A Deformed Geometry Synthesis Technique for Determining Stacking and Cryogenically Induced Preloads for the Space Launch System

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ABSTRACT
The Space Launch System (SLS) stacking and Core Stage (CS) fueling induce significant preloads that contribute to the liftoff pad separation "twang". To accurately capture this, an approach is required that can replicate the physics of all SLS physical stacking steps, CS cryogenic shrinkage, associated geometric nonlinearities, and the transient behavior and decay of the preloads with changing boundary conditions as the vehicle separates from the pad.

The Deformed Geometry Synthesis (DGS) approach presented here satisfies the above requirements. DGS determines induced preloads by modeling components in their deformed geometry states and then enforcing compatibility by closing the resulting "deadbands". DGS seamlessly integrates into the multibody modal synthesis framework and does not require the use of artificial external loads to enforce preloads or post-processing steps to remove their influence. Since DGS iterates to solve for the deformed state inclusive of geometric nonlinearities, running linearized parametrics to exercise different potential orientations of ball jointed struts that connect the CS to Boosters for cryo-shrinkage analyses is entirely avoided.

Relative to the transient behavior and decay of stacking and cryo-induced preloads with SLS liftoff pad separation, this is an area of considerable interest to the SLS program. To capture this in the most accurate way possible, DGS algorithms are designed to work with Henkel-Mar nonlinear pad separation algorithms which operate on the separating longitudinal and lateral degrees of freedom (DoFs) between the vehicle and the pad. As the separating DoFs release, in whatever manner as dictated by the interface geometries, interface loads and interface flexibilities as well as the external loading on the vehicle, the subject preloads generate a complex twang/decay time-trace as dictated by the physics of the problem.

This paper presents DGS numerical verification against the closed-form solution for Timoshenko's 3 ball-jointed strut preload problem. This problem is then extended by the authors to the geometric nonlinear case where DGS is compared to the Newton-Raphson solution of the nonlinear equations. Next, DGS is utilized to solve the SLS stacking and cryogenic shrinkage coupled loads analyses. Finally, Henkel-Mar pad separation simulations are executed that isolate the impact of the induced preloads' twang and decay characteristics.

Keywords: Space Launch System, Deformed Geometry Synthesis, Henkel-Mar Pad Separation, Geometric Nonlinear

INTRODUCTION

A new approach for coupling deformed geometries and determining vehicle load indicators inclusive of prelaunch stacking and cryogenic induced preloads has been developed. This Deformed Geometry Synthesis (DGS) technique [3] is a specialized procedure in modal synthesis where components are coupled in their deformed geometry states by enforcing compatibility at the interfaces via a process of statically closing the resulting deadbands to lock-in the preloads. The procedure evokes a static version of the nonlinear deadband methodology first developed for the Space Shuttle Program (SSP). It has the advantage of being NASA verified and validated against test and utilized in the SSP nonlinear coupled loads analyses (CLAs) from 2005 until final flight in 2011.

To accurately capture the SLS stacking and cryo-induced preloads, DGS replicates the physics of <u>all</u> SLS physical stacking steps, Core Stage (CS) cryogenic shrinkage, associated geometric nonlinearities (e.g., aft strut rotations – a set of 3 ball jointed struts providing the aft connections for each booster to the CS), vehicle stabilizer system (VSS) coupling/preloads (see section on DGS of VSS), mobile launcher (ML) extensible column/preloads (see section on DGS of ML extensible columns), and the transient behavior and decay characteristics of the preloads with changing boundary conditions as the vehicle separates from the ML.

DGS seamlessly integrates into the SLS multibody modal synthesis framework and accurately simulates all stacking without the use of artificial external loads. The preloads are automatically reflected in the load indicator recoveries without any corrections or post-processing steps. All stages of stacking can be simulated including booster "toe-in" (for CS installation) and CS fueling/cryogenic shrinkage.

DGS starts with an initial deformed geometry state and solves for the final system deformed geometry state, inclusive of all preloads and geometric nonlinear effects. This process can proceed iteratively until desired convergence is achieved. With this, executing linearized parametrics to, for instance, exercise different potential aft strut orientations is avoided since geometric nonlinear effects are captured in the final deformed geometry. To reduce the number of iterations, the initial deformed geometry state can include 1G and thermal effects in order to quickly converge to the final state geometry. In practice, this is done and fully converged solutions are achieved in only two iteration steps.

The transient contribution (twang) and decay characteristics of the stacking and cryo-induced preloads is of considerable interest to the SLS program. To accurately capture this, DGS algorithms work together with Henkel-Mar nonlinear pad separation algorithms [2] which operate on the longitudinal and lateral separating DoFs at the ML to booster interface. As these separating DoFs release in the manner dictated by the interface geometries, interface flexibilities, interface loads, and external loads, the interaction of DGS and Henkel-Mar automatically generates the transient time-history, inclusive of the twang and decay characteristics, of the internal strain energy release.

A series of DGS verification problems involving a system of ball-jointed struts are provided in the next section to help make concepts crystal clear. The first set of these problems has a closed form solution provided by Timeshenko and Gere [1]. To verify DGS capability for capturing larger strut rotations, the Timshenko problem is extended to larger preloads. Here, the linear analytical solution no longer holds and DGS is compared with a Newton-Raphson nonlinear solution of the Timoshenko problem.

DGS VERIFICATION PROBLEMS

Verification Problem #1: Ball Jointed Strut Problem – Preloads (Linear Case)

Figure 4 depicts the ball-joint strut problem Timoshenko and Gere [1] utilized as the verification example. The vertical strut has an unstressed length of initial length (L) + change in length (ΔL). It is coupled into the diagonal struts resulting in compression of the vertical strut and associated extension/rotation of the inclined struts. The objective is to predict the strut loads, and the vertical displacement at the vertex.

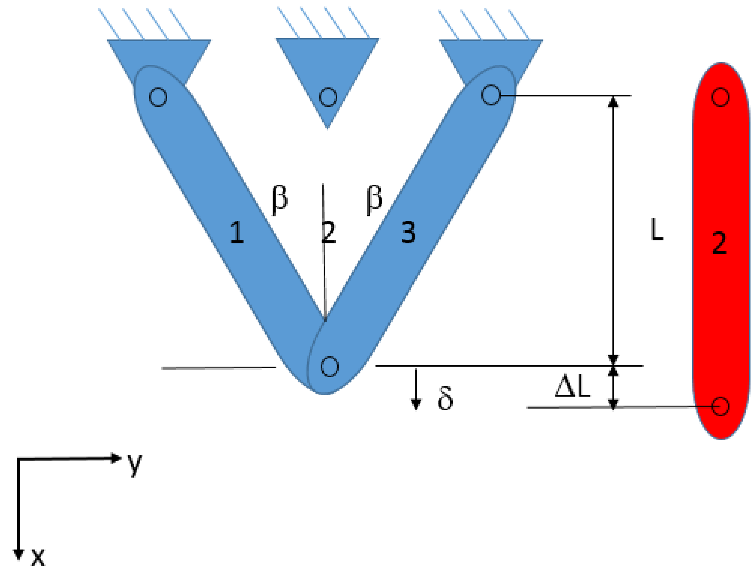

Figure 4. Ball Jointed Strut Verification Problem (Timoshenko)

The parameters used were: E=10e6 psi, A=1 in^2, L=10 in, and ΔL=0.125 in. Timoshenko and Gere [1] provided the following closed form solution for the strut loads as applicable for small displacements:

$$F_2 = \frac{2EA(\Delta L)cos^3\beta}{L(1 + 2cos^3\beta)}$$

$$F_1 = F_3 = \frac{F_2}{2cos\beta}$$

$$\delta = \frac{F_2 L}{2EAcos^3\beta}$$

From the above equations, it can be observed that the strut forces are a function of un-stressed strut lengths and un-deformed orientation which is characteristics of a linear problem. The comparisons to DGS for three orientations are provided in Tables 1 through 3. Note in: this context, the Timoshenko analytical solution assumes small displacements. This problem is later extended to larger displacements, where Timoshenko analytical solution no longer holds.

Table 1. DGS Verification Problem 1 – Preloads Case 1: β = 50º

	Exact (analytical)	DGS (numerical)	Diff
F2	-43363.01	-43363.01	0
F1	33730.44	33730.44	0
F3	33730.44	33730.44	0
δ	8.1637e-2	8.1637e-2	0

Table 2. DGS Verification Problem 1 – Preloads Case 1: β = 5º

	Exact (analytical)	DGS (numerical)	Diff
F2	-83015.02	-83015.02	0.
F1	41666.06	41666.06	0.
F3	41666.06	41666.06	0.
δ	4.1985e-2	4.1985e-2	0.

Table 3. DGS Verification Problem 1 – Preloads Case 1: β = 85º

	Exact (analytical)	DGS (numerical)	Diff
F2	-165.29	-165.29	0.
F1	948.26	948.26	0.
F3	948.26	948.26	0.
δ	1.2483e-1	1.2483e-1	0.

Verification Problem #2: Ball Jointed Strut Problem – Preloads (Nonlinear Case)

For the nonlinear case, the ΔL is increased to 1.75 in. With this, the small displacement solution no longer holds and DGS iterations are required. The angle between the vertical and diagonal struts, ***β***, is initially set to 45º and is expected to decrease by a few degrees with the introduction of the preloaded vertical strut to the multibody system. The DGS solution is compared to the geometric nonlinear solution which utilizes Newton-Raphson. Results after 1 and 2 iterations are shown in Tables 4 and 5, respectively.

Table 4. DGS Verification Problem 2 – Preloads Iteration Step 1

	Geometric Nonlinear*	DGS (numerical)	Diff
F2	-699700.	-675880.90	3.40%
F1	474220.	477919.97	-0.78%
F3	474220.	477919.97	-0.78%
δ	9.2787e-01	9.5584e-01	-3.01%
β	42.461º	42.388º	0.172%

Table 5. DGS Verification Problem 2 – Preloads Iteration Step 2

	Geometric Nonlinear*	DGS (numerical)	Diff
F2	-699700.	-700161.04	0.07%
F1	474220.	473987.38	0.05%
F3	474220.	473987.38	0.05%
δ	9.2787e-01	9.2731e-01	0.06%
β	42.461°	42.4625°	0.00%

APPLICATION TO THE SLS SYSTEM

The SLS stacking procedures and cryogenic shrinkage due to the CS fueling induce significant preloads that contribute to the liftoff pad separation “twang”. These preloads re-distribute and increase loads at the ML to boosters’ separation interface and therefore impact the vehicle’s pad separation dynamics. Figure 1 provides a depiction of the ML, boosters, CS, and Upper Stage (US).

Figure 1 – SLS/ML Coupled System

Figure 2 provides a depiction of the aft struts connecting the CS to the boosters. When fueled, the CS shrinks both longitudinally and radially, rotating the aft struts in the longitudinal direction from the unfueled configuration and resulting in strut preloads.

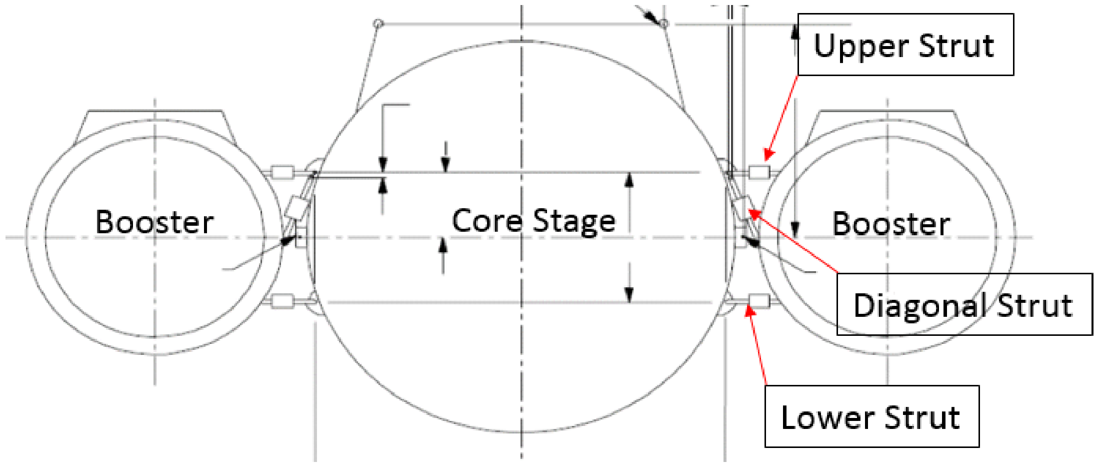

Figure 2 – CS/Boosters Aft Struts

The stacking steps start with the booster stacking, which simulates the ML vehicle support posts (VSPs) (Figure 3) leveling, spacing and shimming under 1G deformed geometry. The boosters naturally "toe-in" as the ML "bows" under 1G. The shims ensure that the booster's forward attach interface (Figure 4) to the CS is within the desired tolerance box to optimize the CS physical integration. The boosters are pulled apart for CS integration therefore inducing a "toe-in" preload and associated moment at the VSP interface which re-distributes the ML/booster interface loads. Given the unfueled CS CG off-set, the CS rotates away from the tower during stacking. This geometric nonlinear rotation step along with the delta rotation in the reverse direction to accommodate the integration of diagonal struts of a fixed length must be simulated in order to relieve this delta rotation which then preloads the diagonal struts. The next step in the stacking procedures involves simulating the upper and lower strut integrations which are adjusted to fill the space and therefore should have zero preloads at this stacking step.

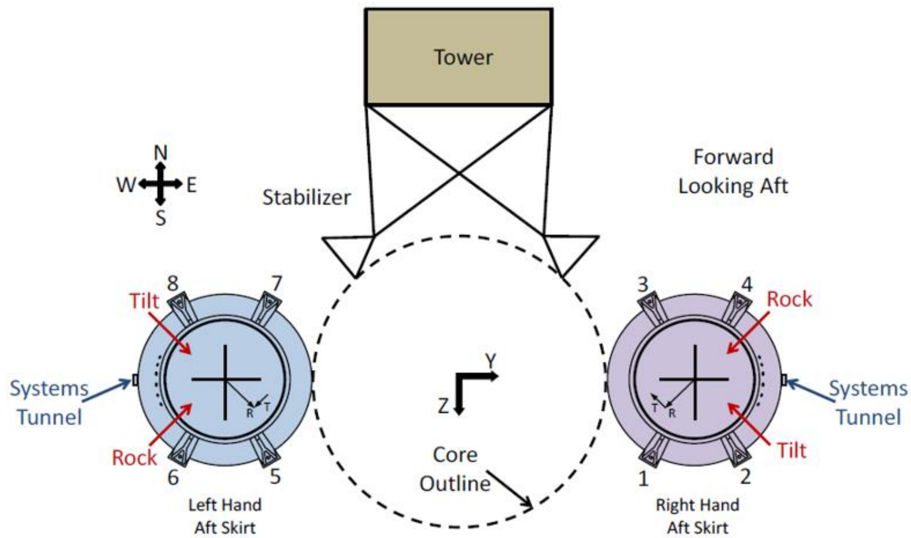

Figure 3 – Vehicle Support Posts (VSPs) Showing Inboard (odd) and Outboard (even) Numbering

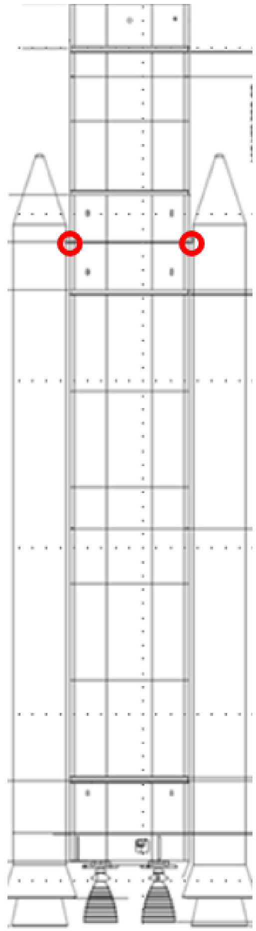

Figure 4 – CS/Boosters Forward Attach Interface (shown with red circles)

Next the US components are integrated: Launch Vehicle Stage Adapter (LVSA), Interim Cryogenic Propulsion Stage (ICPS), MPCV Stage Adapter (MSA), and Multi-Purpose Crew Vehicle (MPCV) (see Figure 5). Note that with this, the upper and lower aft struts are now taking load.

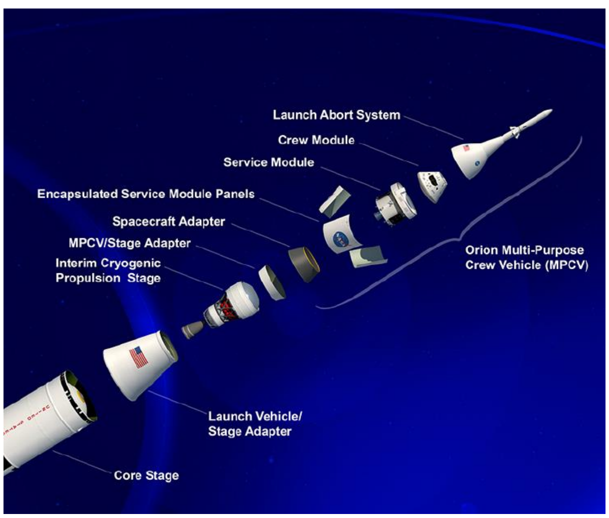

Figure 5 – Upper Stage (US) Components

The final step in the DGS simulations involves the CS cryogenic shrinkage which further adds to the vehicle preloads amplifying the pad separation twang.

DGS OF VEHICLE STABILIZER SYSTEM (VSS) TO THE SLS

Figure 6 depicts the VSS which is designed to provide additional constraints against lateral displacements during the roll-out and prior to liftoff. The preloads at the VSS to CS interface are enforced via the DGS approach. At booster ignition, the VSS separates from the CS relieving the preloads at the subject interface.

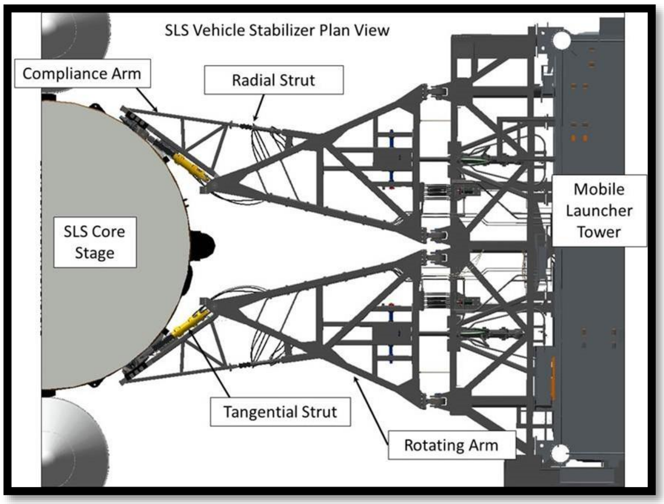

Figure 6 – Vehicle Stabilizer System (VSS)

The VSS includes radial and tangential hydraulic struts which are nonlinear. It is important for the VSS to be modeled in the coupled system as nonlinear given that at larger displacement amplitudes, the behavior of the nonlinear vs linearized VSS system can be significantly different. Figure 7 provides the VSS tangential strut damping force for a nonlinear vs linear VSS model in a SLS coupled loads analysis (CLA) involving an initial 6 inch lateral displacement release at the forward attach (along with 1G and stacking/cryo-induced preloads). It is seen that the behavior of the two models is significantly different for larger amplitudes but converges as the amplitudes reduce. Note: the zero strut damping solution is also provided which should results in a zero force for this particular response item.

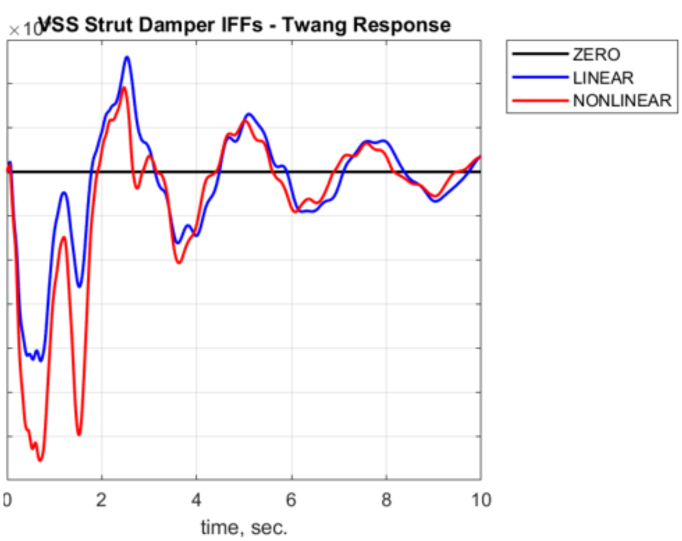

Figure 7 – VSS Tangential Strut Damping Force due to 6 in. Twang (linear vs nonlinear)

DGS OF ML EXTENSIBLE COLUMNS (EC)

For SLS, four removable ECs, in addition to the six fixed launch pad Mount Mechanisms (MMs), provide support for the ML during vehicle fueling and launch at the four corners of the ML exhaust opening. This column concept is based on the ML support developed and used during Apollo/Saturn-V fueling and launch. Figure 8 shows the relative positioning of two ECs and three fixed MMs on the right (East) underside of the ML at the launch pad.

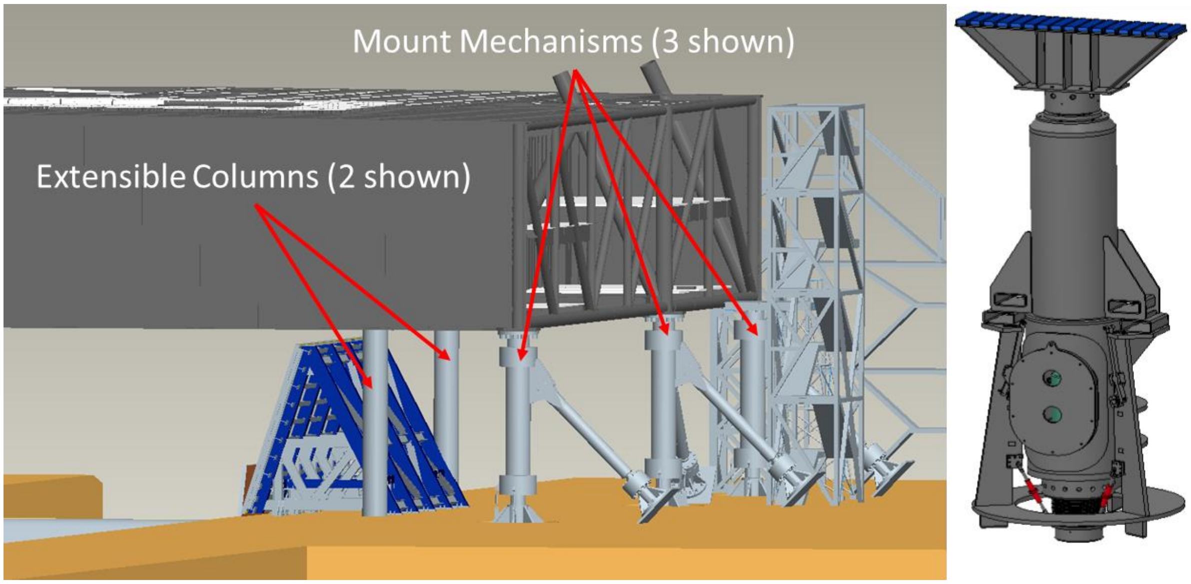

Figure 8. (Left) EC and MM Positioning on the East Underside of the ML at Launch Pad, (Right) EC Concept

These ECs are designed to be preloaded to a pre-determined value to ensure no gapping between the ML and the ECs after pad release. For the EC inclusion in the system model, DGS implemented the methodology to (a) enforce contact between the top of the EC and ML and (b) enforce the preload requirements. Resulting transient loads from this DGS application in pad release will be shown in the next section.

LIFTOFF PAD SEPARATION TWANG – RELEASE OF PRELOADS

The transient contribution (twang) and decay characteristics of the stacking and cryo-induced preloads is of considerable interest to the SLS program. For this, the DGS algorithms work alongside the Henkel-Mar pad release algorithms to ensure a physics-based approach to pad release and the relief of preloads. It is important to note that not all ML/booster interfaces separate at the same time; therefore, the release of strain energy due to preloads must be congruent with the sequence of separating DoFs. The DGS approach is designed for this to occur in an automated physics-based fashion. Figure 9 provides the forces in the upper and lower aft struts from a SLS liftoff transient CLA. The DGS enforced initial conditions, Henkel-Mar pad separation, and the joint workings of the two algorithms results in a "twang" at booster separation which is clearly seen. Figure 10 provides the right booster/CS forward attach time-history in the longitudinal direction again clearly demonstrating the impact of the strain relief of the "toe-in" loads. Figure 11 provides the EC interface forces in the longitudinal direction. From this figure, it is seen that for the scenario simulated, the forces stays positive (i.e., in contact) after the vehicle separates from the pad.

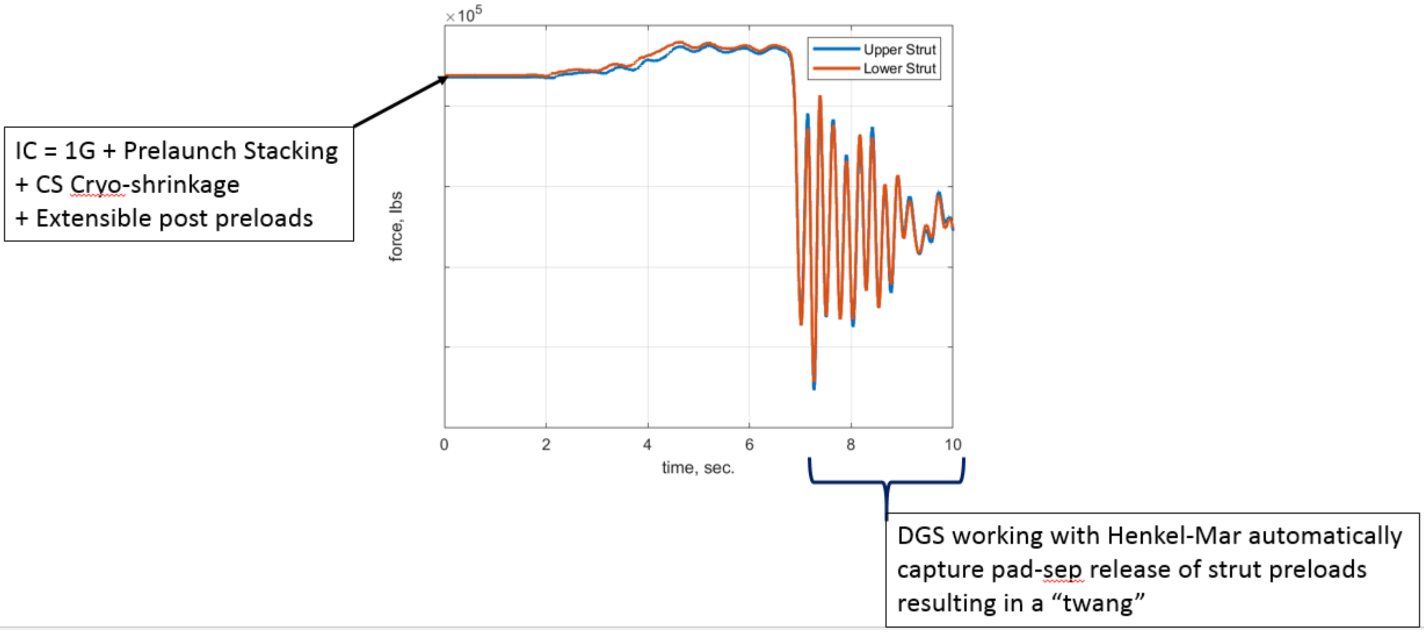

Figure 9 – Upper and Lower Aft Struts Twang and Decay Transient Dynamics

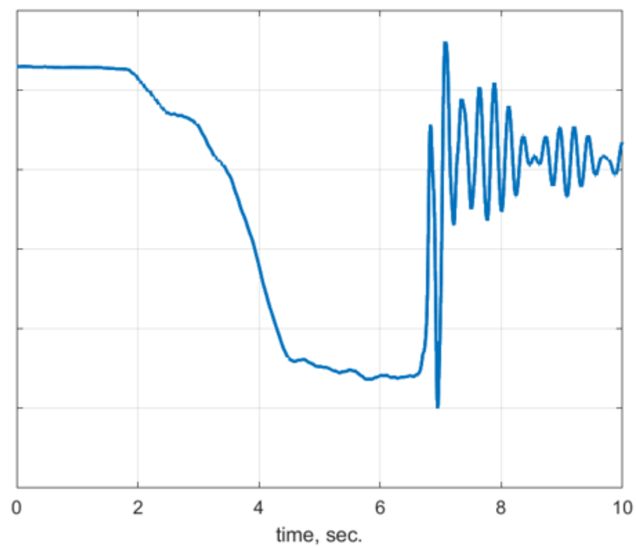

Figure 10 – Right Booster/CS Forward Attach Longitudinal Force

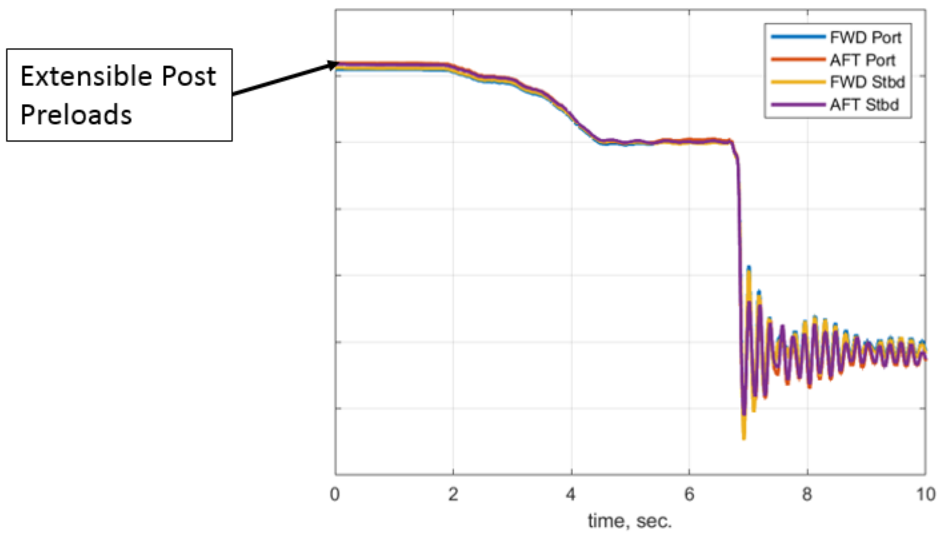

Figure 11 – ML EC Longitudinal Contact Force

CONCLUSION

A new approach for coupling deformed geometries and determining vehicle load indicators inclusive of prelaunch stacking and cryogenic induced preloads has been developed. This Deformed Geometry Synthesis (DGS) technique [3] is a specialized procedure in modal synthesis where components are coupled in their deformed geometry states by enforcing compatibility at the interfaces via a process of statically closing the resulting deadbands to lock-in the preloads. Verification exercises using the Timoshenko ball-jointed struts problem demonstrated the concept and provided confidence in the extension to large displacements/geometric nonlinear where DGS was compared to the Newton-Raphson solution of the Timoshenko problem.

The technique was then applied to the SLS stacked system where the stacking and cryo-induced preloads are captured prior to the Henkel-Mar pad separation and the resulting liftoff twang. To accurately lock-in all preloads, DGS is utilized to simulate all stacking steps including cryo-shrinkage of the fuel tanks, VSS coupling with preloads, and ML EC contact/preloads.

The transient contribution of the stacking and cryo-induced preloads at liftoff is of considerable interest to the SLS program. To solve this, the DGS approach for preload enforcement has the added capability to work with Henkel-Mar and automatically relieve the strain energy as the SLS separates from the ML. As such, it provides a physics-based method for predicting the liftoff twang.

ACKNOWLEDGEMENTS

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