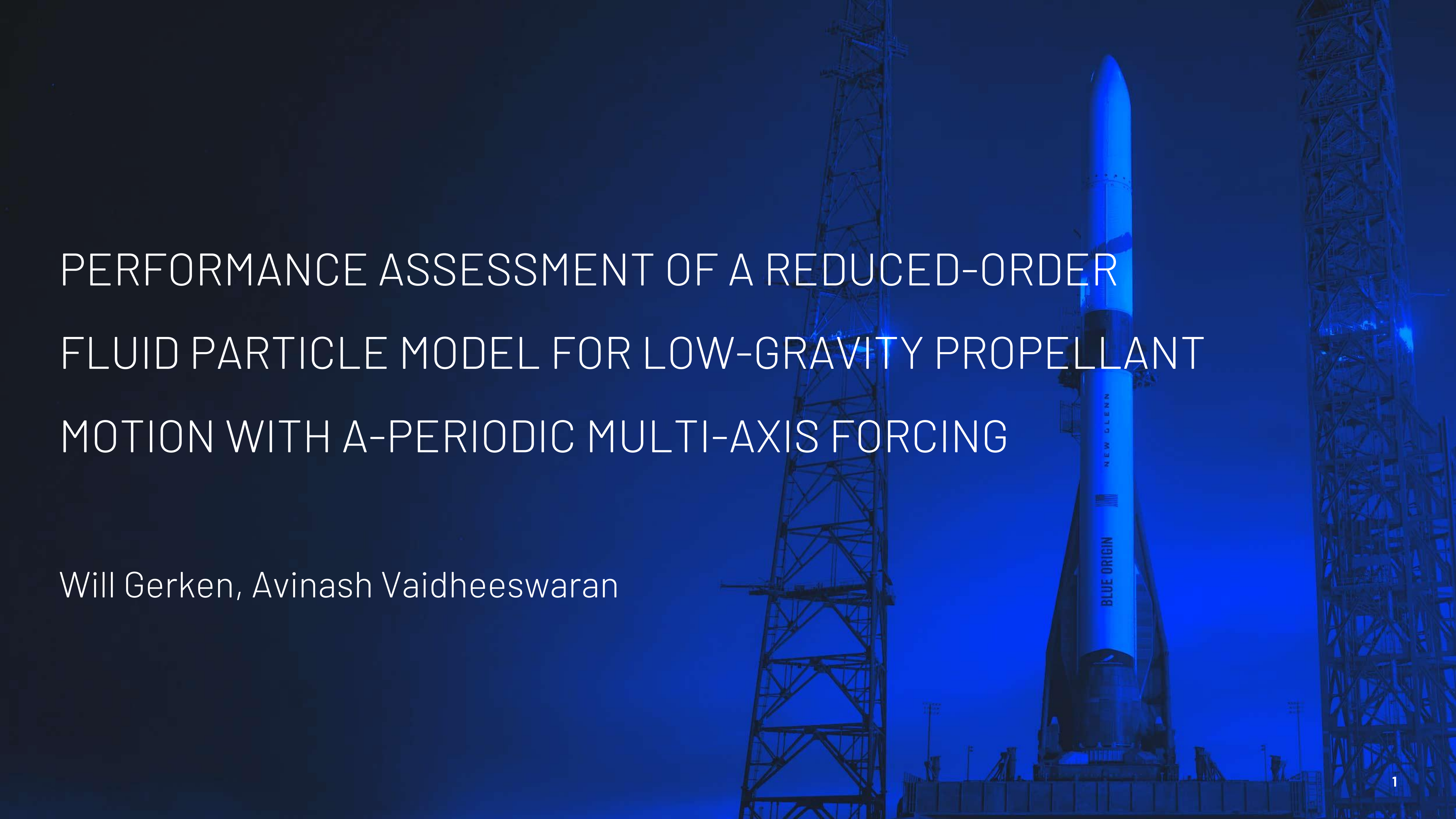


A photograph of a Blue Origin New Glenn rocket standing vertically on its launch pad. The rocket is white with blue accents and features the 'BLUE ORIGIN' logo and 'NEW GLENN' text. It is flanked by two tall, dark metal service towers. The entire scene is bathed in a deep blue light, creating a monochromatic effect.

PERFORMANCE ASSESSMENT OF A REDUCED-ORDER FLUID PARTICLE MODEL FOR LOW-GRAVITY PROPELLANT MOTION WITH A-PERIODIC MULTI-AXIS FORCING

Will Gerken, Avinash Vaidheeswaran

Particle Model Overview

- Due to the computational speed and simplicity (i.e. Monte Carlo setup), we will assess a Particle model implementation
- Per Liam Elke's AAS 26-067 Publication [1], and RPOD work [2];
 - Constrain a fluid particle within an ellipse
 - Calculate constraint penetration depth, and rate of change of penetration depth
 - Calculate the surface normal at the ellipse, projected from the current particle position
 - Calculate the restoring forces on the particle as a result of 2nd order contact dynamics
 - Free particle mass is a quadratic function of volumetric fill fraction;

$$\frac{x^2}{A^2} + \frac{y^2}{B^2} + \frac{z^2}{B^2} = 1$$

$$\vec{F}_{Normal} = -X_{depth} * \omega_C^2 * m_p - C(X_{depth}, \dot{X}_{depth}) \dot{X}_{depth}$$

$$\vec{F}_{Tangential} = -C_f * \left| \vec{F}_{Normal} \right| * \vec{V}_{Tangential}$$

$$M = M_{tot} * ff$$

$$M_p = (1 - ff) * M$$

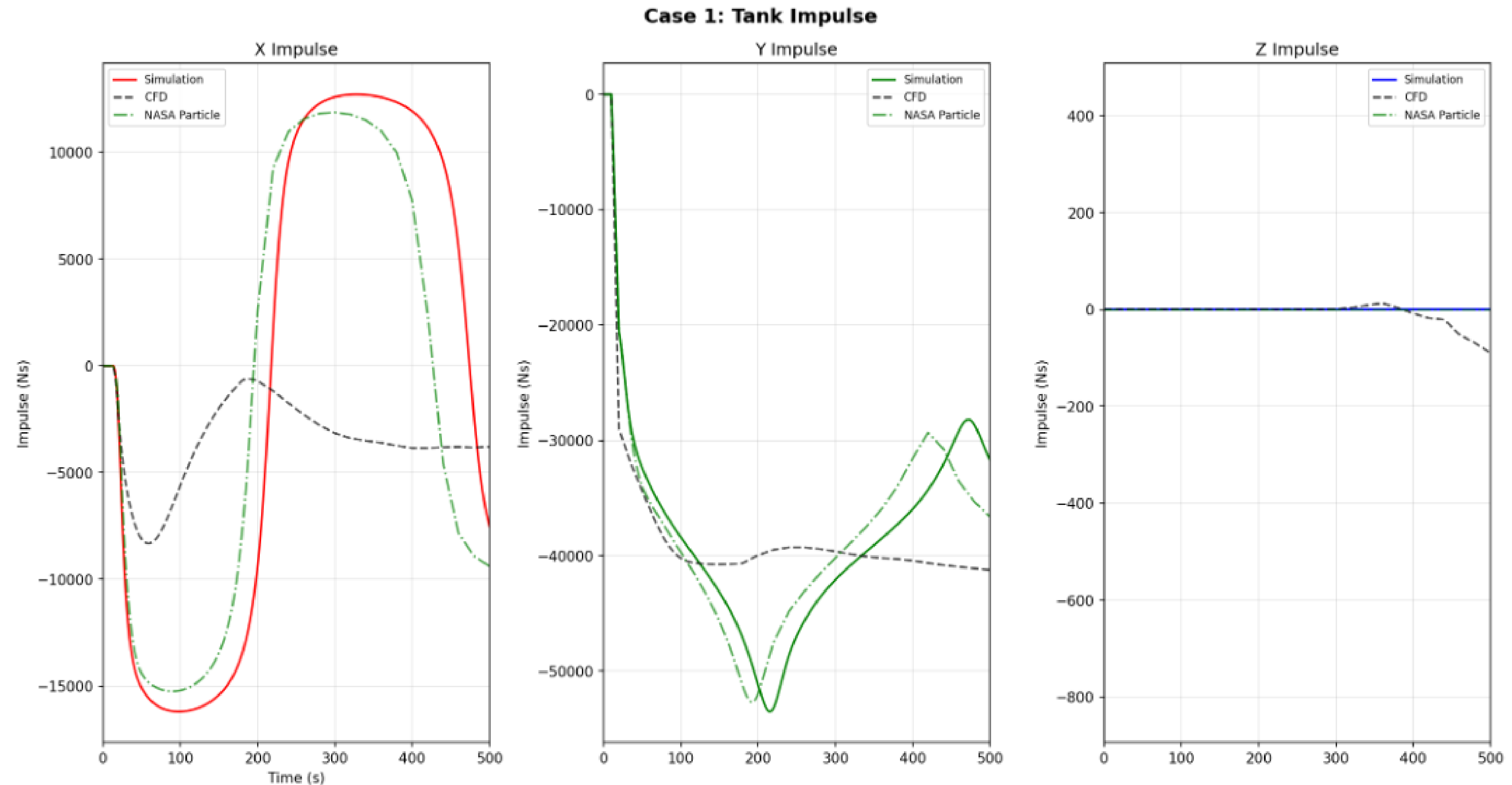
Model Implementation

- A NASA Trick and JEOD simulation is constructed
 - A fluid particle model is constructed and forced from JEOD simulation objects' state information
 - This text based implementation allows for better use of AI tooling in development and code maintenance
- Per Tim Barrow and Jeb Orr's "Dynamics and Simulation of Flexible Rockets" [3] chapter 3 on slosh dynamics
 - Tank relative slosh modeling is employed to couple slosh motion to the rigid body
- In order to confirm our implementation is working as intended, we first re-create the available test cases from [1]

Translational Reference Case 1

- AAS 26-067 Case 1 "Big Pill" +Y accel, 50% fill, 0.01 m/s^2
 - Contact stiffness was fixed at 0.15 rad/sec
 - Contact Damping was 1.0 s/m
 - Ellipse limits derived as $6.8/3.23 \text{ m}$

The exact input parameters used were not available, and so the deviations observed here are believed to be due to input differences.

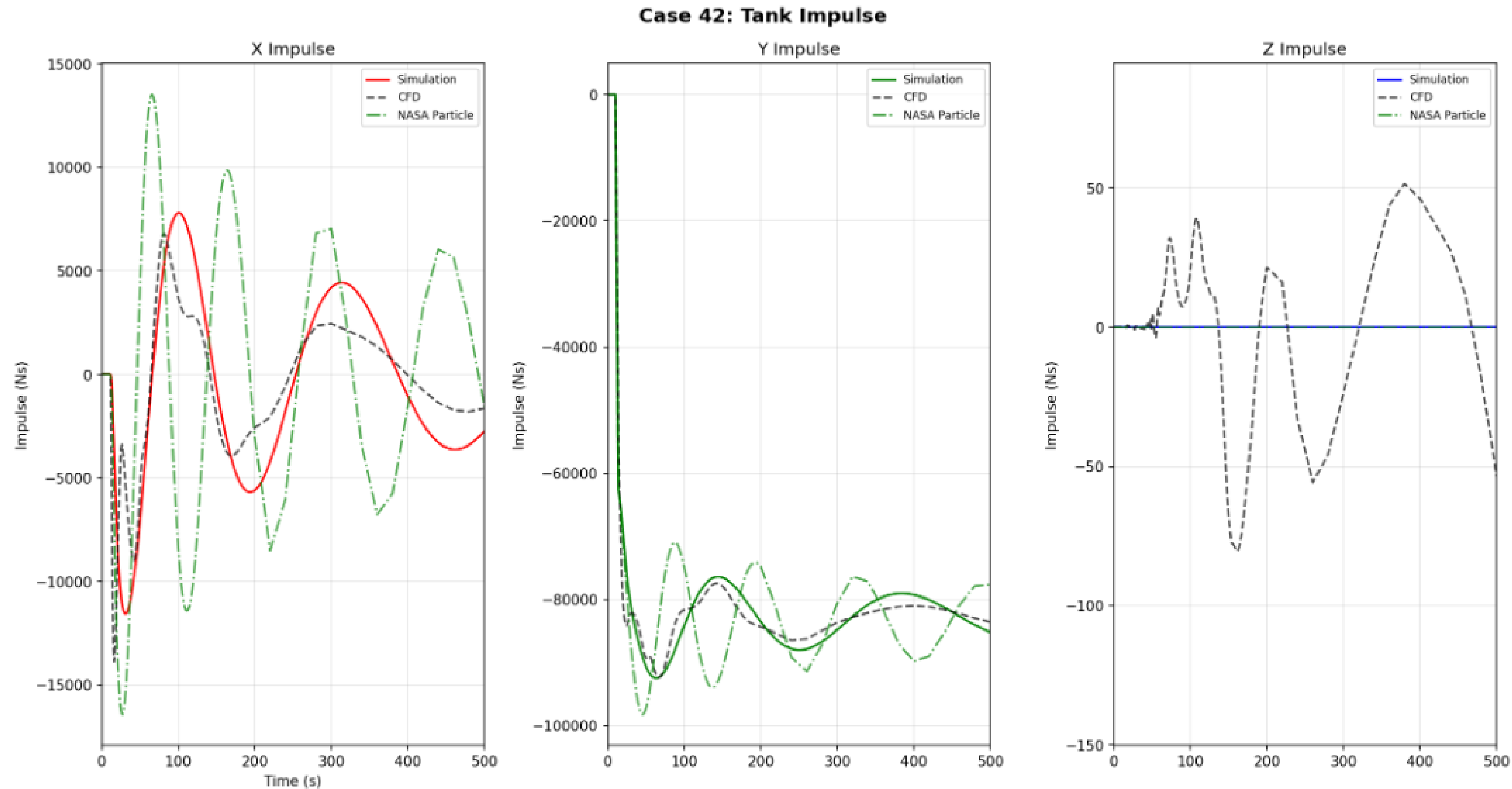


Similar performance to published works is observed in the current simulation.

Translational Reference Case 42

- AAS 26-067 Case 42 "Big Sphere", 0.01 m/s^2 , 75% fill
 - Contact stiffness was fixed at 0.15 rad/sec
 - Contact Damping was 1.0 s/m
 - Ellipse limits derived as $3.09/3.09 \text{ m}$

The exact input parameters used were not available, and so the deviations observed here are believed to be due to input differences.

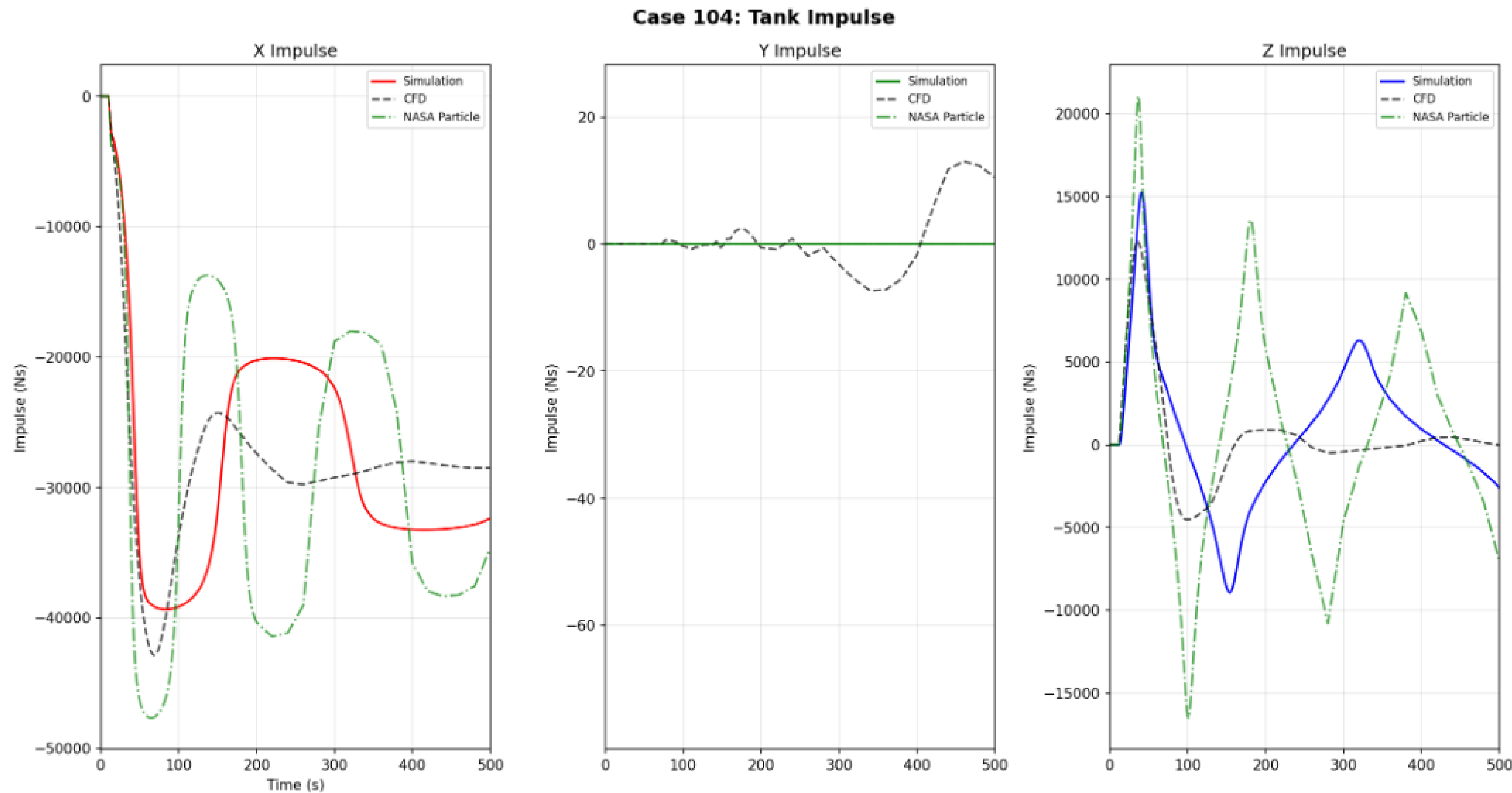


Significantly improved performance to published works is observed in the current simulation.

Translational Reference Case 104

- AAS 26-067 Case 104 "Big Pill", +X 0.1 m/s² accel, 10% fill
 - Contact stiffness was fixed at 0.15 rad/sec
 - Contact Damping was 1.0 s/m
 - Ellipse limits derived as 7.02/3.5 m

The exact input parameters used were not available, and so the deviations observed here are believed to be due to input differences.

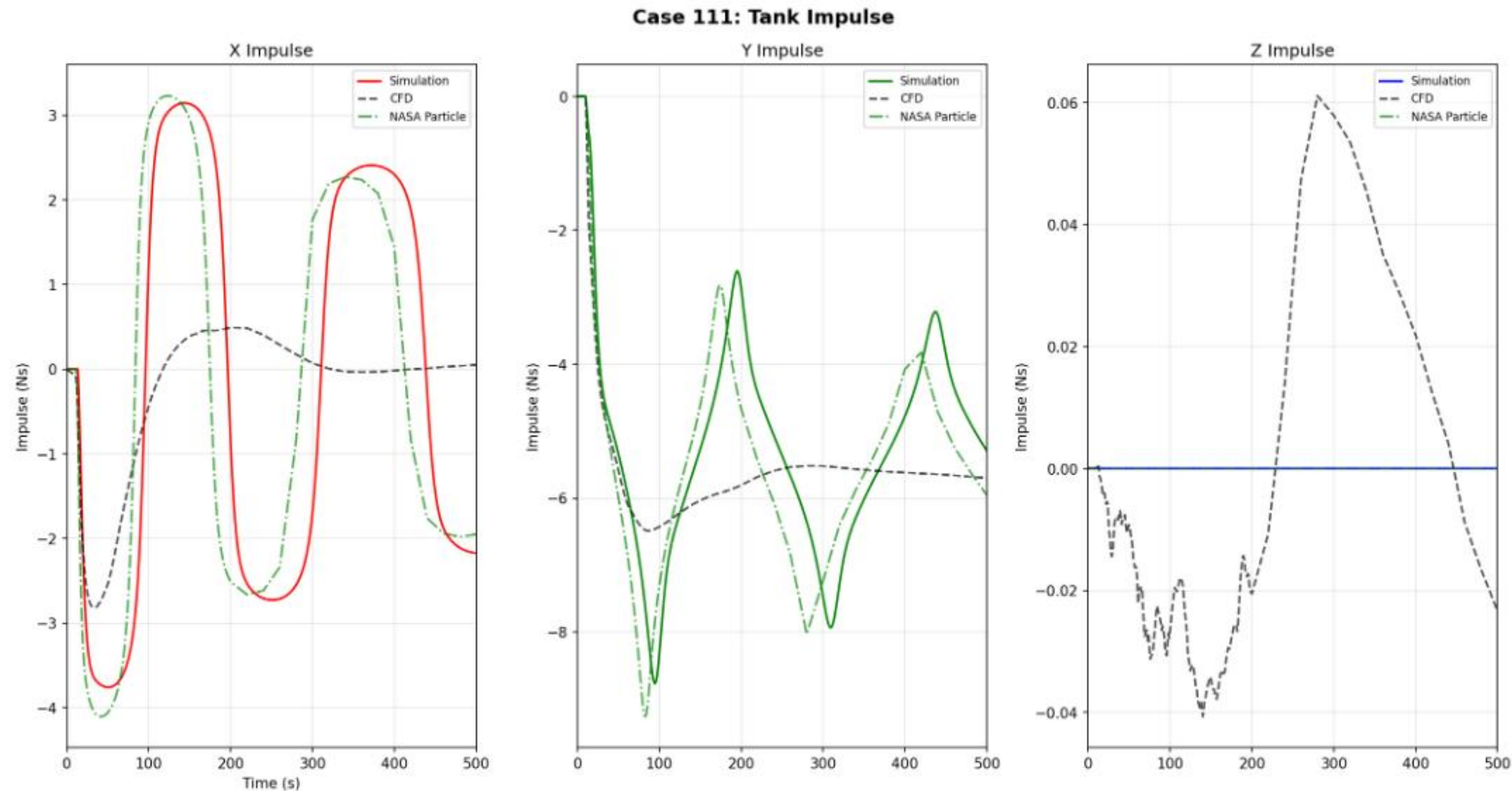


Similar performance to published works is observed in the current simulation.

Translational Reference Case 111

- AAS 26-067 Case 111 "Small Pill", +Y accel, 0.01 m/s^2 , 10% fill
 - Contact stiffness was fixed at 0.15 rad/sec
 - Contact Damping was 1.0 s/m
 - Ellipse limits derived as $0.87/0.44 \text{ m}$

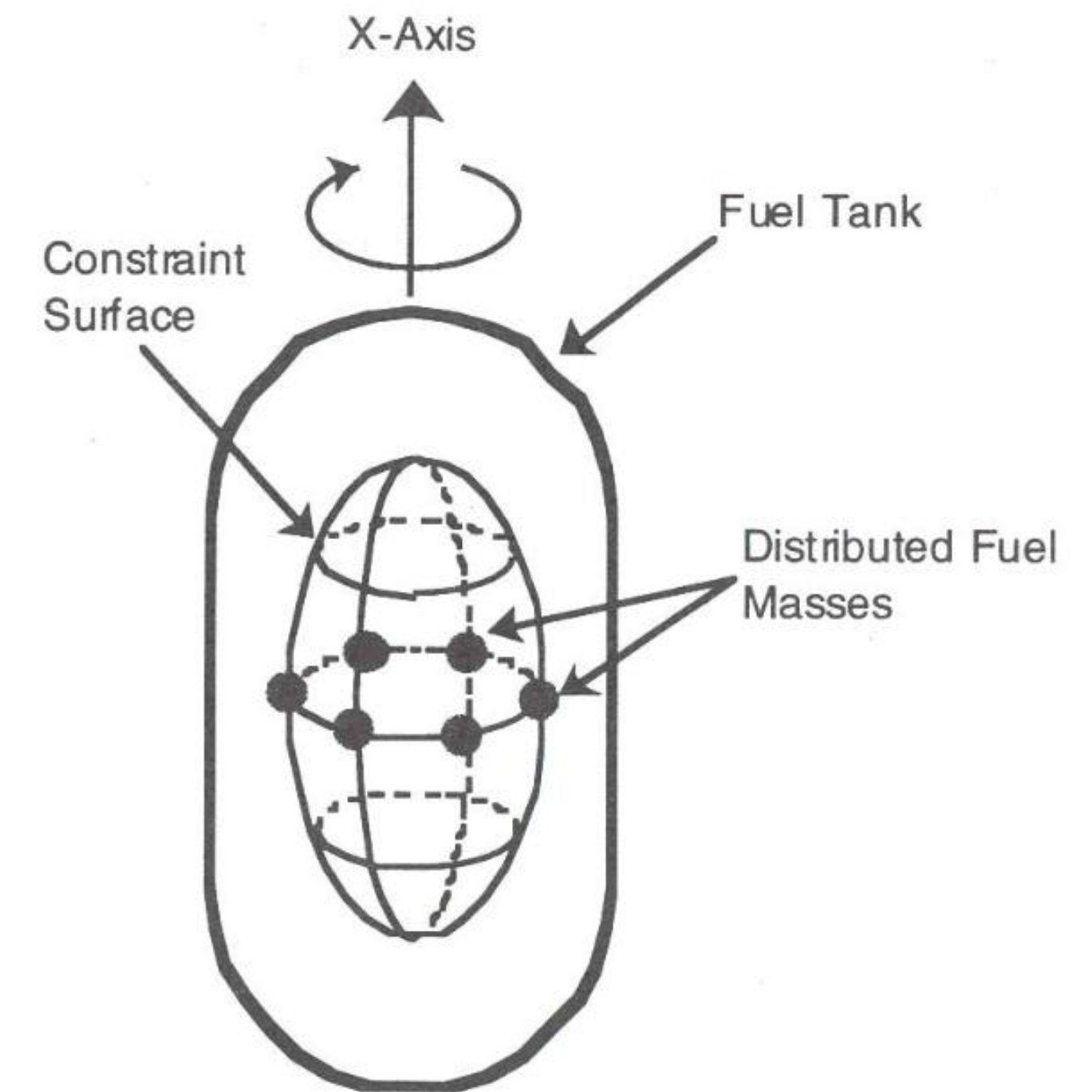
The exact input parameters used were not available, and so the deviations observed here are believed to be due to input differences.



Similar performance to published works is observed in the current simulation.

Translational CFD Comparisons

- While the current work does not exactly match published results it shows similar and as expected behavior, given expected input deviations. (Future work to confirm)
- The current work seeks to;
 - Explore high frequency maneuver forcing functions
 - Extend the current comparison set to rotational and translational tank maneuvers
 - Explore low frequency a-periodic loiter forcing functions
 - Understand low frequency control effects
 - Vary tank fill fraction, and number of particles (Goode et al. [4]) to assess model validity, and potential simple improvements in fidelity
- To do so, a closed loop rigid body simulation was run in a realistic scenario
 - Rotational and translational acceleration time series were captured
 - CFD Simulations were run with these profiles
 - Closed loop control, open loop slosh simulations were used to 'shadow' the simulation dynamics



From Good et al. [4]

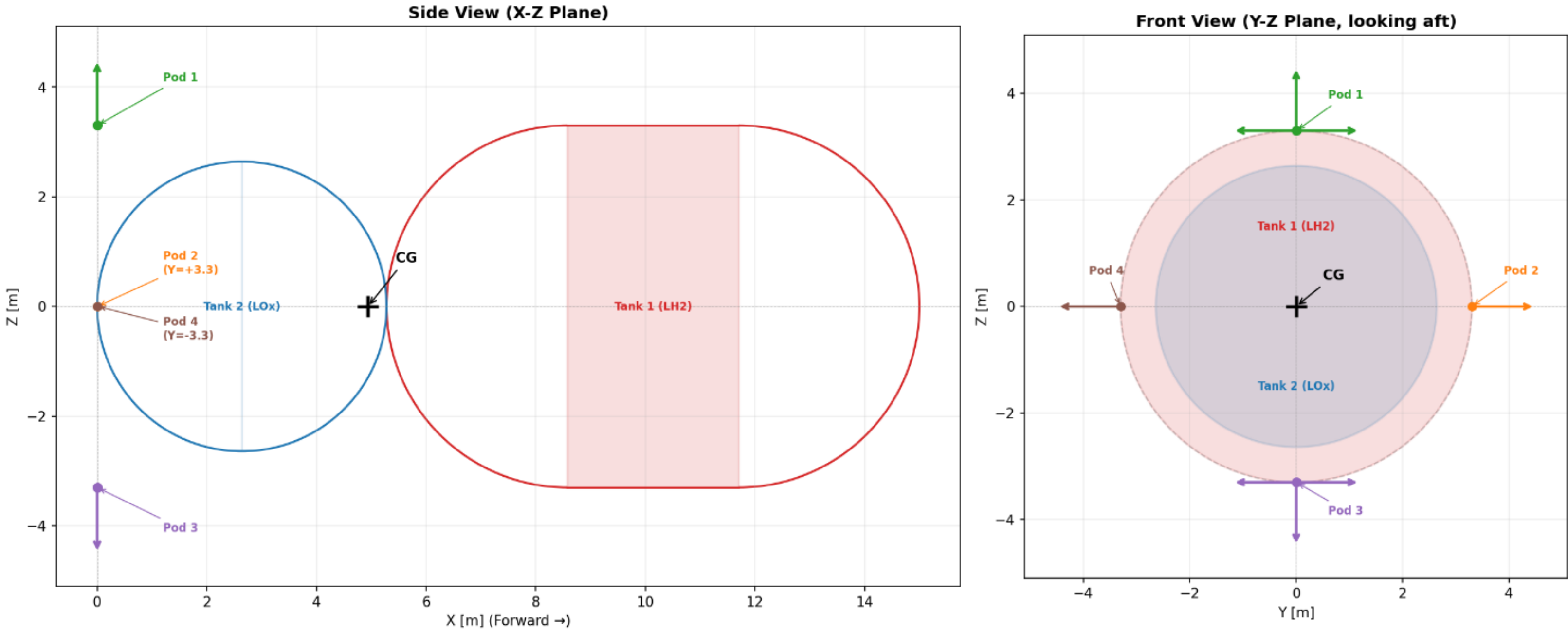
Saturn IVB Test Case

VEHICLE GEOMETRY

- From public data sources, approximate masses, volumes, and inertias for the Saturn IVB vehicle were determined.
- The Saturn IVB vehicle has a common bulkhead, which was not modeled in the current work.

Parameter	Value	Units
Dry Mass	66100	kg
X Dry CG	4.94	m
MOI	1.47e5, 3.56e6, 3.56e6	kg-m ²
LH2 Tank Volume	257.15	m ³
LO2 Tank Volume	77.168	m ³
LH2 Tank Center	2.64	m
LO2 Tank Center	10.14	m
RCS Locations	[0.0, +/- 3.3, +/- 3.3]	m
RCS Force	667.223 (150 lbf)	N

Vehicle Geometry — RCS Maneuver Configuration

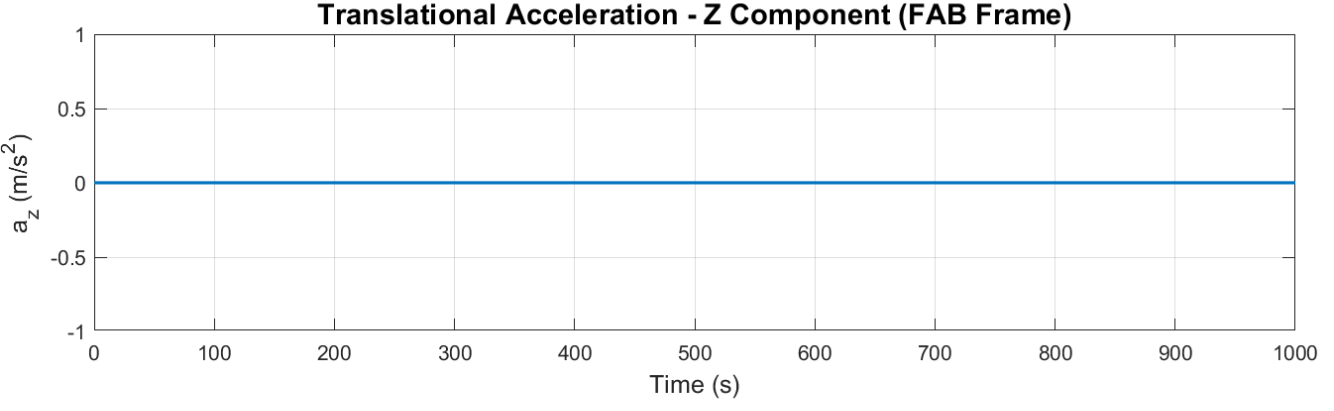
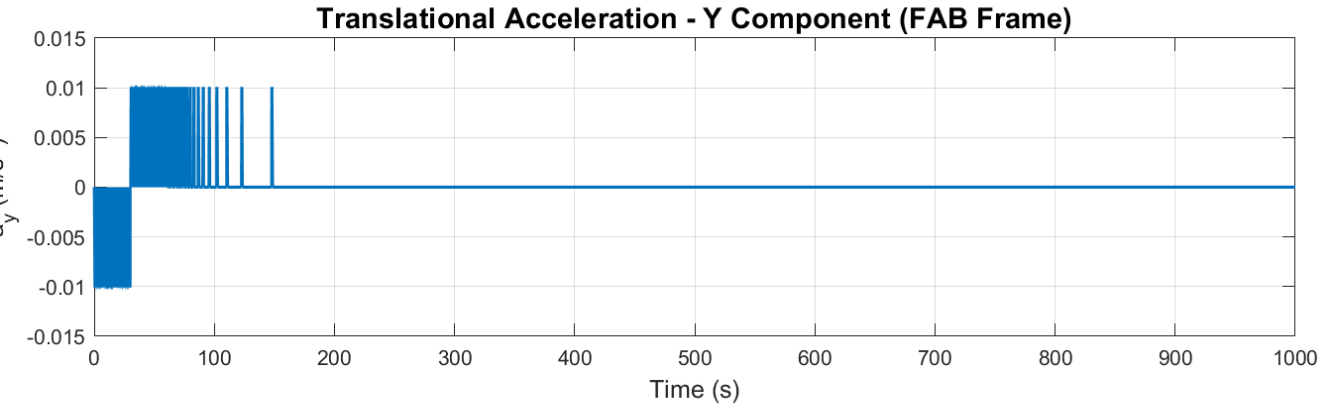
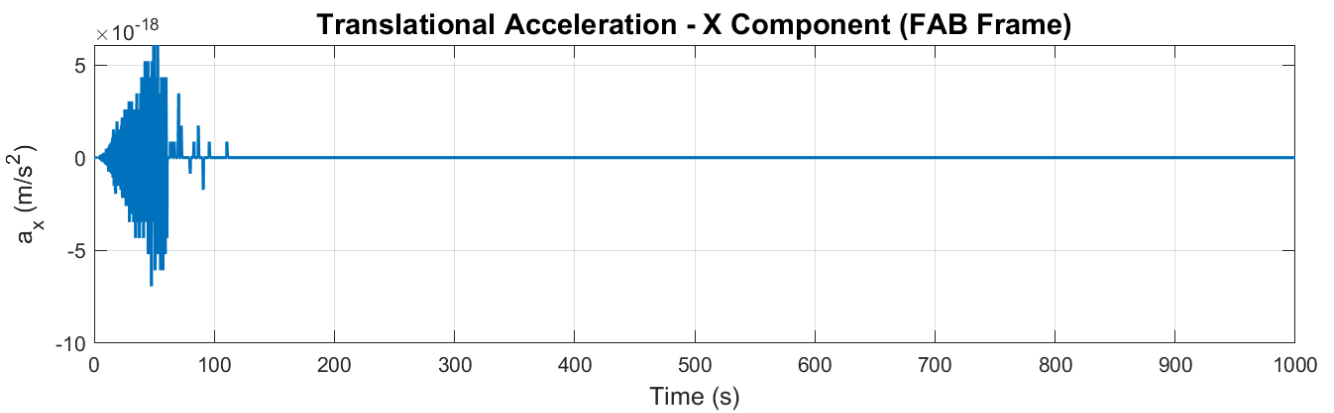
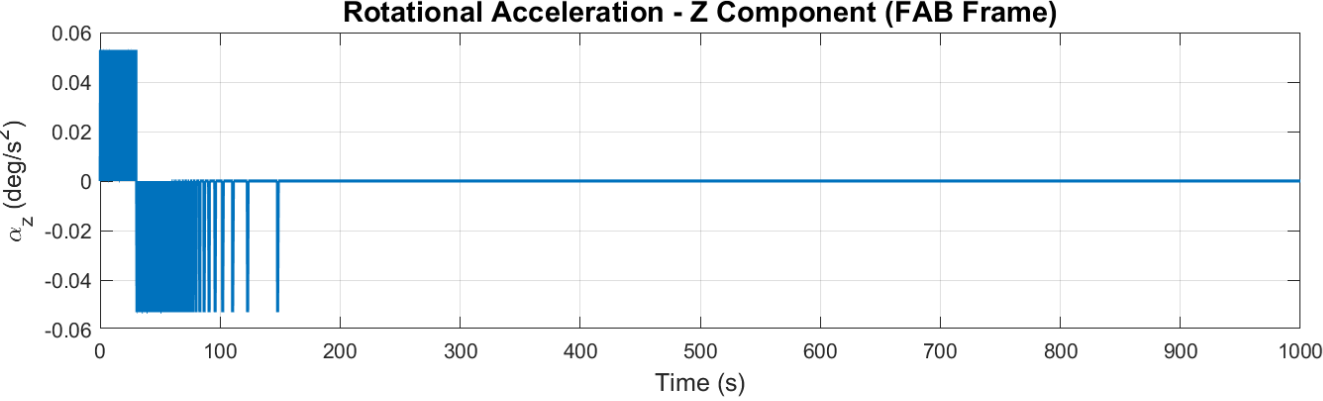
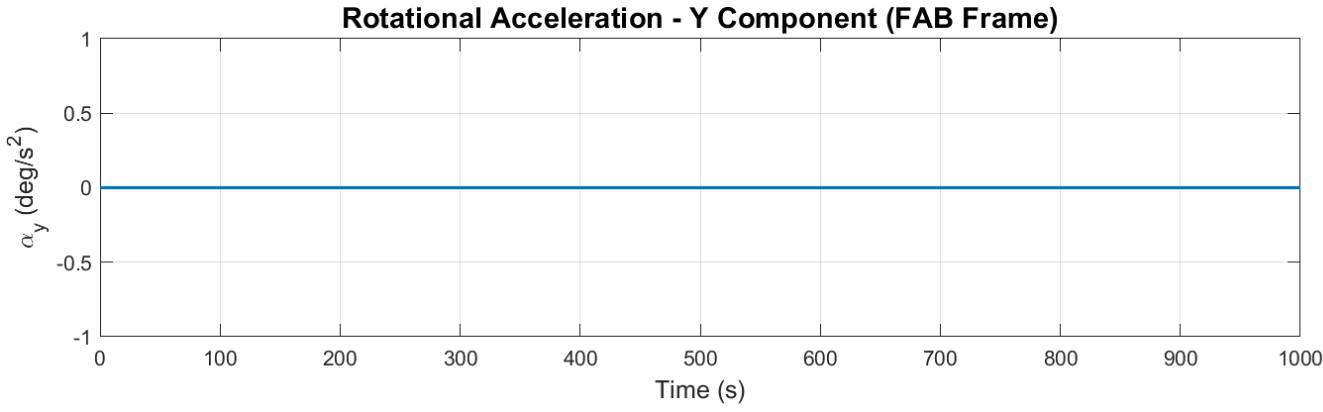
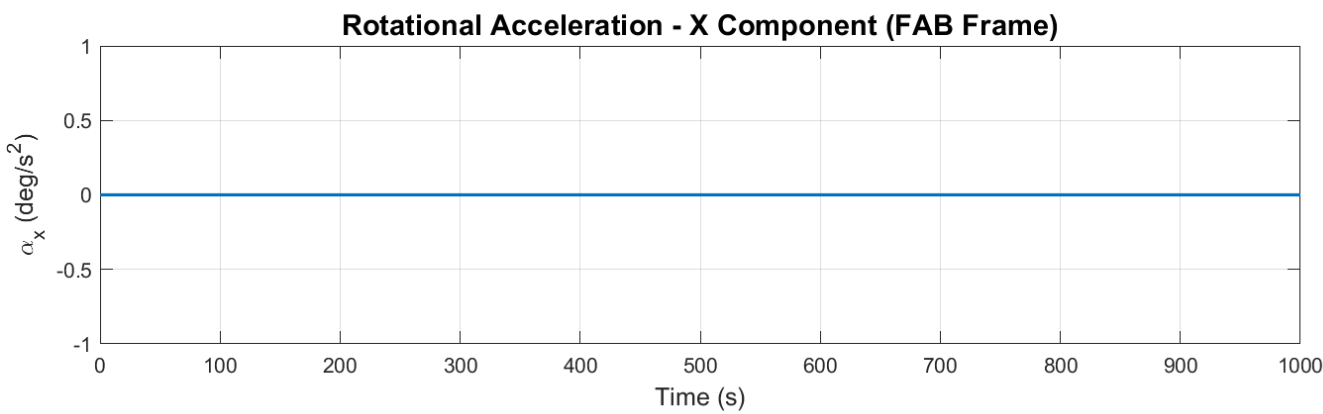
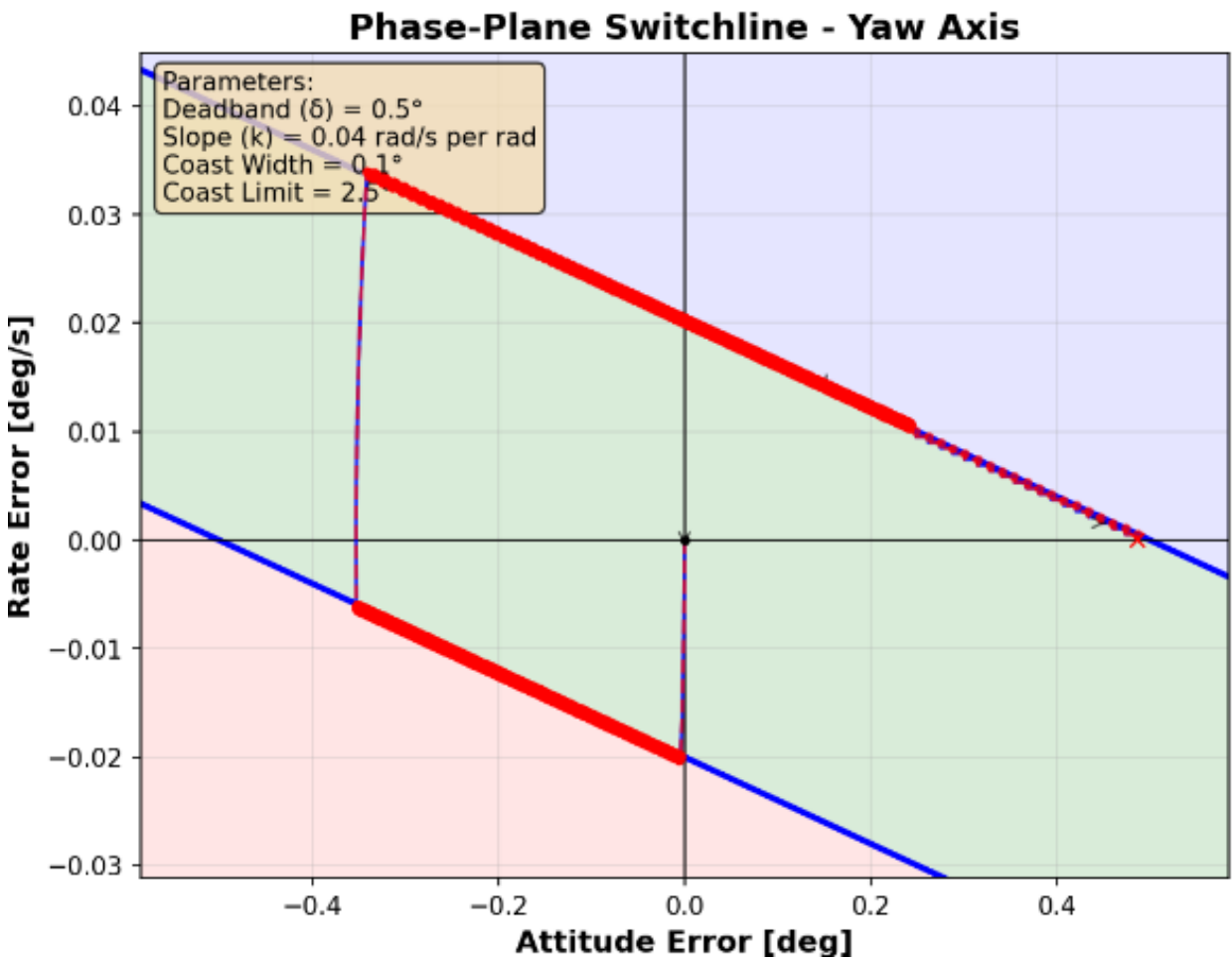
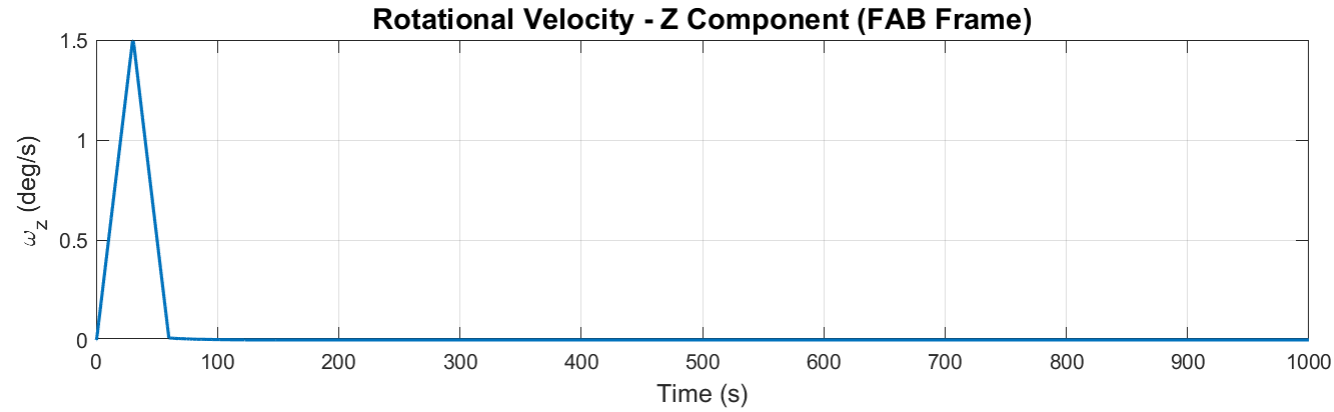
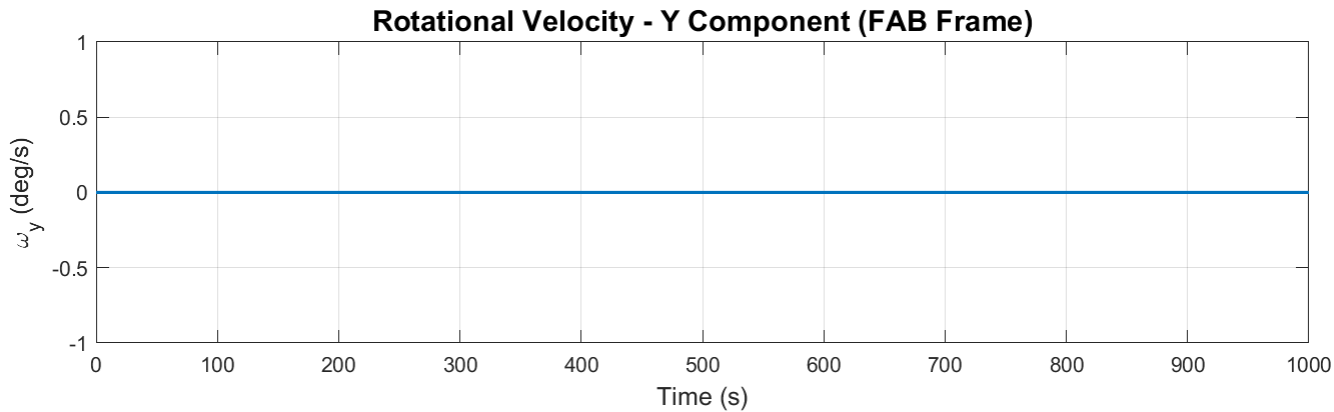
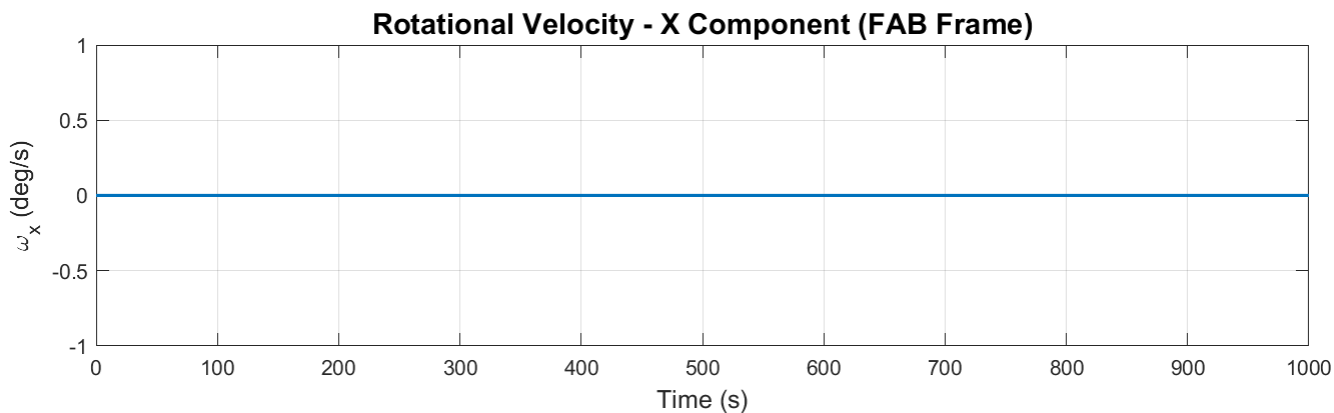


Saturn IVB Test Case

MANEUVER DESIGN

- 45 Degree primary axis turn in 60 seconds
- Peak at 1.6 deg/sec as a stressing fast maneuver
- Bang-Bang switchline control at 100 hz
- Attitude Hold post turn completion
- Comparisons used fixed slosh simulation results to drive CFD/ fluid particle (i.e. no slosh accelerations driving slosh sims)
- For simplicity, the same driving acceleration profile was used for varying fill fractions

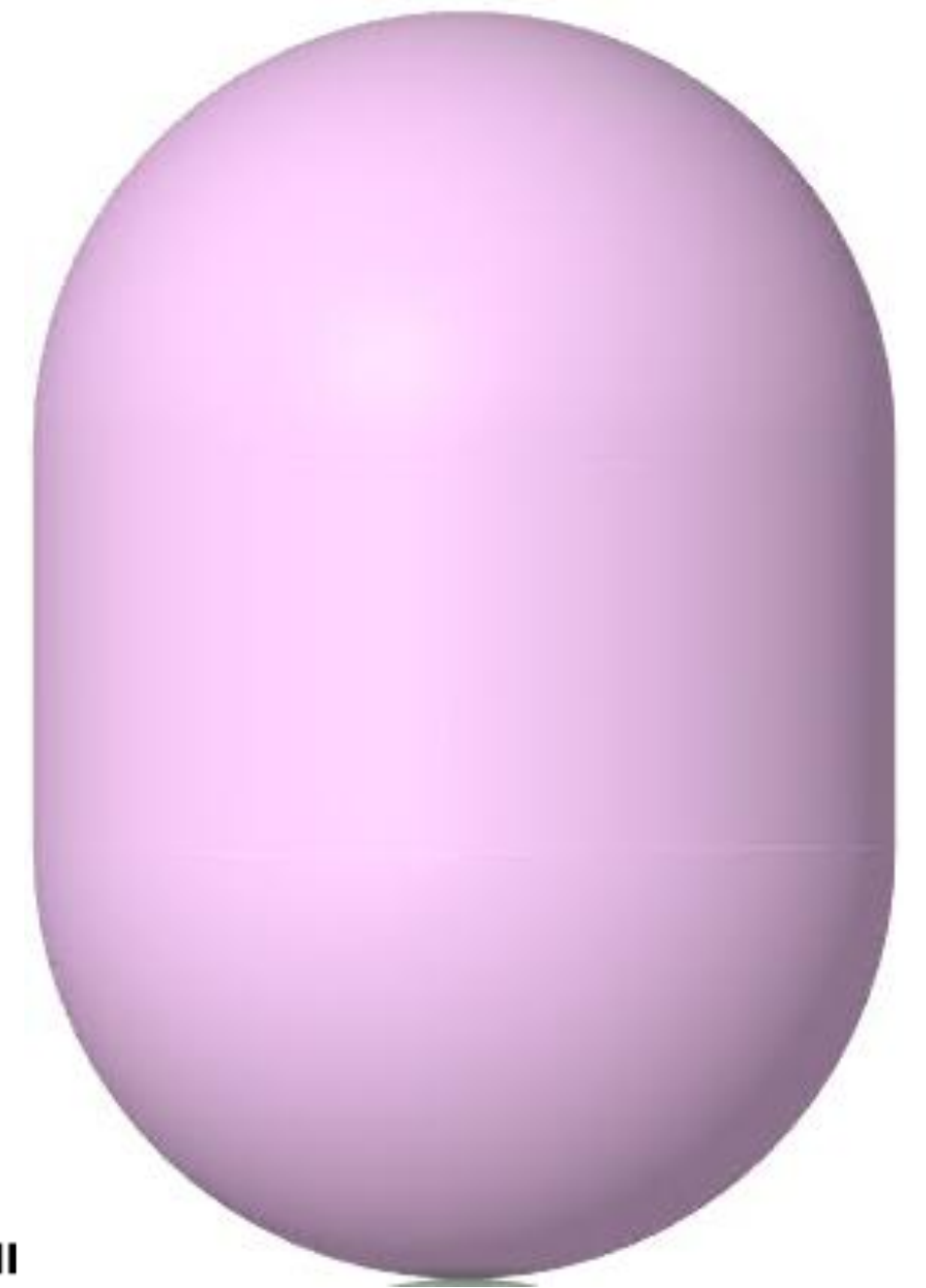
	Lox	LH2
Max Bond Number	27000	9700
Max Weber Number	8800	3100



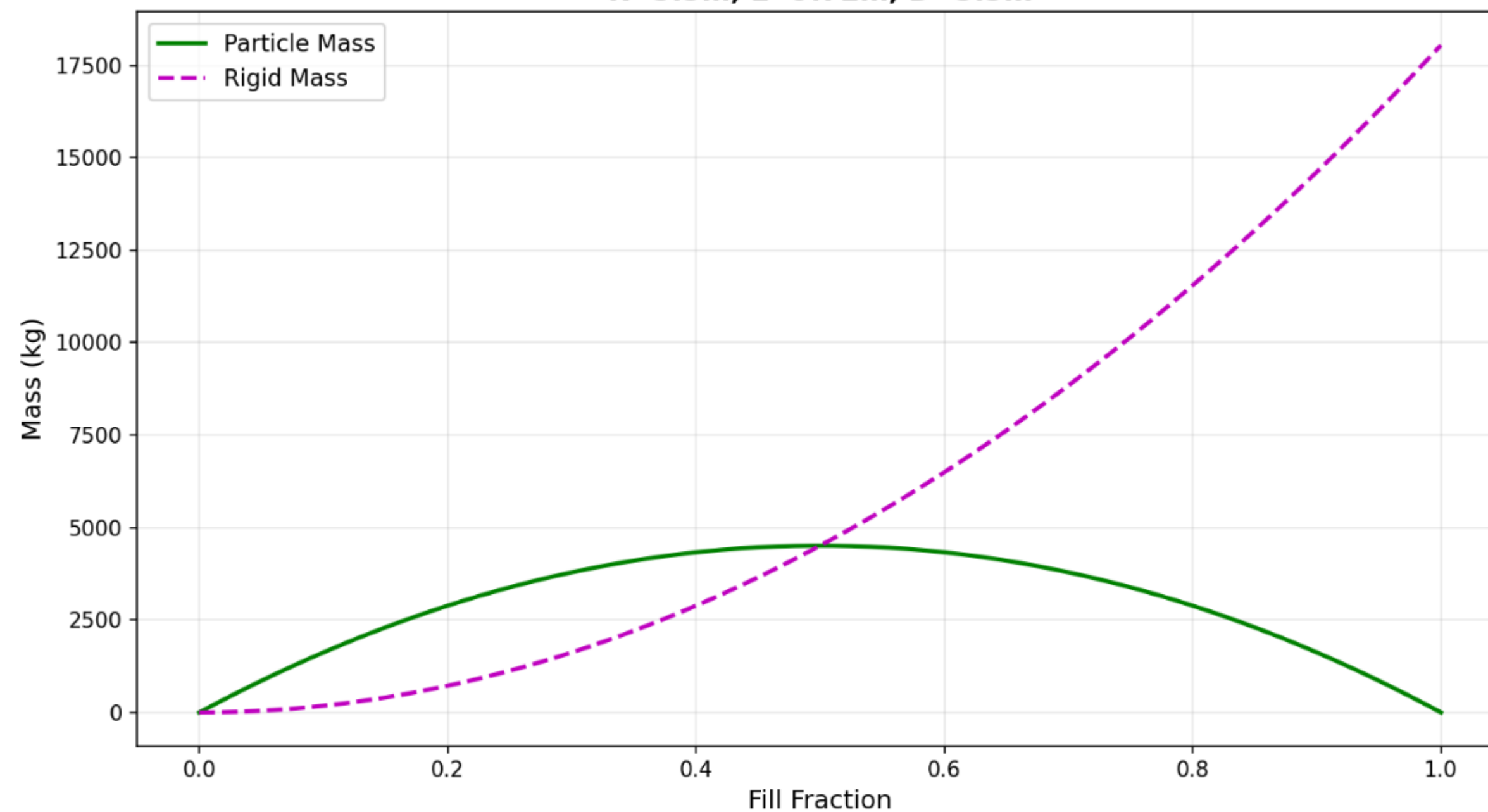
Saturn IVB Test Case

FLUID PARTICLE MODEL INPUTS

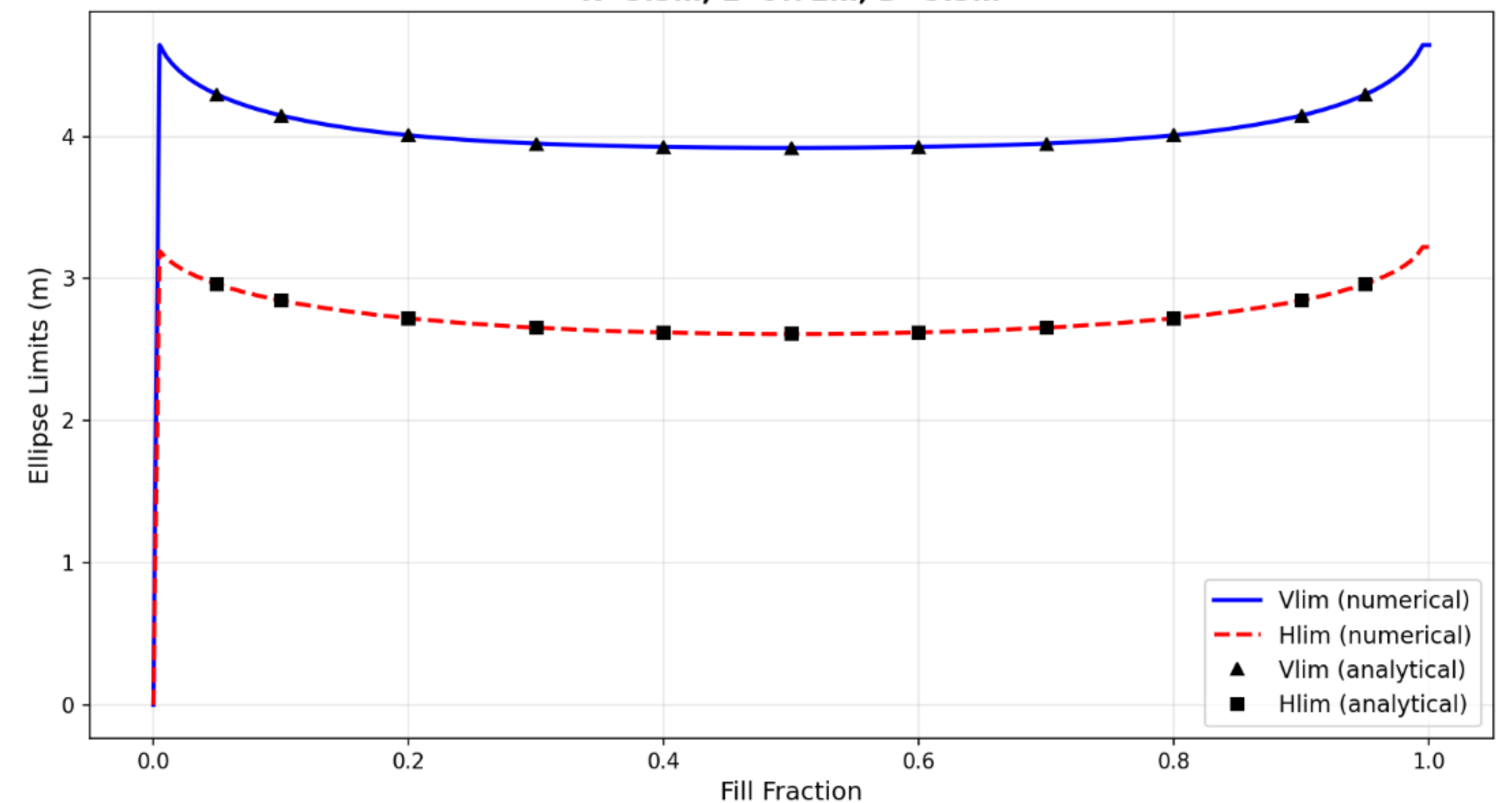
- Numerically integrated to calculate center of mass at various volumetric fill fractions



Slosh Mass Components vs Fill Fraction
R=3.3m, L=9.72m, D=3.3m



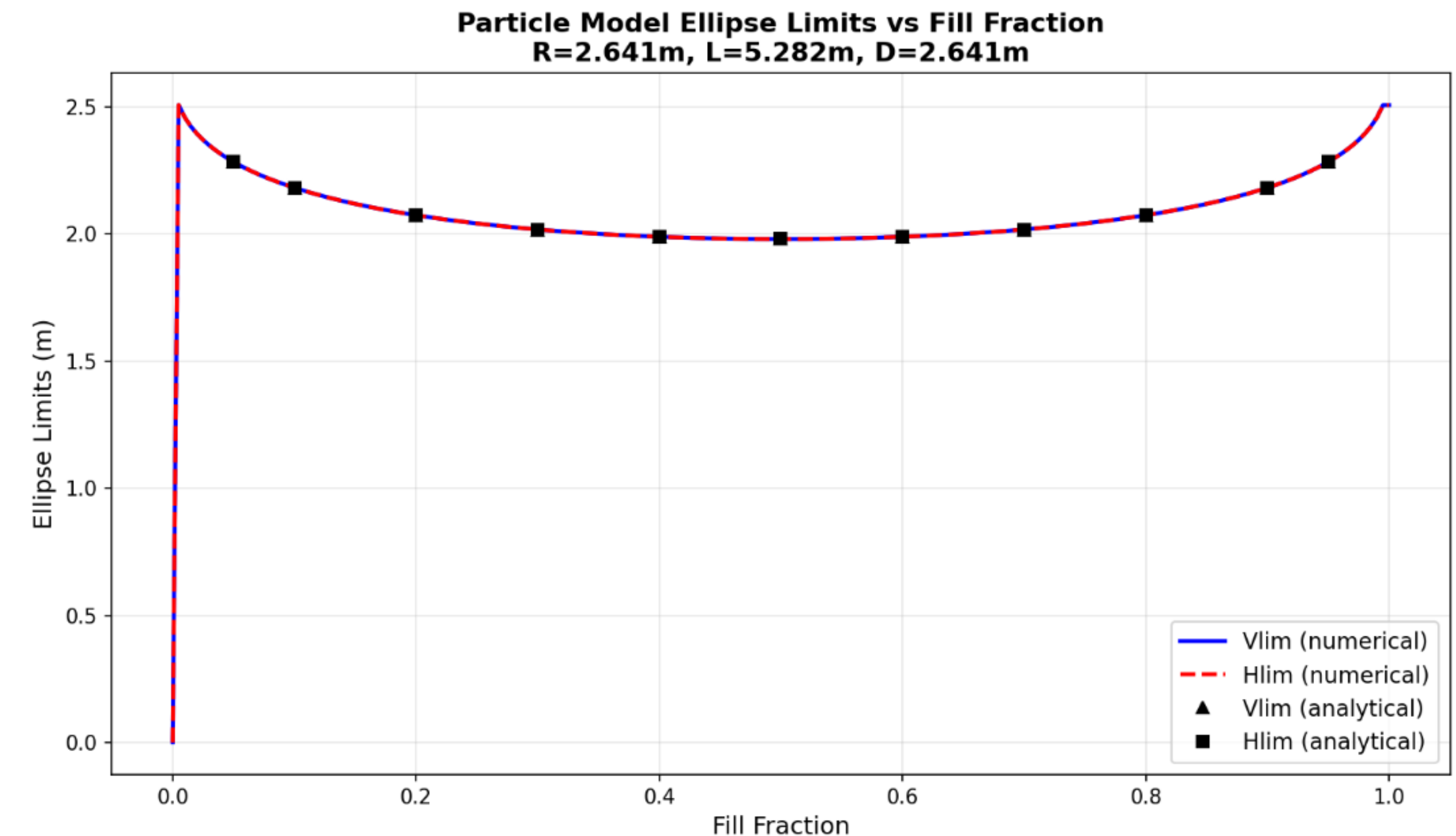
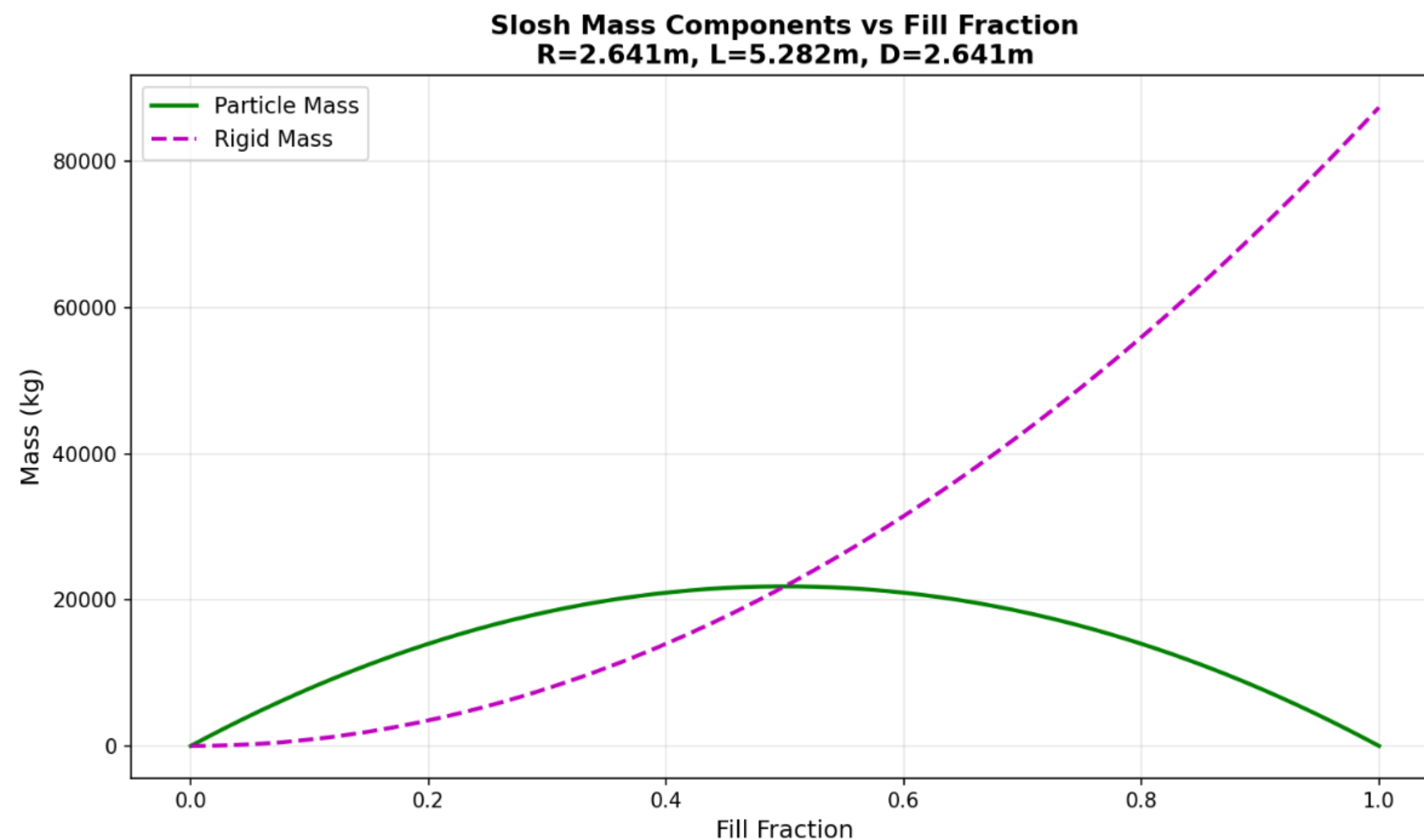
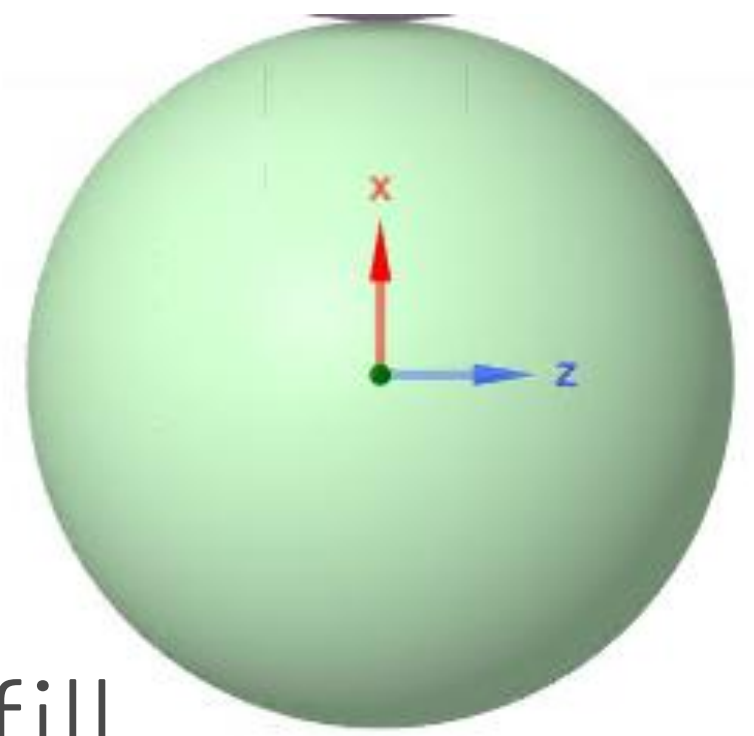
Particle Model Ellipse Limits vs Fill
R=3.3m, L=9.72m, D=3.3m



Saturn IVB Test Case

FLUID PARTICLE MODEL INPUTS

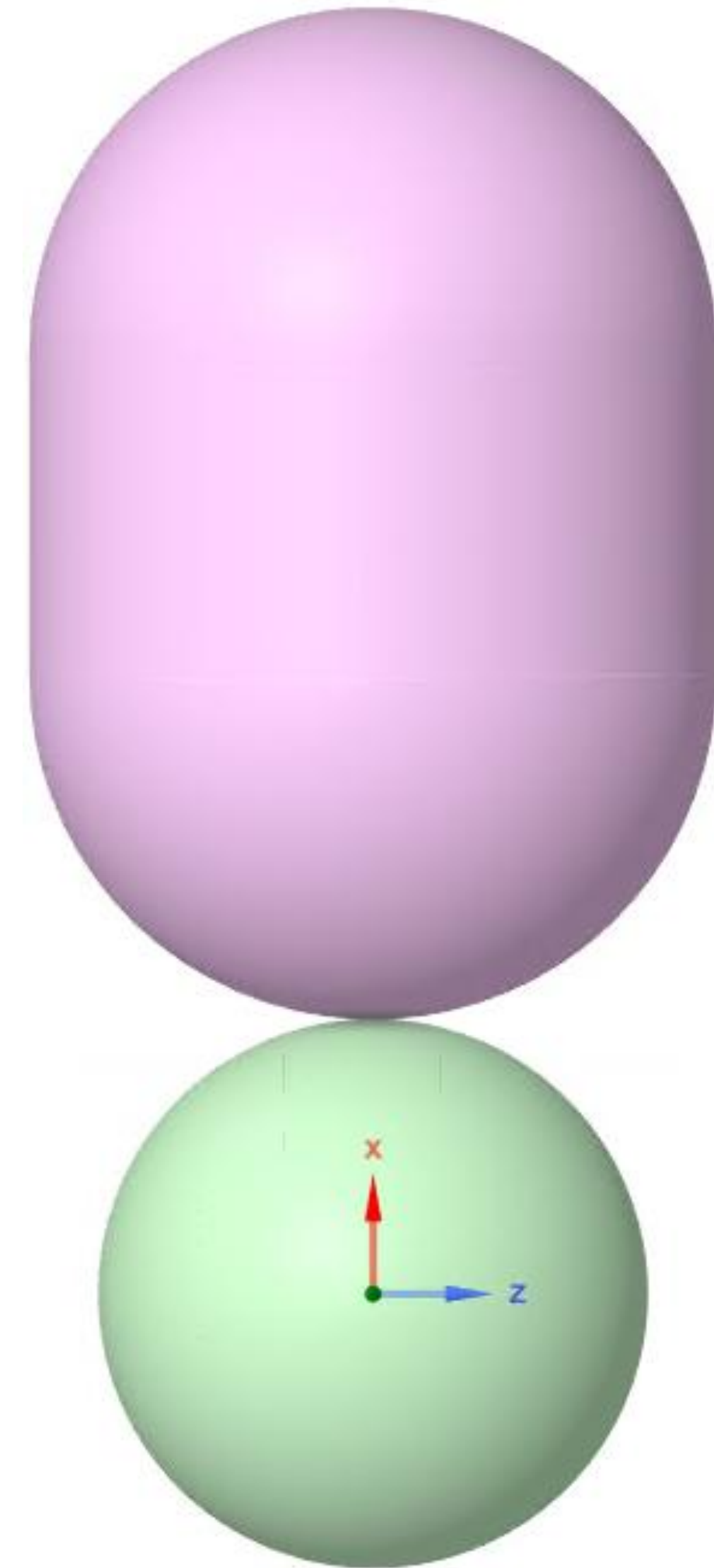
- Numerically integrated to calculate center of mass at various volumetric fill fractions
 - Semi-major and minor ellipse axes are identical due to spherical tank



CFD Overview

	Tank Center	Tank Radius and Cylindrical Section		Fluid Density
	Location (axial) (m)	Dome Depth (m)	Height (m)	(kg/m ³)
LOx Tank	2.64	2.64	-	1130
LH2 Tank	10.14	3.3	3.12	70

- Setup
 - Fluids are assumed to be incompressible and initialized with a flat interface at $t = 0$
 - Second order accurate numerical methods are used
 - Volume-of-Fluid with Split Lagrangian method is used to track interface
 - Non-Inertial Reference Frame
 - Angular velocities specified about CG (4.94, 0, 0)
 - Grid size: LOX tank 0.035 m, LH2 tank 0.045 m
 - Grid is appropriate for integral quantities – forces/moments
 - Grid convergence is confirmed
- Postprocessing
 - Time traces of COM, forces and torques at 100 hz
 - Low-pass filter is used to smooth out numerical oscillations



Saturn IVB CFD Comparisons

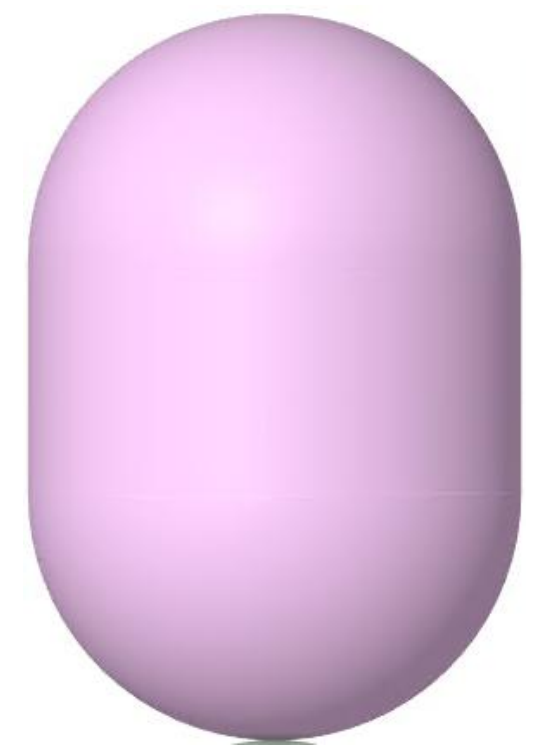
DATA PROCESSING / NOTES

- Data was filtered at 2 Hz to remove chatter from RCS firings, as well as reduce numerical noise from CFD.
- Plots report the force of the fluid on the tank wall
- A 'Rigid Reference' signal is plotted for comparison. This is the inertial force and impulse associated with a 100% rigid mass at the tank center, and the applied acceleration.
- Contact natural frequency is fixed at 0.15 rad/sec
- Contact damping is at 1.0
- When applicable, inter-particle repulsive forces are described via a 200 second time constant
- Particles are initialized at the aft most axial position on the ellipse

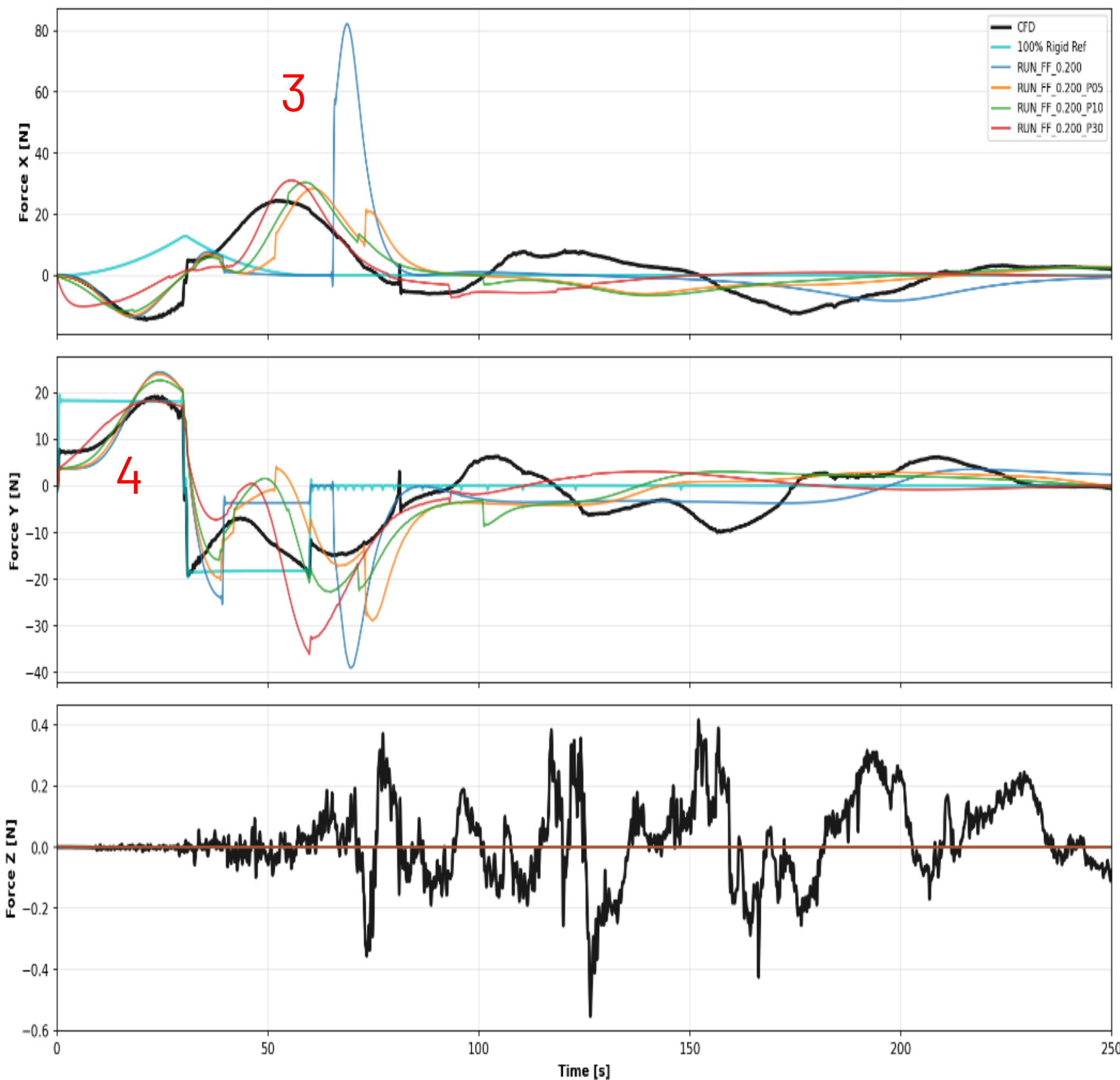
Figures on the next page show X/Y/Z Forces on the left, and X/Y/Z Impulse on the right

Saturn IVB CFD Comparisons

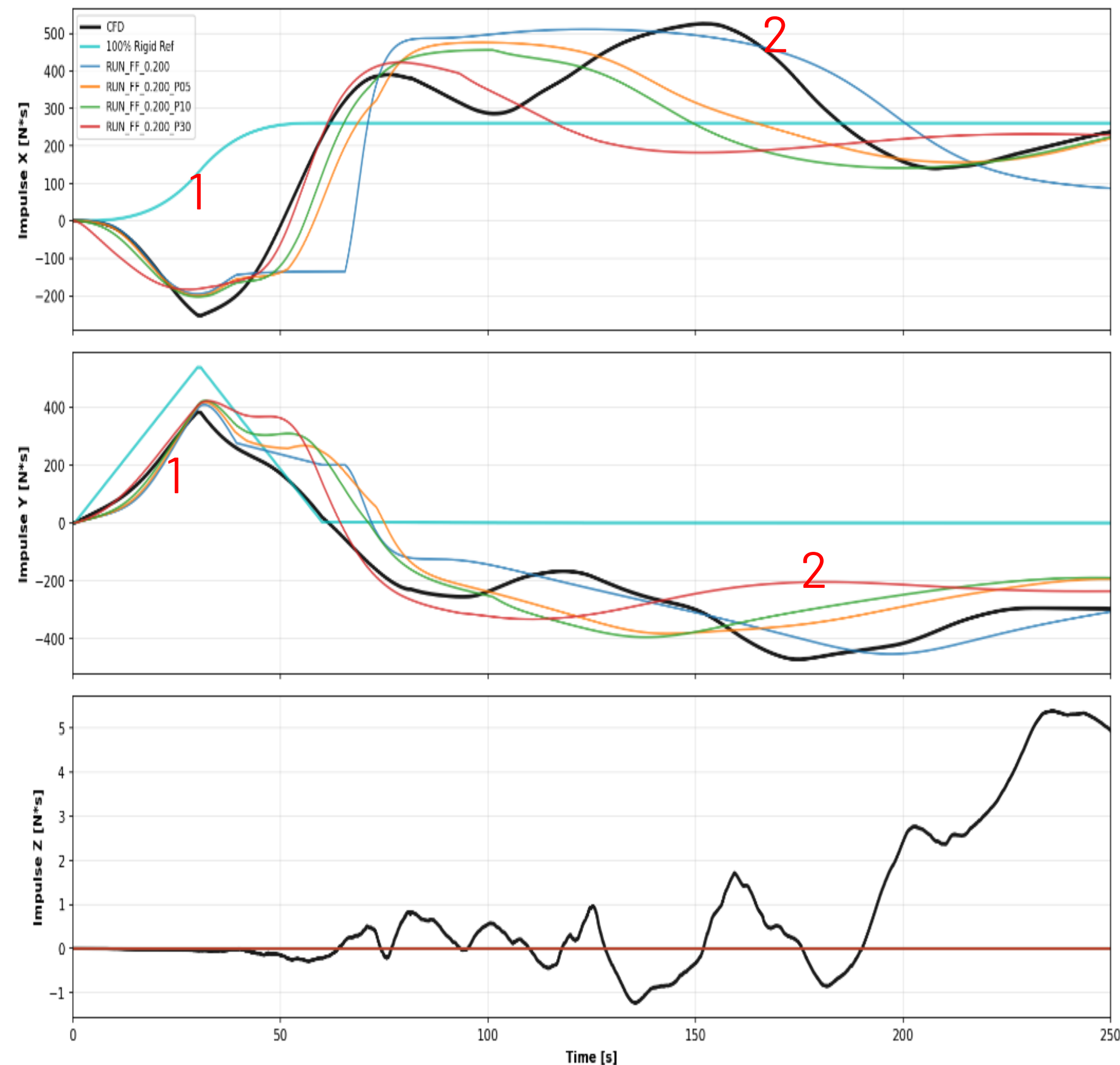
20% FF LH2



SIVB_LH2: Sweep Force Comparison (LPF @ 2.0 Hz) (0.200_ff sweep)



SIVB_LH2: Sweep Impulse Comparison (cumulative force integral) (0.200_ff sweep)

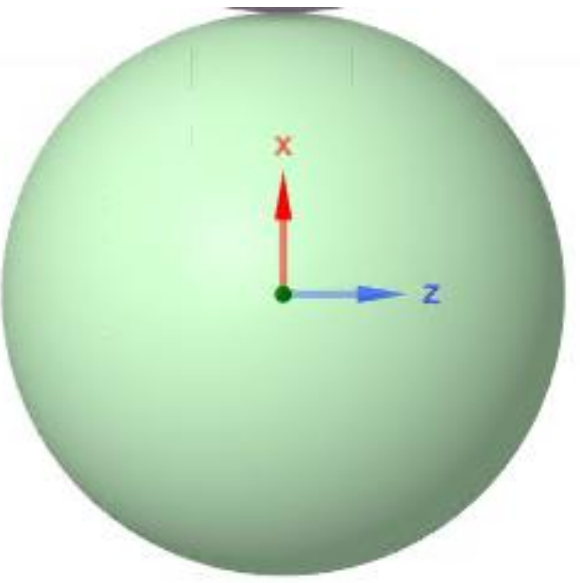


1. Initial impulse response matches CFD
2. Lateral impulse response in both CFD and Particle simulations exceed the rigid response
3. Fluid particle is detaching from the free surface -> Adhesion modeling needed
4. Slosh particle mass agrees with CFD

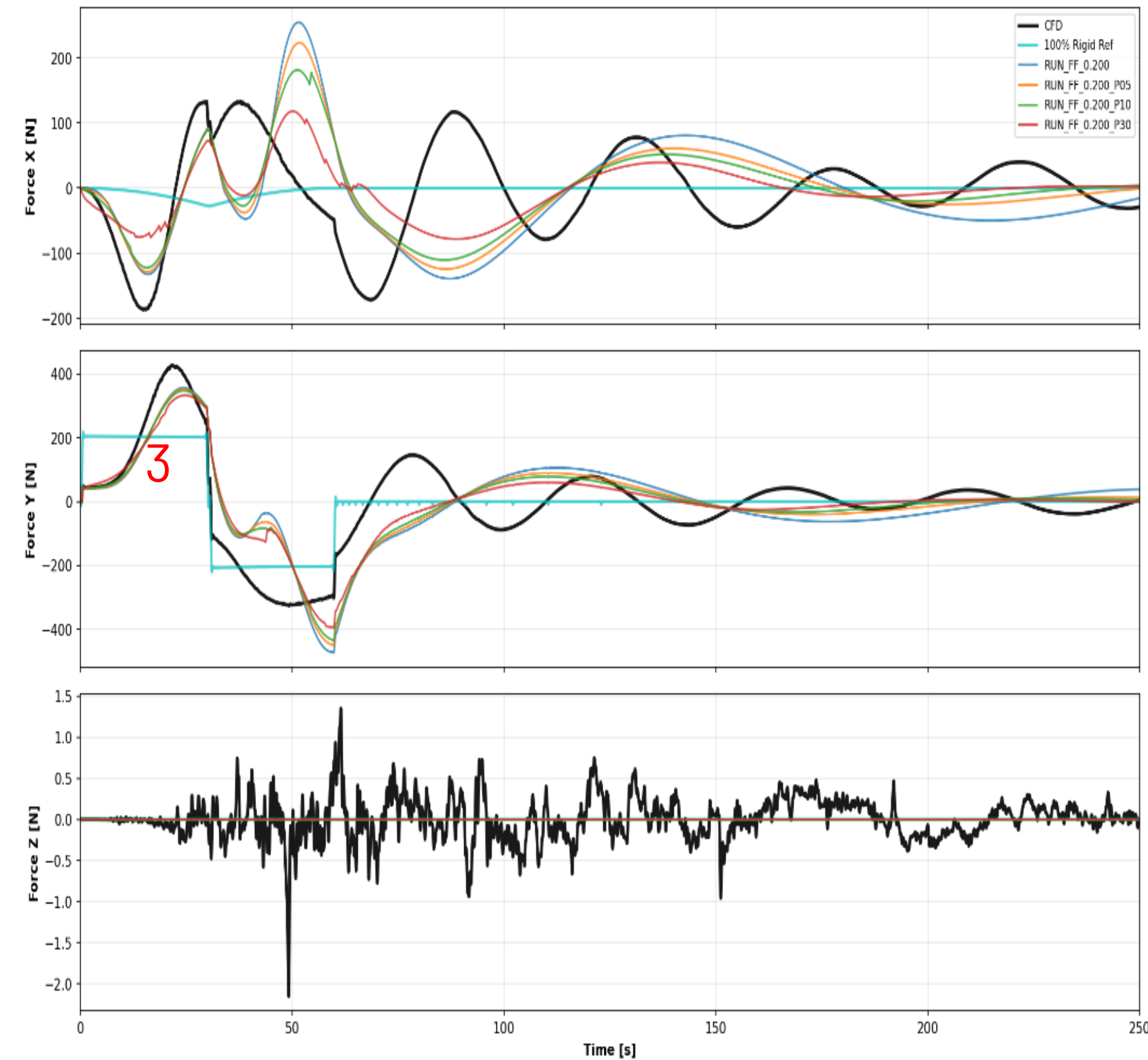
BLUE ORIGIN

Saturn IVB CFD Comparisons

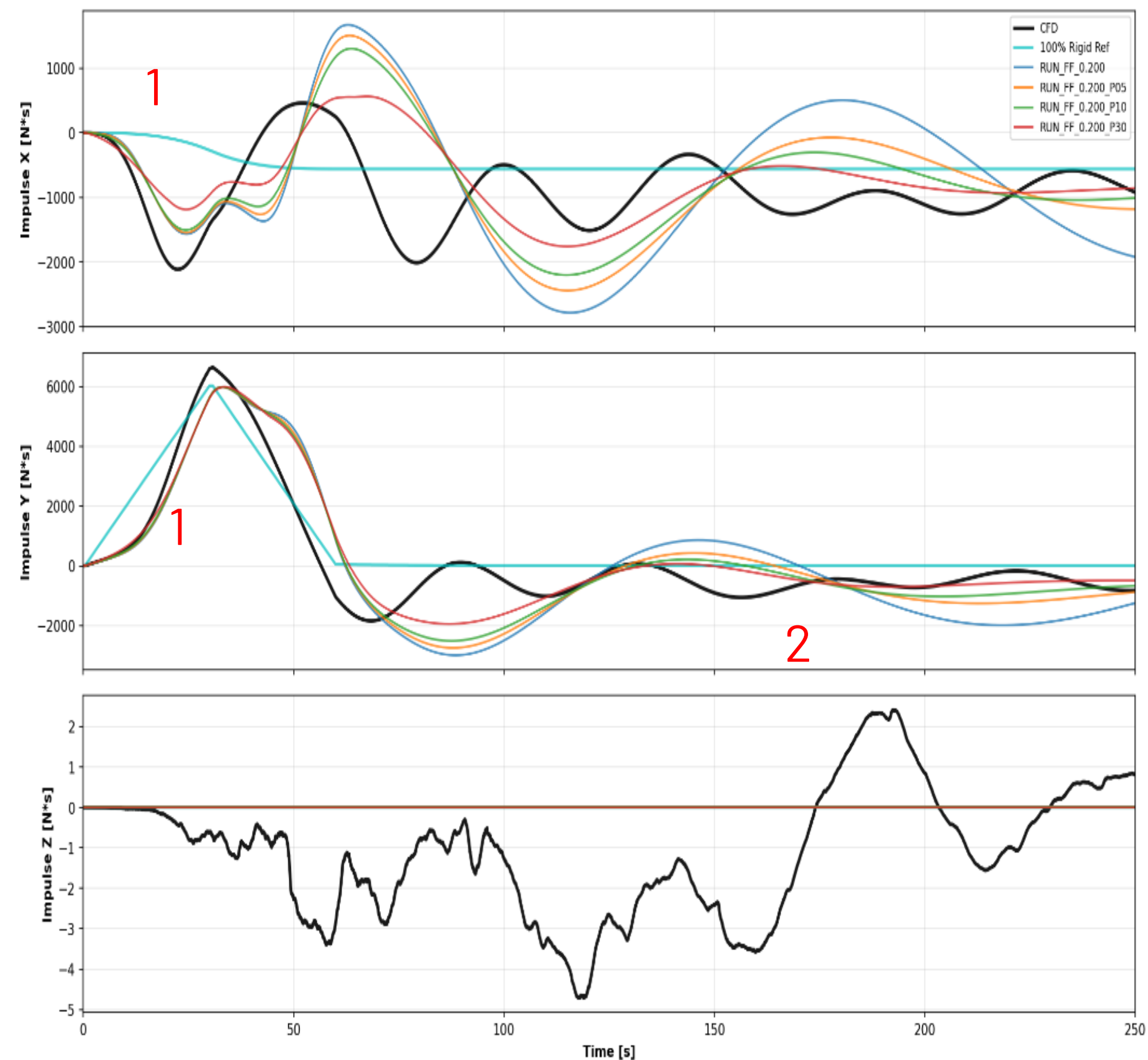
20% FF LOX



SIVB_LOX: Sweep Force Comparison (LPF @ 2.0 Hz) (0.200_ff sweep)



SIVB_LOX: Sweep Impulse Comparison (cumulative force integral) (0.200_ff sweep)

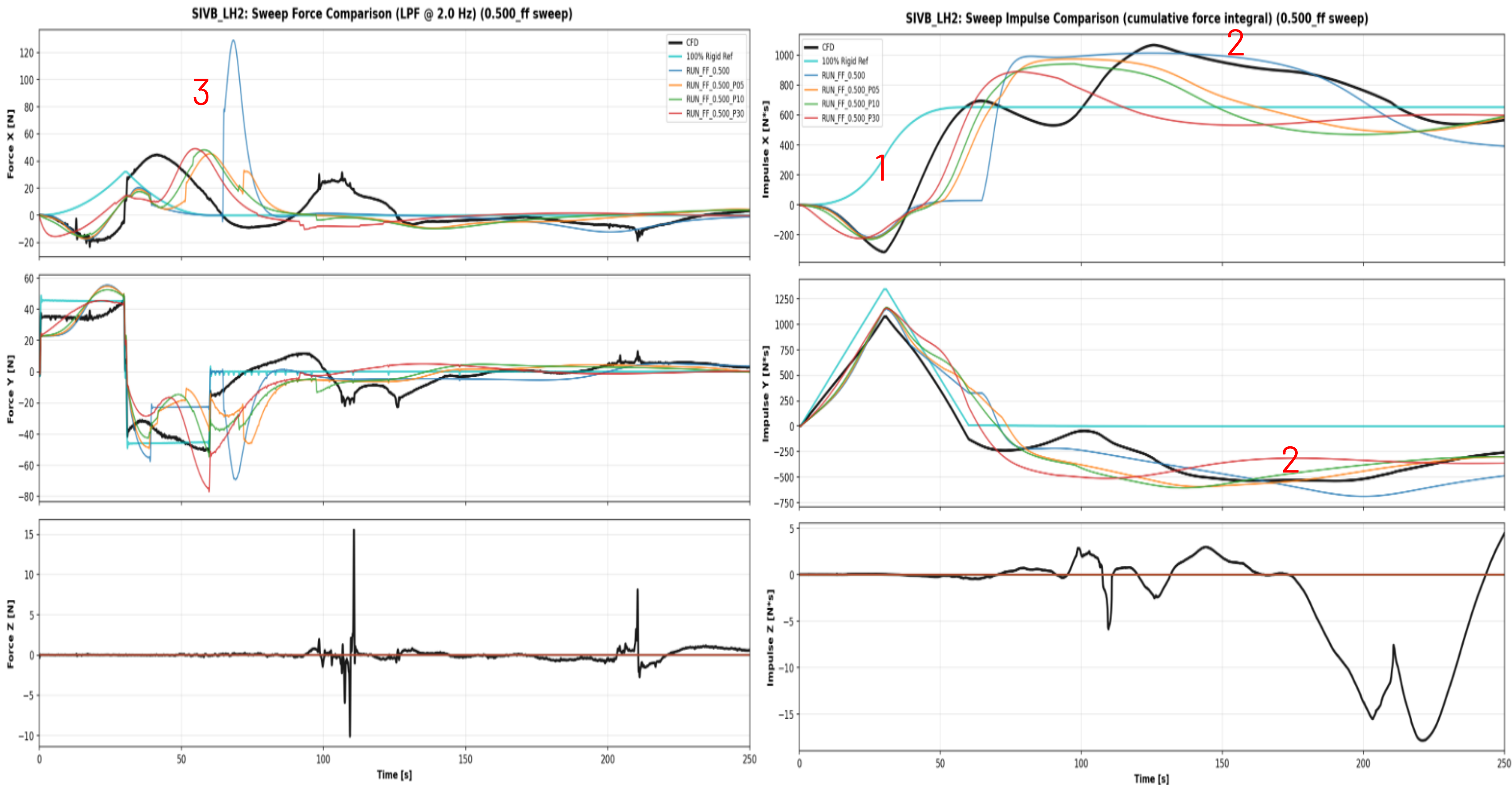
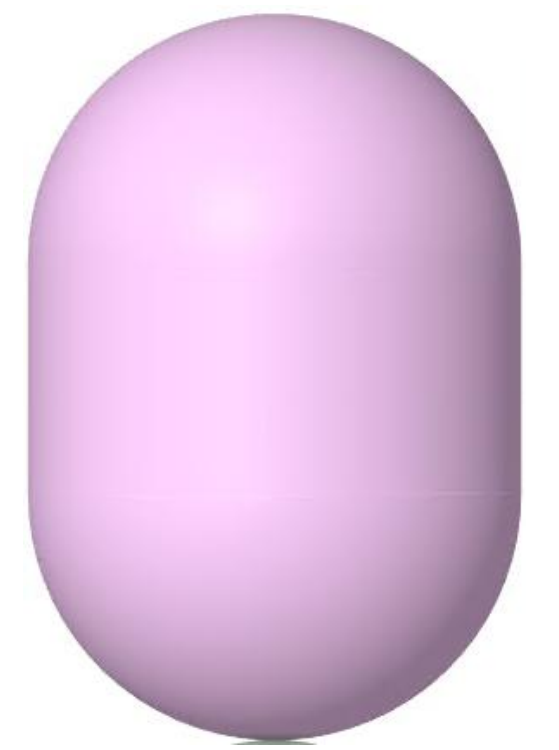


1. Initial impulse response from FP matches CFD
2. Lateral impulse response in both CFD and Particle simulations exceed the rigid response
3. Slosh particle mass is consistent with CFD

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Saturn IVB CFD Comparisons

50% FF LH2

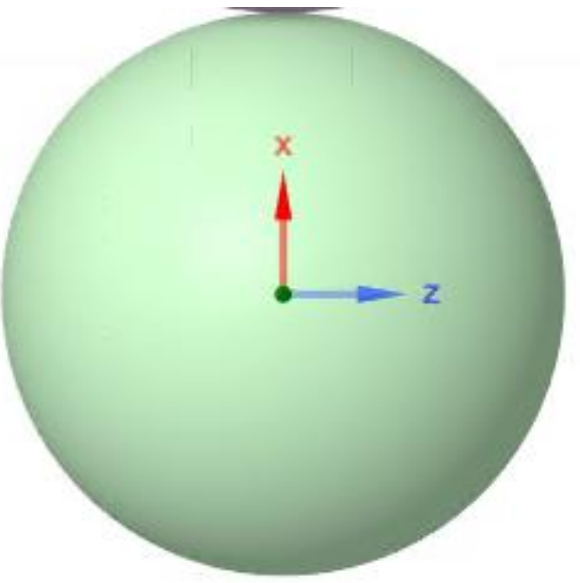


1. Initial impulse matches CFD
2. Peak impulse magnitudes match CFD
3. Fluid particle is detaching from the free surface -> Adhesion modeling needed

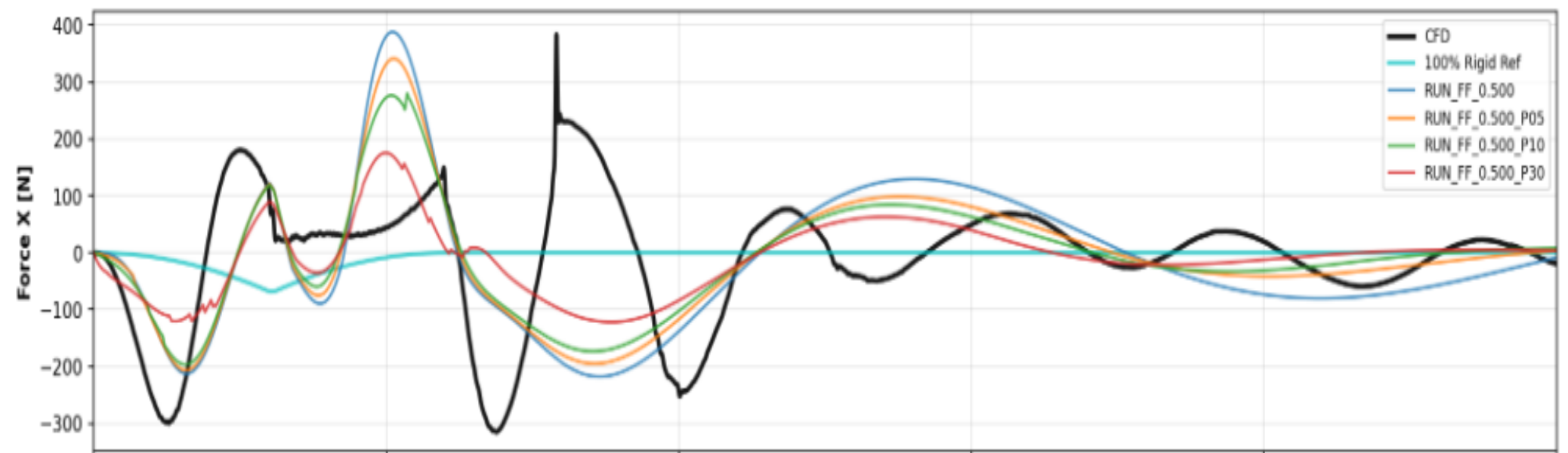
BLUE ORIGIN

Saturn IVB CFD Comparisons

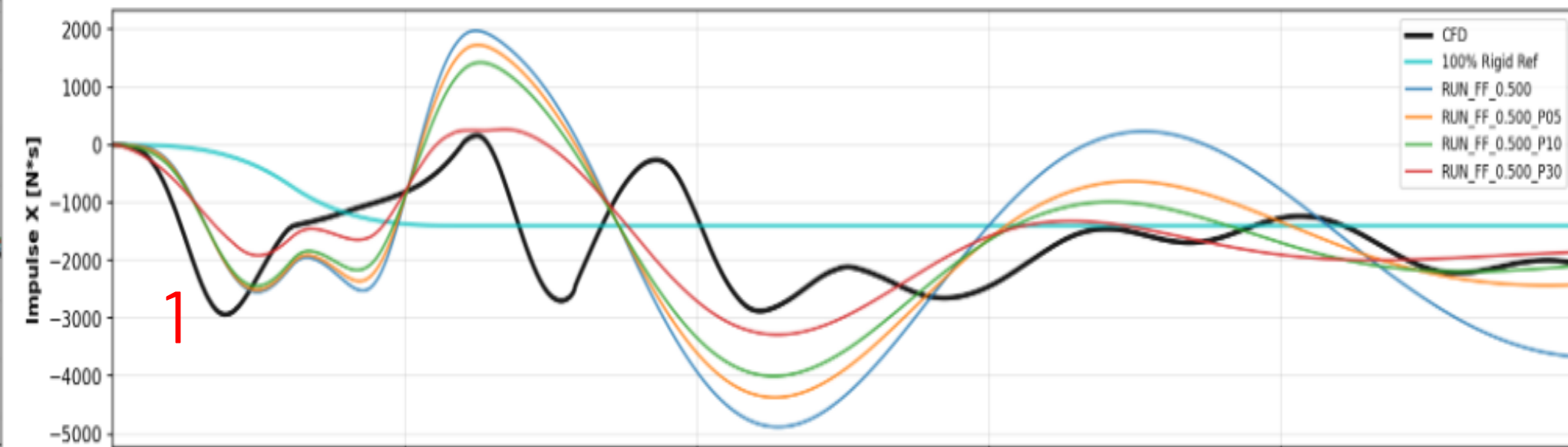
50% FF LOX



SIVB_LOX: Sweep Force Comparison (LPF @ 2.0 Hz) (0.500_ff sweep)



SIVB_LOX: Sweep Impulse Comparison (cumulative force integral) (0.500_ff sweep)

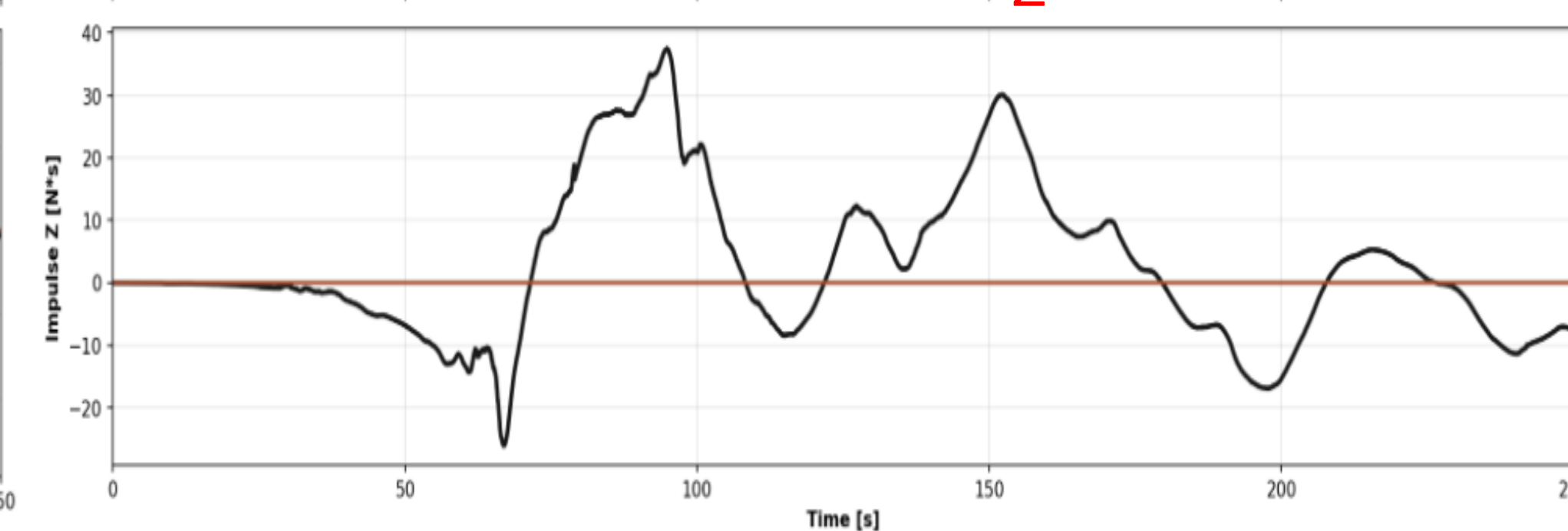
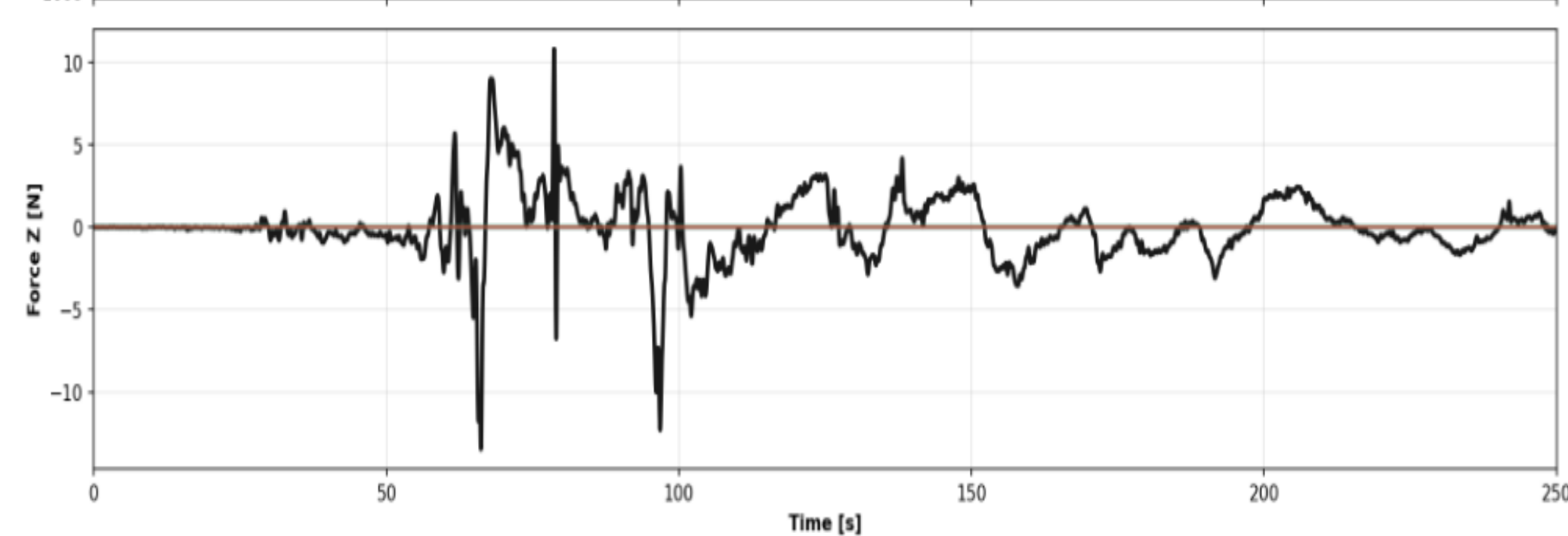
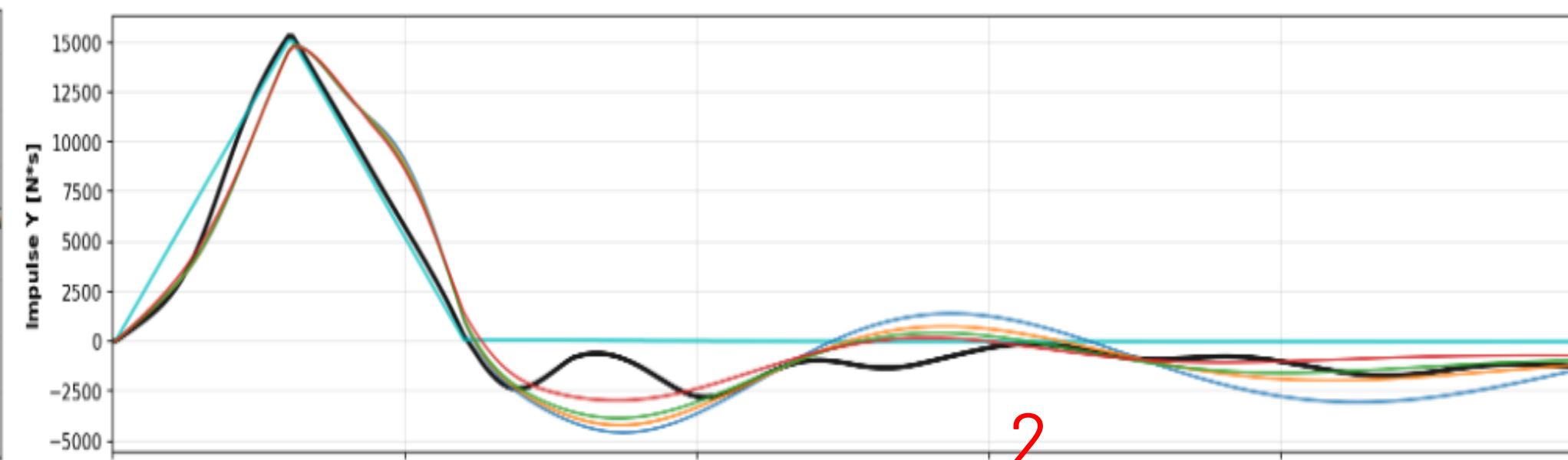
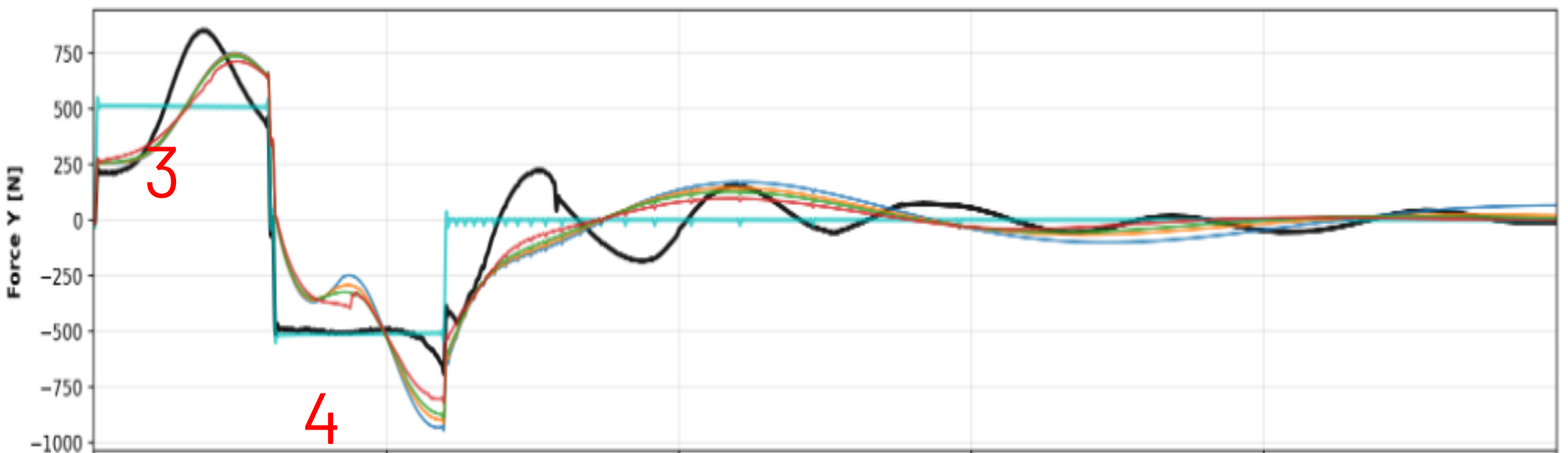


1. Initial impulse response matches CFD

2. Lateral impulse magnitude matches CFD

3. Initial slosh particle mass agrees with CFD

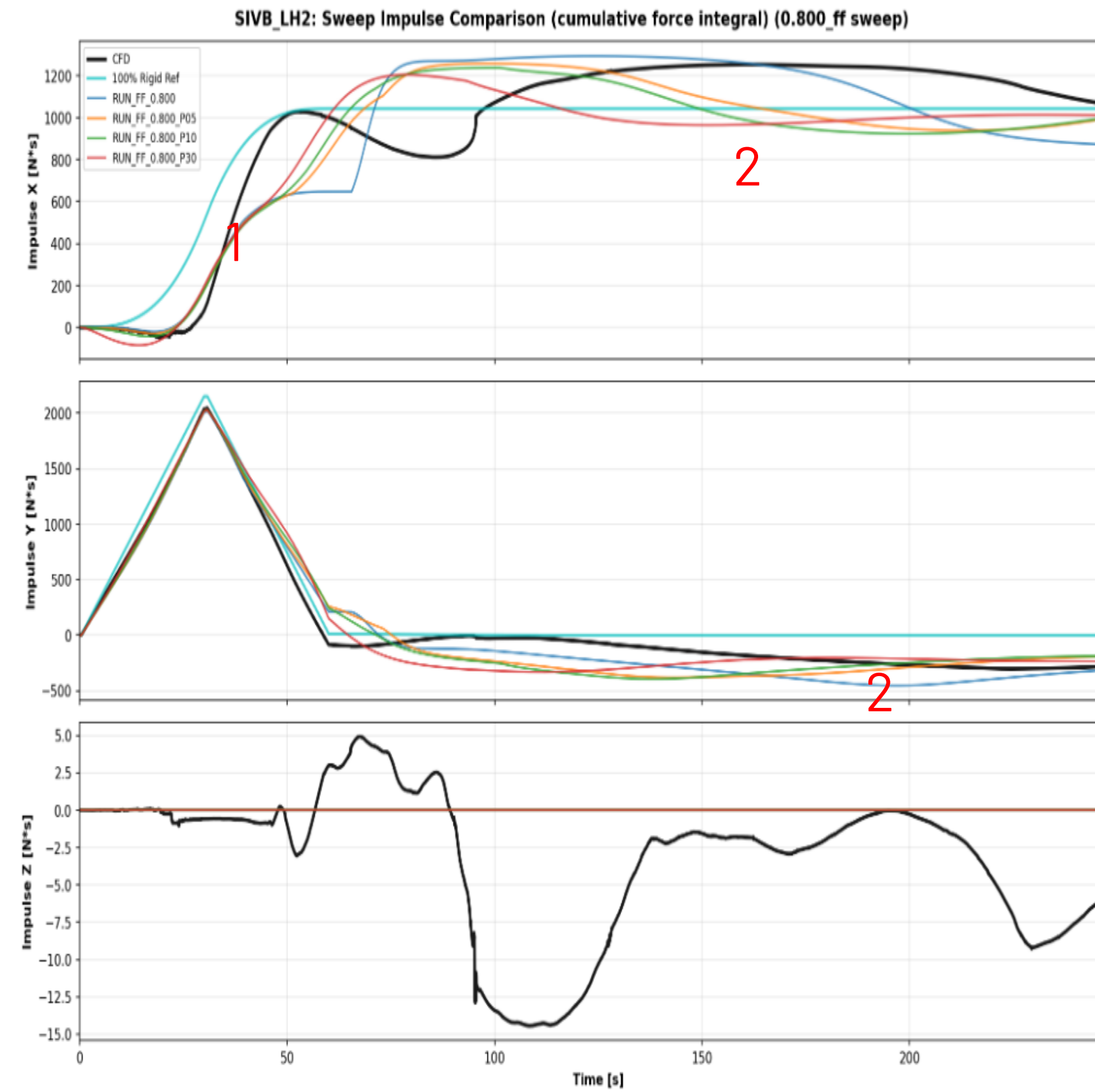
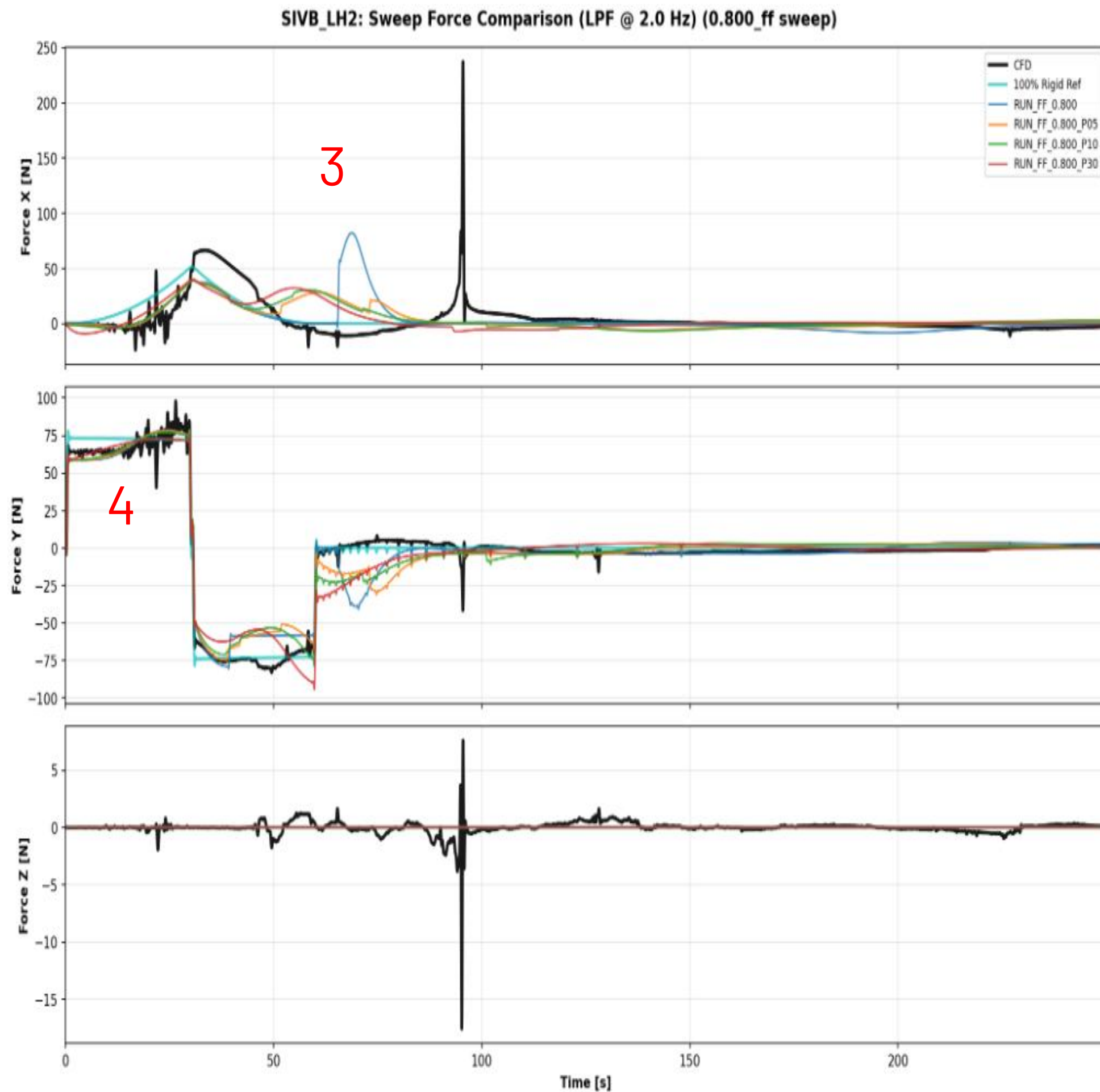
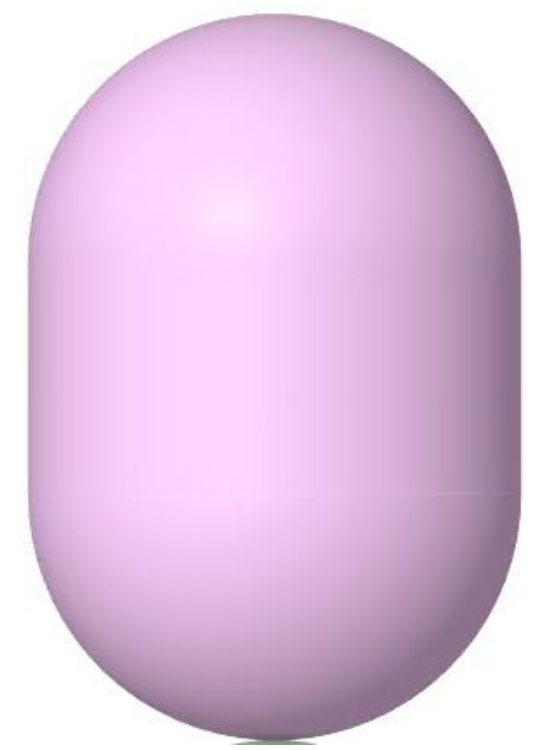
4. CFD predicts an almost rigid liquid response in the second half of the maneuver, in the Lox tank



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Saturn IVB CFD Comparisons

80% FF LH2

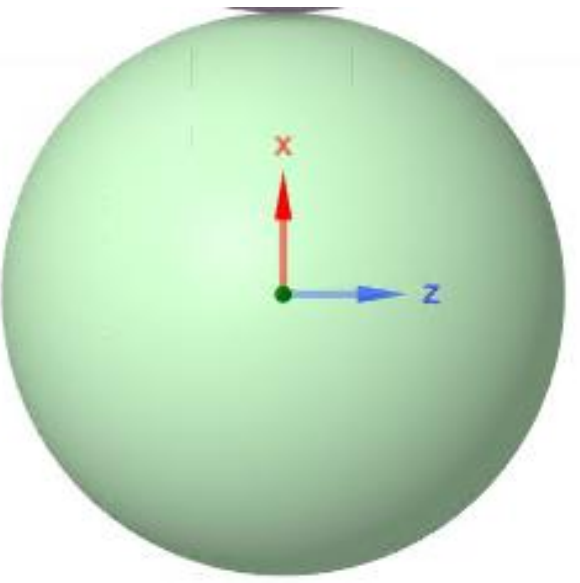


1. Initial impulse response matches CFD
2. Lateral impulse response magnitude matches CFD
3. Fluid particle is detaching from the free surface -> Adhesion modeling needed
4. Free particle mass is consistent with CFD

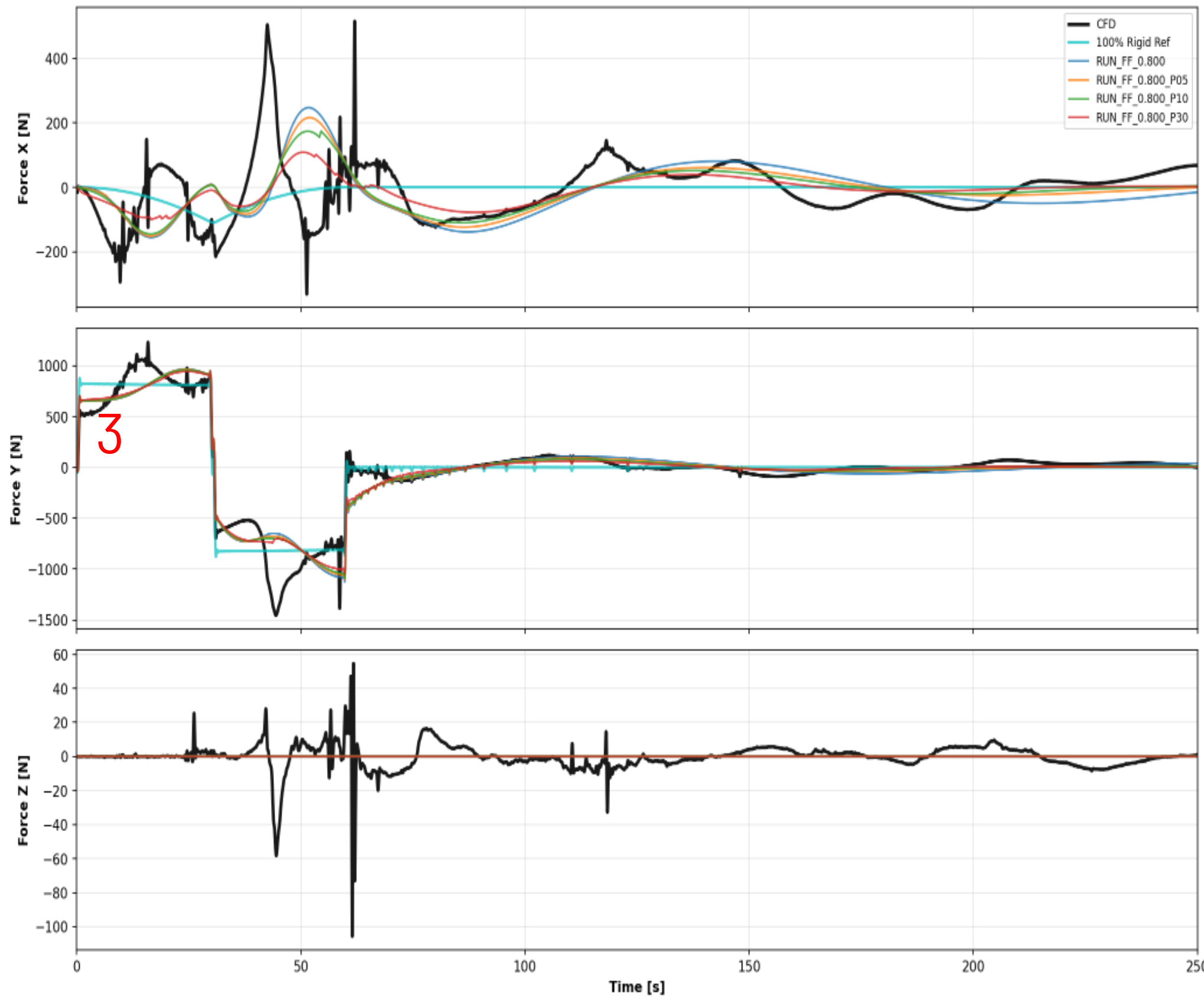
BLUE ORIGIN

Saturn IVB CFD Comparisons

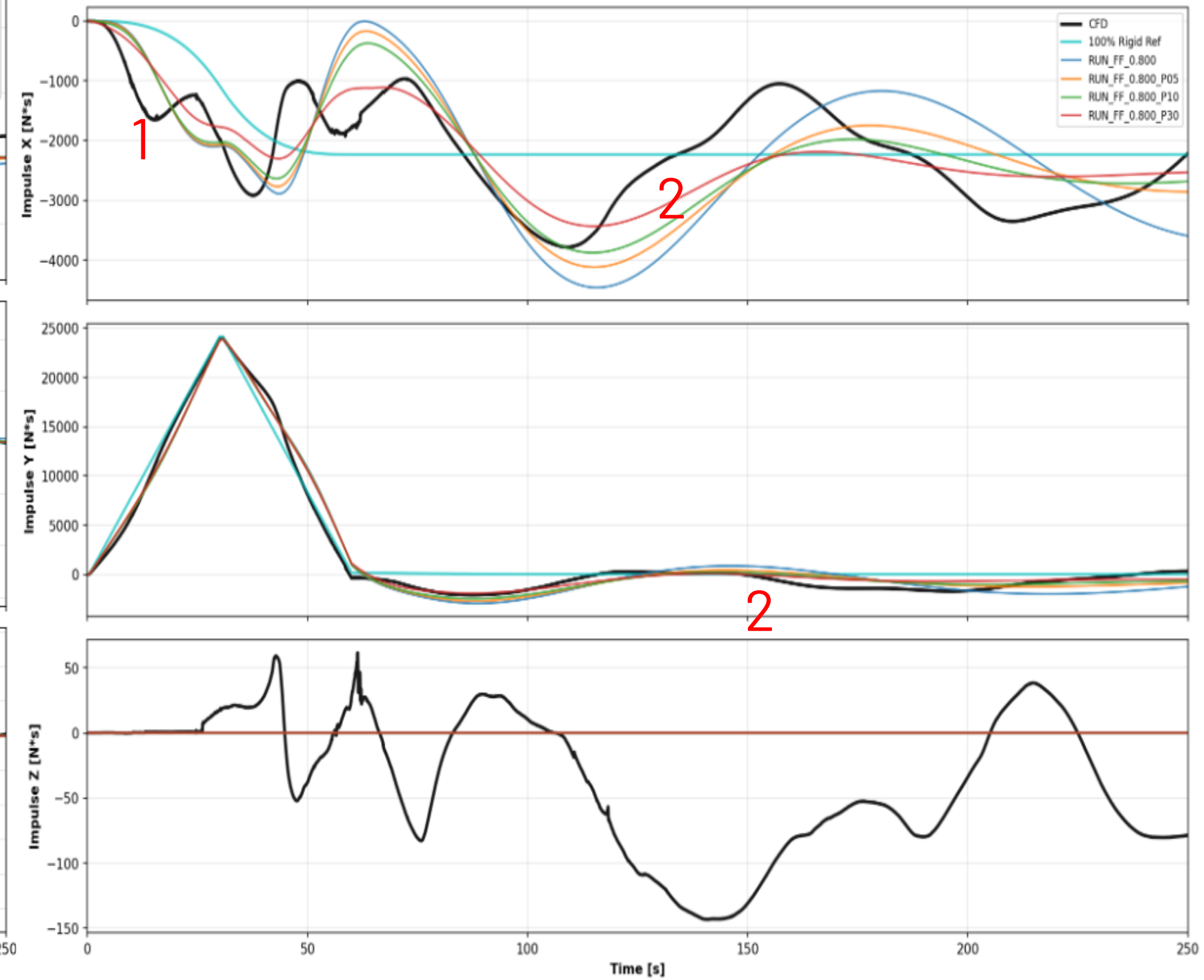
80% FF LOX



SIVB_LOX: Sweep Force Comparison (LPF @ 2.0 Hz) (0.800_ff sweep)



SIVB_LOX: Sweep Impulse Comparison (cumulative force integral) (0.800_ff sweep)



1. Initial impulse response better matches CFD
2. Impulse magnitude and phasing matches CFD
3. Slosh mass is close to CFD, but could be improved

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Conclusions and Forward Work

CONCLUSIONS

The fluid particle shows a definitive improvement over rigid modeling during and after the maneuver, for both LH2 and Lox tanks, across all fill fractions.

1. Force peak and direction
2. Impulse response peak, character, and quiescent values

Multi-particle simulations (1-10s) do not definitively increase fidelity in the current framework;

1. Peak force magnitudes are reduced, leading to less overconservative forcing
2. Better matching CG of the aggregate fluid does not greatly improve impulse response.
3. The benefit of multiple particles may be more pronounced in a pure roll maneuver (i.e. as in [4])

Adhesion modeling will likely improve force matching to CFD results

1. Not shown in the current work, but actively working

Scrubbing of current validation case inputs is required

1. Translational test case data sets should match better to published works

The single particle model roughly captures the major features associated with the CFD time history of forces, and offers a simple improvement over rigid body simulation.

References

1. Elke et al., "A Mechanical Slosh Model for On-Orbit Spacecraft Operations: Tuning and Comparison to CFD", AAS-26-067
2. Elke et al., "Implementation of a Slosh Mechanical Model During Spacecraft Approach and Docking", AAS-25-173
3. Timothy M Barrows, Jeb S. Orr, "Dynamics and Simulation of Flexible Rockets", 2020, 1st Edition
4. Good et al., "Stardust TCM and Despin in the Presence of Complex Fuel Dynamics", AAS 98-142

Questions and Thank You!

Avinash Vaidheeswaran

Liam Elke

Jed Storey

Jeb Orr

Jeff Brouwer



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FOR THE BENEFIT OF EARTH
