National Aeronautics and Space Administration

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SPACE LAUNCH SYSTEM

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SLS Payload Launch Loads Analysis Using the NTRC Method

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Introduction

- **NASA's Space Launch System (SLS) is currently slated to deliver critical components to the lunar-orbiting Gateway space station**
  - International Habitation Module (I-HAB) – Habitat/logistics module with four docking ports, launched on Artemis IV
  - Esprit Refueling Module (ERM) – Fuel storage and observation, launched on Artemis V

- **To date, SLS Block 1B Integrated Vehicle Coupled Loads Analysis (CLA) efforts have incorporated I-HAB as a representative co-manifested payload**
  - I-HAB program is more mature than ERM

- **Prior to the assessment described in this presentation, the SLS Mission Planner's Guide was the only source of launch environment design loads for the ERM program**

- **An alternate payload CLA method has been used to develop *representative* CLA loading environments for the ESPRIT Refueling Module (ERM) based on a recent SLS B1B analysis cycle**
  - D. Kaufman, et al, *Norton-Thevenin Receptance Coupling (NTRC) Coupled Loads Analysis (CLA) Method,* NASA Engineering Safety Center Technical Assessment Report, Version 1.0, June 2018.
  - Goals:
    - Provide PDR fidelity loads to supplement the initial sizing loads in the Mission Planner's Guide
    - To complete the ERM assessment using a small fraction of the effort and resources typically used in a CLA

- **This presentation describes implementation of NTRC for assessment of the ERM**
  - Overview of the NTRC methodology
  - Verification methods
  - Comparison of I-HAB and ERM responses
  - Significant findings

Image of ERM attached to Lunar Gateway

https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Gateway_ESPRIT

SLS Introduction to NTRC

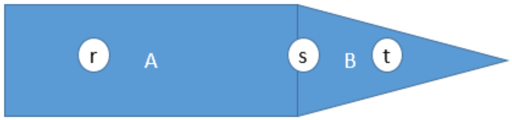
- **SLS was first contacted about NTRC in 2016**
  - Europa Clipper payload model provided to GSFC team as a test case
  - Very limited SLS data and resources available to support tool development
  - With Europa Clipper moving off SLS, no payloads for SLS that could use NTRC
- **SLS CLA community noted the June 2018 paper on the NTRC method**
- **Around this time, the Block 1B concept for SLS had incorporated co-manifested payloads and possible cargo configurations**
  - With encapsulated payloads now part of the SLS architecture, a payload CLA methodology was now beneficial to the program
  - However, no specific payloads were yet available for analysis
- **The International Habitat (I-HAB) Gateway module was manifested as the Artemis IV payload in 2021**
  - The first CLA request came after the completion of the SLS DAC2R cycle
  - Support required rerunning ascent and liftoff for the SLS integrated vehicle with IHAB added
- **When the ERM was manifested on Artemis V, it was no longer feasible to support all SLS payloads with integrated vehicle CLAs**
- **SLS LDI used the NTRC literature and 2016 reference materials to create an implementation of NTRC for SLS models and forcing functions**

Why NTRC?

- **Currently, SLS provides initial sizing environments in the SLS Mission Planner's Guide (MPG), ESD 30000, which is publicly available**
  - Suitable for SRR phase development of payloads
- **SLS Loads, Dynamics, and Integrated Design (LDI) has supported I-HAB by incorporating it into planned integrated vehicle CLA cycles**
  - This delivers a high maturity product with more detailed deliveries, sufficient to support all reviews
- **However, demand from additional SLS payloads has required a different approach**
  - Timing of payload requests does not match planned SLS CLA cycles
  - An intermediate approach to provide PDR-fidelity or higher results without requiring additional integrated vehicle CLAs is required to support payloads within current LDI resource constraints
- **NTRC allows a reference set of forcing functions to be developed from a baseline SLS CLA and applied to any co-manifested payload needing results**
- **Results from NTRC with IHAB indicate that the method produces a good match to traditional integrated vehicle CLA results**
- **ERM results have been completed with the recommended coverage factors**
  - Planned delivery to Payload Integration (PI) pending SERB approval
  - PI will deliver results to ESA

A Synopsis of the NTRC Method*

NTRC Nomenclature



C: Coupled system (A+B)
A: LV (source) with internal DoFs r
B: Payload (load) with internal DoFs t
s: Interface DoFs

H: accelerance [force/accel]
F: [force], A: [acceleration]

$\mathbf{H_{Xyz}}$ = Acceleration for System X with response at y DoFs due to forces applied at z DoFs
$\mathbf{A_{Xy}}$ = Acceleration response of system X at y DoFs
$\mathbf{F_{Xy}}$ = Force applied to system X at y DoFs

A frequency domain representation of Newton's 2nd Law of Motion:

$$A(\omega) = H(\omega)F(\omega)$$

where:

$$H(\omega) = \left[\frac{-\omega^2}{-M\omega^2 + Ci\omega + K}\right]$$

Accelerance

*From **TI-15-01093 Norton Thevenin Receptance Coupling (NTRC) Coupled Loads Analysis Method, pages 16 and 17***

Coupled system partitioned into LV free dof (r), payload free dof (t), and interface dof (s):

$$\begin{bmatrix} A_{Cr} \\ A_{Cs} \\ A_{Ct} \end{bmatrix} = \begin{bmatrix} H_{Crr} & H_{Crs} & H_{Crt} \\ H_{Csr} & H_{Css} & H_{Cst} \\ H_{Ctr} & H_{Cts} & H_{Ctt} \end{bmatrix} \begin{bmatrix} F_{Cr} \\ F_{Cs} \\ F_{Ct} \end{bmatrix} \qquad \text{Eq [1]}$$

Frequency domain representation of a 'classical' base drive:

$$A_{Ct} = H_{Bts} \; H_{Bss}^{-1} A_{Cs} \qquad \text{Eq [3]}$$

Norton-Thevenin approximation of relationship between coupled system acceleration at i/f and LV-only acceleration at i/f:

$$A_{Cs} = [H_{Ass}^{-1} + H_{Bss}^{-1}]^{-1} H_{Ass}^{-1} A_{As} \qquad \text{Eq [4]}$$

Substituting [4] into [3] yields effective coupled system response of payload free dof:

$$A_{Ct} = H_{Bts} \; H_{Bss}^{-1} \; [H_{Ass}^{-1} + H_{Bss}^{-1}]^{-1} H_{Ass}^{-1} A_{As} \qquad \text{Eq [5]}$$

Eqs [4] and [5] generate total acceleration response of payload

NTRC in Practice

- Requires a full CLA assessment using a 'no payload' version of the launch vehicle
- Necessary to diagonalize state matrices using assumed modes
- NTRC damping term will result in slightly different results compared with CLA

SLS Coupled Loads Analysis

- **The SLS CLA process involves the development of loads that represent the required enclosure level for potential loading environments in each analysis cycle**

- **For early payload analyses, the liftoff and ascent regimes are most important**
  - Liftoff Event
    - Buildup and Ignition 5000 case Monte Carlo assessment
    - Encompasses Buildup, Ignition, and Shutdown
      - Shutdown not used in this study
  - Ascent Event
    - Vehicle mission is decomposed into specified Mach ranges, or bins
    - Loading events (buffet, gust, maneuvering, etc.) that occur during a bin are evaluated independently and uncertainty factors are applied to results
    - Most significant loads occur during ‘boost phase’ (first stage) flight
    - Ascent event loads combined into a single response via a Load Combination Equation

- **Only the Liftoff and Ascent Boost events were evaluated for the ERM NTRC analysis**

SLS Block 1B DAC2R/DAC3 Ascent Load Events by Mach Bin

BIN	Lower Mach*	Upper Mach*	AxSTEL	STEL	VLI	Turb. GUST	Tuned GUST	BUFF	PTI	TO 1L	TO 2L	TO 3L	CSE TO	Dynamic MNVR	TVO	TVM
1	0.05	0.2			X	X							X	X	X	
2	0.2	0.4			X	X			X				X	X	X	
3	0.4	0.7	X	X		X			X				X		X	X
4	0.7	0.85	X	X		X		X	X	X	X	X	X		X	X
5	0.85	1	X	X		X		X		X	X	X	X		X	X
6	1	1.3	X	X		X		X		X	X	X	X		X	X
7	1.3	1.65	X	X		X		X		X	X	X	X		X	X
8	1.65	2	X	X		X				X	X	X	X		X	X
9	2	2.8			X		X		X	X	X	X	X		X	
10	2.8	3.2			X		X		X	X	X	X	X		X	
11	3.2	3.6			X		X		X	X	X	X	X		X	
12	3.6	Both Boosters < 50 psi			X		X		X	X	X	X	X		X	
PRESEP	Both Boosters < 50 psi	Sep			X					X			X		X	

* These Mach ranges are used unless they encroach on the PRESEP bin. Also, 10% overlap is applied to each Mach range in the analysis.

Quasi-Static

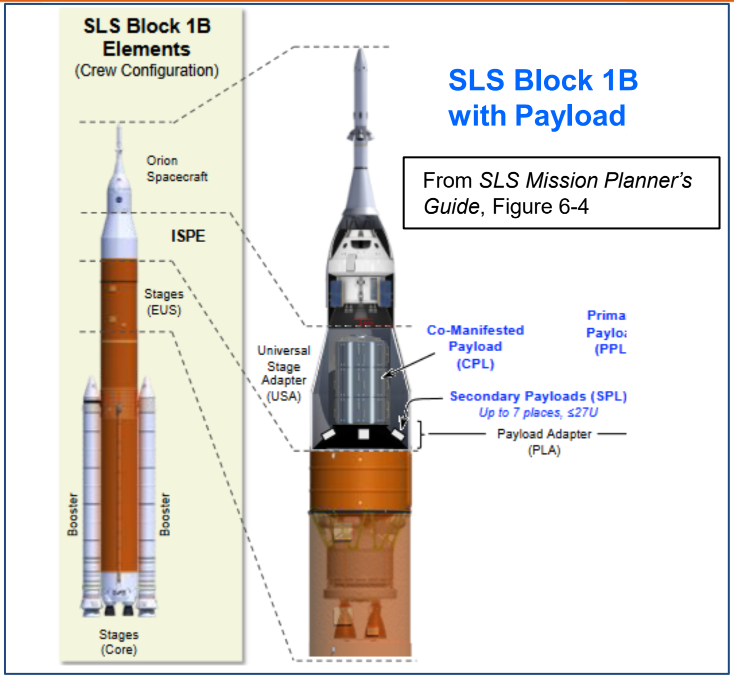
NTRC

NTRC Implementation

- **SLS ran a set of integrated vehicle CLAs with no co-manifested payload to derive a reference set of forcing functions for use in NTRC payload CLAs**
  - Required additional SLS model generation
  - Forcing functions based on SLS CDR analysis cycle
- **The SLS CDR CLA included an IHAB FEM and LTMs**
  - This provided a "truth" set of CLA results to assess the NTRC results against
- **Accelerance and compliance matrices were generated for the free-free IHAB payload and the free-free B1B vehicle with no payload**
  - These were used through NTRC to translate the response into a coupled response at the payload interface as well as payload response
  - The B1B vehicle provided reference matrices for any co-manifested payload requesting analysis outside of IV CLAs
- **After the NTRC method was applied in the frequency domain, an IFFT was then used to transform the payload response back to the time domain**
  - The B1B vehicle provided reference matrices for any co-manifested payload requesting analysis outside of IV CLAs
  - Augmented with gravity solution and displacements resulting from rigid body acceleration
- **Events deemed not to be significant load drivers for the payload omitted from NTRC analysis**
- **DUFs from mainline CLA applied to NTRC results**
- **Load Combination Equation (LCE) unchanged from mainline CLA**
- **Coverage factors applied to NTRC results to ensure conservatism relative to mainline SLS CLA**

SLS B1B, IHAB, and ERM Finite Element Models

- **A series of SLS FEMs are provided for each loads analysis cycle**
  - Represent vehicle at different mission times
  - Baseline SLS B1B CLA delivery consisted of 20+ models
    - Generally 10000+ DOF
    - Coupled damping
    - Included IHAB as co-manifested payload
  - NTRC required 13 additional SLS B1B models (no payload, interface grids in boundary)
    - Liftoff and Ascent Boost models only



- **Payload models**
  - I-HAB model
    - 100+ boundary grids representing IHAB geometry and interfaces
    - 24 boundary grids at SLS PLA attach ring
  - ERM model
    - Pre-PDR maturity
    - Composed of two significant substructures: Windows and Tunnel (WIT) and Unpressurized Module and Xenon Transfer (UMAXT)
    - 1 boundary grid, thousands of modal DOF
  - While the IHAB and ERM FEMs model structures of similar size and mass, they possess different dynamic characteristics

IHAB/ERM FEM CGA-T3 Enforced Acceleration

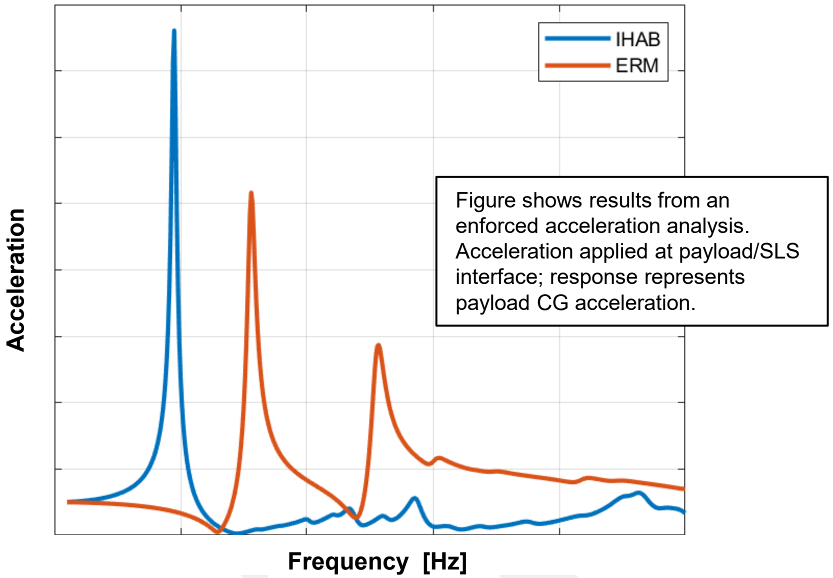
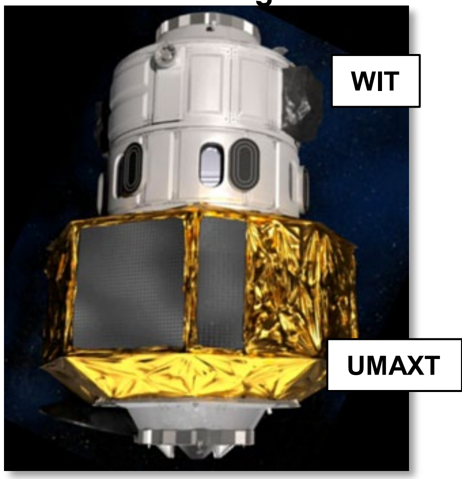


Figure shows results from an enforced acceleration analysis. Acceleration applied at payload/SLS interface; response represents payload CG acceleration.

I-HAB Image

https://www.esa.int/ESA_Multimedia/Images/2021/01/Gateway_zoom_on_I-Hab

ERM Image



https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Gateway_ESPRIT

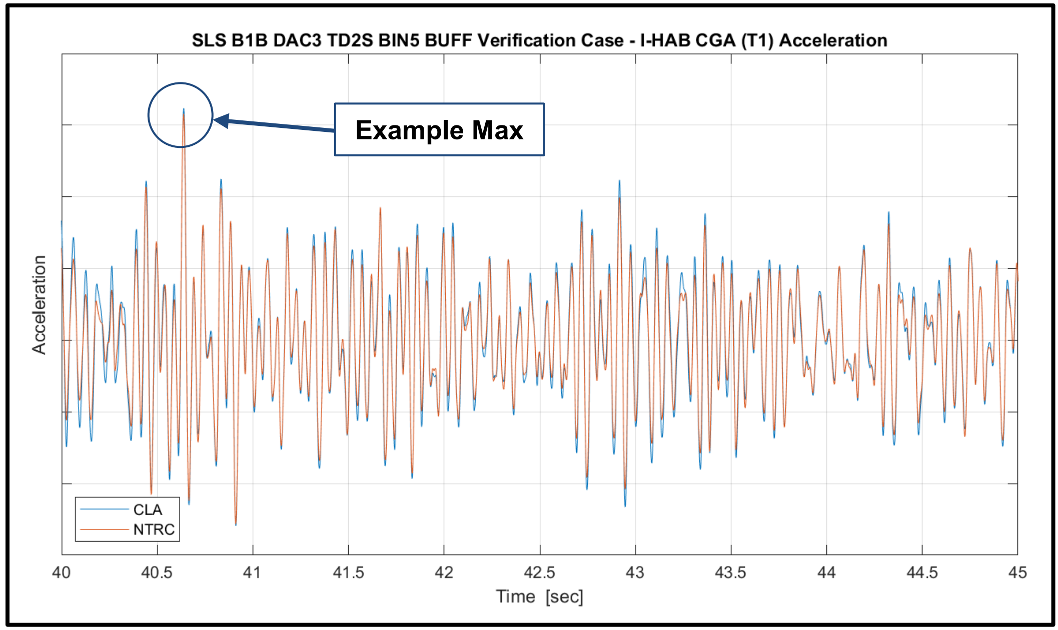
Verification of NTRC with I-HAB

- **An example of the SLS implementation of the NTRC method is a comparison to the I-HAB B1B CLA buffet assessment**
  - Mach Bin 5 FFN as test case, T05 – T55 sec
  - 'Truth' is B1B full CLA results for I-HAB
  - Base drive state made with B1B SLS NTRC model (no payload)
  - Assessment is NTRC using I-HAB payload, damping schedule same as coupled vehicle, 500 Hz resolution of time domain results
  - No adjustments to applied buffet load

- **Three simulations were made for assessment purposes**
  - Run 1 – time domain solution of coupled SLS/I-HAB system
  - Run 2 – time domain solution of SLS, no payload
  - Run 3 – NTRC base drive of I-HAB using results from [2]
  - Figure shows comparison of Run 1 results to Run 3 results

- **Results comparison used IHAB LTMs**
  - CG Acceleration (CGA) shown

- **Results are generally as expected**
  - Trends from NTRC are a good match with SLS integrated vehicle CLA
  - Coverage factor developed to envelope CLA results



I-HAB Buffet Example CGA ABS MAX Comparison

Row	Description	ABS MAX		
		CLA	NTRC	% Diff
1	SE 0 CG ACCEL T1	0.322	0.314	-2.4
2	SE 0 CG ACCEL T2	0.749	0.684	-8.7
3	SE 0 CG ACCEL T3	0.938	1.000	6.6
4	SE 0 CG ACCEL R1	0.033	0.033	0.2
5	SE 0 CG ACCEL R2	0.011	0.012	3.4
6	SE 0 CG ACCEL R3	0.013	0.012	-7.8

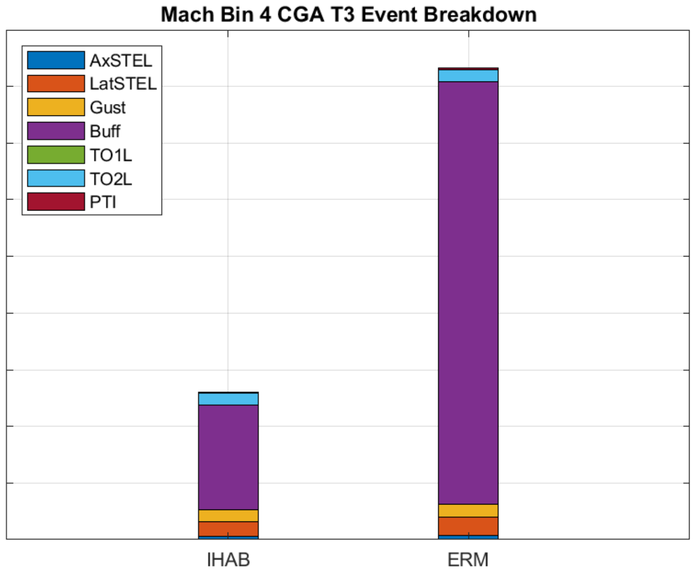
Note - table displays results normalized to largest parameter.

SLS B1B/ERM NTRC CLA Initial Analysis Results Synopsis

- **NTRC SLS/ERM assessment completed in May 2023**
  - Max/min responses for ACC, CGA, DSP, FRC, and IFF output transformation matrices (OTMs) provided to ESA/TAS-F

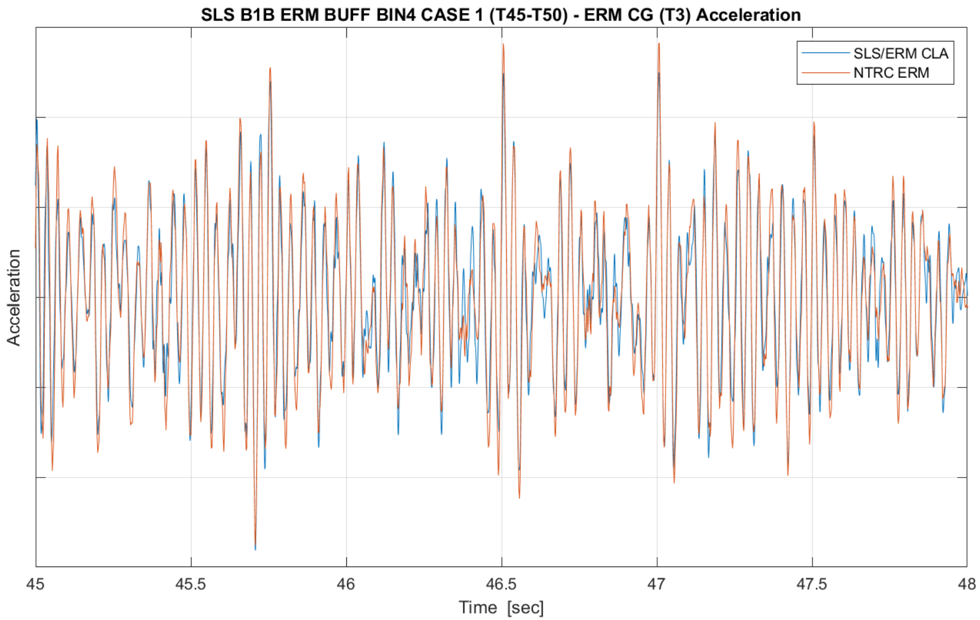
- **Prior to analysis, expectations were that ERM launch loads would be generally similar to I-HAB launch loads**
  - A comparison of I-HAB and ERM responses was presented with the final results package

- **Analysis results showed the ERM experiencing unexpectedly high lateral loads during the first transonic Mach bin**



- **Peak lateral ERM CG acceleration occurred during ascent in early transonic flight**
  - Upper left bar graph shows a comparison of I-HAB and ERM early transonic CGA responses and their relative contributing events
  - Primary contributing event is buffet

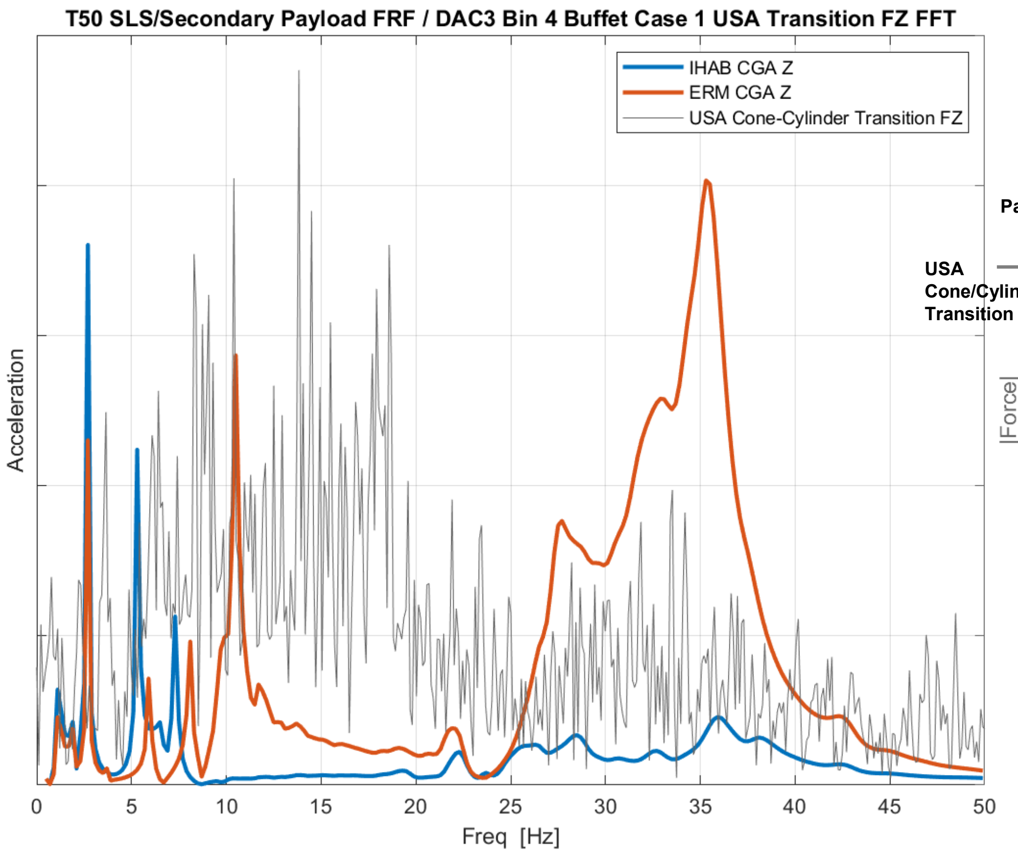
- **NTRC buffet verified with traditional CLA**
  - Coupled SLS/ERM CLA FEMs were used to perform spot checks of buffet results
  - NTRC correctly predicted CLA responses

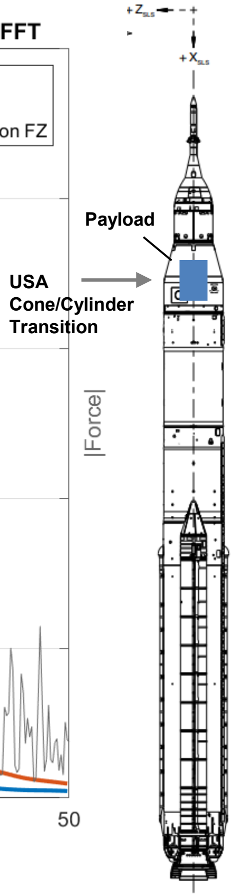


SLS B1B/ERM NTRC CLA Initial Results Assessment

- **A comparison of the co-manifested payload dynamics to an applied buffet force in the frequency domain provides an explanation for the ERM's higher responses**
  - Blue, red curves show frequency response function (FRF) results of the SLS B1B T50 / I-HAB and ERM structures, respectively
    - FRF input is a distributed FZ load at the SLS centerline aero grids
    - FRF output is the secondary payload (I-HAB, ERM) CG acceleration
  - Gray curve represents the FFT magnitude of the FZ buffet force applied to the USA Cone/Cylinder transition from the Mach 0.7/alpha=0/beta=0 buffet case

- **The SLS/ERM model is more reactive to forces with higher frequency content**
  - Particularly sensitive to loads at USA Cone/Cylinder Transition

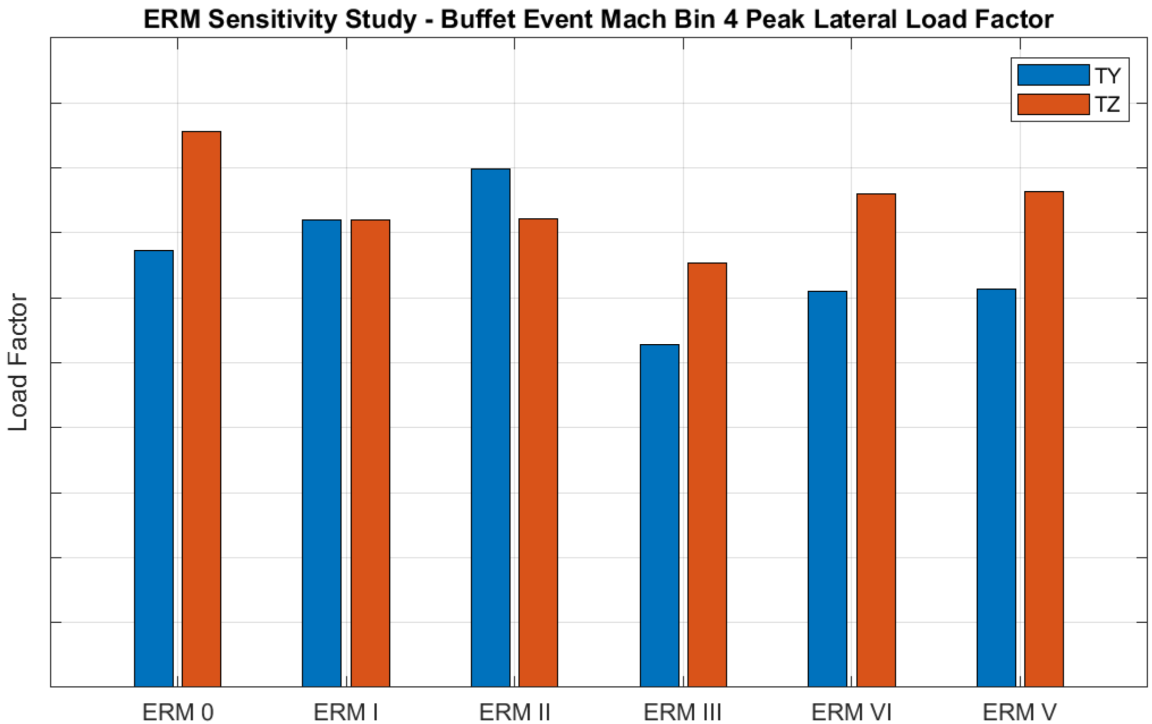




SLS B1B/ERM NTRC Sensitivity Study

- **ERM is currently in a design refinement process. As part of that process, ESA/TAS-F provided MSFC with five (5) simplified ERM finite element models (FEMs) to perform a launch load sensitivity study**
- **Due to time and resource constraints, only a buffet assessment was conducted for each of the five ERM variant models**
- **Without the NTRC process, the sensitivity study would have been infeasible given SLS resource limitations**
- **Equivalent lateral load factors were developed using buffet event results**
  - Assuming the ERM is constrained at the payload attach ring, the load factor represents the equivalent lateral static load applied to the ERM CG required to represent the peak base bending moment
- **The plot shows a comparison of the maximum equivalent quasi-static load factors for Mach Bin 4**
  - Each ERM SS model variant (I-V) yields similar or lower load factors compared to the original ERM model (ERM 0)
  - Variant with lowest response buffet is ERM III

$$LF = \frac{M_{base}}{mass * L_{base}^{cg} * G}$$



NTRC/Standard CLA Resource Comparison

- **After the IHAB/ERM development work, SLS has a standard model, forcing function set, and Load Combination Equation(LCE) for NTRC payload analyses**
  - Initial development for the model, forcing functions, and LCE took about 3 months
- **If a payload requests CLA support that does not fit into a planned integrated vehicle load cycle schedule, NTRC support will be provided**
  - After receipt and checkout of payload model + LTMs, NTRC is run for boost phase ascent and liftoff
    - NTRC provided for regimes with significant dynamic content
    - Method could be used for prelaunch and core phase flight if requested by a payload
  - A very limited set of full CLA runs is also run as check cases
- **NTRC cycles are quicker and less resource intensive than standard CLA**
  - An SLS NTRC cycle takes approximately 2 analysts for 8 weeks
  - Standard SLS CLA cycles take approximately 6 analysts for 12 weeks
- **An intermediate approach to provide PDR-fidelity or higher results without requiring additional integrated vehicle CLAs is required to support payloads given current SLS LDI resource constraints**
- **Given the typical SLS cadence of 2-4 load cycles per year split among SLS Block 1, Block 1B, and Block 2, NTRC provides a key ability to support co-manifested payload development for the Artemis V+ missions**

Summary

- **The SLS coupled loads team needed a payload CLA tool to enable support of multiple co-manifested payloads for the B1B SLS vehicle**
  - Using the Kaufman et. al paper methodology, the SLS team developed an NTRC-based tool to meet this need
  - Benchmarking with the I-HAB results from a standard SLS CLA indicated that the NTRC implementation provided loads comparable to a full CLA
- **The NTRC process was successfully used to provide a set of refined loads for the ERM spacecraft for the SLS B1B liftoff and boost phase ascent environments**
  - Once baseline NTRC input forcing functions and accelerance matrices were developed for NTRC, evaluation took far less time than a typical SLS CLA
- **Initial SLS/ERM results yielded higher-than-expected responses**
  - Expected ERM launch loads to be similar to I-HAB loads
  - Primary loads contributor was transonic buffet
  - NTRC ERM response verified using traditional CLA simulation
- **Based on the initial analysis results, a sensitivity study was conducted using NTRC to develop SLS/ERM coupled loads for buffet events**
  - Evaluated the responses of five candidate ERM models to buffet loads
- **SLS plans to use NTRC to support payloads for Artemis V+ that cannot be included in integrated vehicle CLA cycles**