Repetitive Shock Environments

David S. Parsons

Jet Propulsion Laboratory

California Institute of Technology

Pasadena, CA 91109, USA

The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Government sponsorship acknowledged.

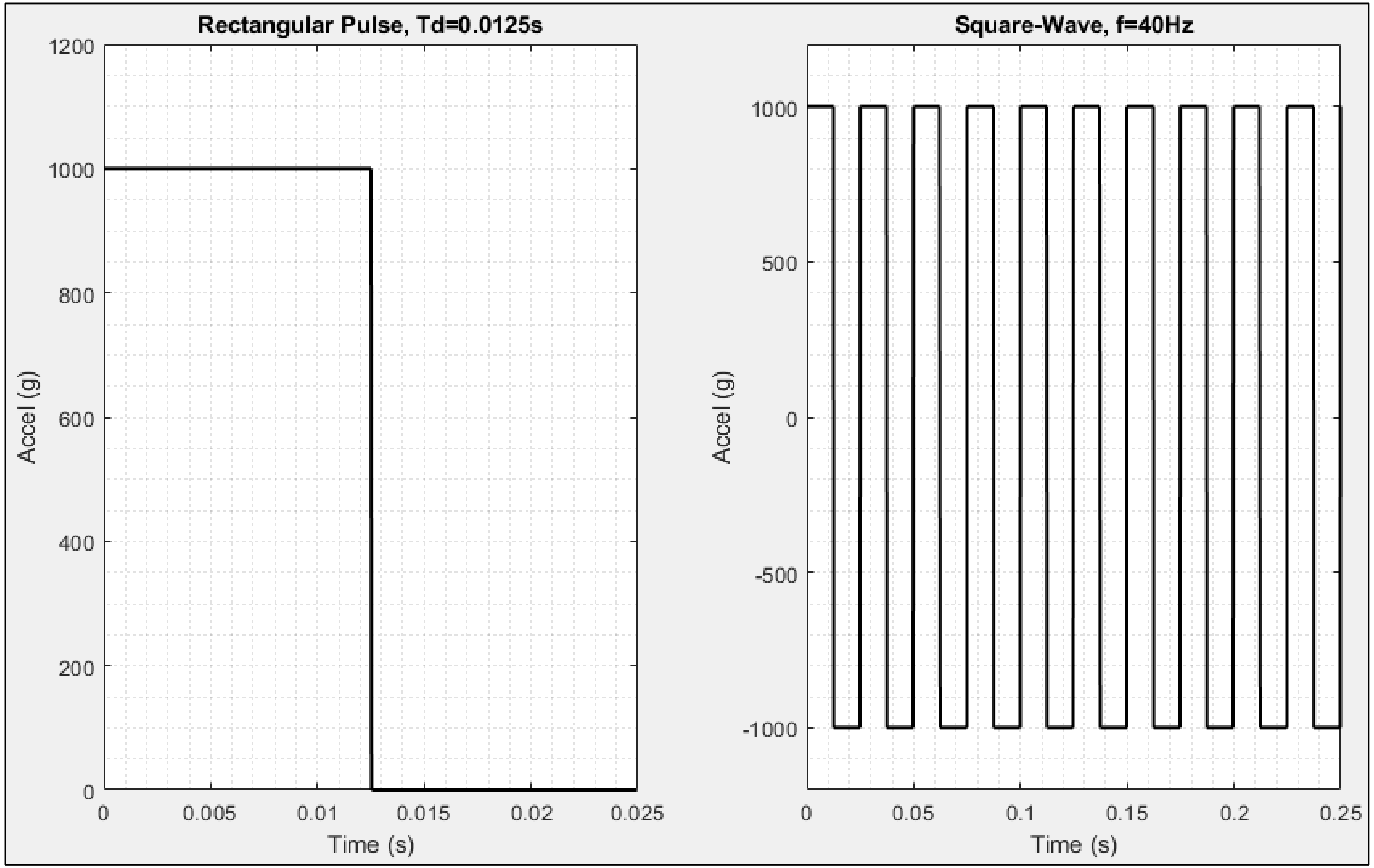
Overview

- Repetitive Shock Environments Overview
  - Rectangular Pulse and Square-Wave
  - Shock Pulse
    - Properties
    - Temporal Characteristics
- Sources of Repetitive Shock and Challenges
- JPL's Current Approach
  - Environment Definition
  - Testing
- Forward Work

Rectangular Pulse & Square-Wave

- Ideal rectangular pulse of pulse width, T_d, and amplitude A.
- Undamped SDOF to ideal rectangular pulse modeled as,

- When the pulse is repeated (A_w=±A & T_p=2T_d) to form a square-wave, the periodic pulse can be approximate with Fourier series expansion to:
  - $Z(t) = \frac{4A_w}{\pi}\sum_{n=1,3,\ldots}\frac{1}{n}\sin(n\Omega t)$
- Where Ω=2π/T_p.



Rectangular Pulse & Square-Wave SDOF Response

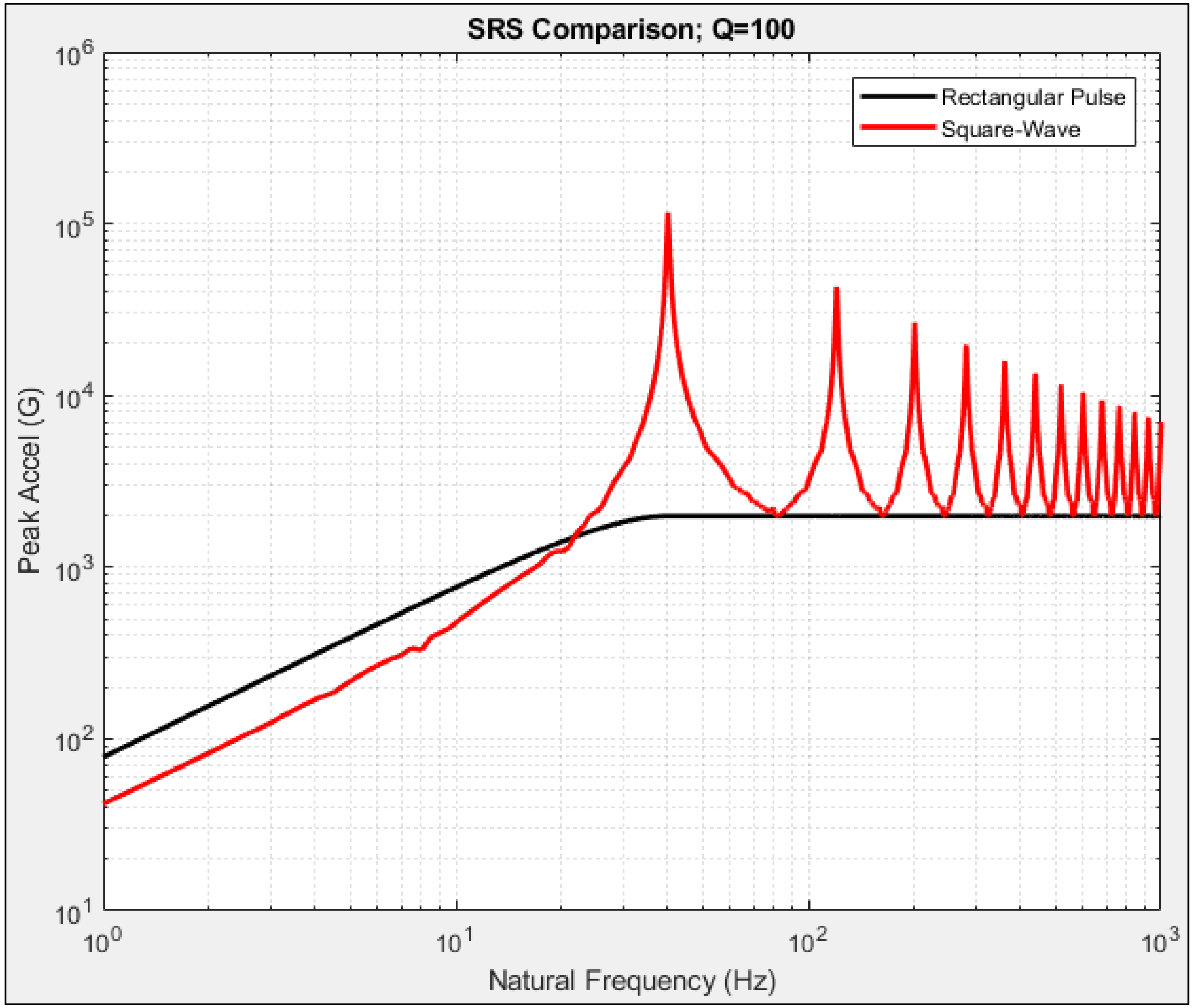
Dynamic Amplification Factor, R.

Undamped SDOF Response to Rectangular Pulse,

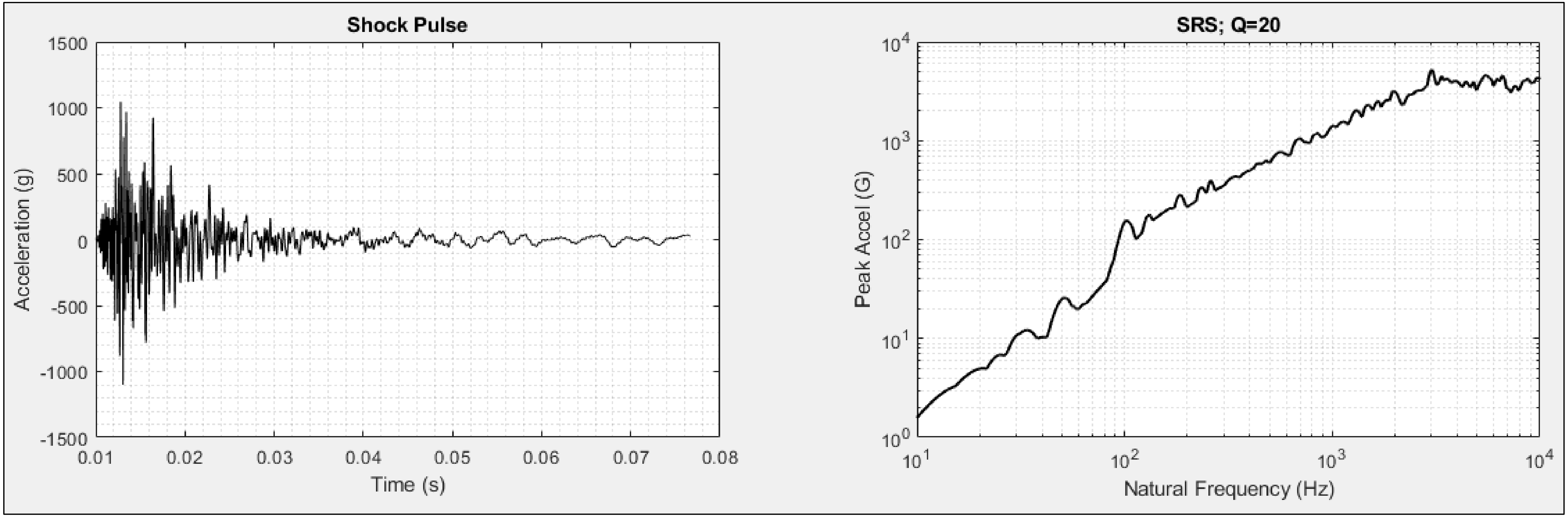
- For $T_d \geq 0.5T_n$ (Force-Vibration), where $T_n = 2\pi/w_n$,
  - $R_1 = 1 - \cos(w_n t)$ and $R_{1max} = 2$
- For $T_d < 0.5T_n$ (Residual-Response),
  - Free vibration with I.C. $R_1(T_p)$ & $\dot{R_1}(T_p)$.
  - & $R_{2\_max} = 2\sin(\frac{\pi T_d}{T_n})$.

Undamped SDOF Response to Square-Wave,

- $R = \sum_{n=1,3,\ldots} \frac{(\frac{n\Omega}{\omega_n})^2}{1-(\frac{n\Omega}{\omega_n})^2} * \frac{4}{n\pi} * \sin(n\Omega t)$
- Coupling can now occur when $w_n = n\Omega$.
- SRS indicates that, for $w_n \geq \Omega$, the peak response to the square-wave is equivalent to the max response to a rectangular pulse when $w_n = (n+1)\Omega$.



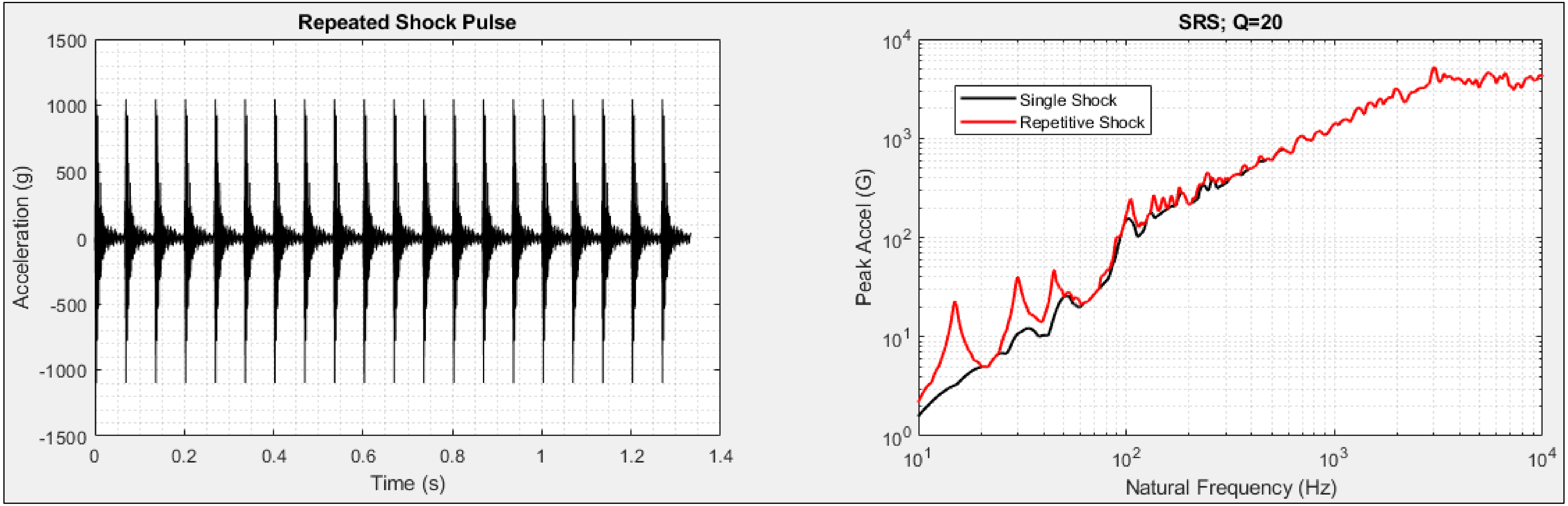
Repetitive Shock Description



Single Shock Pulse Statistics
Amplitude Stats
mean = 0.0
std dev = 129.4
RMS = 129.4
skewness = 0.116
kurtosis = 18.02

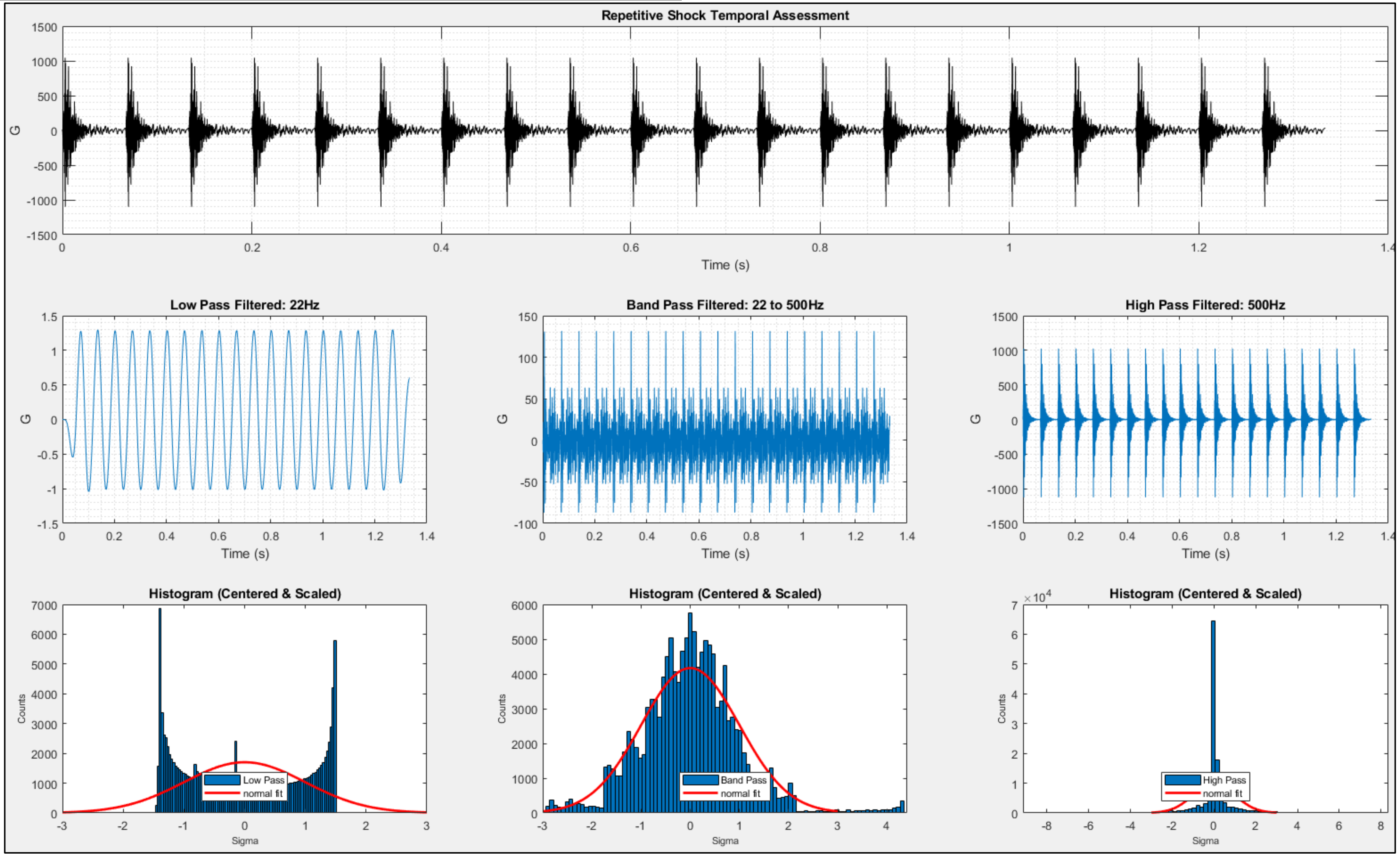
Maximum = 1045
Minimum = -1100
Crest Factor = 8.497

Repetitive Shock Description Cont'd…

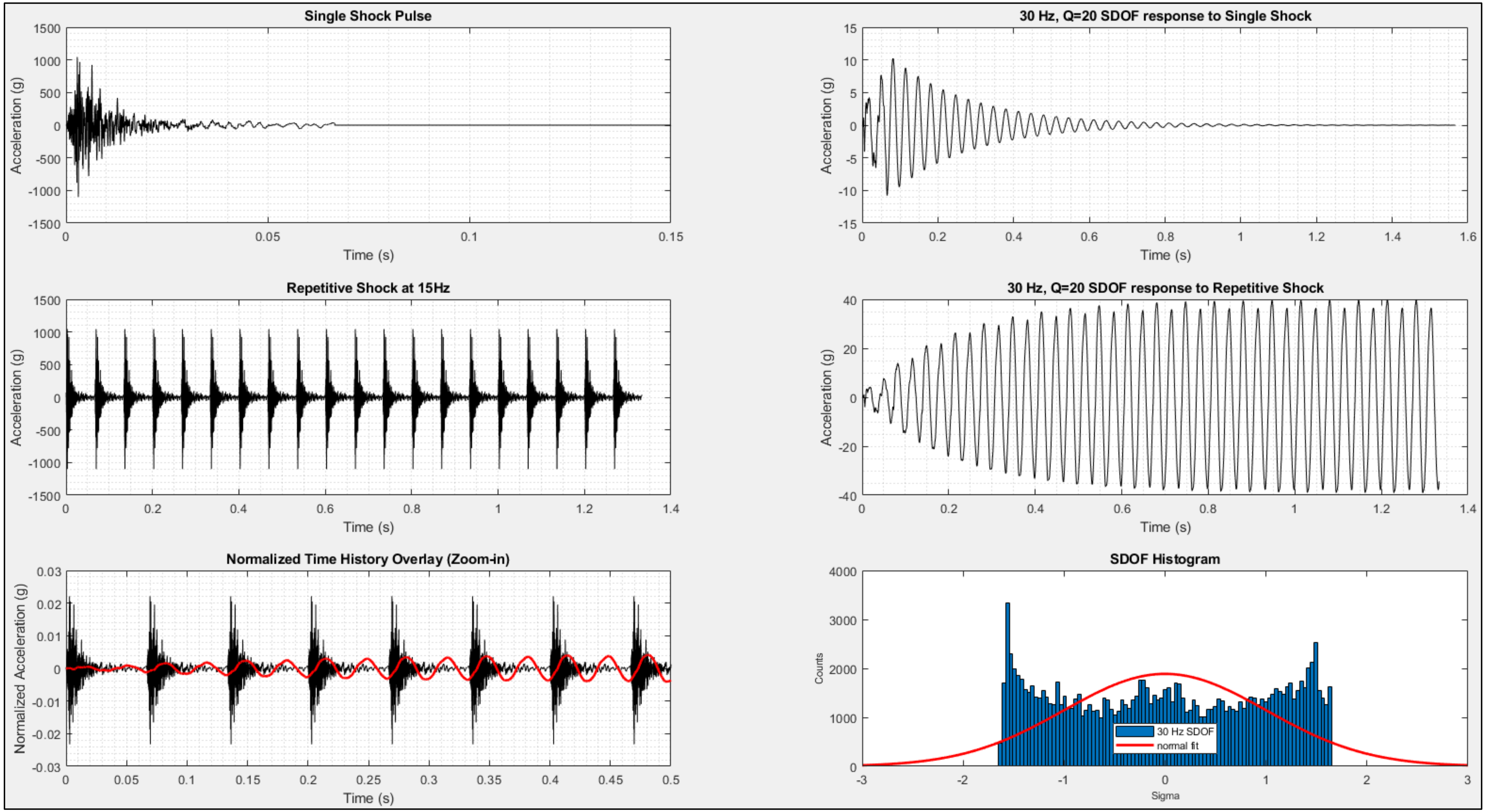


Similar observations as the rectangular pulse and square-wave example.

Temporal Characteristics

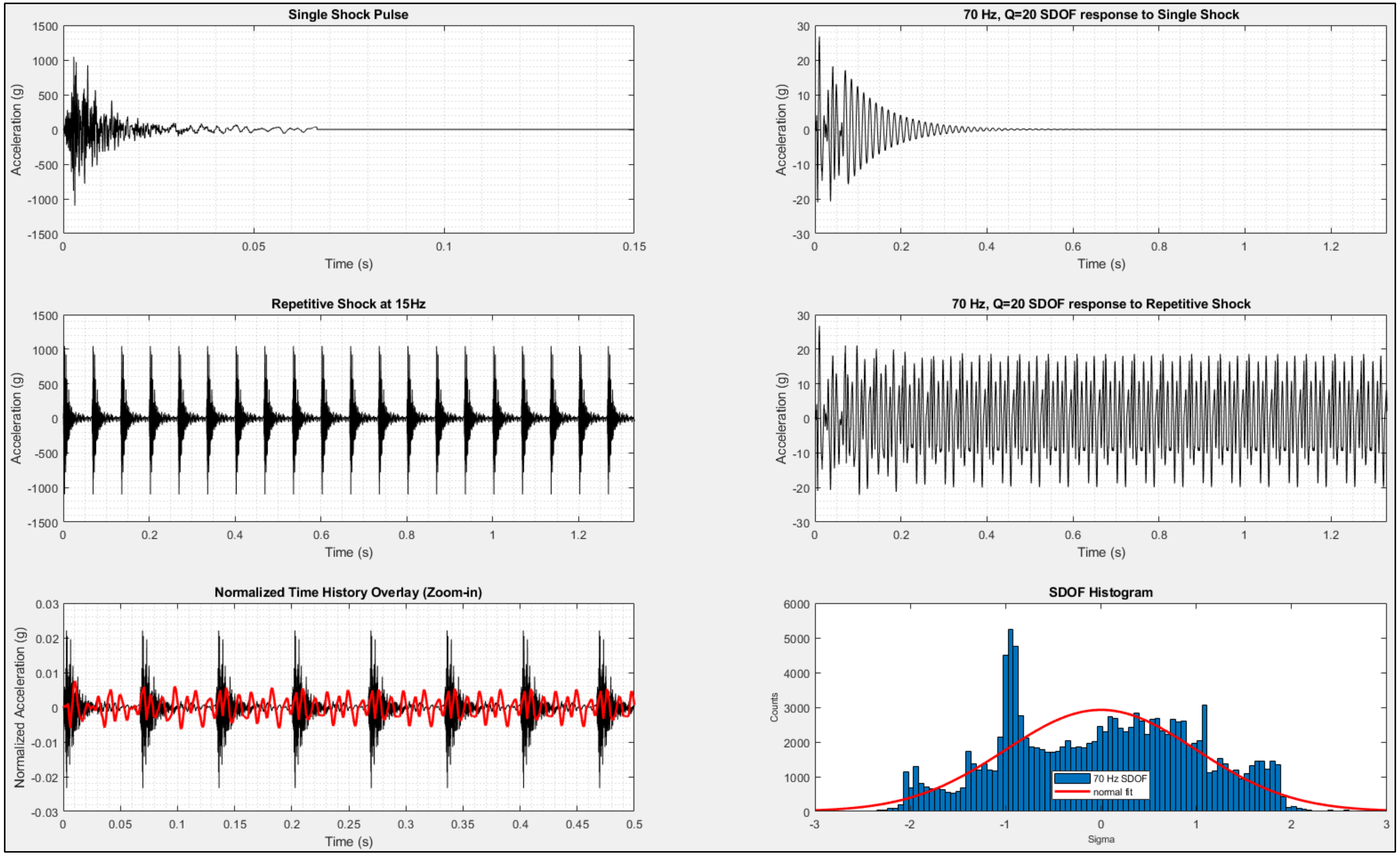


SDOF Response

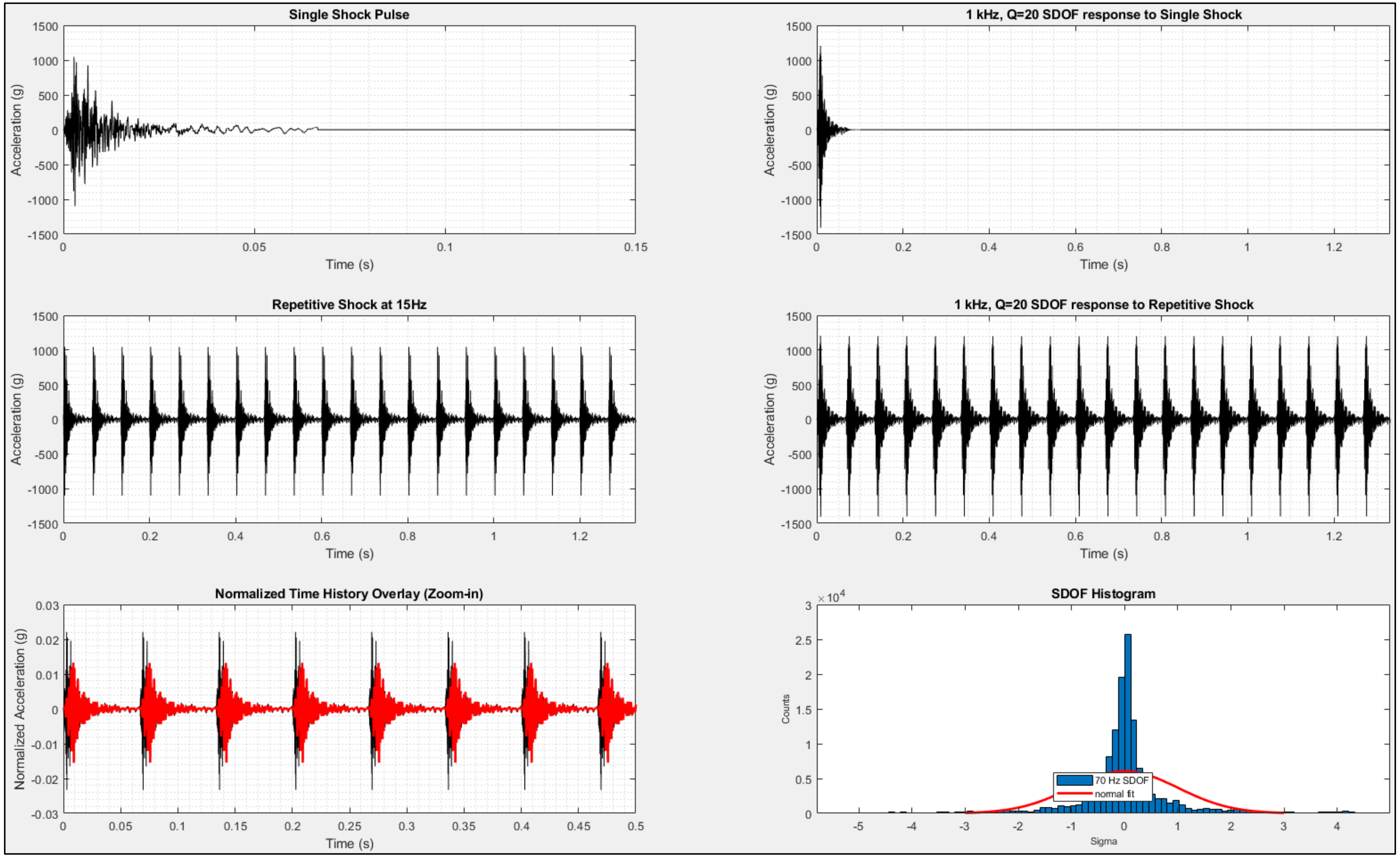


SCLV Dynamics Environment Workshop, 26 June, 2018

SDOF Response Cont'd…



SDOF Response Cont'd…



Examples of Repetitive Shock

- Mars 2020: Percussion Corer
- Gunfire

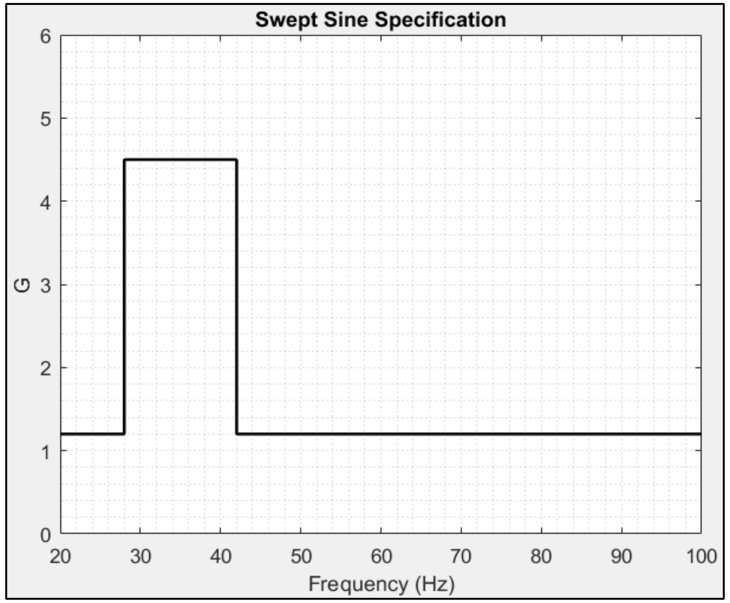
Challenges of Repetitive Shock

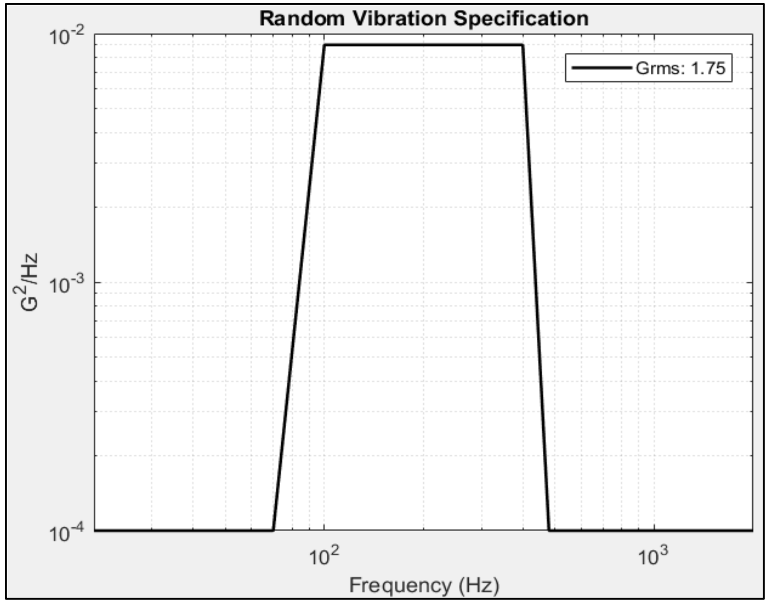
- Requirement Definition
  - In a manner useful for analyst
  - Applying margin
- Test Implementation
  - Simulation
  - Condition monitoring

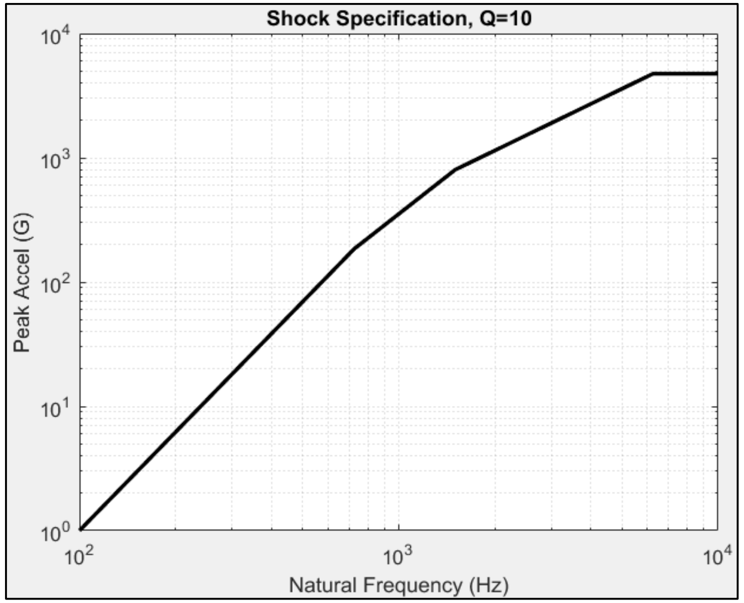
Requirement Definition

JPL's Current Approach

- Combination of Swept-Sine, Random Vibration (PSD), and Shock (SRS) to account for the observed temporal characteristics.
- Using the equivalent response method, each specification was designed to encompass the frequency range of its temporal characteristic such that the combined sum of each specification produces as equivalent fatigue response of the actual measured repetitive shock.







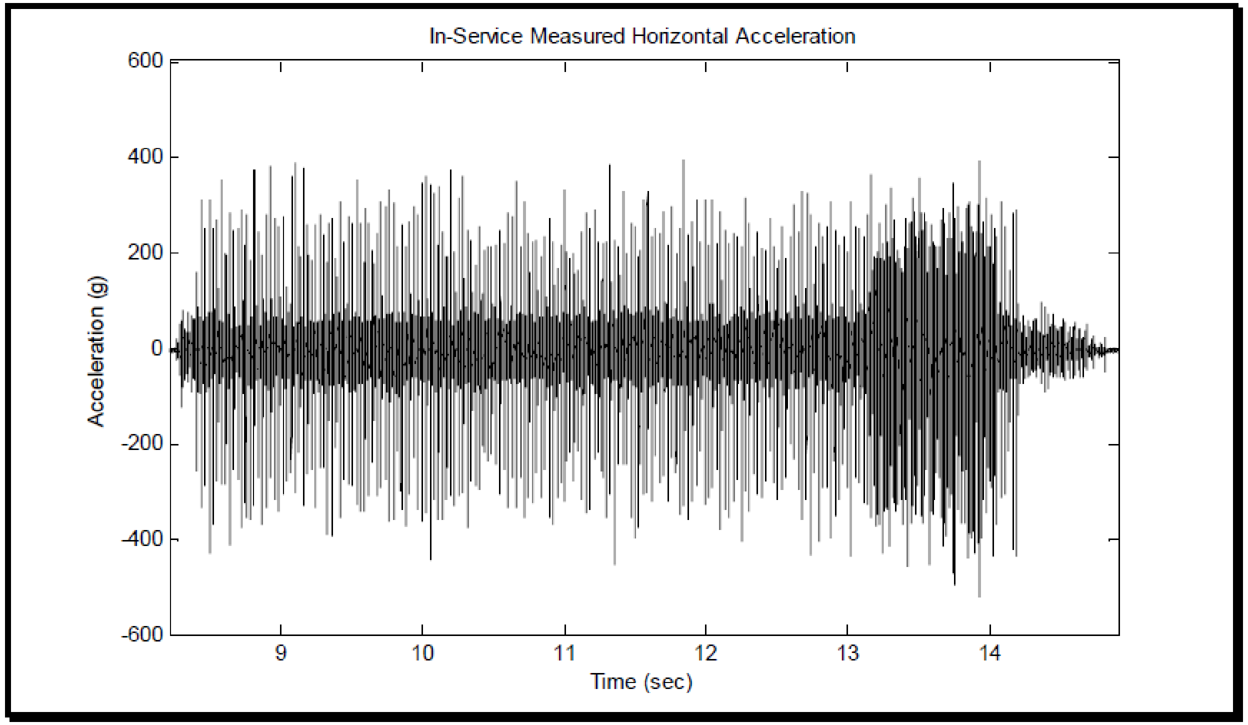
$$FatigueDamage(10 - 10000Hz)_{Repetitive\ Shock} = D(10 - 100Hz)_{SweptSine} + \cdots$$
$$D(100 - 400Hz)_{RandomVibration} + D(400 - 10000Hz)_{SRS*\#ofShocks}$$

MIL-STD-810G

- Gunfire Environment (519.6): repetitive shock produced by 1) a blast pressure wave impinging on component at the gun firing rate and 2) structure-borne shock transmitted through structure.
- Repetitive shock applied to a complex multi-modal material system will cause the material to respond 1) at forced frequencies imposed on the material from the external excitation and 2) the materiel's resonant natural frequencies either during or immediately after application of the external excitation.

MIL-STD-810G Recommended Approaches to Gunfire:

1. Time Domain/Waveform Replication (Recommended)
2. Sine-on-random
3. Narrowband-random-on-random



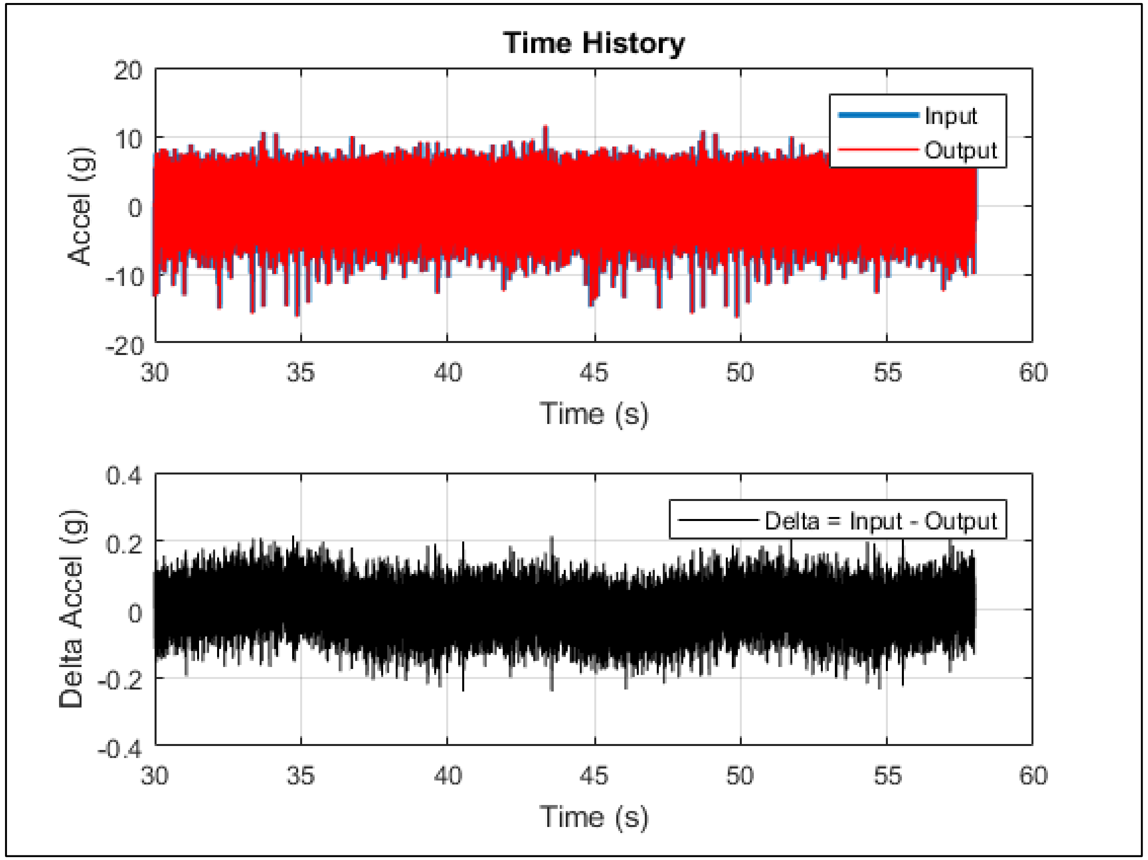
Testing

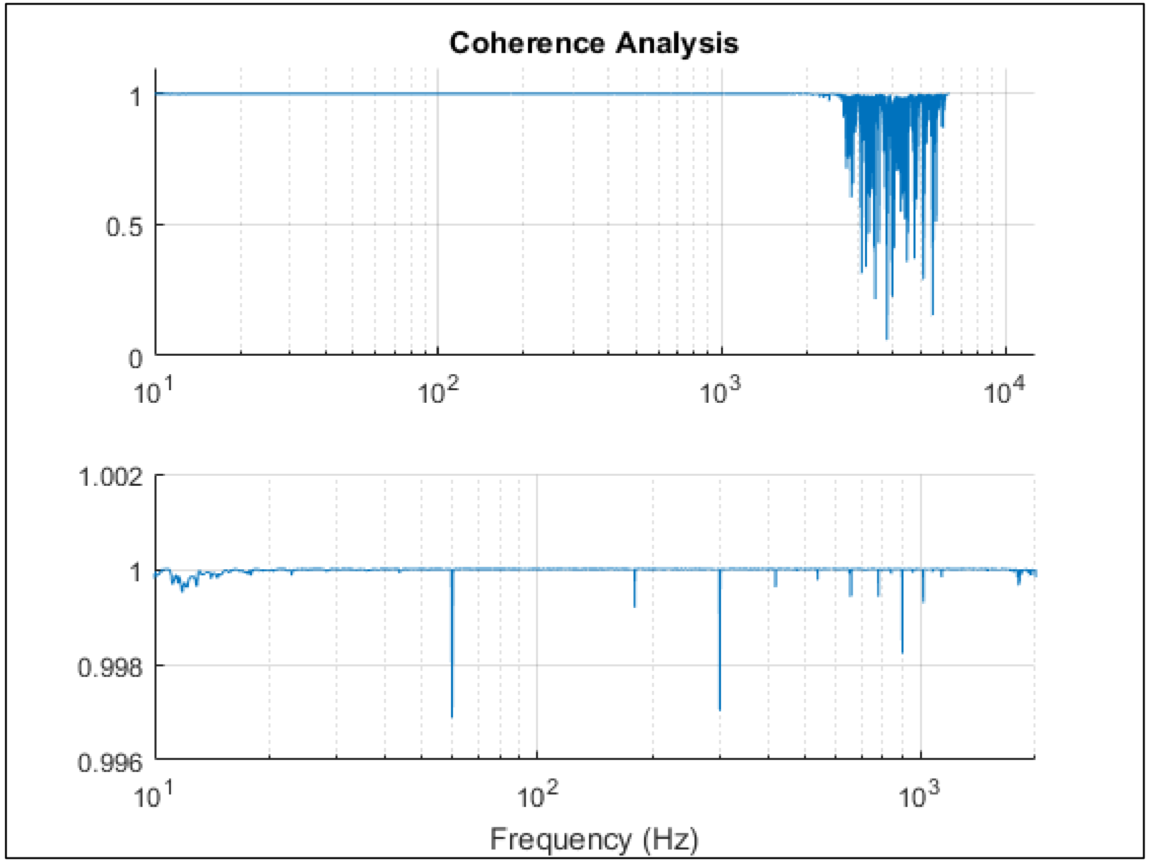
Actual Hardware

- Prototype Corer
  - Pros: Actual operating environment with flight-like interfaces for components, i.e., “test like you fly”.
  - Cons: Programmatically complex. Potentially limited life of the hardware.
- Lab-built Repetitive Shock Machine.
  - Pros: Simpler to implement.
  - Cons: Very limited control. Extremely sensitive to mounting conditions.

Shaker: Time Waveform Replication

- M+P Road Load Time Domain Replication Shaker Control Software
  - Pros: Offers accurate replication of any time-sign. Can perform infinite loop of signal for long-duration testing.
  - Cons: Frequency range (<2kHz) and single-axis excitation limitations make it a poor repetitive shock simulator. JPL does not have any shaker tables with thermal capabilities on lab.





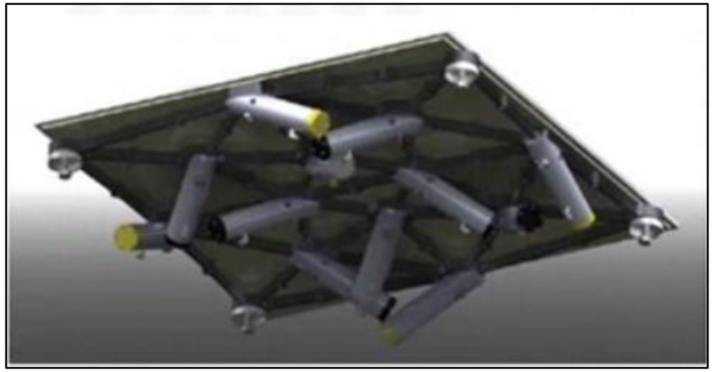
HALT Chamber Capabilities

- HALT
  - Pros: Produces a multi-axis, repetitive-shock environment of similar dynamics characteristics as the M2020 Corer. HALT can operate at temperature.
  - Cons: Limited control options for the dynamics environment. Mass model testing needs to be performed prior to actual hardware to determine appropriate G_{rms} level and adjusted duration if necessary.

Thermotron AST-8 Chamber

- Workspace dimensions (WxDxH): 24”x22”x24”
- 300 lb load capability
- -100°C to 200°C

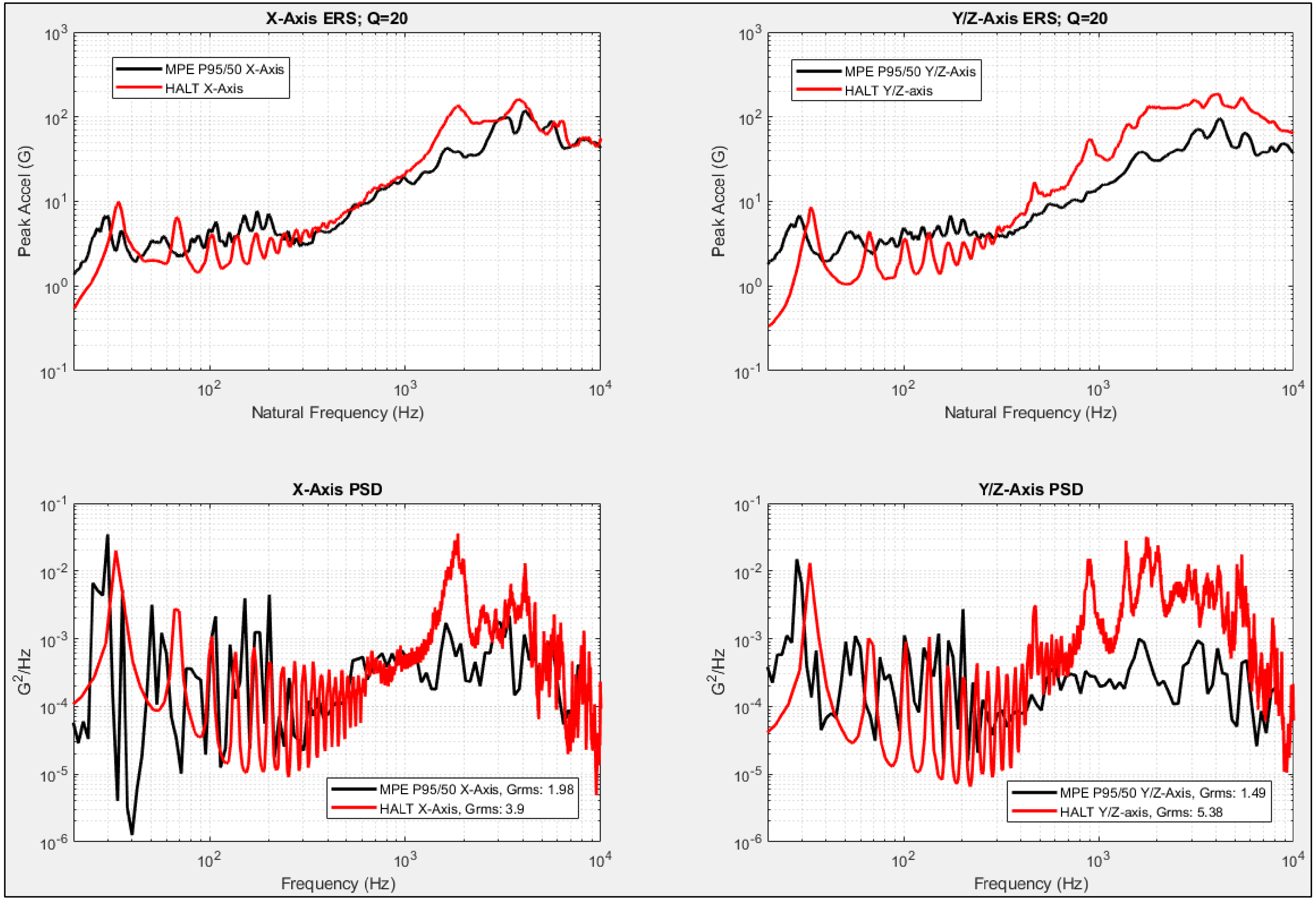
RS-16 Repetitive Shock Table



Underside of repetitive shock table with pneumatic actuator arrangement.

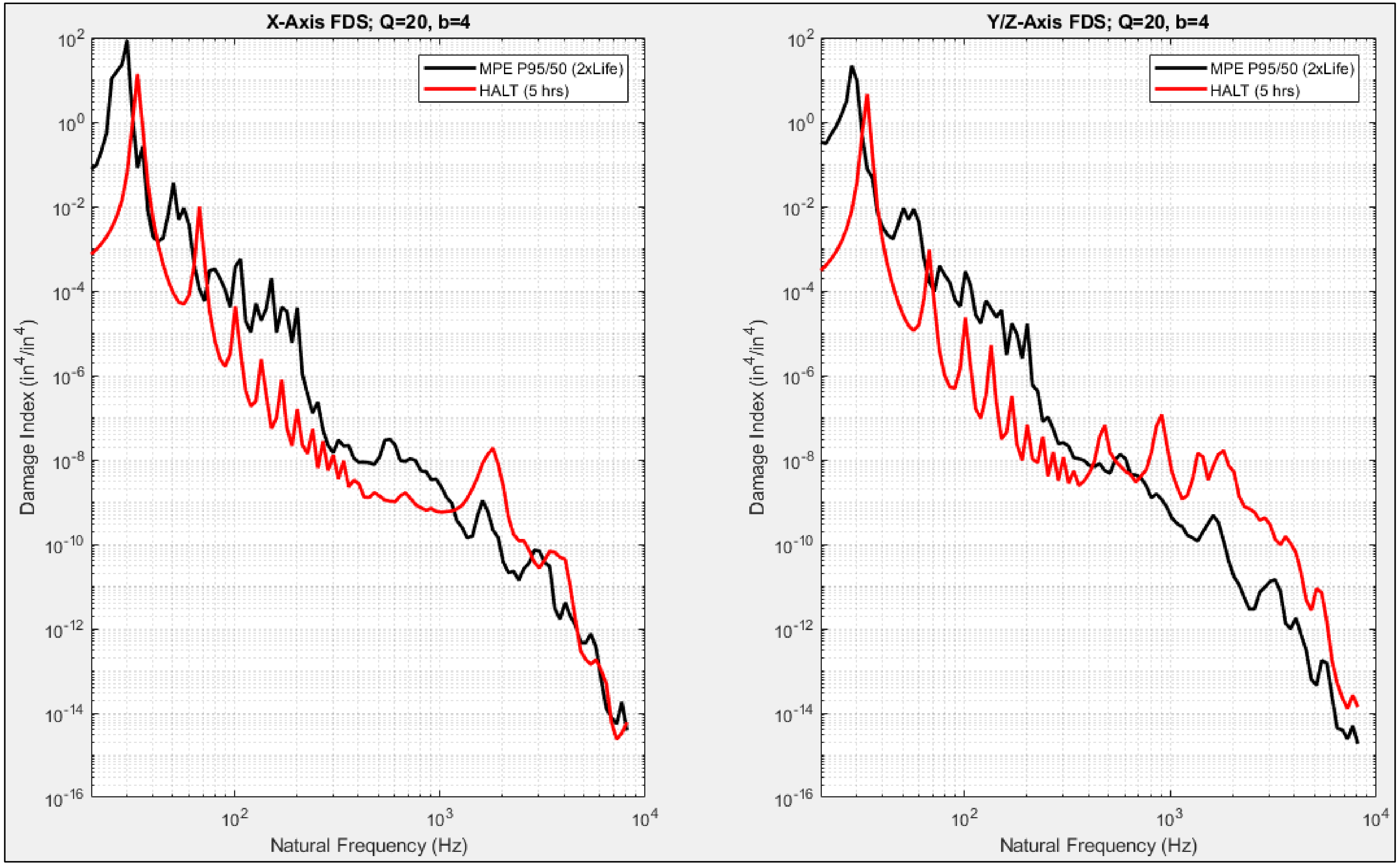
- Key differences from shaker table:
  - Semi-rigid table vs “infinite” impedance.
  - Single control accel for overall Grms control.
  - Does offer live monitoring capability for hardware condition monitoring.
- 16”x16” grid size of 4”x4” 3/8-16 bolt pattern.

HALT Cont'd…

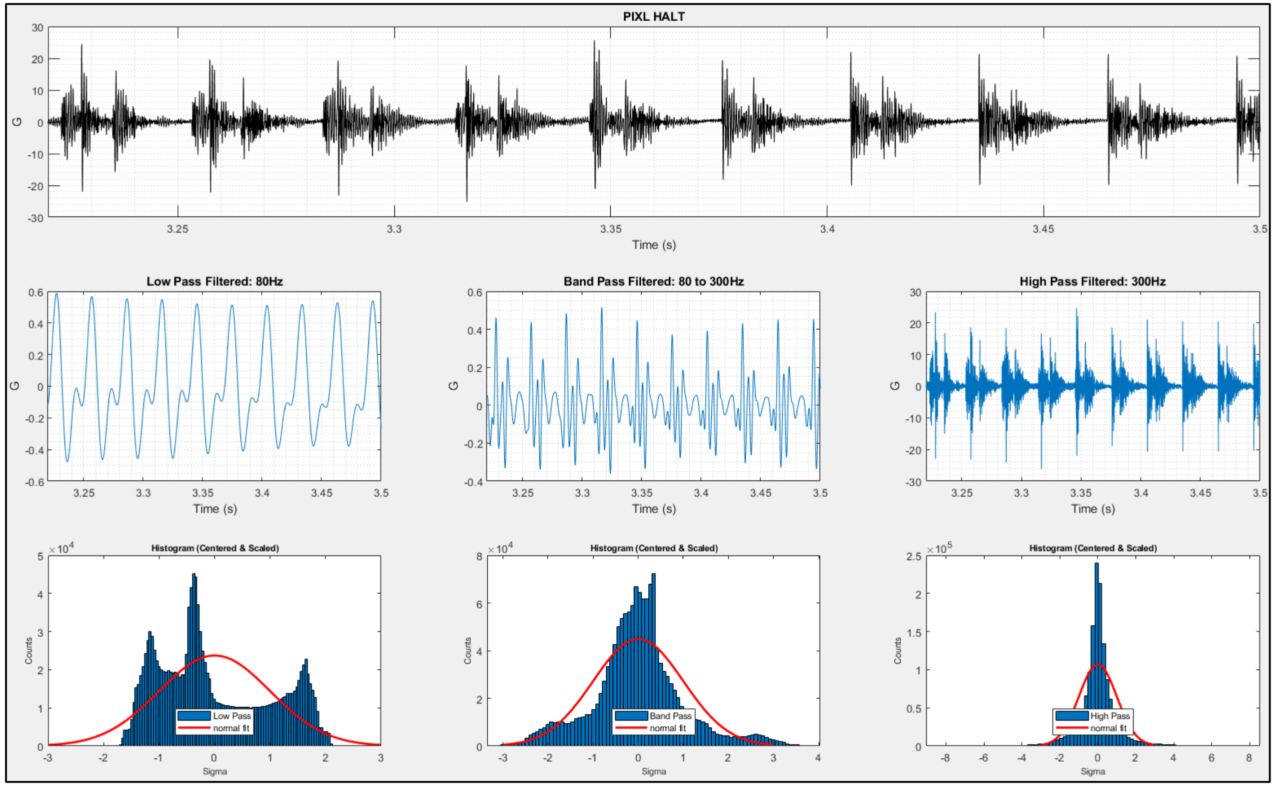


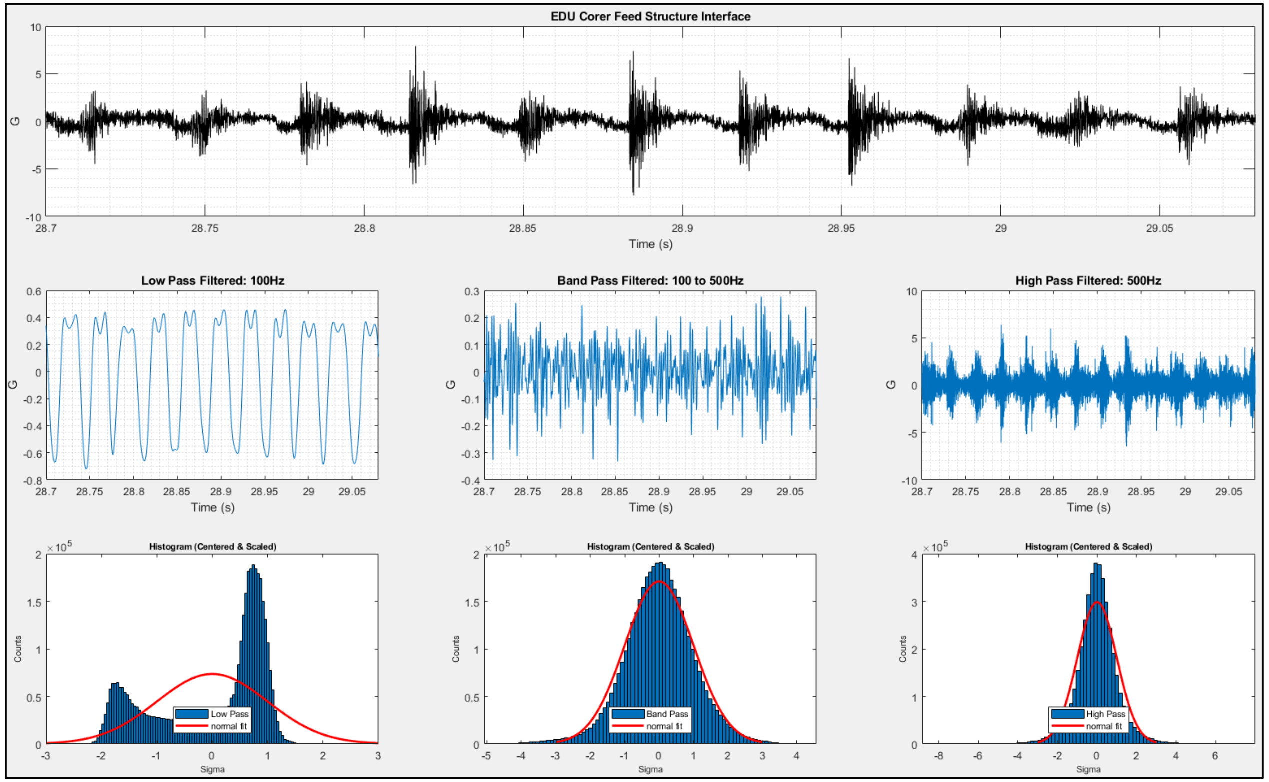
X-Axis ERS; Q=20
MPE P95/50 X-Axis
HALT X-Axis
Peak Accel (G)
Natural Frequency (Hz)
Y/Z-Axis ERS; Q=20
MPE P95/50 Y/Z-Axis
HALT Y/Z-axis
Peak Accel (G)
Natural Frequency (Hz)
X-Axis PSD
MPE P95/50 X-Axis, Grms: 1.98
HALT X-Axis, Grms: 3.9
G²/Hz
Frequency (Hz)
Y/Z-Axis PSD
MPE P95/50 Y/Z-Axis, Grms: 1.49
HALT Y/Z-axis, Grms: 5.38
G²/Hz
Frequency (Hz)

HALT Cont'd…


X-Axis FDS; Q=20, b=4
Y/Z-Axis FDS; Q=20, b=4
MPE P95/50 (2xLife)
HALT (5 hrs)
Damage Index (in^4/in^4)
Natural Frequency (Hz)
10^2
10^0
10^-2
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
10^-16
10^3
10^4

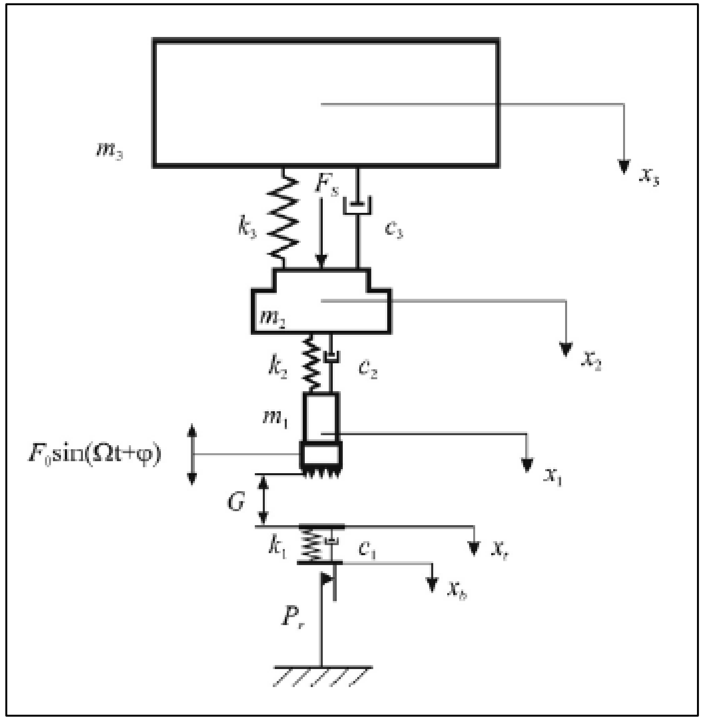
HALT Cont'd…


PIXL HALT
Time (s)
Low Pass Filtered: 80Hz
Band Pass Filtered: 80 to 300Hz
High Pass Filtered: 300Hz
Histogram (Centered & Scaled)
Low Pass
Band Pass
High Pass
normal fit
Counts
Sigma
G


EDU Corer Feed Structure Interface
Time (s)
Low Pass Filtered: 100Hz
Band Pass Filtered: 100 to 500Hz
High Pass Filtered: 500Hz
Histogram (Centered & Scaled)
Low Pass
Band Pass
High Pass
normal fit
Counts
Sigma
G

Future Work

- Modeling & Environment prediction
- Refining specification definition (narrowband random, etc.)



E. Pavlovskaia, D. C. Hendry, and M. Wiercigroch. Modelling of high frequency vibro-impact drilling. *International Journal of Mechanical Sciences*, 91:110{119, 2015.

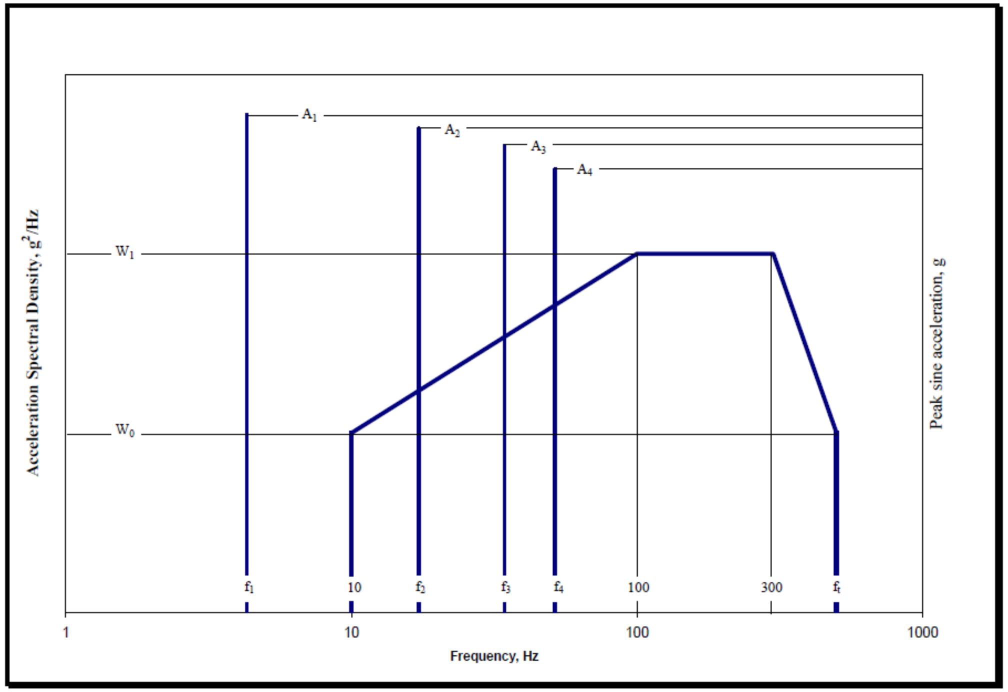


Figure 514.6D-3 Category 14 – Helicopter vibration (Same as Annex C, Figure514.6C-8).

MIL-STD-810G

Summary

- As NASA pursues more rocky body exploration, drills and other sources of repetitive shock will continue to be a part of NASA missions.
- Repetitive shock environments offer unique challenges for specification development and testing with plenty of opportunities for further improvement.

QUESTIONS?

BACKUP

MIL-STD-810G: Helicopter

- Helicopter vibration (514.6) is characterized by dominant peaks superimposed on a broadband background. The peaks are sinusoids produced by the major rotating components & occur at rotation speed (frequency). The broadband background is a mixture of lower amplitude sinusoids and random vibrations.
  - Vibration levels and spectrum shapes vary widely depending on strength and location of sources and the geometry and stiffness of the structure.
  - "The broadband background is expressed as random vibration for design and test purposes as a matter of expediency."

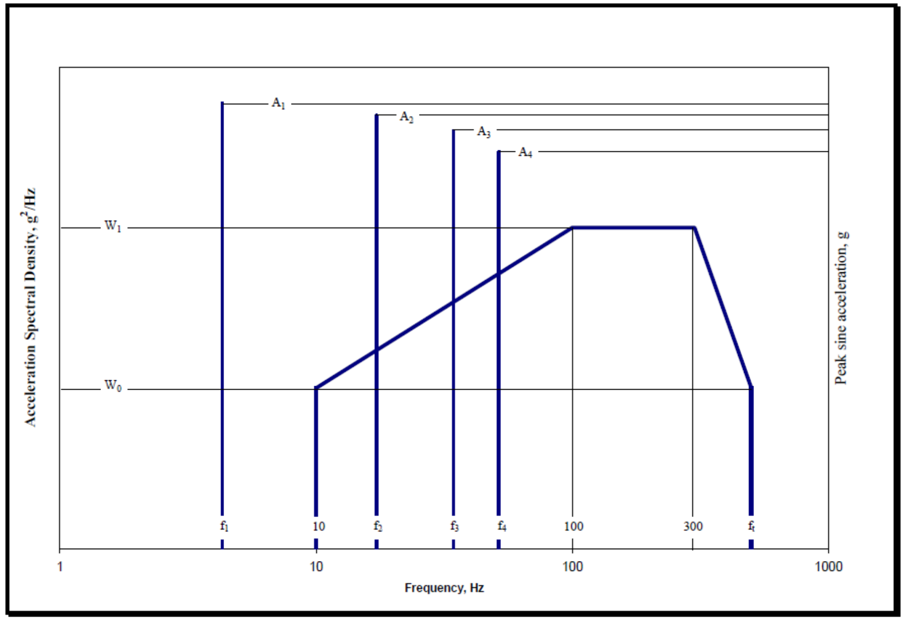


Figure 514.6D-3 Category 14 – Helicopter vibration (Same as Annex C, Figure514.6C-8).

Table 514.6D-III – Category 14 - Helicopter vibration exposure. (Same as Annex C, Table 514.6C-X.)

MATERIEL	RANDOM LEVELS	SOURCE FREQUENCY (f_x) RANGE (Hz)	PEAK ACCELERATION (A_x) at f_x (GRAVITY UNITS (g))
General	W_0 = 0.0010 g^2/Hz W_1 = 0.010 g^2/Hz f_t = 500 Hz	3 to 10 10 to 25 25 to 40 40 to 50 50 to 500	0.70 /(10.70 - f_x) 0.10 x f_x 2.50 6.50 - 0.10 x f_x 1.50
Instrument Panel	W_0 = 0.0010 g^2/Hz W_1 = 0.010 g^2/Hz f_t = 500 Hz	3 to ≤ 10 >10 to 25 25 to 40 40 to 50 50 to 500	0.70 /(10.70 - f_x) 0.070 x f_x 1.750 4.550 - 0.070 x f_x 1. 050
External Stores	W_0 = 0.0020 g^2/Hz W_1 = 0.020 g^2/Hz f_t = 500 Hz	3 to ≤ 10 >10 to 25 25 to 40 40 to 50 50 to 500	0.70 /(10.70 - f_x) 0.150 x f_x 3.750 9.750 - 0.150 x f_x 2.250
On/Near Drive System Elements	W_0 = 0.0020 g^2/Hz W_1 = 0.020 g^2/Hz f_t = 2000 Hz	5 to ≤ 50 > 50 to 2000	0.10 x f_x 5.0 + 0.010 x f_x
Main or Tail Rotor Frequencies (Hz) Determine 1P and 1T from the Specific Helicopter or from the table (below).			**Drive Train Component Rotation Frequency (Hz)** Determine 1S from Specific Helicopter and Component.