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N-O-MAD Research Institute

NOMAD XIII FINAL PRESENTATION

Implementing Multiple-Input-Multiple-Output Shock Capabilities

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U.S. DEPARTMENT of ENERGY

NNSA National Nuclear Security Administration

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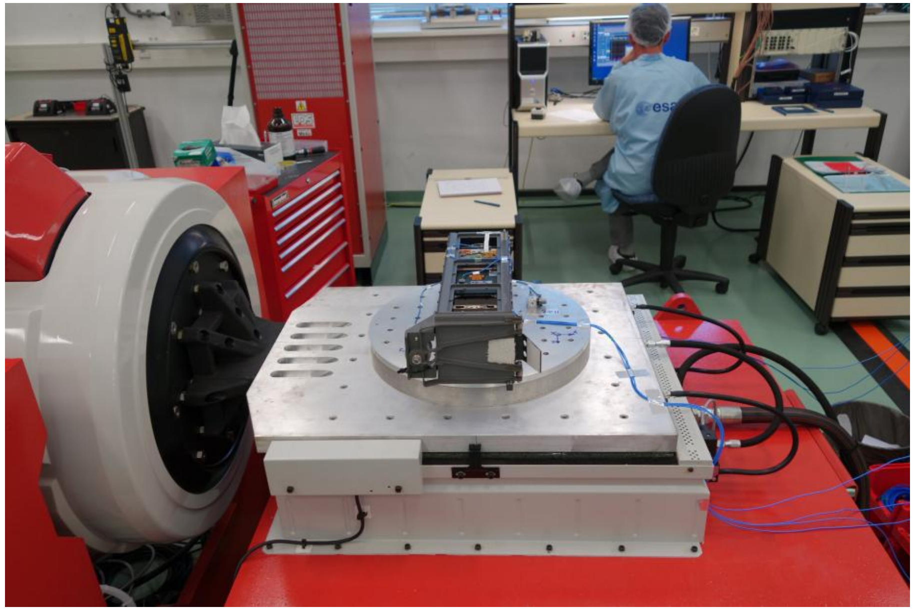
IN THIS PRESENTATION

- **Overview**
  - **Background & Motivation**
  - **Goals**
- Methodology
  - Environmental specification methods
  - Experimental setup
- Results
  - SRS metrics (single realization and NTL)
  - Method comparison
  - FEA model

MOTIVATION & BACKGROUND

- **Why shock testing?** Critical for validating engineering structures under realistic conditions
- **Traditional methods:** Single-axis testing has limitations—incorrect boundary conditions, resonance risks, costly redesigns
- **MIMO testing:** Offers more accurate boundary conditions, modular setups, and cost savings



Single-axis Testing Table [1]

6-DOF Shaker Table for MIMO Testing [2]

[1] https://www.esa.int/ESA_Multimedia/Images/2014/11/Vibration_test_set-up

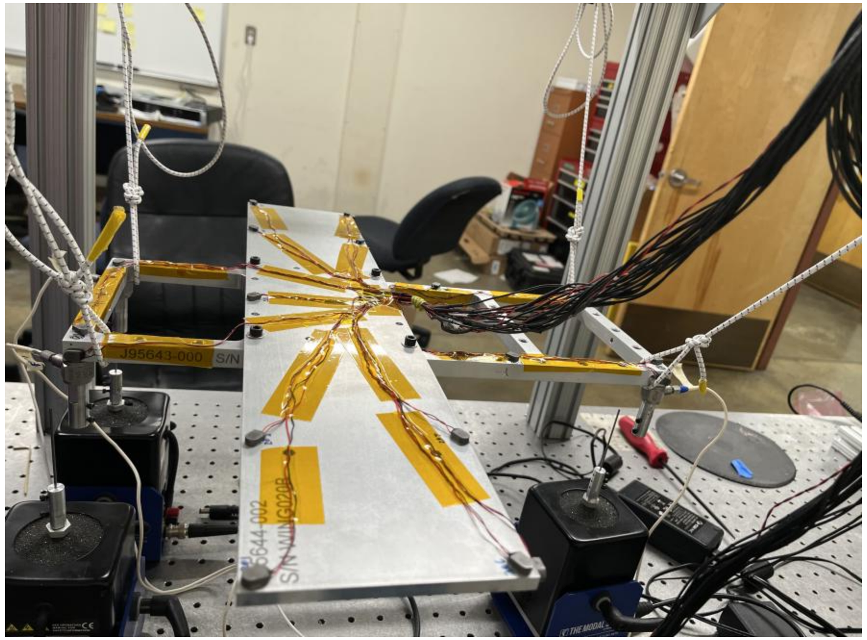
[2] https://www.sandia.gov/labnews/2024/07/25/transforming-testing-one-shake-at-a-time/#:~:text=%E2%80%9CIn%20single-axis%20testing%2C%20we%20test,multiple%20input%2C%20multiple%20output%20test.

PROJECT GOALS

- **Objective:** Demonstrate and validate MIMO shock specification and testing approaches

- **Key question:** How well can lab tests replicate real-world shock environments?

Aircraft Hard Landing [3]



Round Robin Frame-wing Structure

[3] https://picryl.com/media/a-us-navy-usn-f-14d-tomcat-fighter-squadron-two-vf-2-bounty-hunters-makes-a-c160fc

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METHODOLOGY OVERVIEW

Step 1: Impart shock load using modal hammer **(field test)**

Step 2: Run modal burst test for **system identification** and **basis data**

Step 3: Derive MIMO **shock specifications** and test inputs from field data and basis data

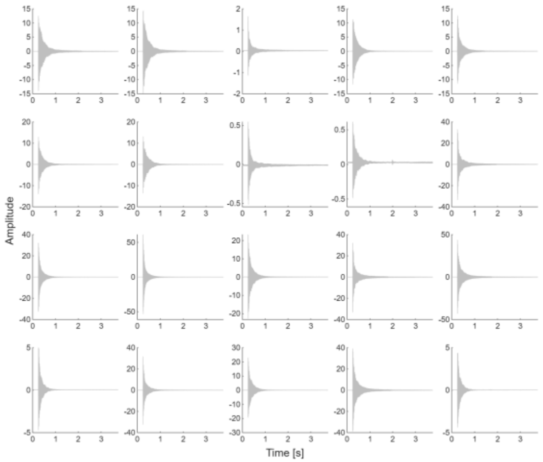
Step 4: Apply shaker inputs in lab, **collect experimental data**

Step 5: **Compare** MIMO response to target specification and field response

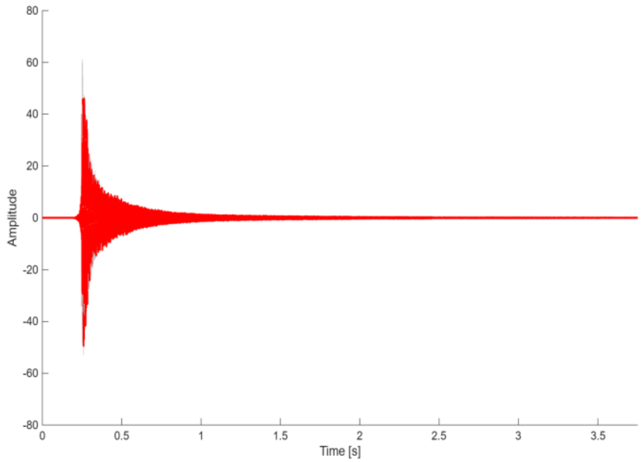
Step 6: **Validate** with Finite Element Analysis (FEA) modeling

MAXIMUM PREDICTED ENVIRONMENT

- **Goal:** Generate a synthetic maximum predicted environment (MPE) using a normal tolerance limit (NTL) based on the SRS, FFT, or wavelet nodal energies of an ensemble of field time histories (representation of extreme case for an environment)
- **NTL with P = 95% and C = 50%** → 50% confident that NTL will exceed 95% of the data
  - Population mean and standard deviation are unknown, so sample parameters are used
  - $P_{\mu,\sigma}(\underbrace{\bar{X} + kS}_{\textbf{NTL}} \geq X_p) = C$
  - n = **20 samples** were used



Ensemble of time histories from field testing

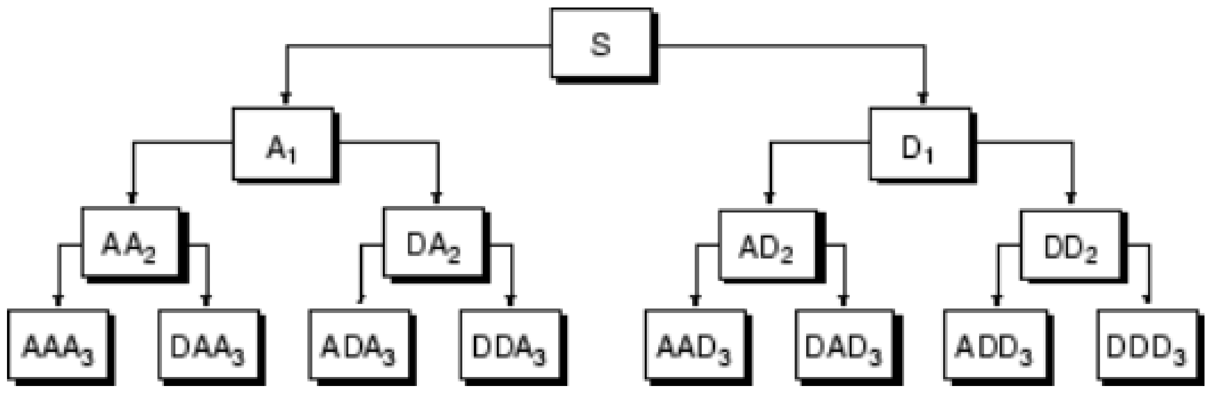


MPE time history

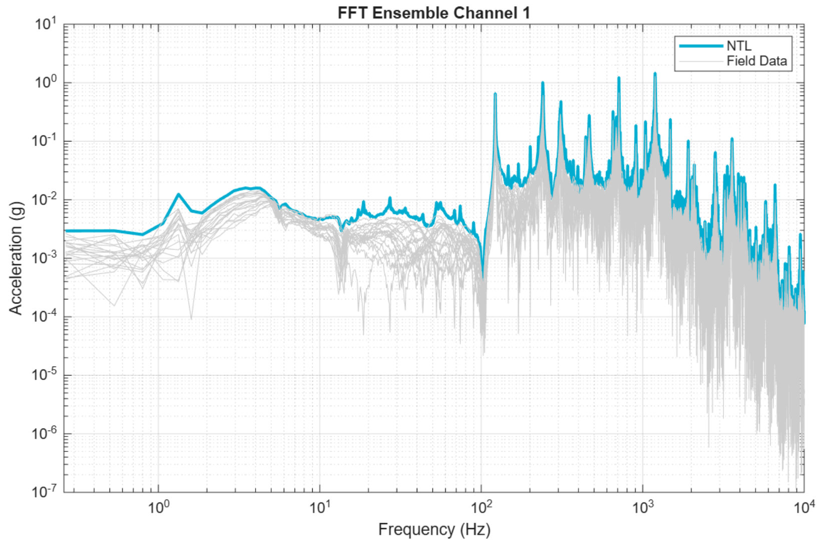
ENVIRONMENTAL SPECIFICATION METHODS

- **Direct time history methods**
  1. Wavelet packet transform (WPT)
  2. Fast Fourier transform (FFT)

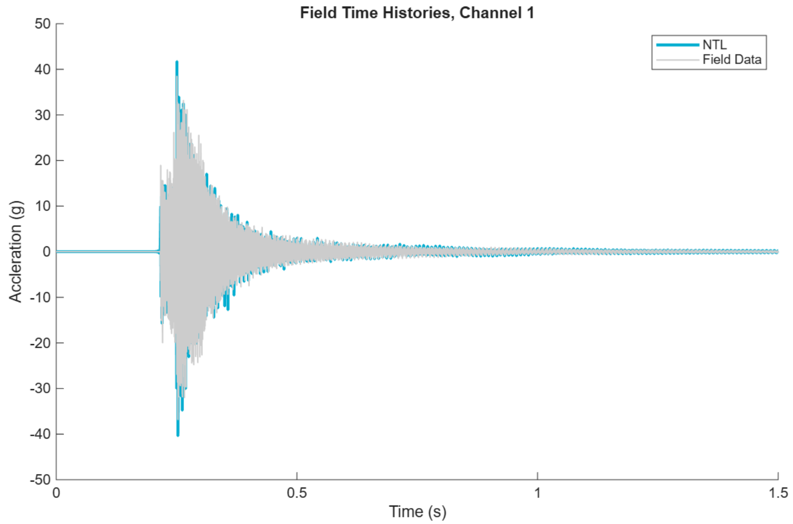
Wavelet packet decomposition tree with level 3 decomposition



FFT of NTL and ensemble samples for field test 2, FFT method



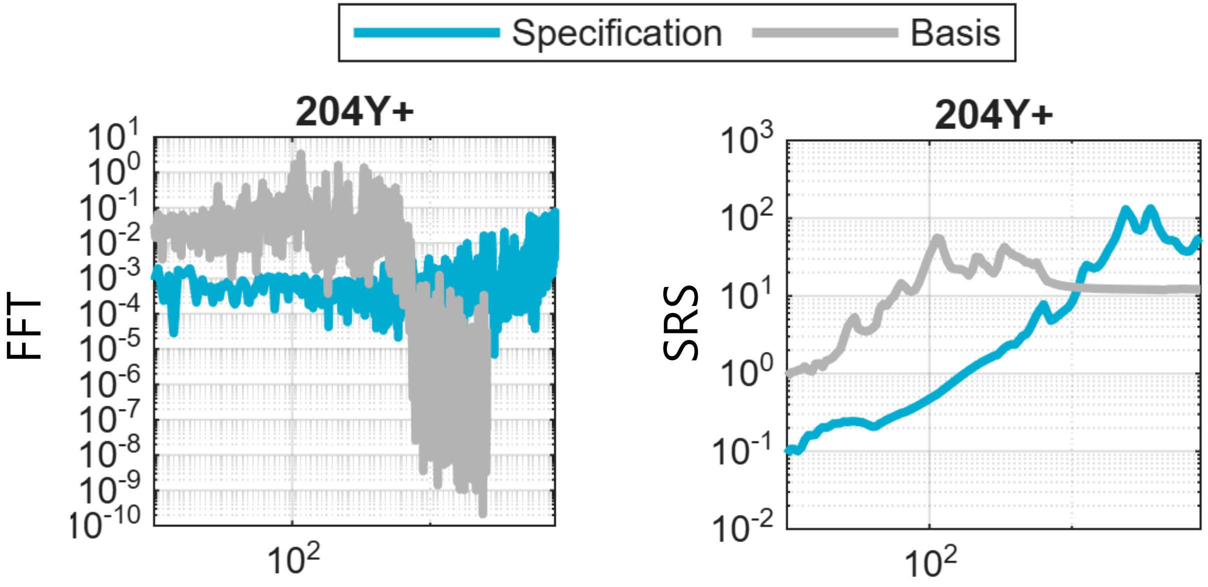
Time history of NTL and ensemble samples for field test 2, wavelet method



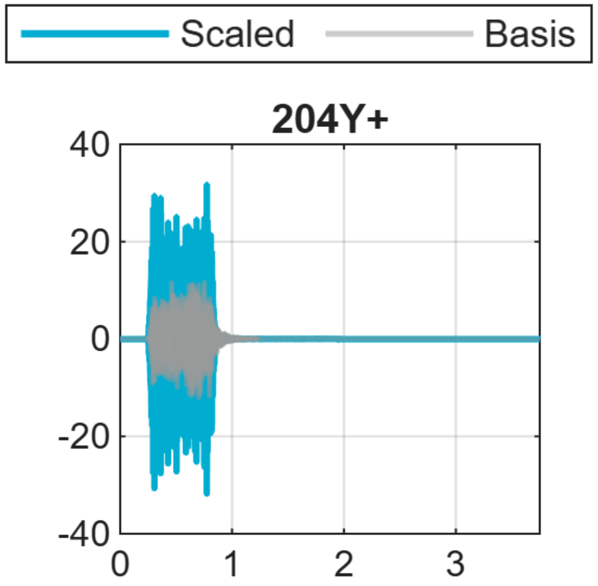
[4] https://www.mathworks.com/help/wavelet/ug/wavelet-packets.html

ENVIRONMENTAL SPECIFICATION METHODS

- **Basis scaling methods**
  3. WPT with basis scaling
  4. FFT with basis scaling
  5. SRS with basis scaling



Scale the SRS, FFT, or WPT nodal energy of the basis data to the same metric of the specification (field data NTL)

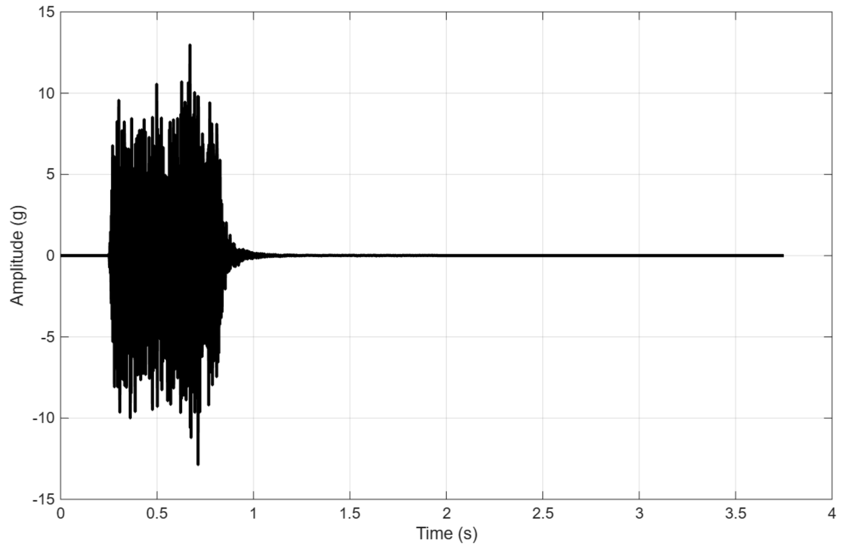


Convert back into time domain to obtain the time history that the MIMO experiment is controlled to

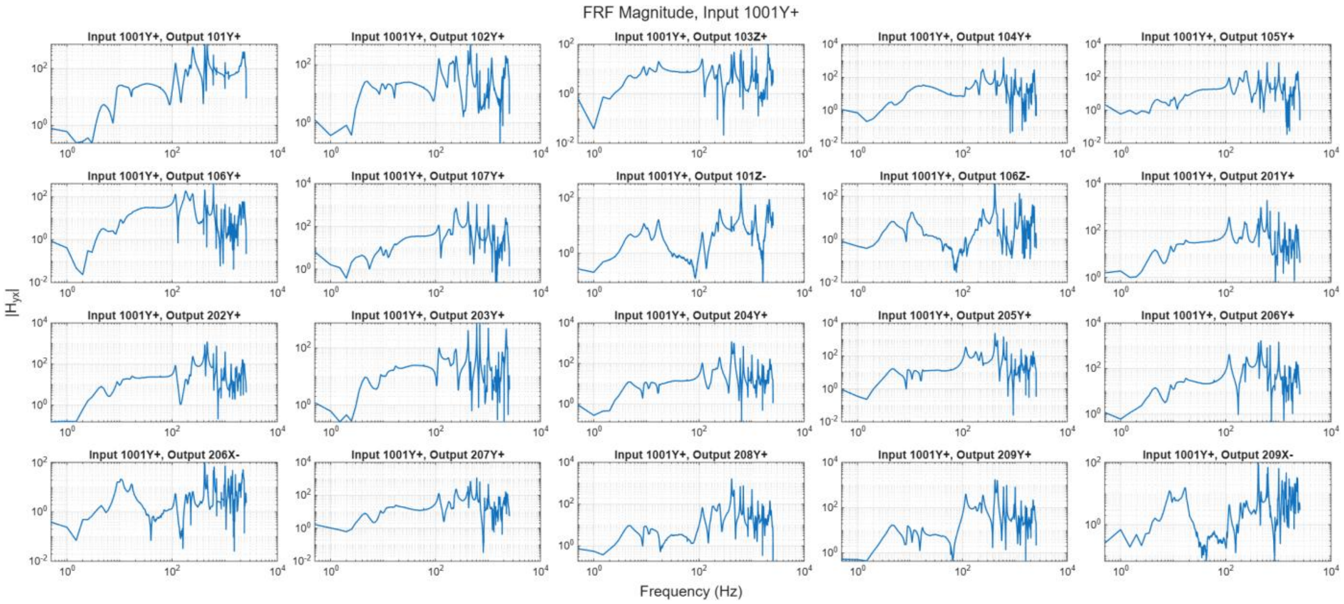
ENVIRONMENTAL SPECIFICATION SCRIPT OVERVIEW

1. Extract system ID data (burst random test, mimics shock)

Isolated burst from modal test time history with zero-padding for basis data, channel 1 (sample rate: 5120 Hz)



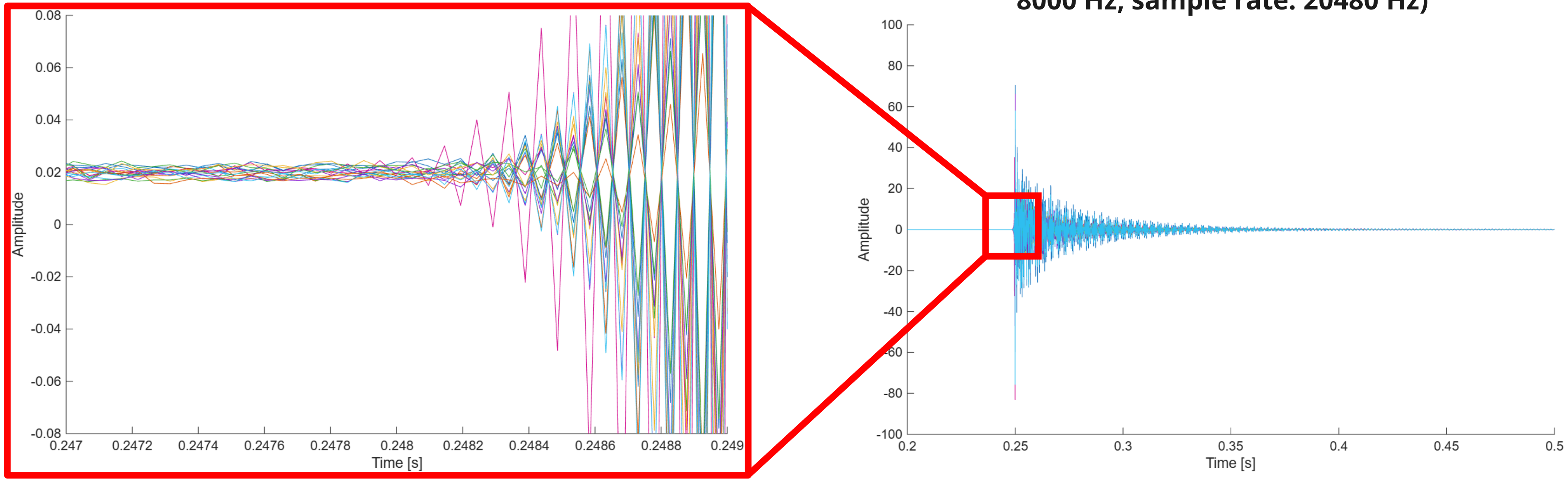
FRF magnitudes extracted from system ID repeated burst modal test



ENVIRONMENTAL SPECIFICATION SCRIPT OVERVIEW

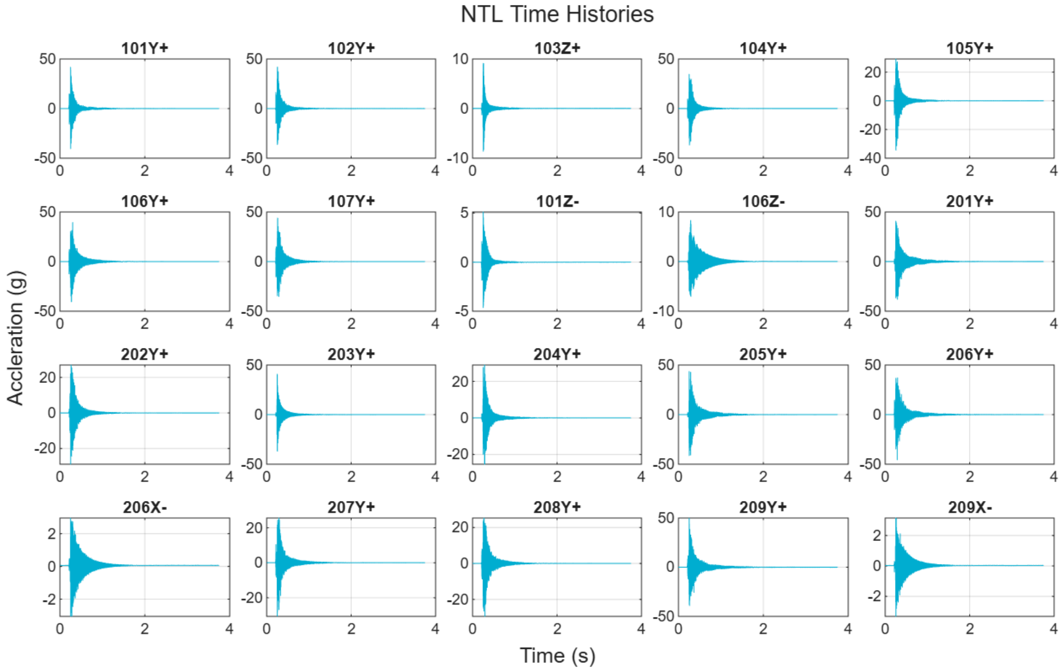
1. Extract system ID data (burst random test, mimics shock)
2. Extract field data and align

Field test 1 (simple shock landing) time histories by channel overlayed, wavelet method (bandwidth: 10-8000 Hz, sample rate: 20480 Hz)

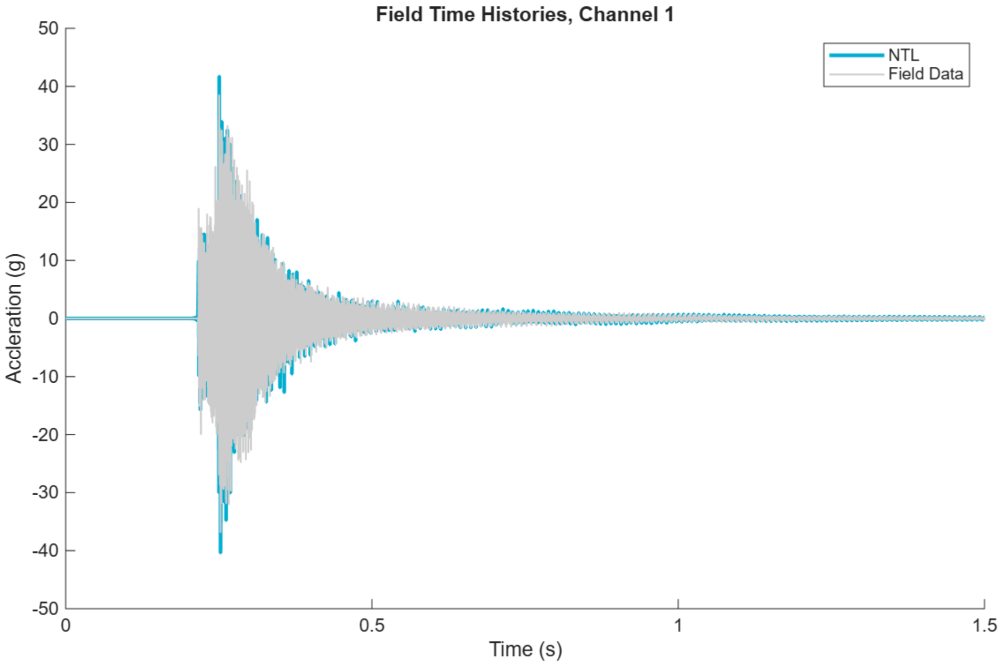


ENVIRONMENTAL SPECIFICATION SCRIPT OVERVIEW

1. Extract system ID data (burst random test, mimics shock)
2. Extract field data and align
3. Determine specification (MPE)



Wavelet-based MPE time histories by channel for field test 1



Wavelet-based MPE time history for channel 1

ENVIRONMENTAL SPECIFICATION SCRIPT OVERVIEW

1. Extract system ID data (burst random test, mimics shock)
2. Extract field data and align
3. Determine specification (MPE)
4. Find shaker drive voltages by solving the inverse problem (TWR)

"Inverse Problem"

Input (drive voltages) ← **Output (field data/MPE)**

$$X(\omega) = H_{yx}^{+}(\omega)Y(\omega)$$

FRF pseudoinverse
(from system ID)

ENVIRONMENTAL SPECIFICATION SCRIPT OVERVIEW

1. Extract system ID data (burst random test, mimics shock)
2. Extract field data and align
3. Determine specification (MPE)
4. Find shaker drive voltages by solving the inverse problem (TWR)
5. Solve the forward problem to predict the response

Input (drive voltages) $\longleftarrow$ **Output (field data/MPE)**

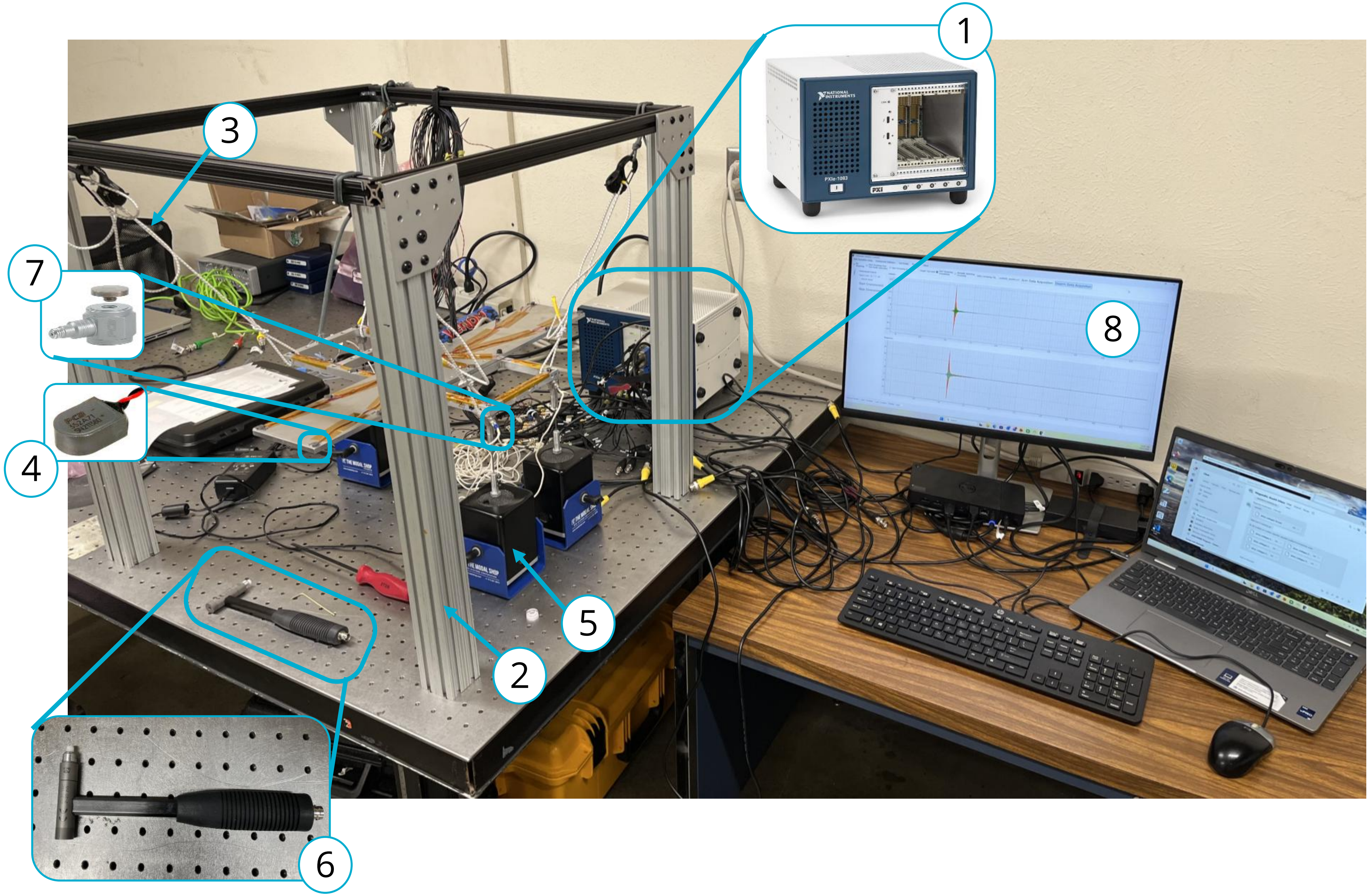
$$X(\omega) = H_{yx}^{+}(\omega)Y(\omega)$$

"Forward Problem"

$\longrightarrow$ **Output (predicted MIMO response)**

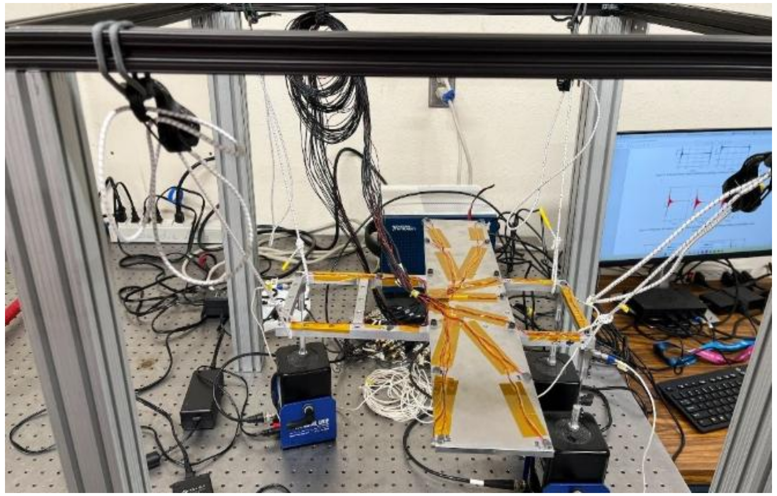
$$H_{yx}(\omega)X(\omega) = Y_p(\omega)$$

THE SETUP/INSTRUMENTATION

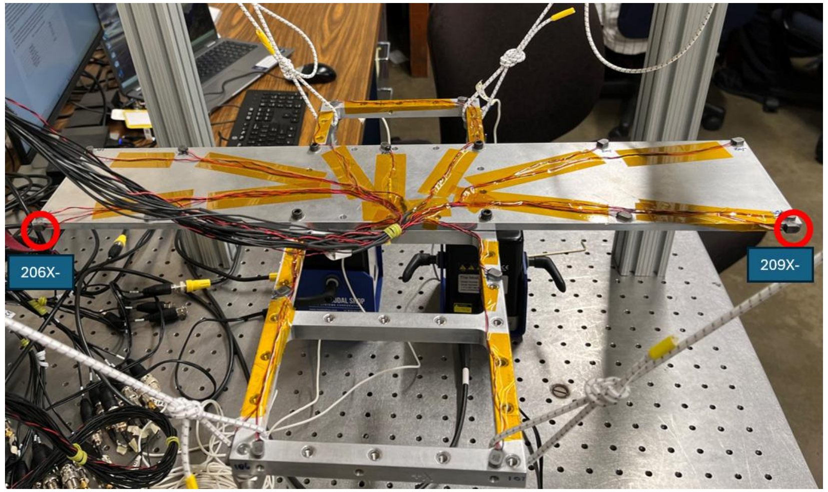


Instrumentation
1. NI PXIe-1083 DAQ
2. Optical rail frame
3. Bungee cords
4. PCB 352A71 uniaxial accelerometers
5. Mini SmartShakers
6. Modal hammer
7. PCB 208C03 force sensors
8. Rattlesnake Controller software

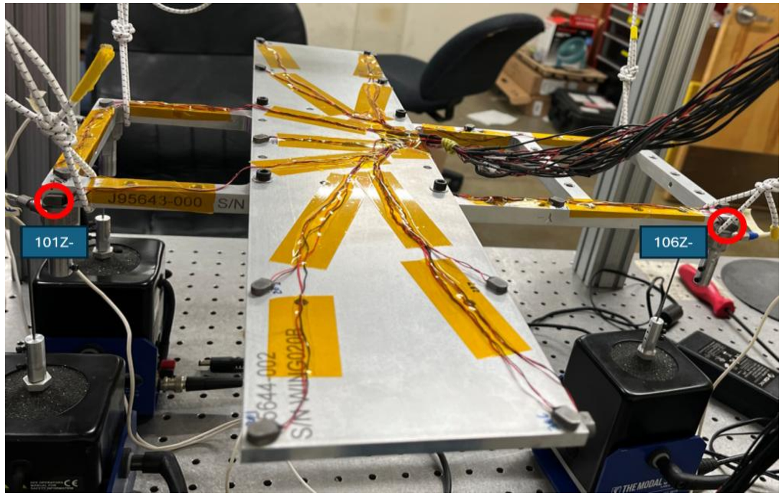
THE SETUP/INSTRUMENTATION



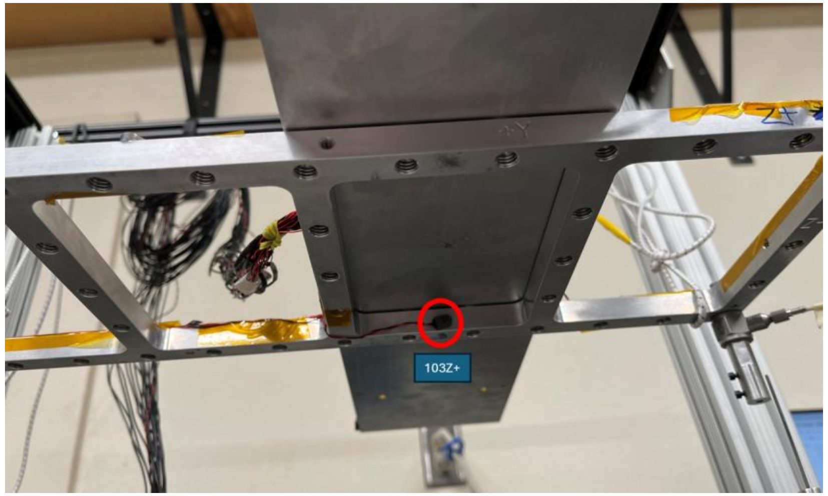
Frame-Wing Structure Experimental Setup



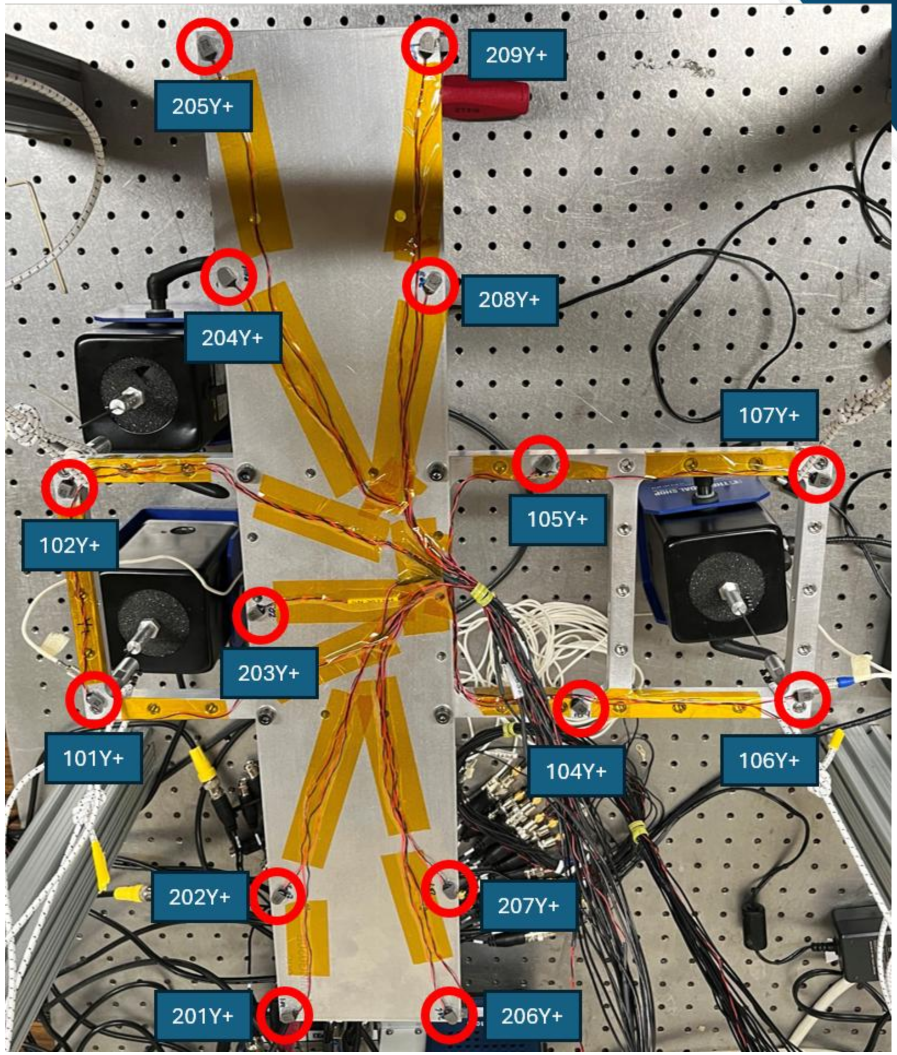
Wing Tips



Side of Frame



Underneath Wing



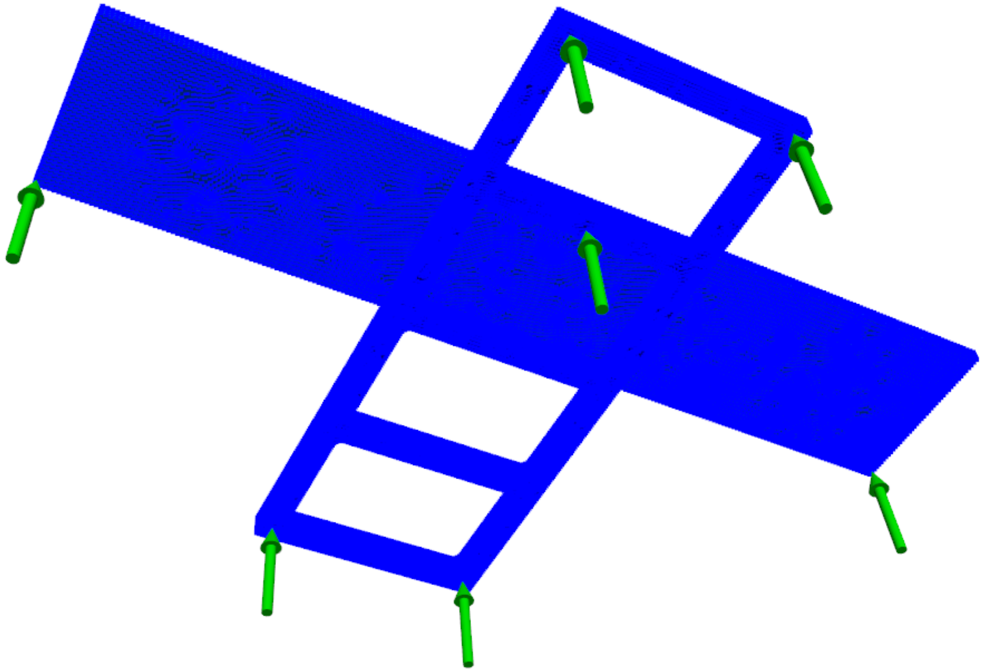
Accelerometer Location Across DUT

MODAL TESTING

- **Purpose**: Validate FE model
- **Procedure**: 7 modal hammer tests done using Rattlesnake's "Modal Testing" environment

Test specifications

Parameter	Value
Sampling Rate	4000 Hz
Frame Time	2 sec
Frequency Spacing	0.5 Hz
Averaging Type	Linear
Number of Averages	5
FRF Window	Rectangle

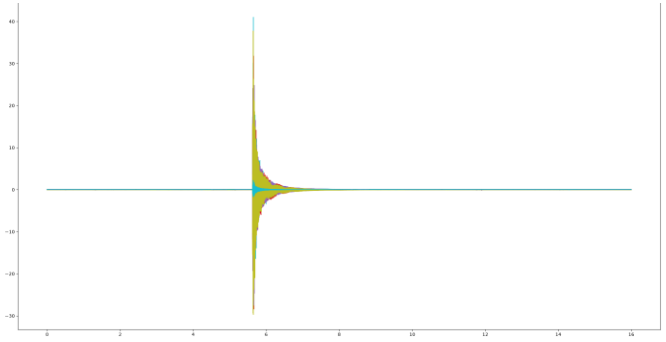


Impact Hammer Locations for Modal Tests

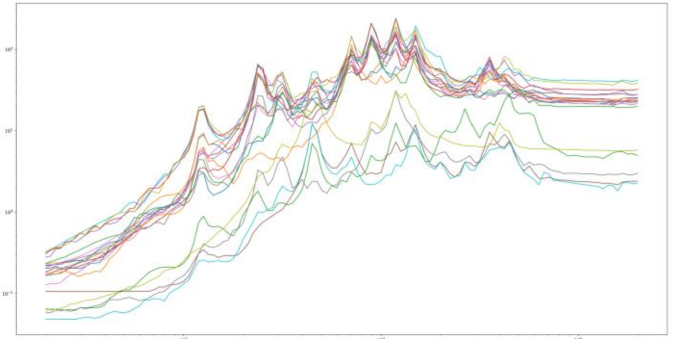
FIELD TESTING

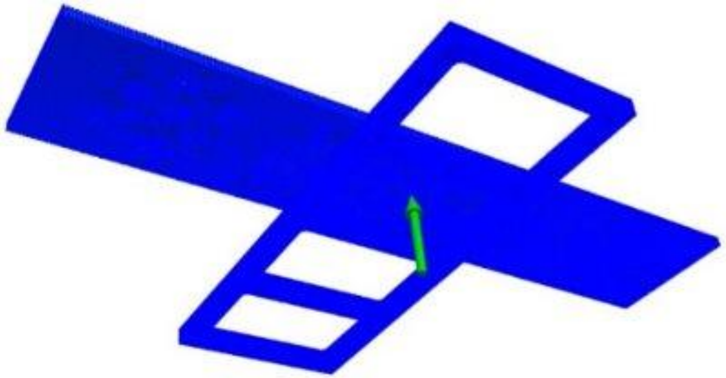
- **Shocks:** 5 aircraft environment shocks
- **Procedure:**
  - 20.48 kHz sampling rate
  - 20 samples for each field
  - No shakers/force gauges attached

Time History of Field Test 2

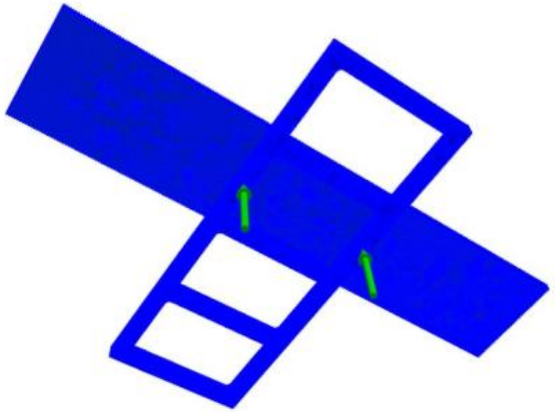


SRS of Field Test 2

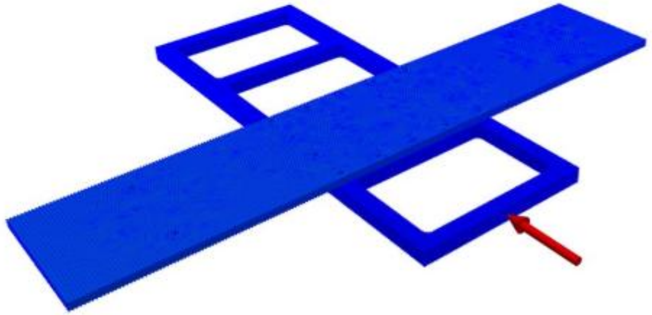




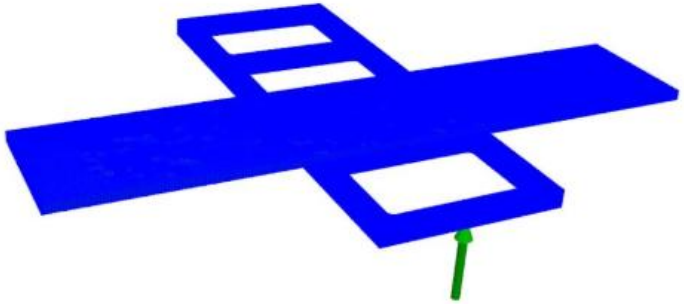
1. Simple Landing Shock



2. Landing Gear shock

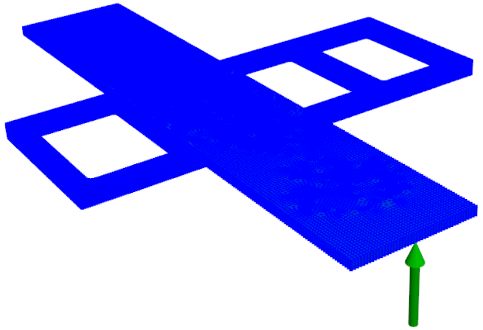


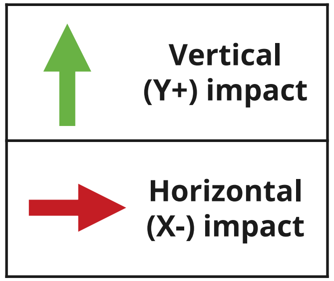
3. Nose Bird Strike



4. Nose Wind Gust

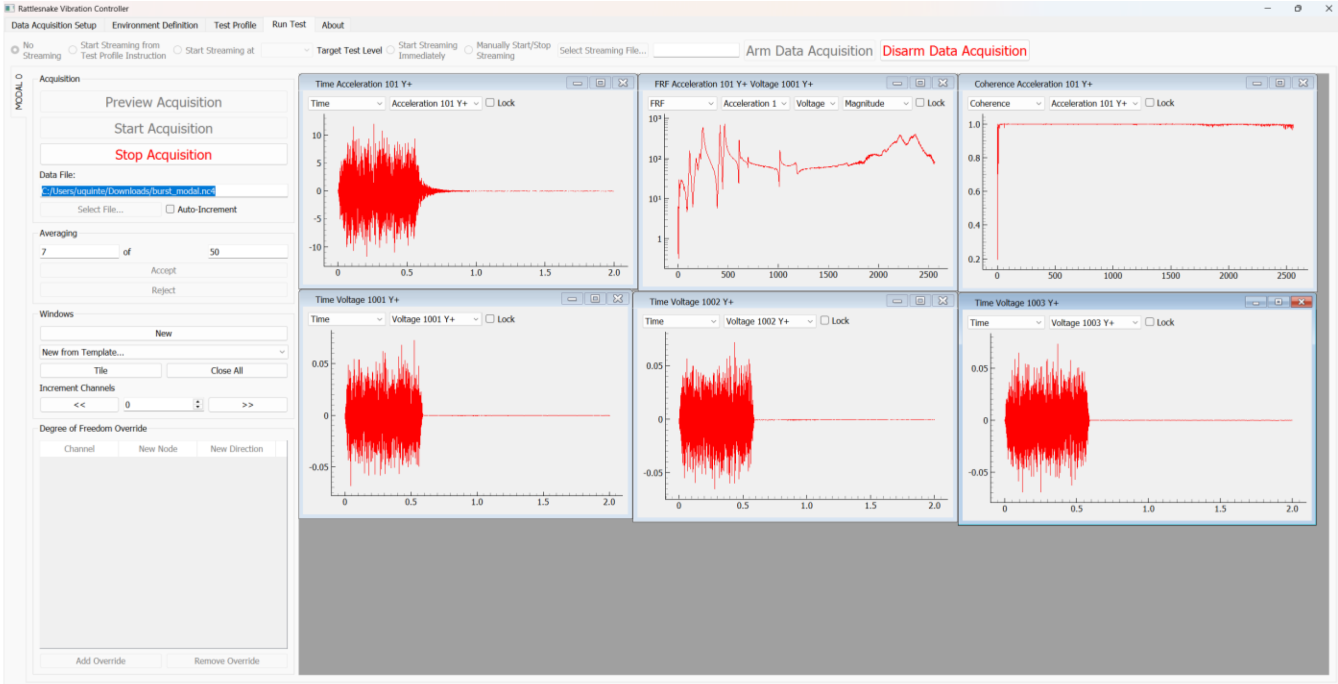
5. Wing Tip Wind Gust





SYSTEM IDENTIFICATION

- **System ID:** Burst random test, modal analysis for transfer functions
  - Same shaker locations for MIMO tests
  - Burst duration determined from 10% rule for shock response
  - Rattlesnake "Modal Testing" environment utilized



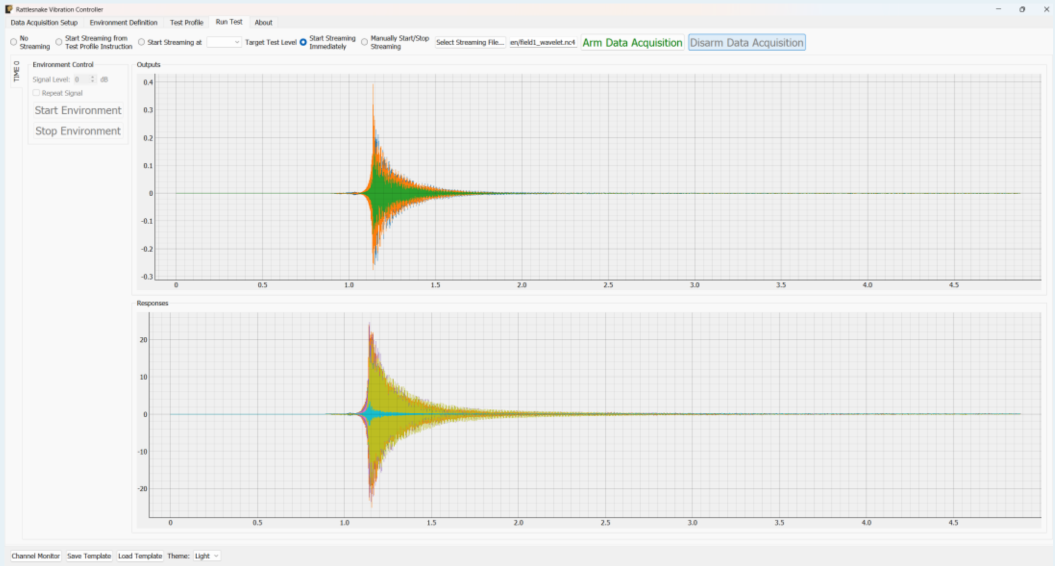
Burst Random Test in Rattlesnake

Test specifications

Parameter	Value
Sampling Rate	5120 Hz
Frame Time	2 sec
Frequency Spacing	0.5 Hz
Averaging Type	Linear
Number of Averages	50
FRF Window	Rectangle
Signal Type	Burst Random
Signal Bandwidth	2560 Hz
Signal % of Frame	29.50 %
Signal Duration	0.5900 s

MIMO SHOCK TESTING

MIMO Shock Control with Rattlesnake	
Time Signal Generation	**MIMO Shock**
• Takes voltage time histories as inputs • The inverse problem is solved "offline" in MATLAB/Python	• Sum-of-Decayed-Sines method • Takes SRSs for each control channel as inputs • Solves the inverse problem "online" in Rattlesnake



"Run Test" Tab for Time Signal Generation

1- Environment Definition

2- System ID

4- Run Test

3- Test Predictions

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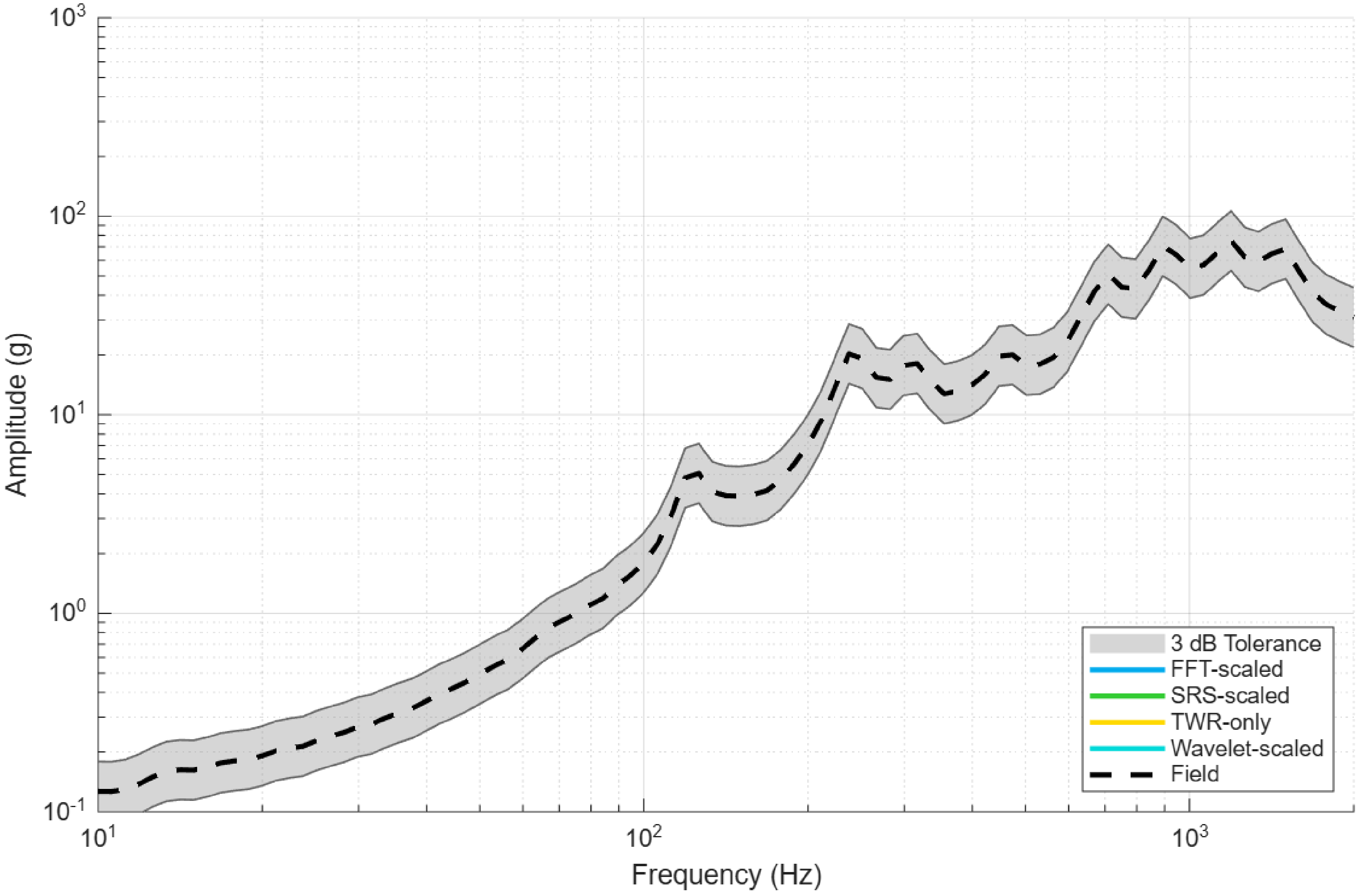
SRS Average Spectrum by Method

Field Test 2: Landing Gear Shock, Single Realization



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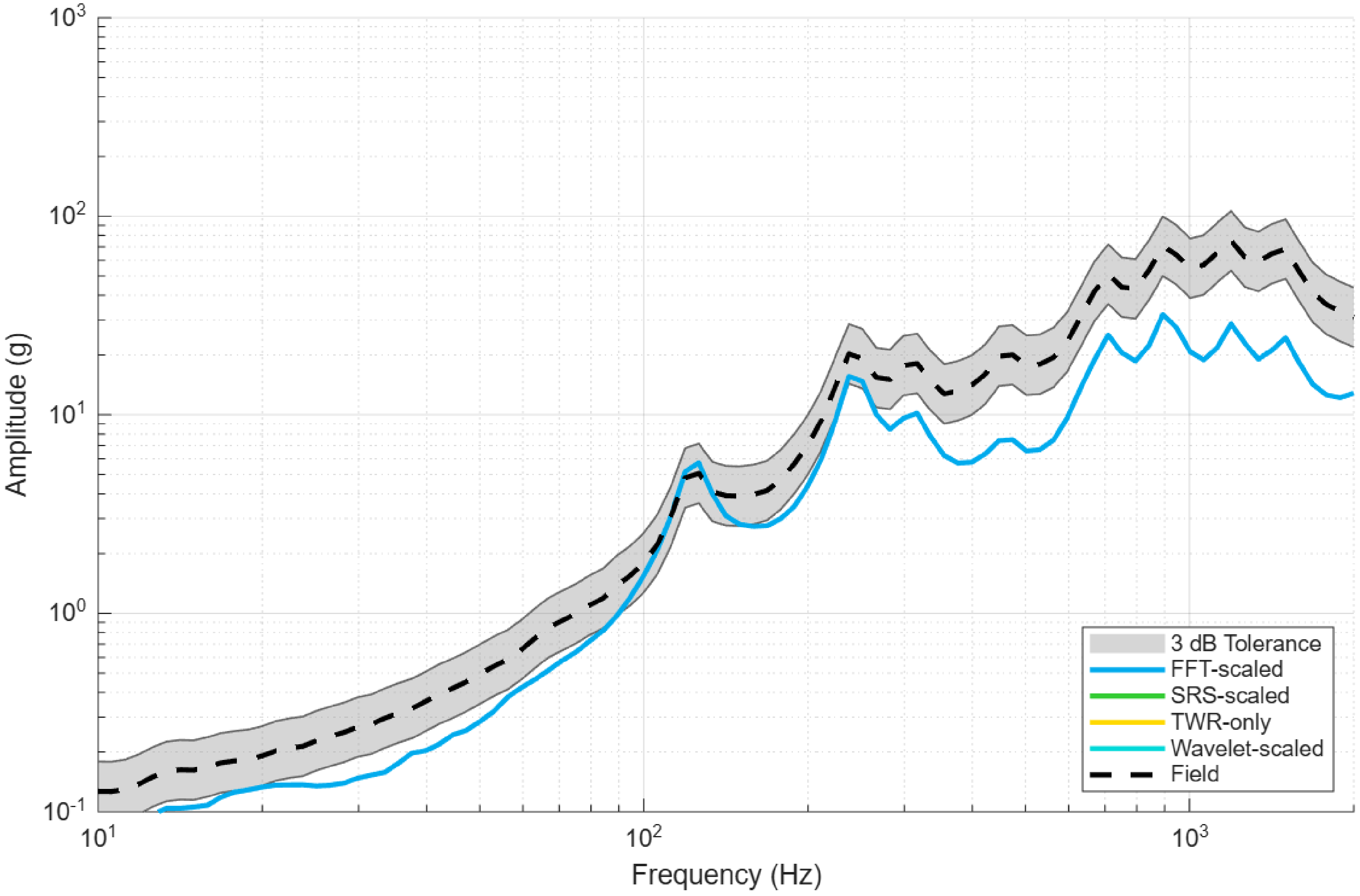

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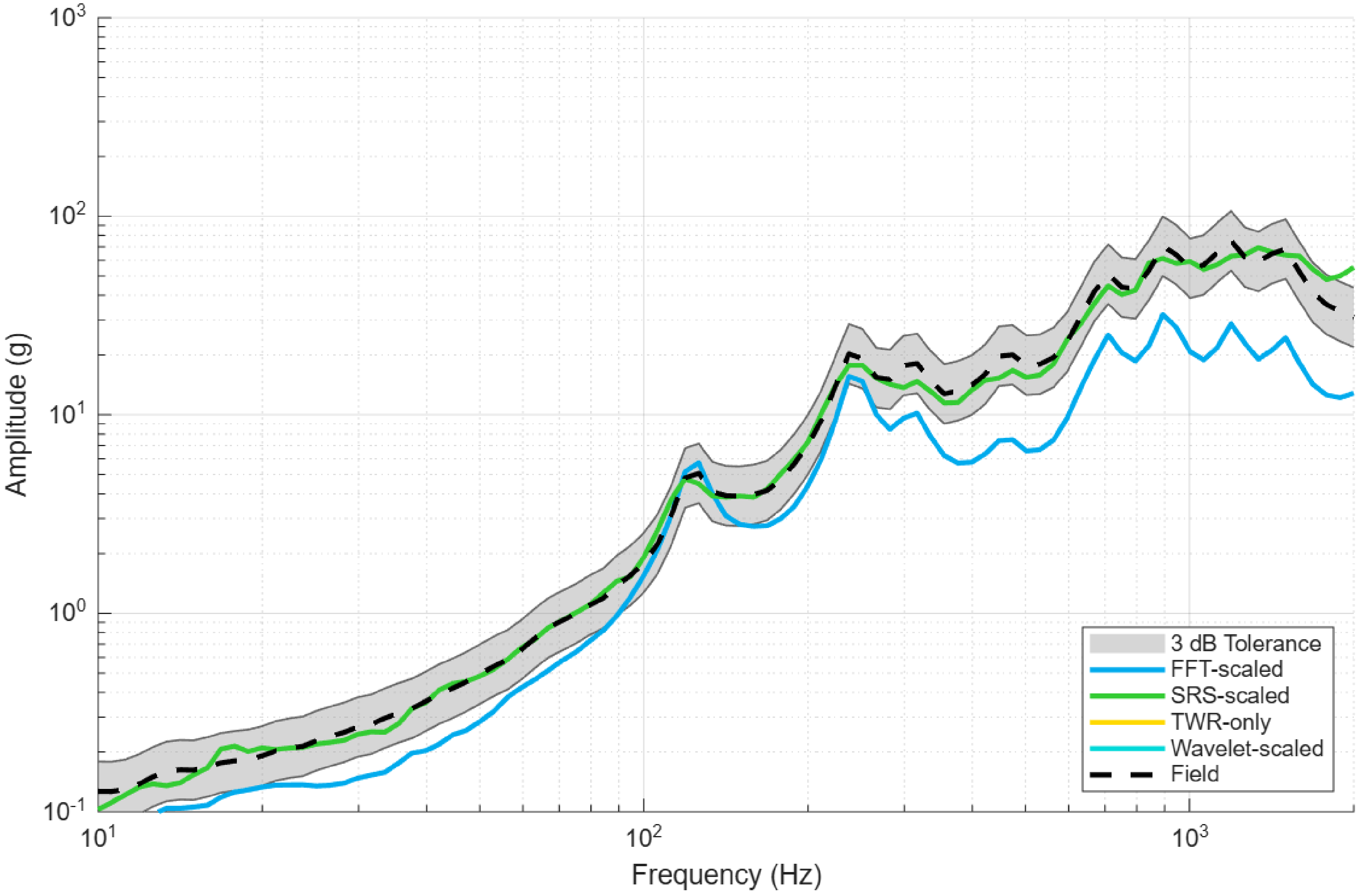

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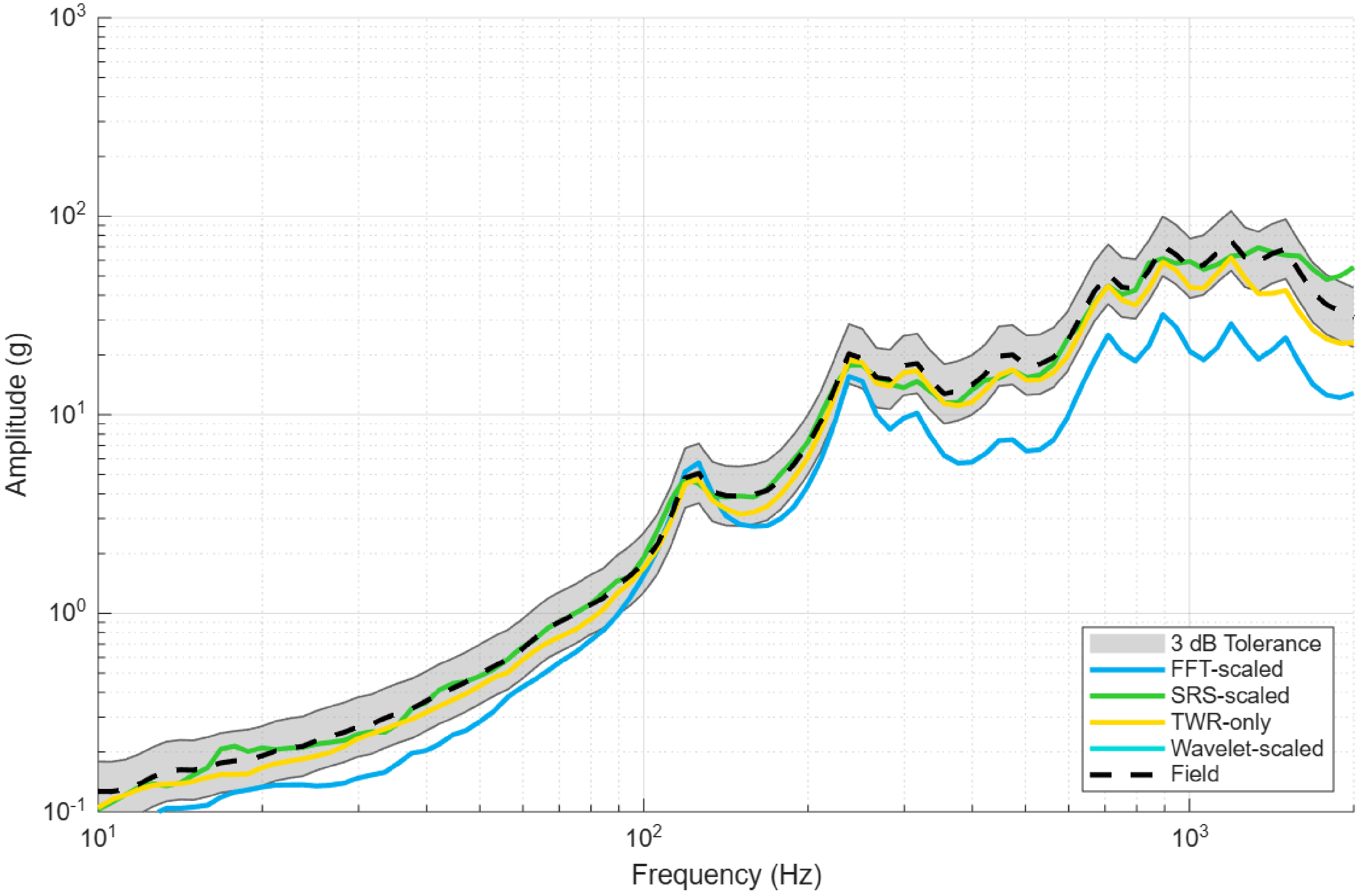

SRS Average Spectrum by Method

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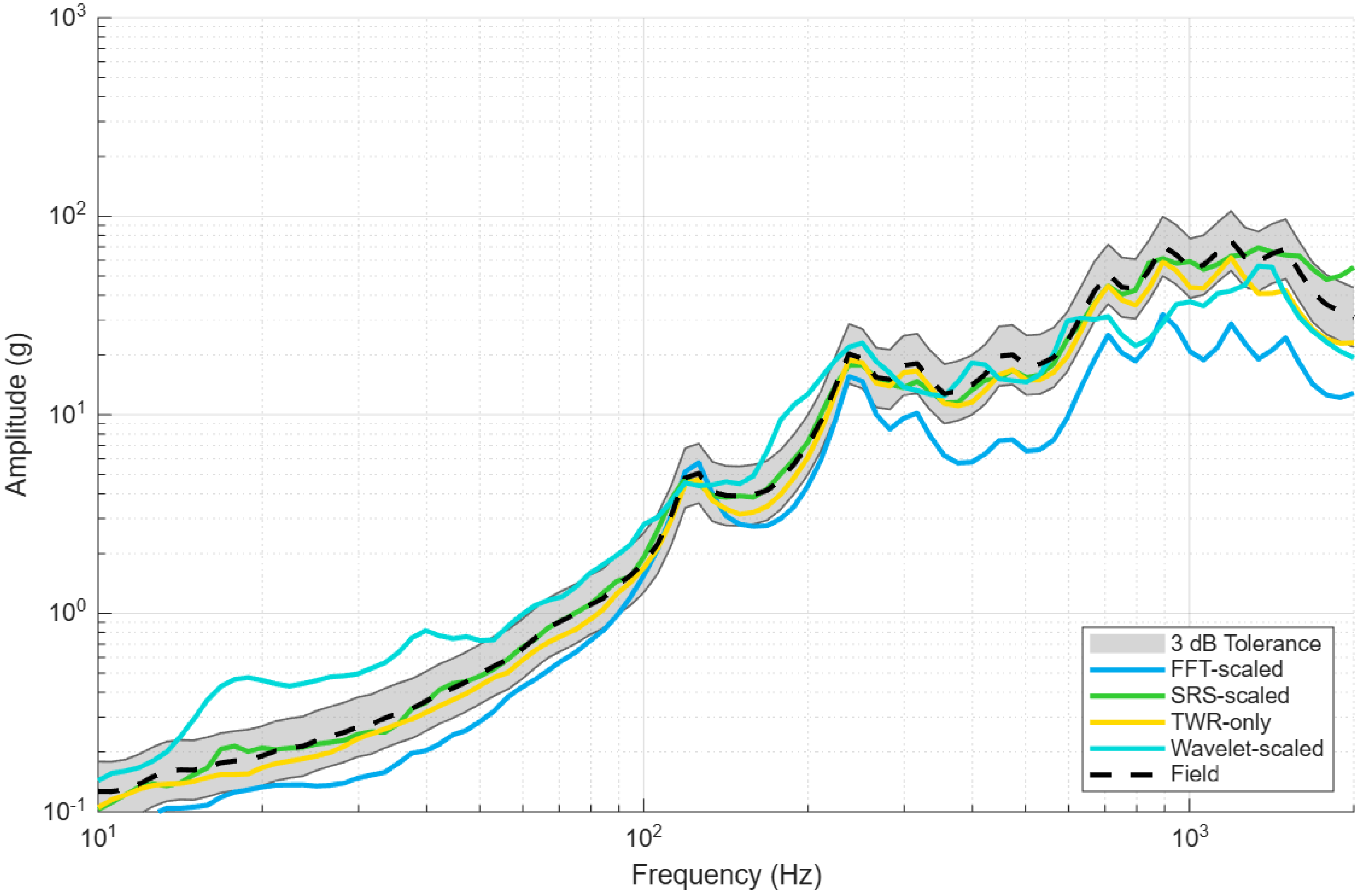
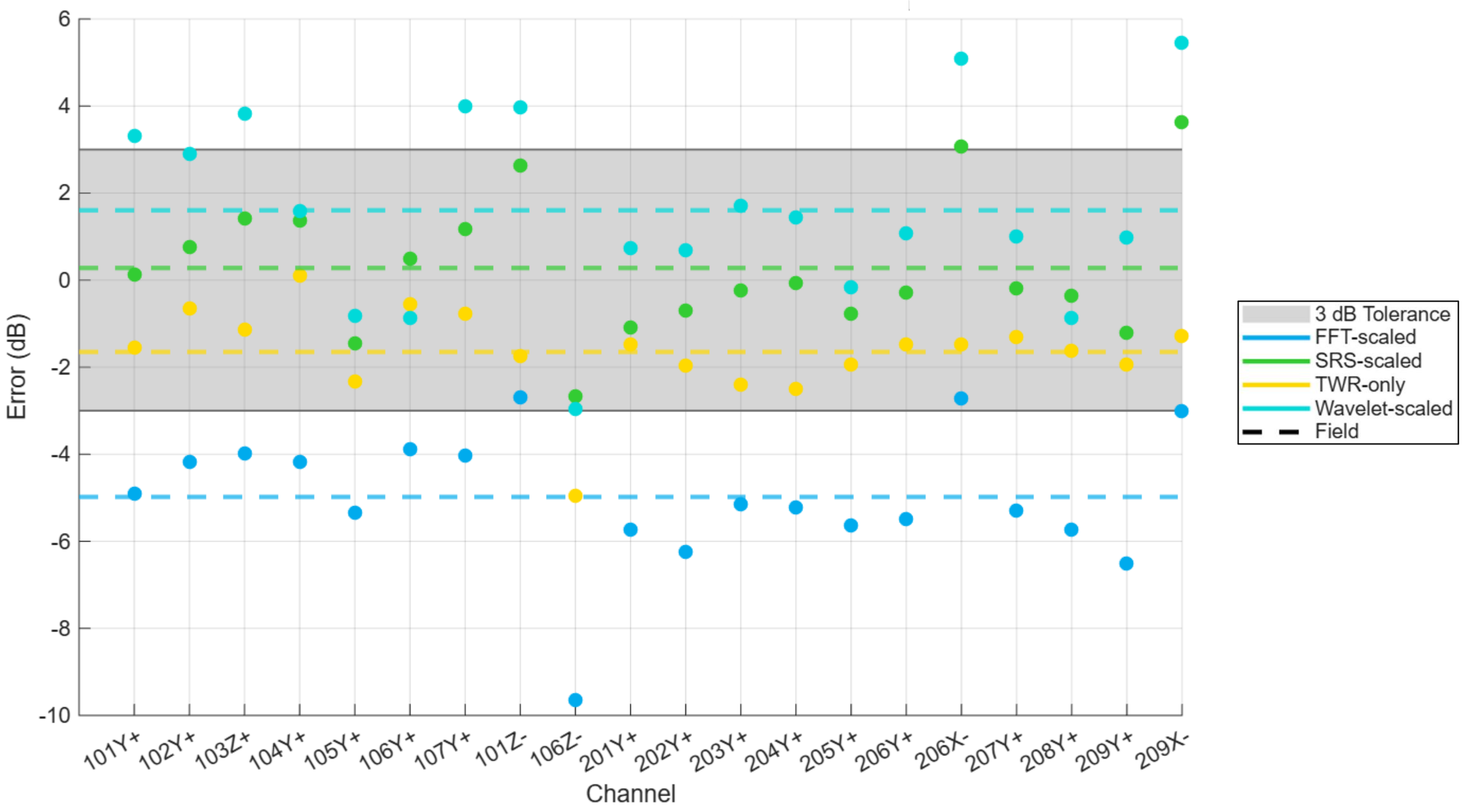


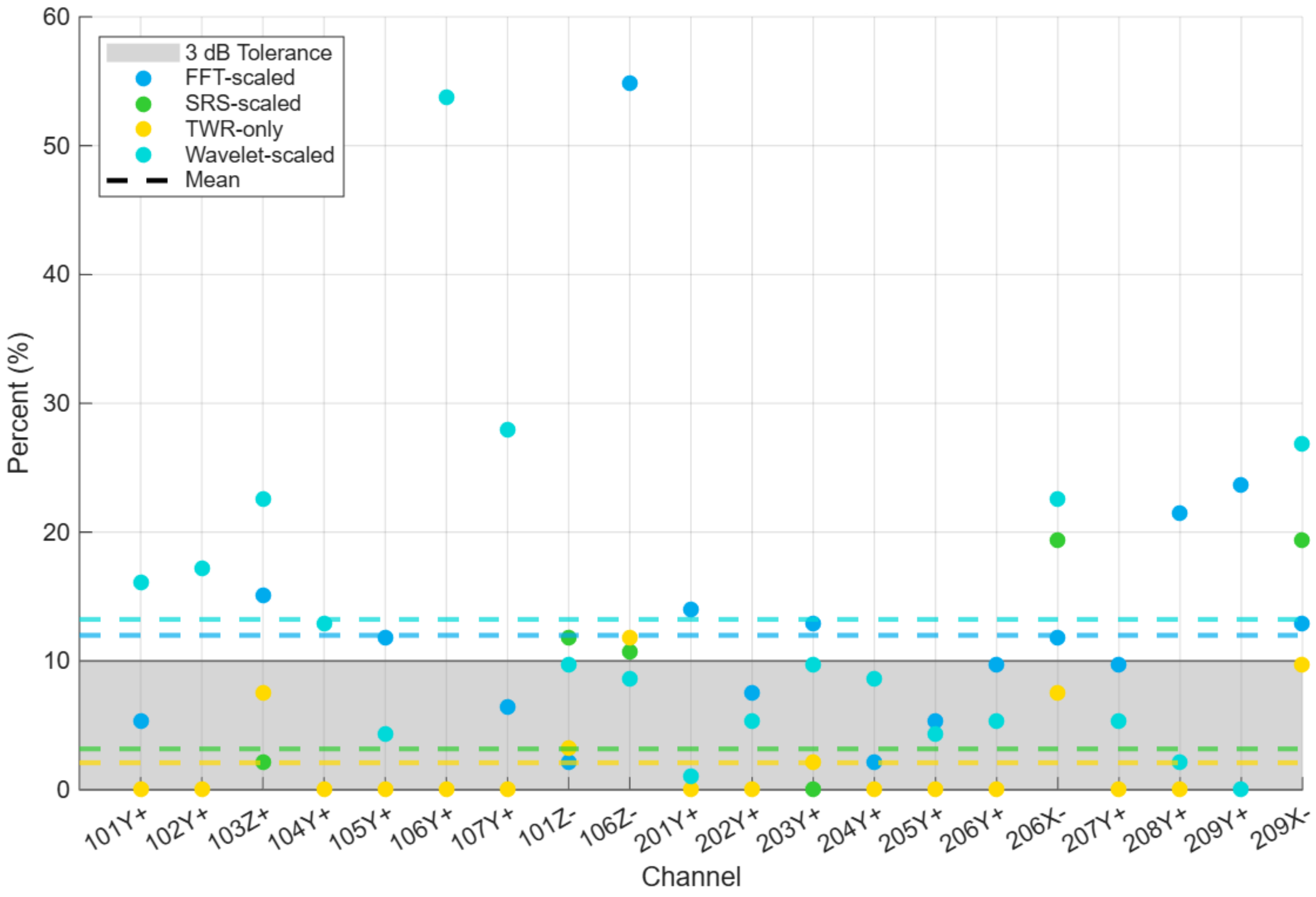
SRS Mean Error by Channel

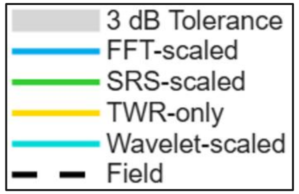
Field Test 2: Landing Gear Shock, Single Realization



SRS Frequency Lines Failed by Channel

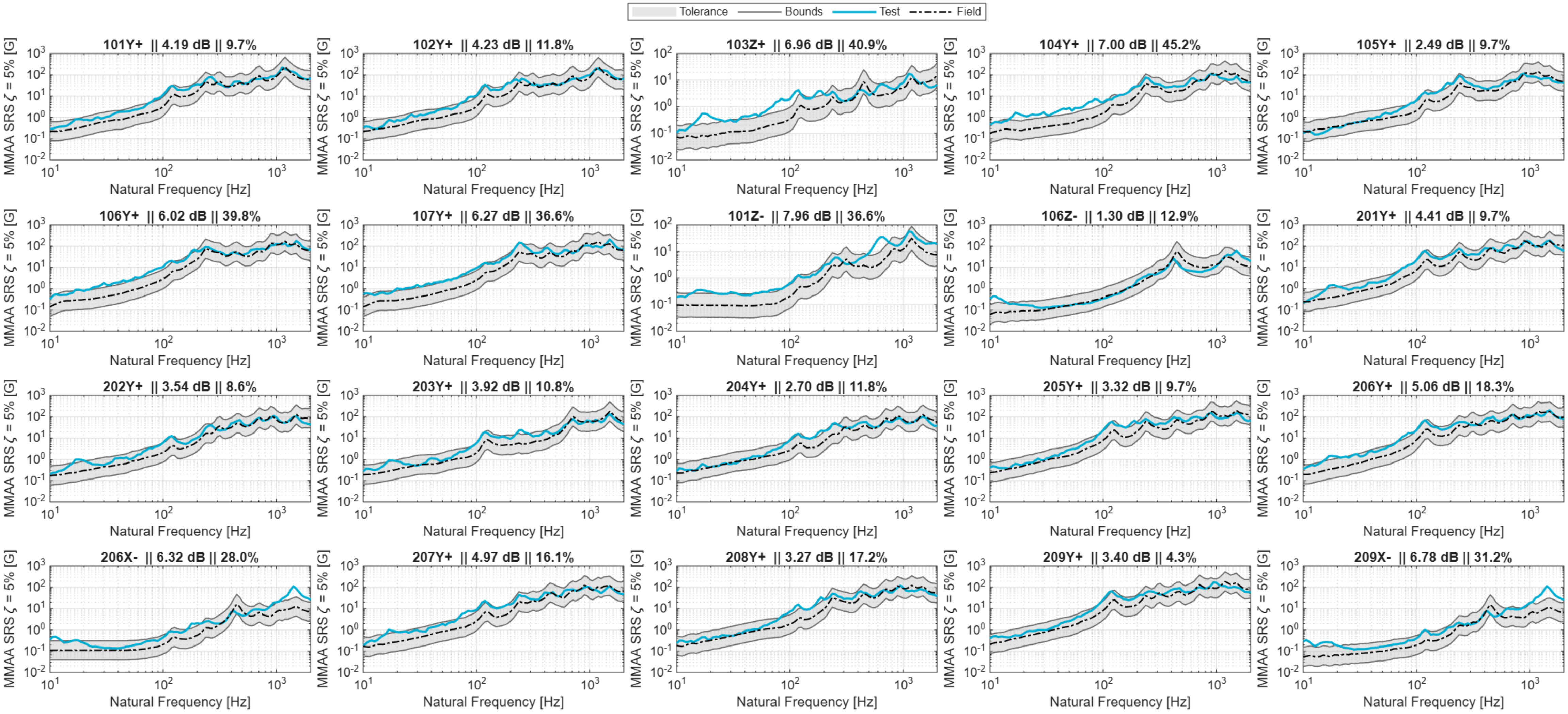
Field Test 2: Landing Gear Shock, Single Realization





SRS Accuracy by Channel

Field Test 2: Landing Gear Shock – Wavelet-scaled Method, NTL



SRS Accuracy by Channel

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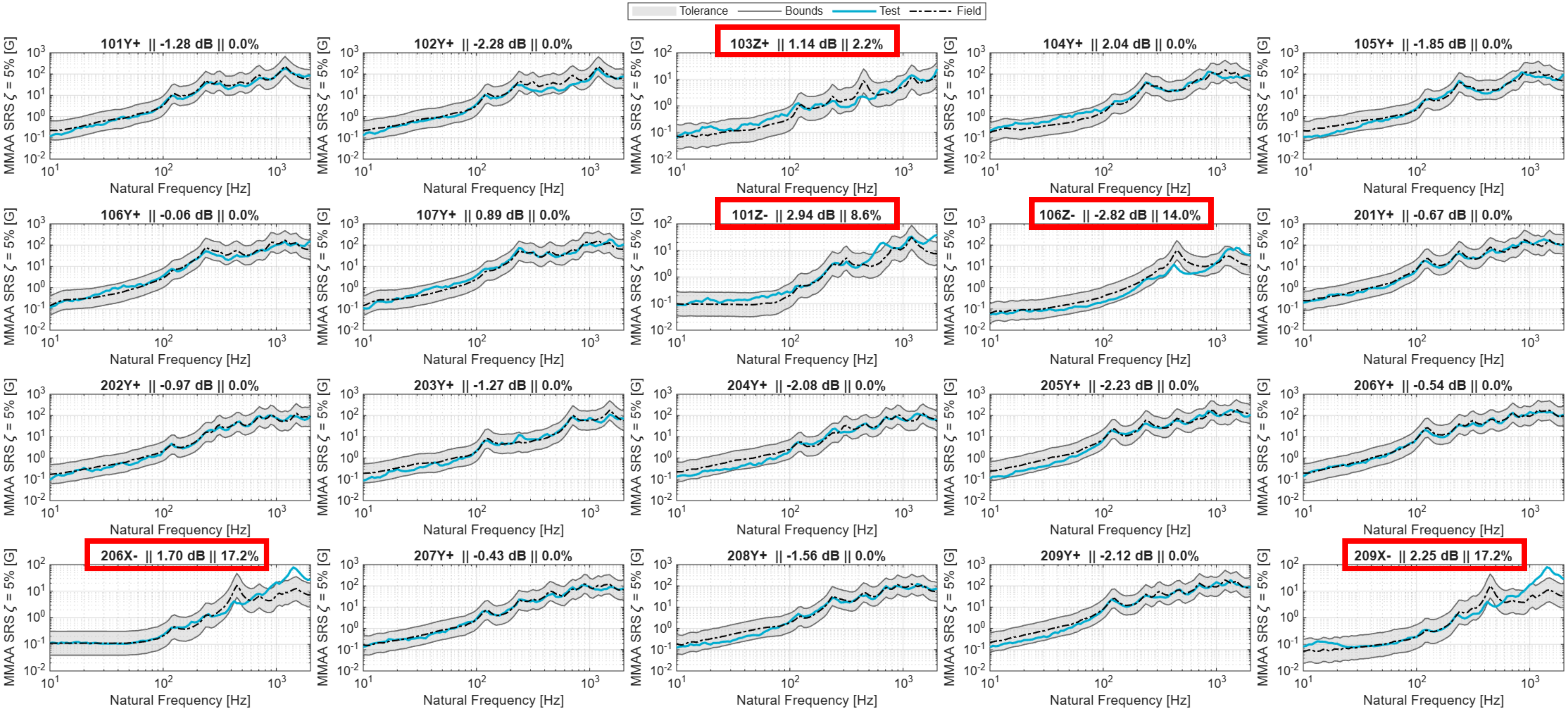
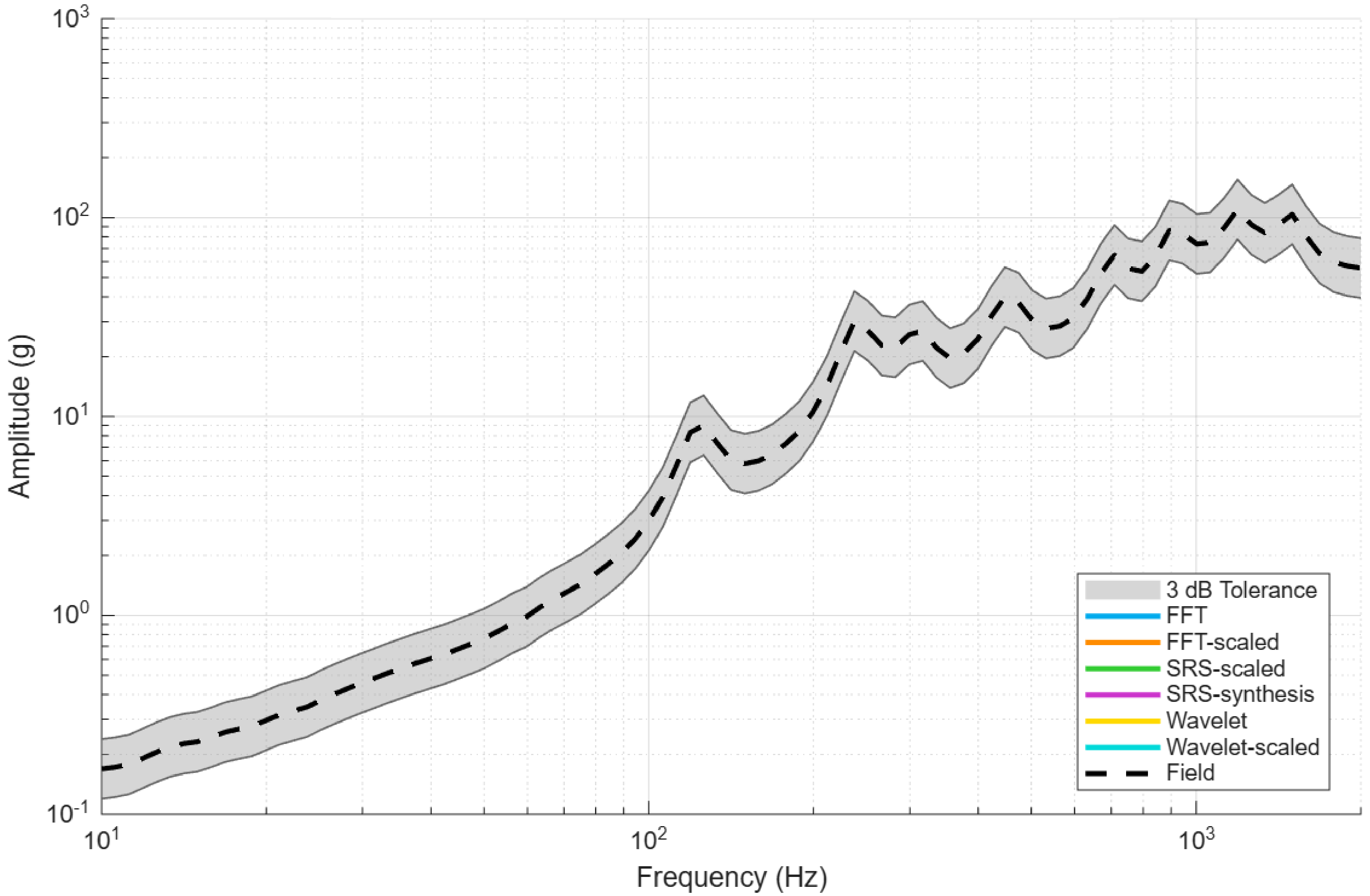


SRS Average Spectrum by Method

Field Test 2: Landing Gear Shock, NTL



SRS Average Spectrum by Method

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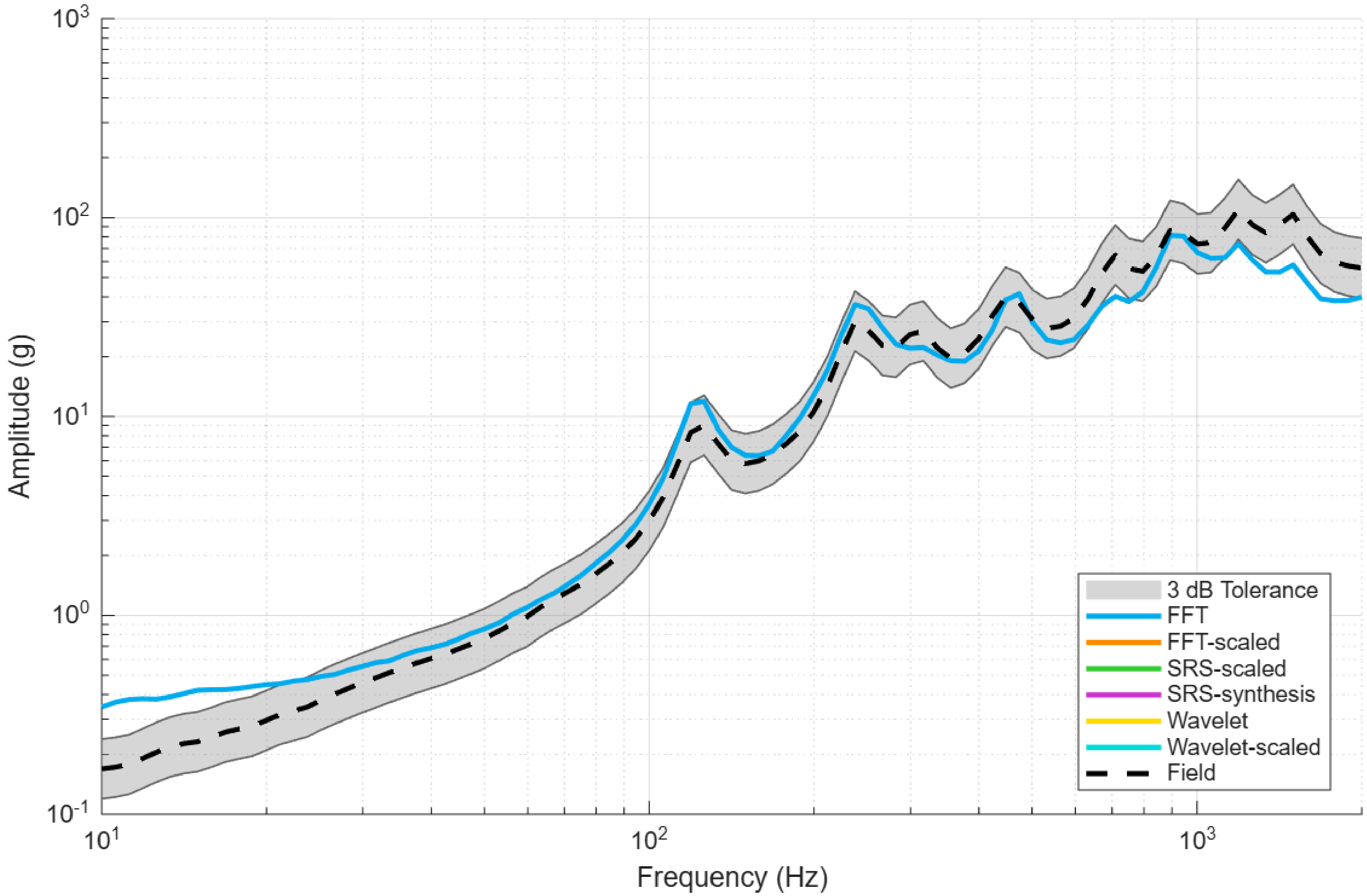

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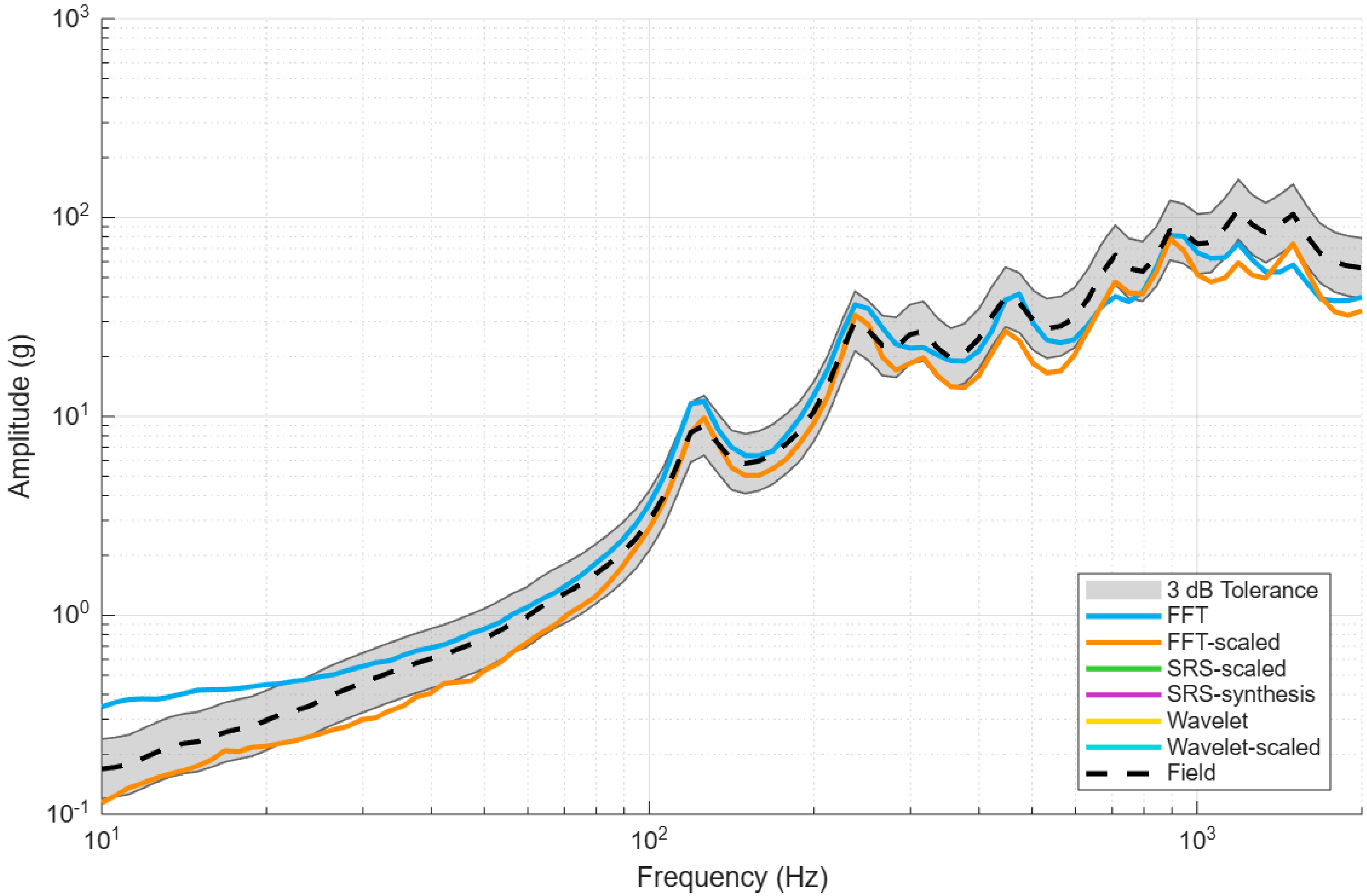

SRS Average Spectrum by Method

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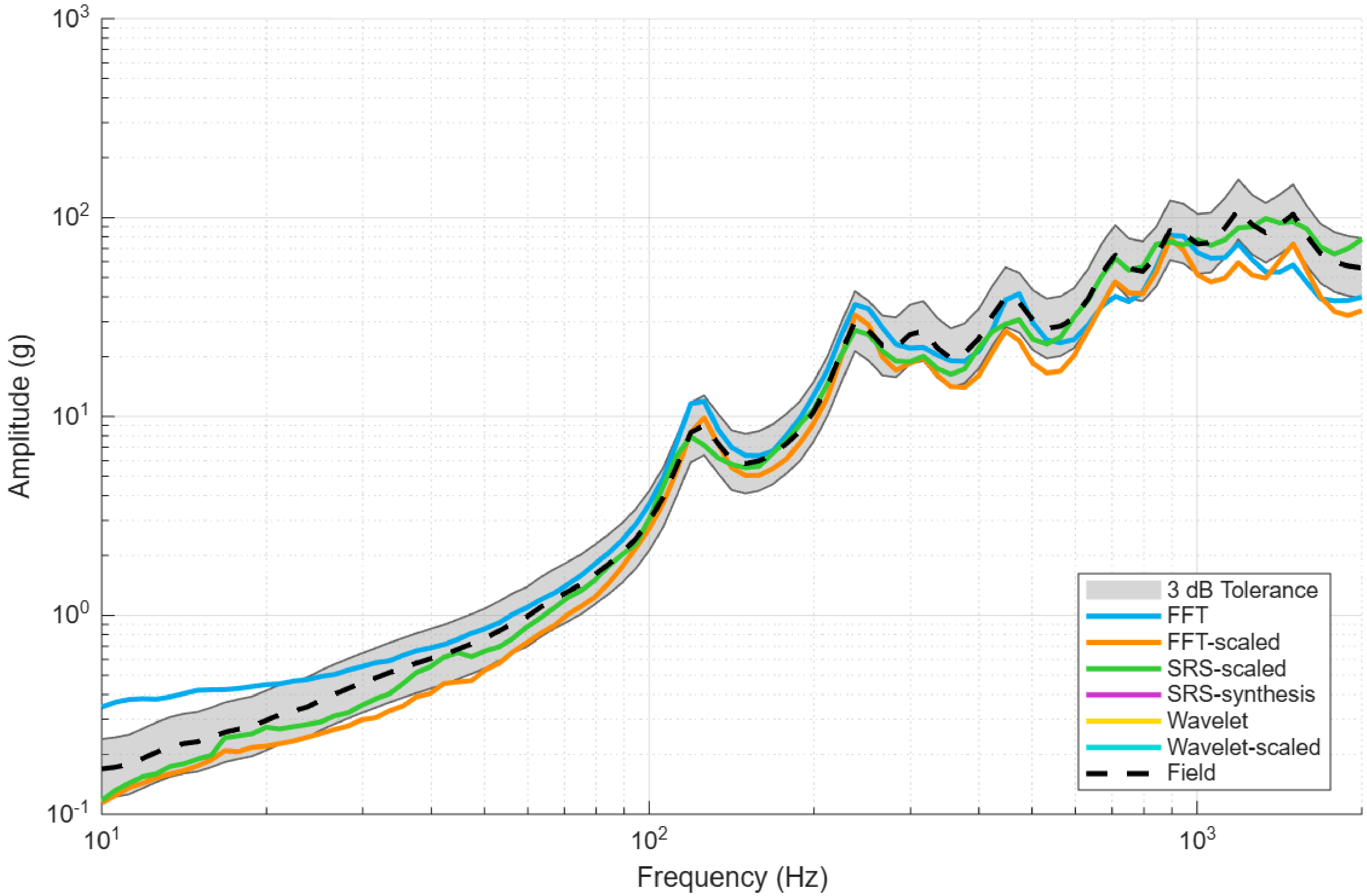
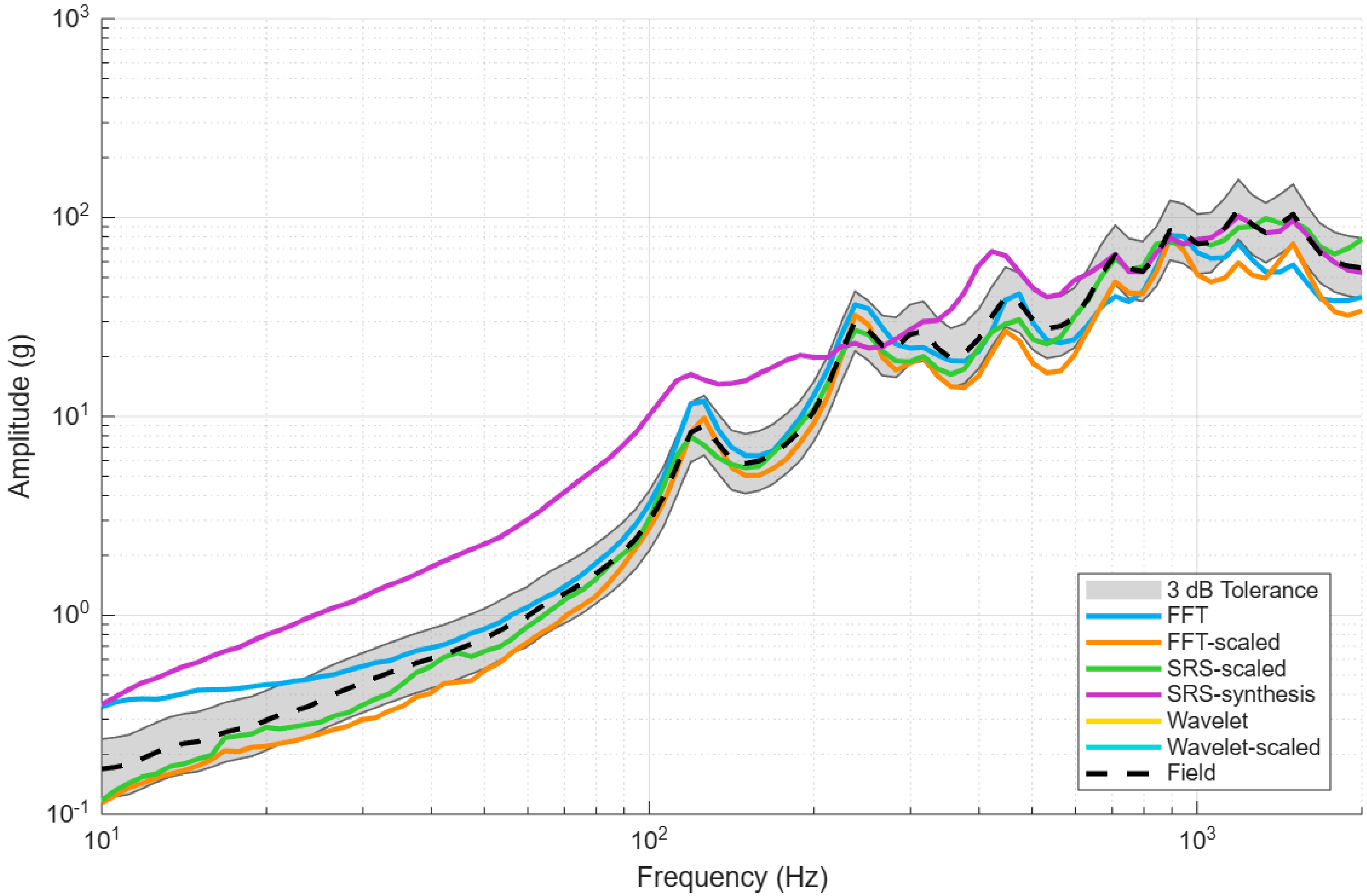


SRS Average Spectrum by Method

Field Test 2: Landing Gear Shock, NTL



SRS Average Spectrum by Method

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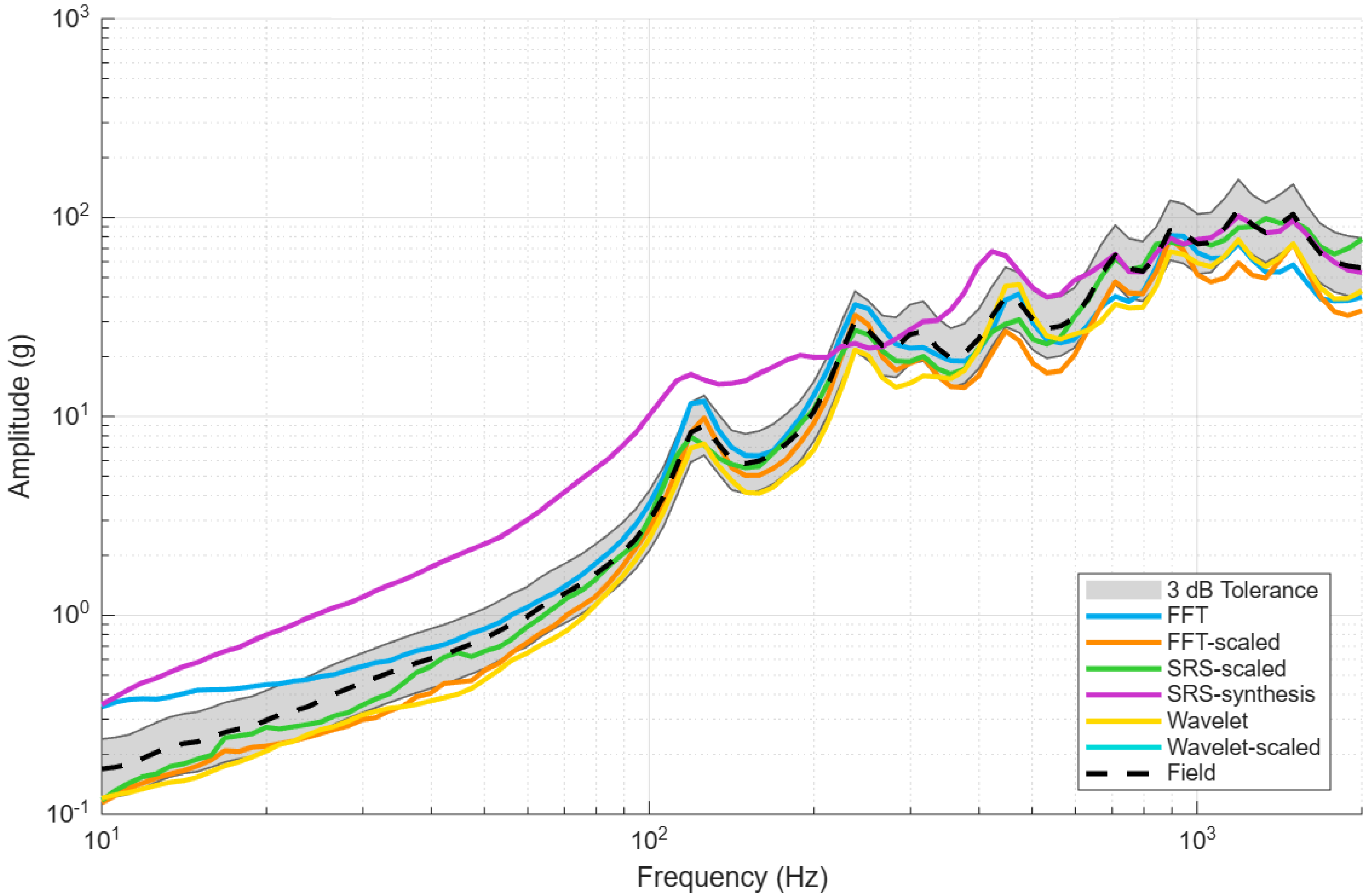
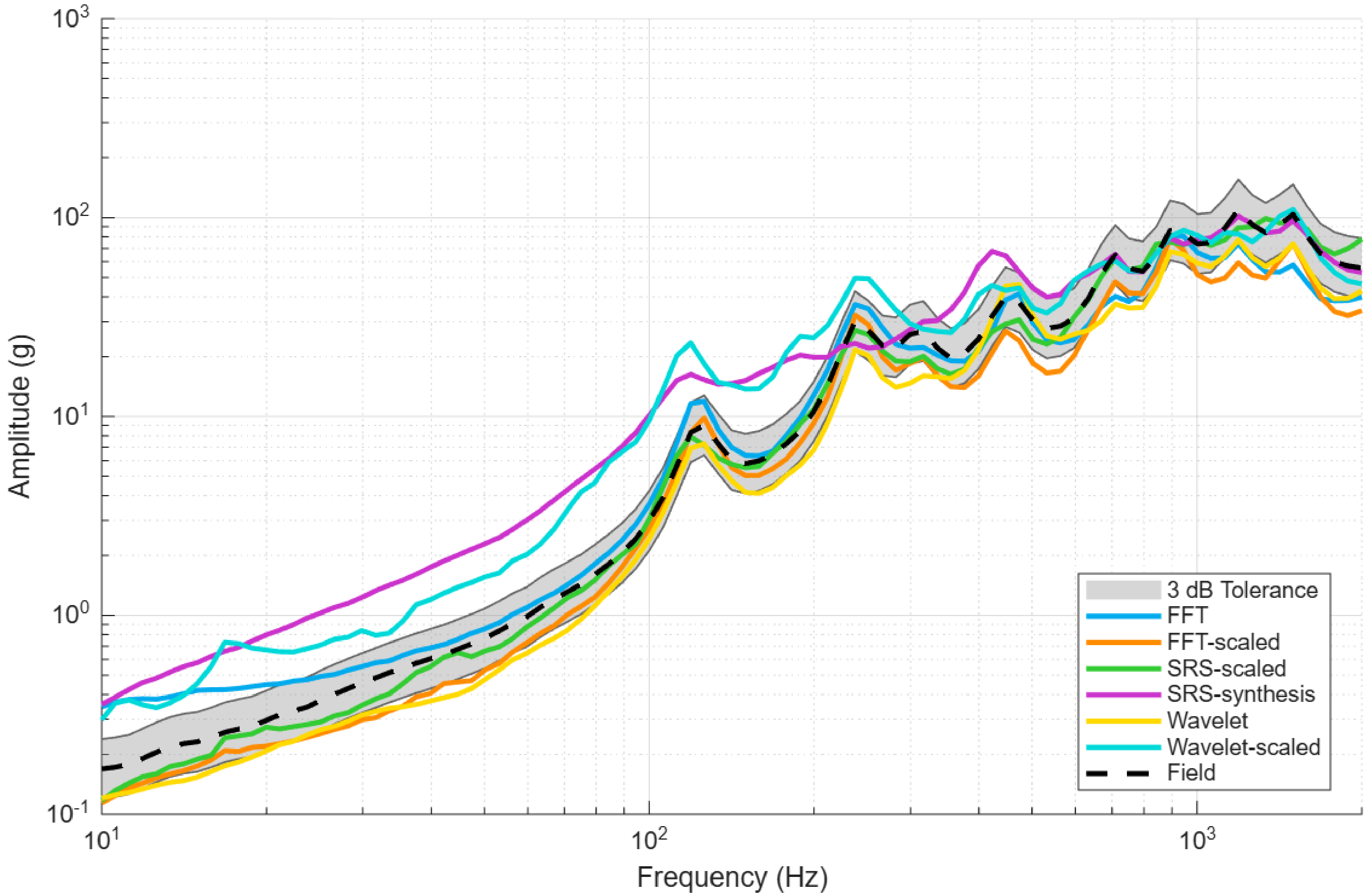


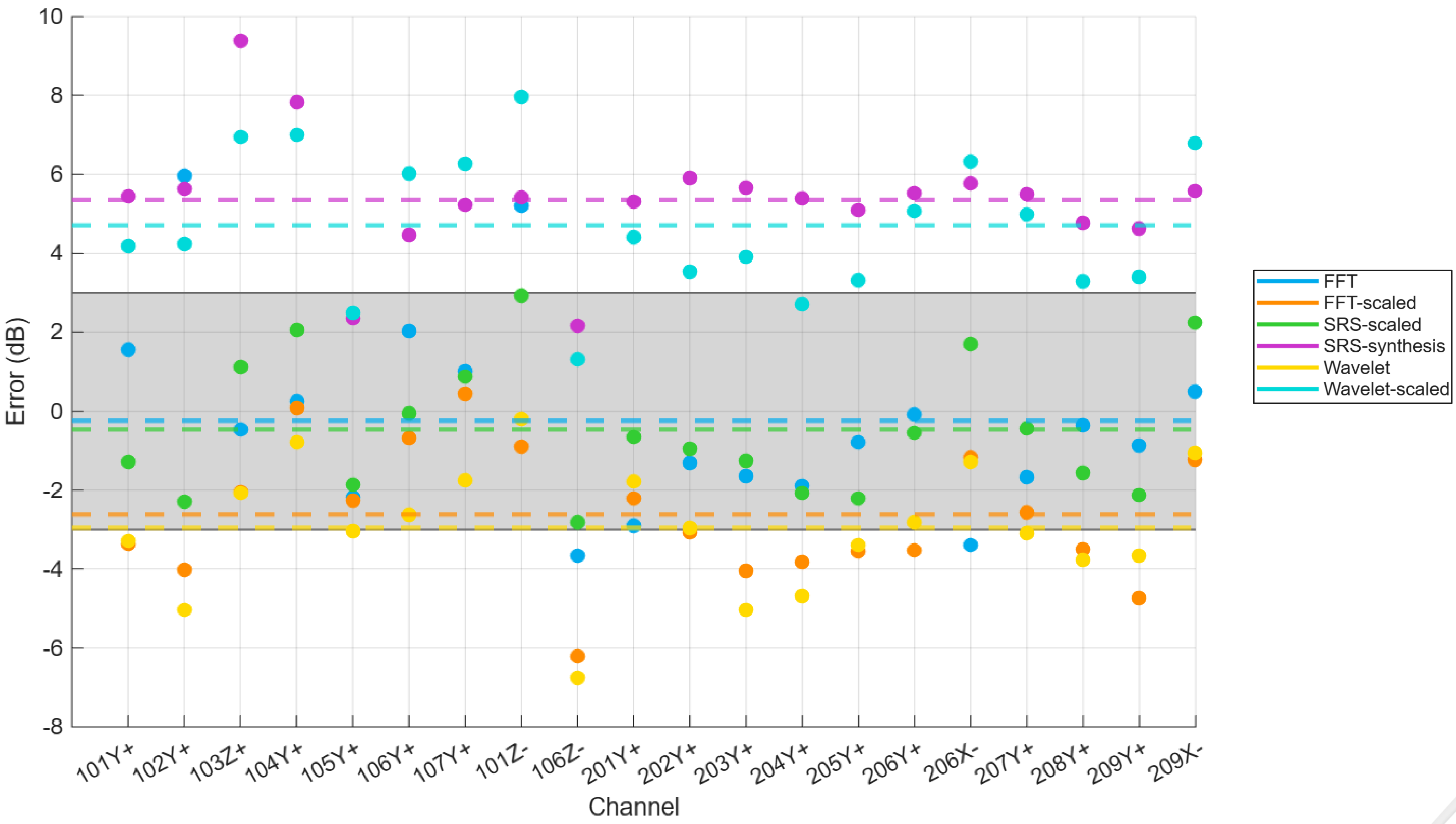
SRS Average Spectrum by Method

Field Test 2: Landing Gear Shock, NTL



SRS Mean Error by Channel

Field Test 2: Landing Gear Shock, NTL



SRS Frequency Lines Failed by Channel

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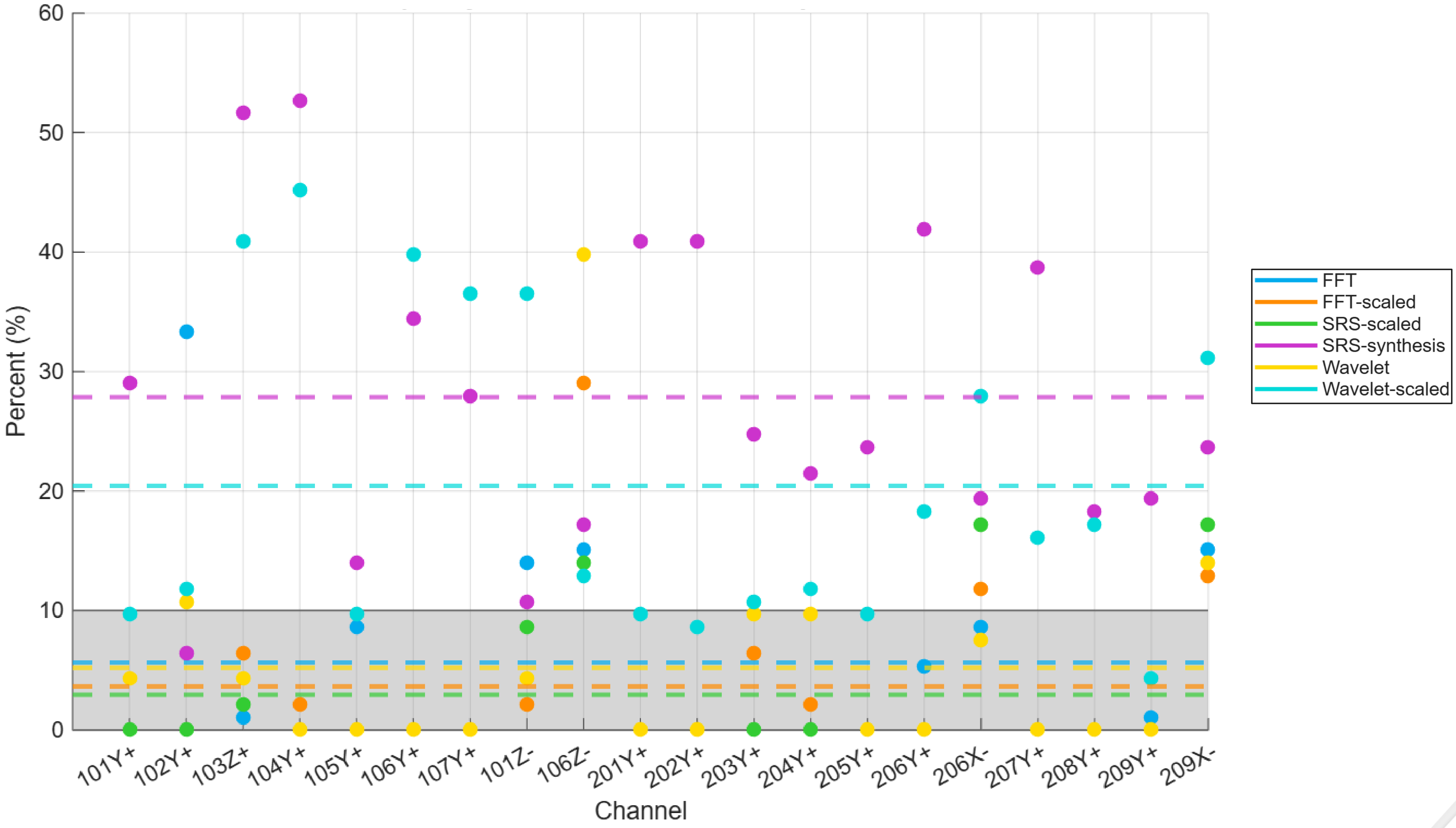
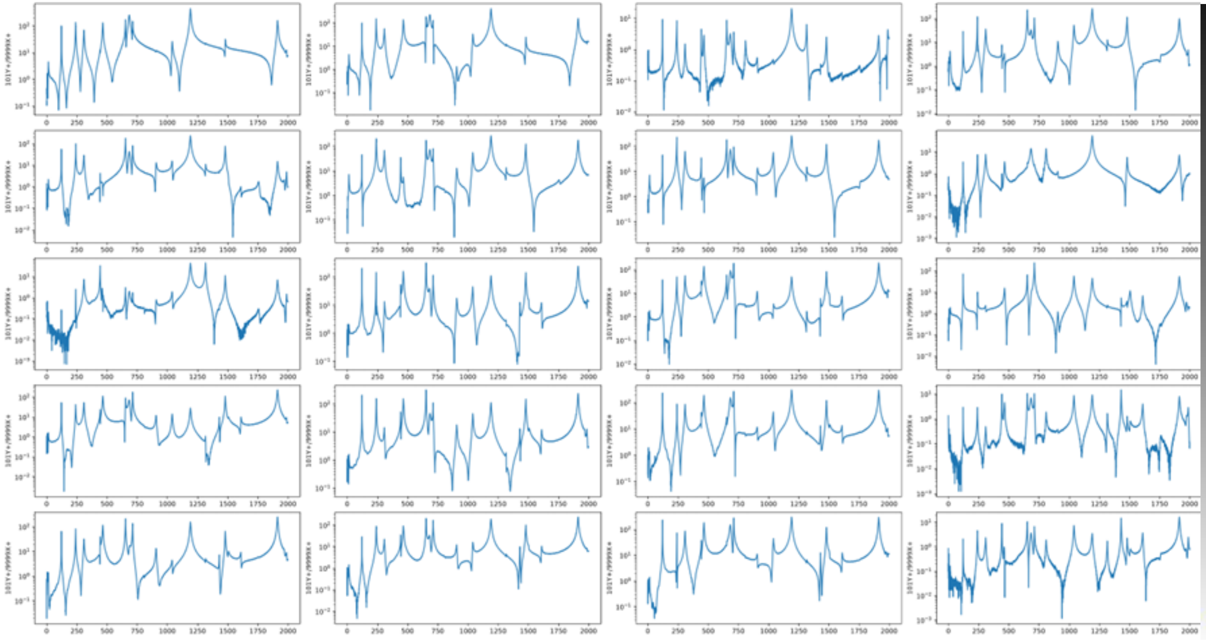
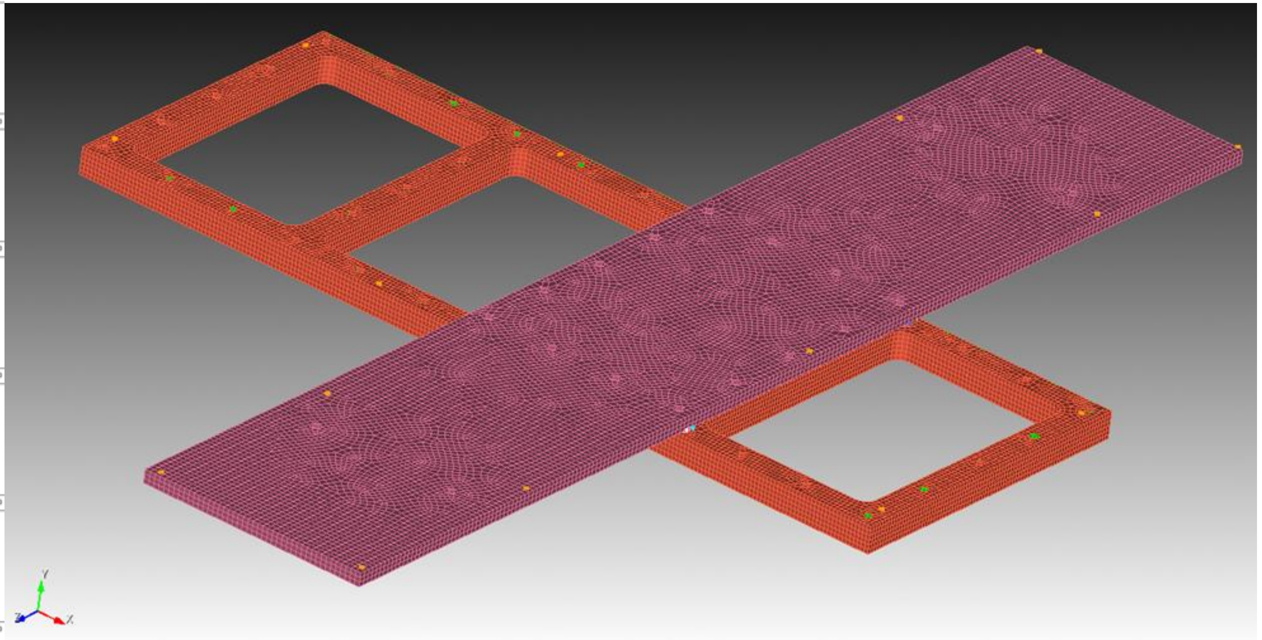


FINITE ELEMENT ANALYSIS - SETUP

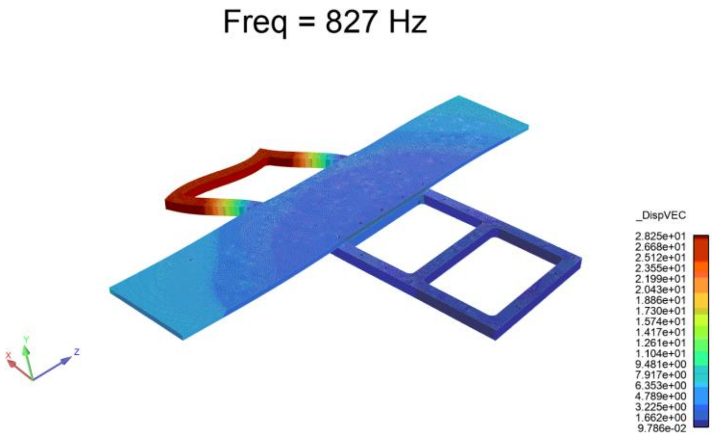
- **Objective:** Comparison of achieved vs. predicted data
  - Achieve better future predicted results
  - Interpolate values not measured, such as stress, strain, and accelerations where not instrumented
  - Verify similar results between shocks and shaker replicated shocks

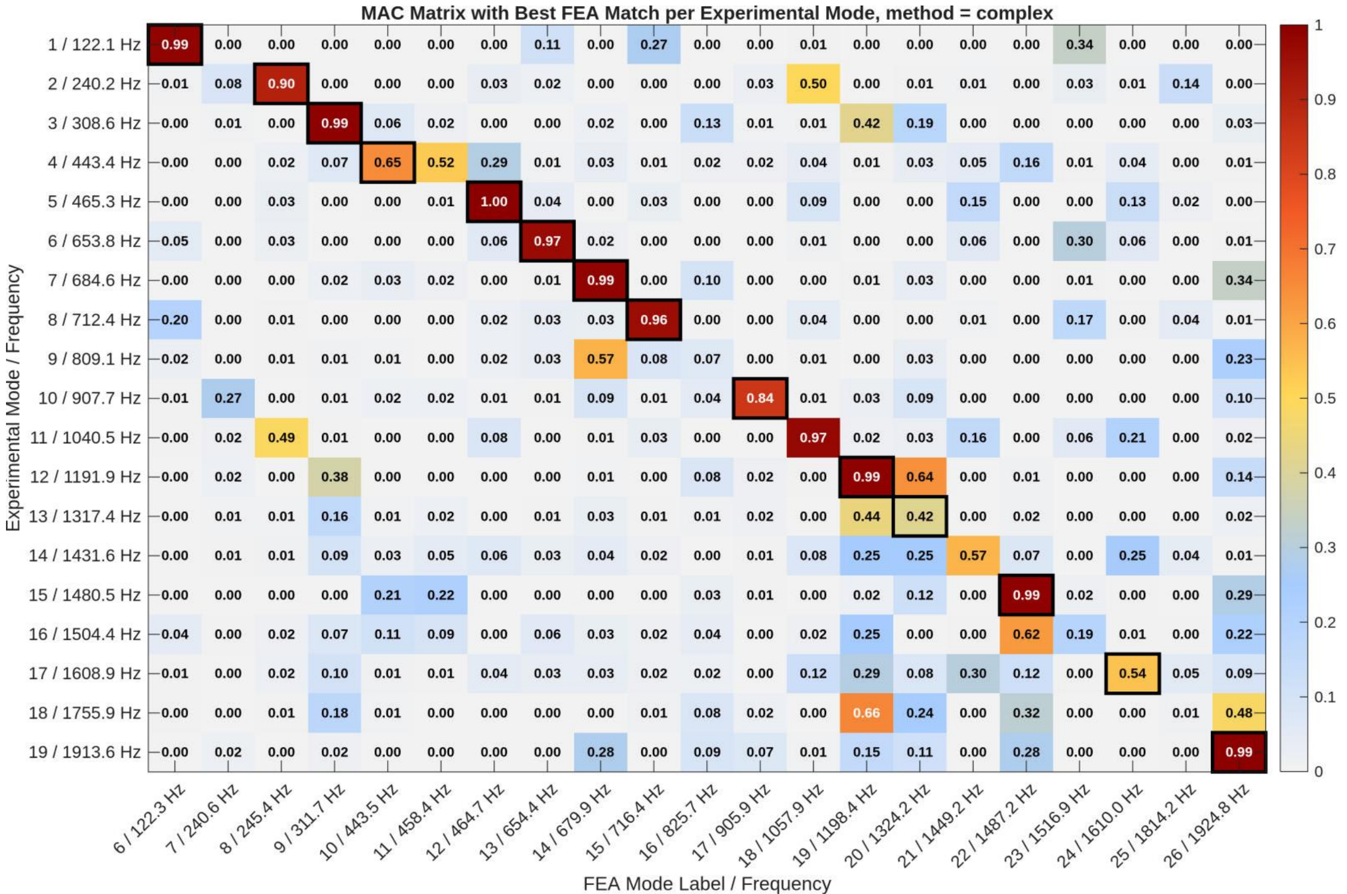




FINITE ELEMENT ANALYSIS – VALIDATION

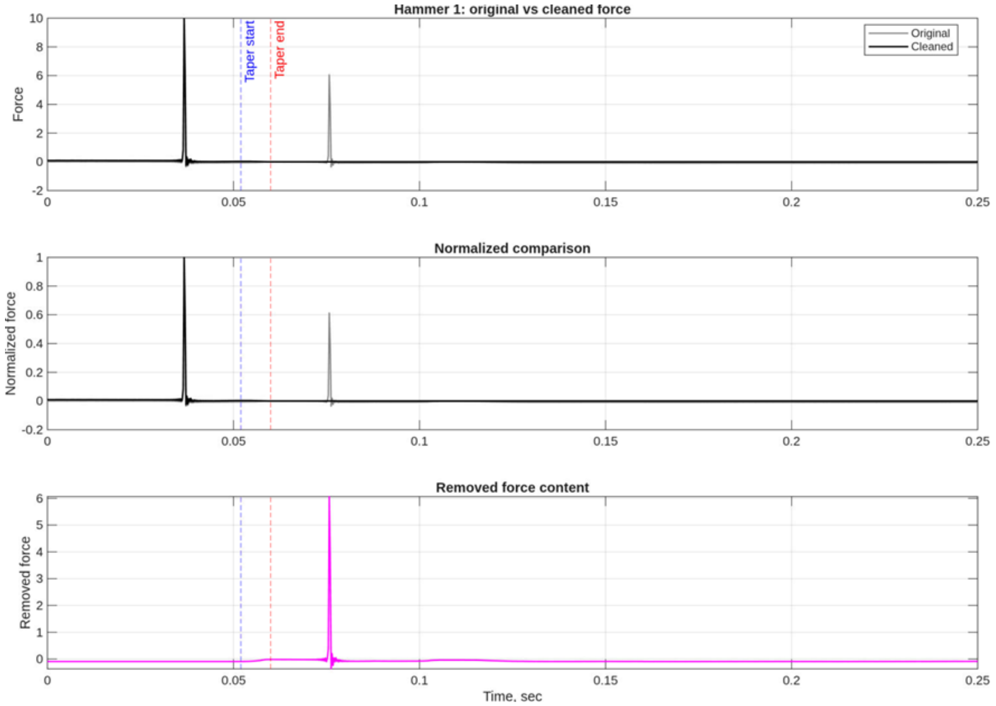
- **Purpose:** Confirm FEA simulations mirror lab test results
  - Modal results were gathered in the lab
  - Tested/tuned against the models modal results

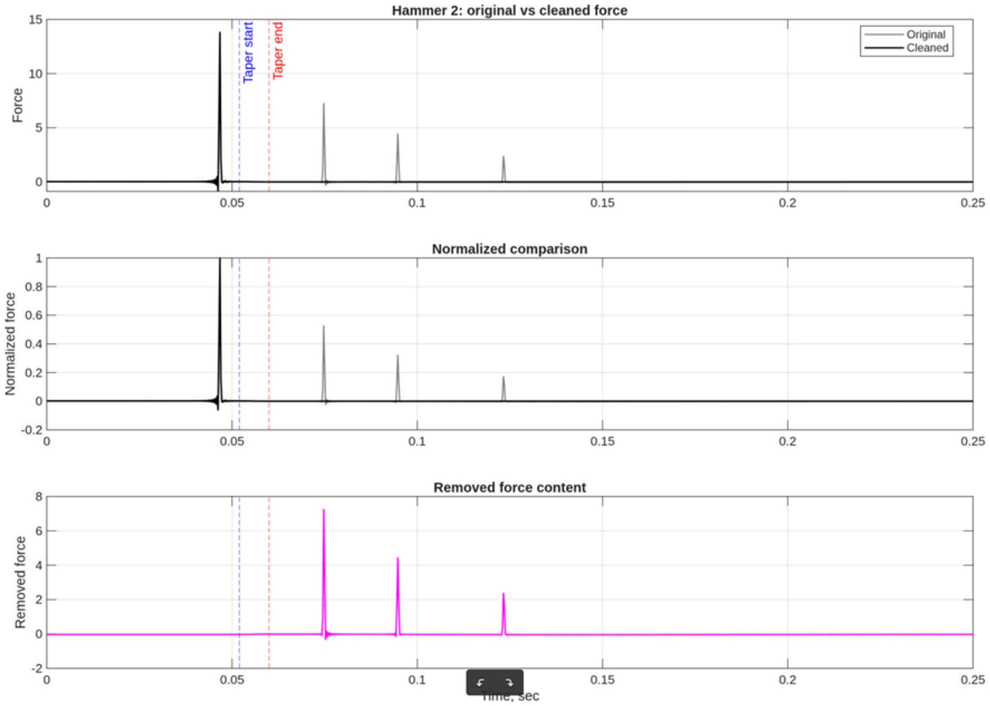




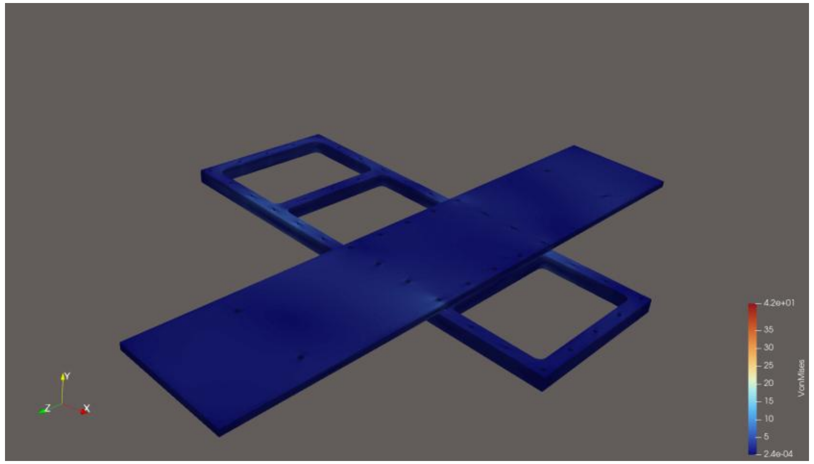
FINITE ELEMENT ANALYSIS – REPLICATION I

- **Windowing, Smoothing, and Retuning**
  - Windowing input force data to resolve non-impacting forces
  - Apply a zero-phase filter to both experimental and analytical acceleration data to smooth higher frequency noise
  - Retune after applying these changes to match the new data

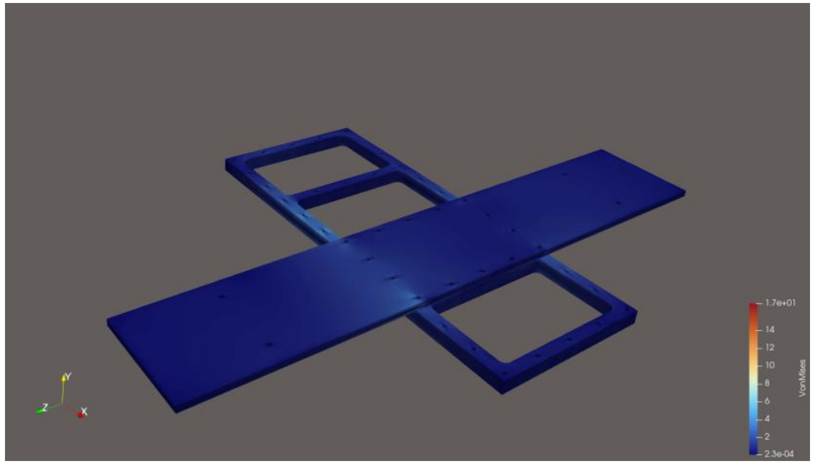




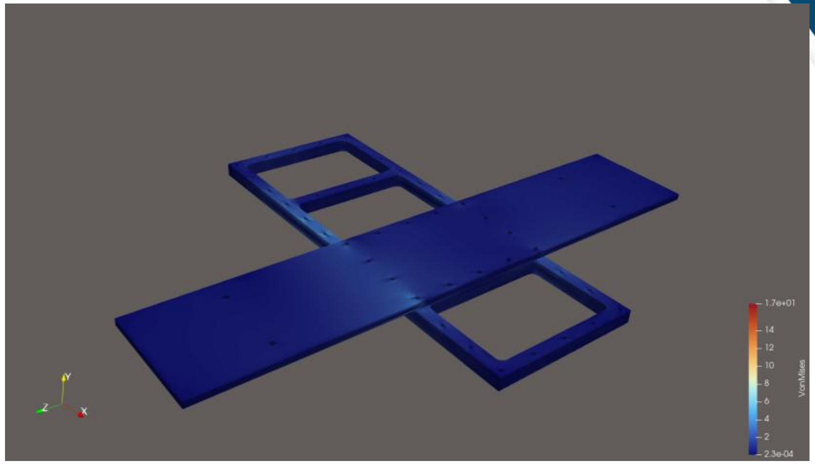
FINITE ELEMENT ANALYSIS – REPLICATION II



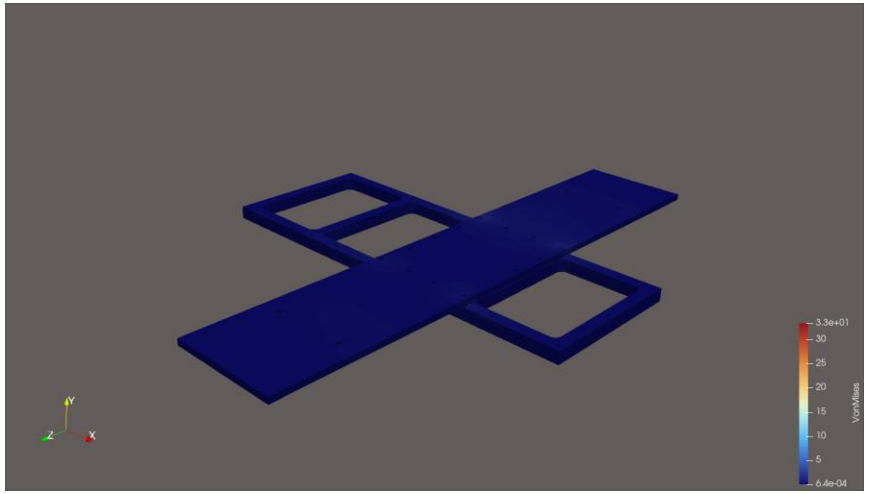
Stress From MIMO Shaker Shock – SRS-scaled



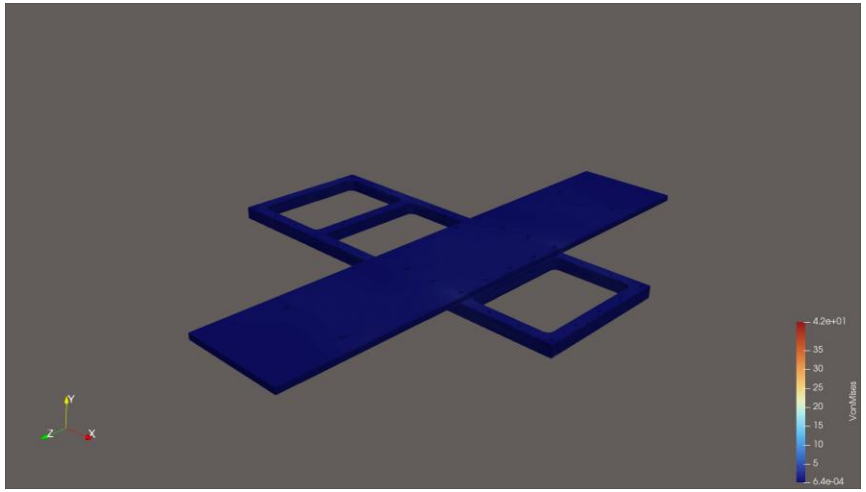
Stress From MIMO Shaker Shock – FFT-scaled



Stress From MIMO Shaker Shock – TWR



Stress From Field Test - Hammer Shock



Stress From MIMO Shaker Shock – Wavelet NTL

CONCLUSION & FUTURE WORK

- **Summary:**
  - MIMO shock testing methods validated, lab replication shown effective
  - SRS method for environmental specification performs best, but still exceeds tolerances for some channels
  - Highest errors in accelerometers measuring directions in X or Z directions

- **Next steps:**
  - Varying shaker locations and directions to optimize replication of field results
  - Refining specification methods and TWR process by tuning certain parameters to improve performance
  - Testing at higher sample rate to correspond with highest frequency levels in SRSs
  - Further FEM refinement, finetuning, and comparison

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