

Installation and In-situ Calibration of Force Gages

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June 4-6 2012

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.

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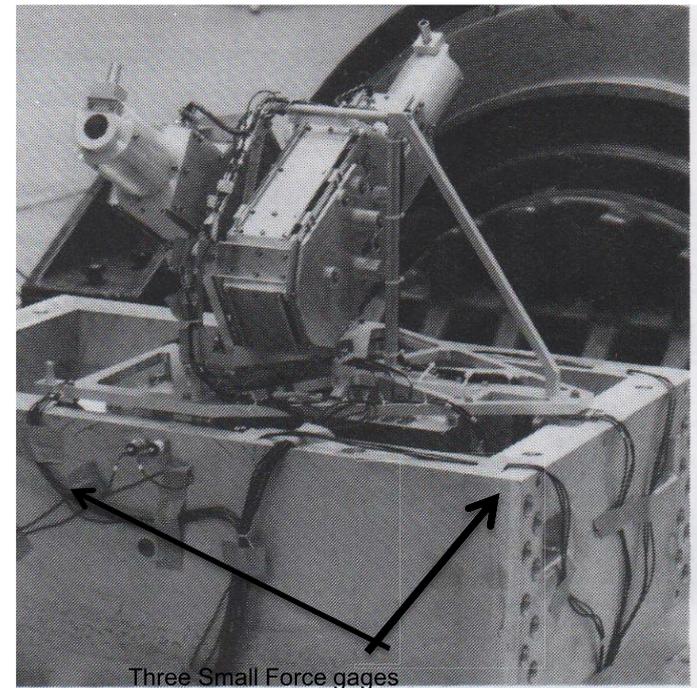
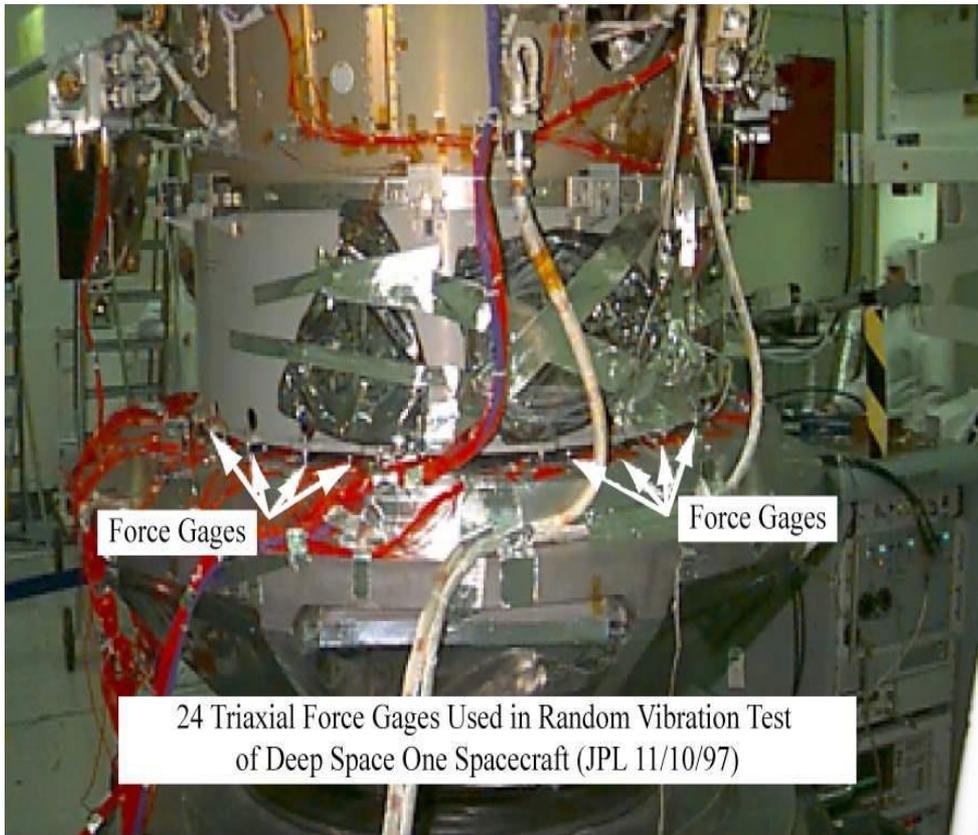
OUTLINE

- Gage Selection, Mounting, and Signal Processing
- Examples Using Single Gage At Each Mounting Point
- Some Installation Considerations
- Criteria for Selecting Preload
- Effect of Preload on Gage Sensitivity
- What is “In-situ Calibration”
- Steps for In-situ Calibration
- Five Case Studies of In-situ Calibration
- Recommendations
- Reference and Acknowledgements

GAGE SELECTION, MOUNTING, AND PROCESSING

- Gage Selection
 - *Triaxial gages with quartz piezoelectric elements are typically used.*
 - *Select size and number of gages for maximum loads.*
 - *Design mounting configuration to accommodate selected gages and payload interface.*
- Mounting Configuration Options
 - *Single gage at each interface using longer flight bolts (Chart 4)*
 - *Single gage at each interface using manufacturers' supplied preload bolt or "link" (Chart 5)*
 - *Single adapter plate between gages and test item (dynamometer)*
 - *Multiple gages at each interface using local adapter plates*
- Signal Processing
 - *Desired combination of total and individual forces, and moments*
 - *Sensors can be connected electrically in parallel to sum forces*

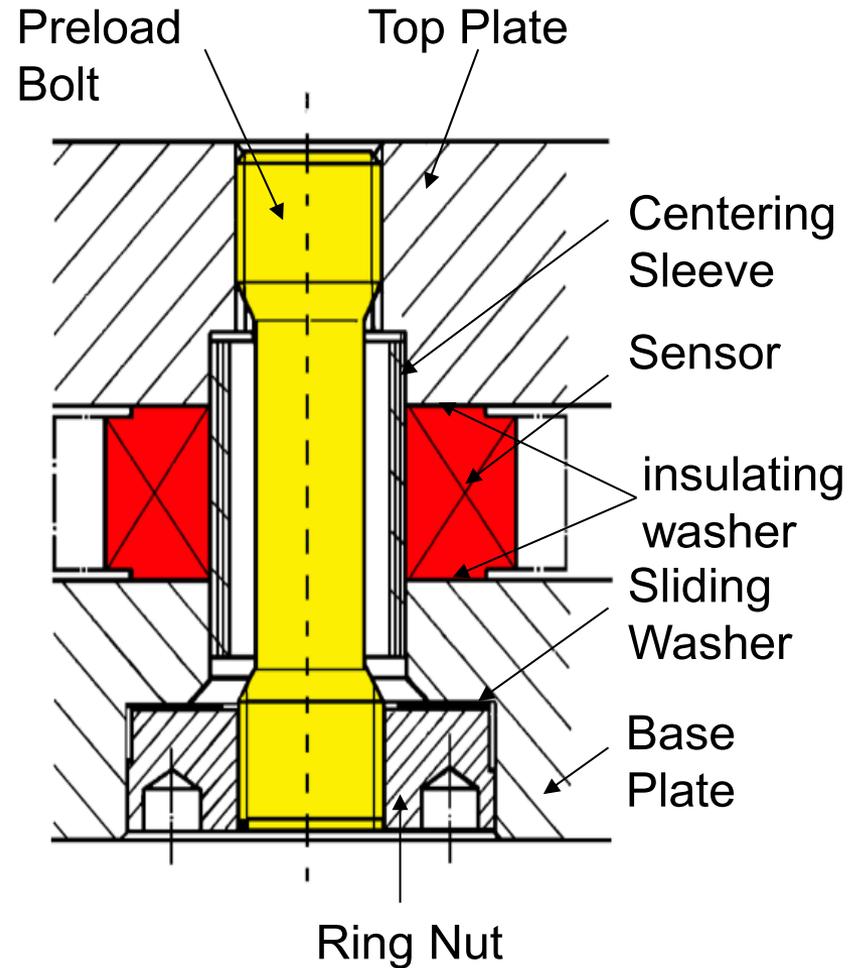
EXAMPLES USING SINGLE GAGE AT EACH MOUNTING POINT WITH LONGER FLIGHT BOLTS



Cassini RPWS Antenna Force Limited Random Vibration Test (circa 1994)

SOME INSTALLATION CONSIDERATIONS

- Preload configuration options:
 - Gage and longer flight bolt
 - Manufacturer's preload bolt (Shown at right.)
 - Manufacture's preload "link"
- Radial clearance and soft centering sleeve
- Insulating washer or accept case ground
- Parallel, flat, and stiff mating surfaces
- Controlled friction washer or use gage to set preload



CRITERIA FOR SELECTING PRELOAD

- Gage manufacturers recommend a preload of approximately ten (10) times the maximum lateral forces.
 - *A factor of ten provides a margin of two for preventing gross slip (assuming a coefficient of friction of 0.2), and prevents “micro-slip”.*
 - *Note that in random vibrations, maximum loads of four to five sigma are frequently measured.*
- The preload should be adequate to prevent “heel-toe” due to local bending loads
- The preload must be high enough to “tighten up” the gages to close up interior gaps and to provide rigidity
- The combination of preload and dynamics loads must fit within the maximum load set for the gages, with margin
- The preloaded gage configuration should be proof tested to the maximum expected load, plus the institutional margins

EFFECT OF PRELOAD ON GAGE SENSITIVITY

- The gage manufacturers' sensitivities (charge or volts per unit force) given in their specification sheets assume a certain preload configuration and preload value. (See their footnotes.)
- The sensitivity of the quartz itself is independent of the preload, but the shunting of the preload bolt, and at lower preloads, microgaps in the quartz stack, will affect the gage sensitivity.
- In aerospace applications, rather than using the manufacturer's preload configuration, it is often preferable to utilize the gages sandwiched between the test item and the shaker adapter plate, with the preload provided by longer flight mounting bolts.
 - *This avoids adding height, and increased moment in the lateral axes, and also minimizes the noise floor due to dead weight above the gages.*
 - *However, the preloads attainable with the flight bolts are typically lower than those assumed in the manufacturer's specifications, and therefore the sensitivities may be lower than the manufacturer specifies*

EFFECT OF BOLT SHUNTING ON SENSITIVITY

- The ratio of the load seen by the gage to the total load (gage plus bolt) is given by the corresponding ratio of stiffness's, i.e.,

$$K_{\text{gage}} / (K_{\text{gage}} + K_{\text{bolt}})$$

bolt)

- *The gage axial and lateral stiffness's are provided in the gage manufacturer's specification sheet (as the gages are relatively stiff, any compliance in the gage load path should be included in the calculation)*
- *The bolt stiffness's can be calculated from simple formulas, e.g., $K_{\text{axial}} = AE/L$, where A is the bolt cross-section area, E is Young's modulus, and L is the bolt length. The bolt is usually softer in the lateral direction due to bending.*
- If the users preload bolt configuration is significantly different than that assumed in the manufacture's specified sensitivities, then the effect of bolt shunting may be recalculated, using the equation above with stiffness ratios for the manufacture's and the users bolts.
- *The sensitivity of the final installed configuration may be determined empirically with in-situ calibration.*

WHAT IS “IN-SITU CALIBRATION”

- What is the purpose of an in-situ calibration?
 - *To conduct an end-to-end check of the integrity of the installed force gages, mounting, wiring, and signal processing system*
 - *To update the force gage sensitivities specified by the manufacturer with values corresponding to the installed configuration*
- In-situ calibration uses force and acceleration data obtained in a low-level sine-sweep or random vibration test (often the initial signature vibration test) with the force gages, control accelerometers, and test item in place.
- The low-frequency asymptote of the ratio of the measured total in-axis force to the control acceleration, herein called the “in-situ calibration mass”, is compared to the actual total mass (weighed or calculated) above the gages, i.e., that of the test item and of any gage mounting hardware.

STEPS FOR IN-SITU CALIBRATION (1)

- 1) Begin the vibration testing in each axis, with a low-level sine-sweep or random vibration initial signature test, with the force gages, control accelerometers, and test item in place.
- 2) Compute the ratio of the measured total in-axis force to the in-axis control acceleration at the lowest frequency where the data are available and reliable. This ratio, the in-situ calibration mass, may also be read directly off a frequency response function generated by the data analysis computer.
- 3) If the lowest frequency (f) is above 20% of the fundamental resonance frequency (f_o), calculate the non-resonant calibration mass by reducing the measured force by the amplification factor of an undamped single-degree-of-freedom system below the first resonance, i.e., $1/[1-(f/f_o)^2]$. (For a frequency ratio of 20%, the amplification factor is approximately 1.04.)

STEPS FOR IN-SITU CALIBRATION (2)

- 4) Compare the measured ratio of non-resonant force to control acceleration, the calibration mass, with the actual total mass above the force gages, i.e., that of the test item and any mounting hardware above the gages. (In the following, this ratio of the calibration mass to the actual mass is referred to as “the in-situ calibration factor” or just the “calibration factor”.)
- 5) If the calibration factor is not greater than 0.8 in the axial axis, and/or not greater than 0.9 in the lateral axes, look for gage, mounting, wiring, or signal conditioning problems. (Calibration factors greater than 1 may also indicate a problem, e.g., resonance amplification of the measured force.)
- 6) After any, and all, of the aforementioned are resolved, try to explain the in-situ calibration factors, e.g., by considering the bolt shunt path, test item resonances, local bending, etc.

STEPS FOR IN-SITU CALIBRATION (3)

7) After it has been determined that the force gage system is operating properly, and the measured in-situ calibration factors have been rationalized and deemed acceptable, use the factors to adjust the gage sensitivities for the subsequent force limited vibration tests in the subject axis. Options for taking into account the in-situ calibration factors include:

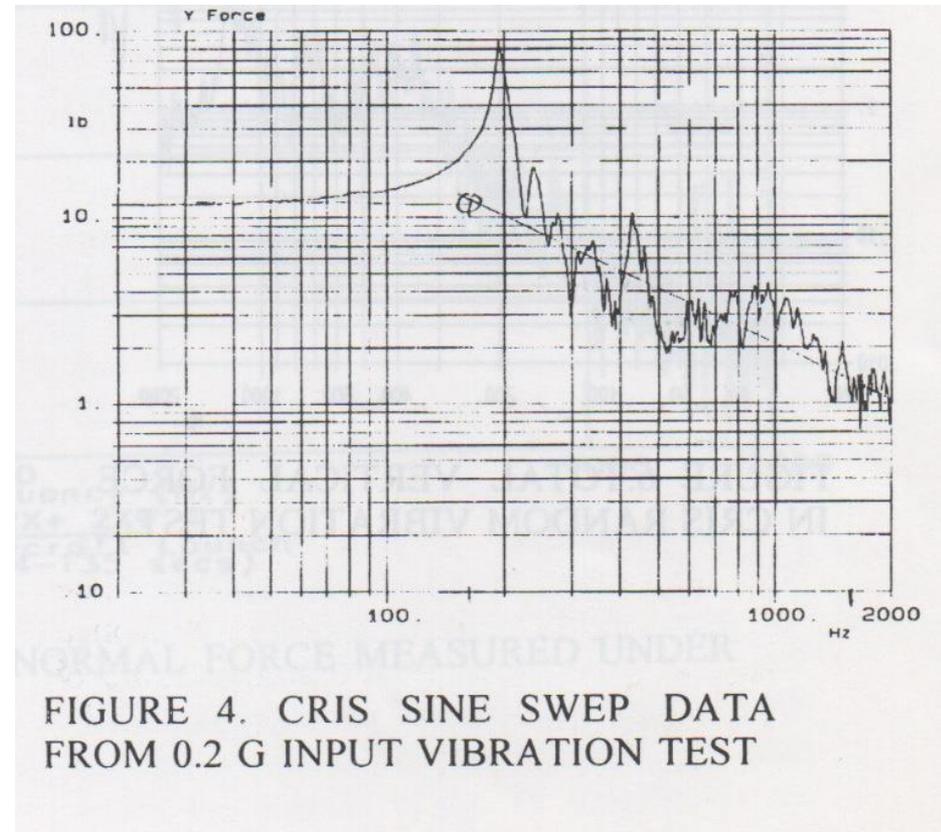
- *changing the gage sensitivities in the charge amplifiers or computer,*
- *scaling the force data in the computer, or*
- *changing the force limit specification.*

(Different test labs and test engineers will have different preferences regarding methods of accommodating the in-situ calibration factors .)

8) After in-situ calibration, there may still be small errors due to: repeatability (particularly in random tests), connector problems, cable vibration, sensor misalignment, and sensor and charge amp. drift, non-linearity, hysteresis, and temperature effects.

Case History #1: ACE Spacecraft CRIS Instrument

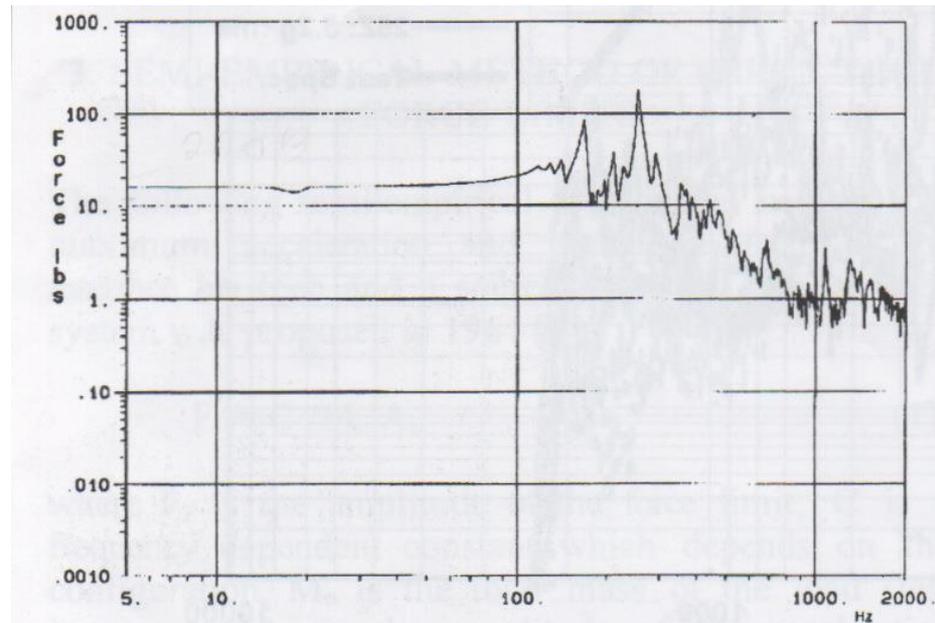
- Force in 0.2 G test ~ 11 lb
- Calibration mass ~ 55 lb
- Instrument weight ~ 65 lb
- Ratio of calibration mass to actual mass: $55/65 = 0.85$.
- Bolt shunting calculation:
 - $K \text{ gage} = 5.7 \times 10^6 \text{ lb/in}$
 - $K \text{ } \frac{1}{4}'' \times 1'' \text{ bolt} = 1.5 \times 10^6 \text{ lb/in}$
 - $K \text{ gage} / (K \text{ gage} + K \text{ bolt}) = 0.8$
- Bolt shunting, and possibly low preload, reduced sensitivity
- Multiply the gage sensitivity by the in-situ calibration factor of 0.85, to increase the magnitude of the force data in subsequent tests.



Proceedings European Conference on Spacecraft Structures, Materials and Mechanical Testing, Braunschweig, GR, 4-6 Nov. 1998, ESA SP-428

Case History #2: Cassini Spacecraft RPWS Antenna (see photo in Chart #4)

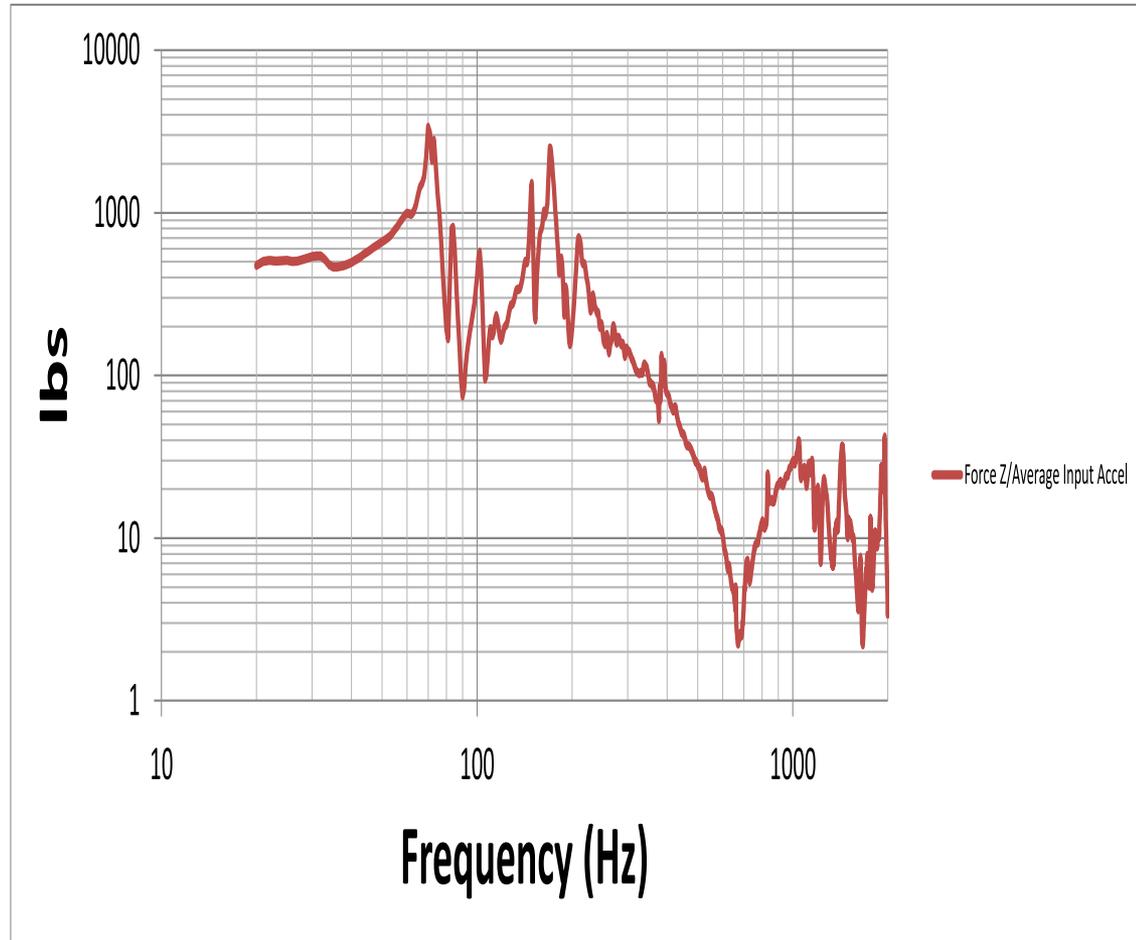
- Force in 0.25 G test ~ 15 lb
- Calibration mass ~ 60 lb
- Instrument weight ~ 65 lb
- Ratio of calibration mass to actual mass: $60/65 = 0.92$
- Bolt shunting, and possibly low preload, reduced sensitivity
- Multiply the gage sensitivity by the in-situ calibration factor of 0.92, to increase the magnitude of the force data in subsequent tests.



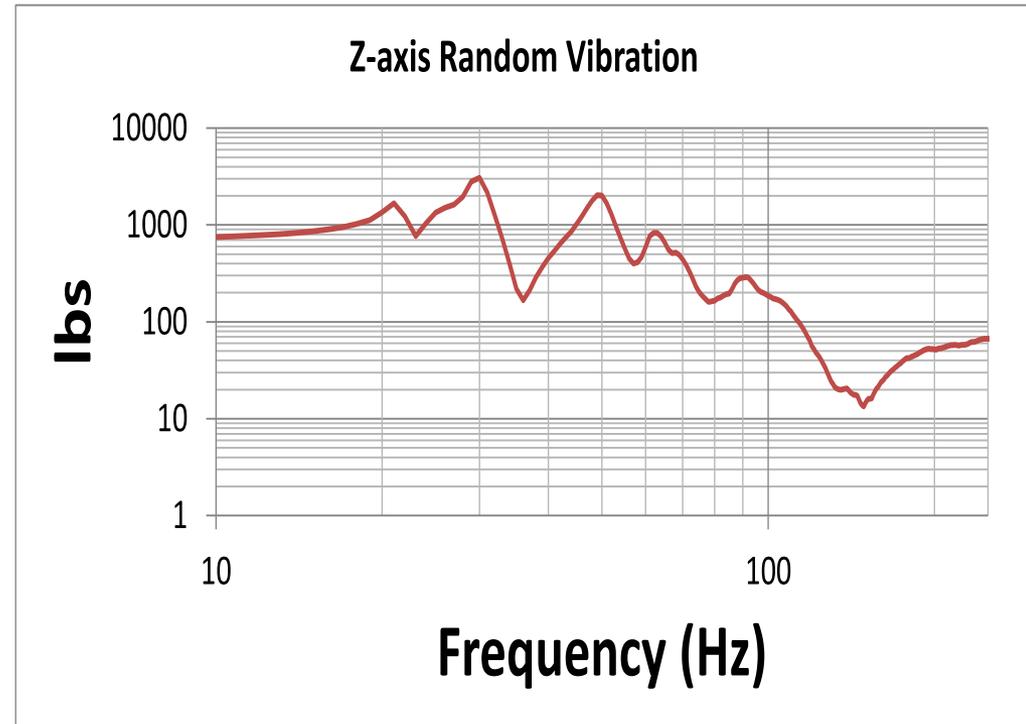
Proceedings of Third International Symposium on Environmental Testing for Space Programmes, ESTEC, Noordwijk, NL, 34-27 June 1997, SP-408)

Case History #3: An Instrument

- Ratio of Force/Accel. at 20Hz ~ 475 lb
- But instrument weighs only ~ 427 lb
- In-situ calibration factor: $475/427 = 1.11$
- Amplification due to first mode at 70 Hz is 1.09 (Chart 10), this probably caused calibration error. (Could be remedied by taking data at lower frequency.)
- Don't change sensitivities.

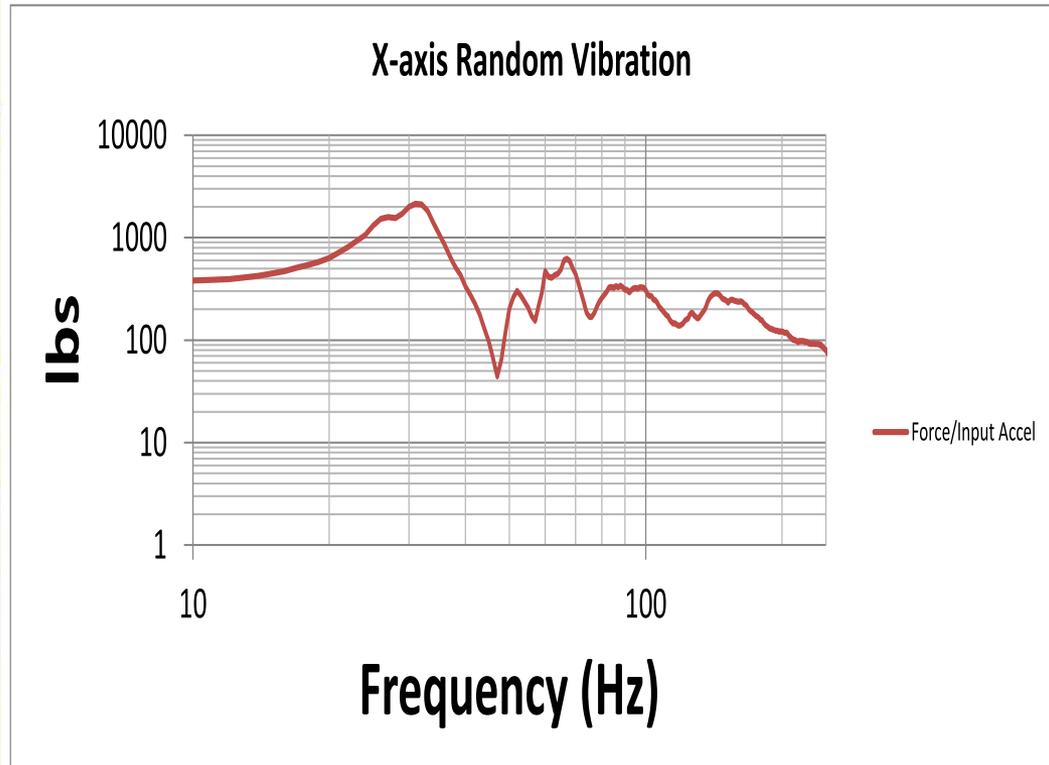


Case History #4: Aquarius Instrument Axial Random Vibration Test



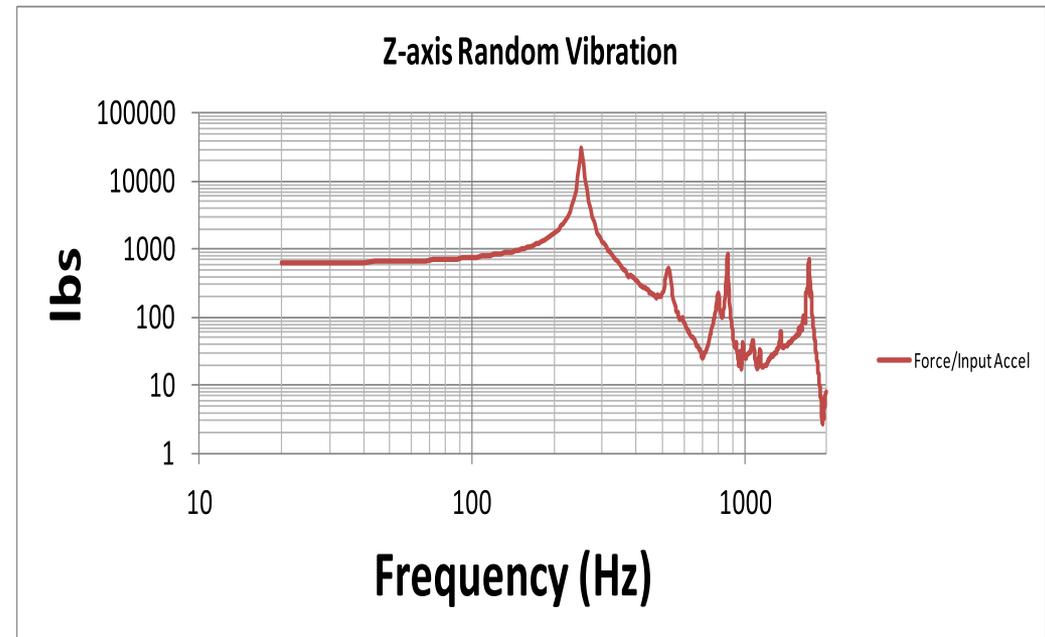
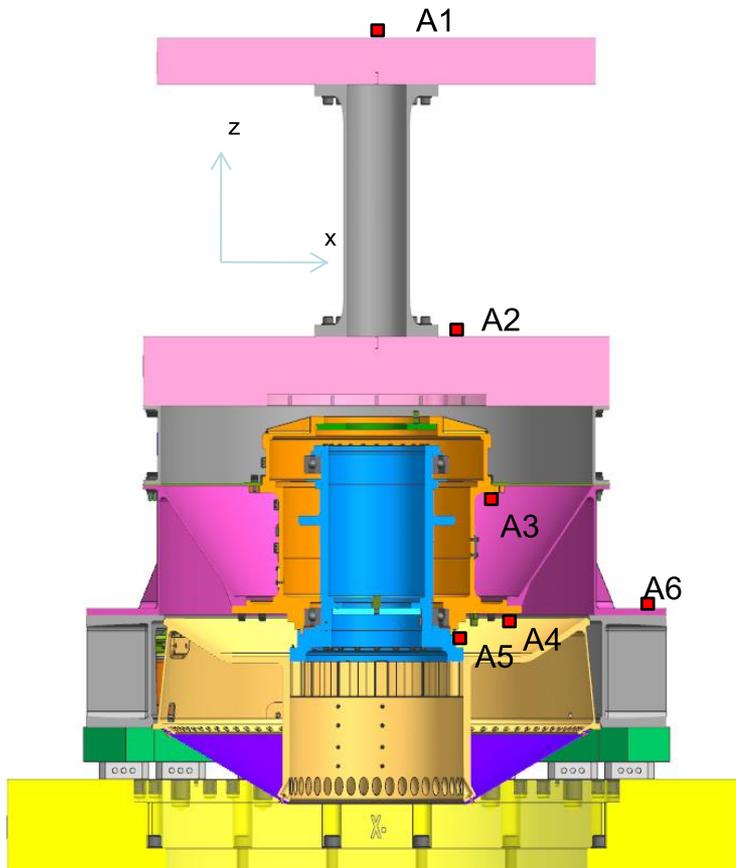
Force/Accel. @ 10 Hz = 751 lb
compared to 708 lb weight
In-situ calibration factor = $751/708 = 1.06$
Probably resonance amplification. Don't
change sensitivities.

Case History #4: Aquarius Instrument Lateral Random Vibration Test



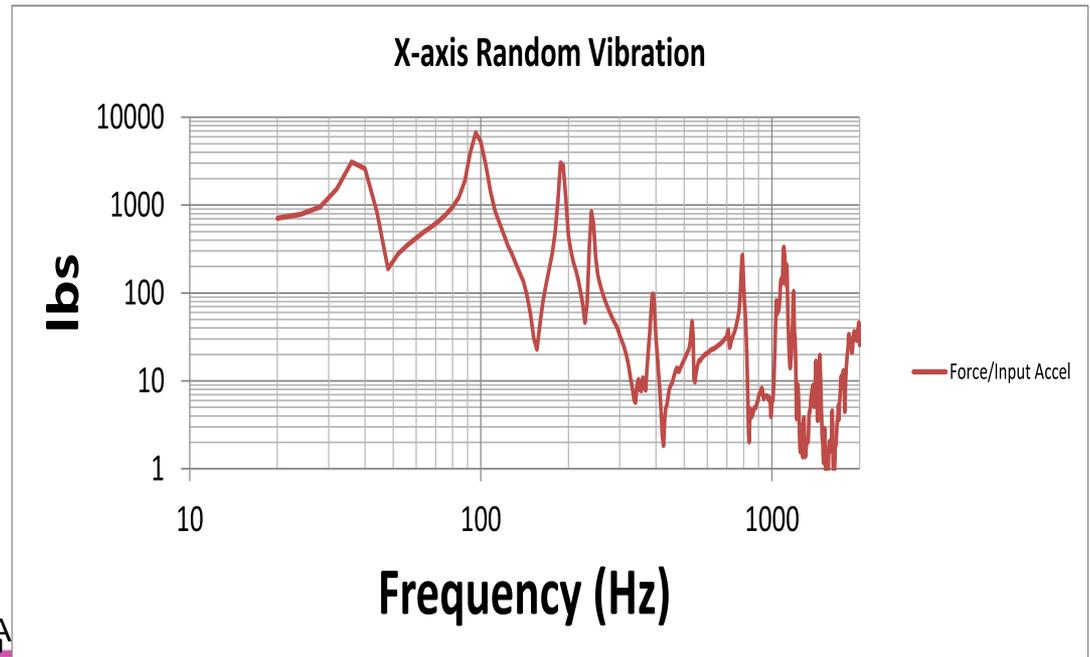
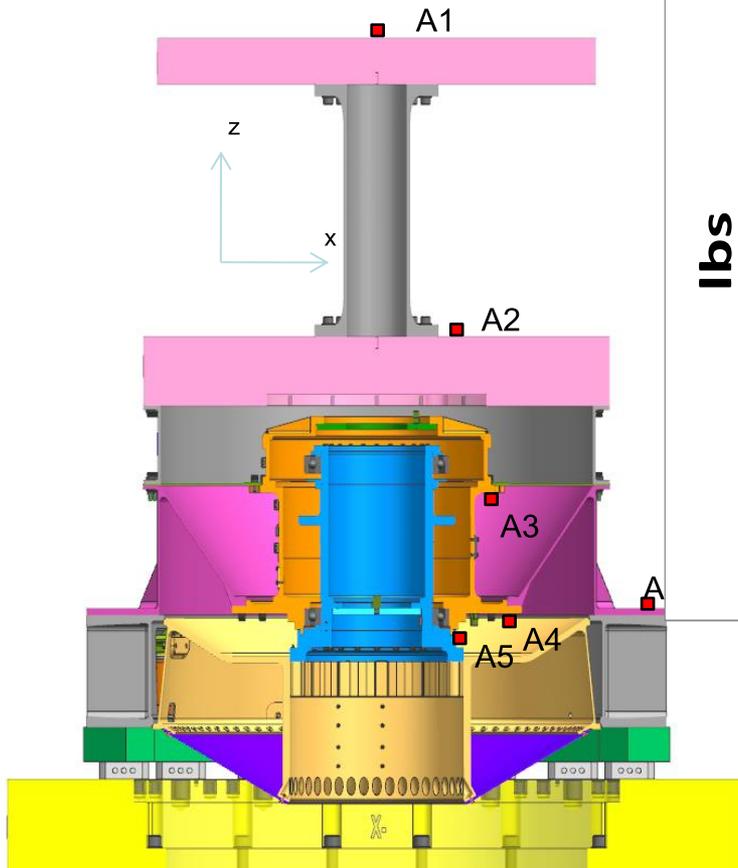
Force/Accel @10 Hz = 420 lb vs 708 lb weight
In-situ calibration factor = $420/708 = 0.59$
Problem may be related to bending of fixture blocks or mono-ball interfaces

Case History #5: SMAP Cone-Clutch Assembly Axial Random Vibration Test



- Total Force @ 20 Hz = 631 lb vs 625 lb weight
In-situ calibration factor $\sim 631/625 = 1.01$
- Don't change sensitivities.

Case History #5: SMAP Cone-Clutch Assembly Lateral Axis Random Vibration Test



Total Force @ 20 Hz = 711 lb vs 625 lb weight
In-situ calibration factor $\sim 711/625 = 1.14$
Amplification factor due to first mode at 38 Hz
is 1.33 (Chart 10), but damping will result in a
smaller correction. Don't change sensitivities.

Recommendations

- *Gage Configuration Considerations*
 - Select size and number of gages for configuration and maximum loads
 - Use sufficient preload to prevent slip in lateral axes. (Manufacturer's recommend minimum of 10 times lateral load.)
 - Flight-like bolts used to minimize height and weight usually result in lower preloads than manufacture's preload configurations (force links).
 - *Preload bolt should have radial clearance and soft centering sleeve*
 - *Provide insulating washer, or accommodate case ground*
 - *Proof test mounted gages to institutional margins*
- *In-situ Calibration Considerations*
 - *Recommended for end-to-end check-out of force measurement system and for adjustment of manufacturer's specified force gage sensitivities*
 - *Use low-level initial signature test for in-situ force gage calibration*
 - *Try to rationalize the measured in-situ calibration factors, i.e., bolt shunting, low preload, resonance amplification, local bending, etc.*

Reference

Karl H. Martini, “Multicomponent Dynamometers Using Quartz Crystals as Sensing Elements”, *Instrumentation in the Aerospace Industry*, Vol.28, 1982, obtainable from the Instrument Society of America, Research Triangle Park, NC, (919) 549-8411

Acknowledgements

- The authors would like to gratefully acknowledge the help provided by the following gentlemen and their organizations:
 - Bob Metz, Product Manager, PCB Aerospace & Defense, PCB Piezotronics Div., bmetz@pcb.com
 - Conrad Sonderegger, Director of Sales Division Sensor Technology, Kistler Instrumente AG, conrad.sonderegger@kistler.com

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Thank you



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