



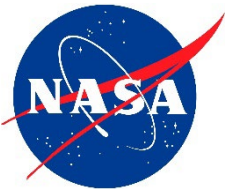
A Flexible Multibody Framework for Space Launch System Liftoff with Umbilical Separations

*2022 Spacecraft and Launch Vehicle
Dynamic Environments Workshop*

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Background

- ICPSU clearances to the lifting SLS vehicle were computed utilizing a coupled system nonlinear simulation approach in order to accurately capture the impact of system flexibilities, SLS forcing functions, pad separation (twang), ML dynamics and timings
 - i.e., integrate ICPSU model into a SLS nonlinear Coupled Loads Analysis (CLA)
- This required utilizing a flexible multibody framework for the CLA and the integration of large displacements/rotations capabilities into that CLA
 - Gantry rotation
 - Disconnect and retraction of flexible hoses

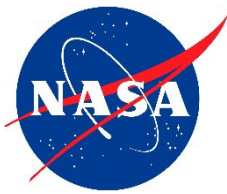


Interim Cryogenic Propulsion Stage Umbilical
(ICPSU)



SLS Liftoff Transient Multibody Nonlinear CLA Methods Overview

- **Multibody Dynamics Framework**
 - Enables robust computationally efficient inclusion of component-specific nonlinearities
- **Deformed Geometry Synthesis (DGS) algorithm**
 - Stacking and cryogenic shrinkage preloads initial conditions
- **Newton-Raphson algorithm**
 - Hydraulics (VSS struts)
- **Stiffness updating algorithm**
 - Geometric Nonlinearities/aft strut rotations
- **Henkel-Mar algorithm**
 - Pad Separation
 - Umbilical Separations
- **Precedence algorithm**
 - Pad Separation
- **Timed-separation algorithm**
 - VSS separation
- **Contact/Re-contact algorithm**
 - Pad Separation
 - Extensible columns/ML
 - Umbilical Separation
 - **Ground plate/net capture**
- **Damping**
 - Component Damping (Fully Coupled)
 - Hydraulic dampers
- **E-Points**
 - “Extra-Point” equations enables inclusion of physical DoFs not in Dynamic Math Model (DMM)
- **Rope (Nonlinear) Elements**
 - Nonlinear elements (large displacement/rotations) for modeling rope behavior for inclusion in multibody dynamics
- **Nonlinear Beam Elements**
 - Nonlinear elements (large displacements/rotations) for modeling hoses for inclusion in multibody dynamics
- **Catch-net**
 - Nonlinear model
- **Winch Motors**
 - Algorithm for simulating motor reeling in lanyard rope elements
 - Back-drive capability
- **Gantry Rotation**
 - Flex-body quaternion driven; rotation rates from test



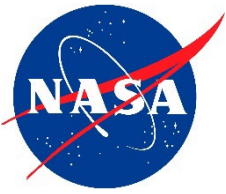
Analysis Steps (1/2)

1. **Input data familiarization**
 - a. ICPSU System, ICDs, reports, data
 - b. ML FRAC (VAB and Liftoff Configuration FEMs)
 - c. Updated CS FRAC FEM
 - d. Model checks
 - e. Review and implementation of Interface Control Documents (ICDs), report data, and Microsoft Excel data sheets
2. **DMM generation**
 - a. Generation of residual flexibility mixed-boundary (RFMB) ML DMMs
 - b. Generation of RFMB CS DMM
3. **Booster stacking analysis (DGS algs)**
 - a. Coupled boosters inclusive of VSP leveling and spacing effects
 - b. Coupled boosters inclusive of VSP leveling, spacing, and shimming effects
4. **CS stacking analysis (DGS algs)**
 - a. Simulation of the CS hanging and rotation on the FA
 - b. Couple in diagonal struts
 - c. Compute upper and lower strut unstressed lengths
5. **US stacking analysis**
 - a. Stack LVSA, ICPS, MSA, and MPCV DMMs
6. **Extensible Columns Preloads (DGS algs)**
 - a. Enforce extensible columns preloads using contact/separation methodology
 - b. Check preload adequacy (e.g., static nonlinear CLA)
7. **Cryogenic shrinkage (e.g., axial + thermal radial data) (DGS algs)**
 - a. Compute load indicators inclusive of preloads for the CS axial shrinkage (e.g., ~5 inches) + delta axial shrinkage + radial shrinkage from thermal analysis for the hot and cold ambient temperature conditions



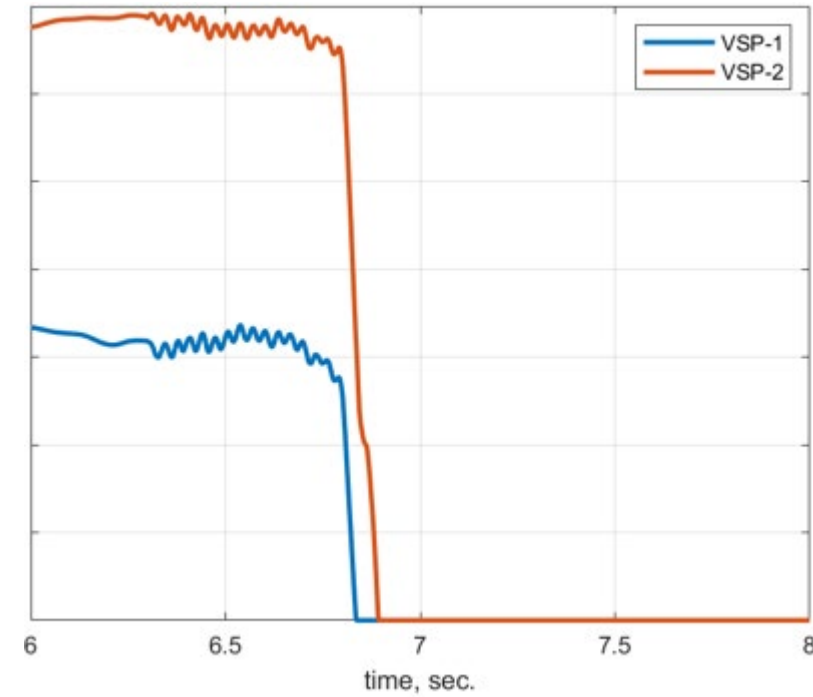
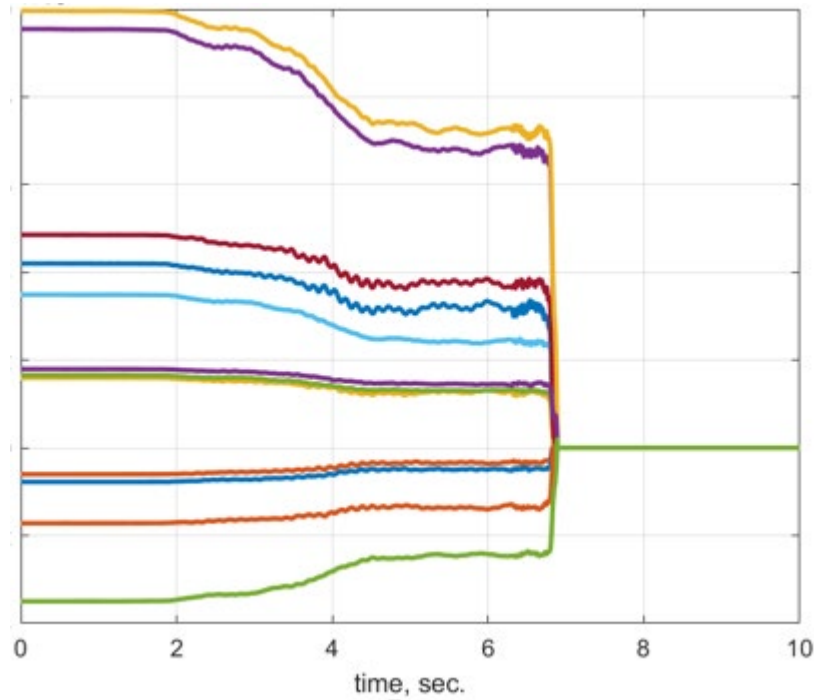
Analysis Steps (2/2)

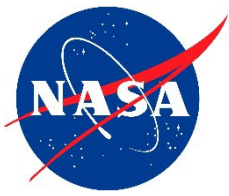
8. **Coupling of CS Umbilicals + related nonlinear separation (Henkel-Mar) algorithms**
 - a. TSMU LOX
 - b. TSMU LH2
 - c. CSITU
 - d. CSFSU
 - e. VSS
9. **Execute Multibody CLA**
 - a. Preloads and Pad release twang response checkouts
10. **Add E-Points for ICPSU DMM umbilical interface locations**
 - a. Run checkouts
11. **Generated LVSA RFMB DMM with LVSA umbilical interface locations**
 - a. Run checkouts
12. **Build ICPSU local models and algs** (winch, pulley, lanyard, hose, catch net)
 - a. Fwd GP
 - b. Aft GP
 - c. Pu1Pu2
 - d. LVSA
13. **Incorporate ICPSU local models and algs into multibody CLA**
 - a. Fwd GP
 - b. Aft GP
 - c. Pu1Pu2
 - d. LVSA
14. **Execute Multibody CLA**
 - a. Run full multibody CLA
 - All FFs + Zero wind
 - All FFs + Z wind
 - All FFs + Z wind + Z gust
 - All FFs with - Z wind
 - All FFs with -Z wind and - Z gust
 - b. Iterate on gust timing to achieve ~ worst case
 - c. Extract ICPSU umbilical disconnect forces
 - d. Extract lanyard tensions
 - e. Assess ICPSU/Vehicle clearances



Liftoff Pad Separation Transient Forces

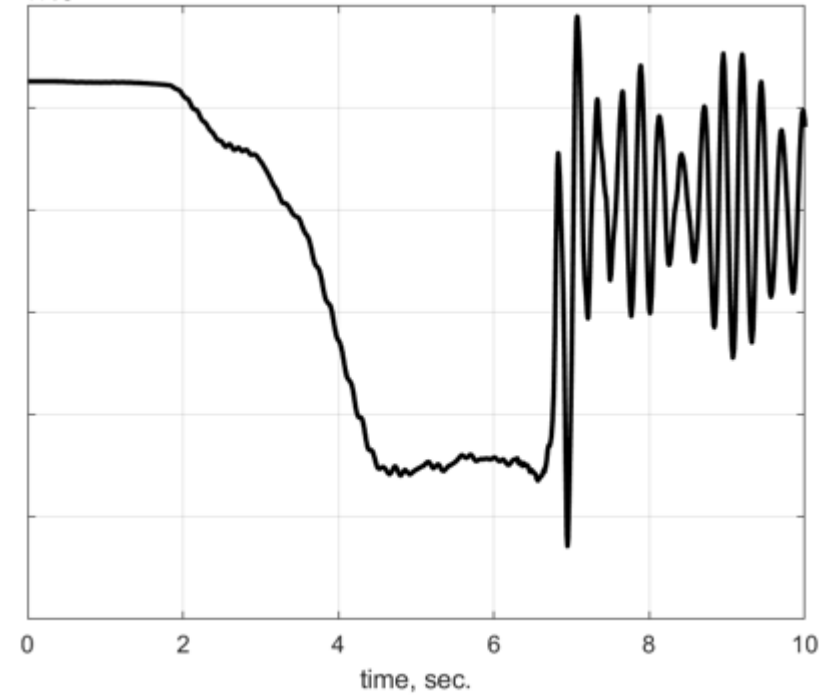
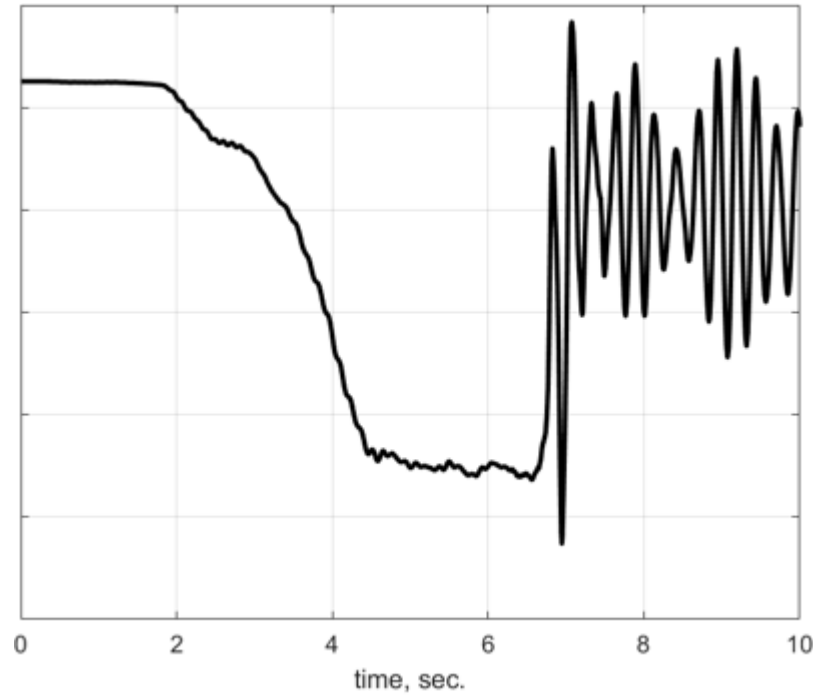
Henkel Mar Pad Sep / Release of Strain Energy and Preloads

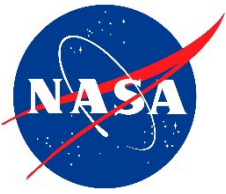




CS FWD Attach

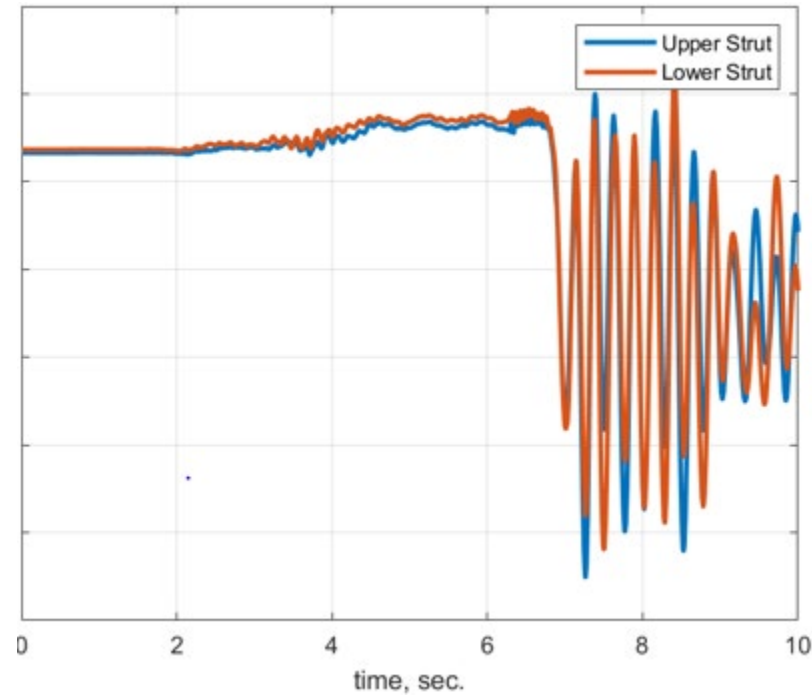
Booster Pressurization and Pad Separation “Twang”

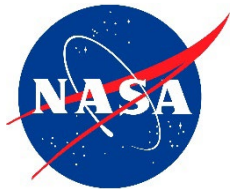




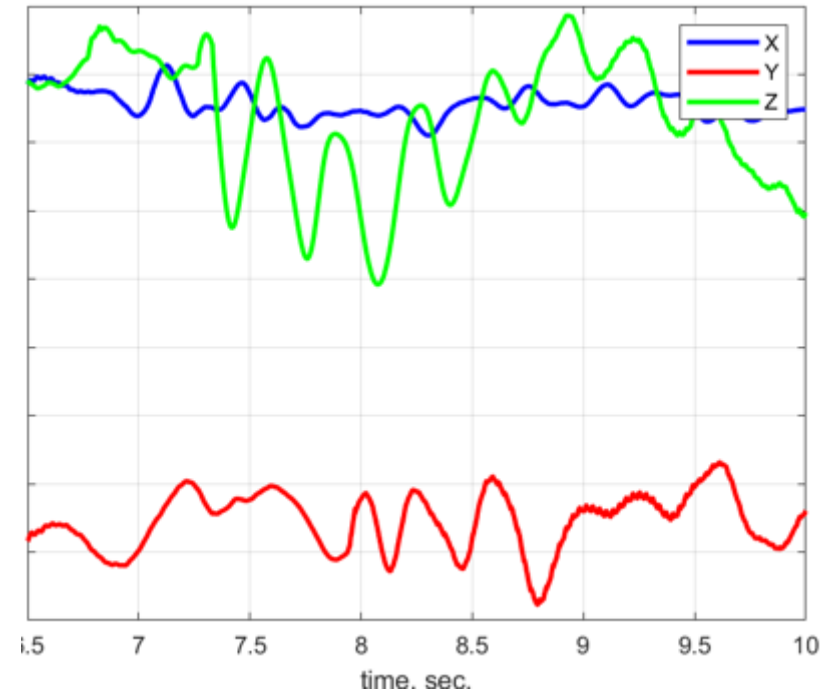
CS/Booster Aft Struts

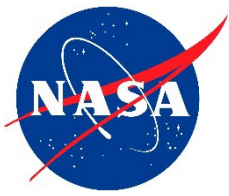
Preloads and Pad Separation Twang



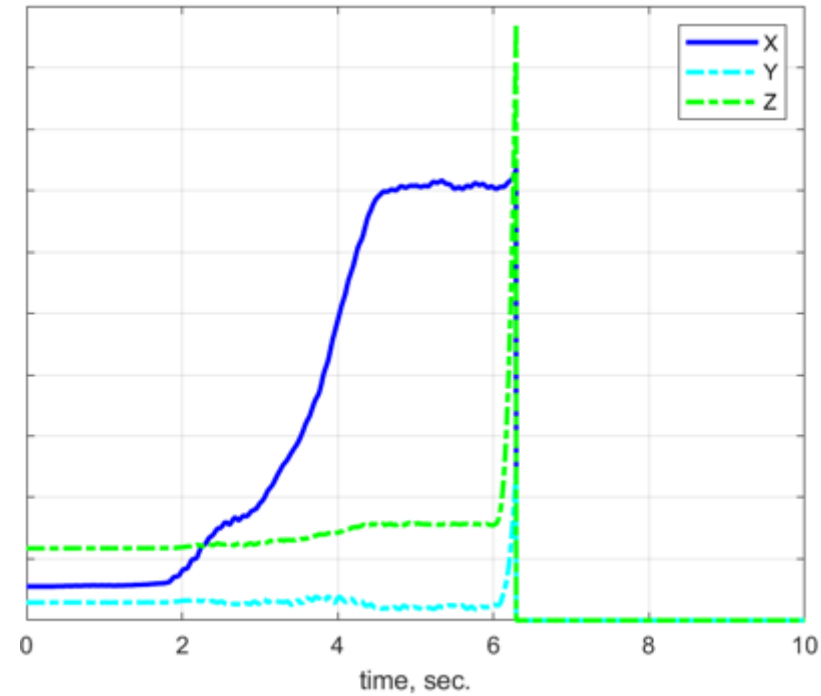


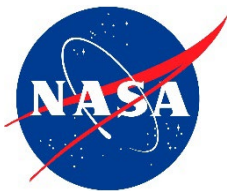
ML Gantry





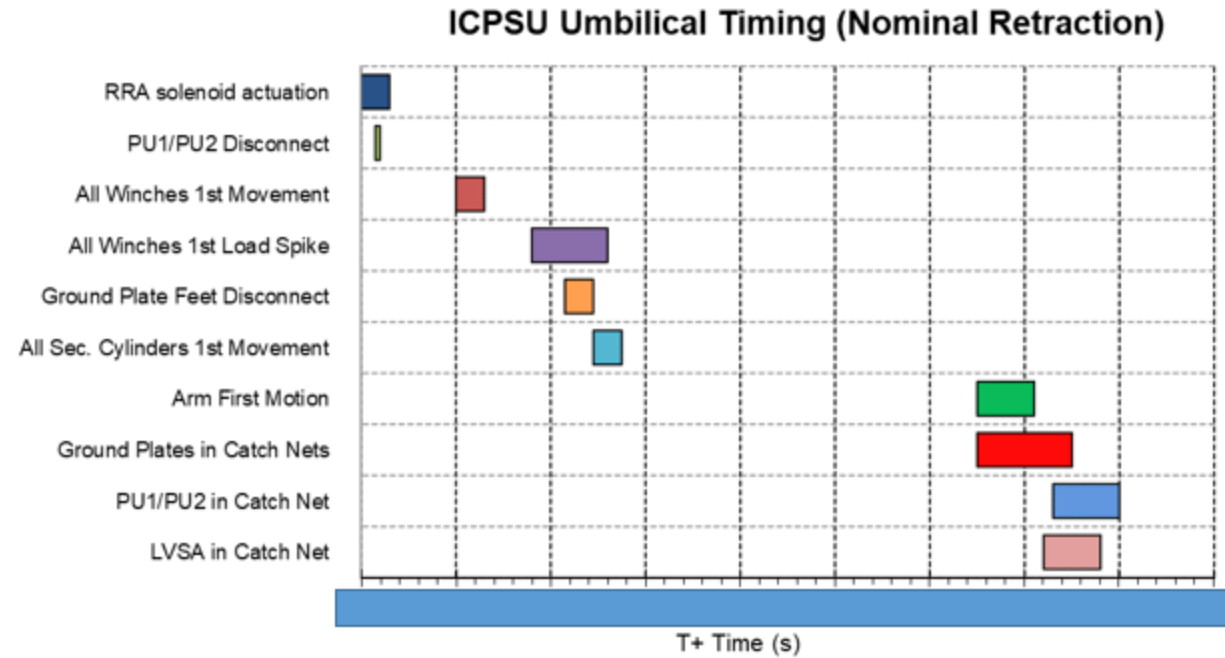
TSMU Secondary Disconnect

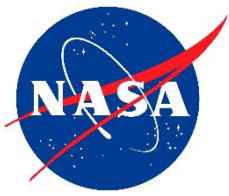




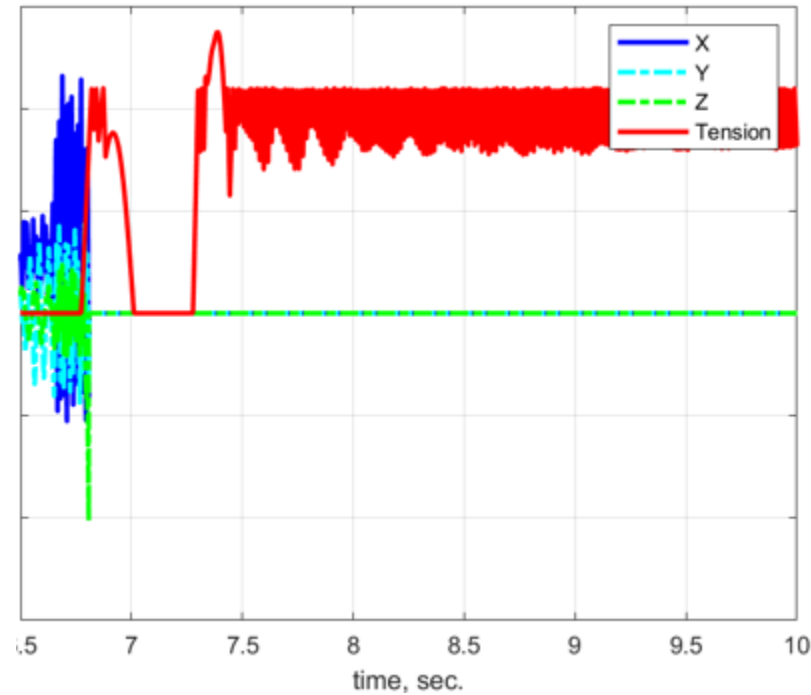
ICPSU Umbilical Timing (Nominal Retraction)

ICPSU Retract Timing (Primary Retraction)		
	Start Time	End Time
RRA solenoid actuation		
PU1/PU2 Disconnect		
All Winches 1st Movement		
All Winches 1st Load Spike		
Ground Plate Feet Disconnect		
All Sec. Cylinders 1st Movement		
Arm First Motion		
Ground Plates in Catch Nets		
PU1/PU2 in Catch Net		
LVSA in Catch Net		



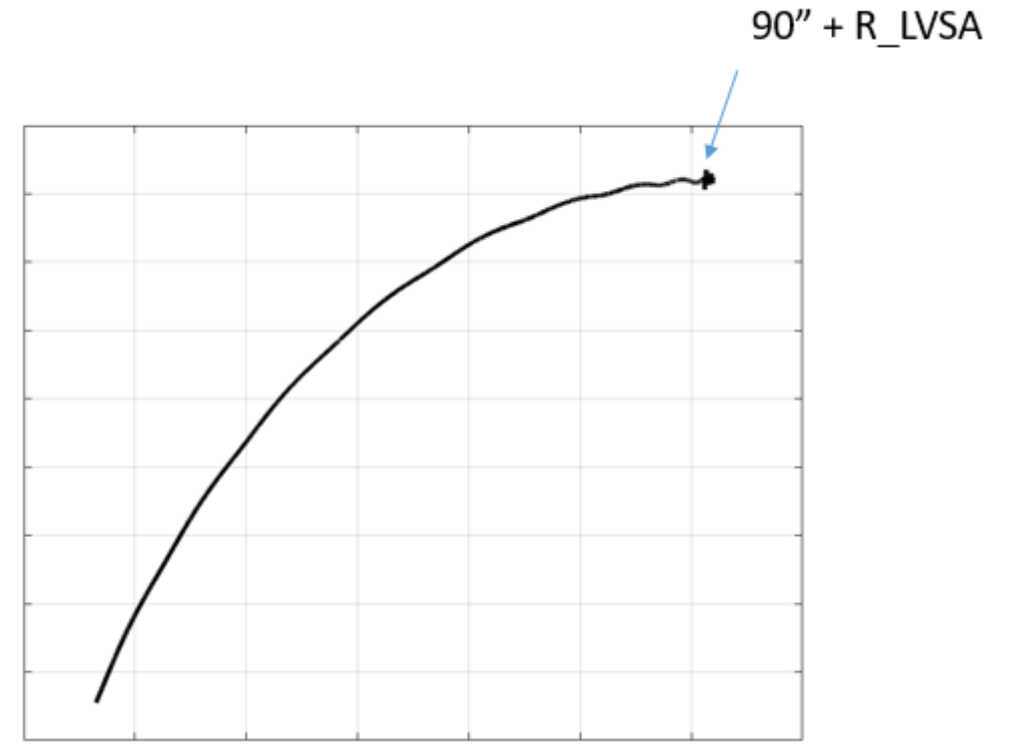
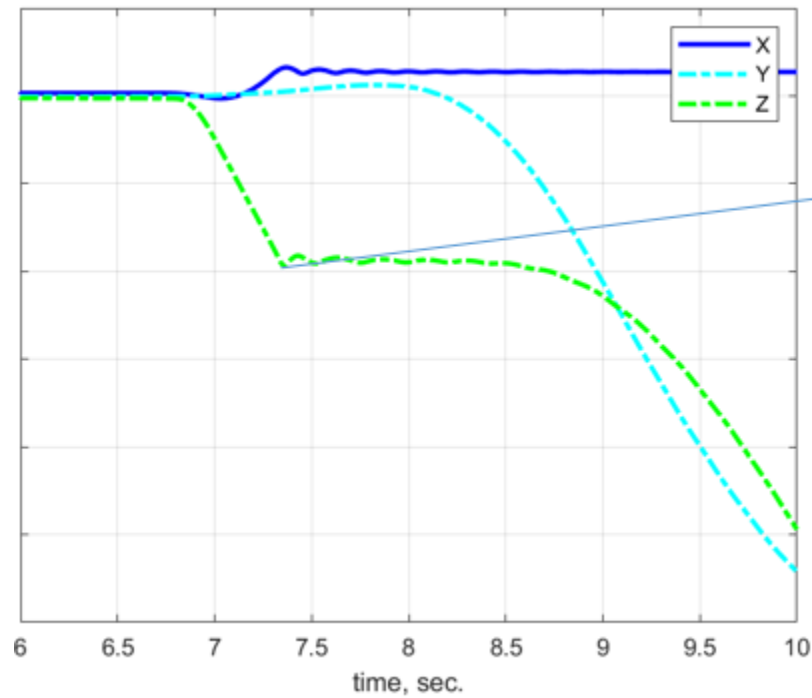


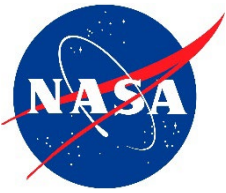
Aft GP Disconnect Interface Forces and Winch Lanyard Tension



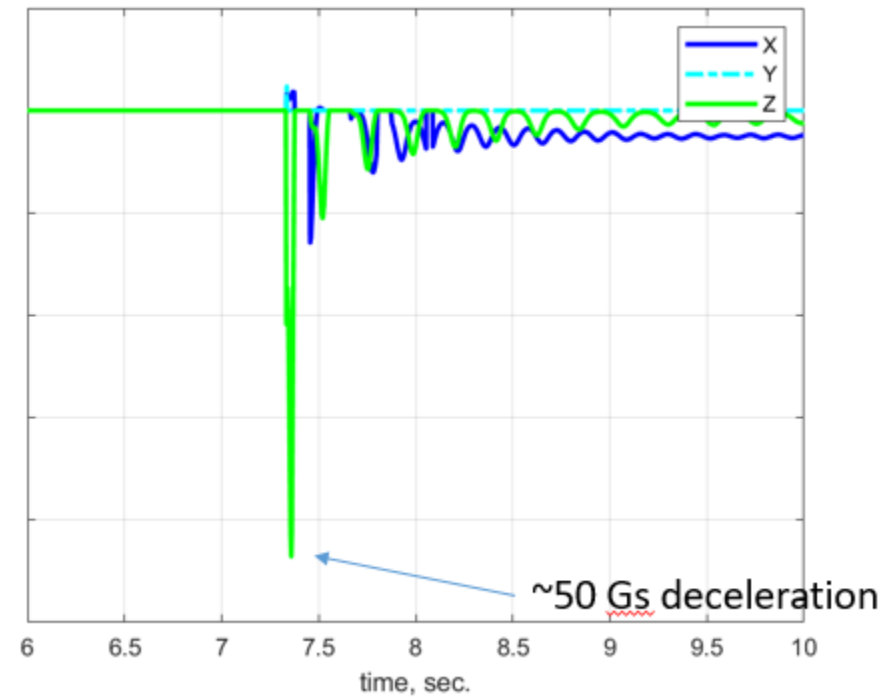


Aft GP Trajectory

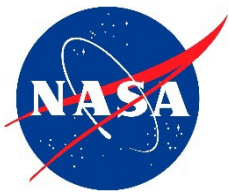




Aft GP/Catch-net Contact Forces

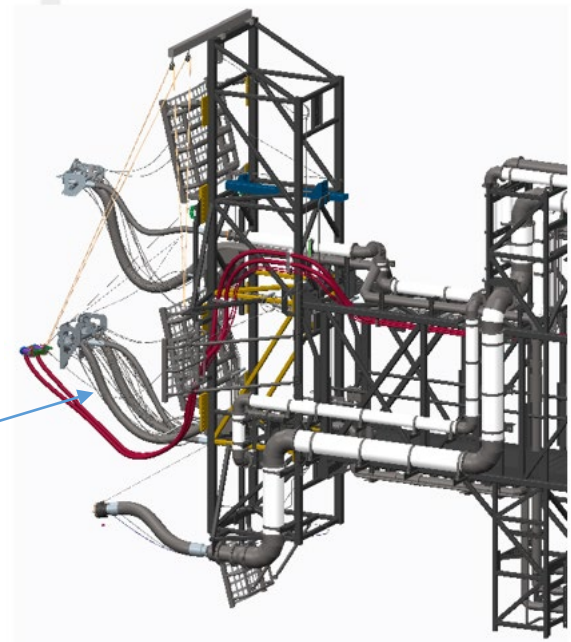


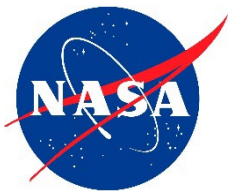
Nonlinear contact model of
Catch-net



Aft LH2 F/D Cryo Hose

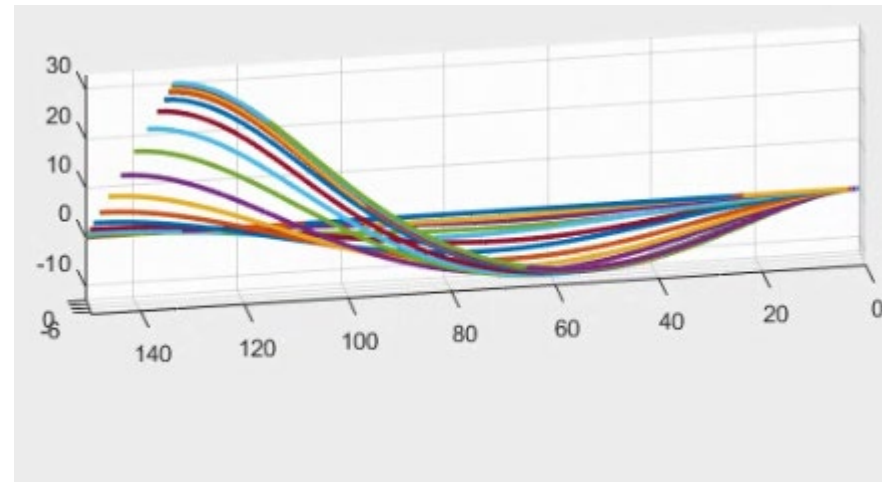
NOMINAL



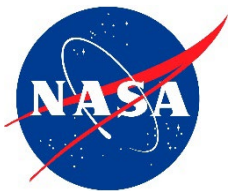


Aft LH2 F/D Hose

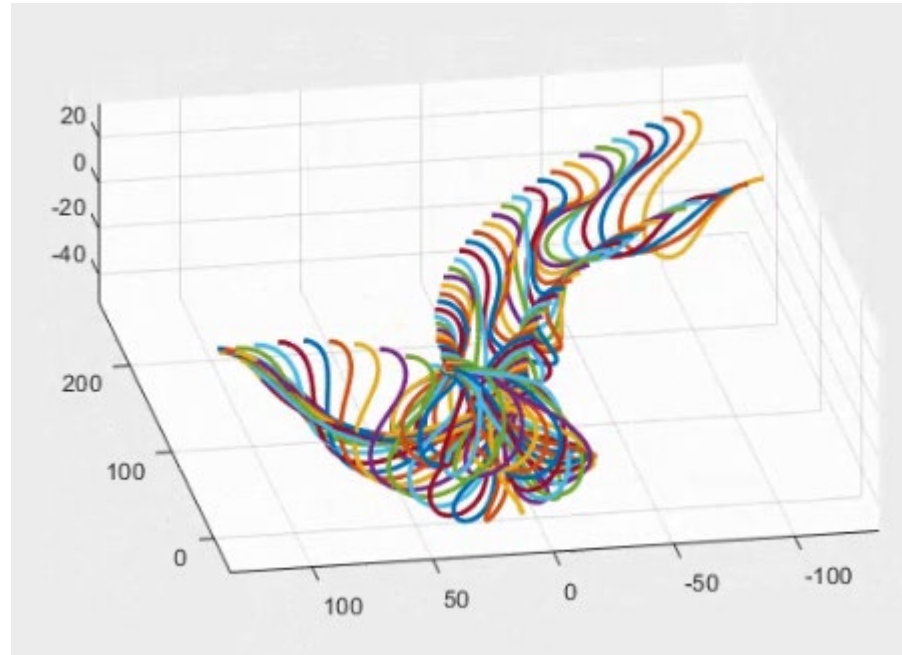
Buildup to Initial Configuration



Extracted from nonlinear CLA
All dimensions in inches

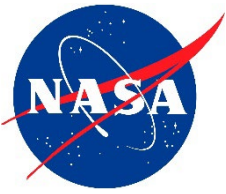


Aft LH2 F/D Hose Dynamics

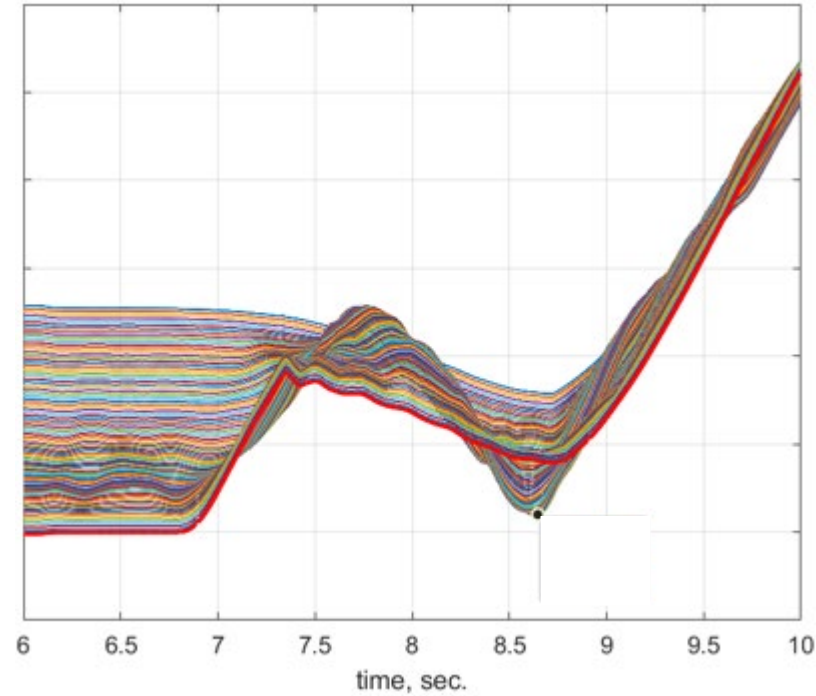


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Extracted from nonlinear CLA
All dimensions in inches



Aft LH2 F/D Hose Clearance

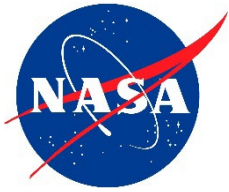


Tracking 100 locations along the hose

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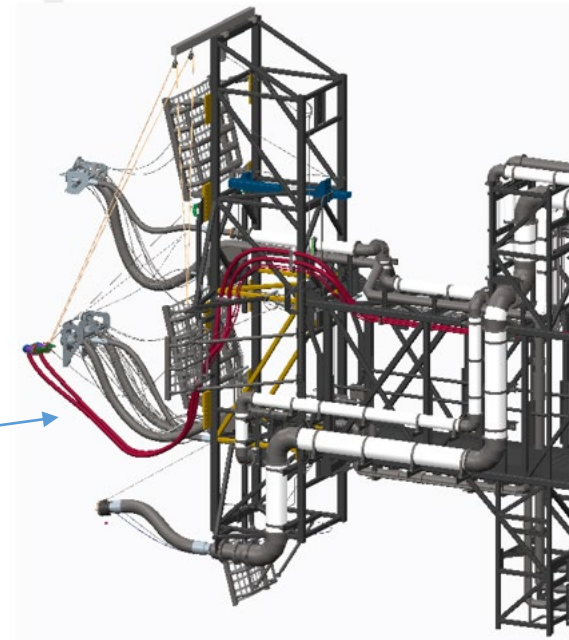
red is the trajectory of GP

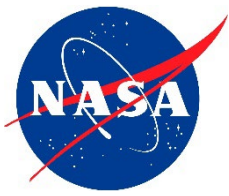
All clearance calculations relative to the
CL of the hose (radius needs to be added)



PU1 Cable

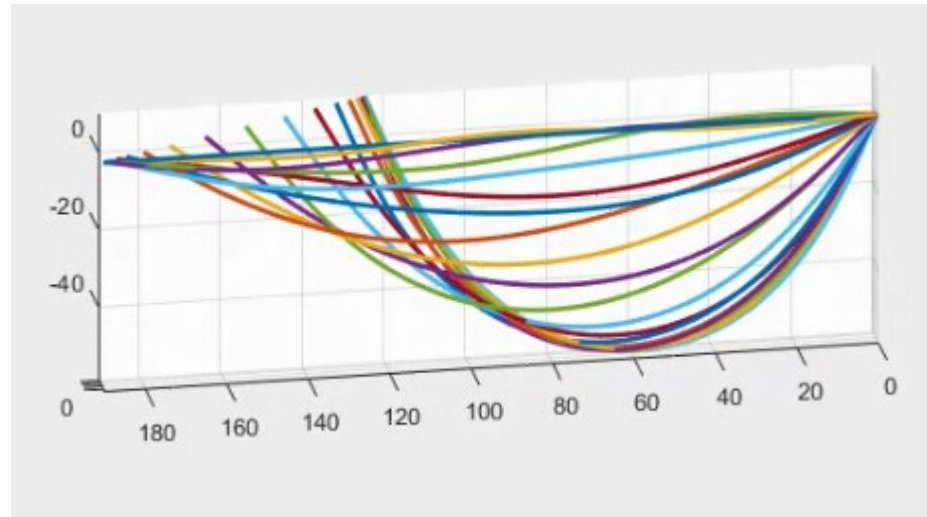
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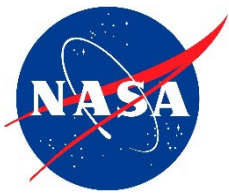


PU1 Cable

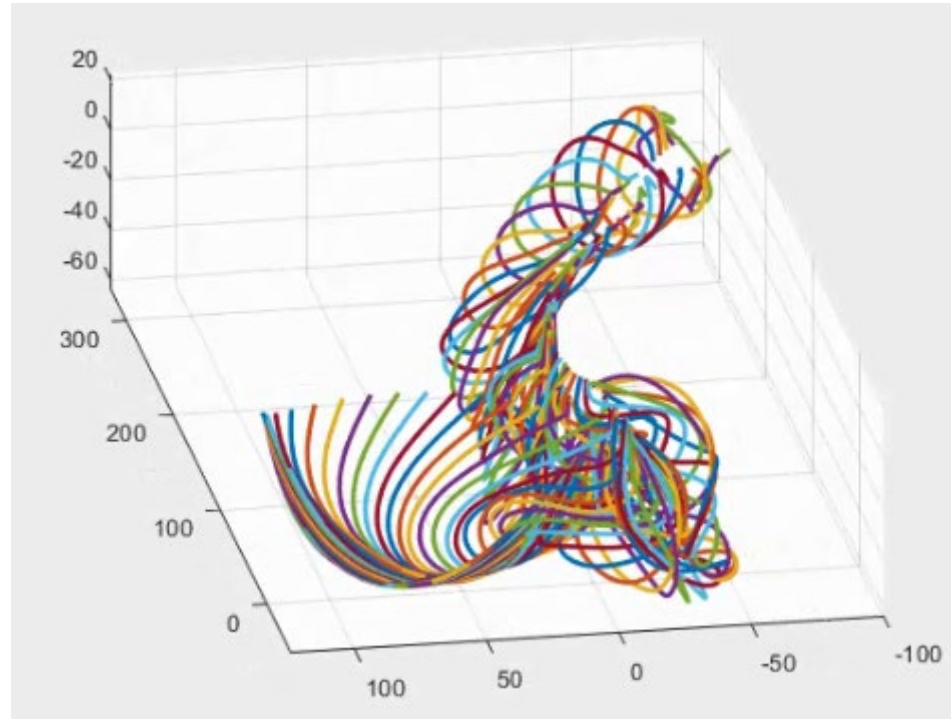
Buildup to Initial Configuration



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All dimensions in inches

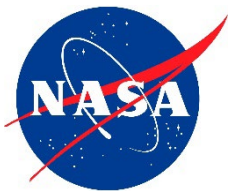


PU1 Cable Dynamics

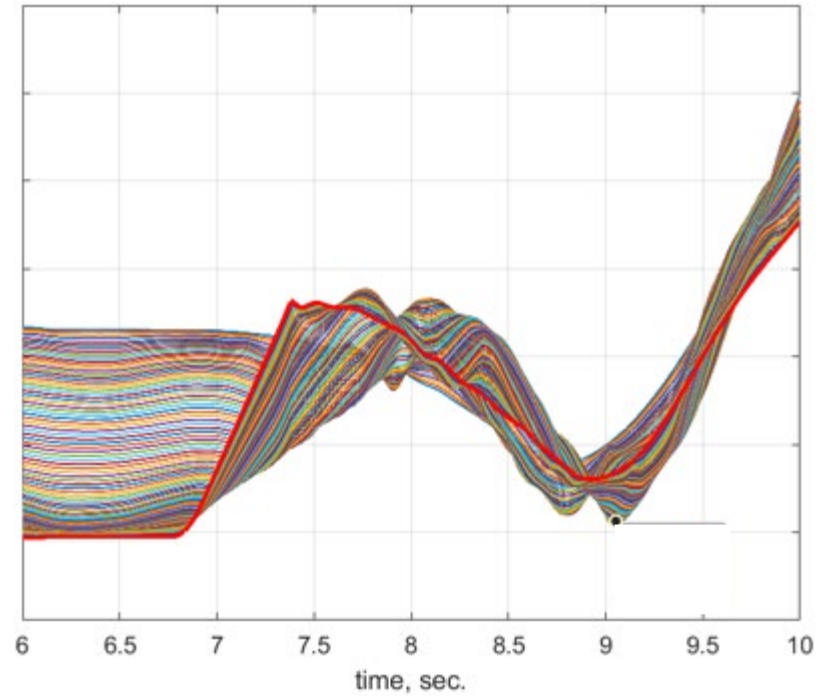


NOMINAL

Extracted from nonlinear CLA
All dimensions in inches

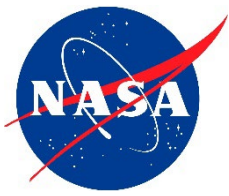


PU1 Cable Clearance



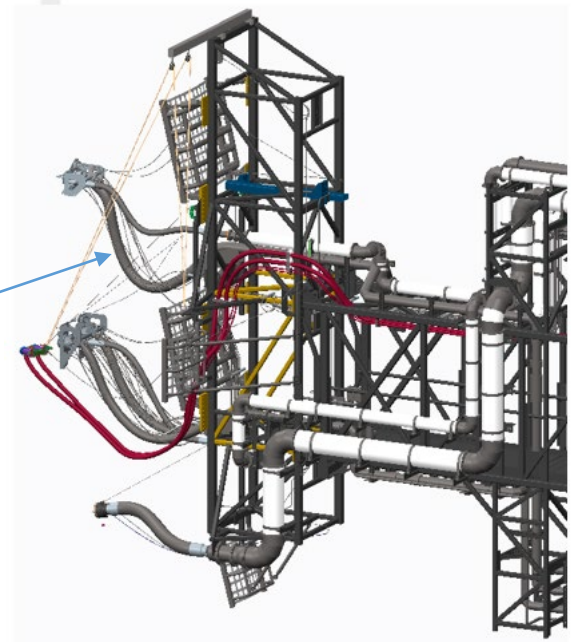
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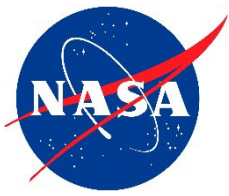
red is the trajectory of GP



Fwd Vent Cryo Hose

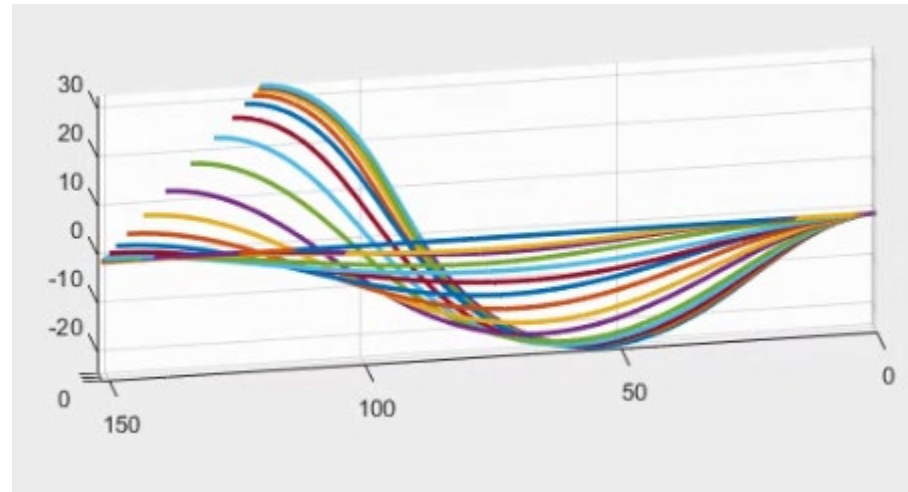
Nominal



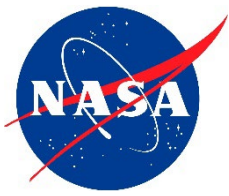


Fwd Vent Cryo Hose

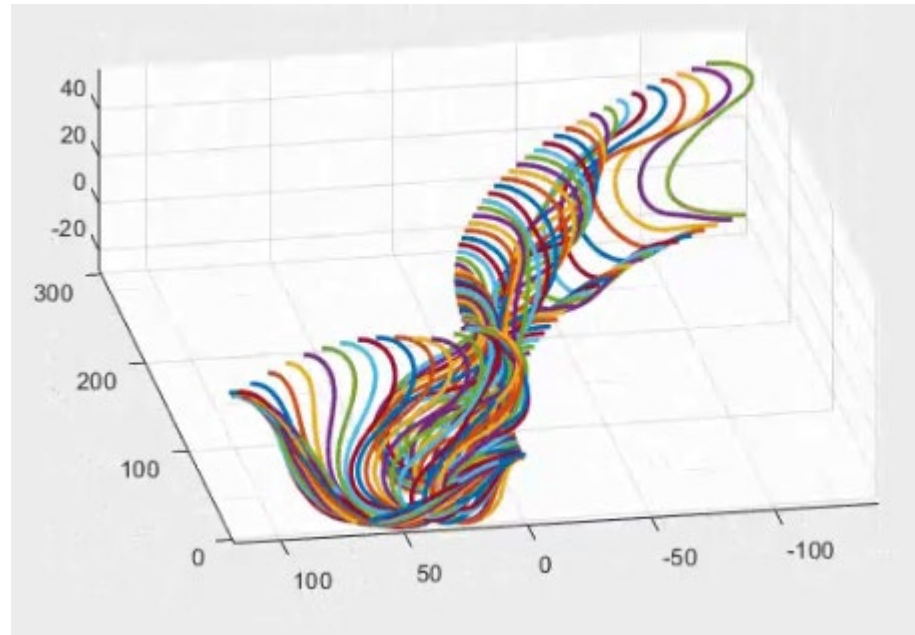
Buildup to Initial Configuration



Extracted from nonlinear CLA
All dimensions in inches

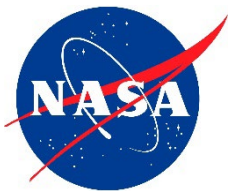


Fwd Vent Cryo Dynamics

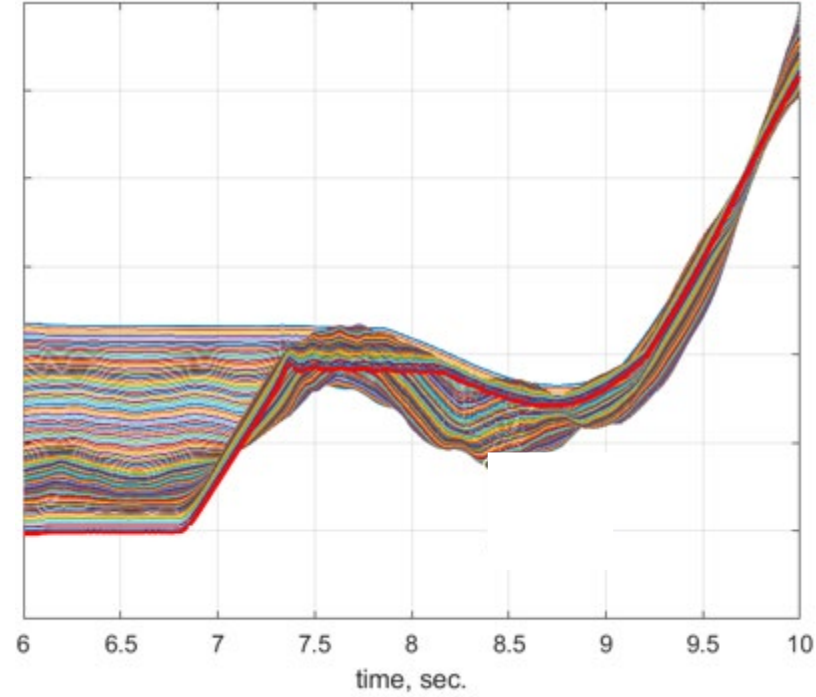


NOMINAL

Extracted from nonlinear CLA
All dimensions in inches

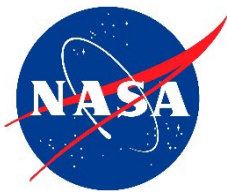


Fwd Vent Cryo Clearance



NOMINAL

red is the trajectory of GP



Concluding Remarks

- A flexible multibody framework for SLS CLAs has been established verified
- Key benefits of this nonlinear CLA framework include
 - Solver algorithms designed to handle component nonlinearities without affecting overall system computational performance
 - Fast computation speeds enabling sensitivity and risk reduction studies
- The multibody CLA capability includes large displacements/rotations of highly nonlinear components such as umbilical hoses
- This particular CLA included high resolution simulation of the ICPSU umbilical disconnect, retraction, capture, and gantry rotation with complete tracking of 100 locations along each hose (for vehicle clearance assessments) all within a complete SLS liftoff pad separation
 - Dynamics/flexibilities of the SLS and ML acted upon by the SLS forcing functions



LETF Testing

