Welcome

“Model Informed” Vibroacoustic Scaling for Space Launch System Booster Forward Skirt, DYN-CY14-082

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Introduction

- Topics include:
  - *Overview of SLS Booster architecture*
  - *Changes to SLS Booster forward skirt vs Shuttle*
  - *Review of general vibroacoustic scaling method*
  - *Application of general scaling on SLS forward skirt*
  - *Model Informed vibroacoustic scaling overview*
  - *Application of Model Informed scaling on forward skirt*
  - *Model considerations*
  - *Model validation and parametric study results*
  - *Conclusions*

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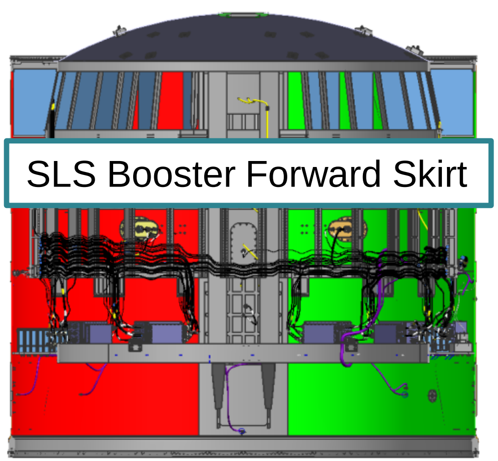
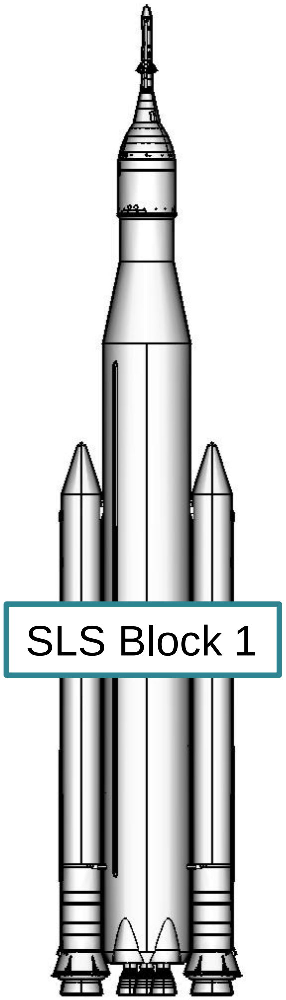
SLS Block 1 Boosters

Space Launch System (SLS) Block 1:

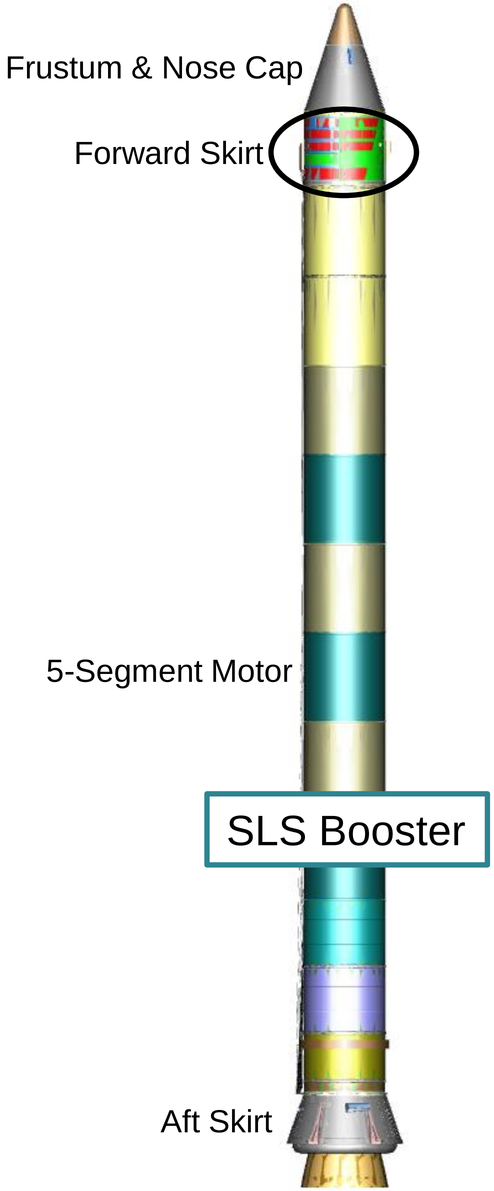
- 2 Space Shuttle (STS) derived solid rocket boosters (SRB)
  - 5-segment motor
  - Nozzle
  - Aft skirt with TVC system
  - Frustum and nose cap (no parachutes)
  - Forward skirt with avionics



SLS Booster Forward Skirt



SLS Block 1

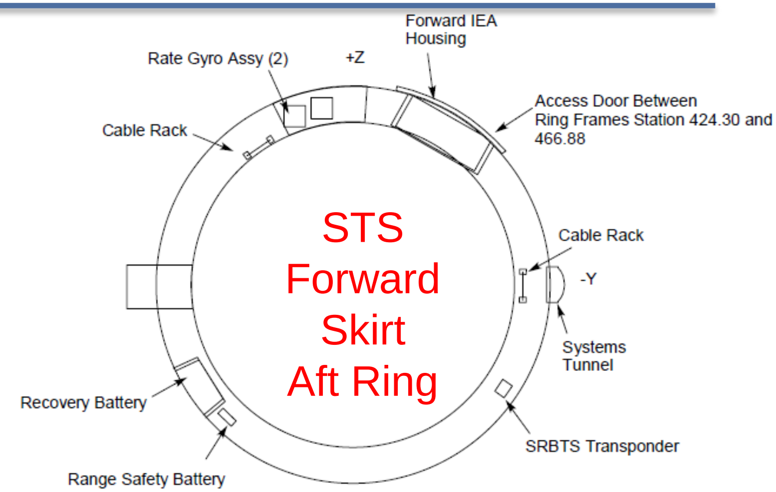


SLS Booster

SLS Forward Skirt Random Vibration Environments

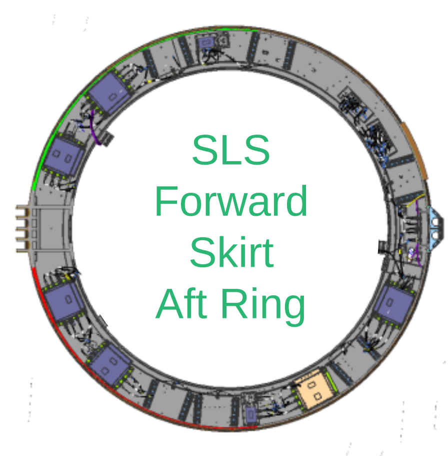
Forward skirt flight random vibration environments are driven by external fluctuating pressures (i.e., transonic aero-acoustics)

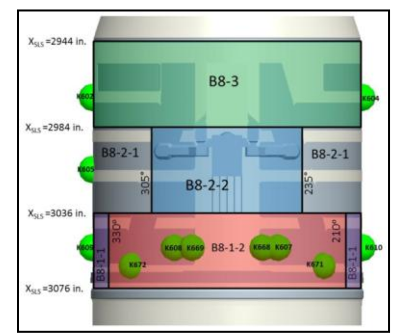
- SLS criteria predicted by scaling STS data



STS vs. SLS

- **Configuration differences**:
  - Additional components on aft ring
  - Removal of panels
  - Minor changes to forward skirt structure (addition of buckling stringers, cable brackets, etc.)
- **Aero-acoustic environment differences**:
  - Transonic aero-acoustic environments increased (based on wind tunnel testing)
  - Acoustic zones changed





Traditional Vibroacoustic Scaling (Barrett's Method)

- "Traditional" vibroacoustic scaling is described in NASA-TM-215902 as a "semi-empirical method of predicting the acoustically induced broadband random vibration criteria for component installations located on space vehicles"
- This scaling approach leverages measured data from a reference vehicle (STS SRB) and corrects for acoustic and design differences of the new vehicle (SLS)
- Scaling was used to predict environments for STS, Titan II, Saturn IB, and Saturn V

SLS random vibration environment

SLS acoustic criteria at location of interest

STS acoustic criteria at DFI accelerometer location

$$G_N(f) = G_R(f)\left[10^{\frac{dB_N(f)-dB_R(f)}{10}}\right]\left[\frac{M_R}{M_N}\right]\left[\frac{W_N}{W_N+W_C}\right]$$

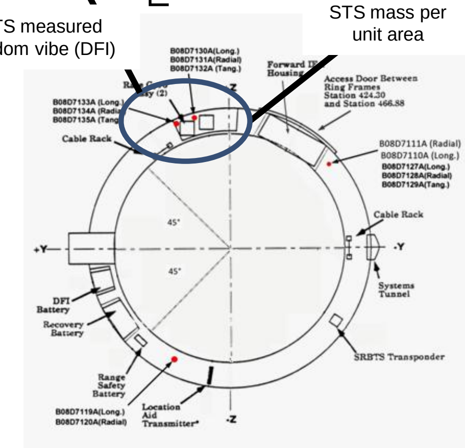
STS measured random vibe (DFI)

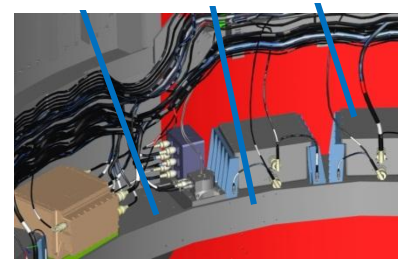
STS mass per unit area

SLS mass per unit area

SLS backup structure weight

SLS component weight





Traditional Scaling Assumptions and Limitations

Assumptions:

- Similar local structural configuration and similar dynamic characteristics (damping & natural frequencies) between reference and new vehicle
- Similar acoustic field (liftoff vs flight) between reference and new vehicle (i.e., same efficiency factor)
- Structure responds linearly with acoustic amplitude

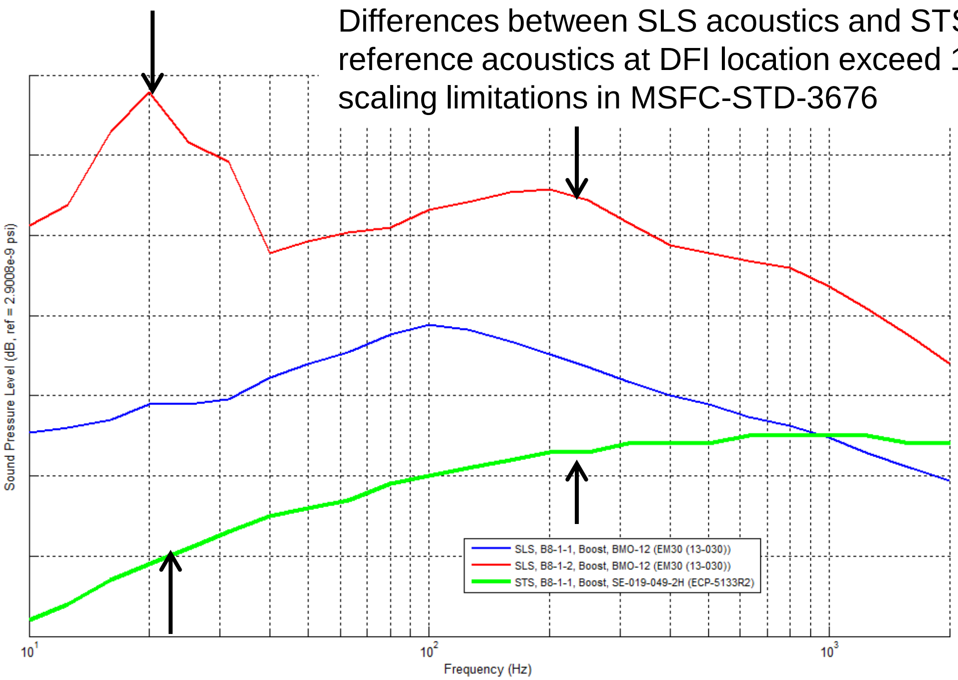
Limitations:

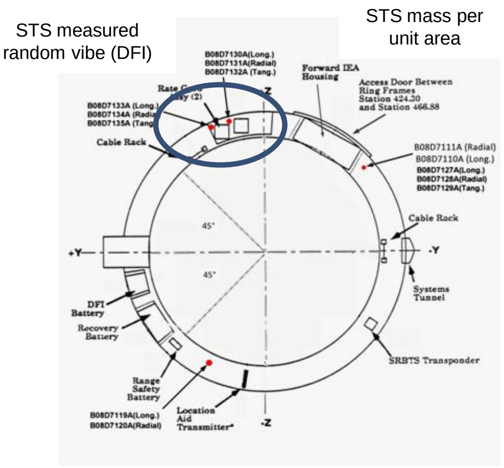
- Does not account for changes in local dynamics (only accounts for static mass effects)
- Does not account for energy transfer between zones
- Does not account for differences in acoustic zone size/shape
- Should not be used to scale upward beyond 10 dB without test data for validation

SLS Forward Skirt Random Vibration Prediction

- STS flight data was scaled using the traditional scaling methodology to generate SLS Booster random vibration environments
- Large difference in SLS and STS acoustic criteria drove predictions of very severe random vibration environments
  - *Exceeded recommended 10 dB upward bound for scaling*
  - *Did not account for changes in acoustic environments in other forward skirt zones, changes in acoustic zone sizes, or energy smearing between zones*

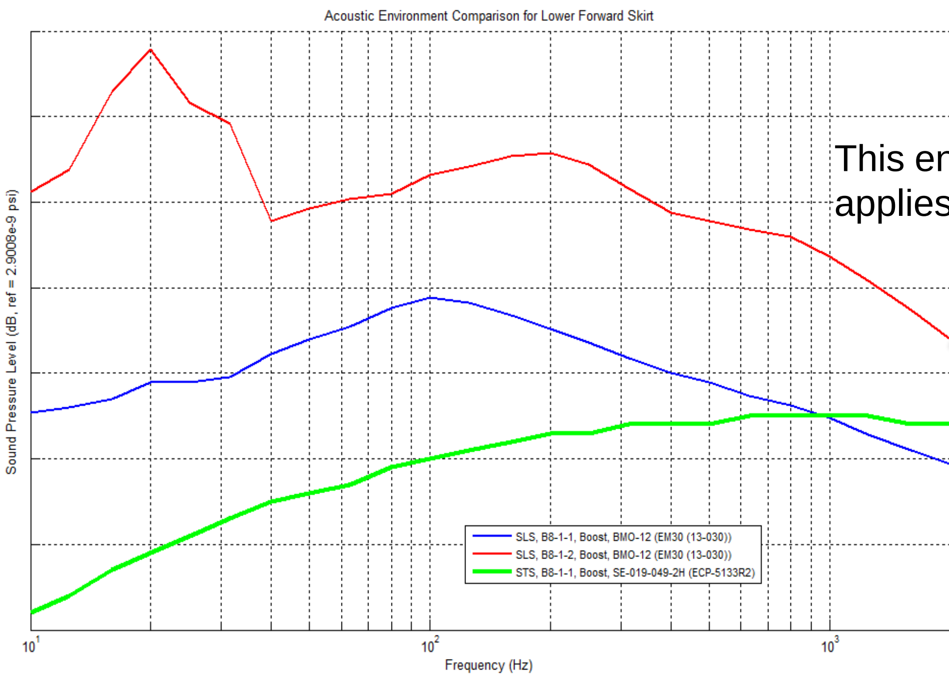
Differences between SLS acoustics and STS reference acoustics at DFI location exceed 10 dB scaling limitations in MSFC-STD-3676





Zonal Environment Application

Large difference in acoustic environment within a few inches on the structure is difficult to scale



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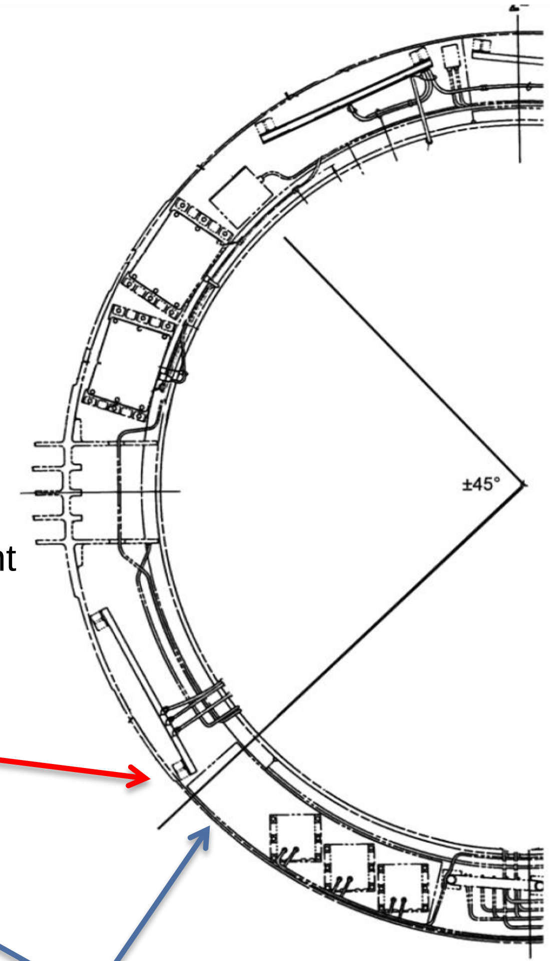

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Model Informed Vibroacoustic Scaling

To more accurately account for the aero-acoustic environment changes and configuration changes, VA One models were used to derive the acoustic and mass/stiffness scaling factors:

Traditional Scaling:

$$G_N(f) = G_R(f)\left[\frac{P_N(f)}{P_R(f)}\right]^2\left[\frac{M_R}{M_N}\right]$$

Model-based Scaling:

$$G_N(f) = G_R(f)\left[\frac{P_{N,Model}(f)}{P_{R,Model}(f)}\right]\left[\frac{M_{N,Model}(f)}{M_{R,Model}(f)}\right]$$

STS DFI data still used

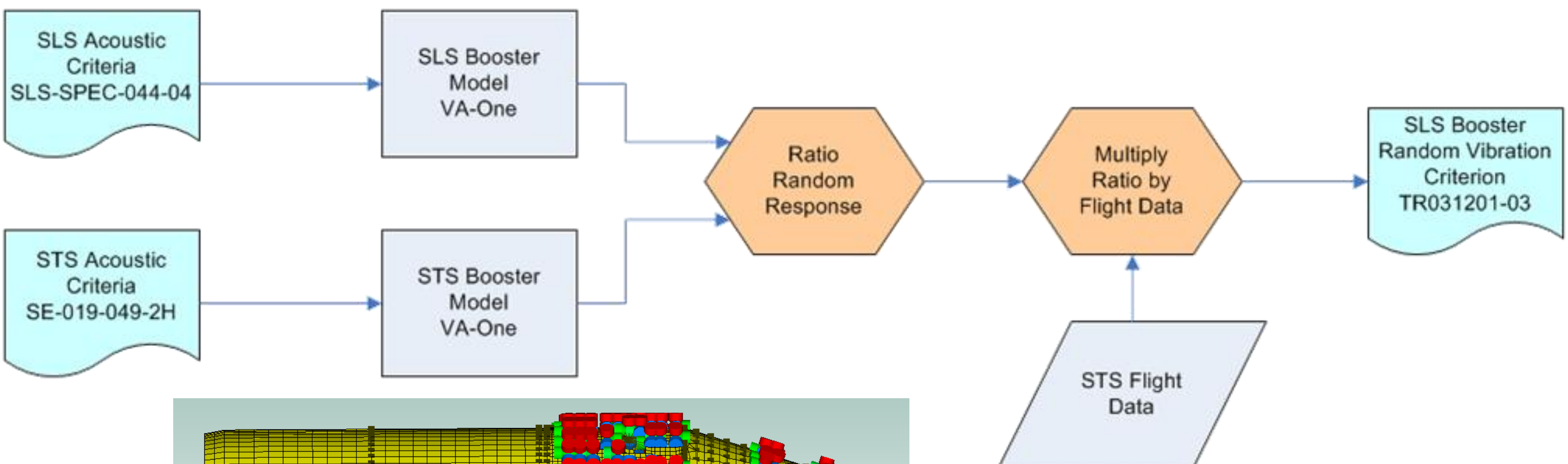
Acoustic-driven response scale factor (SLS model and SLS acoustics divided by SLS model and STS acoustics) – acoustic change

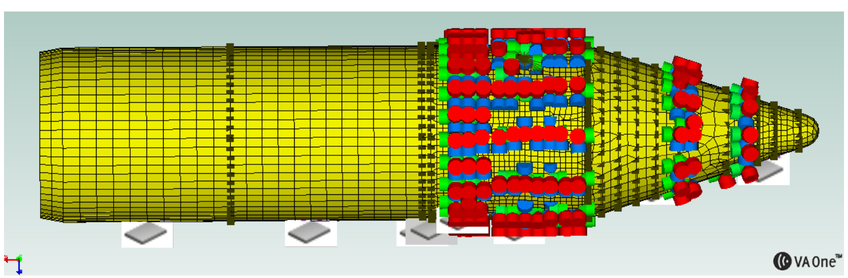
Model based mass and stiffness scale factor (SLS model and STS acoustics divided by STS model and STS acoustics) – model change

Model Informed Vibroacoustic Scaling Flow Diagram

Model-based scaling approach shown in the flow diagram

- STS flight data was scaled to generate SLS Booster random vibration environments
- Model-based scaling results used in low to mid frequencies, depending on model refinement
  - *Traditional scaling results defined criteria at higher frequencies (alternatively, SEA model-based scaling could have been employed)*

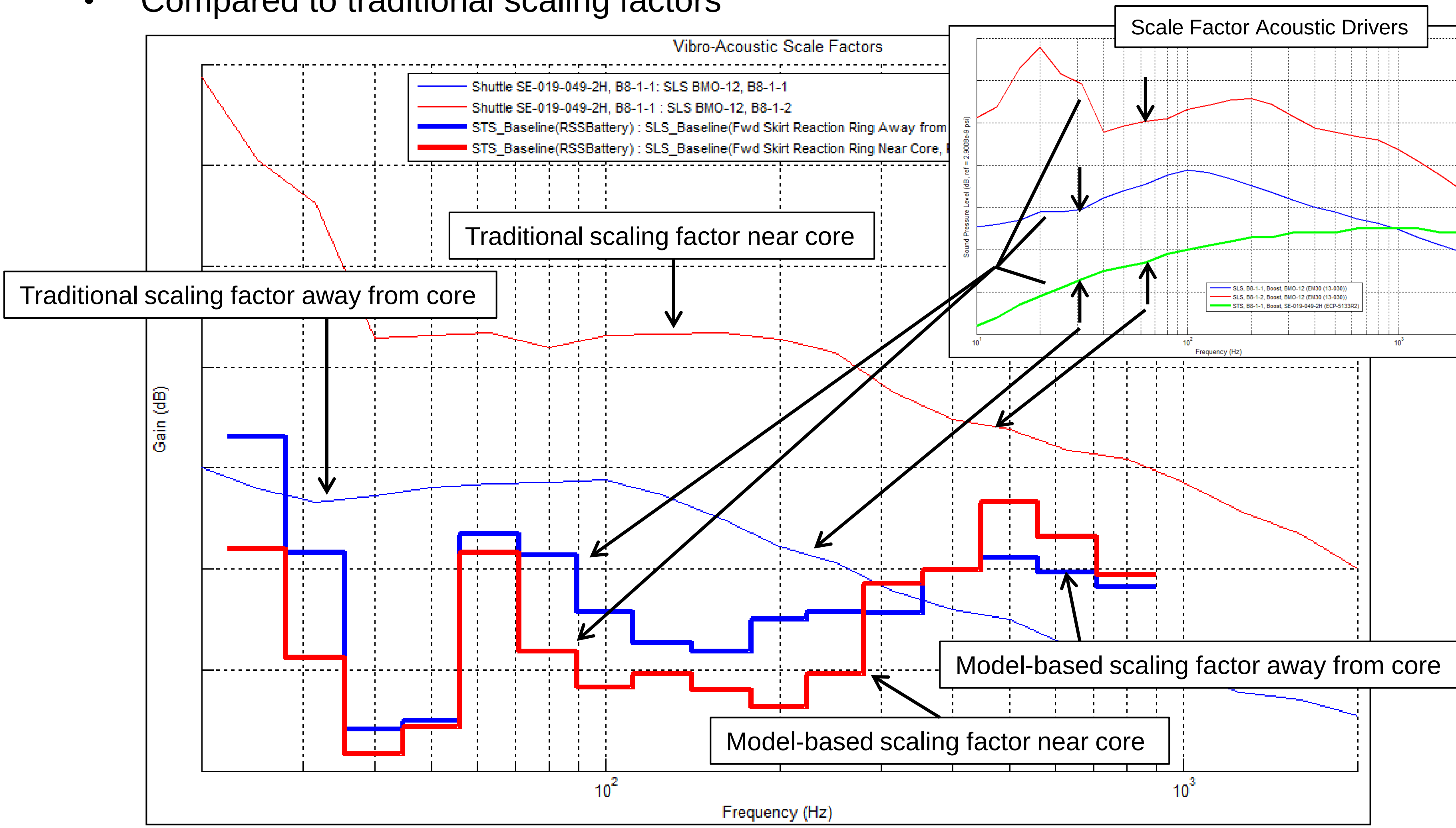




Model Informed Vibroacoustic Scaling Example

Example scale factors for the forward skirt aft ring are shown:

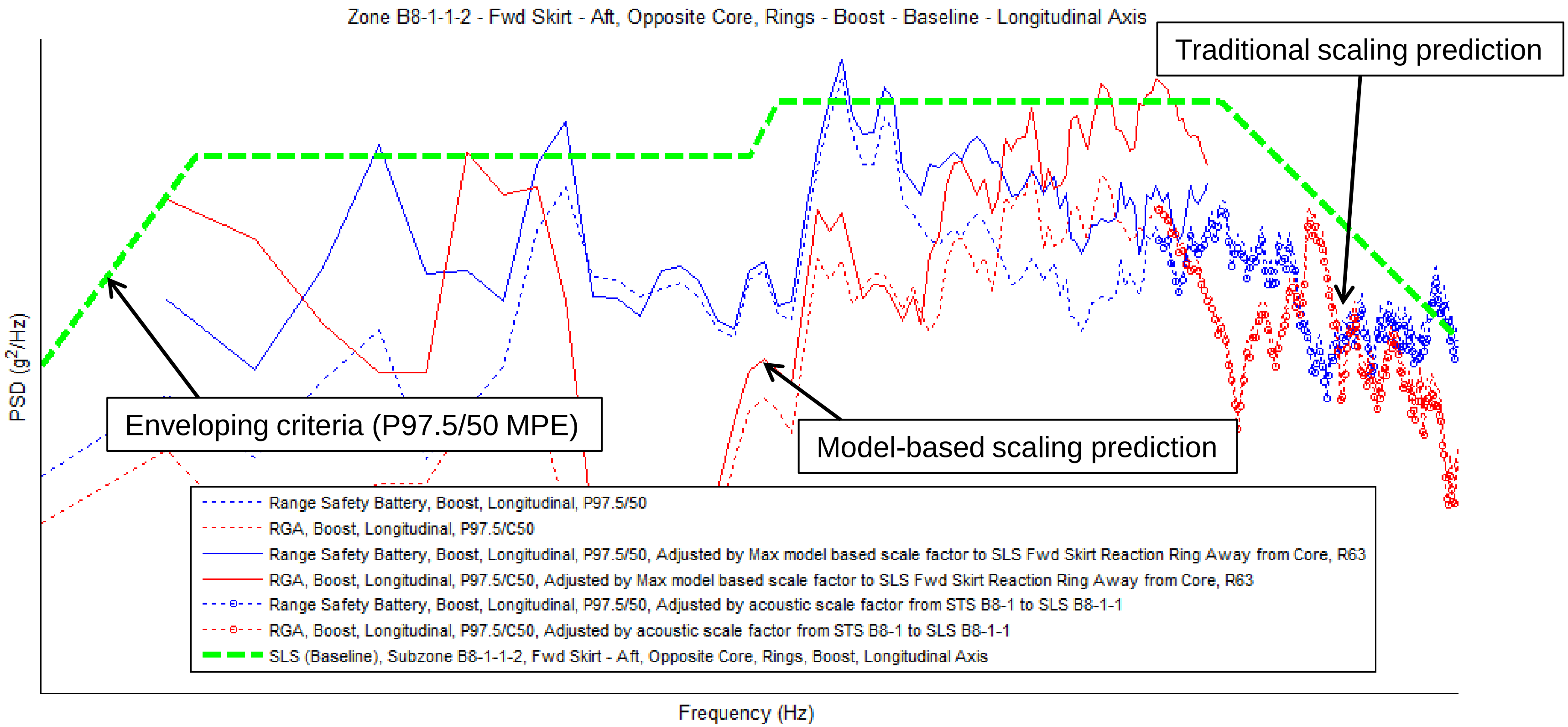
- Compared to traditional scaling factors



Random Vibration Criteria

Random vibration criteria is generated by enveloping scaling predictions

- Some engineering judgment is required to keep slopes within test equipment capability, clip peaks, and cover frequency uncertainty



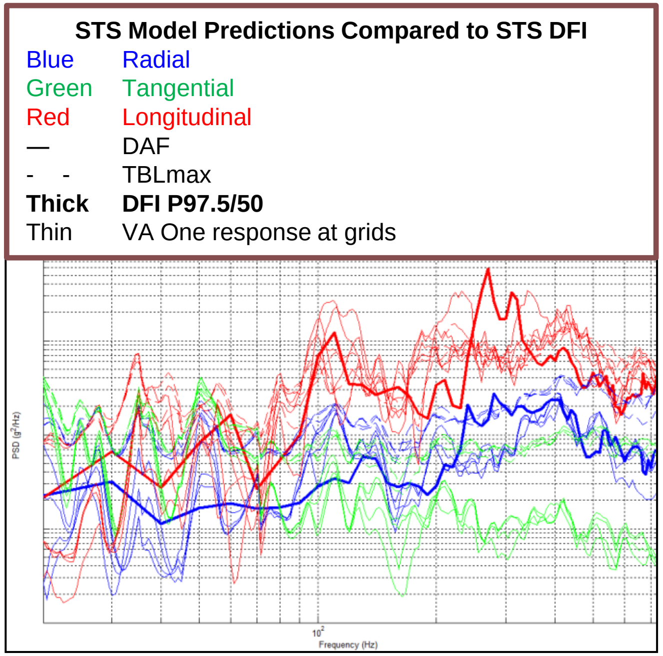
Model Considerations

- Ensure FE model is of sufficient accuracy to define modal response up to frequency of interest (i.e., minimum of 4 elements per modal wavelength)
  - *For higher frequencies consider using SEA rather than FEA*
  - *Normal modes run may include higher fidelity model than needed for vibroacoustic solution*
- Ensure mesh density and acoustic zones are sufficient for application of external fluctuating pressure excitations
  - *Minimum of 3 elements per acoustic wavelength, 4 to 8 preferred*
  - *Maximize acoustic zone size (FE face size) to minimize low frequency error*
- Consider boundary conditions
- Ensure acoustic environments are defined for full structure to adequate spatial resolution
  - *Response sensitive to acoustic environment in nearby zones*
- Recommend using spatial average response (rather than individual nodal responses) to generate scale factors
  - *Detailed spatial response may be too sensitive to FE modelling assumptions*
- Solve for narrowband response (1/36 octave or so) and then post-process to coarser bandwidth (1/6 octave or so)

Model Verification and Validation

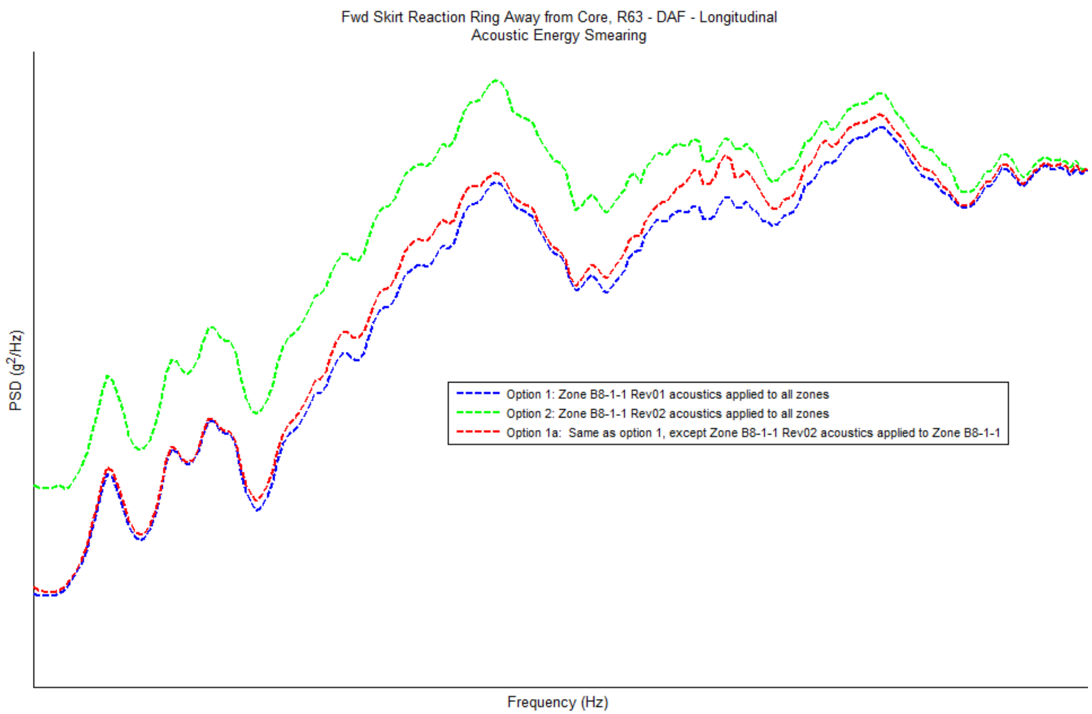
Model-based scaling uses model results on a relative basis, vs absolute prediction, which minimizes model induced error

- Model response ratio procedure reduces sensitivity of model assumptions
  - *STS and SLS models share same primary structure models* (differences are limited to SLS program changes)
- STS model results were compared to limited flight data, which showed that the model produced similar results to the STS flight response
- Parametric studies were performed to verify the model was being used and understood properly
  - Damping, energy smearing, component modeling, boundary condition influence, post-processing bandwidth, spatial averaging
- Currently evaluating the feasibility of a forward skirt model validation test



Model Parametric Study: Energy Smearing

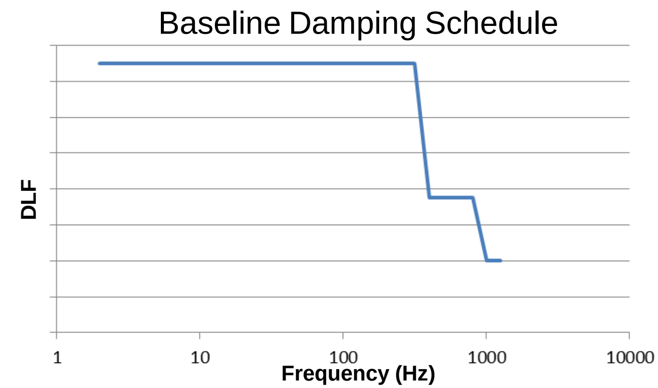
- Evaluated the change in response under different acoustic environments:
  - *Observed 1-to-1 increase in response after uniform acoustic environment change*
  - *Did not observe 1-to-1 increase in response after change in local acoustic environment*

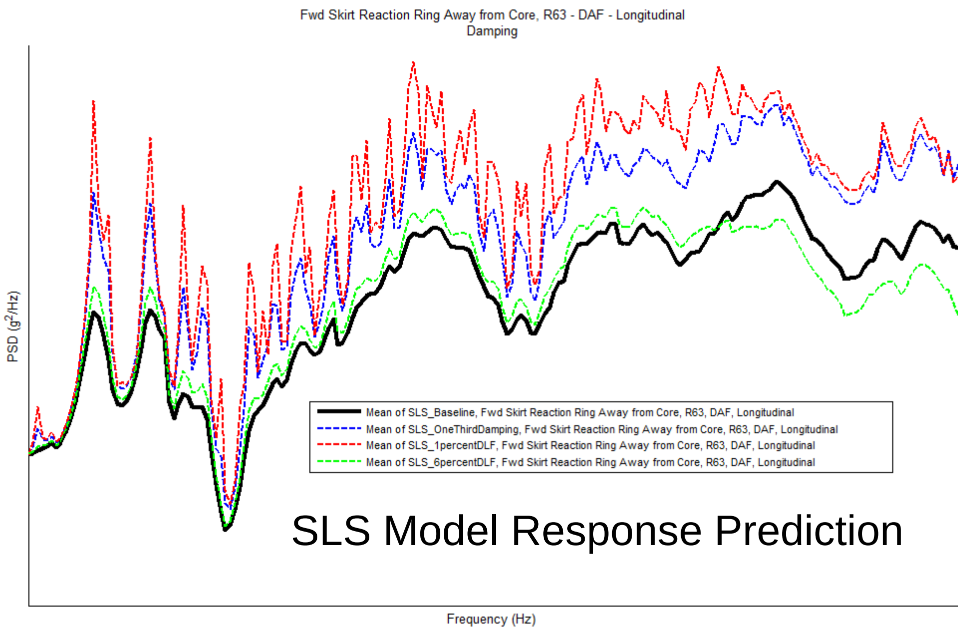


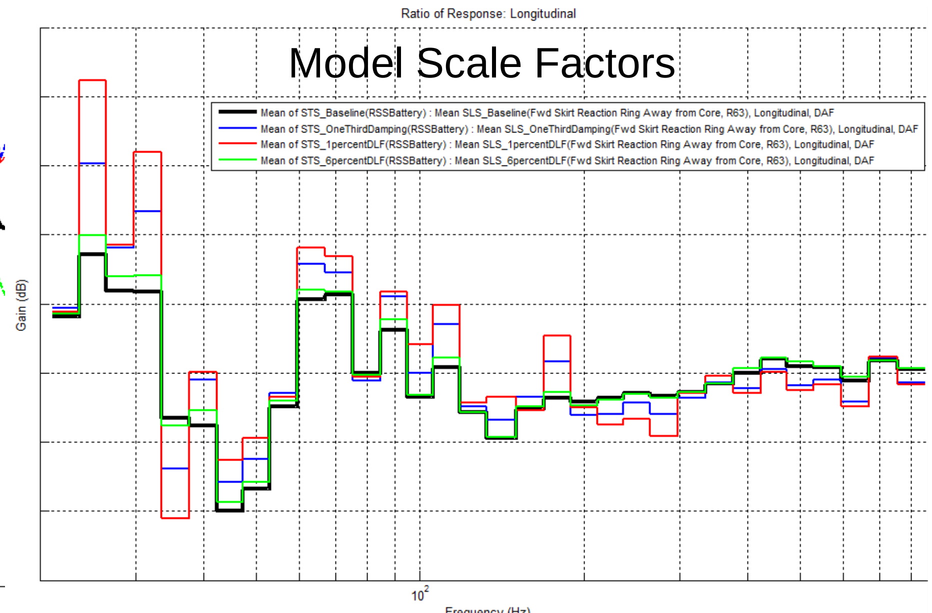
Response in local zone is a function of excitation in all zones (energy is smeared)

Model Parametric Study: Damping

- 4 different damping schedules evaluated:
  - *Baseline damping schedule*
  - *1/3 of baseline*
  - *0.5% critical (1% DLF)*
  - *3% critical (6% DLF)*



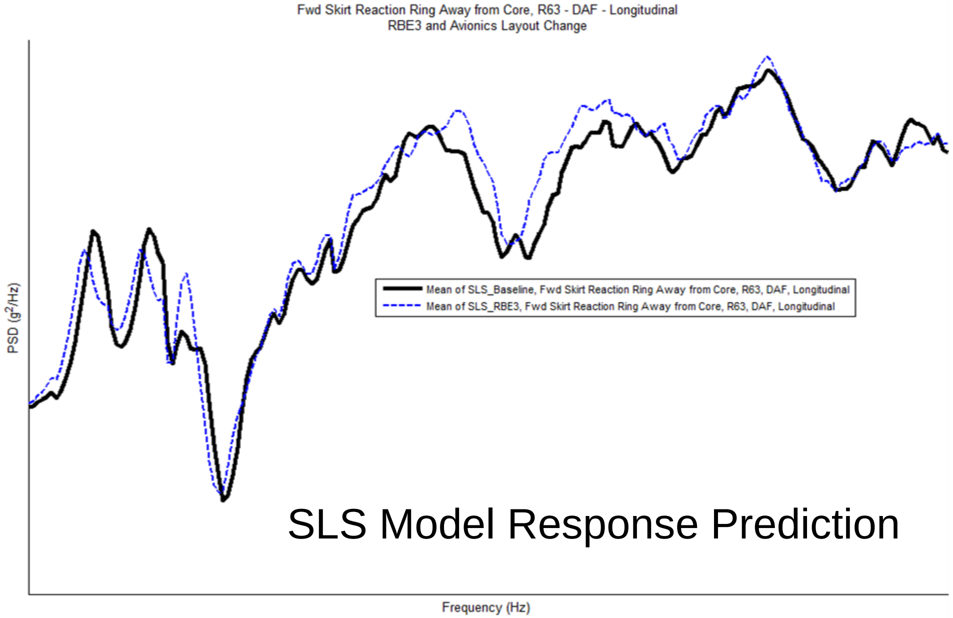


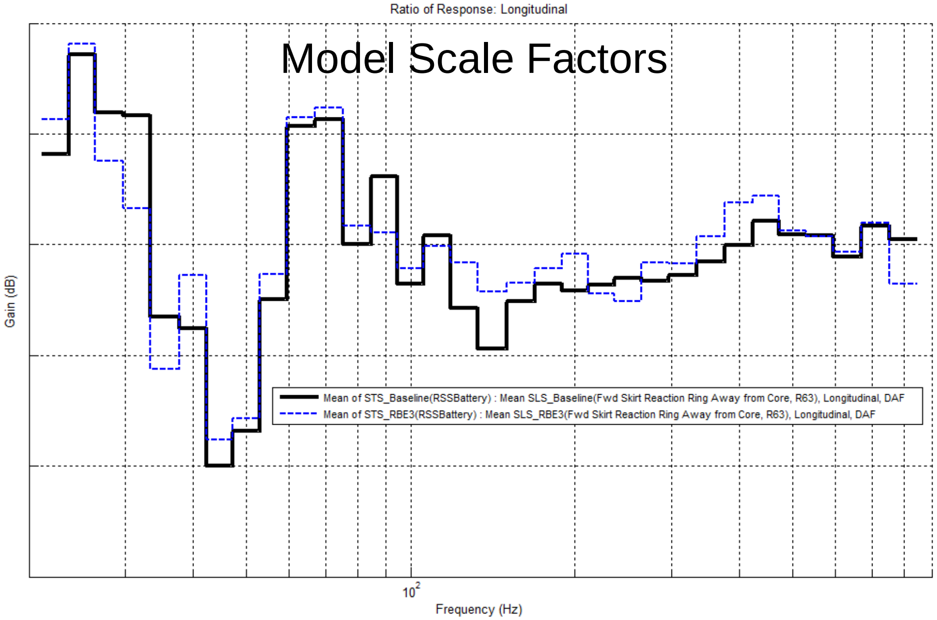


Raw response prediction is much more sensitive to damping than model scale factors (especially in high frequency)

Model Parametric Study: RBE3 vs RBE2 Components

- Avionics components included in model as lumped mass elements at CG:
  - *Baseline model used RBE2 elements*
  - *Evaluated use of RBE3 elements*

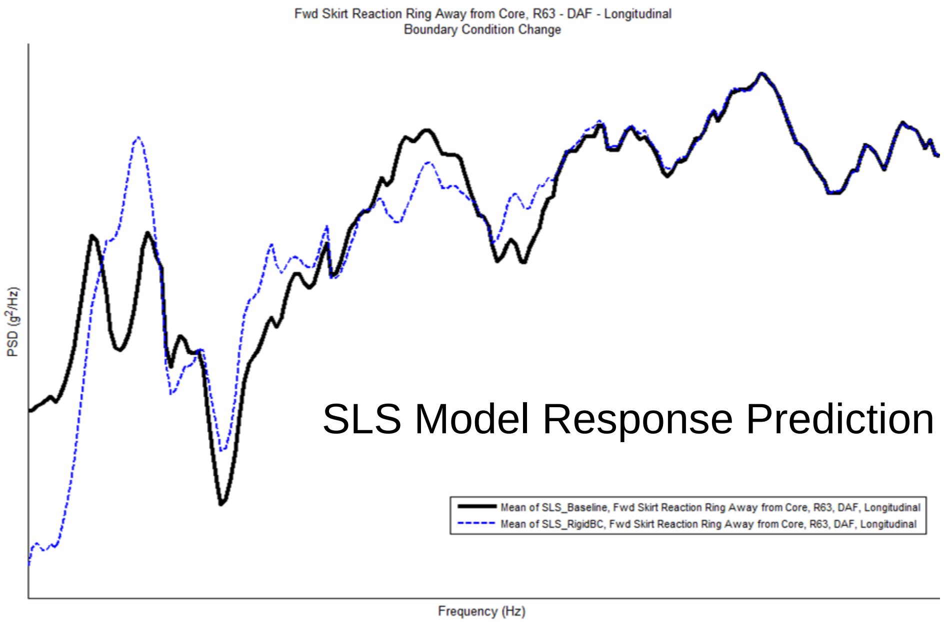


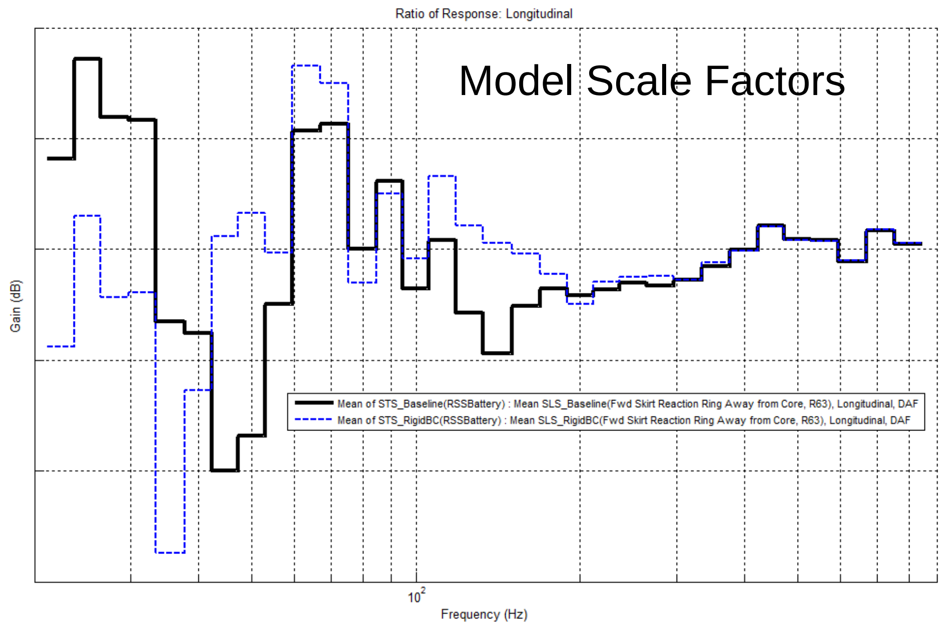


Change from RBE3 to RBE2 elements had less effect than expected

Model Parametric Study: Forward Attach BC

- Evaluated the impact from the forward attach boundary condition:
  - *Baseline model used flexible constraint at forward attach point*
  - *Evaluated rigid boundary condition (fully constrained at forward attach point)*



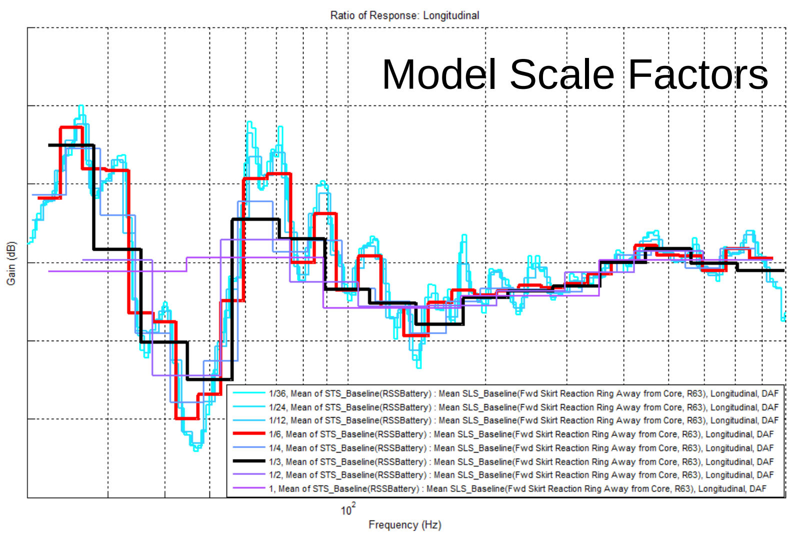


Forward attach boundary condition had large effect in low frequency

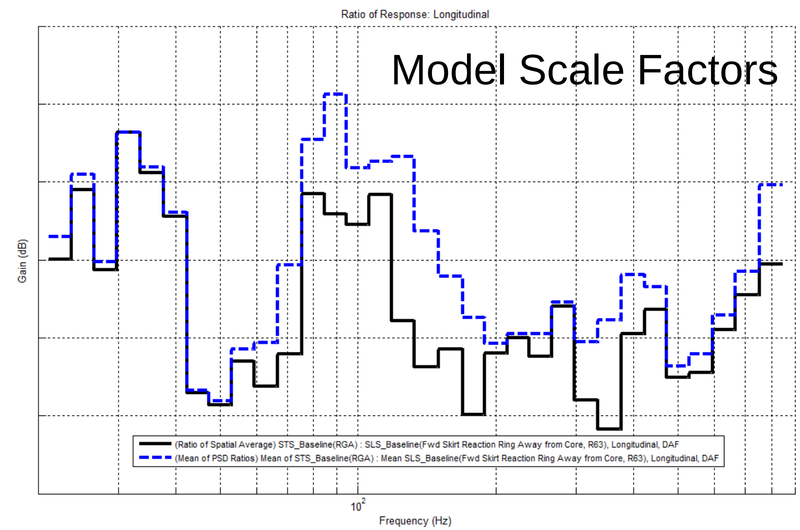
Model Parametric Study: Bandwidth & Spatial Avg

- Evaluated choice of post-processing bandwidth on model scale factors
  - 1/36, 1/24,1/12, 1/6, ¼, ½, and 1 octave bandwidth
  - Optimal bandwidth should not be overly sensitive to local model dynamic effects and should reduce dynamic range of data to avoid spurious scale factors from dividing by very small numbers
- Evaluated difference between spatial average response ratios vs average of node-to-node response ratios

Bandwidth



+/-15% Modulus Change



1/6 octave BW provides good approximation of results – spatial averaging recommended to reduce dynamic range/sensitivity to local response predictions

Conclusions

- Model informed vibroacoustic scaling provides advantages compared to traditional scaling and pure model predictions
  - Leverages model predictions, which can account for aero-acoustic environment changes and configuration changes
  - Leverages actual flight data, which includes correct physics that are generally not completely captured in analysis
  - Uses model results on a relative basis, vs absolute prediction, which minimizes model induced error
- Parametric study:
  - Acoustic energy tends to be smeared over the structure such that response at one location is sensitive to the total external acoustic environment, and not as sensitive to the local acoustic environment
    - Change to acoustic environments outside of zone of interest could affect environments
  - Damping schedule and boundary conditions have significant impact to results
  - Component models (RBE3 vs RBE2) had less impact to results than expected
  - Post-processing bandwidth is an important consideration
  - Spatial averaging has big impact to results

Validation testing is recommended to validate system damping schedule and FE model

Thank you