Pyrotechnic Shock Testing:
Real Test Lab Experiences at EBA&D

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EBA&D's Pyrotechnic Shock Facility

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Pyrotechnic Shock Testing

Presentation Overview

- Introduction to Ensign-Bickford Aerospace & Defense Company (EBA&D)
- Pyrotechnic Shock Test Capability
  - Our Facility, Equipment, and General Test Guidelines
- Observations Regarding Shock Response Spectrums (SRS) for Aerospace Components.
- Experiences With Data Acquisition Variability
- Opportunities For Enhancement Of Test Method

EBA&D's objectives relating to pyrotechnic shock are to establish technical interchange with those knowledgeable in the field, promote understanding of the challenges posed by today's test requirements and drive standardization in the aerospace community.

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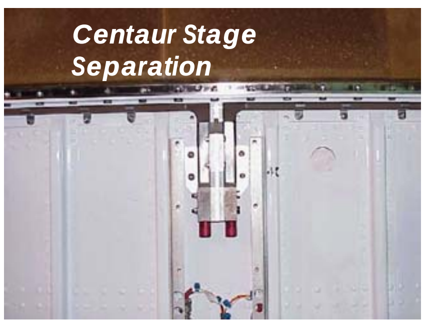
ENSIGN-BICKFORD AEROSPACE & DEFENSE COMPANY

EBA&D delivers reliable energetic solutions to a wide variety of customers.

Products Supplied for Launch Vehicles



- EBA&D manufactured products:
  - Flexible Confined Detonating Cord Assemblies (FCDCA)
  - Transfer Manifolds
  - Ordnance Disconnects
  - Detonator Booster Assemblies (DBA)
  - Safing Interrupter
  - Lanyard Pull Initiators (LPI)
  - Destruct Linear Shaped Charge Assembly (LSCA)
  - Pyro Vent Assembly
  - Stage Separation Systems
  - Frangible Joint Assemblies

EBA&D opened a new Pyrotechnic Shock Facility on the Simsbury, CT campus in the Spring of 2003

Pyrotechnic Shock Testing

Our Facility, Equipment, and General Test Approach

- What was the motivation for developing this capability?
  - EBA&D was and continues to be determined to provide in-house capability for performing the common environmental tests dictated by the aerospace industry.
    - In addition to Pyrotechnic Shock Testing, EBA&D is now successfully conducting:
      - Mechanical Testing
      - High Temperature Storage
      - Thermal Cycling (including cryogenic temperature)
      - Vibration
  - We will segway our understanding of pyrotechnic shock testing into an ability to build components that are effectively designed to perform in the rigorous environments required by our customers.

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Pyrotechnic Shock Testing

Our Facility, Equipment, and General Test Approach

- EBA&D's Pyrotechnic Shock Test Facility:
  - Enclosed concrete shock vault
    - Equipped with heating and cooling systems to maintain a test temperature of $\approx$ 70°F.
    - Currently developing the capability to perform pyrotechnic shock test at high and low temperatures.
  - Remote test initiation and data acquisition room.
  - Data Acquisition Capability
    - 16, 24-bit acquisition channels
    - 102 KHz useable bandwidth per channel (after anti-aliasing, Nyquist)
    - Direct Integration algorithm for determination of SRS curves

EBA&D's objective as a environmental test facility is to perform pyroshock testing in the most complete, correct and accurate way possible and to attain a 100% test success rate.

Pyrotechnic Shock Testing

Our Facility, Equipment, and General Test Approach

- EBA&D has demonstrated reasonable success using multiple fixture designs.
  - Most notably, the aluminum welded shelf plate.
    - The product under test is mounted to the aluminum shelf.
    - X, Y, and Z accelerometers are typically threaded into a common tri-axial block and then located adjacent to the test specimens.

ADVANTAGES

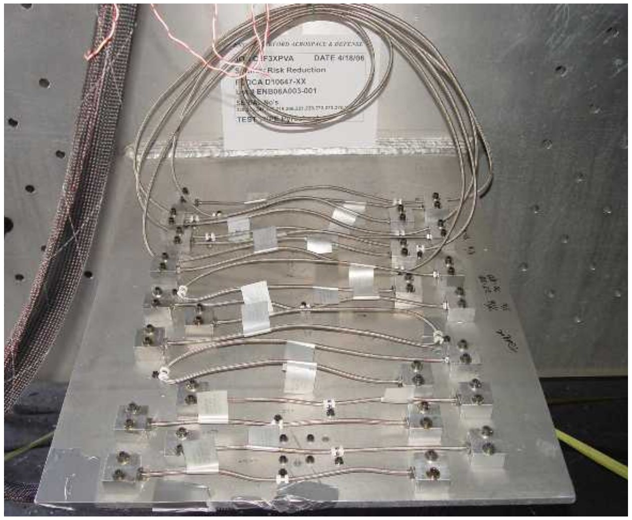
– Most repeatable way that we have achieved 3-axis simultaneous excitation.

DISADVANTAGES

– Cannot readily modify fixture to tune knee frequency.

– Z-Axis overtest, relative to in-plane shock response.

– In-plane SRS likely amplified by the rotational acceleration due to fixture design.



Pyrotechnic Shock Testing

Our Facility, Equipment, and General Test Approach

- Meanwhile, on the back-side of the shock fixture…
  - EBA&D test technicians affix detonating cord, which, upon detonation provides the shock excitation.
    - Textile explosive cord with a coreload of 50 gr/ft (PETN explosive)
    - Up to 50 ft of Detonating Cord has been used, that equals 0.36 pounds.
  - Many methods for positioning the detonating cord have been evaluated.
  - At times, the cord is sandwiched between the fixture and a steel back-up plate, helping to couple the shock into the fixture.
  - EBA&D documents the test setup details for every shock test.

Pyrotechnic Shock Testing

Our Facility, Equipment, and General Test Approach

- Data Acquisition Signal Path
  - Industry proven accelerometers and data acquisition equipment is employed.
  - Our Signal Path is as follows:

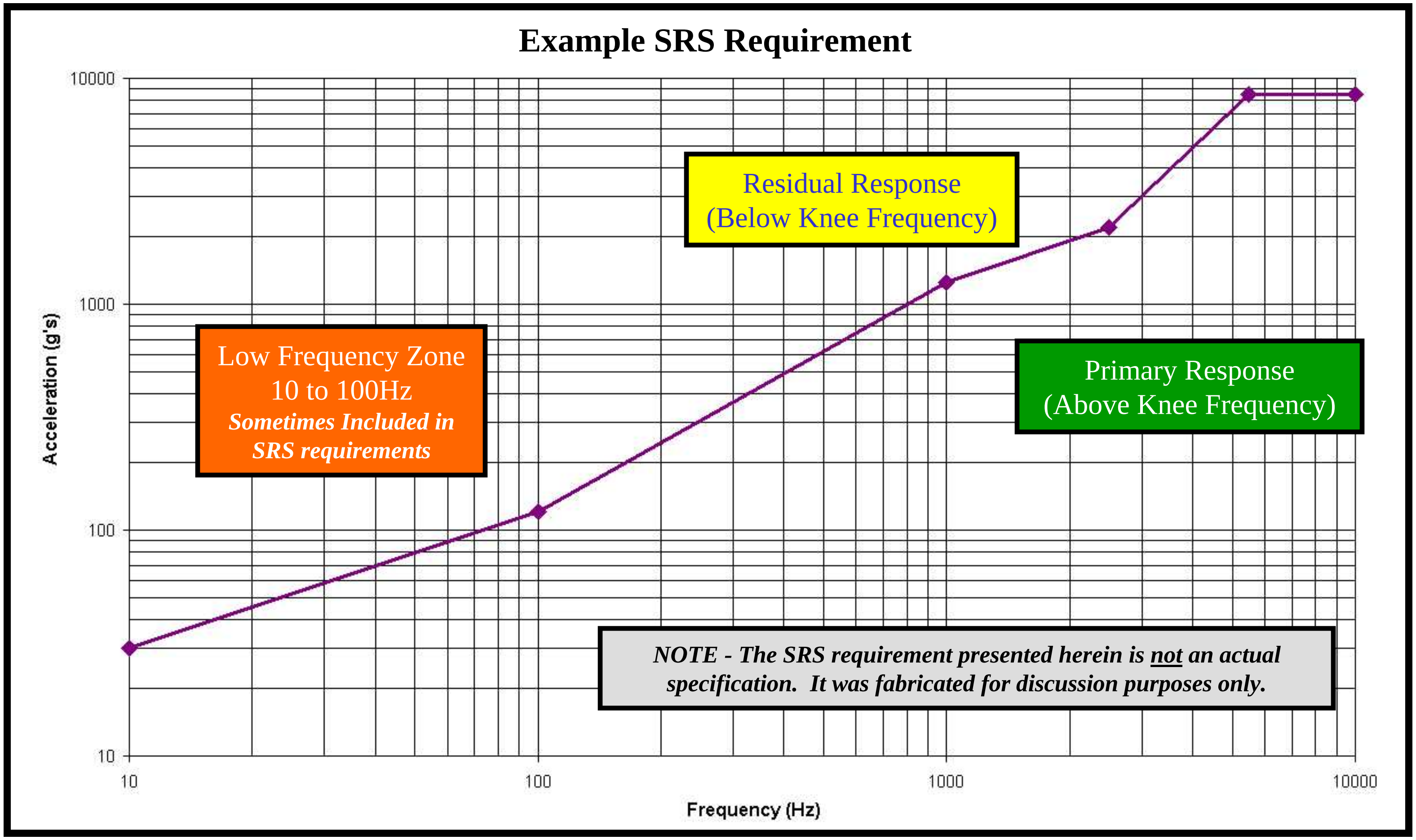
PCB 350B02 & 350C02 ICP® Accelerometers → **Cable Connector Standard #10-32** → **PCB 002 Coaxial Cable, Teflon Jacket ~ 150 Feet** → **Coaxial Cable travels out the shock test vault and underground to the control room.**

→ **SCADAS III Mainframe (LMS Engineering Systems)** → **LMS Programmable Quad Amplifier** → **LMS SP90 Signal Processor** → **LMS Test Lab Data Navigation Software (SRS Algorithm)**

EBA&D's Experience With Various Shock Response Spectrum (SRS)

Pyrotechnic Shock Testing

Experiences With Shock Response Spectrum (SRS)



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Experiences With Shock Response Spectrum (SRS)

- Low Frequency Zone, 10 to 100 Hz
  - EBA&D's technical stance on frequencies below 100 Hz as they relate to pyrotechnic shock is as follows:

"The practical lower limit of pyrotechnically-excited shock test requirements is 100Hz"

  - EBA&D's technical stance is consistent with MIL-STD-810 F, Section 26
    - MIL-STD-810F Section 26 addresses this issues in the following manner:
      - Para. 1.2.1, "Pyroshocks are generally within a frequency range of 100 Hz to 1,000,000 Hz, and a time duration from 50 μsec to no more than 20 msec."
      - Para. 1.2.1, "Because of the limited velocity change in the structure brought about by firing of the pyrotechnic device, and the localized nature of the pyrotechnic device, structural resonances below 500Hz will normally not be excited."
      - Para. 1.2.2, "Frequencies below 100Hz are never of concern."

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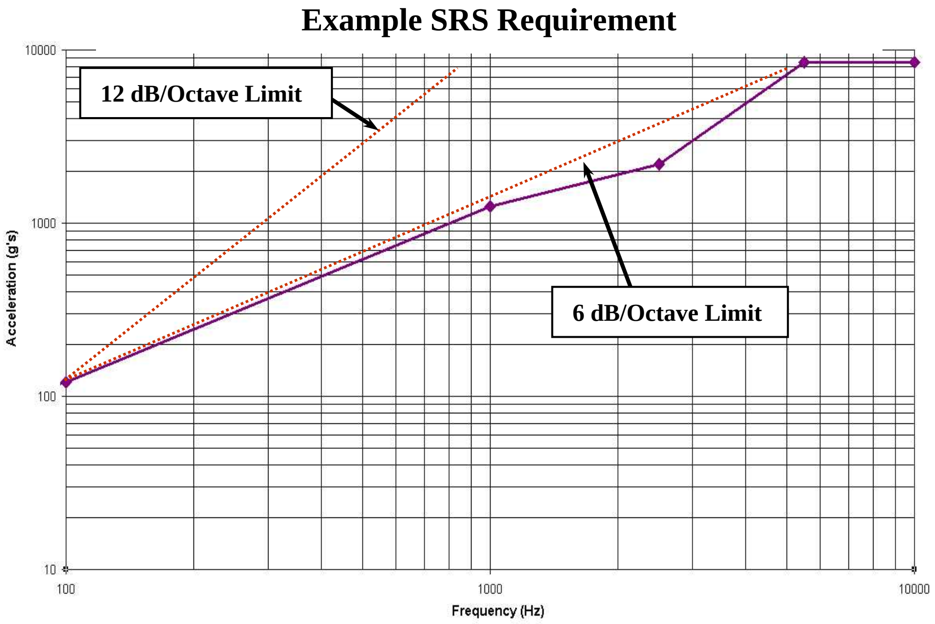
Experiences With Shock Response Spectrum (SRS)

- Residual Response of the SRS (Below the Knee Frequency)
  - The "Residual Response" portion of the SRS curve relates primarily to the "late-time" behavior.
  - The theoretical limits of the SRS slope are between 6 dB/Octave and 12 dB/Octave.
    - The Example Shock Profile lies below the 6dB/Octave theoretical limit. Therefore over-testing in the 100 to 5,000Hz range is inevitable.
  - SRS Requirements with a high acceleration value between 100 - 400Hz will drive the entire SRS.



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Experiences With Shock Response Spectrum (SRS)

- Primary Response of the SRS
  - Very high natural frequency SDOF systems approach "perfect stiffness".
    - Above the knee-frequency, the SRS curve should 'converge' on a value equivalent to the highest acceleration seen in the time-history.
  - Acceleration levels at the knee frequency are tied to the "convergence" value by the Damping ratio "Q".
  - Adding more detonating cord will shift the "convergence" level and shift the entire curve upwards.
    - This effect is non-linear and we reach what seems to be a "saturation" limit

Pyrotechnic Shock Testing

Experiences With Shock Response Spectrum (SRS)

- From our Aerospace customers, EBA&D receives a wide variety of SRS requirements.
  - The default SRS requirement originates from EWR 127-1. The break points are as follows:
    - **100 g's at 100 Hz**
    - **1,300 g's at 2000 Hz**
    - **1,300 g's at 10,000 Hz**

    This default SRS is easy to reproduce.
  - Test challenges arise when SRS requirements include one of the following:
    - Shallow slope (< 6dB/octave)
    - Steep slope (> 12dB/octave)
    - Frequency content below 100 Hz
    - Acceleration values of greater than 300 g's at 100Hz
    - Too many break points. (example: SRS with 6 breakpoints)
  - EBA&D often asks our customers to provide rationale / origin for such unique SRS requirements.

Pyrotechnic Shock Testing

Experiences With Shock Response Spectrum (SRS)

- Our Customers have communicated the following with regards to rationale / origin of an SRS requirement.
  - Flight Termination System (FTS) components are held to higher scrutiny because of Range Safety requirements.
    - This is with regards to MPE calculations and applied test margin.
  - Component SRS requirements are often "Composite" requirements for one of the following reasons:
    - Component is used in many different locations in the launch vehicle. Composite SRS requirements are used to simplify Lot Acceptance Testing. Explosive Transfer Lines are a good example of such a component.
    - Component LAT will serve as acceptance data for multiple launch vehicles having very different shock profiles.
    - SRS requirement is a composite of multiple non-simultaneous shock events.
      - Separation of Preloaded Devices (e.g. Separation Nuts)
      - Detonation Transfer Events (e.g. Transfer Lines)
      - Stage Separation (e.g. Linear Shaped Charge)

Pyrotechnic Shock Testing

Experiences With Shock Response Spectrum (SRS)

- Our Customers have communicated the following with regards to rationale / origin of an SRS requirement. (cont.)
  - Conservatism in SRS requirements is driven by the data available at the time of requirements definition. Sometimes our customers encounter the following limitations:
    - Flight data is over 20 years old. Original data may be unavailable, therefore there's no opportunity to correct measurement errors.
    - Available data originates from experiments or ground tests.
      - Sub-system experiments.
    - Measured flight data is from a different area of the vehicle. Analysis is then required to predict SRS.
    - No specific flight data is available, SRS requirement is based on flight data from a similar launch vehicle.
    - Uncertainty in flight data results in extra safety margin applied to the MPE.

Data Acquisition Variables When Measuring and Presenting Pyrotechnic Shock Data

Pyrotechnic Shock Testing

Variables Associated with Data Acquisition

- Accuracy of Pyrotechnic Data is dependant upon many variables along the signal path.
  - These are well-known data acquisition variables with many technical studies published on them.
  - Despite being well-known, inaccuracy still plagues today's tests.
  - The following variables will be discussed in this presentation:
    - Data Processing / Correction Methods
    - Accelerometer Mounting
    - Accelerometer Selection
  - Other variables include:
    - SRS Algorithm - multiple versions could result in small variances in SRS.
    - Pyrotechnic Shock Fixture Design

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Variables Associated with Data Acquisition

<u>Data Processing / Correction Methods</u>

When performing Pyrotechnic Shock, sometimes we are presented with flawed data.

- Common Causes - Zero shifts, overloads, clipping, and impulsive noise.
- Effect on SRS - low frequency acceleration values are artificially high.
- Effect on Acceleration Time History - often difficult / impossible to detect.
- Effect on Velocity Time History - trace is not centered on V = 0, or velocity trace heads towards infinity.
- Effect on Displacement Time History - displacement heads towards infinity.

Many Data Processing / Correction Methods have been developed to remove the flawed information from the data set.

Today's Laboratories however are not equipped with the necessary information to diagnose the root cause of the flawed data and then implement the appropriate data processing / correction method.

Lack of data correction also an issue with SRS Requirement Definition.

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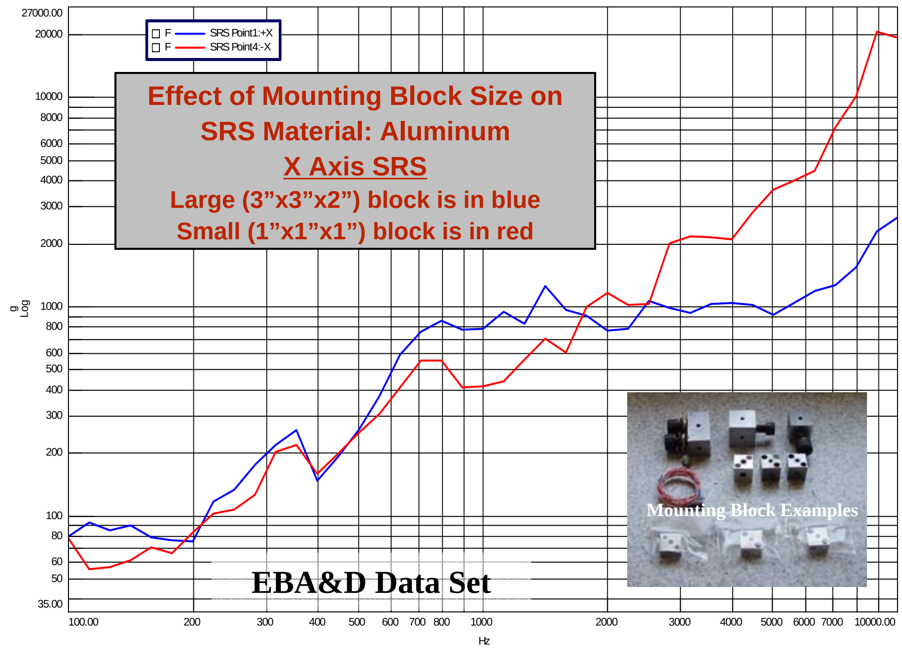
Variables Associated with Data Acquisition

Accelerometer Mounting

The method for coupling the data acquisition equipment (e.g. accelerometer) to the shock fixture is a critical variable in the resulting SRS.

- Objectives Related to Accelerometer Mounting are:
  - Measure the “true” shock that the UUT is being subjected to.
  - Avoid introducing a natural mechanical filter.
    - Plot (to the right) Shows an 8dB difference in the SRS at 3000Hz and above.
- Current variations include:
  - Welded vs. Bolted Blocks
  - Steel, Aluminum & Titanium (Material selection varies)
  - Size varies

These variables may impact the shape of the SRS, but the shock on the UUT is unchanged.



Pyrotechnic Shock Testing

Variables Associated with Data Acquisition

Accelerometer Selection

Selecting an appropriate accelerometer to acquire pyrotechnic shock data is critical to the validity of the test.

- EBA&D utilizes an industry proven ICP Accelerometer for capturing shock data.
  - Manufacturer PCB, Model No. 350B02 or 350C02
    - Measurement Range +/- 50,000 g's
  - Other common manufacturers are Endevco and Kistler.
- A published study from 1986 evaluated 11 different accelerometers. **(Ref. #1)**
- Only 1 was found to provide accurate shock data.
  - Erratic data acquisition (in other Accels) resulted in over 12dB over-estimation of the SRS accelerations from 20 to 600Hz.
  - Instrumentation improvements (over the last 20 years) has certainly increased the number of accelerometers that are capable of reproducing accurate shock data.
- Despite technological advancements, accelerometers still contribute measurement error during pyrotechnic shock, especially for today's aerospace SRS.
  - The challenges of selecting the best accelerometer still exist.

Pyrotechnic Shock Testing

Variables Associated with Data Acquisition

Excerpts from a technical paper written by Roy Melander and Strether Smith. (October 1995) (Ref. #2)

<u>“Why Shock Measurements Performed at Different Facilities Don’t Agree”</u>

“This study shows that different data acquisition and analysis strategies can cause significant differences between the SRS results obtained at different facilities. The primary problems occur at the upper and lower ends of the analysis frequency range where discrepancies of 30 to 200% have been demonstrated. It should be noted that this is the effect on a single time history and hence is probably not a worst case.

This is obviously an unacceptable situation and a means of justifying and/or correcting the data to provide agreement is required.”

“It would appear that, at least for the organizations that responded to the questionnaire, that large differences (hundreds of %) in results cannot be blamed solely on either analysis method or basic data acquisition technique. To resolve these problems, an intensive study of <u>real laboratory practices</u> must be taken.”

The Pyrotechnic Shock Test:

Areas for Enhancement in Test Methodology and Accurate Data Collection

Pyrotechnic Shock Testing

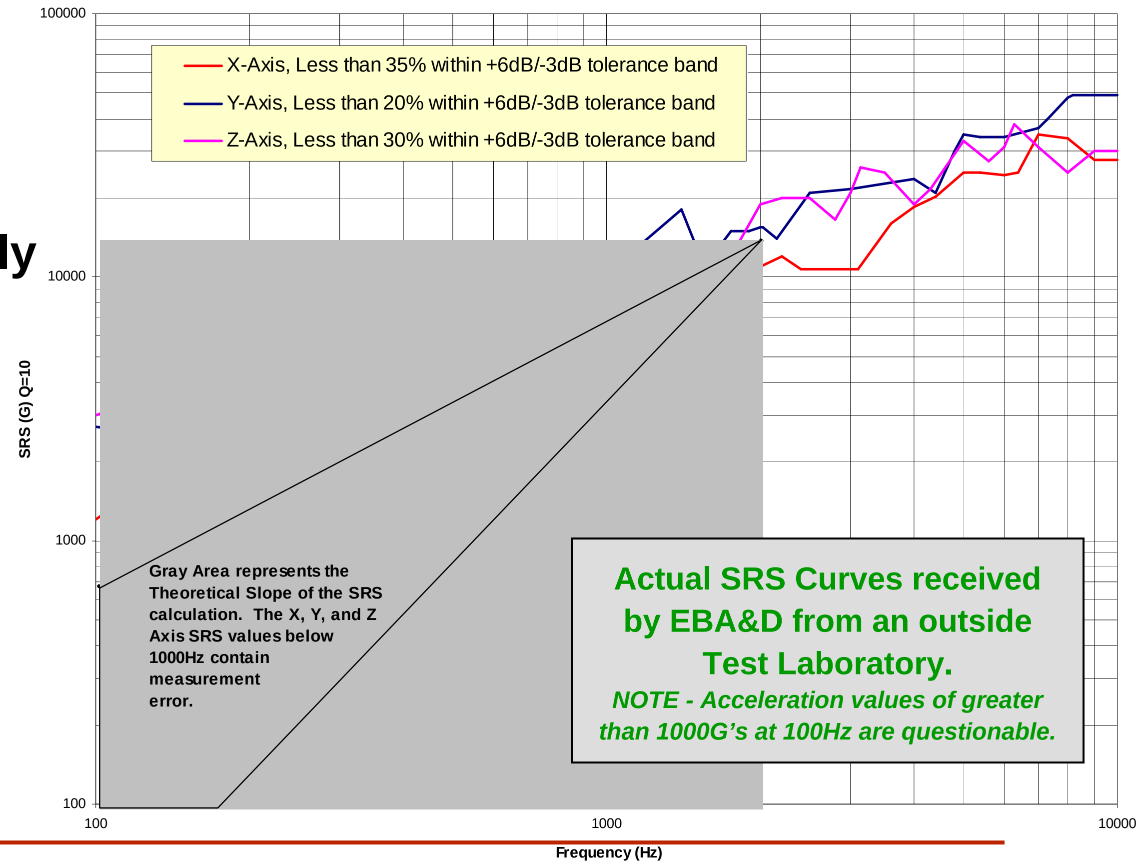
Observations Regarding Today's Practices

#1. In general, today's Test Laboratories do spend time post-processing data to increase the SRS in local areas. This practice addresses spikes below the -3dB tolerance line. However, little to no time is spent correcting the resulting data if it appears to comply with the required SRS requirement.

Observation from Test Data

(See Plot to the right)

- **Inaccurate acceleration values below 700Hz.**
- **High risk that corrected test data would not have met specification.**



Pyrotechnic Shock Testing

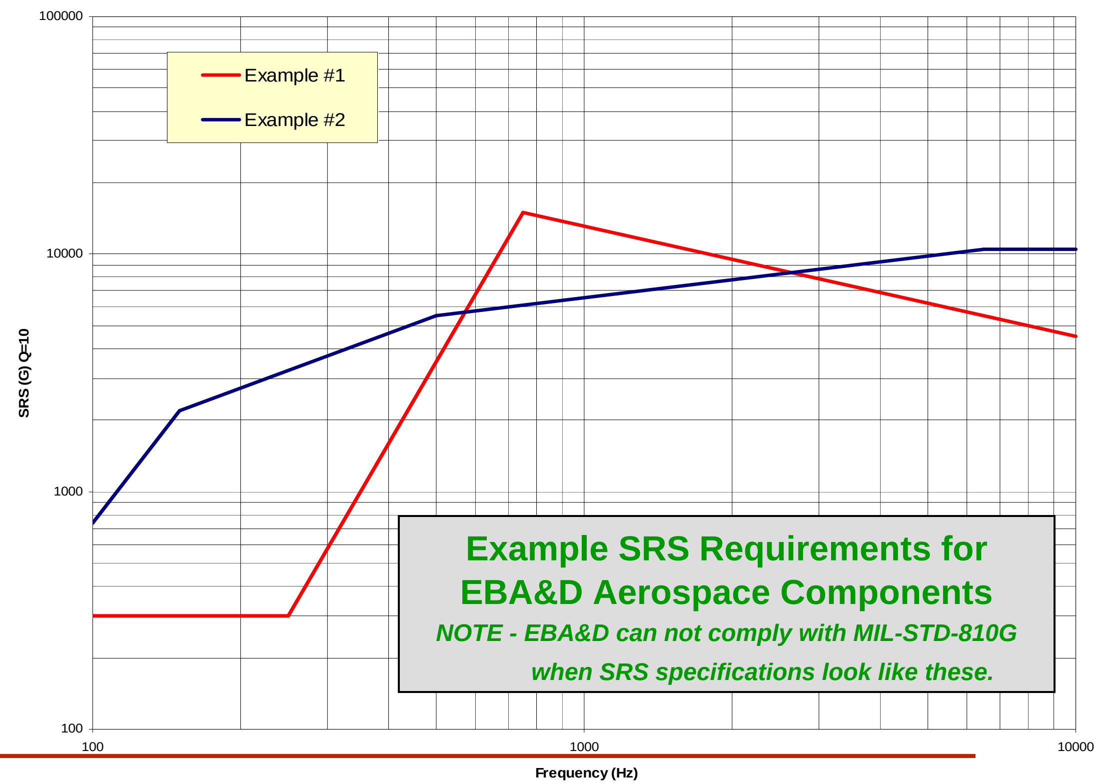
Observations Regarding Today's Practices

#2. EBA&D continue to receive SRS requirements that are inappropriate for Pyrotechnic Shock Testing. EBA&D's technical response to our customers centers around first being able to produce the required acceleration levels and secondly understanding the resulting frequency ranges where overtest is expected. Refer to Example SRS to the right.

Compliance with MIL-STD-810G

(Rev. G is currently under review)

- **Para. 4.2.2.2 states all acceleration SRS are to be within -3dB and +6dB over a minimum of 90 percent of the overall frequency bandwidth from 100Hz to 10,000Hz.**



Pyrotechnic Shock Testing

Observations Regarding Today's Practices

#3. Current standards require the addition of +6dB safety margin (minimum) to entire frequency range (100 - 10,000Hz) of an SRS. This method of applying margin to component SRS requirements results in significant jumps in displacement needed at low frequencies.

- Some of today's SRS Requirements are challenging the physical limits of the pyrotechnic shock test method.
- The displacement values in the table were acquired by the following method:
  - Create an SRS, defining the acceleration at 100Hz, then using a slope of 9 dB/octave up to a knee freq. of 2000Hz.
  - Use "srs-syn.exe" to synthesize an acceleration time history.
  - Integrate that time history to a displacement time history.

Value of 1st Breakpoint (@ 100Hz)		**Estimated Pk-Pk Displacement**
MPE =	100 g's	~ 0.07 inch
+6dB =	200 g's	~ 0.13 inch
MPE =	300 g's	~ 0.18 inch
+6dB =	600 g's	~ 0.37 inch
Maximum Requested at 100Hz =	800 g's	~ 0.52 inch
3000 g's (as illustrated on Slide 26)		~ 2 inch

Pyrotechnic Shock Testing

Observations Regarding Today's Practices

#4. For the SRS requirements levied on EBA&D components, spikes below the -3dB tolerance are prohibited. Such occurrences often times result in the repeat of an individual shock test upon Customer request. For all the data acquisition variables associated with pyrotechnic shock, it is very interesting that there is no allowance for narrow -band drop outs.

- Plot to the right illustrates a spike due to accelerometer mounting.
- Test labs feel pressured to use excessive explosive quantity as the shock source to avoid condition.
- Test labs will leave measurement error in the final data.

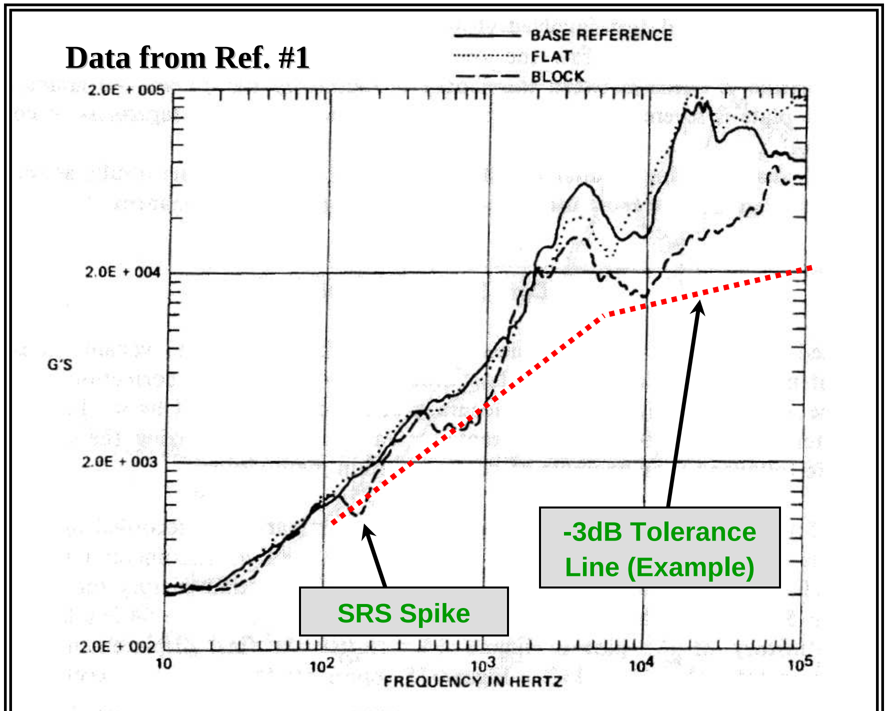


Figure 47. SRS means: accelerometer mounting: flat versus block.

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Areas for Enhancement in Test Methodology

<u>EBA&D Suggestions</u>

- Incorporate allowance for narrow-band spikes below the -3dB tolerance line.
  - This is especially true for frequencies below 1000Hz. May also be valuable above 5000Hz.
- Perform SRS algorithm beyond 10,000Hz (at least 20,000Hz).
  - Energy beyond 10,000Hz is capable of causing damage.
- Expand the Pyrotechnic Shock Data Package to include other plots beyond the Acceleration Time History and SRS.
  - Displacement Time History
  - Velocity Time History
  - Pseudo Velocity Response Spectrum
- Standardize Accelerometer Block mounting configurations.
  - For example: When using an aluminum shock fixture, it is highly recommended that an aluminum mounting block be welded to the fixture.

Pyrotechnic Shock Testing

Areas for Enhancement in Test Methodology

<u>EBA&D Suggestions (cont.)</u>

- Publish a global data processing and correction manual.
  - <u>Or</u> update a current publication to reflect test laboratory practices. (This publication would be one that the community mutually agreed to.)
- Review methods for applying margin to Shock MPE.
  - At low frequency, additions of +6 dB significantly alter the test severity; Shock source approaches 1/3lb of explosive material located ~ 2 feet from UUT.
- Decrease the emphasis on the actual SRS data and characterize the pyrotechnic shock test by a qualified test set-up.
  - Configuration Controlled Pyrotechnic Shock Fixture.
  - Specify the exact quantity of explosive to be used.
  - Specify the exact distance from the UUT that the detonation will occur.
  - Use SRS data to qualify set-up, but acquire <u>For Info Only</u> during individual shocks.

Pyrotechnic Shock Testing

Referenced Publications

- Reference #1, Slide 23 & 29 - Smith, James Lee: Effects of Variables Upon Pyrotechnically Induced Shock Response Spectra, 1986.
- Reference #2, Slide 24 - Melander, Roy, and Smith, Strether: Why Shock Measurements Performed at Different Facilities Don’t Agree, 1995.