2021 Shock and Vibration Conference Presentation
August 15, 2021

Controlled Pyroshock Test Transients Can Be Used To Better Match Operational Shock Transients and Reduce Artificial Pyroshock Test Failures

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Shock Analysis and Testing Issues

- Shock analysis is typically done via SRS (shock response spectrum)
  - Oftentimes shock analysis is not performed because most loads specifications only supply SRS requirements with no representative shock transients that can be used for analysis
- SRS analysis is too conservative
  - There is no structural dynamics involved as all modes are assumed to have peak responses simultaneously and in-phase with each other
  - Possible that all other loads and combination of loads show the design to be good, whereas SRS analysis (1000 g's are involved) results may require redesign
- Multiple shock transients can satisfy a SRS, yet most loads documents don't provide a representative shock transient that could be used for shock analysis
- Shock testing is less common than harmonic and random vibration testing
  - Engineers typically go into shock tests with very little knowledge of what to expect P
  - Pass/fail type of approach with very little engineering done to prepare for the test or to control the type of shock transient
  - Most engineers will not model the shock test fixture due to lack of knowledge about the details of the test setup
  - Shock analysis and testing is often an open loop type situation - no test setup modeling, no test correlation, and no control over the test shock transient

Desire To Change The Shock Approach Narrative

Approach is to:

1) Get government agencies/contractors to provide representative operational shock transients as well as SRS
   a) SRS alone is not sufficient
2) Understand the shock test setup and prepare for shock testing and understand expected shock test responses (similar to sine and random vibration responses) through more detailed and accurate shock transient modeling and analysis
3) Correlate shock analysis FE model to shock test modes and transient results
4) Dictate to test lab the applied shock transient to obtain the desired reference accelerometer transient desired
   1) shape, peaks, damping, duration to match operational transients and meet SRS criteria
5) Don't allow test lab create an arbitrary transient that meets SRS criteria

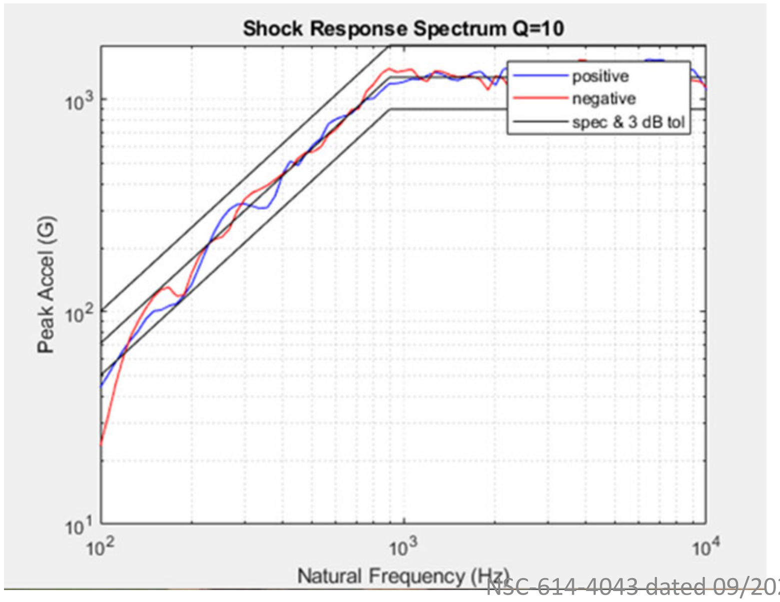
Assumptions/Goal For This Study

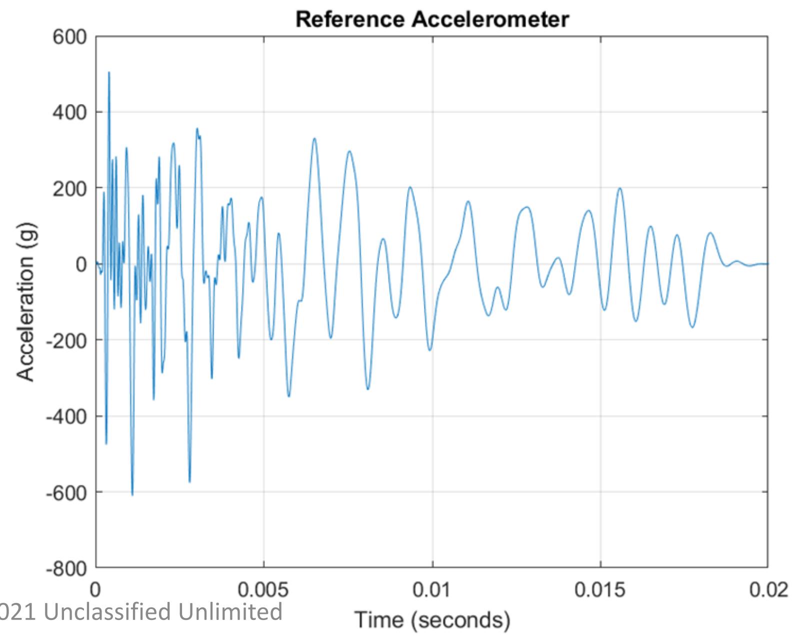
- Assume that there is excellent modal and transient correlation between test and analysis results
  - Nastran FE model has been modified to closely match shock test results
- Assume that the desired shock transient is a damped sine type of shock transient with peaks, shape, damping, and duration that closely matches operational transients
- Calculate test shock force transient that creates desired acceleration shock transient at reference accelerometer
  - If can create applied test force transient that comes close to matching calculated force transient then a more reasonable acceleration transient will be created at the test reference accelerometer that better matches operational shocks

GOAL

Desired Shock Transient That Matches Operational Shocks

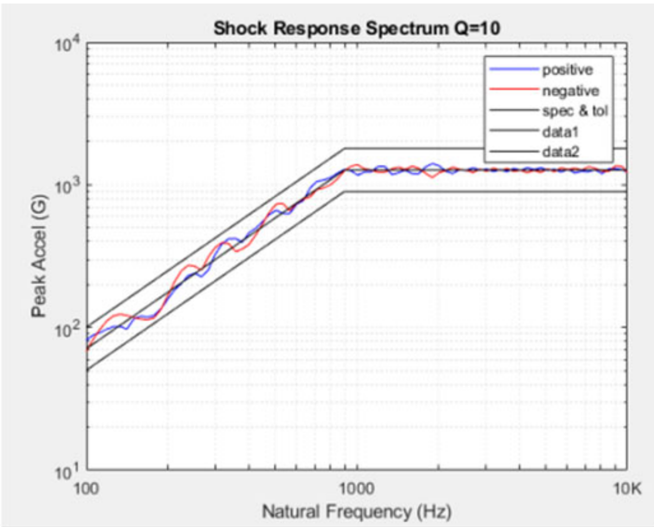
- Assume this is the desired shock transient at the interface between a subsystem to be shock tested and the vehicle it mounts to in all three axes
- The spec SRS is the straight line between the two tolerance straight lines and the positive and negative peak curves show how the reference accelerometer transient satisfies the spec SRS

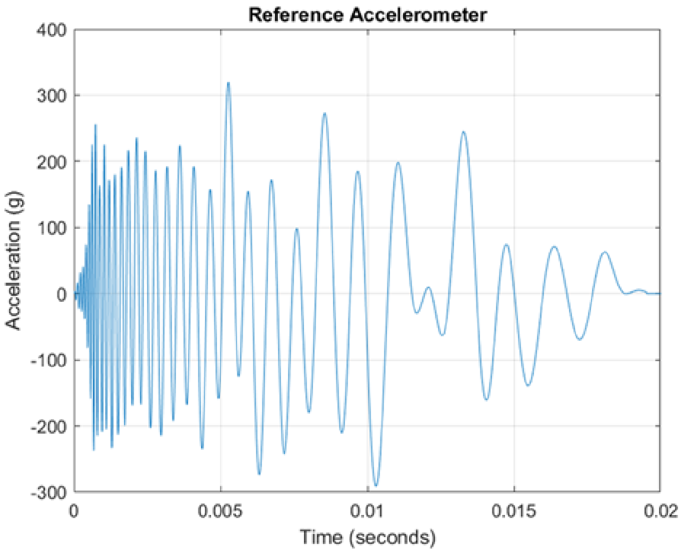




Wavelet Transient Also Meets SRS

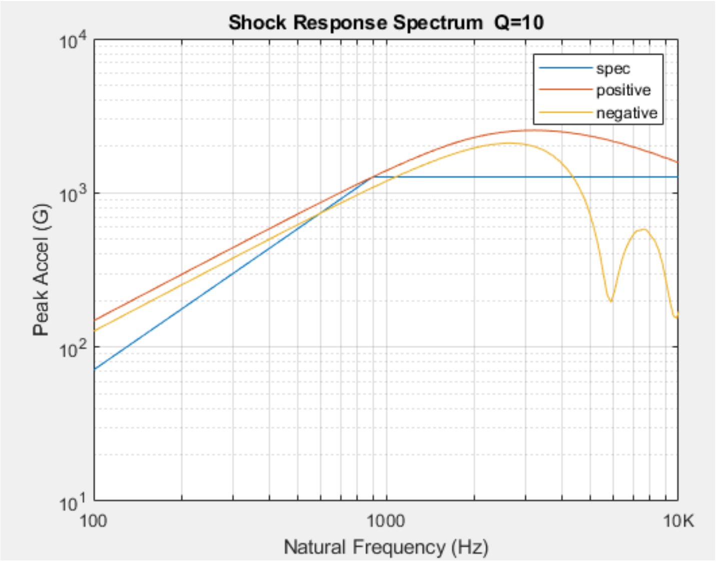
- Instead of a damped sine transient that matches the operational shock transient it is possible to create this wavelet type of transient at the reference accelerometer
- Satisfies SRS, but not operational shock transient

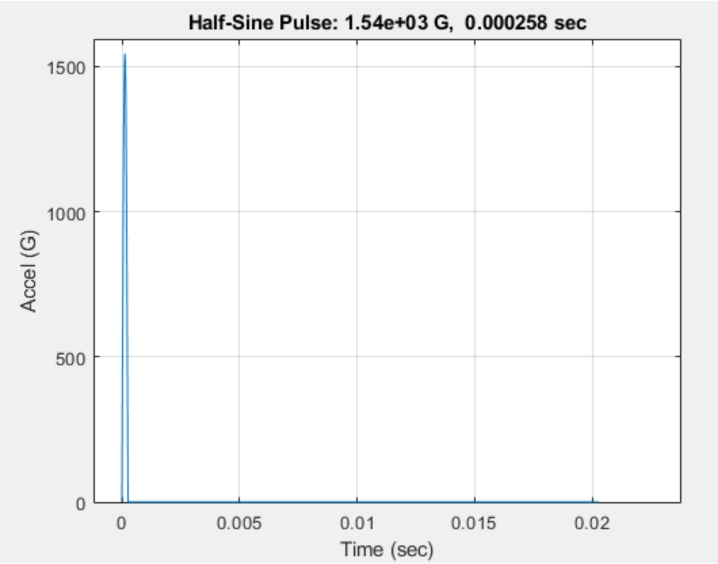




Classical Half-Sine Pulse Transient

- Instead of a damped sine transient that matches the operational shock transient it is possible to create this half-sine pulse transient at the reference accelerometer
- Misses SRS above 1 kHz and not close to operational shock transient





Analysis Approach

- Determine applied shock force transient from target reference acceleration via Matlab:

$\ddot{x}_i$(t)ref →	$\ddot{x}_i$(jw)ref via FFT
$\ddot{x}_i$(jw)ref →	f_j(jw)strike via H(jw)
f_j(jw)strike →	f_j(t)strike via IFFT

Complex frequency function H(jw) can be determined from this complex frequency equation:

$$\ddot{x}_i(jw) = \sum \frac{\varphi_{ir} * \varphi_{jr} * f\,jr(jw) * (jw)^2}{M_r * wr^2 * [1 - \left(\frac{w}{w_r}\right)^2 + 2 * j * \zeta_r * \left(\frac{w}{w_r}\right)]}$$

Summed over all modes

φ_{ir} = eigenvector at reference accelerometer dof (degree-of-freedom) for rth mode

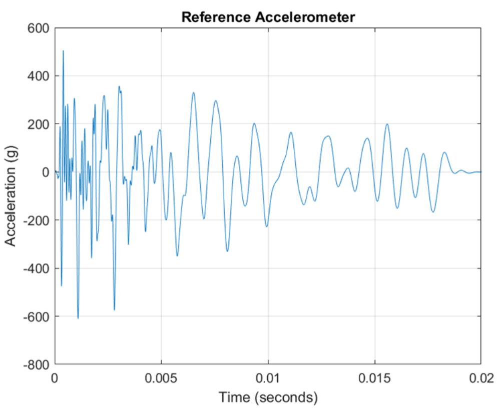
φ_{jr} = eigenvector at force strike dof for rth mode

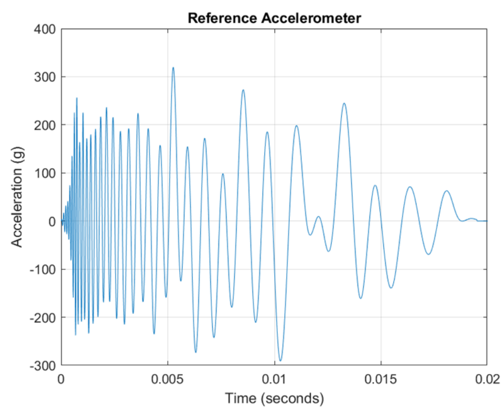
Reference Accelerometer Transients Time vs Frequency Content

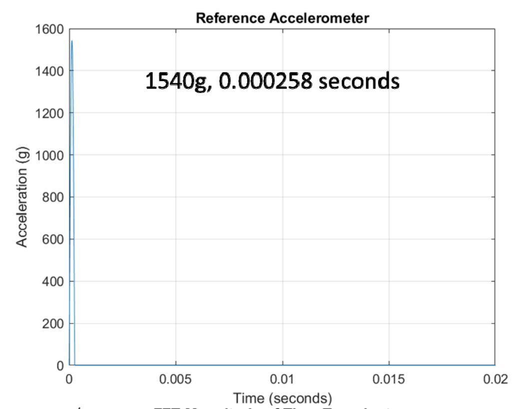
Target damped sine transient

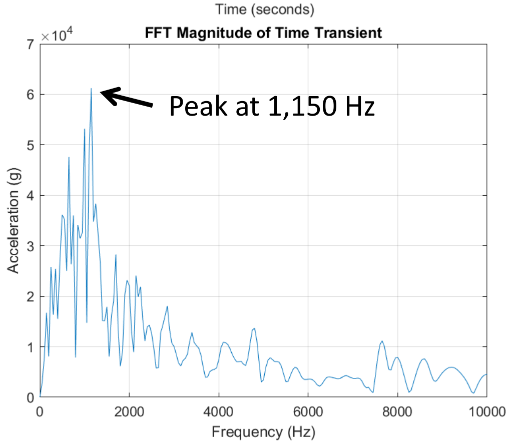
Wavelet transient

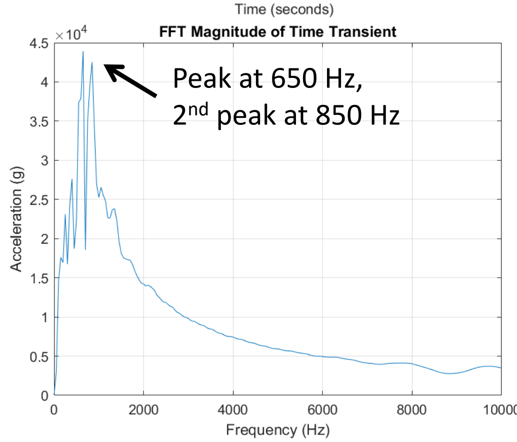
Half sine pulse

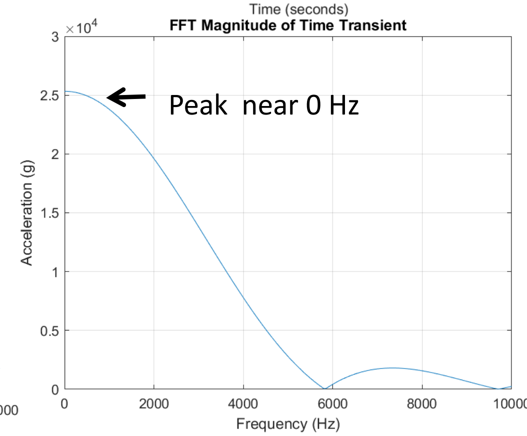






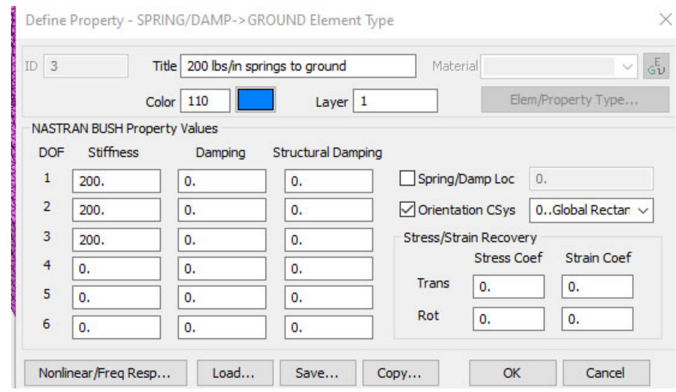


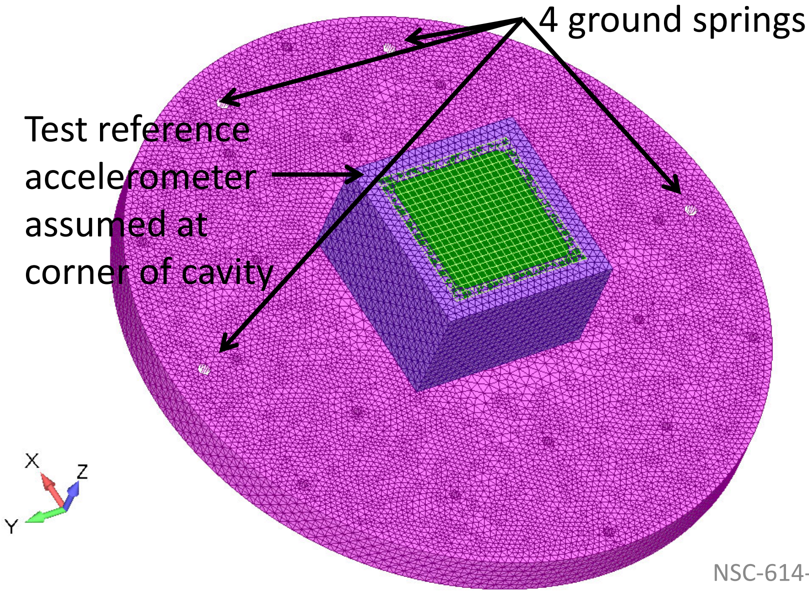


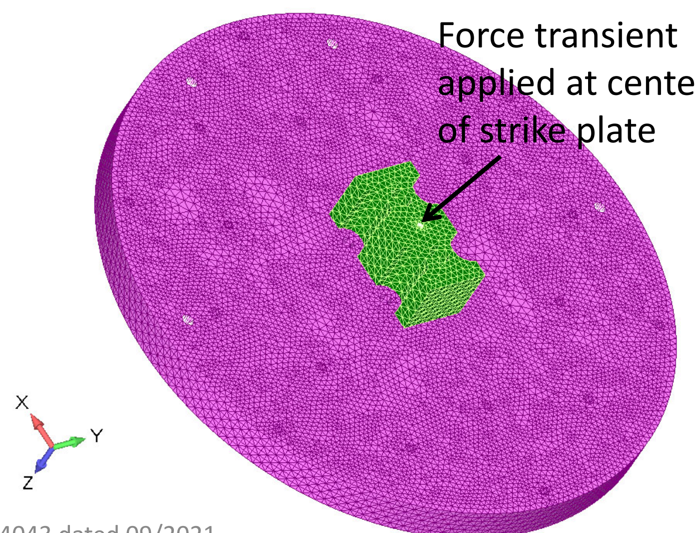


17” OD Circular Plate Shock Test Setup FEM

- W FEM = 31.9 lbs
- BC: 4 ground springs
- 4” square 0.064” thick polyimide (E=3e6 psi) electronics board (W=0.41 lbs) fixed to edges of cavity or mounted on 4 corner isolators
- Board glued to cavity; Cavity glued to plate







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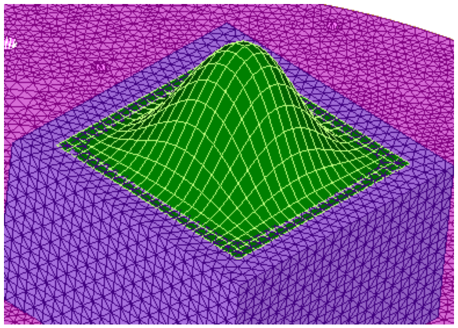
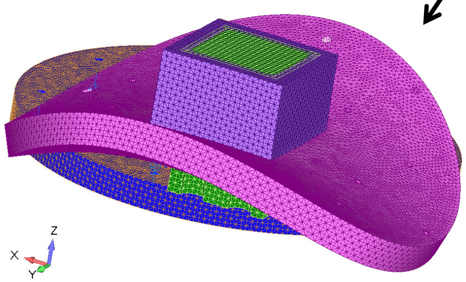
Modal Results

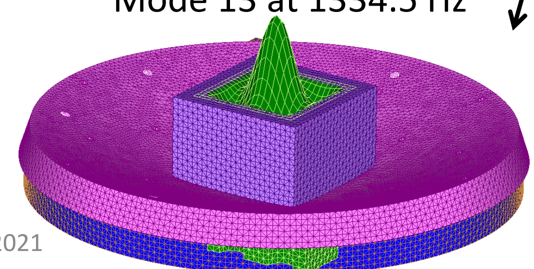
Mode 7 at 448.2 Hz



Mode 10 at 961.9 Hz



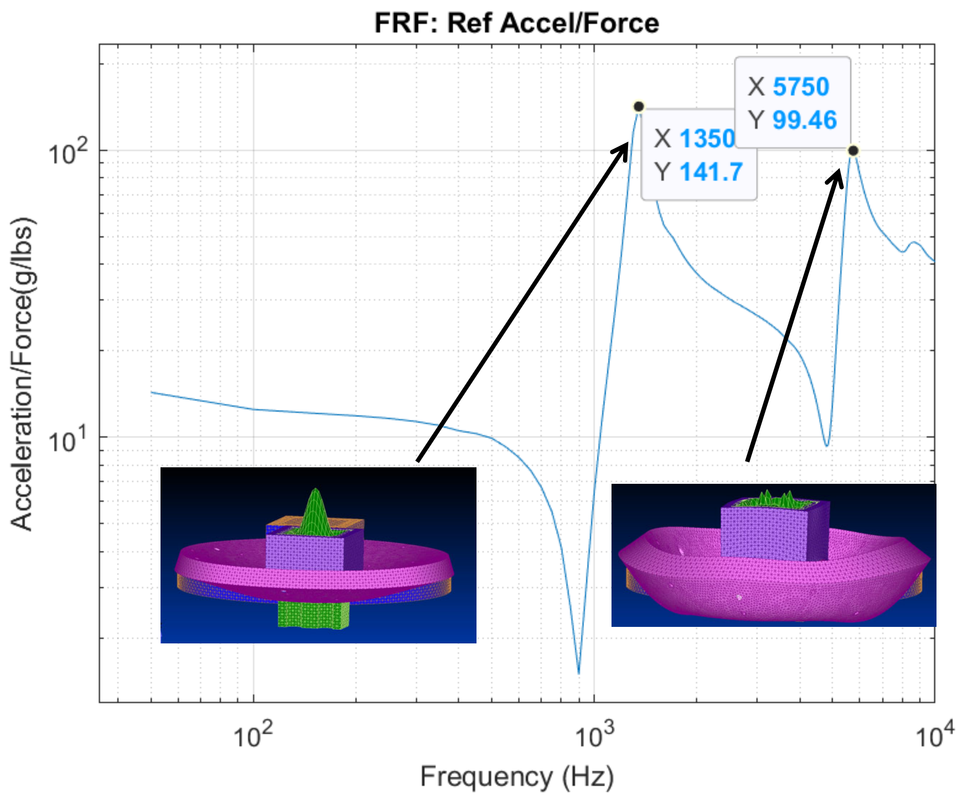
Mode 13 at 1334.5 Hz



1..Mode 1, 9.330824 Hz
2..Mode 2, 12.74235 Hz
3..Mode 3, 15.66738 Hz
4..Mode 4, 22.21954 Hz
5..Mode 5, 23.52189 Hz
6..Mode 6, 23.74209 Hz
7..Mode 7, 448.1774 Hz
8..Mode 8, 910.3213 Hz
9..Mode 9, 910.3641 Hz
10..Mode 10, 961.8896 Hz
11..Mode 11, 1007.344 Hz
12..Mode 12, 1326.18 Hz
13..Mode 13, 1335.456 Hz
14..Mode 14, 1631.805 Hz
15..Mode 15, 1646.972 Hz
16..Mode 16, 1798.287 Hz
17..Mode 17, 1801.792 Hz
18..Mode 18, 2009.157 Hz
19..Mode 19, 2009.196 Hz
20..Mode 20, 2228.004 Hz
21..Mode 21, 2235.724 Hz
22..Mode 22, 2611.657 Hz
23..Mode 23, 2611.766 Hz
24..Mode 24, 2639.103 Hz
25..Mode 25, 2940.474 Hz
26..Mode 26, 2954.987 Hz
27..Mode 27, 2999.902 Hz
28..Mode 28, 3003.256 Hz
29..Mode 29, 3518.762 Hz
30..Mode 30, 3518.897 Hz
31..Mode 31, 3824.346 Hz
32..Mode 32, 3831.746 Hz
33..Mode 33, 4130.05 Hz
34..Mode 34, 4130.189 Hz
35..Mode 35, 4327.628 Hz
36..Mode 36, 4441.148 Hz
37..Mode 37, 4462.431 Hz
38..Mode 38, 4632.302 Hz
39..Mode 39, 4652.957 Hz
40..Mode 40, 5060.163 Hz
41..Mode 41, 5267.147 Hz
42..Mode 42, 5267.311 Hz
43..Mode 43, 5317.682 Hz
44..Mode 44, 5363.716 Hz
45..Mode 45, 5367.546 Hz
46..Mode 46, 5373.509 Hz
47..Mode 47, 5373.759 Hz
48..Mode 48, 5542.558 Hz
49..Mode 49, 5552.767 Hz
50..Mode 50, 5631.468 Hz
51..Mode 51, 5859.996 Hz
52..Mode 52, 5908.296 Hz
53..Mode 53, 6001.501 Hz
54..Mode 54, 6001.777 Hz
55..Mode 55, 6079.412 Hz
56..Mode 56, 6086.015 Hz
57..Mode 57, 6096.319 Hz
58..Mode 58, 6141.452 Hz
59..Mode 59, 6327.42 Hz
60..Mode 60, 6637.105 Hz
61..Mode 61, 6666.292 Hz
62..Mode 62, 6877.33 Hz
63..Mode 63, 6937.265 Hz
64..Mode 64, 6959.645 Hz
65..Mode 65, 7188.299 Hz
66..Mode 66, 7188.541 Hz
67..Mode 67, 7286.4 Hz
68..Mode 68, 7301.587 Hz
69..Mode 69, 7480.176 Hz
70..Mode 70, 7489.553 Hz
71..Mode 71, 7503.508 Hz
72..Mode 72, 7503.831 Hz
73..Mode 73, 7540.36 Hz
74..Mode 74, 7559.383 Hz
75..Mode 75, 7578.942 Hz
76..Mode 76, 7597.341 Hz
77..Mode 77, 7870.607 Hz
78..Mode 78, 7885.322 Hz
79..Mode 79, 8156.151 Hz
80..Mode 80, 8156.448 Hz
81..Mode 81, 8280.713 Hz
82..Mode 82, 8283.084 Hz
83..Mode 83, 8323.914 Hz
84..Mode 84, 8569.879 Hz
85..Mode 85, 8841.923 Hz
86..Mode 86, 8856.789 Hz
87..Mode 87, 8885.09 Hz
88..Mode 88, 8927.871 Hz
89..Mode 89, 9037.775 Hz
90..Mode 90, 9043.276 Hz
91..Mode 91, 9156.395 Hz
92..Mode 92, 9248.689 Hz
93..Mode 93, 9268.541 Hz
94..Mode 94, 9385.418 Hz
95..Mode 95, 9385.592 Hz
96..Mode 96, 9660.986 Hz
97..Mode 97, 9719.805 Hz
98..Mode 98, 9765.902 Hz
99..Mode 99, 9801.765 Hz
100..Mode 100, 9837.811 Hz
101..Mode 101, 9848.723 Hz
102..Mode 102, 9849.89 Hz
103..Mode 103, 9860.38 Hz
104..Mode 104, 9890.151 Hz

Assume excellent correlation of modes, damping, and transient results between FE model and shock test results

Z Axis FRF – Applied force to reference accelerometer location



Requires good modal results to 50th mode at 5,631 Hz – not ideal

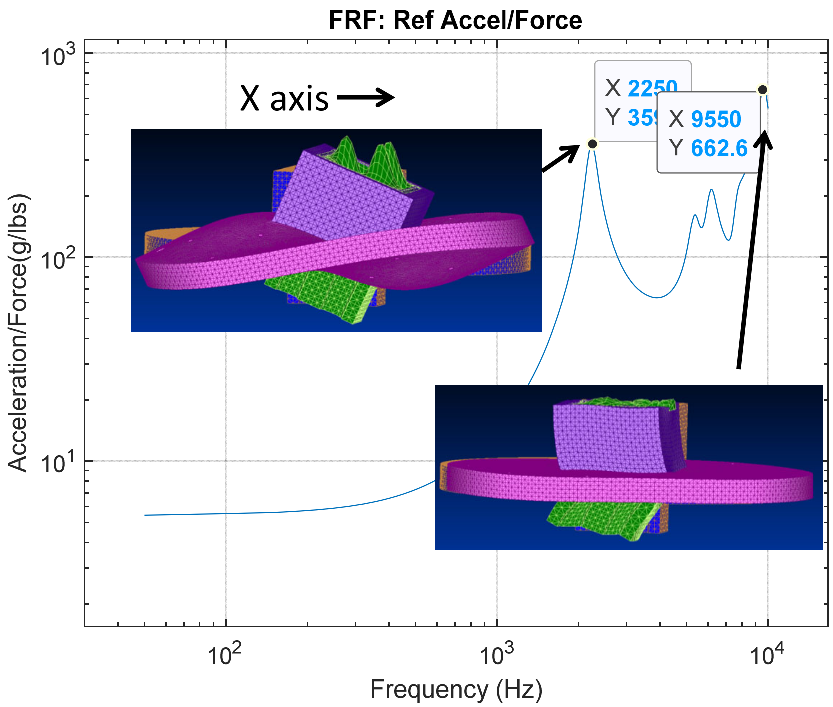
Modal participation at 1,350 Hz peak

Mode No.	Frequency (Hz)	%
13	1,335	91
5	24	5
1	9	3

Modal participation at 5,750 Hz peak

Mode No.	Frequency (Hz)	%
13	1,335	38
50	5,631	28
5	24	18
1	9	12

X Axis FRF – Applied force to reference accelerometer locations



Lateral direction requires even higher modal results to 96th mode at 9,661 Hz – not ideal

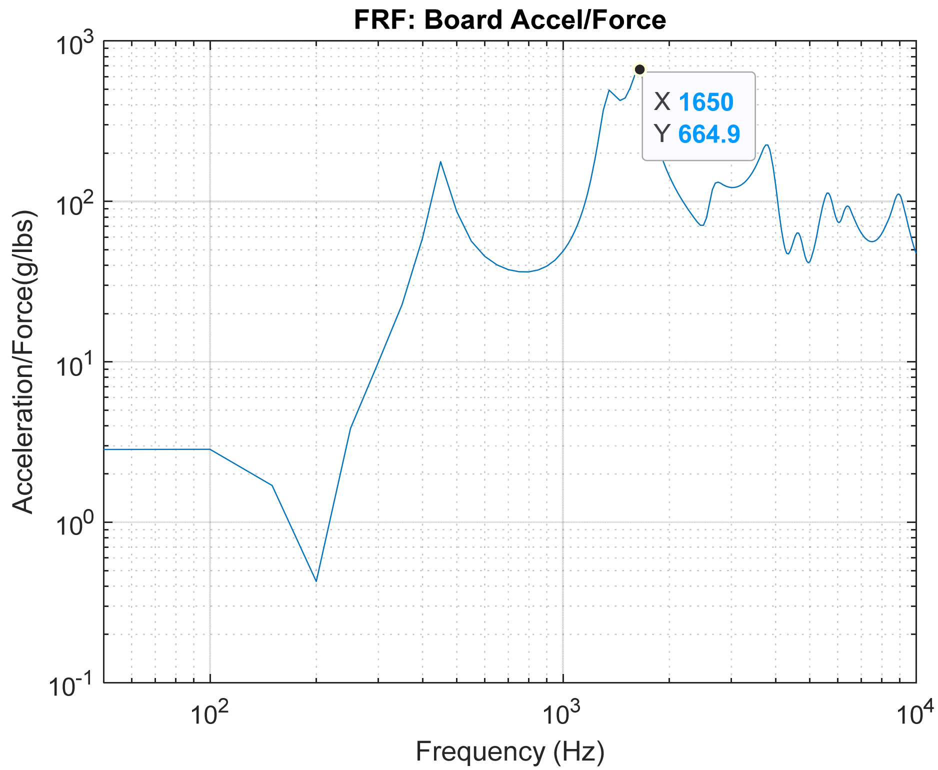
Modal participation at 2250 Hz peak

Mode No.	Frequency (Hz)	%
20	2228	91
3	16	3

Modal participation at 9550 Hz peak

Mode No.	Frequency (Hz)	%
96	9661	81
58	6141	5
20	228	5

Z Axis FRF – Applied force to board center location

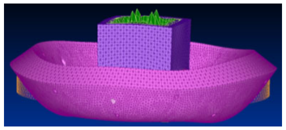


Important board mode is 50th mode at 5,631 Hz – again not ideal

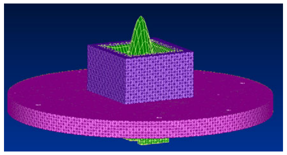
Modal participation at 1,650 Hz peak

Mode No.	Frequency (Hz)	%
50	5,631	28
15	1,624	22
13	1,335	15

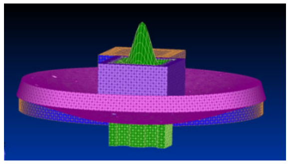
Mode 50



Mode 15



Mode 13



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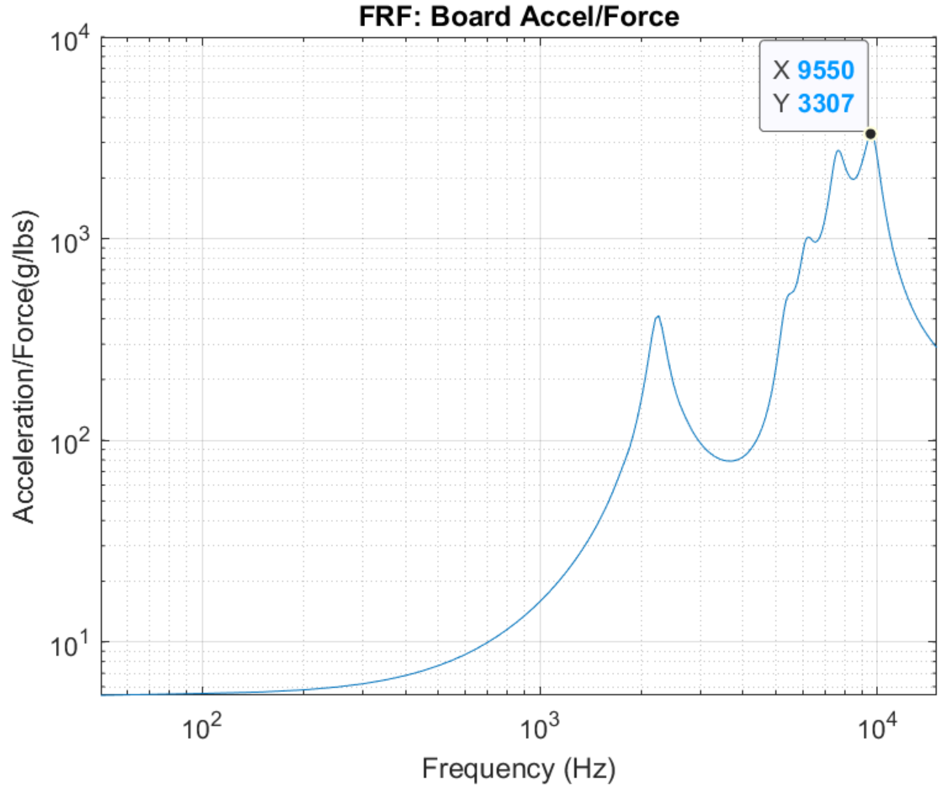
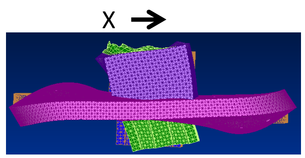
X Axis FRF – Applied force to board center location



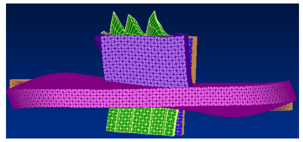
Modal participation at 9,950 Hz peak

Mode No.	Frequency (Hz)	%
58	6,132	37
46	5,354	23
76	7,493	23

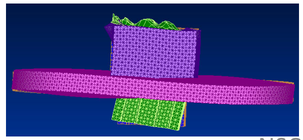
Mode 58



Mode 46



Mode 76

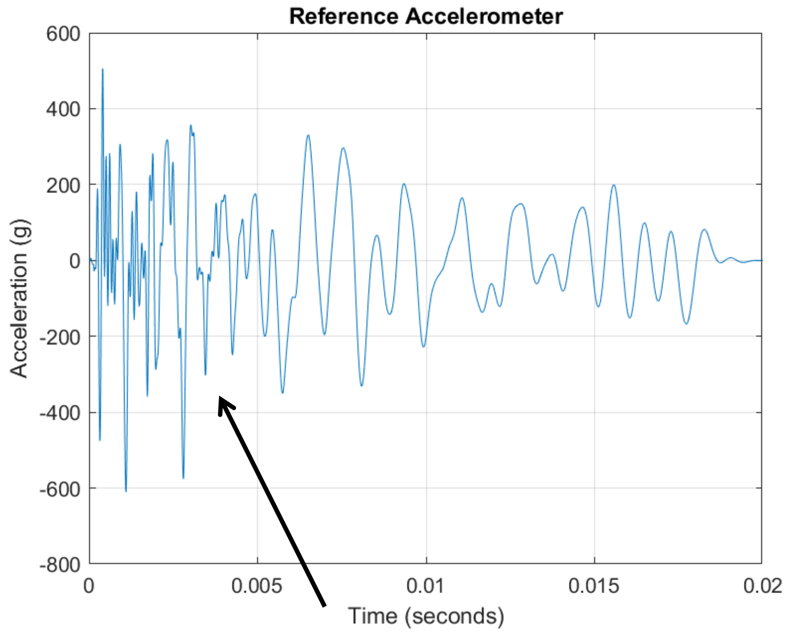


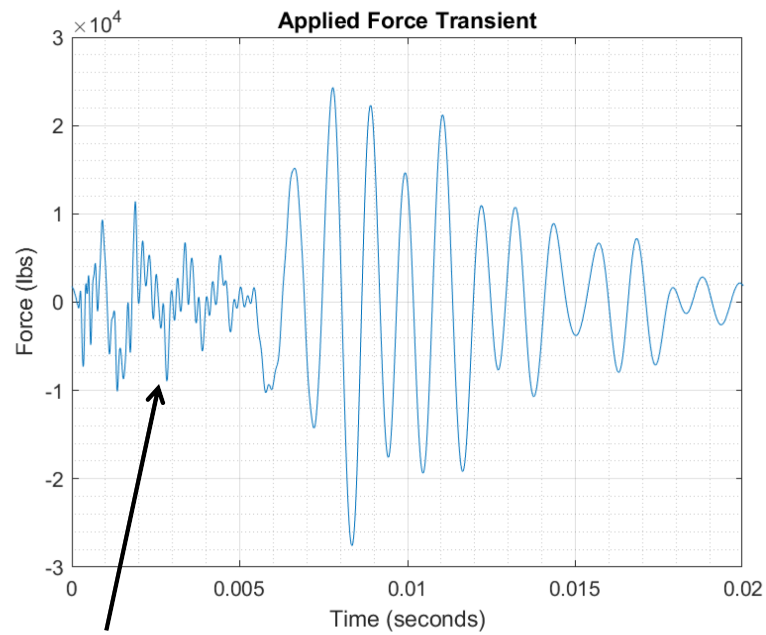
Lateral direction board modes are even higher at 58th mode at 6,132 Hz and 76th mode at 7,493 Hz – again not ideal

Derived Applied Force Transient From Reference Accelerometer

Damped Sine Pulse Z Axis Results

This is derived, desired force transient applied to strike plate to produce the desired reference accelerometer transient

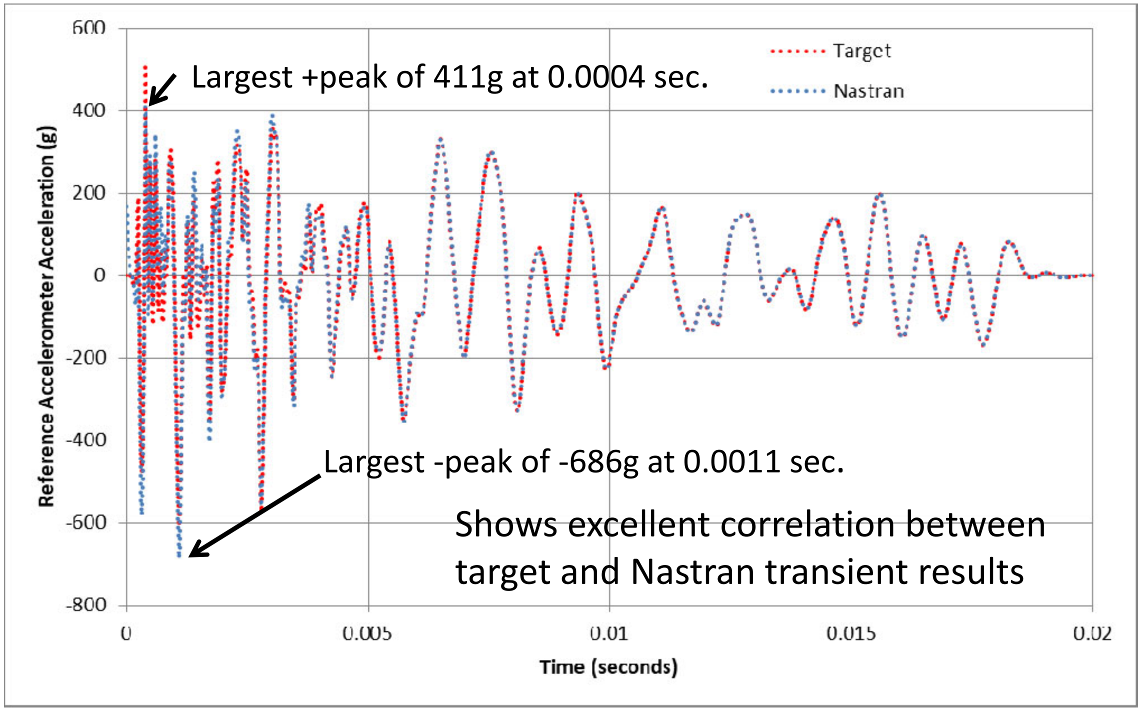




This acceleration transient has higher frequency content to about 0.005 seconds, resulting in rather strange looking force transient at beginning

Reference Accelerometer Target vs. Nastran Transient Results

Damped Sine Pulse Z Axis Results



Derived force transient from Matlab is applied in Nastran transient analysis to get acceleration responses at reference accelerometer location

Nastran transient modal contributions at largest + peak at 0.0004 seconds

Mode	fn (Hz)	%
50	5,631	59
13	1,335	30
5	24	5

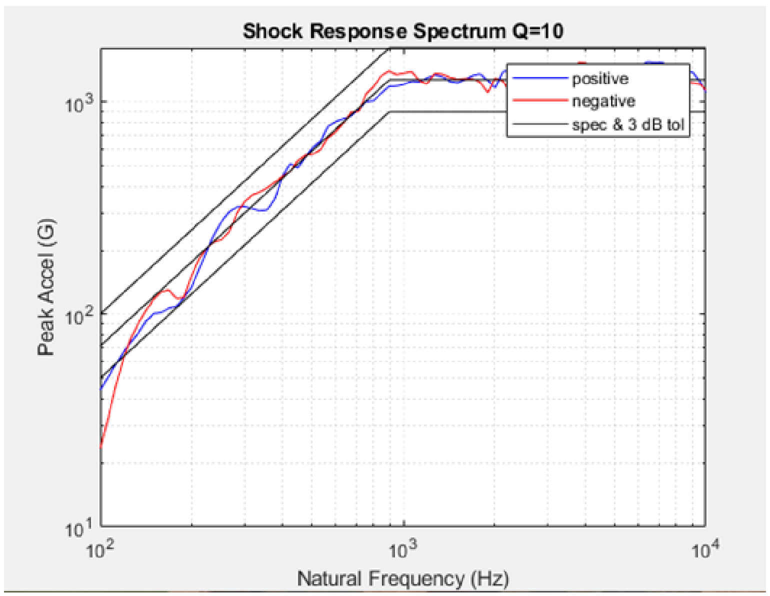
Nastran transient modal contributions at largest - peak at 0.0011 seconds

Mode	fn (Hz)	%
13	1,335	69
5	24	14
1	9	9

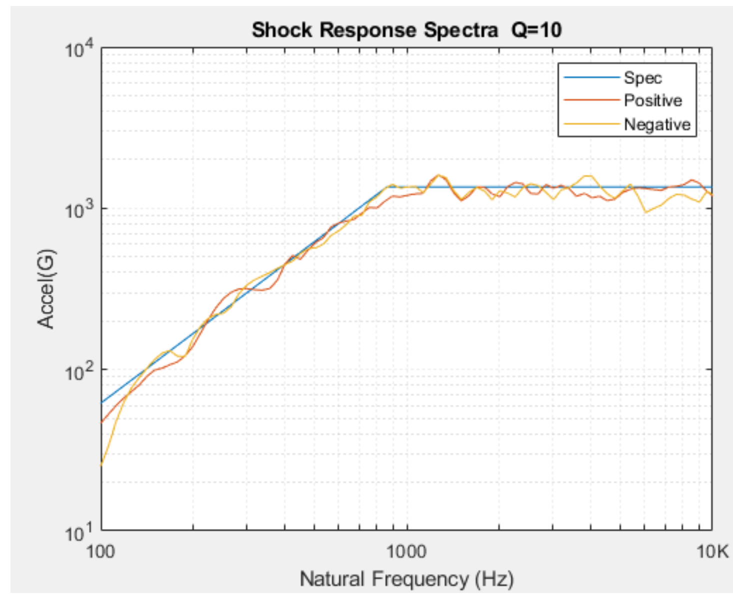
SRS Comparison

Damped Sine Pulse Z Axis Results

Original SRS used to create reference accelerometer transient

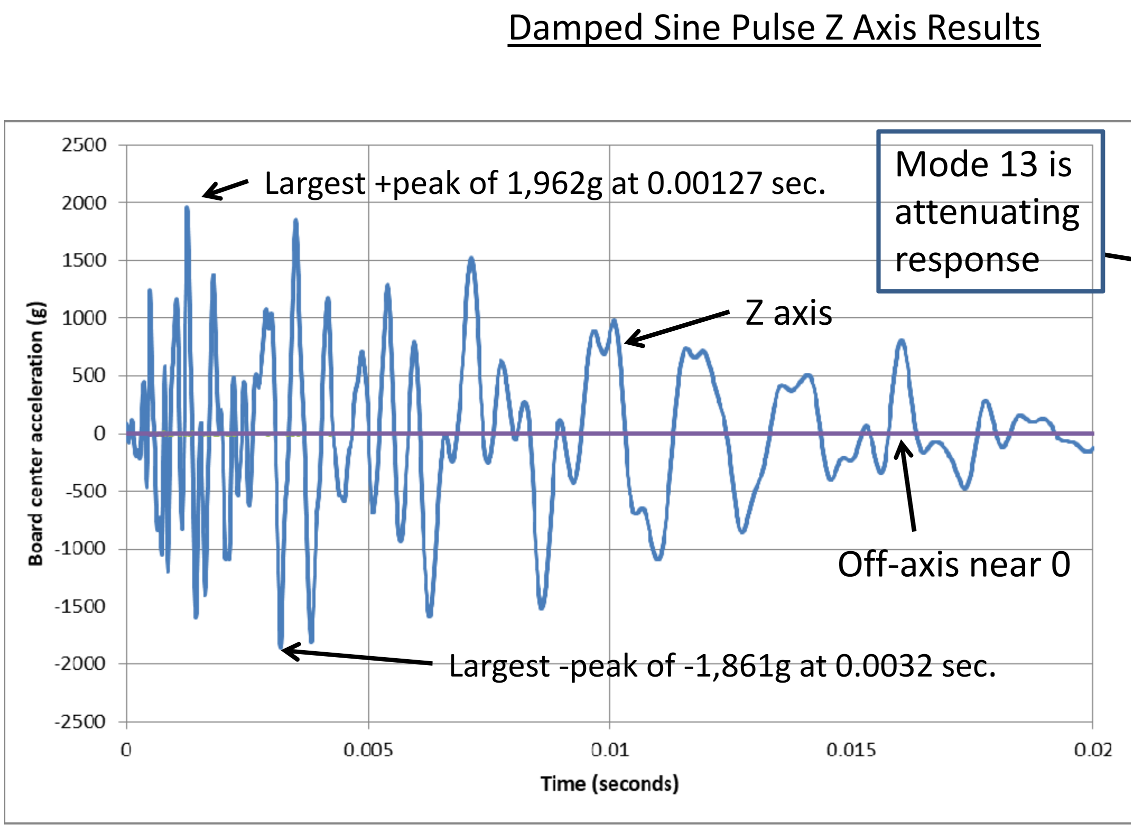


Calculated SRS from Nastran reference accelerometer transient using Matlab derived force transient



Results: Excellent correlation – thus if can develop test applied force transient very close to derived force transient should develop accurate reference transient that matches desired reference transient (shape, peaks, damping, duration) and satisfies SRS

Board Center Accelerations



Nastran transient modal contributions at largest + peak at 0.00127 sec.

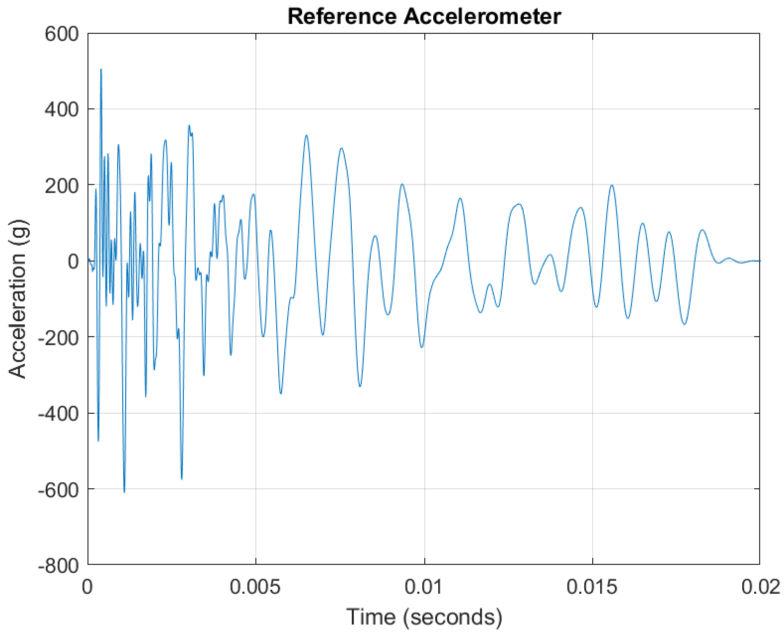
Mode	fn (Hz)	%
15	1,624	87
13	1,335	-46
32	3,772	42
63	6,839	11

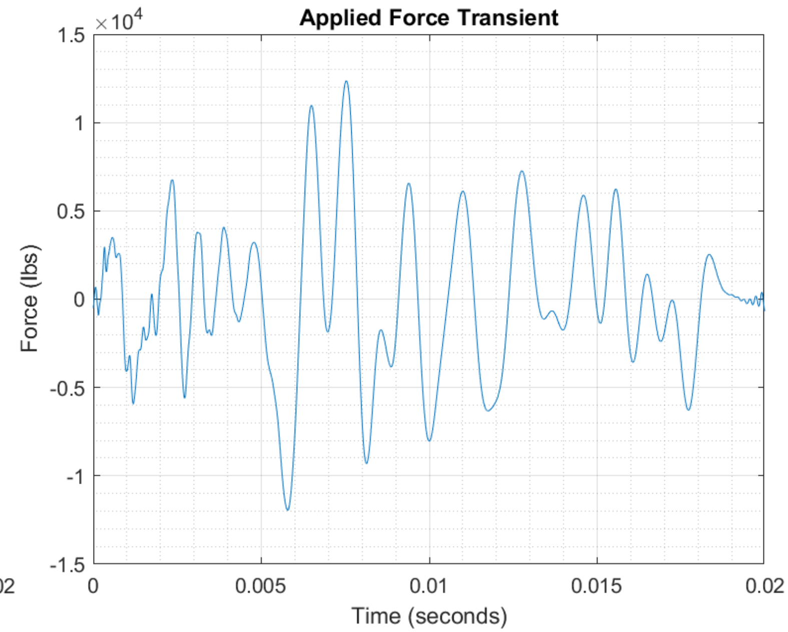
Nastran transient modal contributions at largest - peak at 0.0032 seconds

Mode	fn (Hz)	%
15	1,624	78
63	6,839	14
39	4,578	12

Derived Applied Force Transient From Reference Accelerometer

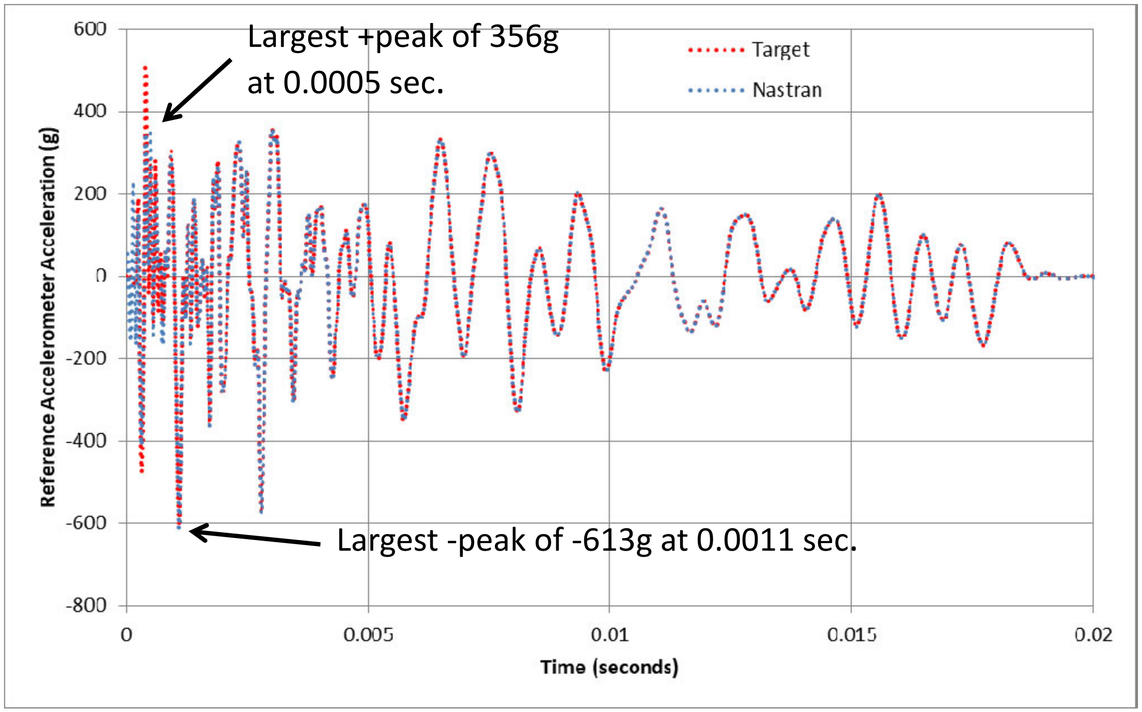
Damped Sine Pulse X Axis Results





Reference Accelerometer Target vs. Nastran Transient Results

Damped Sine Pulse X Axis Results



Nastran transient modal contributions at largest + peak at 0.0005 seconds

Mode	fn (Hz)	%
96	9,644	37
20	2,227	35
3	16	27

Nastran transient modal contributions at largest - peak at 0.0011 seconds

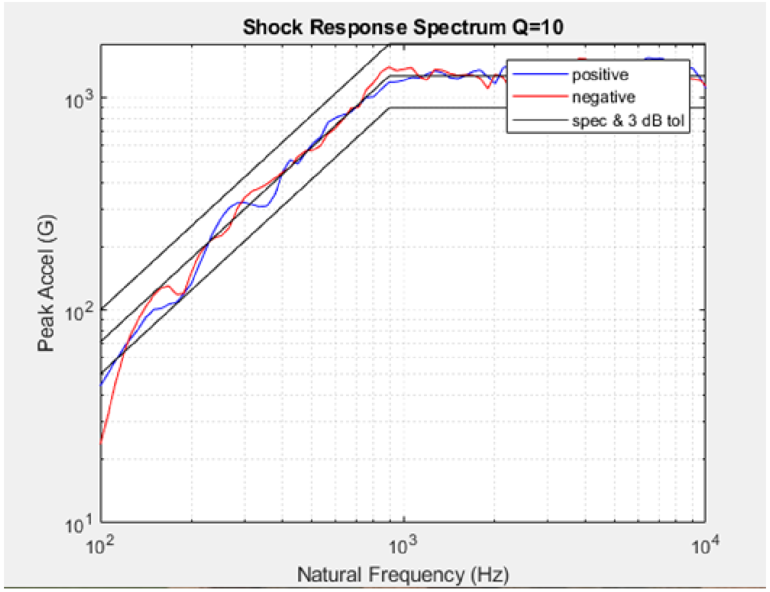
Mode	fn (Hz)	%
20	2,227	72
3	1,567	17
46	5,354	13

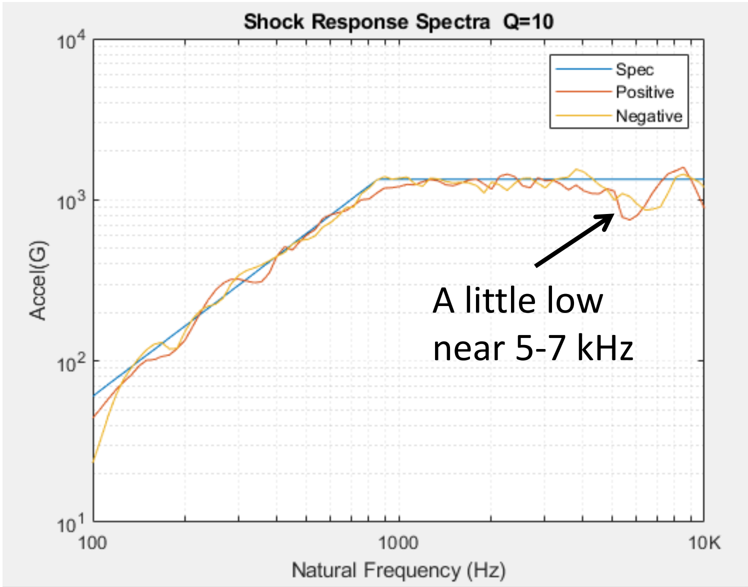
SRS Comparison

Damped Sine Pulse X Axis Results

Original SRS used to create reference accelerometer transient

Calculated SRS from Nastran reference accelerometer transient calculated using Matlab derived force transient

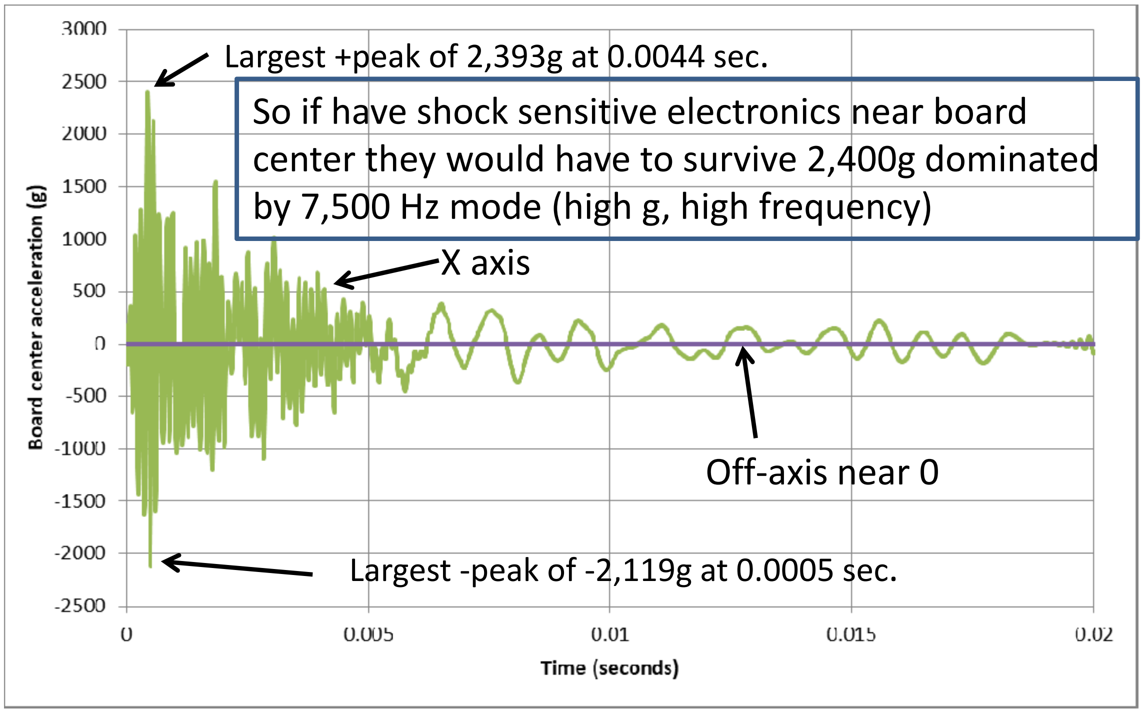




Results: Good correlation

Board Center Accelerations

Damped Sine Pulse X Axis Results



Lateral board transient accelerations are higher than normal to board accelerations – it appears that this would be load direction that would cause sensitive electronic failures

Nastran transient modal contributions at largest + peak at 0.0044 sec.

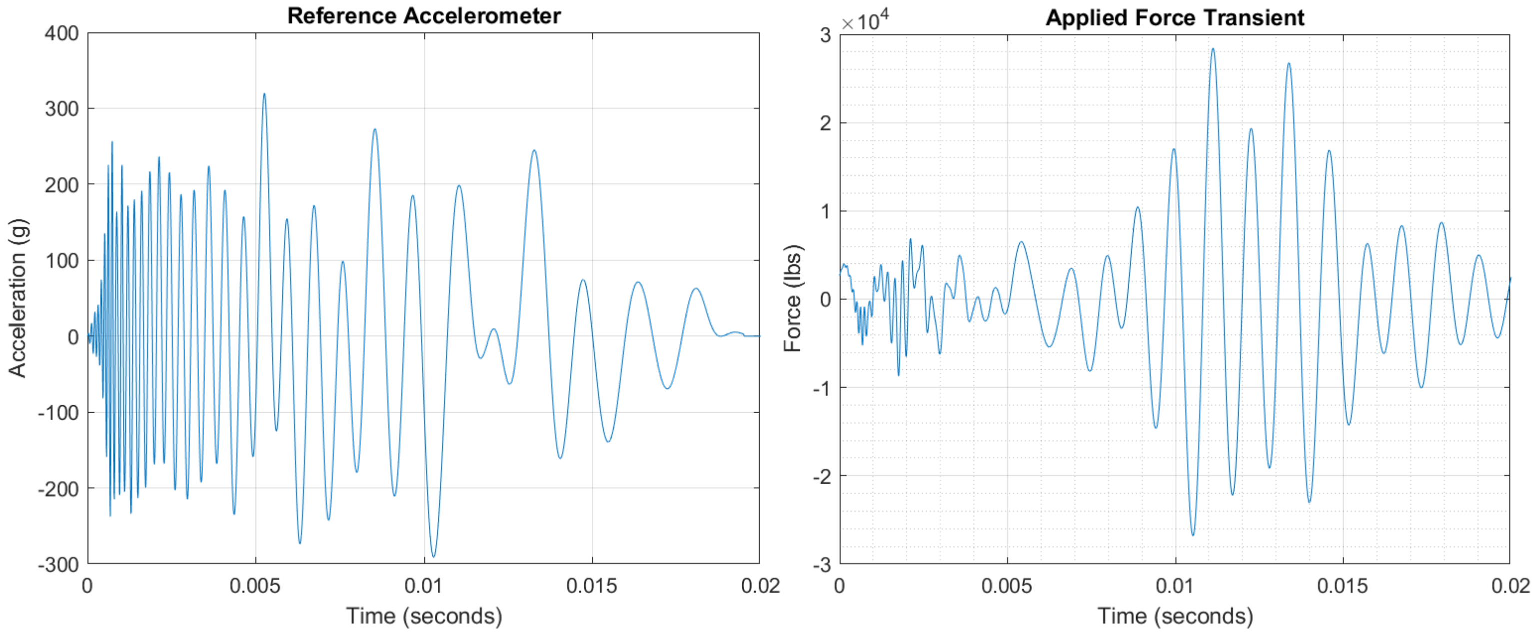
Mode	fn (Hz)	%
76	7,493	77
96	9,644	17
58	6,132	-15
46	5,354	14

Nastran transient modal contributions at largest - peak at 0.0005 seconds

Mode	fn (Hz)	%
76	7,493	83
96	9,644	32
58	6,132	-10

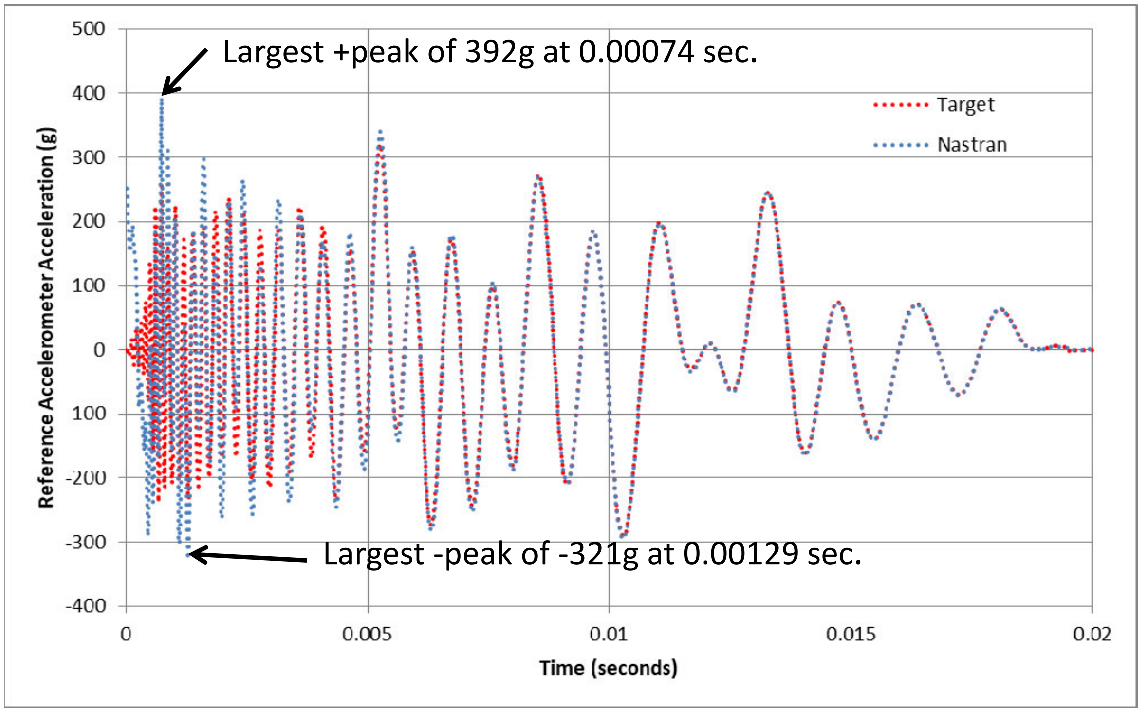
Derived Applied Force Transient From Reference Accelerometer

Wavelet Z Axis Results



Reference Accelerometer Target vs. Nastran Transient Results

Wavelet Z Axis Results



Nastran transient modal contributions at largest + peak at 0.00074 sec.

Mode	fn (Hz)	%
13	1,335	77
50	5,631	26
5	24	4

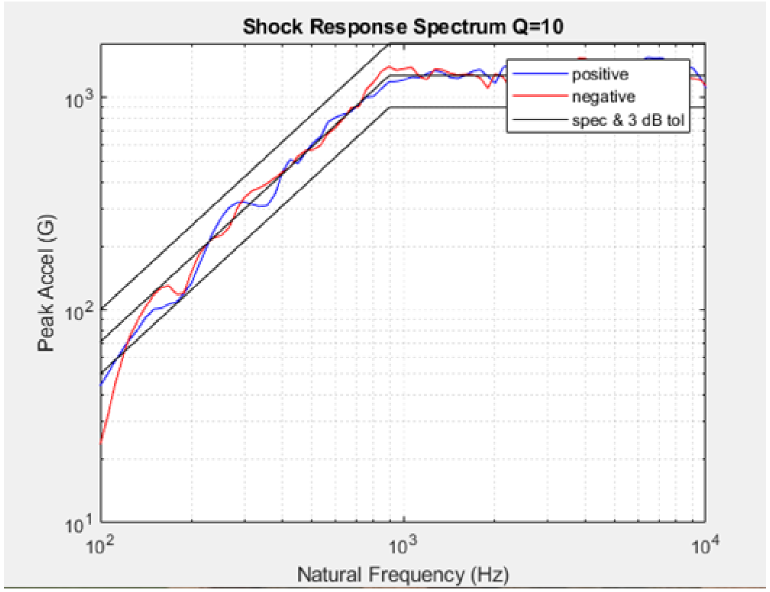
Nastran transient modal contributions at largest - peak at 0.00129 sec.

Mode	fn (Hz)	%
13	1,335	66
50	5,631	46
5	24	-8

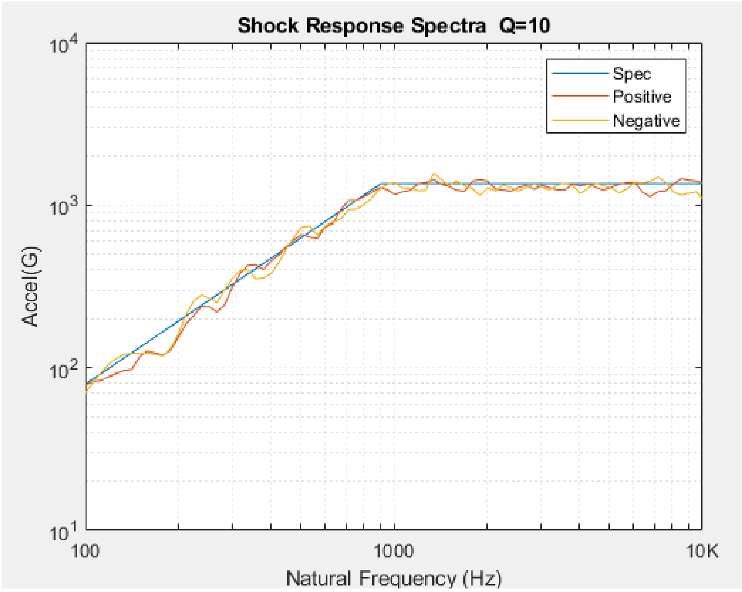
SRS Comparison

Wavelet Z Axis Results

Original SRS used to create reference accelerometer transient

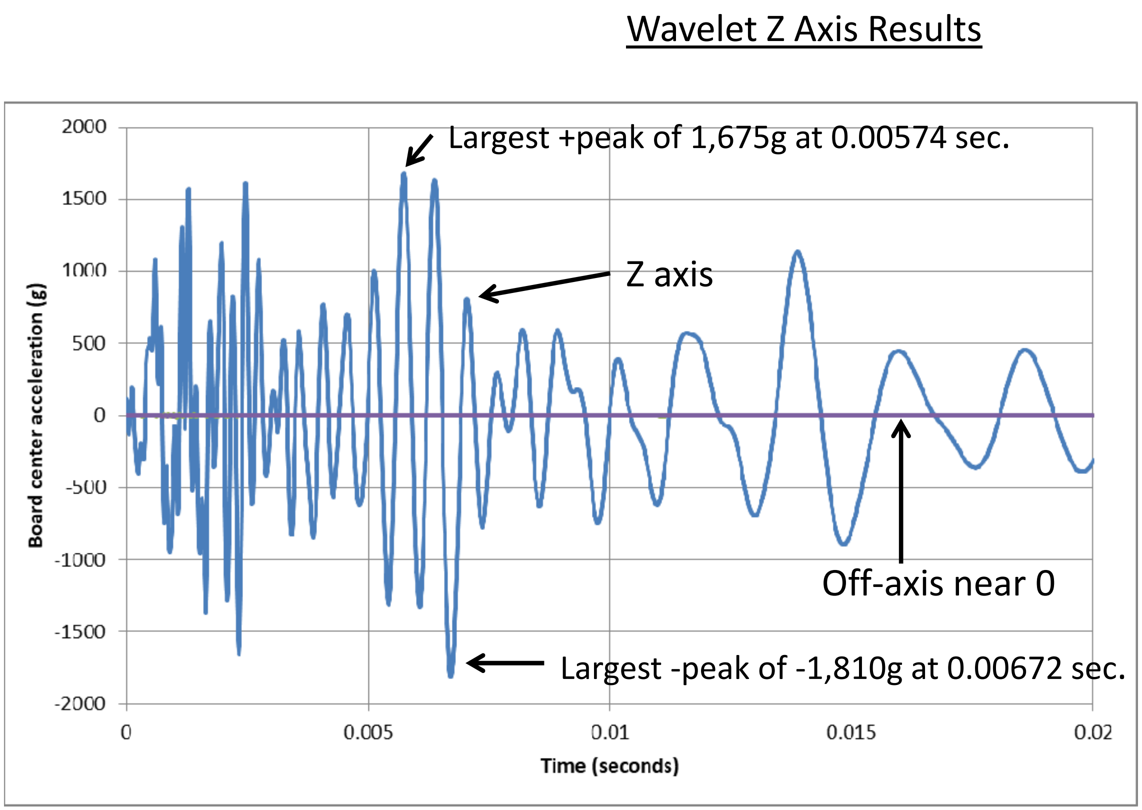


Calculated SRS from Nastran reference accelerometer transient calculated using Matlab derived force transient



Results: Excellent correlation for SRS, however wavelet transient is not desired transient shape

Board Center Accelerations



Nastran transient modal contributions at largest + peak at 0.00574 sec.

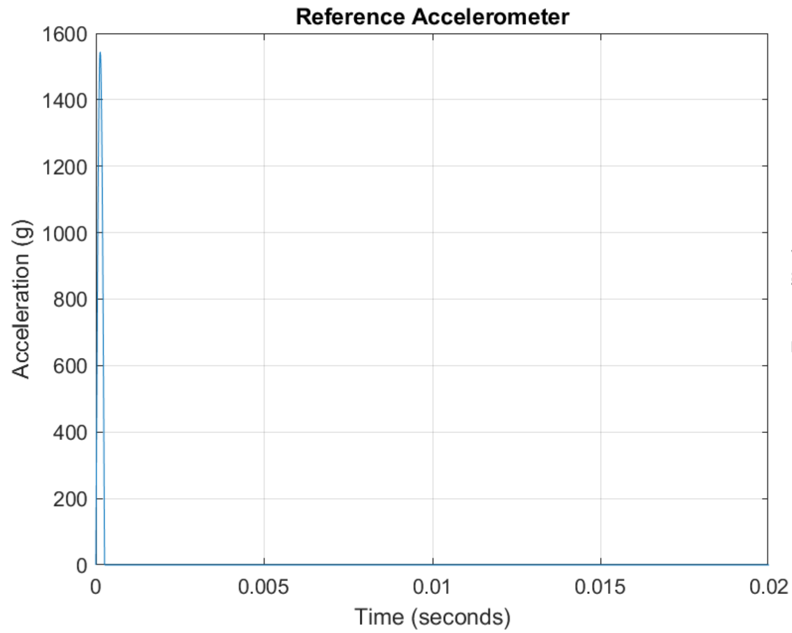
Mode	fn (Hz)	%
15	1,624	67
13	1,335	23
7	442	7

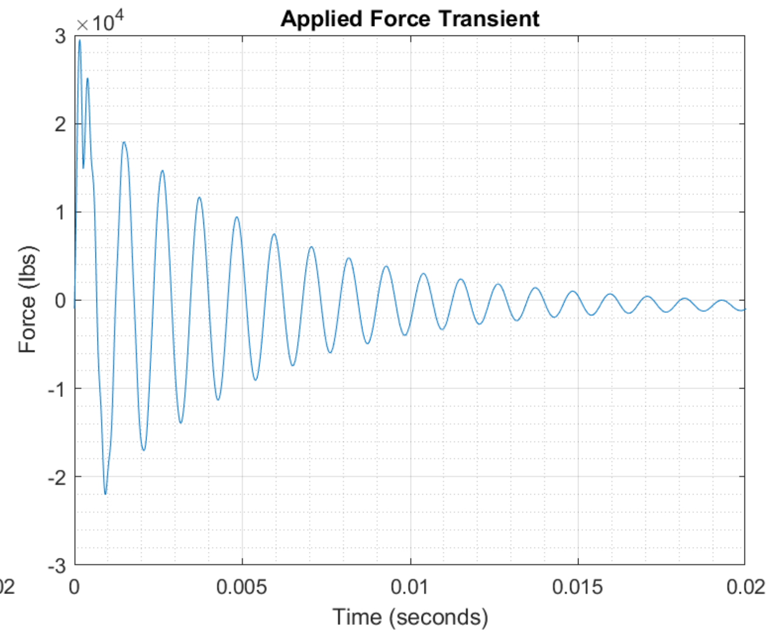
Nastran transient modal contributions at largest - peak at 0.00672 sec.

Mode	fn (Hz)	%
15	1,624	52
13	1,335	27
7	442	25

Derived Applied Force Transient From Reference Accelerometer

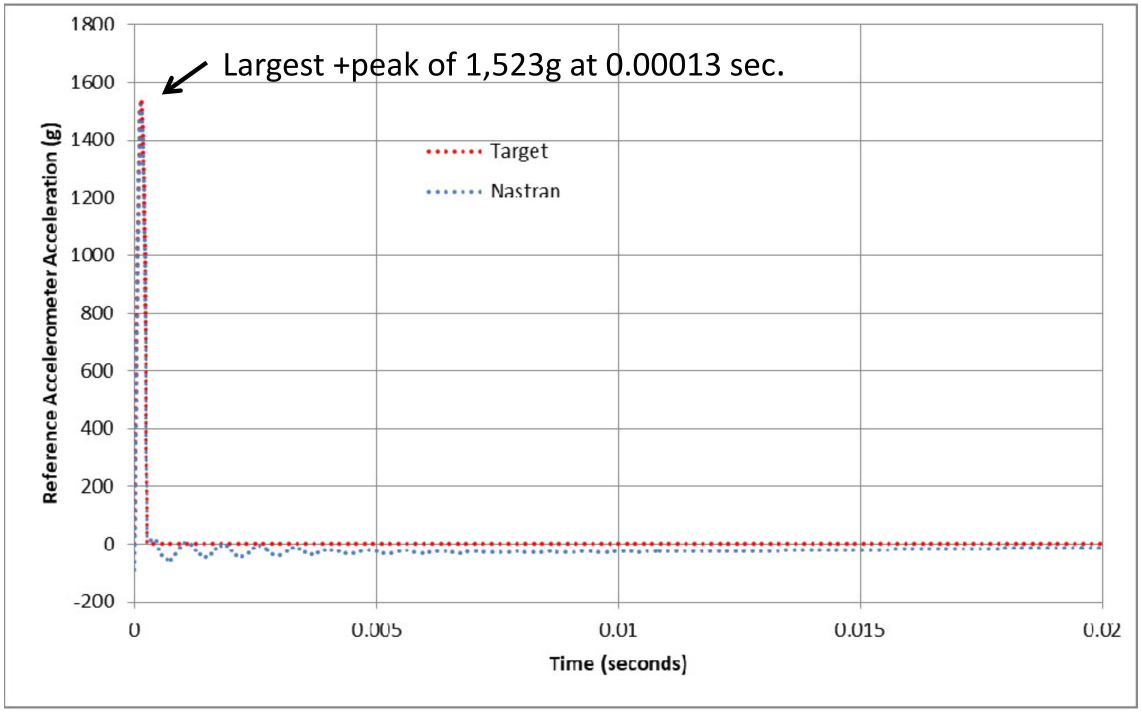
Half-Sine Pulse Z Axis Results





Reference Accelerometer Target vs. Nastran Transient Results

Half-Sine Pulse Z Axis Results



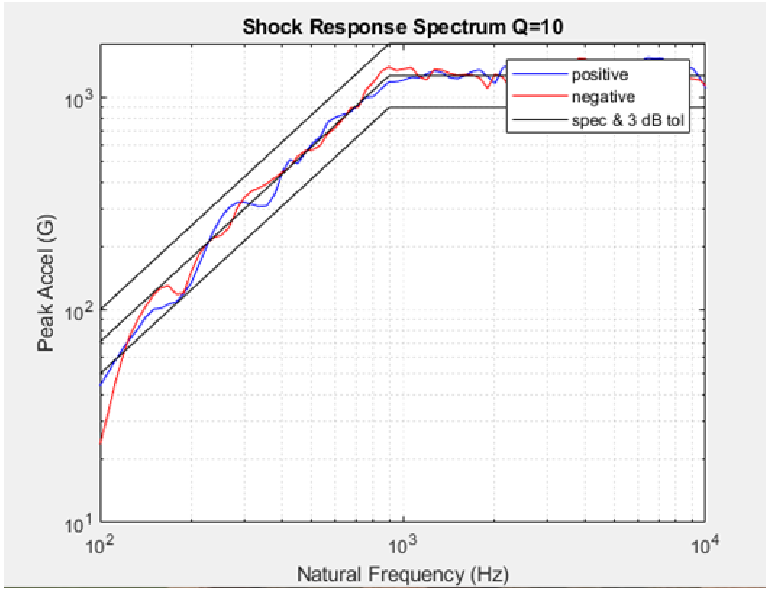
Nastran transient modal contributions at largest + peak at 0.00013 sec.

Mode	fn (Hz)	%
13	1,335	52
5	24	34
1	9	23

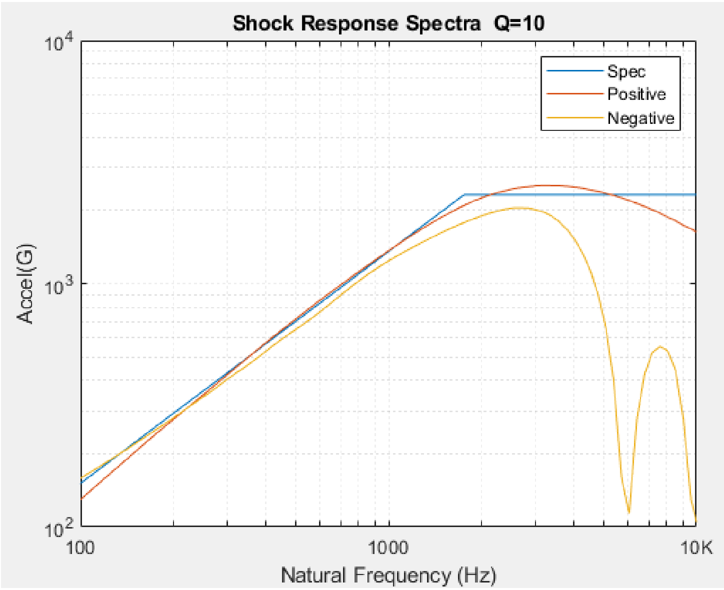
SRS Comparison

Half-Sine Pulse Z Axis Results

Original SRS used to create reference accelerometer transient

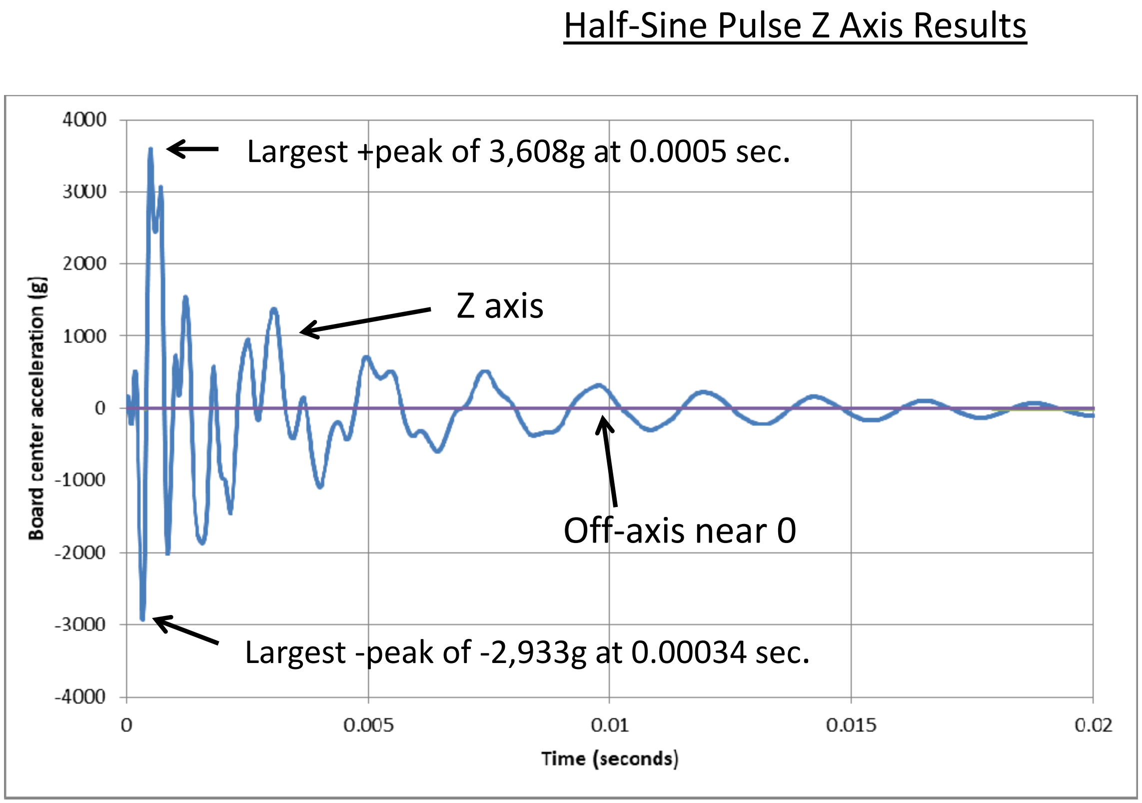


Calculated SRS from Nastran reference accelerometer transient calculated using Matlab derived force transient



Results: Poor correlation for SRS – misses knee frequency of 900 Hz; positive and negative peaks don't match; negative peaks above 3 kHz are way off

Board Center Accelerations



Nastran transient modal contributions at largest + peak at 0.0005 sec.

Mode	fn (Hz)	%
13	1,335	65
32	3,772	34
15	1,624	-19

Nastran transient modal contributions at largest - peak at 0.00034 sec.

Mode	fn (Hz)	%
15	1,624	130
13	1,335	-76
32	3,772	53

Summary of Results

Item	Parameter	Damped Sine	Wavelet	Sine Pulse
Target/Nastran Ref. Accel. (g)	Largest Z positive /negative peaks	+505/+411 -611/-686	+320/+392 -290/-320	+1,544/+1,523
Applied Force (lbs)	Largest Z positive /negative peaks	+24,323/ -27,564	+28,382/ -26,788	+29,500/ -22,000
Board Center Accel. (g)	Largest Z positive /negative peaks	+1,961/ -1,836	+1,670/ -1,793	+3,608/ -2,933
Board Center Accel. (g)	Largest X positive /negative peaks	+2,393/ -2,119	Not recovered	Not recovered

- Even though wavelet transient had same SRS as reference damped sine transient the wavelet peak accelerations are significantly lower at reference accelerometer (36% on positive peak and 52% on negative peak)
  - This indicates that SRS is not good criteria to create an arbitrary transient because can lead to significant over test or under test
- As expected the sine pulse accelerations at reference accelerometer and board center are excessive, partly because the sine pulse transient SRS was too high
  - Difficult to achieve desired SRS over wide frequency band with classical sine pulse

Conclusions

- If good correlation exist between FE model and test lab modal and shock results it should be possible to create desired shock transient that closely matches operational shock
- Will result in more accurate shock analysis results and more representative shock test
- Creating an arbitrary transient from SRS can lead to significant over test or under test
  - Need to match operational shock is necessary