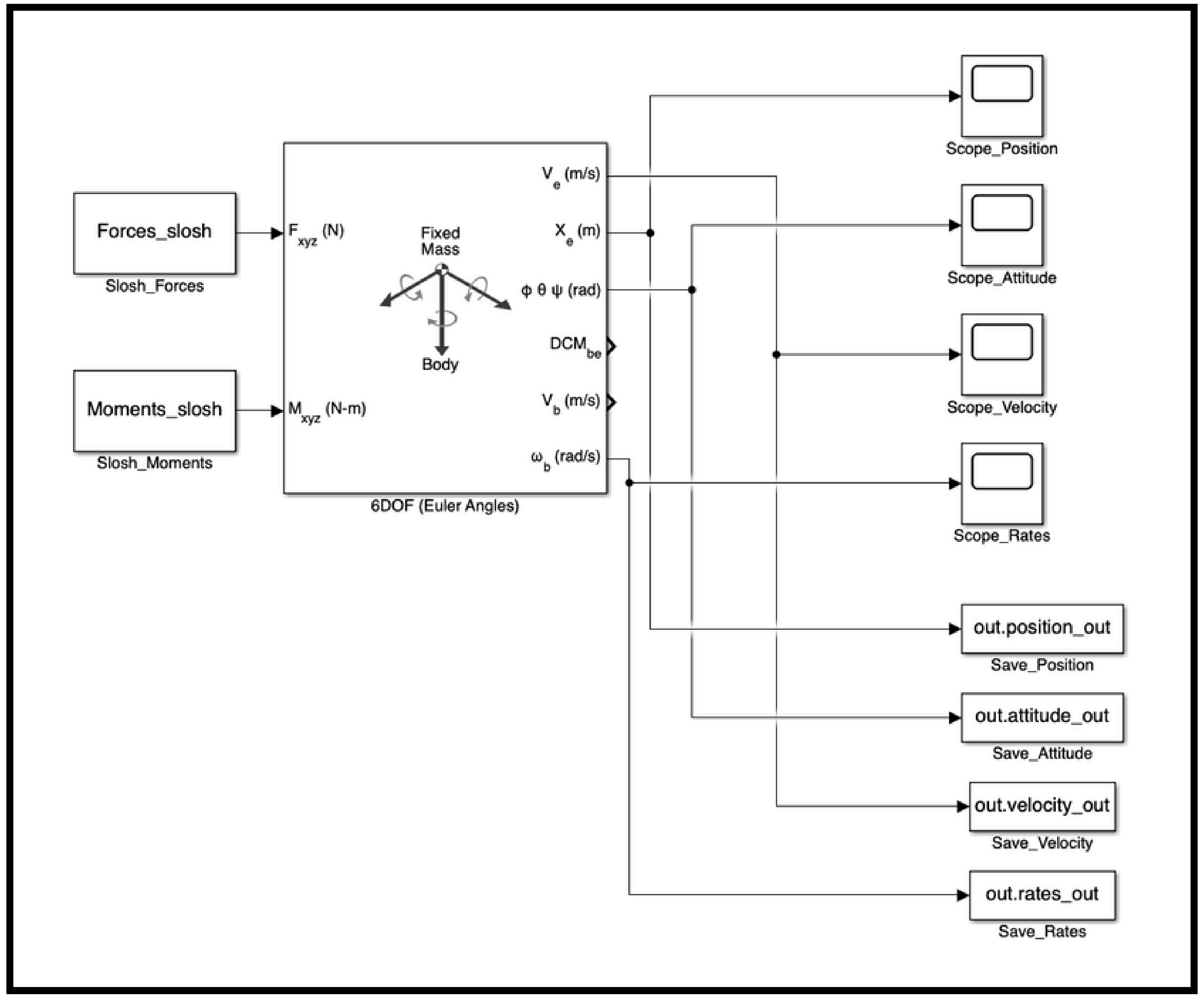
- Sloshing Force
- Sloshing Moment
- Center of Mass of Propellant

Simulink Outputs

- Positional Drift
- Angular Drift
- Velocity
- Angular Rate

Desired Outputs

- Linear Momentum
- Torque
- Accumulated Angular Momentum



Block Diagram of Matlab Simulink Setup

$$I = \begin{bmatrix} 36.25 & 0 & 0 \\ 0 & 29.7478 & 0 \\ 0 & 0 & 44.8639 \end{bmatrix} \mathrm{kg} \cdot \mathrm{m}^2$$

m = 205.112 kg

Attitude Analysis: 6DOF derivation

Spacial Calculations:

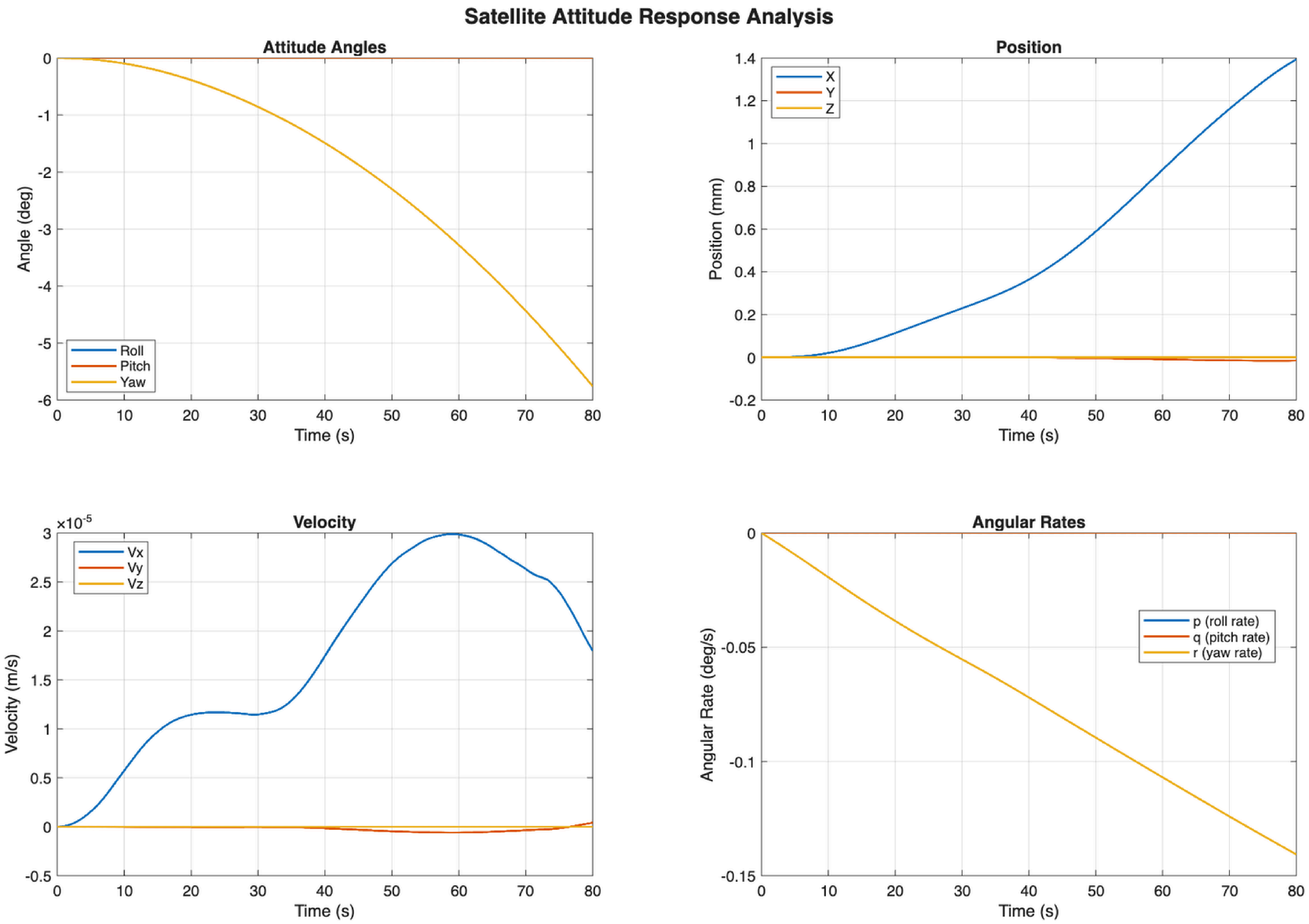
$$\mathbf{a} = \frac{1}{m}\mathbf{F}_{CFD} \longrightarrow \mathbf{v} = \mathbf{v}_0 + \int_0^t \mathbf{a}\ dt \longrightarrow \mathbf{s} = \mathbf{s}_0 + \int_0^t \mathbf{v}\ dt$$

Angular Calculations:

$$\begin{tikzcd}
 & \psi = \psi_0 + \int_0^t \dot{\psi}\ dt \arrow[dd, leftrightarrow, bend left] \\
\mathbf{M}_{CFD} = \mathbf{I}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times (\mathbf{I}\boldsymbol{\omega}) \arrow[d] & \\
\dot{\boldsymbol{\omega}} = \mathbf{I}^{-1}\left[\mathbf{M}_{CFD} - \boldsymbol{\omega} \times (\mathbf{I}\boldsymbol{\omega})\right] \arrow[r, bend left] & \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi\sec\theta & \cos\phi\sec\theta \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}
\end{tikzcd}$$

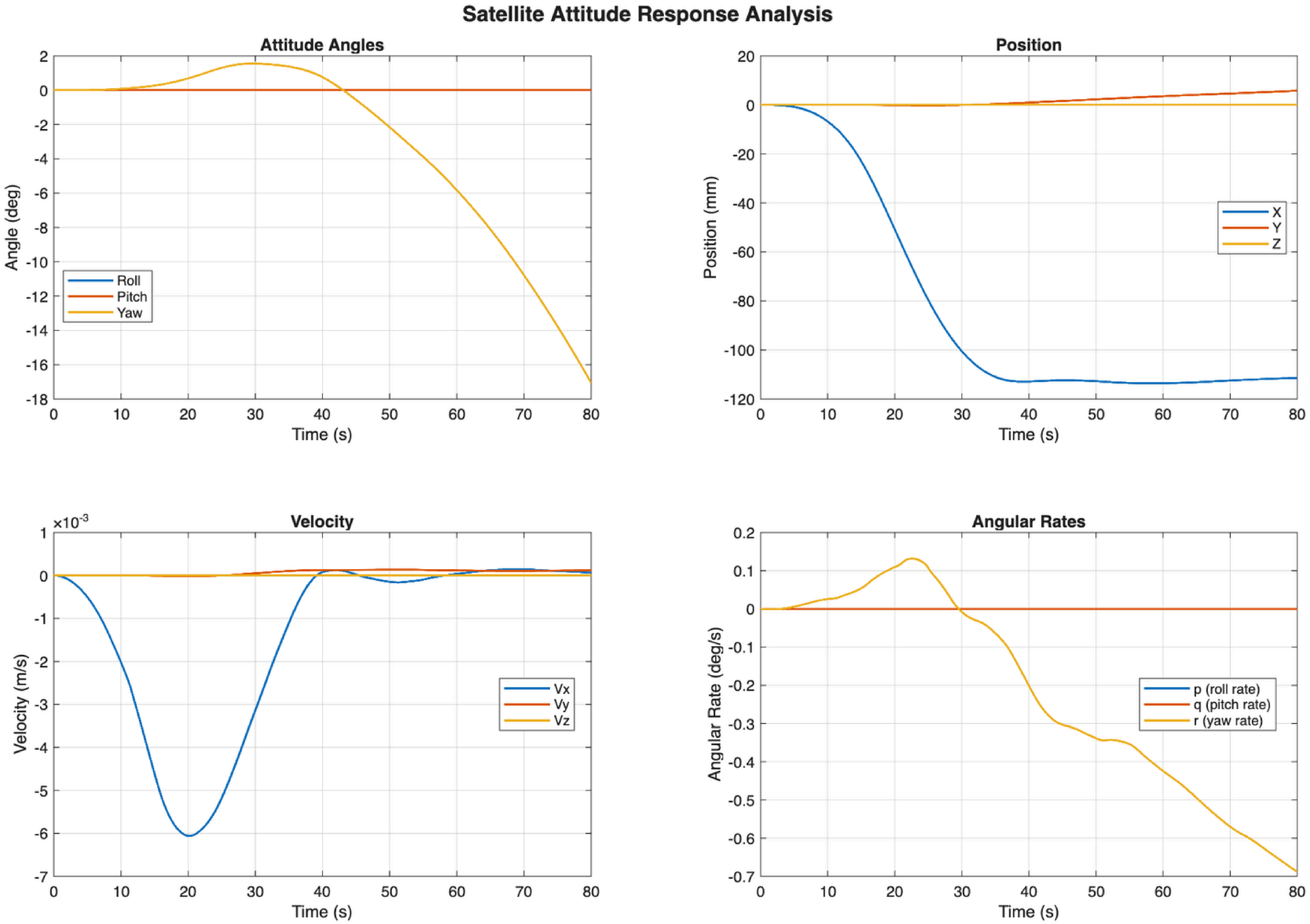
Attitude Response

Reorientation Maneuver



Attitude Response

Translational Maneuver



Attitude Analysis: Torque and Momentum Derivations

Torque (Nm):

$$\tau = \mathbf{M}_{CFD}$$

Accumulated Angular Momentum (Nms):

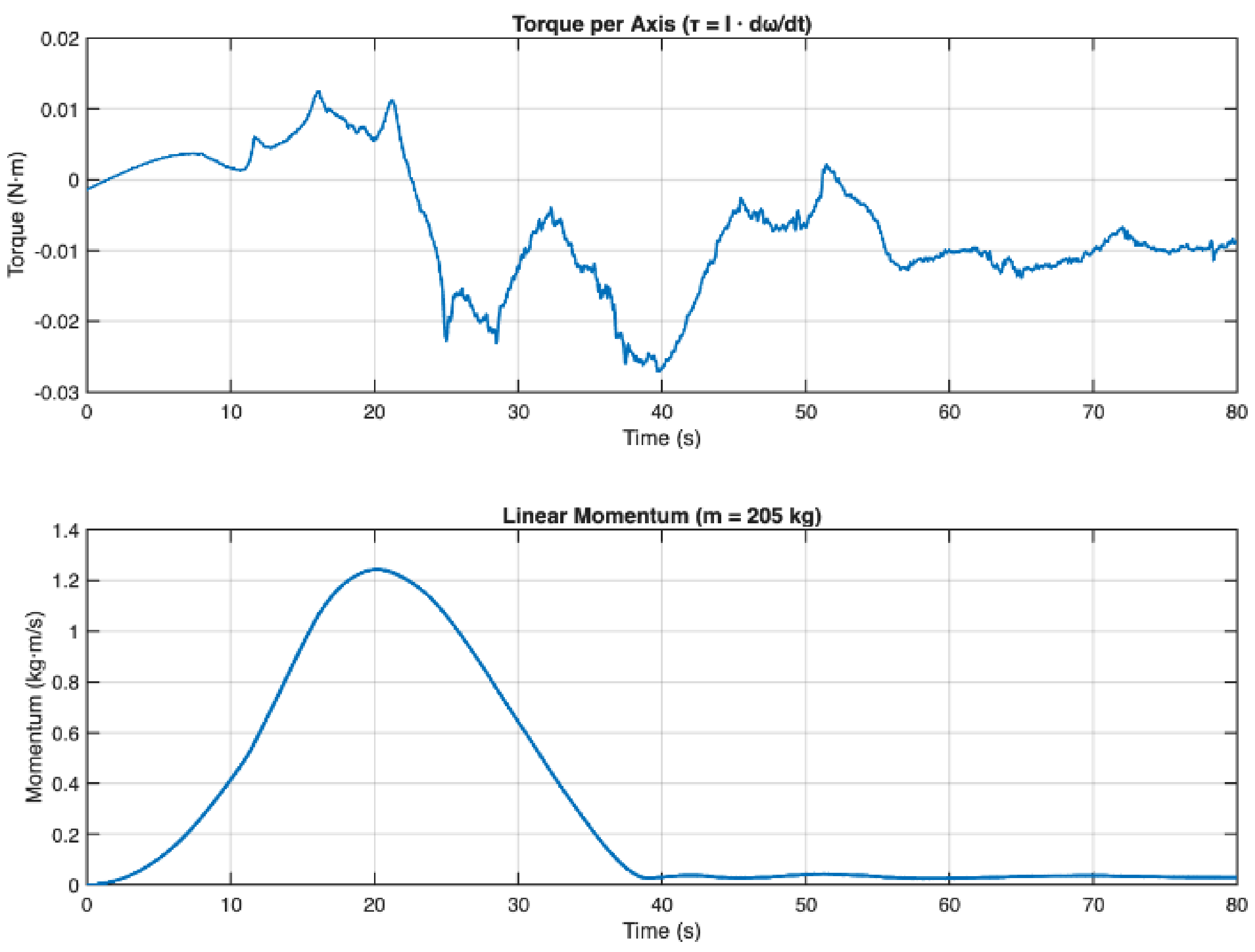
$$\mathbf{H}_{slosh}(t) = \int_{t_0}^{t} \mathbf{M}_{CFD}(\tau)\, d\tau$$

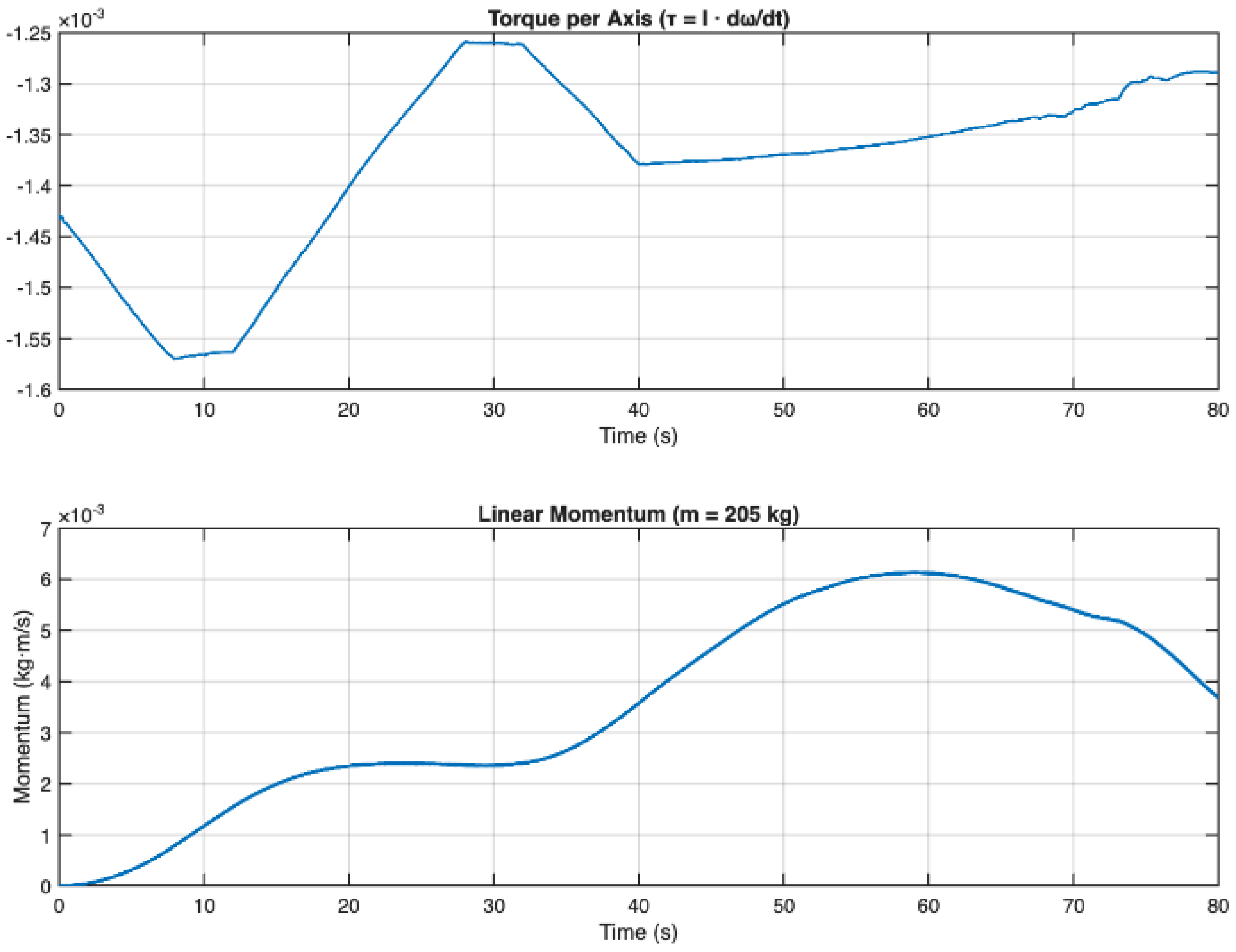
Linear Momentum (kg m s^{-1}):

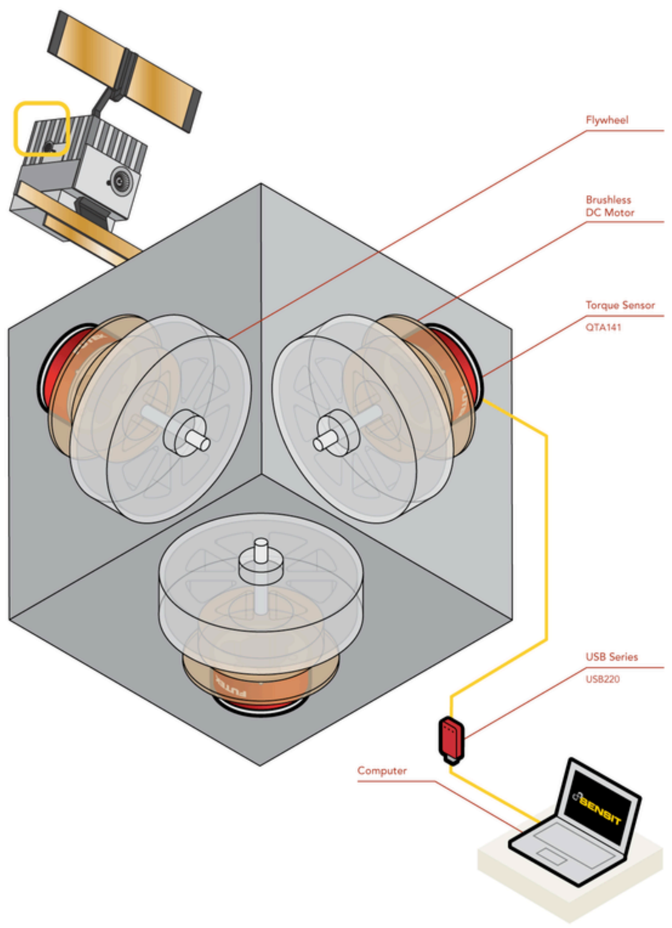
$$\mathbf{p}(t) = m(t)\mathbf{v}(t) = \frac{d}{dt}\mathbf{F}_{CFD}$$

- Torque and Accumulated Angular Momentum are primary design specs of Satellite Reaction Wheels
- Mass and Inertia have no effects on momentum or torque!

Torque and Momentum Response







Translational Maneuver

- Max Instant Torque: **0.027 Nm**
- Max Total Torque: **0.538 Nms**

Rotational Maneuver

- Max Instant Torque: **0.00157 Nm**
- Max Total Torque: **0.110 Nms**

ARW-1a Reaction Wheel

- Max Instant Torque: **0.1 Nm**
- Max Total Torque: **1.0 Nms**

Comparative Analysis – Satellite Mass

How does affecting the mass of the satellite affect the attitude response?

High Mass: m = 205.112 kg

$$I_{high} = \begin{bmatrix} 36.25 & 0 & 0 \\ 0 & 29.7478 & 0 \\ 0 & 0 & 44.8639 \end{bmatrix} \mathrm{kg} \cdot \mathrm{m}^2$$

Low Mass: m = 118.496 kg

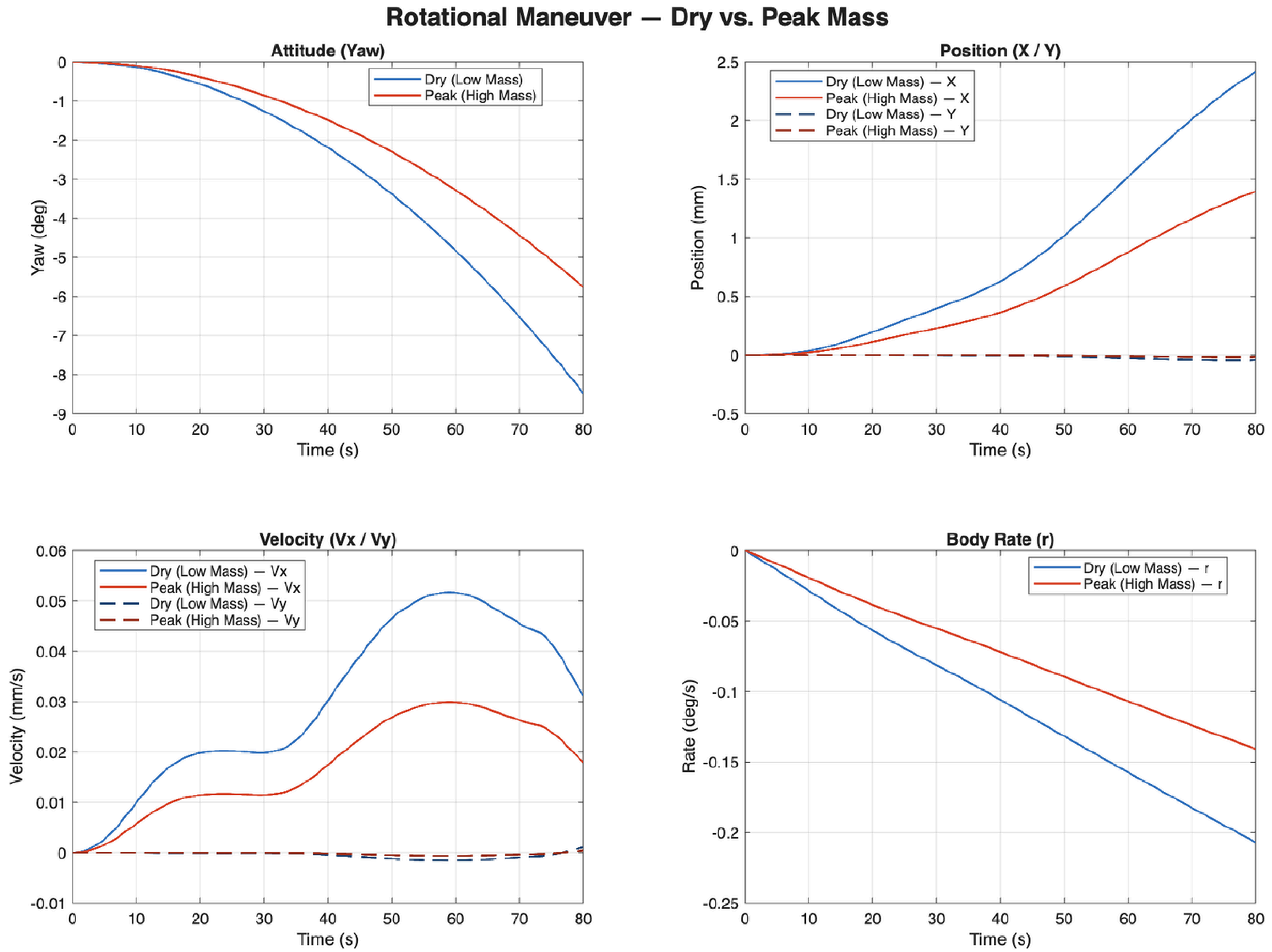
$$I_{low} = \begin{bmatrix} 25.7839 & 0 & 0 \\ 0 & 16.6069 & 0 \\ 0 & 0 & 30.4959 \end{bmatrix} \mathrm{kg} \cdot \mathrm{m}^2$$

No effects on Torque or Linear Momentum!

Comparative Analysis – Satellite Mass

Reorientation Maneuver

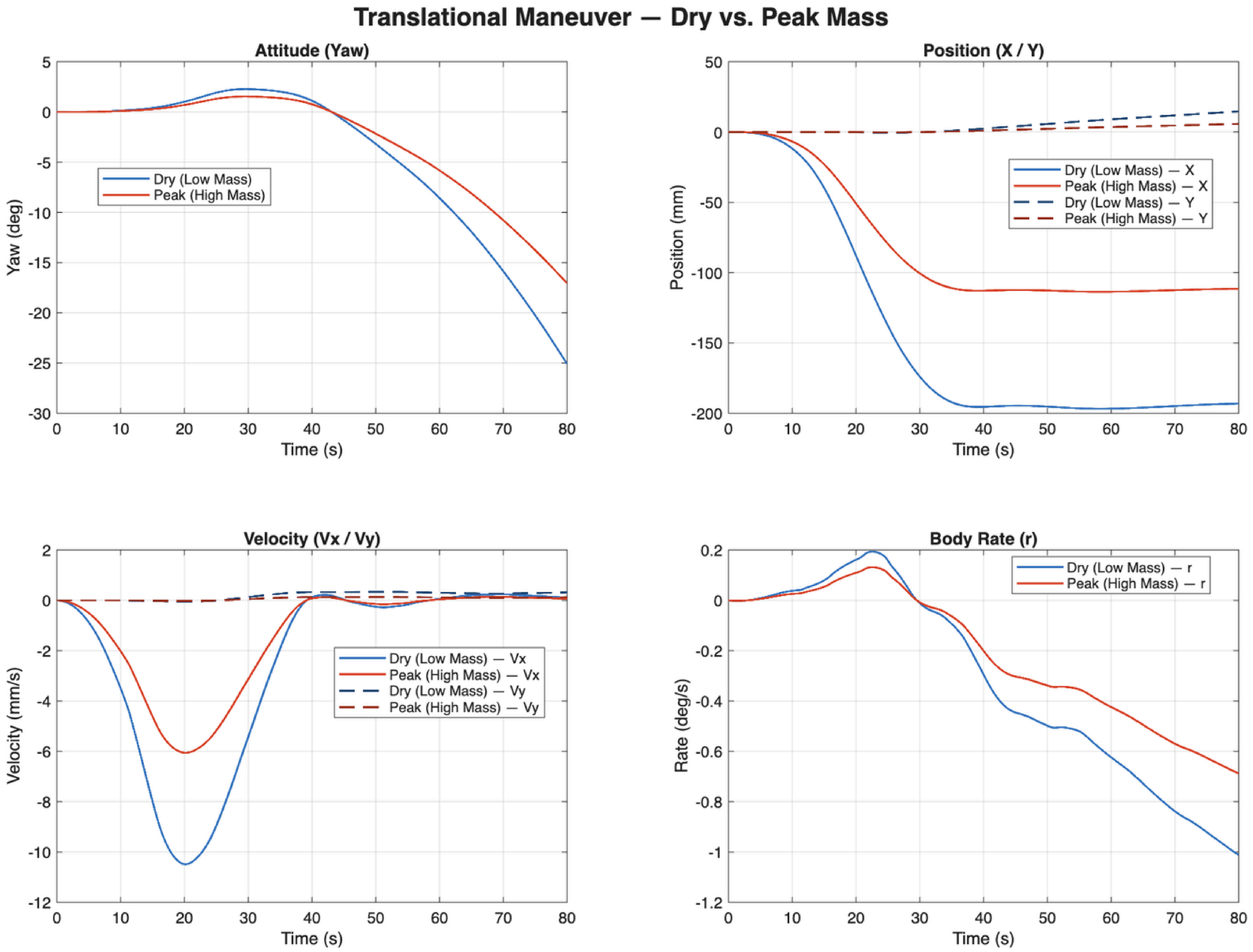
	Low Mass (118.5 kg)	High Mass (205 kg)
Final Yaw (deg)	8.47	5.76
Peak X Position (mm)	2.41	1.39
Peak X Velocity (mm/s)	0.0517	0.0299
Pea Yaw Body Rate (deg/s)	0.207	0.141



Comparative Analysis – Satellite Mass

Translational Maneuver

	Low Mass (118.5 kg)	High Mass (205 kg)
Final Yaw (deg)	25.10	17.06
Peak X Position (mm)	196.7	113.6
Peak X Velocity (mm/s)	10.49	6.06
Pea Yaw Body Rate (deg/s)	1.01	0.69

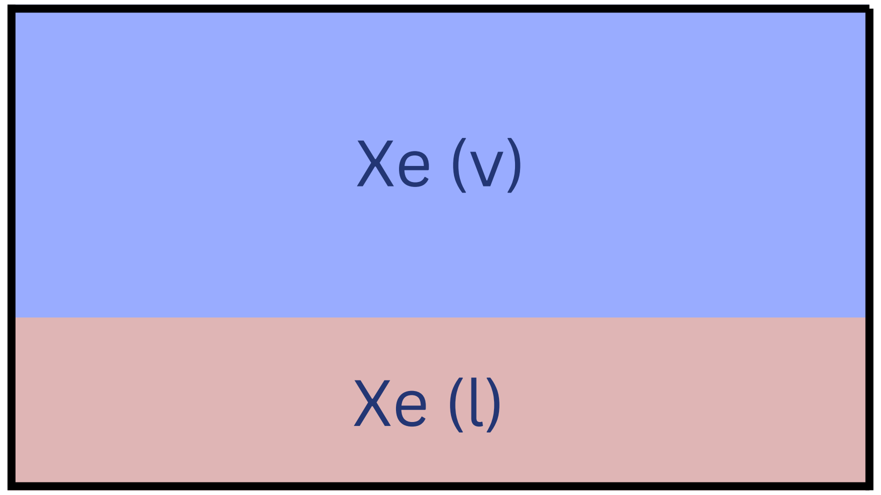


Comparative Analysis – Propellant Mass

How does adjusting the fill ratio of the propellant tank affect attitude and disturbance?

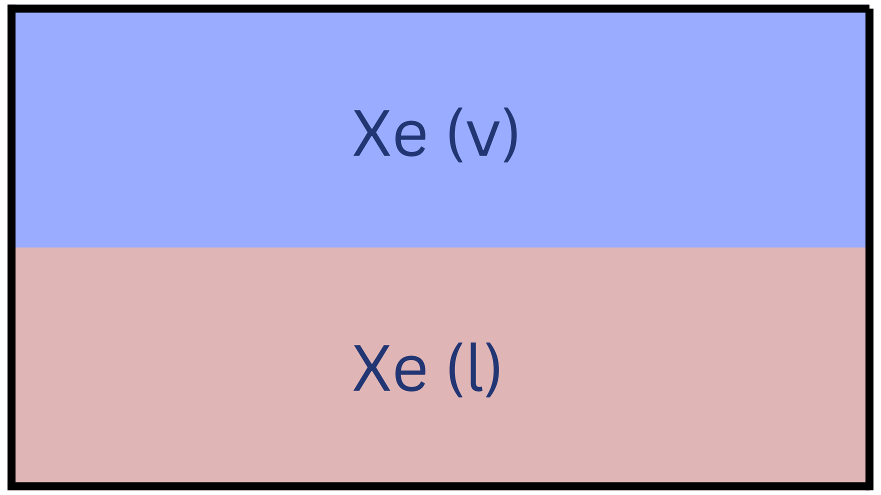
Case 1: 30% Fill

$m_{Xe} = 18$ kg



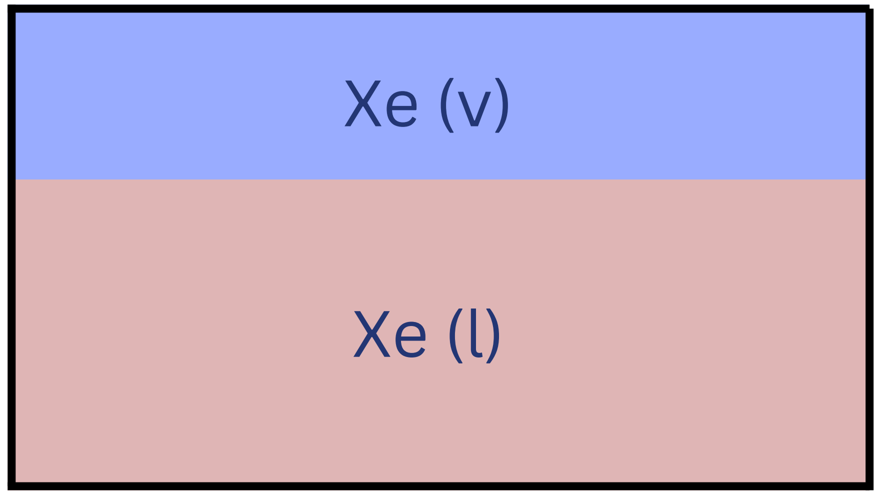
Case 2: 50% Fill

$m_{Xe} = 24$ kg



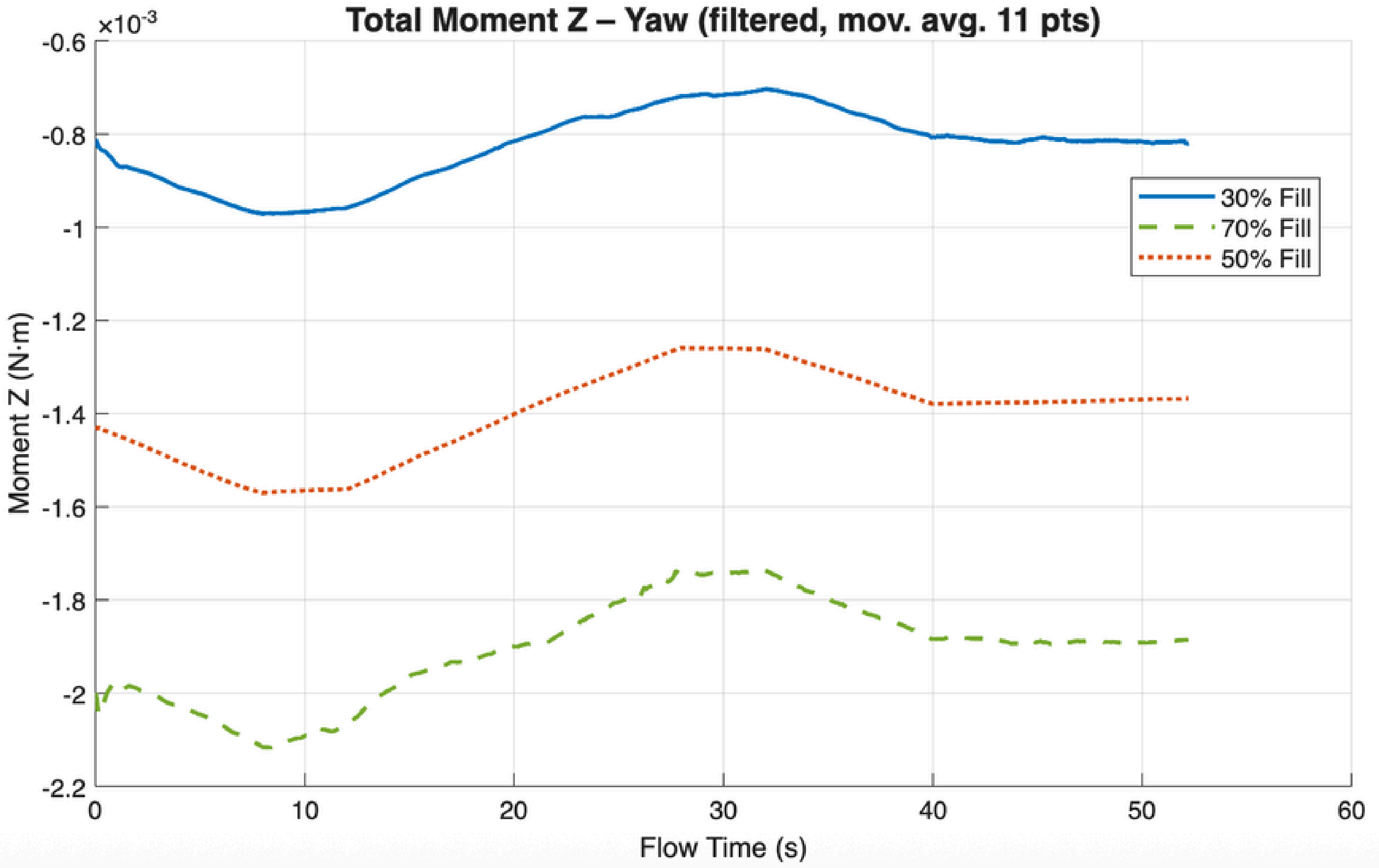
Case 3: 70% Fill

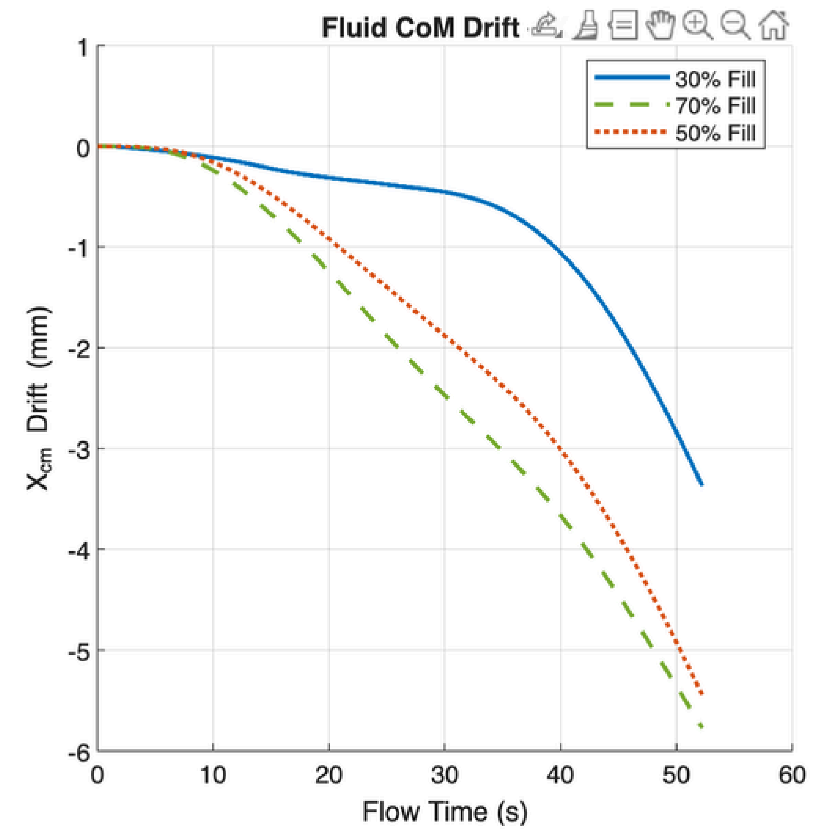
$m_{Xe} = 29$ kg



Comparative Analysis – Fill CFD

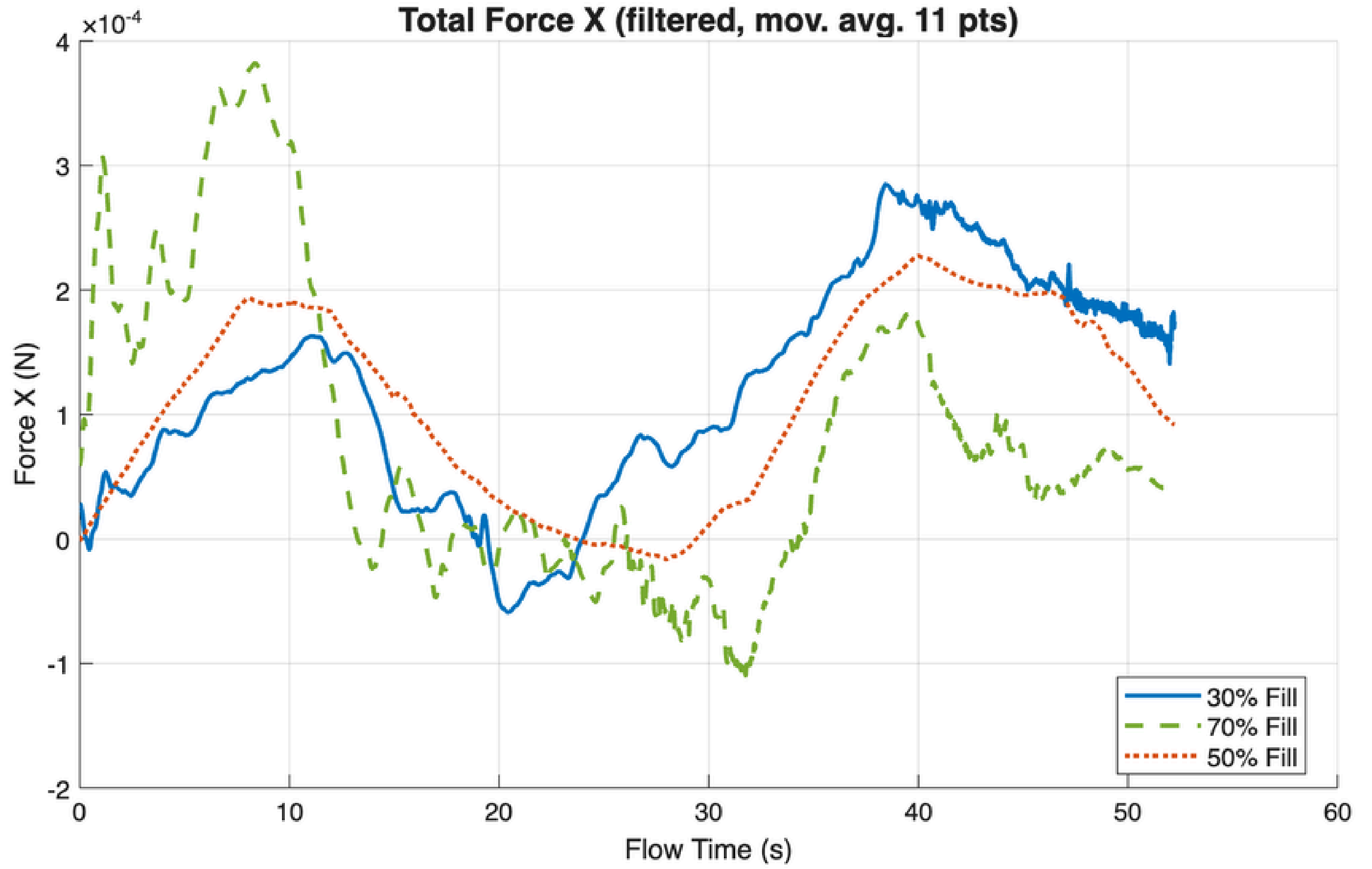
Reorientation Maneuver:

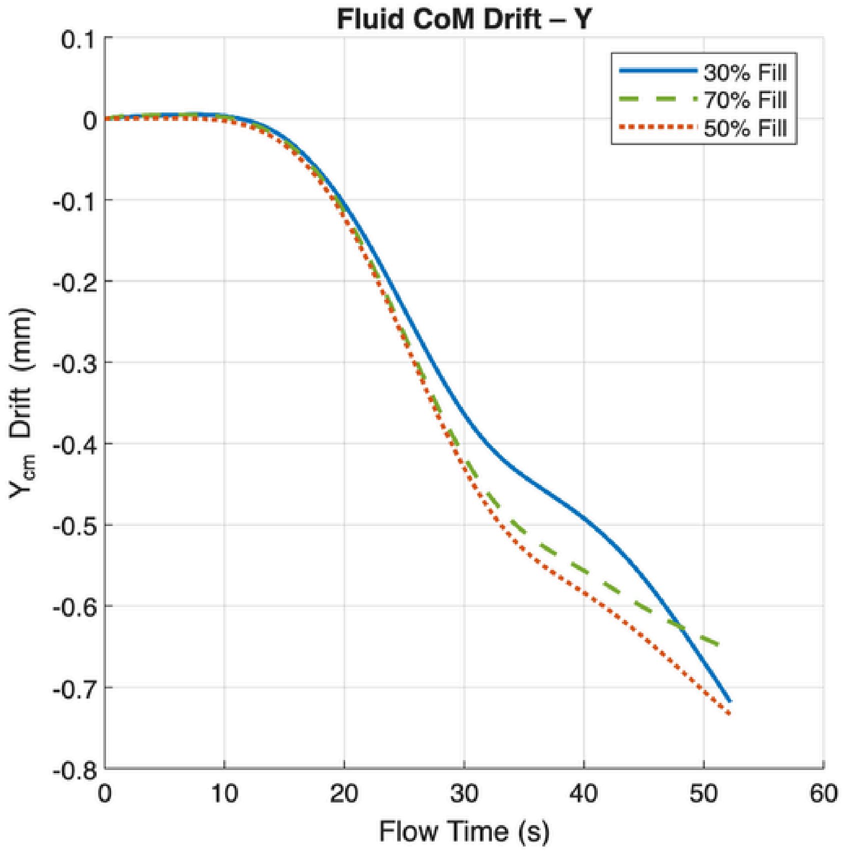




- Higher Fill Yields Higher Force, Moment, and COM Drift

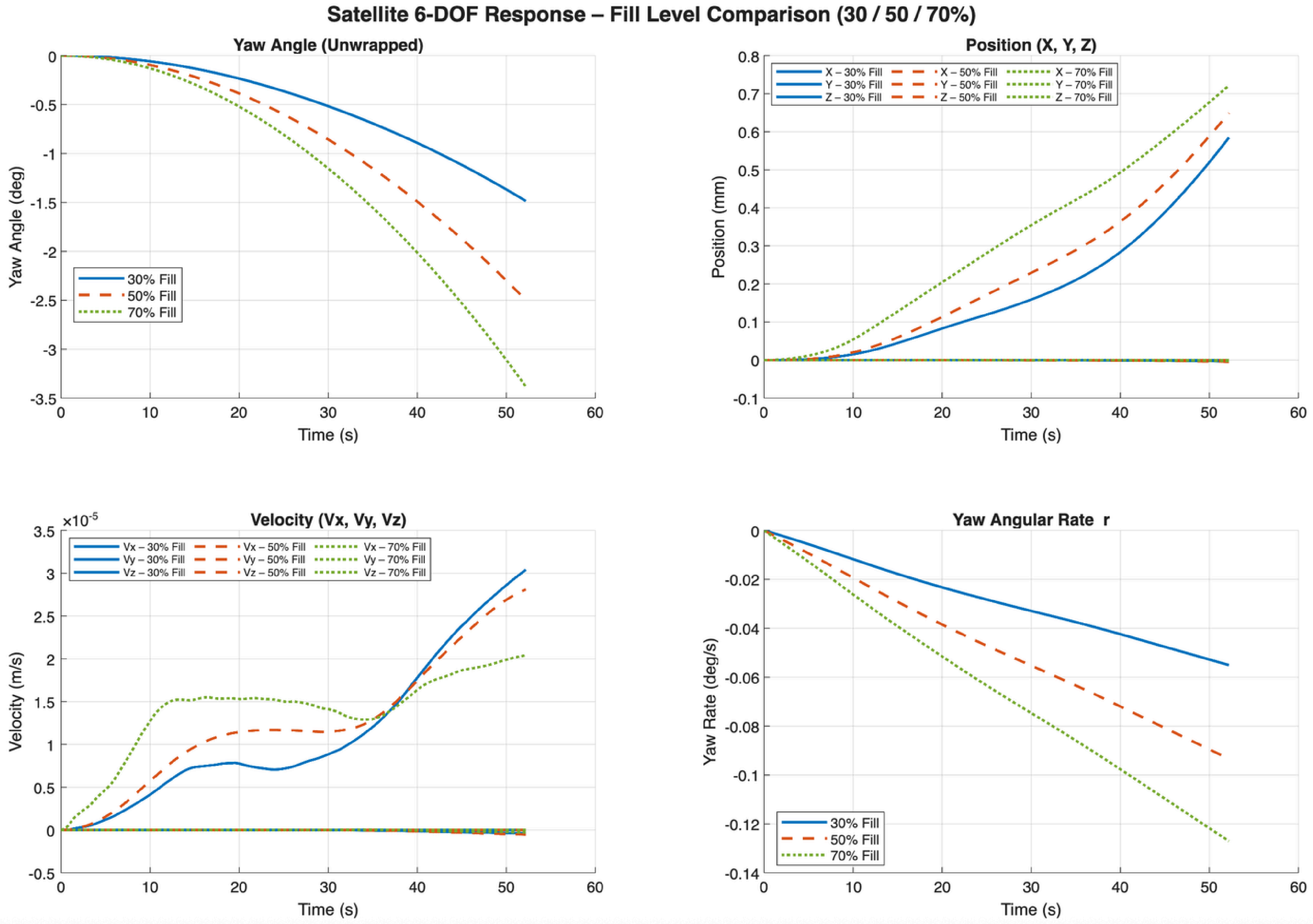
- Moment Response has similar shape for different fills

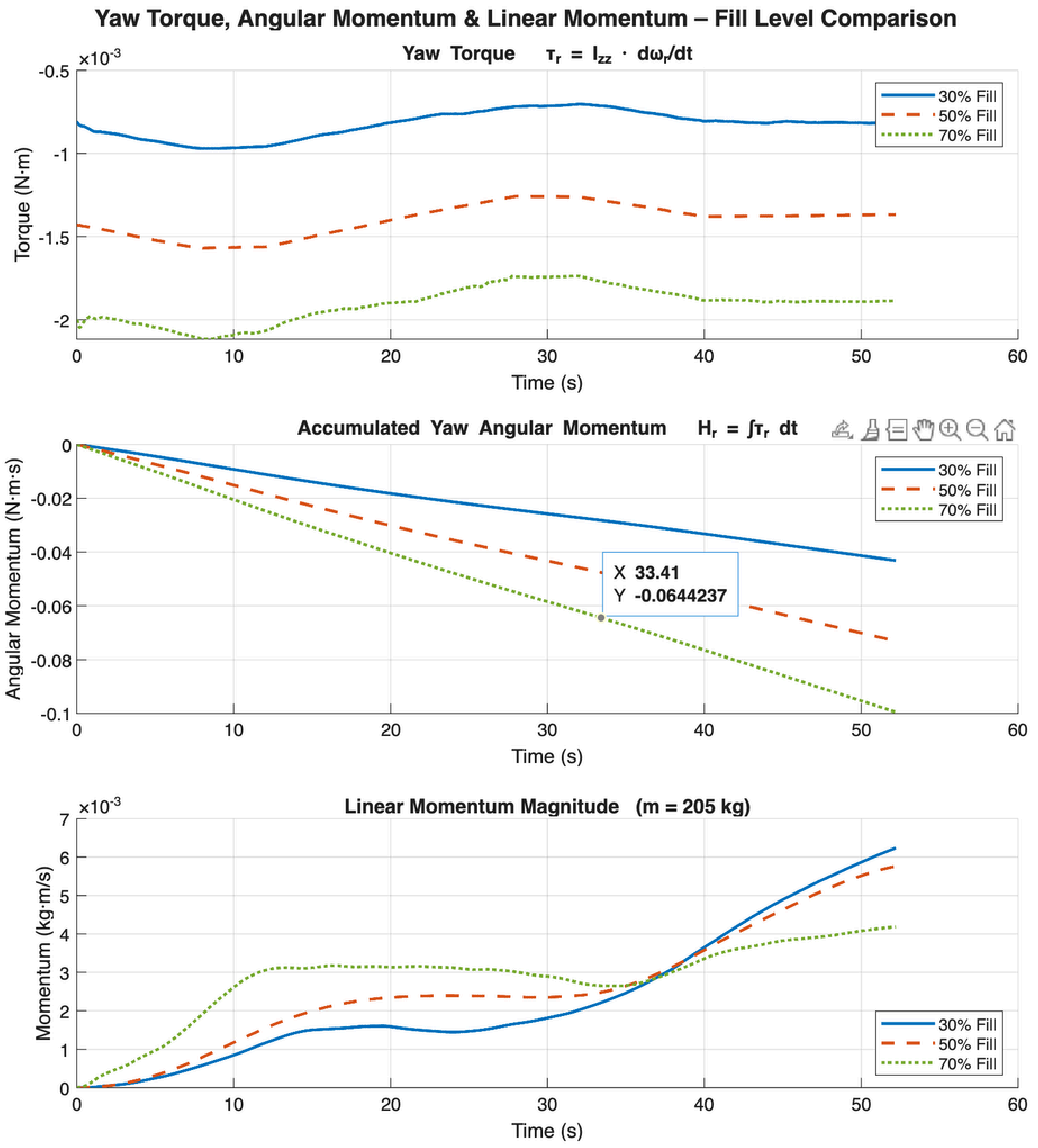




Comparative Analysis – Fill Response

Reorientation Maneuver:

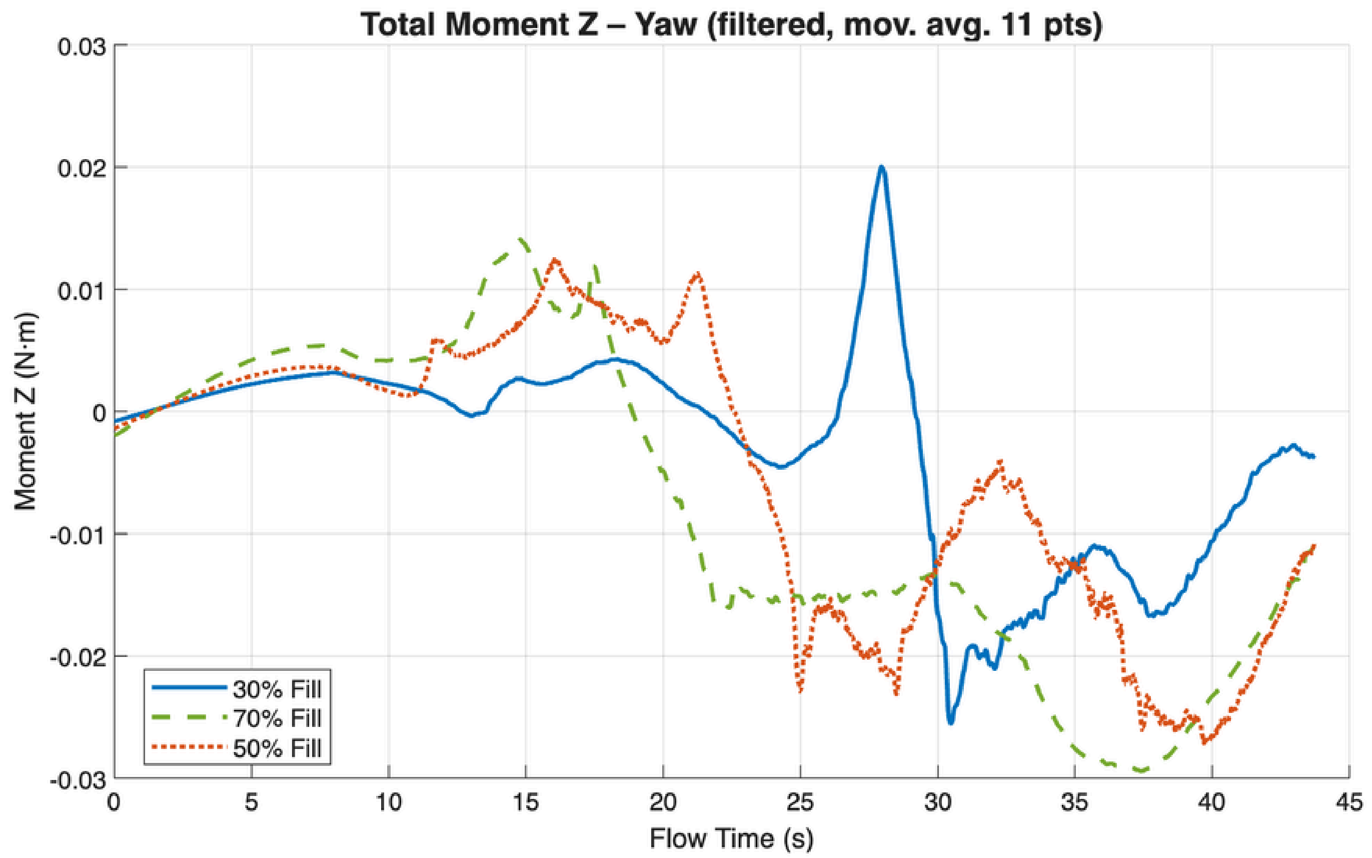

Satellite 6-DOF Response – Fill Level Comparison (30 / 50 / 70%)

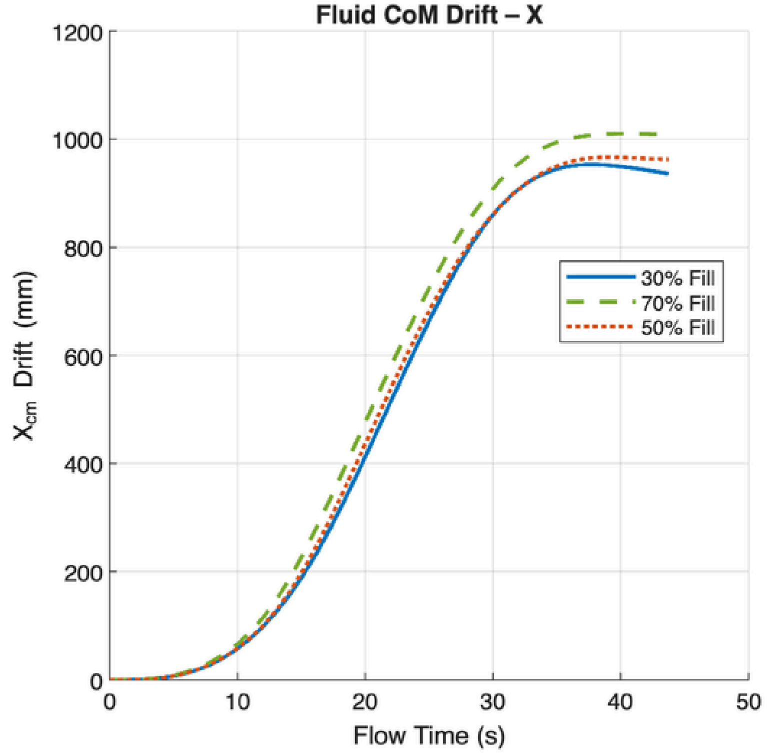

Yaw Torque, Angular Momentum & Linear Momentum – Fill Level Comparison

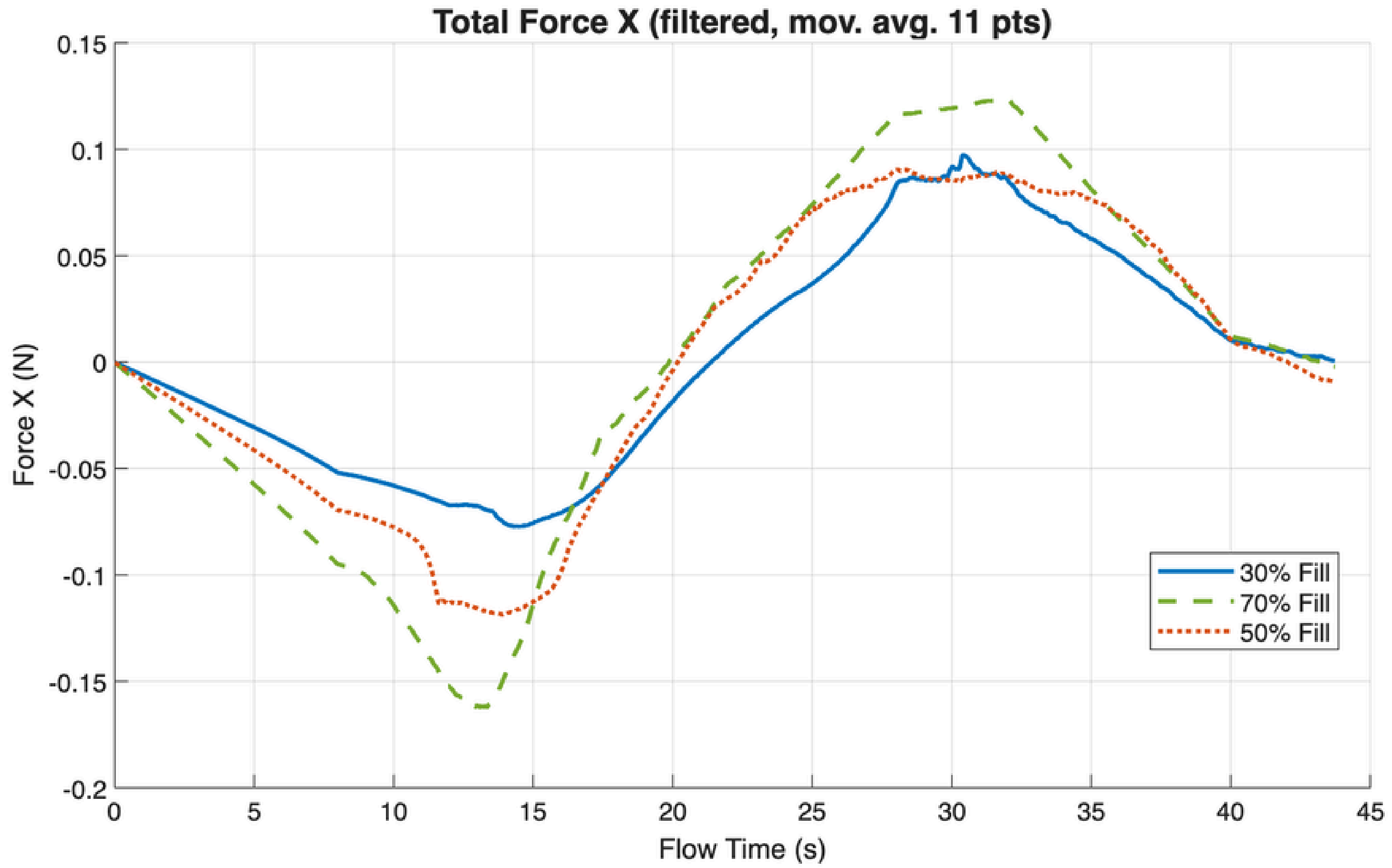
Comparative Analysis – Fill CFD

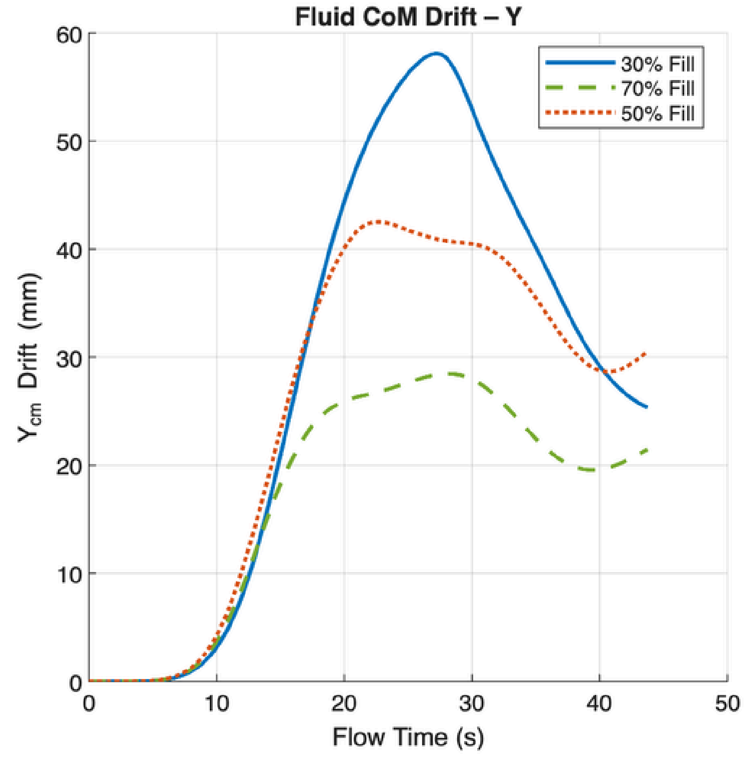
Translational Maneuver:

- Higher Fill Yields Higher Force and COM Drift
- Lower Fill has a delayed Moment Response



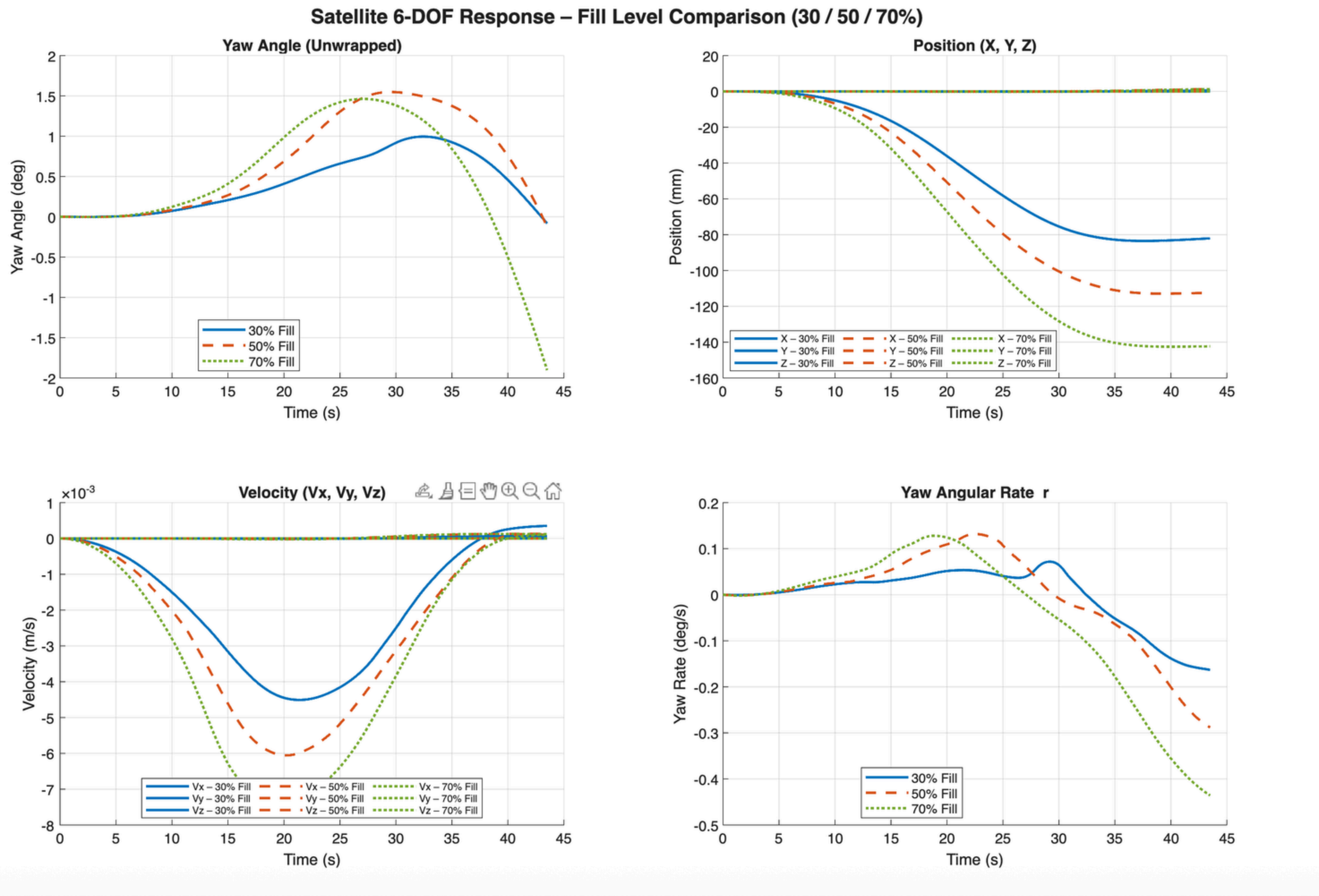


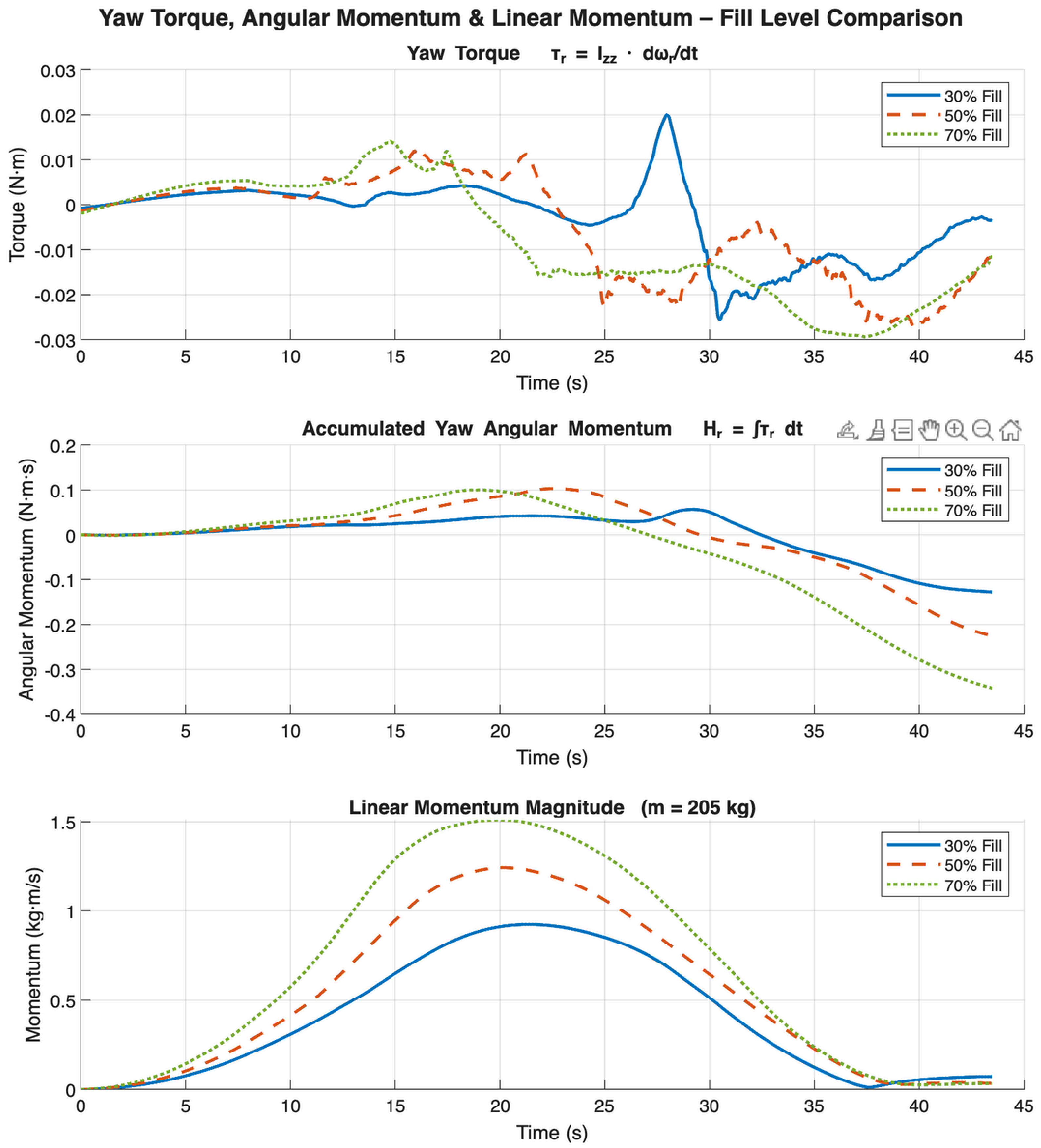




Comparative Analysis – Fill Response

Translational Maneuver:





Attitude Analysis Results

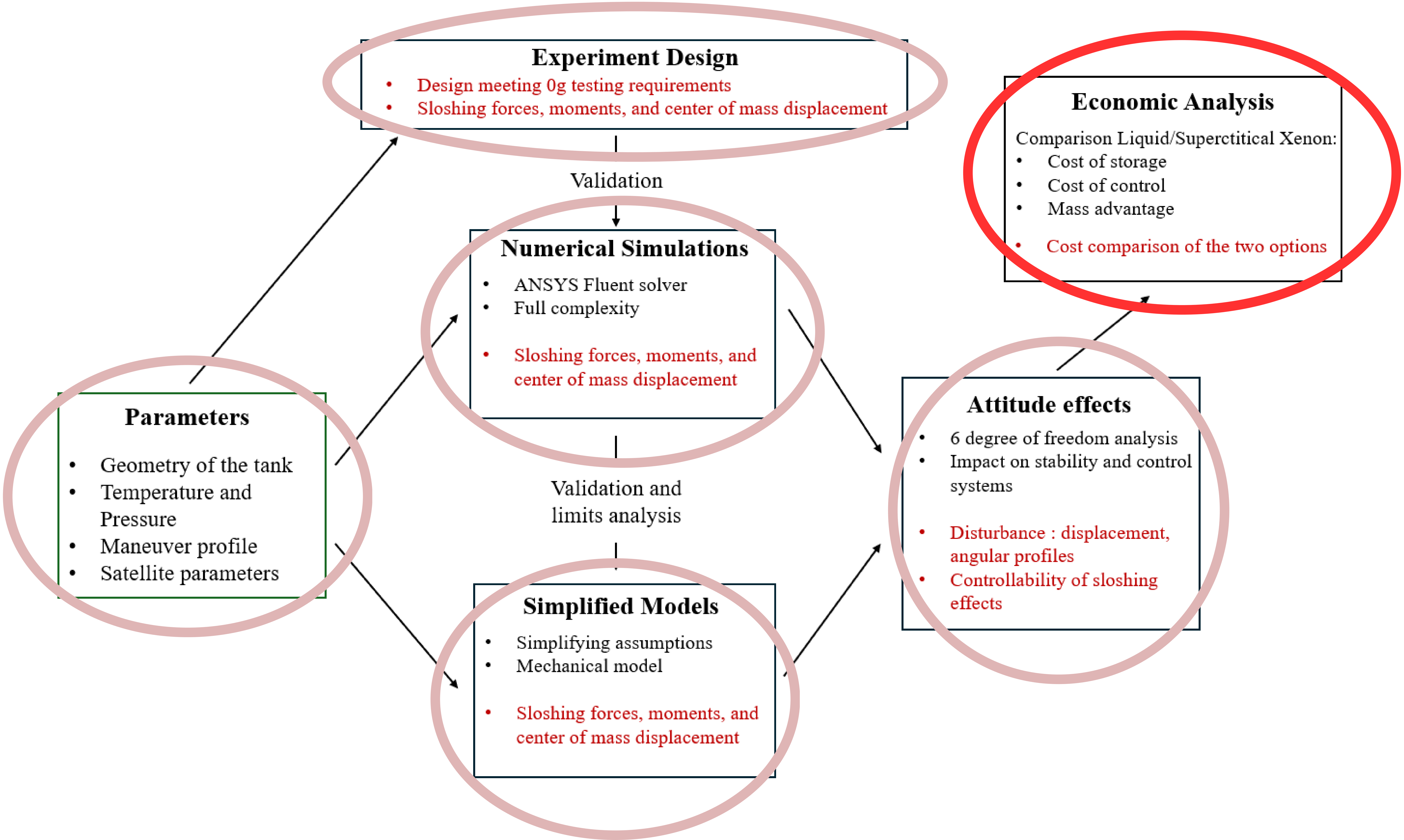
The sloshing effects are **fully controllable** for standard sized reaction wheels

Mass Comparison:

- Changing the Mass of a Satellite has **no effect** on Torque and Momentum
- A lower Mass has a **greater** response for attitude and position

Fill Comparison:

- A higher fill percentage results in **greater** effects in the Forces, Moments, and their respective attitude responses
- A lower fill percentage often has a delayed response in Moment



Experiment Design

- Design meeting 0g testing requirements
- Sloshing forces, moments, and center of mass displacement

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- ANSYS Fluent solver
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- Geometry of the tank
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- Satellite parameters

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- 6 degree of freedom analysis
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- Disturbance : displacement, angular profiles
- Controllability of sloshing effects

Economic Analysis

Comparison Liquid/Superctitical Xenon:

- Cost of storage
- Cost of control
- Mass advantage

- Cost comparison of the two options

Economic Analysis

Is the energy used to keep Xenon in a supercritical state greater than the energy needed from reaction wheels to account for sloshing?

Case 1: Industry Method

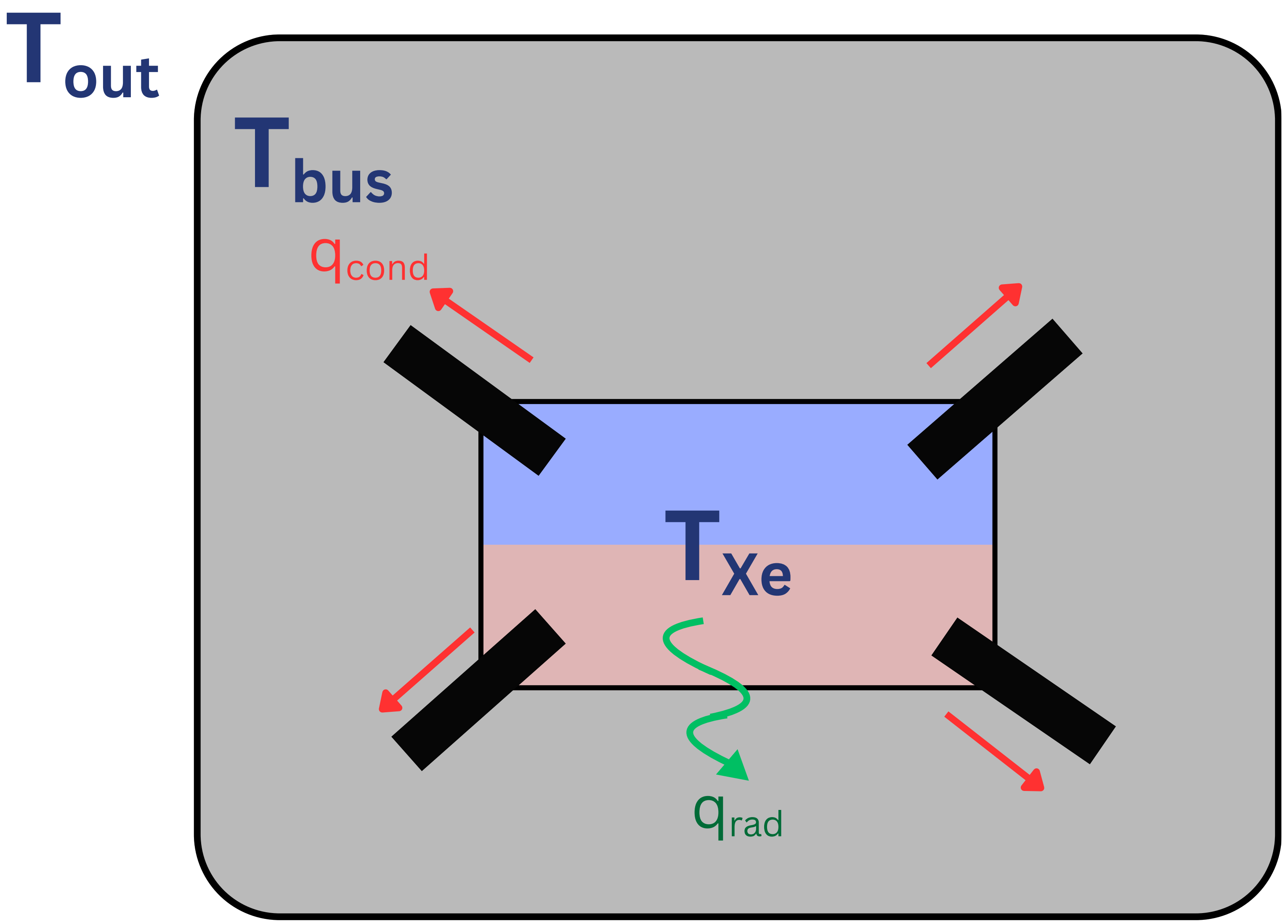
- Xenon is kept as a vapor at 21°C
- No Sloshing occurs
- No Work from Reaction Wheel

Case 2: Sloshing Method

- Xenon is kept as a liquid at −3°C
- Sloshing Occurs
- Work from Reaction Wheel

Economic Analysis – Heat Cost

- Assume the propellant tank's heat is controlled **separately** to the rest of the satellite
- Heat is transferred by radiation and conduction through struts



$T_{in,\ min}$ = -20°C $T_{in,\ max}$ = 50°C

Assumptions

Struts: Ti-6Al-4V Titanium

$A_{struts} = 1\ cm^2$

$n = 4$

$k_{struts} = 6.7\ W/m\text{-}K$

$L = 3\ cm$

Tank Coating: MLI (multi-layer insulation)

$\varepsilon = 0.018$

Economic Analysis – Heat Cost

$$m_{\text{prop}} c_p \frac{dT}{dt} = q_{\text{in}} - q_{\text{loss}}$$

$$P_{\text{heating}} = q_{\text{loss}} = q_{\text{rad}} + q_{\text{cond}}$$

$$q_{\text{rad}} = \epsilon \sigma A_{\text{sat}} \left(T^4 - T_{\text{bus}}^4\right)$$

$$q_{\text{cond}} = \frac{k A_{struts}}{L} \left(T - T_{\text{bus}}\right)$$

$$\Delta E = \int \left(P_{heating}(T_{sc}) - P_{heating}(T_{lv})\right) dt$$

Internal Bus Temperature	**Supercritical (T_{sc}) Heating Power [W]**	**Liquid/Vapor ($T_{l/v}$) Heating Power [W]**
High End (50°C)	0.0000	0.0000
Average (15°C)	0.7832	0.0000
Low End (-20°C)	5.0730 *	2.0092

*Based on real data, the low end can be up to 8-10 Watts!

Assuming Average Internal Bus Temperature,

ΔE = 4229.34 J

Economic Analysis – Reaction Cost

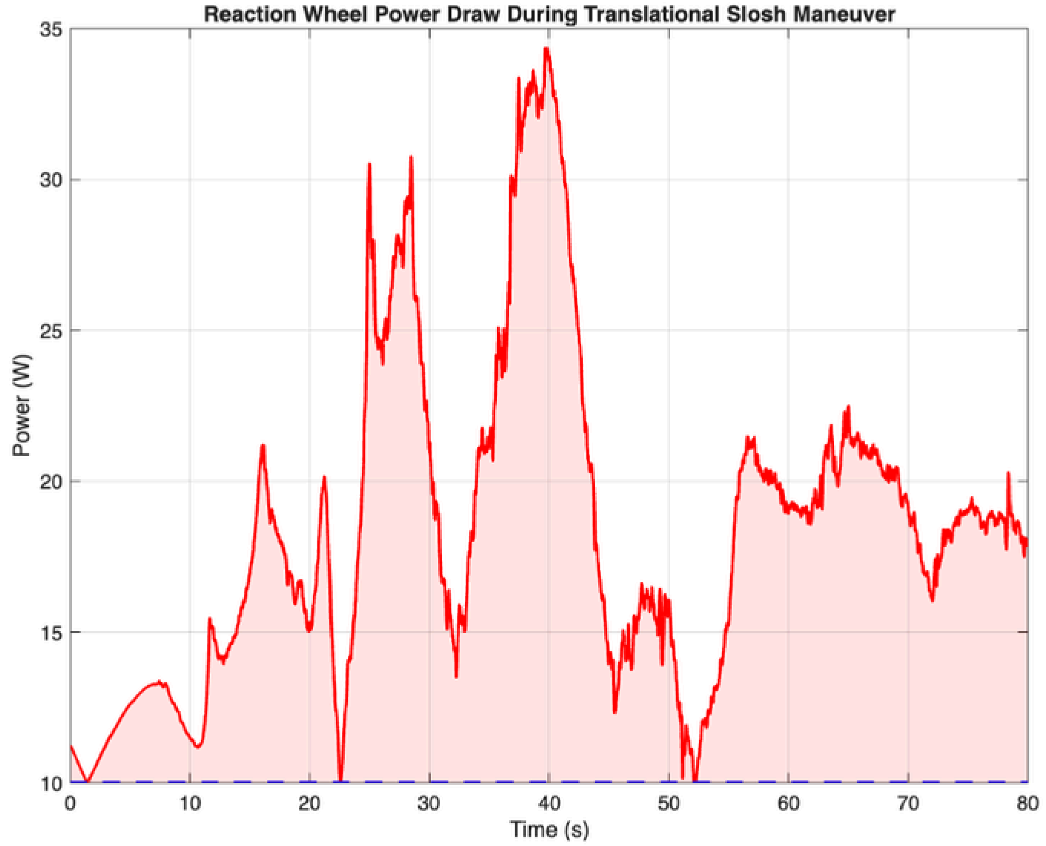
- A Linear Power Model is proposed for Reaction Wheel Power

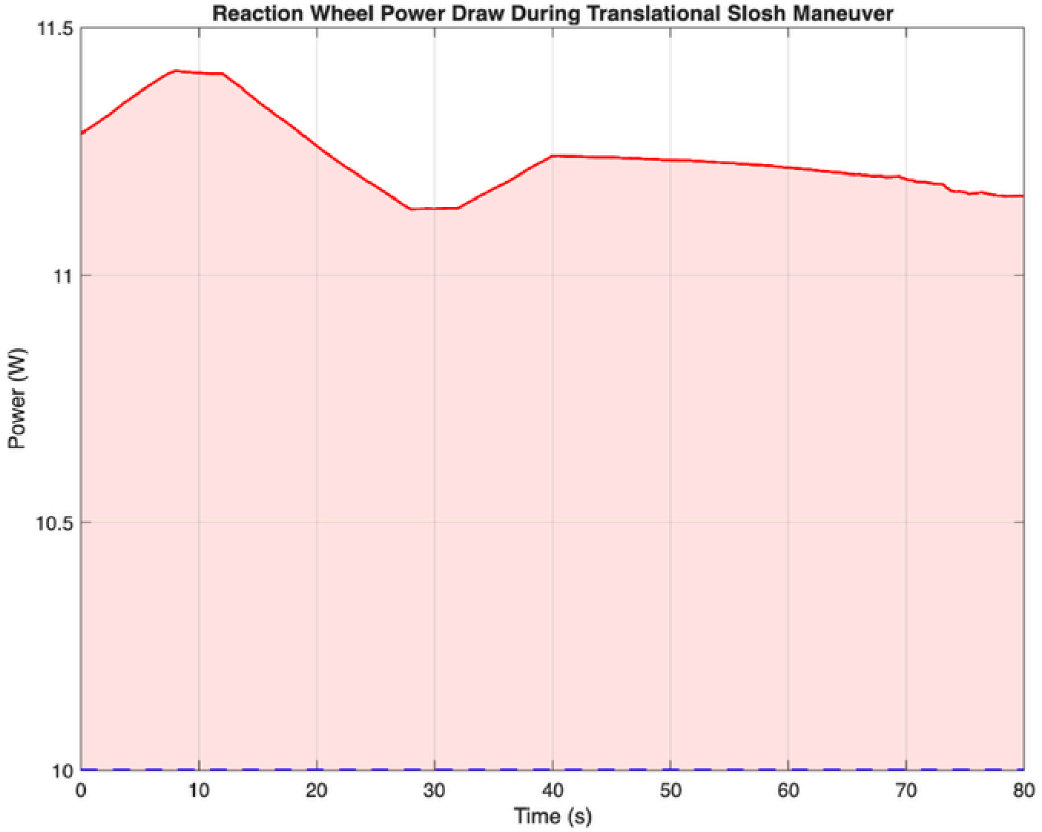
P_{steady} = 10W P_{max} = 100W

T_{max} = 0.1 Nm

$$P_{slosh-induced} = \frac{P_{max} - P_{steady}}{\tau_{max}} * \tau_{slosh}$$

$$P_{total} = P_{steady} + P_{slosh-induced}$$





	Translational Maneuver	Rotational Maneuver
Average Power Consumption [W]	8.43	1.24
Energy Cost for Maneuver [J]	674.09	99.13

Economic Analysis Review

Case 1: Traditional Method

- Heat cost of propellant heating can get up to 8-10 W
  - ~50 kJ per orbit at peak times
- Assuming 15°C internal temperature, 0.48W
  - 4.23 kJ per 90 min orbital cycle

Case 2: Sloshing Method

Translational Maneuver:

- 674 J per maneuver
- Occur few times a month

Reorientation Maneuver:

- 99 J per maneuver
- Occur few times per 90 min orbital cycle

The Sloshing Method saves a significant amount of energy over time

- Can be redirected to other equipment
- Future Satellites can downsize solar arrays and batteries
  - saves mass and launch cost

Conclusion

- The cross-validation between the **Numerical Methods** and the **Simplified model** provided a proper estimate for the **Xenon CoM**, **Slosh Force**, and **Slosh Moment**
- The **Experiment Design** provides the framework for a real life model to verify the numerical results
- The **attitude** can be preserved, as the torque is controllable by the satellite's reaction wheel
- A substantial amount of energy can be preserved through allowing Xenon propellant to enter liquid phase

Note:

This project came with several assumptions. However, it can be used as a baseline for future projects and considerations.

Thank You!

Any Questions?

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