Artemis I Booster Push/Pull Pretest Analysis:
Impact Deformed Geometry Synthesis and Nonlinearities

2022 Spacecraft and Launch Vehicle Dynamic Environments Workshop

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Background I

- The Artemis I booster pull test evolved from a continuous re-evaluation of the Artemis I dynamic building block test program.
- The original Artemis I building block test program included a partial stack modal test (PSMT) that served as a pre-cursor to the integrated modal test (IMT), which sought to gather system response data of the integrated SLS system mounted to the ML at eight VSPs.
- With the removal of the PSMT, it was still recognized that characterization of the booster to the ML interface was critical to informing the analytical models. This realization gave rise to the booster pull test to provide needed information prior to the IMT.
- The IMT represents a convergence of civil structure, in the form of the ML, and aerospace structure, in the form of the SLS system, with the ML serving as the test fixture for the IMT
- This system of system tests represents a new paradigm in testing and departs from the more traditional modal testing where you minimize any interactions between the test fixture and the article under test.

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Background II

- The original objective of the Booster Pull Test was to “Determine the stiffness of ML/Haunches/VSP and SRB aft structures in both the Y and Z directions” by pulling on the left Booster in the Y-Axis and Z-Axis directions [1].
  - These models must accurately capture the stiffness of the Vehicle Support Posts (VSPs), ML Deck, Aft Skirt, Booster casing, etc.
- The Booster Pull Test then was expanded to include manually pushing on the left Booster to excite its fundamental lateral bending modes in the in the Y-Axis and Z-Axis directions and collecting free decay data from which modal parameters could be extracted. This was then referred to as the Booster Push/Pull Test (BPPT).
- The BPPT was performed in the Vehicle Assembly Building (VAB) at Kennedy Space Center (KSC) on March 24^{th} – 26^{th}.

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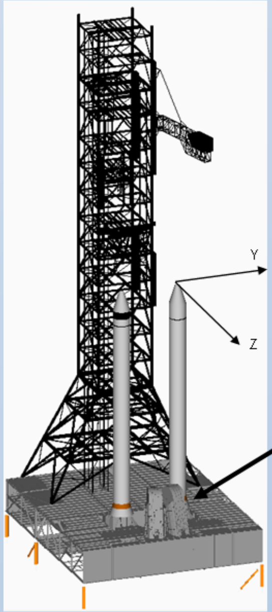
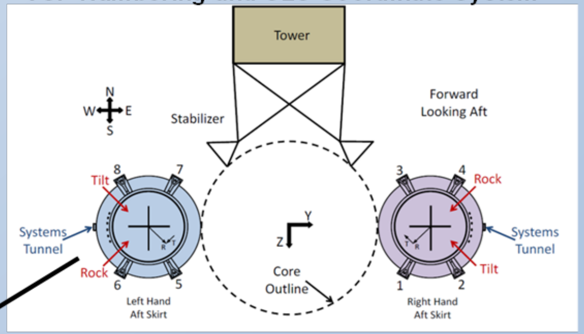
Booster Pull Test Overview

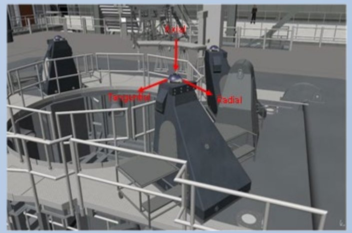
- The main objectives is to obtain lateral deflections (i.e., displacements) in two orthogonal directions
- This will be accomplished by applying applied loads near the top of the booster and recording deflection data at five separate distributed locations along the length of the booster
- The rationale for collecting data in two orthogonal directions is that the interface between the booster and the ML is asymmetric
  - As a result of this geometric feature, one has a strong axis and a weak axis to measure to determine coupling stiffness. An attempt will also be made to record strain from strain gauges located on each VSP
- A Booster push test that is synonymous to a sine dwell test followed by a free decay will be performed to characterize the Booster cantilever bending mode and obtain 10 minutes of frequency and damping data from the decay on the Booster



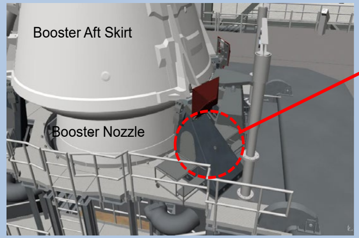
VSP Numbering and SLS Coordinate System

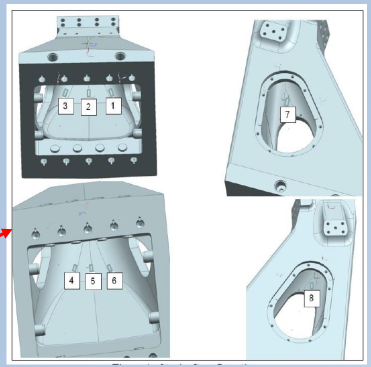


VSPs on Mobile Launcher



Booster on VSP





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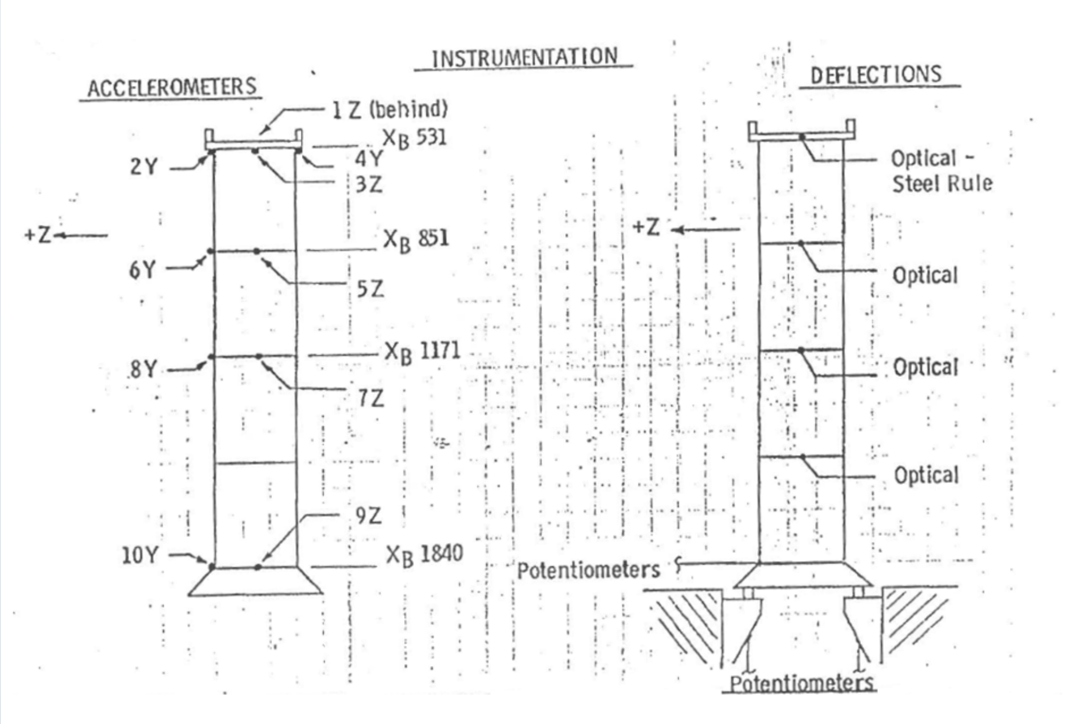
Historical Perspective

- Similar test occurred in 1979 using an inert booster mounted to the Shuttle era Mobile Launcher Platform (MLP)
- Necessity for this test was driven by concerns regarding Shuttle umbilical capabilities
- Objectives for this test were to measure the stiffness and determine the frequency of the first pitch bending mode of the combined booster and MLP
- Results from this proved to be important as it indicated that the actual hardware was on the order 10% stiffer than the FEM predictions
- Post-test, it was determined that for this cases the cantilevered mode structural stiffness characteristics were more sensitive to the booster stiffness rather than the MLP stiffness



What is Deformed Geometry Synthesis (DGS)?

- Component-modal synthesis (CMS) couples dynamic math models (DMMs) in their undeformed (FEM) geometry state
- Deformed Geometry Synthesis (DGS) couples DMMs in their deformed geometry states "locking in" preloads in an accurate/physically realizable manner
- In the subject SLS Prelaunch and CLA work, DGS is utilized to simulate:
  - ML VSPs leveling/Spacing while ML is in 1G deformed state
  - ML VSP X-shims for booster toe-in and CS integration
  - CS integration soaking-up the toe-in resulting in pre-loads that increase out-board VSP X-IFFs
  - Booster/CS aft strut integration
  - CS fueling cryogenic shrinkage and aft strut rotations

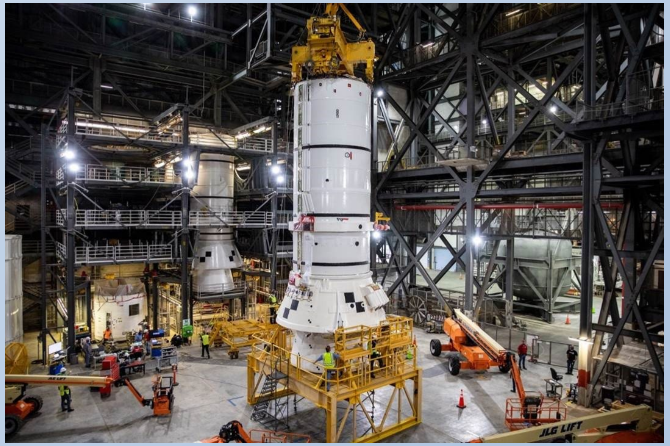
BPPT (first two items)

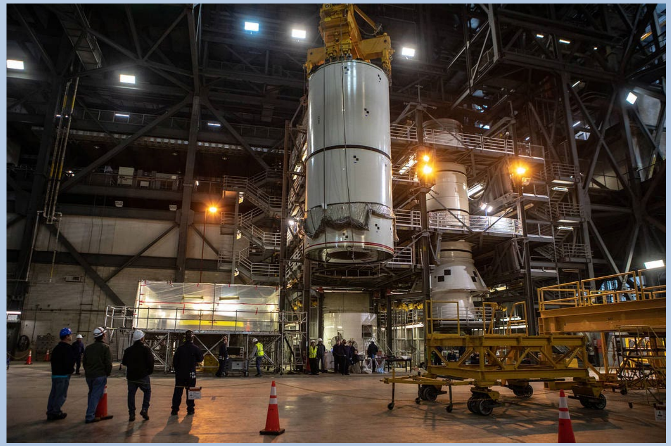
SLS Prelaunch and CS fueling (last four items)

- Finally, DGS works seamlessly with the SLS multibody CLA framework and Henkel-Mar pad separation method to automatically relieve these locked-in preloads as the SLS undergoes pad separation, contributing to the liftoff pad separation "twang"

Exploring the Effects of Stacking Parameters

- First characterize the interface flexibility between the booster aft skirt and the ML VSP
  - Critical to understanding the influence of each side of the interface to the coupled system
- Next steps are to methodically evaluate the effect of the following on the test outcome:
  - Effects of gravity (1-g) acting on both the booster and ML and the effects that booster stacking has on the system
- Each booster is comprised of multiple segments and these segments are assembled onto the ML with requirements to level, space, and shim to meet tolerance requirements
  - Effects are captured using a Deformed Geometry Synthesis (DGS) approach.
- Determine the geometric nonlinear effects due lateral displacements as booster is pulled to maximum load
- Further, system coupling between the booster under test, ML, and the second booster is explored when subjected to dynamic transient inputs





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Approach Selection

- The approach selected for the BPPT analyses includes a method (Deformed Geometry Synthesis (DGS)) for enforcing the ML 1-G deformed geometry state while preserving VSP leveling and spacing. With this, the ML is in its true “bowed” 1-G stress state prior to booster coupling with the VSPs leveled and spaced.
  - Includes DGS to incorporate VSP X-shims to enforce toe-in.
- The selected approach includes geometric nonlinear effects to capture delta increases in lateral displacements and over-turning moments which manifest to re-distribute ML/Booster interface forces (IFF)s.
- For comparison, an alternate approach for the BPPT analyses is to enforce ML 0-G since the VSPs are leveled and spaced in the undeformed FEM.
  - The ML is in a “zero-stress” un-bowed state prior to booster coupling.

Booster Aft Skirt to ML VSP Interface Flexibility

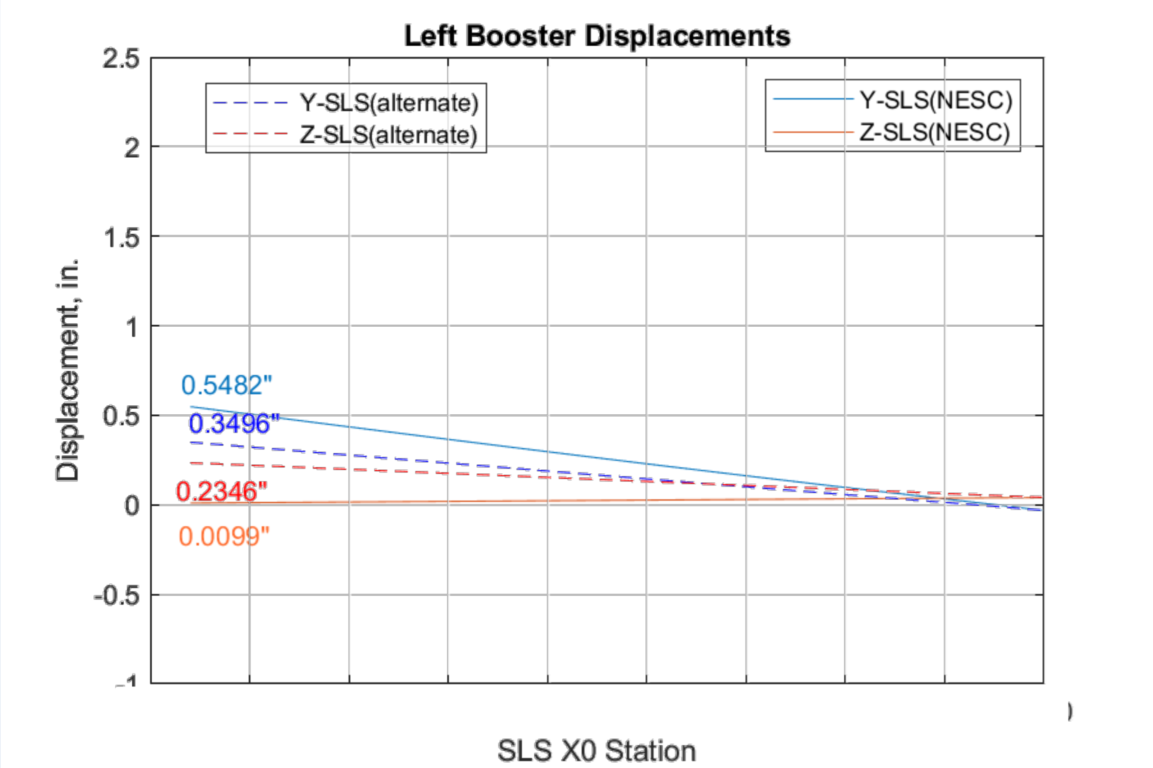
- Sensitivity analyses serve to inform what flexibility exists between the ML side of the interfaces and the booster aft skirts
- Results indicate that the aft skirt side stiffness is less that the ML interface stiffness at the VSP interface
  - This exercise is confirming of the conclusions from the 1979 testing
- This is an important result as it indicates that accurate capture of aft skirt flexibilities during the pull test is critical to updating the booster aft skirt region of the stacked ML/SLS system
  - This in turn is important as this interface has an impact on stacking preloads and SLS/ML liftoff separation
- Further sensitivity studies pursued understanding the aft skirt modeling to understand the local stiffness effects
  - To determine the element member membrane displacement field sensitivity, the CQUAD4 elements were promoted to CQUAD8 elements
  - This has the effect of promoting the plate element membrane displacement fields from linear to parabolic
- Conclusion from this exercise is that the booster aft skirt interface flexibilities show considerable sensitivity to modeled membrane displacement field approximation

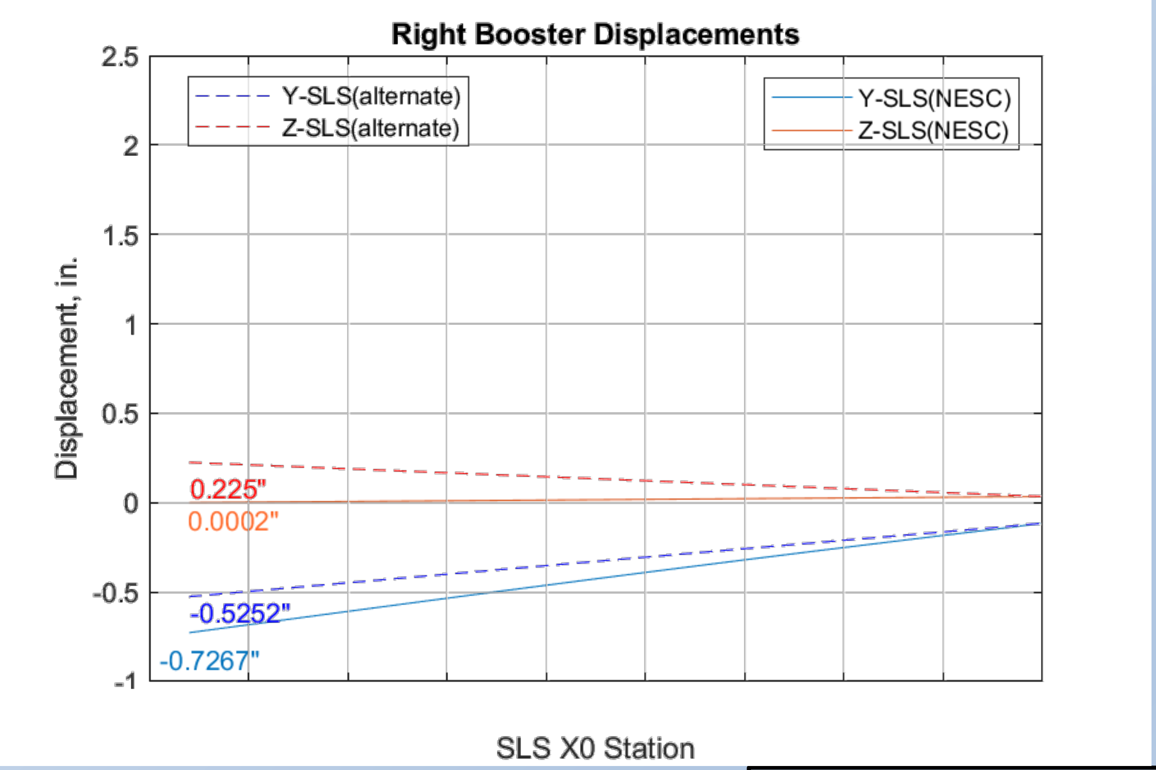
Booster to ML Coupling

- Boosters are coupled to the ML in the exact physical manner in which they are stacked for flight using the Deformed Geometry Synthesis (DGS) technique
  - ML VSPs are leveled and spaced under 1G environment with ML in deformed (“bowed”) state
- Shims are utilized in a pitch/yaw procedure to enforce booster “toe-in” for correct positioning to mate with the Core Stage

Booster Displacements
DGS Method vs Alternate Method

DGS Method





Alternate Method

DGS Method: ML under 1G (bowed); DGS for VSP leveling/spacing and X-shims; Geometric nonlinear on
Alternate Method: ML under 0G (undeformed geometry)

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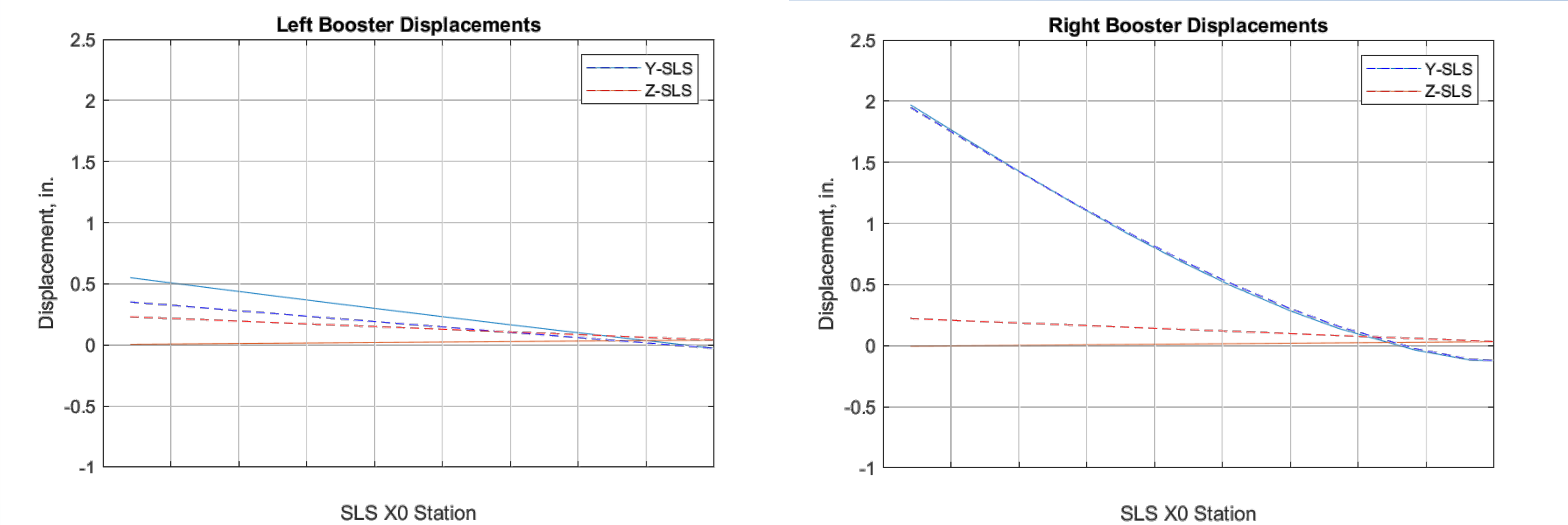
Summary – ZERO Pull Load Cases

- The comparison of the DGS and alternate methods as applied to the BPPT analysis clearly demonstrate significant differences in booster lateral displacements
- The alternate method tends to under-predict the toe-in (Y-SLS) [e.g., 38% under-prediction for the right booster] while not enforcing displacements orthogonal to the toe-in plane (Z-SLS).

Booster Displacements under Static Load

15 Kips +Y-SLS Right Booster
DGS vs Alternate Method

DGS Method



Alternate Method

DGS Method: ML under 1G (bowed); DGS for VSP leveling/spacing and X-shims; Geometric nonlinear on
Alternate Method: ML under 0G (undeformed geometry)

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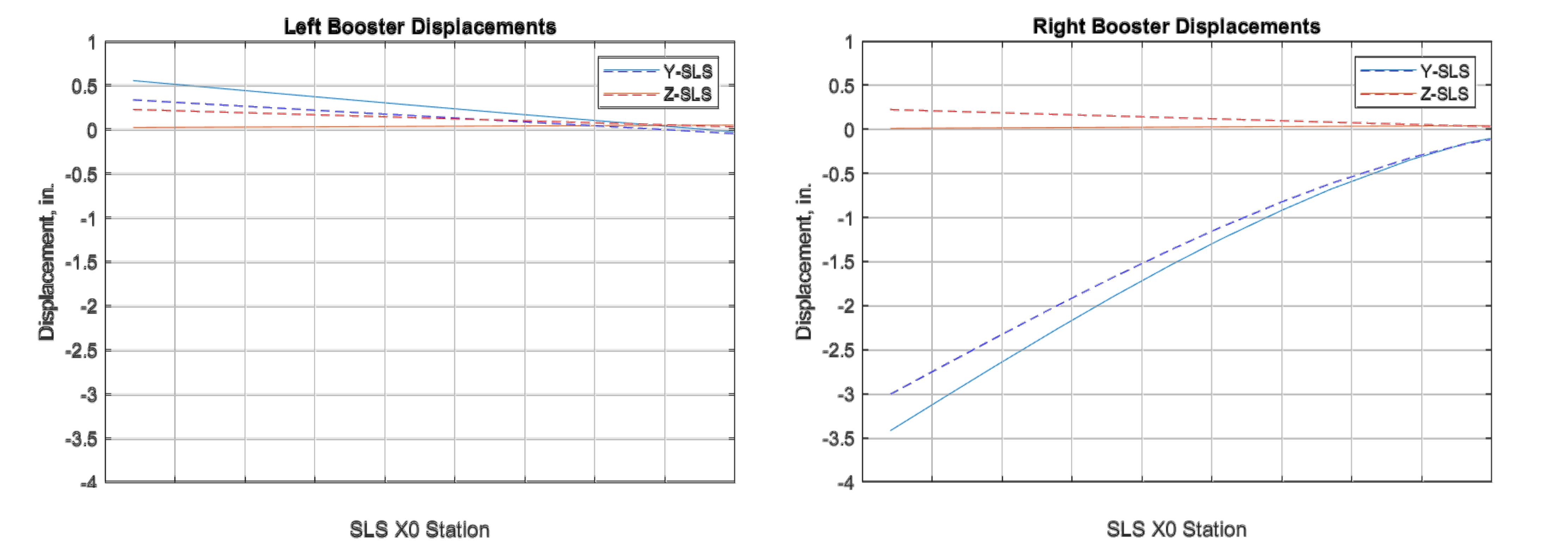
Booster Displacements under Static Load

15 Kips minus Y-SLS Right Booster
NESC vs Alternate Method

DGS Method



Alternate Method

NESC Method: ML under 1G (bowed); DGS for VSP leveling/spacing and X-shims; Geometric nonlinear on
Alternate Method: ML under 0G (undeformed geometry)

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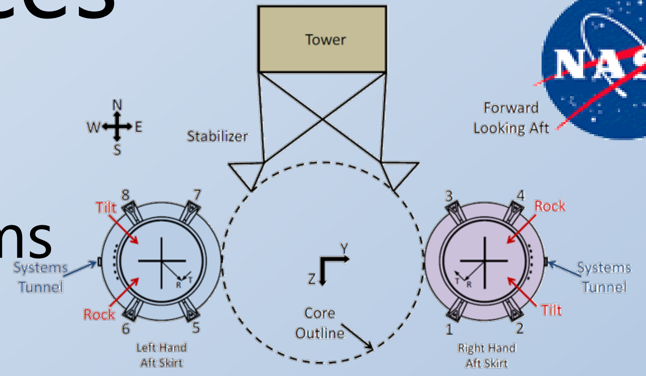
ML/Boosters Interface Forces

15 Kips +Y-SLS Right Booster
VSPs leveled/spaced with
ML bowed under 1G / Boosters 1G; X-shims



No Geom NL

VSP	R_Booster	VSP	L_Booster
1	-118862.40 3559.45 -49985.07	5	570.16 95.80 404.94
2	118862.40 3326.48 50645.41	6	-570.16 179.72 -159.87
3	-121538.11 4154.61 51048.66	7	-570.16 -158.88 72.27
4	121538.11 3959.46 -51709.01	8	570.16 -116.64 -317.35

SUM:	X	0.00
	Y	15000.00
	Z	0.00

With Geom NL

VSP	R_Booster	VSP	L_Booster
1	-127748.87 3547.99 -53855.75	5	595.66 99.03 430.29
2	127734.82 3292.63 54562.93	6	-613.21 195.04 -168.82
3	-130608.14 4182.26 54997.82	7	-604.26 -166.61 79.06
4	130622.19 3977.12 -55705.00	8	621.81 -127.46 -340.53

SUM:	X	0.00
	Y	15000.00
	Z	0.00

% Diff

VSP	R_Booster	VSP	L_Booster
1	7.48% -0.32% 7.74%	5	4.47% 3.38% 6.26%
2	7.46% -1.02% 7.74%	6	7.55% 8.52% 5.60%
3	7.46% 0.67% 7.74%	7	5.98% 4.87% 9.39%
4	7.47% 0.45% 7.73%	8	9.06% 9.28% 7.30%

Notes:
- At each VSP, forces provided in SLS X, Y, Z
- All forces in lbf

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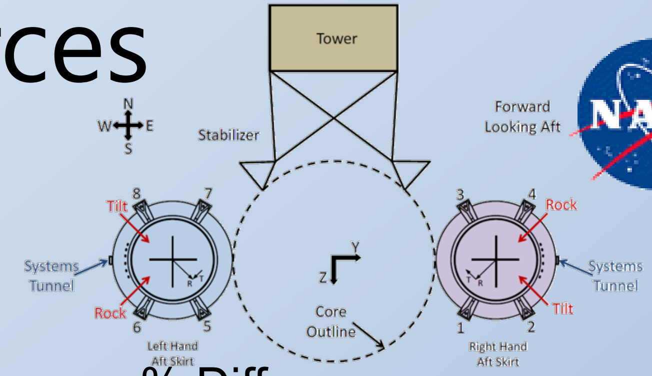
ML/Boosters Interface Forces

15 Kips +Y-SLS Right Booster
DGS vs Alternate Method



DGS

VSP	R_Booster	VSP	L_Booster
1	-127748.87	5	595.66
	3547.99		99.03
	-53855.75		430.29
2	127734.82	6	-613.21
	3292.63		195.04
	54562.93		-168.82
3	-130608.14	7	-604.26
	4182.26		-166.61
	54997.82		79.06
4	130622.19	8	621.81
	3977.12		-127.46
	-55705.00		-340.53

SUM:	X	0.00
	Y	15000.00
	Z	0.00

Alternate

VSP	R_Booster	VSP	L_Booster
1	-118862.40	5	570.16
	3559.45		95.80
	-49985.07		404.94
2	118862.40	6	-570.16
	3326.48		179.72
	50645.41		-159.87
3	-121538.11	7	-570.16
	4154.61		-158.88
	51048.66		72.27
4	121538.11	8	570.16
	3959.46		-116.64
	-51709.01		-317.35

SUM:	X	0.00
	Y	15000.00
	Z	0.00

% Diff

VSP	R_Booster	VSP	L_Booster
1	-6.96%	5	-4.28%
	0.32%		-3.27%
	-7.19%		-5.89%
2	-6.95%	6	-7.02%
	1.03%		-7.85%
	-7.18%		-5.30%
3	-6.94%	7	-5.64%
	-0.66%		-4.64%
	-7.18%		-8.58%
4	-6.95%	8	-8.31%
	-0.44%		-8.49%
	-7.17%		-6.81%

Notes:
- At each VSP, forces provided in SLS X, Y, Z
- All forces in lbf

DGS Method: ML under 1G (bowed); DGS for VSP leveling/spacing and X-shims; Geometric nonlinear on
Alternate Method: ML under 0G (undeformed geometry)

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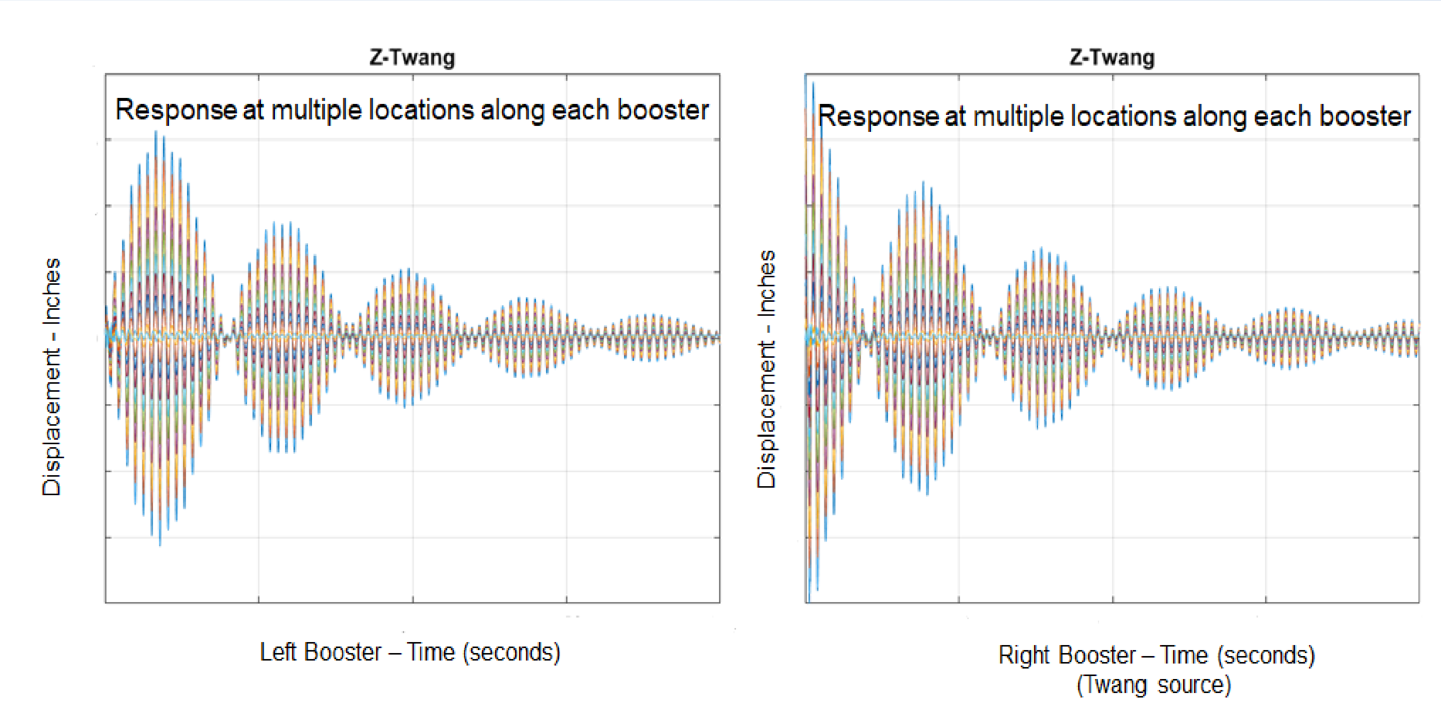
Simulating the Booster Dynamic Input (I)

- Booster was displaced at four inches in each of the lateral directions and displacements measured along the length of the booster
- The Z direction results show that the left booster responds out of phase as the right hand booster responds
- While the first inclination is to classify the response as a beat frequency, the response is indicative of sympathetic vibration.



Booster CL DMMs

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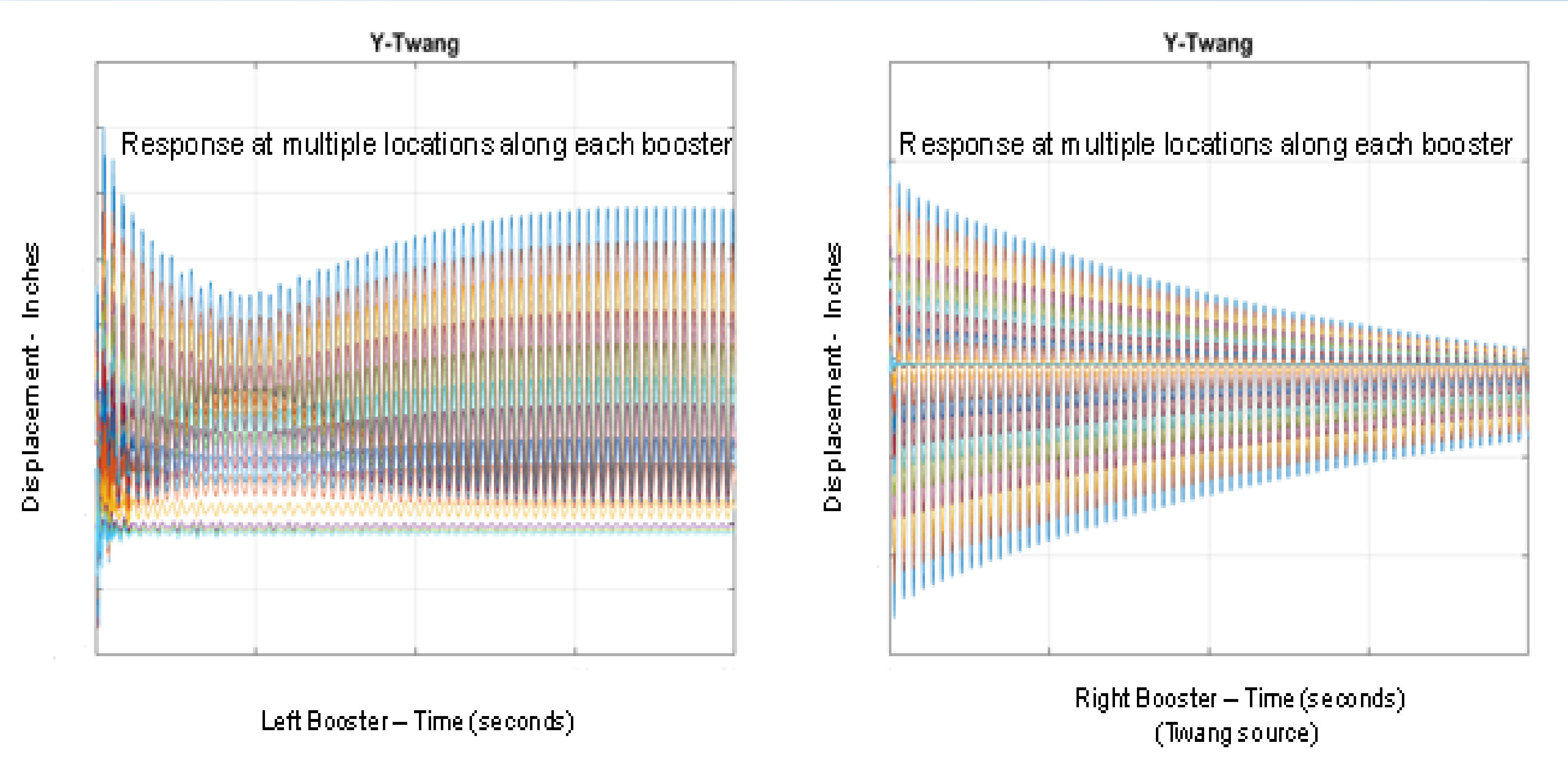
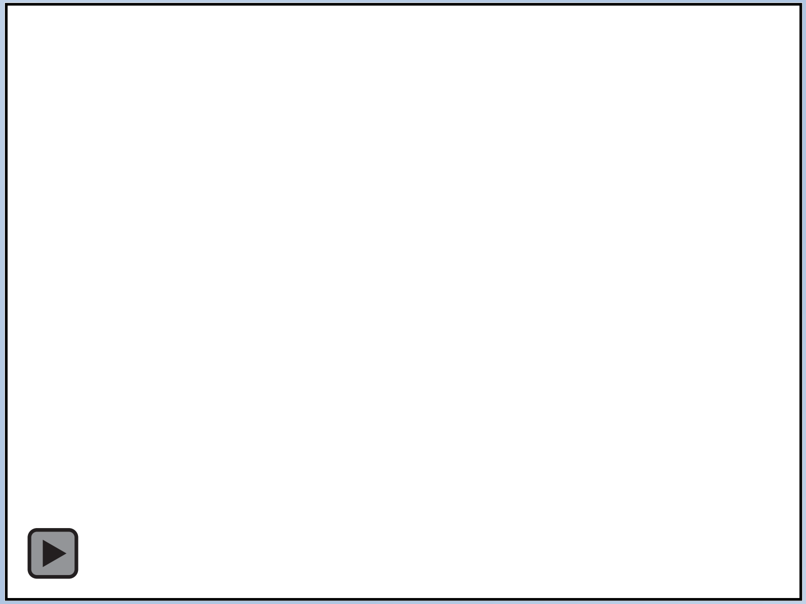
Simulating the Booster Dynamic Input (II)

- Y direction excitation displacements due to the same magnitude input, one see a very different response. This is due in part to the differences in symmetry between axes at the ML VSP to booster aft skirt interface.
- Each time-history vibrates about its respective “X-shim + CG off-set” datum and will eventually settle at that value with simulation carried for a longer duration

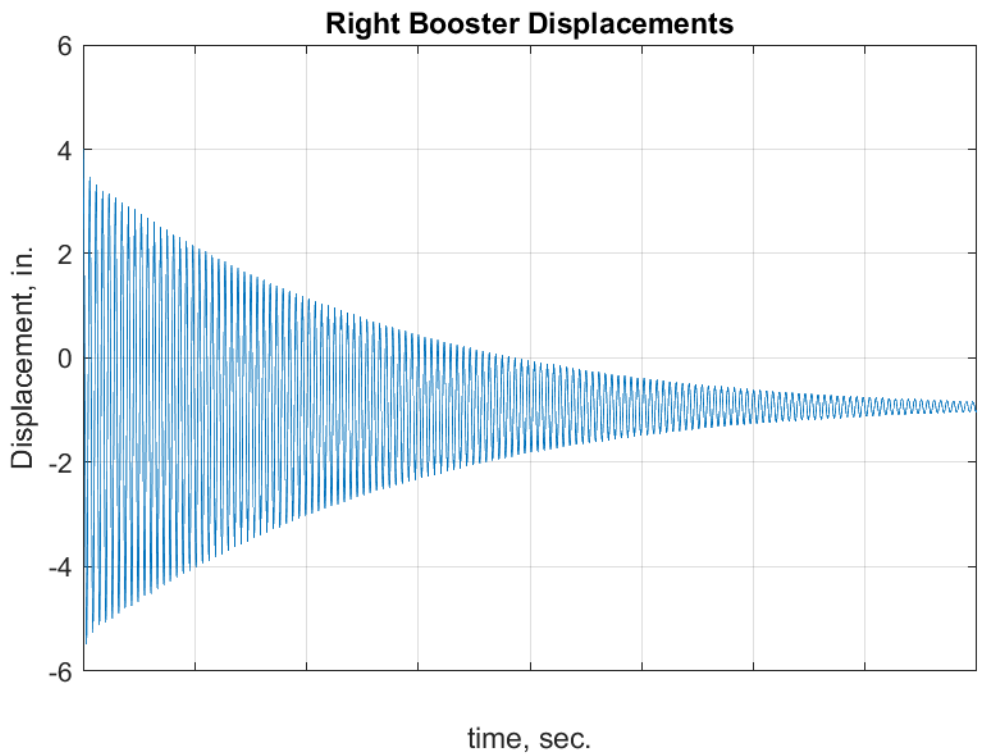



Booster CL DMMs

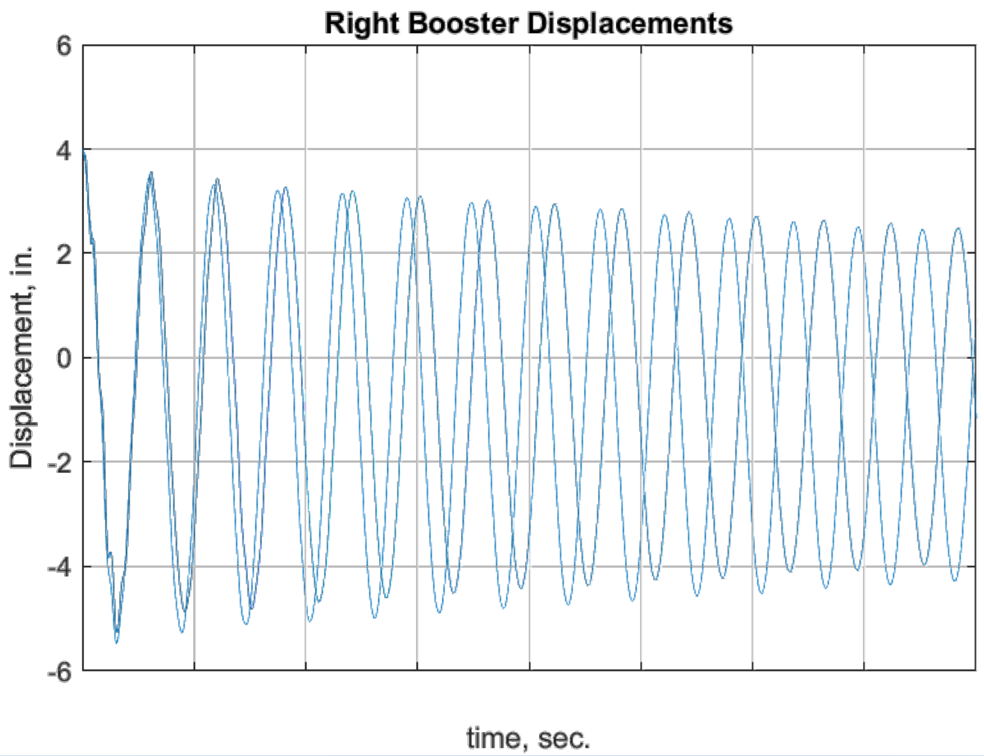
Booster Displacements
4" +Y-SLS on Right Booster

DGS Approach

Response at top location



Right Booster
(Twang Source)



Right Booster
(Twang source)

Differences in dynamic response booster toe-in (DGS) and geometric nonlinear effects

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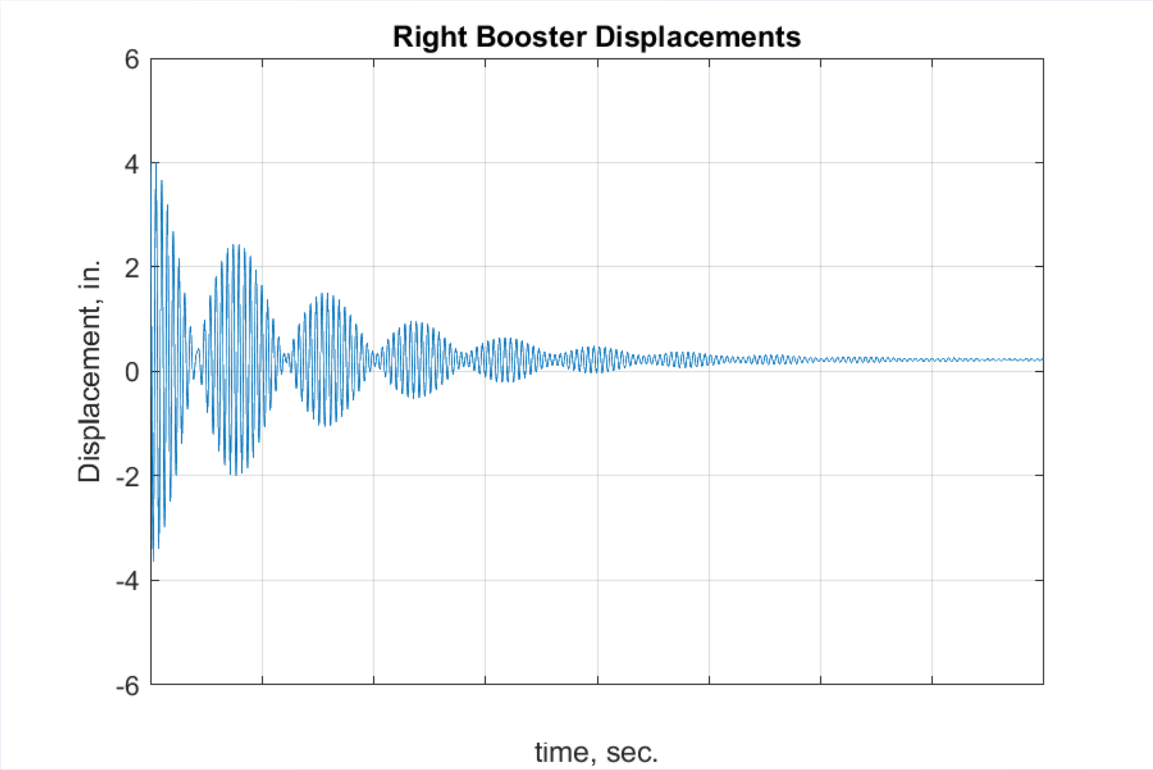
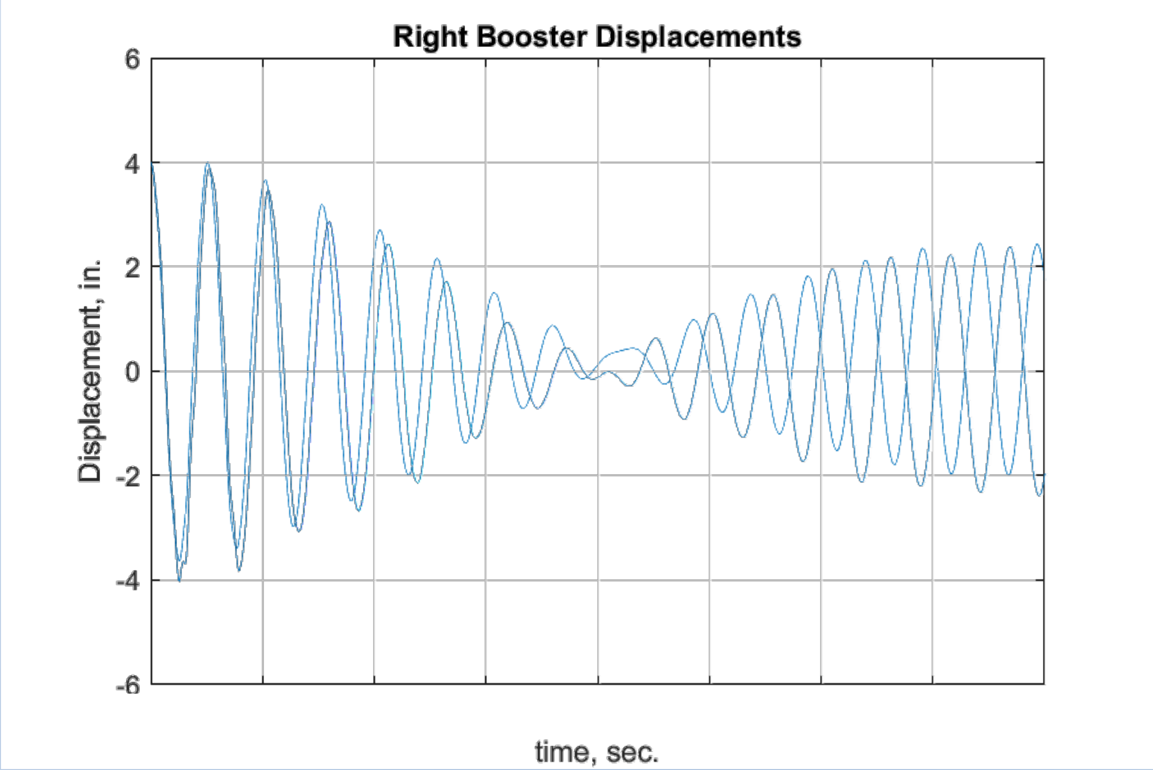
Booster Displacements
4" +Z-SLS on Right Booster

Response at top location

DGS Approach



Right Booster
(Twang Source)



Right Booster
(Twang source)

Differences in dynamic response booster toe-in (DGS) and geometric nonlinear effects

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Summation

- A methodical process for the BPPT pre-test analysis utilizing Deformed Geometry Synthesis (DGS) is presented that accounts for the VSP leveling and spacing in a 1G environment, enforces booster toe-in (X-Shims), and accounts for geometric nonlinear effects in an attempt to provide a complete understanding of coupled system statics and dynamics
- For the zero-pull case, the alternate/simplified representation tends to under-predict the toe-in (Y-SLS) [e.g., 38% under-prediction for the right booster compared to DGS] while not enforcing displacements orthogonal to the toe-in plane (Z-SLS).
- For the pull cases, geometric nonlinear effects accounted for increases in ML/Booster interface forces in the range of 7-10% and tip displacements of 10-15%.
- Dynamic excitation of a single booster results in sympathetic vibrations of the other booster since the two boosters are attached to the ML haunches form a coupled dynamic system and cannot be handled as decoupled components.

End

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