Structural Test Design and Interpretation

for Aerospace Programs

Objectives: Improve your understanding of how to ...

- identify or define test objectives
- design (or recognize) a test that satisfies the identified objectives while minimizing risk
- establish pass/fail or success criteria
- design the instrumentation
- interpret test data
- write a good test plan and a good test report

Audience: All engineers involved in ensuring that flight vehicles and their payloads can withstand mission environments and function as needed

Course developed and taught by Tom Sarafin

Course Topics

Introduction

1. Overview of Structural Testing
2. Designing and Documenting a Test
3. Loads Testing of Small Specimens
4. Static Loads Testing of Large Assemblies
5. Testing on an Electrodynamic Shaker
6. Example: Notching a Random Vibration Test
7. Overview of Other Types of Structural Tests
8. Case History: Vibration Test of a Spacecraft Telescope

Summary/Wrap-up

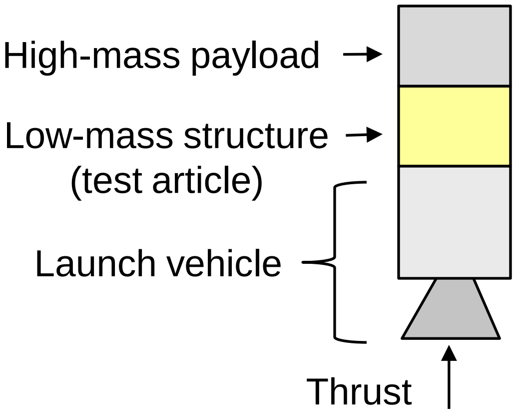
What Are Some Likely Reasons for Doing a Structural Test?

- ~~Customer-imposed requirement~~
  - Contractually this might be the case.
  - But you, the engineer, must understand and embrace the true reason (e.g., why your customer is requiring the test).
- Verify compliance with one or more requirements
  - Quite often the ability to withstand mission environments, which typically means verification of certain required characteristics (see later discussion)
  - Also can pertain to a required characteristic that is not directly related to mission environments
    - e.g., constraints (see later discussion)
- Acquire information
  - To obtain needed properties for materials or joints
  - To learn to control manufacturing processes
  - To improve a design
  - To correlate a math model

Two main reasons for doing a test:

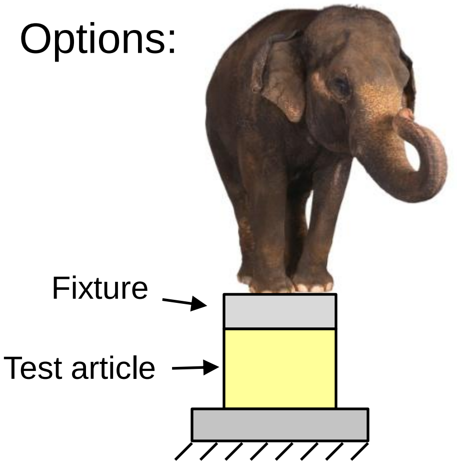
- **Verify a requirement**
- **Obtain information**

Options for Strength Testing

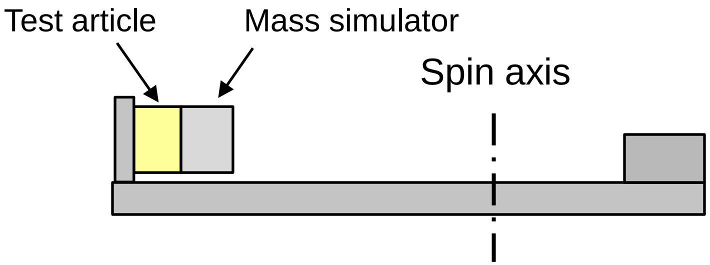


- Let’s assume we’ve designed a low-mass structure that supports a high-mass payload on top of a launch vehicle.
- For this simple example, the limit load is specified in terms of uniform axial acceleration caused by thrust, with no side loads.
- We want to test the low-mass structure to verify that it has enough strength to withstand the design ultimate load without rupture or collapse.

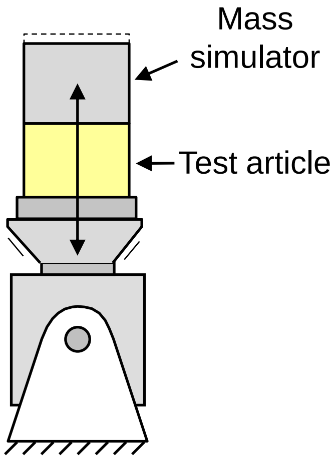
Options:



1. Static loads test



2. Centrifuge test



3. Vibration (e.g., sine burst)

Which is the best strength test, and why?

Two Things All Tests Need

- **Objectives**
  - Clearly defined and specific, e.g., “The objective is to verify that the flight structure has sufficient strength per requirement xxx.”
  - Not “The objective is to do a static loads test.”
  - The engineer responsible for the test must understand and clearly define the objectives, and all stakeholders must buy in

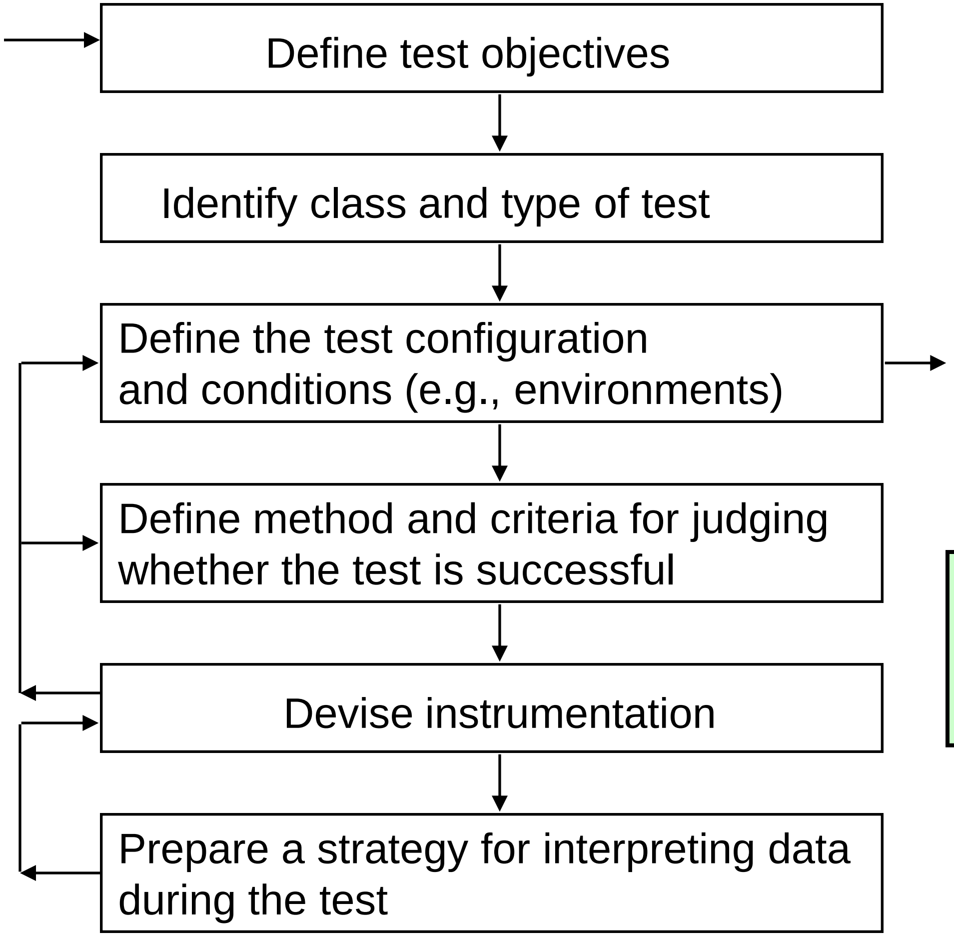
- **Pass/fail or success criteria**
  - How will we know whether the test achieved its objectives (***success criteria***) or whether the test article passed the test (***pass/fail criteria***)?
  - Criteria must be clearly defined—in advance of the test!
    - Otherwise, how will we know we have designed the right instrumentation?
  - However, failure to meet the criteria does not necessarily mean test failure
    - Pass the criteria: no-brainer; move on
    - Fail to meet criteria: investigation and disposition required
    - Make sure this philosophy is clear before starting the test

You can’t have a good test without a clear understanding of objectives and criteria

For a test to be meaningful, valuable, and cost effective, it must be carefully designed to meet the objectives and enable assessment of the criteria

Designing a Test

Always start with a clear definition of the objectives!



Define test objectives

Identify class and type of test

Define the test configuration and conditions (e.g., environments)

Define method and criteria for judging whether the test is successful

Devise instrumentation

Prepare a strategy for interpreting data during the test

Iterate: Develop a preliminary plan in order to scope the test, then revise it as the design evolves.

Identify needed equipment; develop a schedule

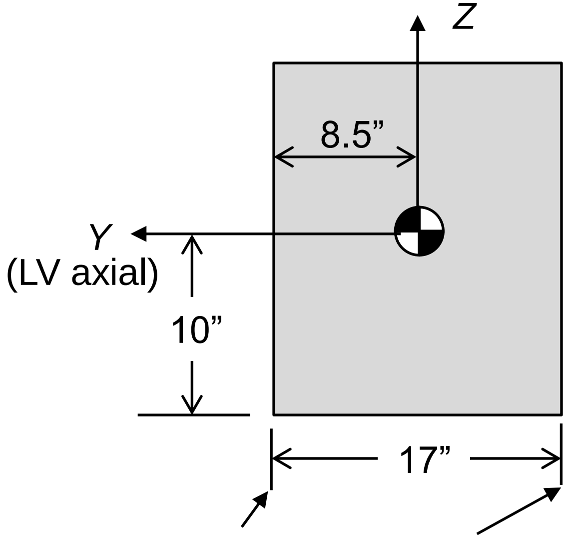
Coordinate the test with a test plan.

What should go in a test plan?

Class Problem 2-1

Given:

- The spacecraft is attached to the base adapter with four bolts, one at each corner of a 17” square pattern.
- The CG is 10” above the plane of the bolt pattern and centered on the Z axis.
- The spacecraft weighs 150 lb.
- The specified design limit loads are +/- 8.5 *g* in the Y direction acting simultaneously with +/- 8.5 *g* acting in either X or Z.
- Sine-burst tests will be run in the X, Y, and Z directions.
- The structure must be tested to 1.25 times limit.



Axes of mounting bolts

(view in the *X*-*Z* plane looks the same)

Problem statement: **Using Option 4 on the previous page, select the test axis (*X*, *Y*, or *Z*) that would most efficiently load the bolts in tension, then derive the required acceleration for sine-burst testing in that axis to ensure the bolts are adequately tested in tension.**

Make Sure the Test Data are Reasonable and Investigate Anomalies before Dismantling the Test Setup!

Possible causes of bad data:

- Misaligned or faulty instruments
- Displacement gages mounted on flexible support structure
- Inadequately bonded strain gages
- Accelerometers mounted on locally flexible structure
- Improper calibration factors used to convert electrical output to meaningful data
- Incorrect applied loads or environments because of improper computer input or calibration factors
- Improper data filtering or processing
- Unknown effects of test fixtures

Make sure instrumentation is verified prior to test (e.g., use a gage block to check displacement gages, use a calibrated resistor for checking load cells, etc.), but recognize that such verification is not foolproof.

If you are the responsible engineer for a test whose success depends on acquired data, it is crucial for you to ensure you have accurate data and have adequately investigated any anomalies before allowing the test setup to be torn down!

Come prepared to interpret data within minutes of seeing it!

Case History: Designing a Test

Background and problem statement

- NASA’s standard (since 1989) for analyzing preloaded bolts, NSTS-08307, was thought by many to be overly penalizing, driving cost and weight unnecessarily, requiring …
  - The ultimate margin of safety for bolt tension to include the effects of preload
  - A positive margin of safety on bolt yield
  - Analysis for shear loading to include interaction with preload
- NASA’s Engineering and Safety Center (NESC) was tasked in 2007 to develop a new standard for threaded fastening systems.
  - A team of civil servants and contractors was established.
- The NESC team decided to design a test program to answer the following questions for joints using A-286 fasteners and aluminum fittings (attached parts):
  - Does preload reduce the ultimate tensile or shear strength of a typical joint? In other words, can we ignore preload in ultimate-strength analysis?
  - Is bolt yielding detrimental?

Notes: 1. There were many other objectives of this project. The case history presented here addresses only the above questions and includes only the design of the tensile test.

2. The product, NASA-STD-5020, was released in March 2012.

Class Exercise

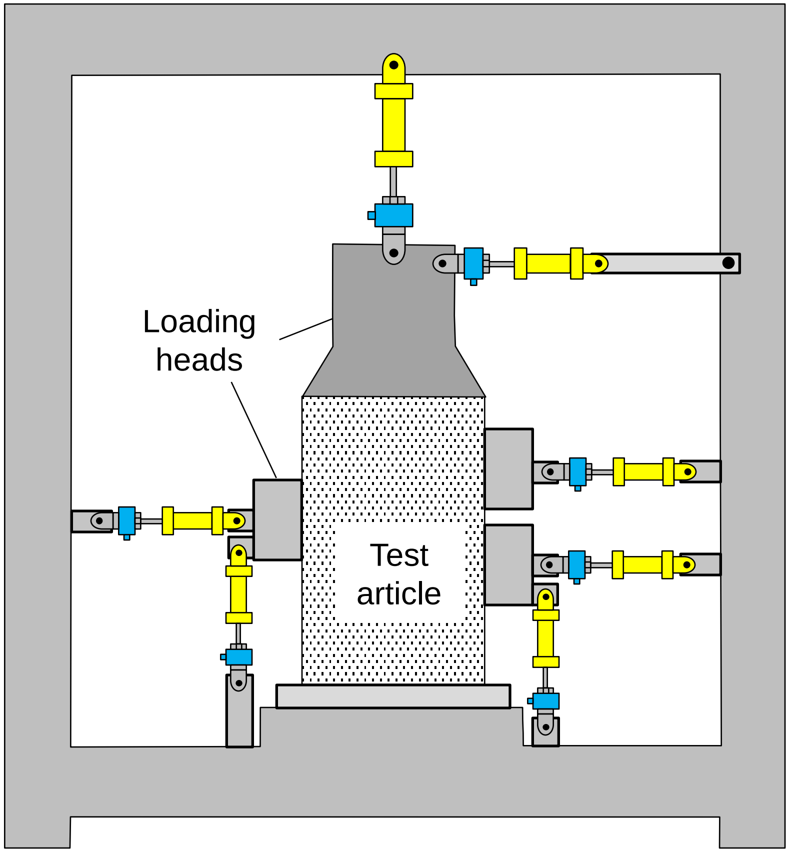
Brainstorm ideas for a test that meets the objectives of the NESC team given the noted constraints. Consider …

- **Configuration**
- **Instrumentation**
- **Test procedure**

Computerized Load Control with Hydraulic Jacks

Advantages

- Can easily accommodate many load lines, with simultaneous loading
- Near-continuous data acquisition
- Can program safety provisions such as “hold” tolerances (perhaps +/- 3% of load magnitude) and “dump” tolerances (e.g., +/- 6%)

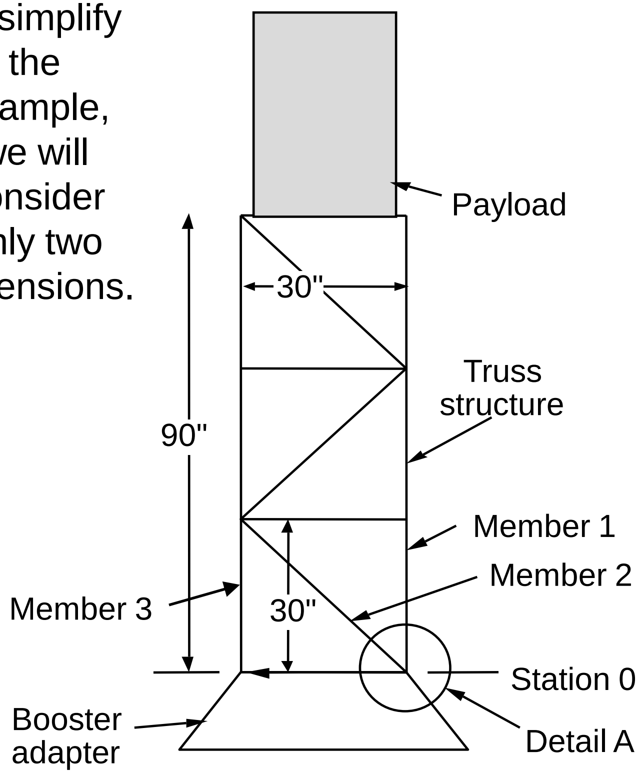


Disadvantages and Limitations

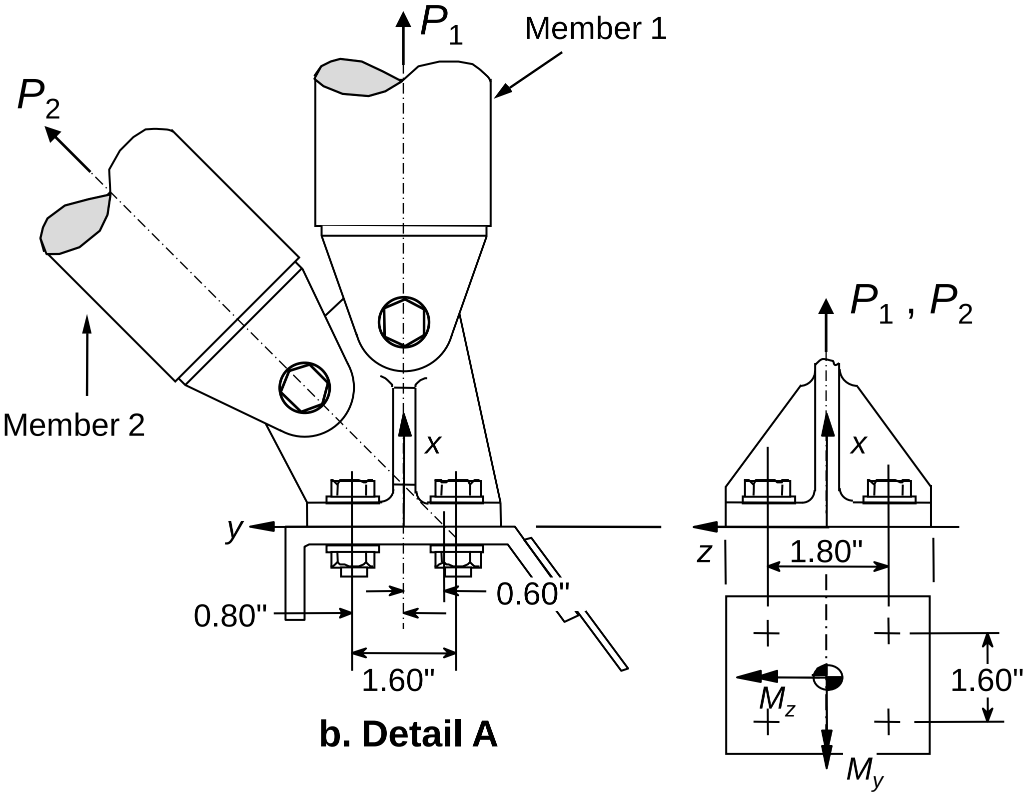
- Requires expensive equipment that needs periodic maintenance
- As with any use of computers, we have to check the program and input data (easy to become complacent)

Example Problem 4-1: Designing a Static Load Case

To simplify the example, we will consider only two dimensions.



a. Stowed spacecraft



b. Detail A

Problem statement: Design a static load case that will hit target loads for (a) tension in member 1 and (b) bolt tension, to 1.25 times limit.

Example adapted from Sarafin, Thomas P. “Designing Effective Static Tests for Spacecraft Structures.” AIAA 97-0882. Presented at the 35th Aerospace Sciences Meeting & Exhibit, January 1997.

Example Problem 4-1 (continued)

Step 6: Use the LTM to assess the initial load case from Step 4. Modify the load case, if necessary to achieve the target internal loads while maintaining positive margins of safety.

$$\begin{Bmatrix} P_1 \\ P_t \\ V_y \\ M_x \end{Bmatrix} = \begin{bmatrix} 3.00 & 2.00 & 1.00 & 0. \\ 1.19 & 0.936 & 0.686 & 0.436 \\ 1.00 & 1.00 & 1.00 & 1.00 \\ -120. & -90.0 & -60.0 & -30.0 \end{bmatrix} \begin{Bmatrix} 2100 \\ 2050 \\ 2000 \\ 1950 \end{Bmatrix} = \begin{Bmatrix} 12{,}400 \\ 6640 \\ 8100 \\ -615{,}000 \end{Bmatrix}$$

Parameter	Predicted Load	Target Load	Ratio	Allowable Ratio
P_1 (lb)	+ 12,400	+ 13,400	0.93	1.07
P_t (lb)	+ 6640	+ 6400	1.04	1.04
V_y (lb)	+ 8100	± 8100	1.00	N/A
M_x (in-lb)	- 615,000	± 615,000	1.00	N/A

Conclusions:

The proposed load case under-tests Member 1 and over-tests the bolt (marginal).

Example Problem 4-1 (continued)

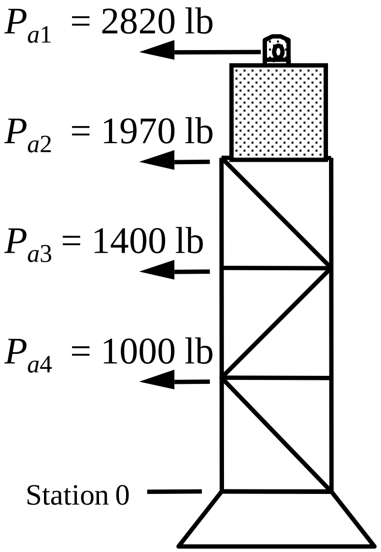
Modify the load case:

This matrix has no inverse. There is no load case that would hit all four targets exactly.

Overall shear apparently does not peak at the same time as overall moment.

- We could confirm this by seeing if they peaked at different time points in the coupled loads analysis.

Let’s aim only at overall moment, axial load in member 1, and bolt tension. By iteration, we find the following load case satisfies our criteria:

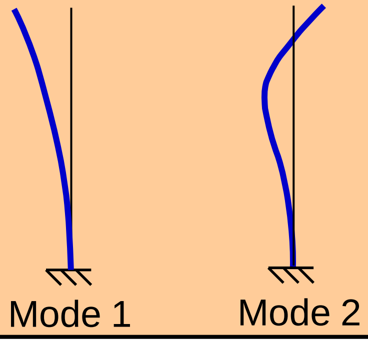


Parameter	Predicted Load	Target Load	Ratio	Allowable Ratio
P_1 (lb)	+ 13,400	+ 13,400	1.00	1.07
P_t (lb)	+ 6420	+ 6400	1.00	1.04
V_y (lb)	+ 7010	± 8100	0.87	N/A
M_x (in-lb)	- 614,000	± 615,000	1.00	N/A

Limitations of Testing on a Shaker

- Introduces acceleration uniformly through the mounting interface
  - Tends to over-stress the hardware (see later discussion on notching)
- One axis at a time
- Translational input only; no angular (rotational) acceleration
- Can't excite all modes of vibration from base translational input
  - Depends on the ***modal effective mass*** as a ratio of total mass, which tells us …
    - how much mass relative to total mass is moving in a given direction from base input,
    - and whether (or how effectively) a mode can be driven by motion in the various degrees of freedom at the mounting interface
  - The mathematics are beyond the scope of this course, but modal effective mass can be computed with FEA.

Which of these two modes can be more easily excited with lateral motion at the base?



Answer: Mode 1. For Mode 2, mass is moving in opposite directions, so the net mass motion is low.

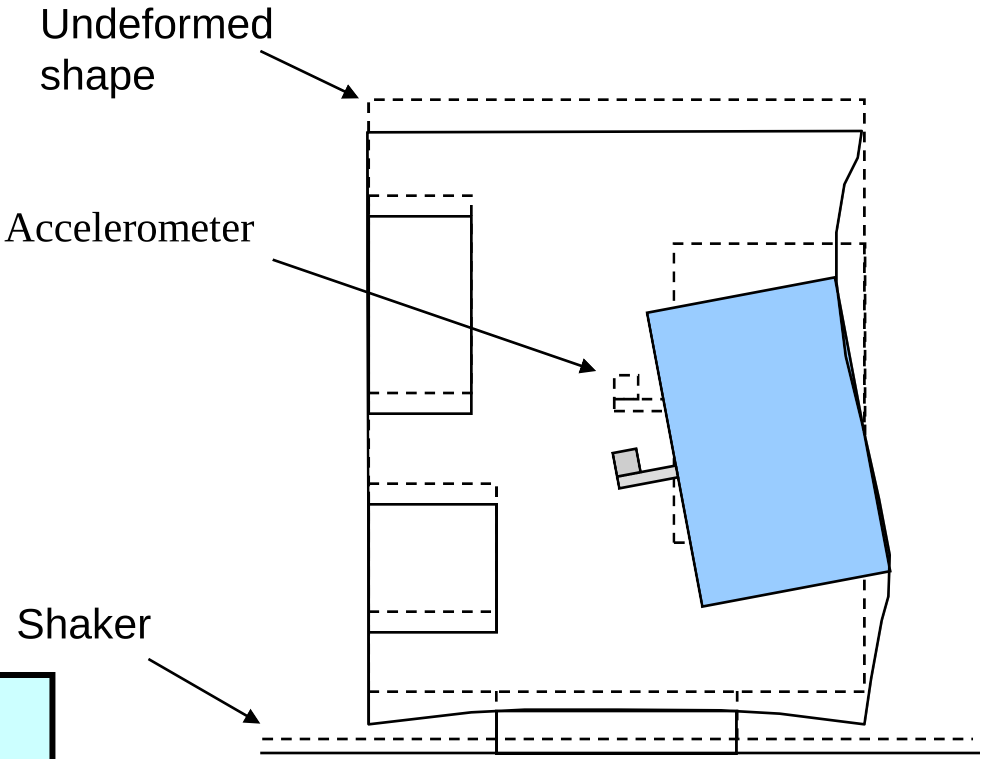
If one of the test objectives is to excite a mode that can't be excited with a shaker, you need to find a different test!

Option 1: Put an Accelerometer at the CG

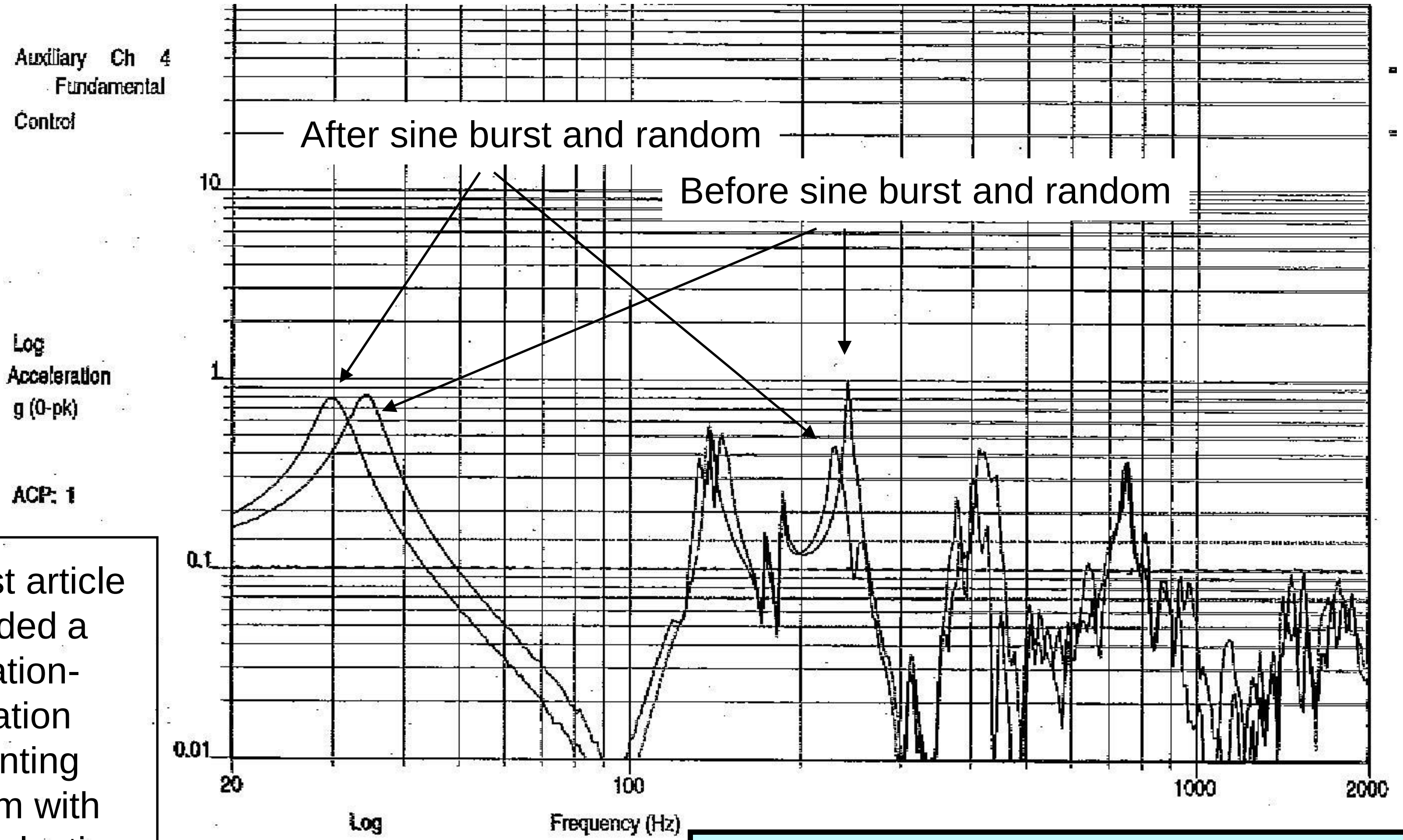
- An accelerometer is placed at the spacecraft CG by cantilevering it off a component that mounts to a side wall.
- The spacecraft is mounted to a shaker, and vibration is introduced is introduced in the vertical axis.

Putting an accelerometer at the CG does NOT necessarily mean the measured acceleration will be the average or net acceleration.

Be careful how you interpret accelerometer data!



Example Comparison of Pre- and Post-test Sine-sweep Data



After sine burst and random

Before sine burst and random

The test article included a vibration-isolation mounting system with visco-elastic materials.

How would you interpret this data?

Be Careful When Testing on a Shaker

- High Energy Solar Spectroscopic Imager (HESSI) suffered over $1M damage in a test mishap.
  - Sine-burst test, intended to input 1.88 *g* (-12 dB from full 7.5-*g* level)
  - Actual input acceleration hit 21 *g*.
- What went wrong:
  - The shaker was old, parts were misaligned, and a bearing had failed.
  - Input force was increased to overcome “stiction”.
  - Evidence of the problem from previous tests went unnoticed.
  - No validation test was performed beforehand.

HESSI after repair. The test in March 2000 that caused the failure was lateral, on a slip table.

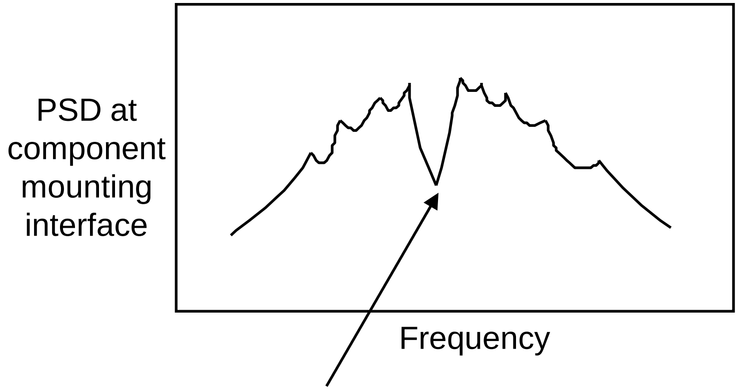
To protect expensive test articles, maintain and check test equipment and …

- **dry run the test with a mass simulator.**
- **pay attention to test data, noises, and the like, and pursue anomalies.**
- **consider static and acoustic tests for a large spacecraft rather than putting it on a shaker.**

Avoiding Over-test for Random or Sine Vibration

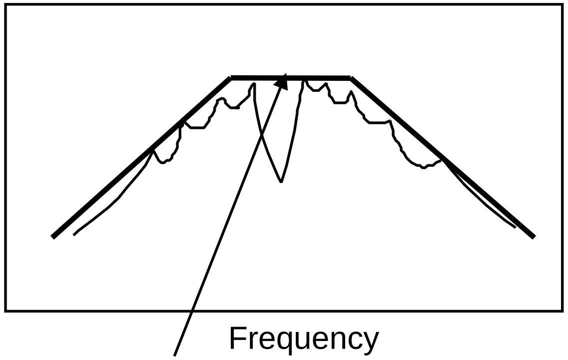
- Vibration testing to a traditionally defined PSD or sine sweep works best for a component that is small in mass when compared to its mounting structure.
- When the masses of the component and its mounting structure are the same order of magnitude, controlling a test solely by input acceleration can severely overstress the hardware. Forces are unrealistically high at the component's fundamental frequency.

What actually happens during launch or during a vehicle acoustic test:



Vibration energy is limited, so at resonance much of the energy transfers to the component

Then we draw a smooth envelope for test:



Forcing the shaker to achieve this acceleration at the component's fundamental frequency can result in 10× or more over-test!

This is why we may "notch" the test environment

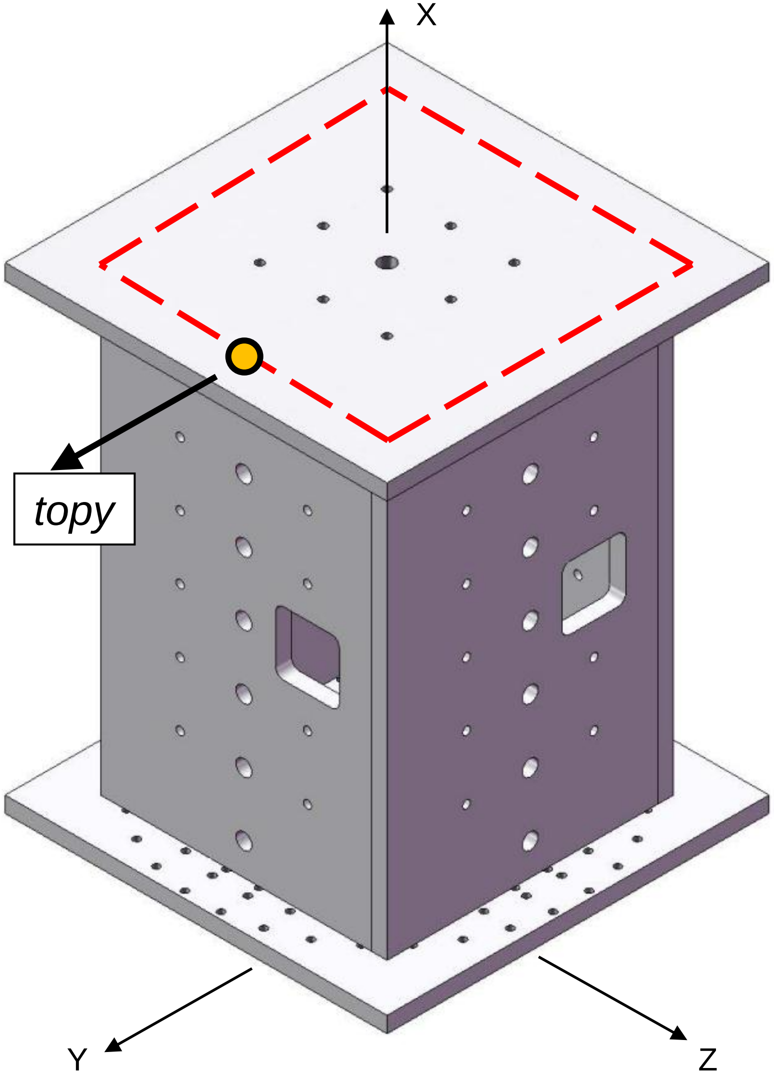
Notching Strategy for Y-axis Test (Z Moment)

- Frequency band for initial low-level tests: 20 – 100 Hz
- From FEA, the RMS SM moment, M_z, is calculated from RMS acceleration as

$$M_z = 3840 \cdot topy$$

Influence coefficient derived from FEA

- Tailor the notch to hit M_z = 22,700 ± 1000 in-lb, RMS, when projected up to full qual levels



Make Sure the Data Channels Can Adequately Capture the Target Modes

- Pretest orthogonality check:

$$\left[\Phi_{\text{FEM}}\right]^{\mathrm{T}}\left[M\right]\left[\Phi_{\text{FEM}}\right]=\left[I+\varepsilon\right]$$

where

$\left[\Phi_{\text{FEM}}\right]=$ modes matrix from FEM, partitioned to test-channel DOFs

$\left[M\right]=$ mass matrix from FEM, reduced to test-channel DOFs

$\left[I+\varepsilon\right]=$ identity matrix plus some error, ε, in diagonal and off-diagonal terms

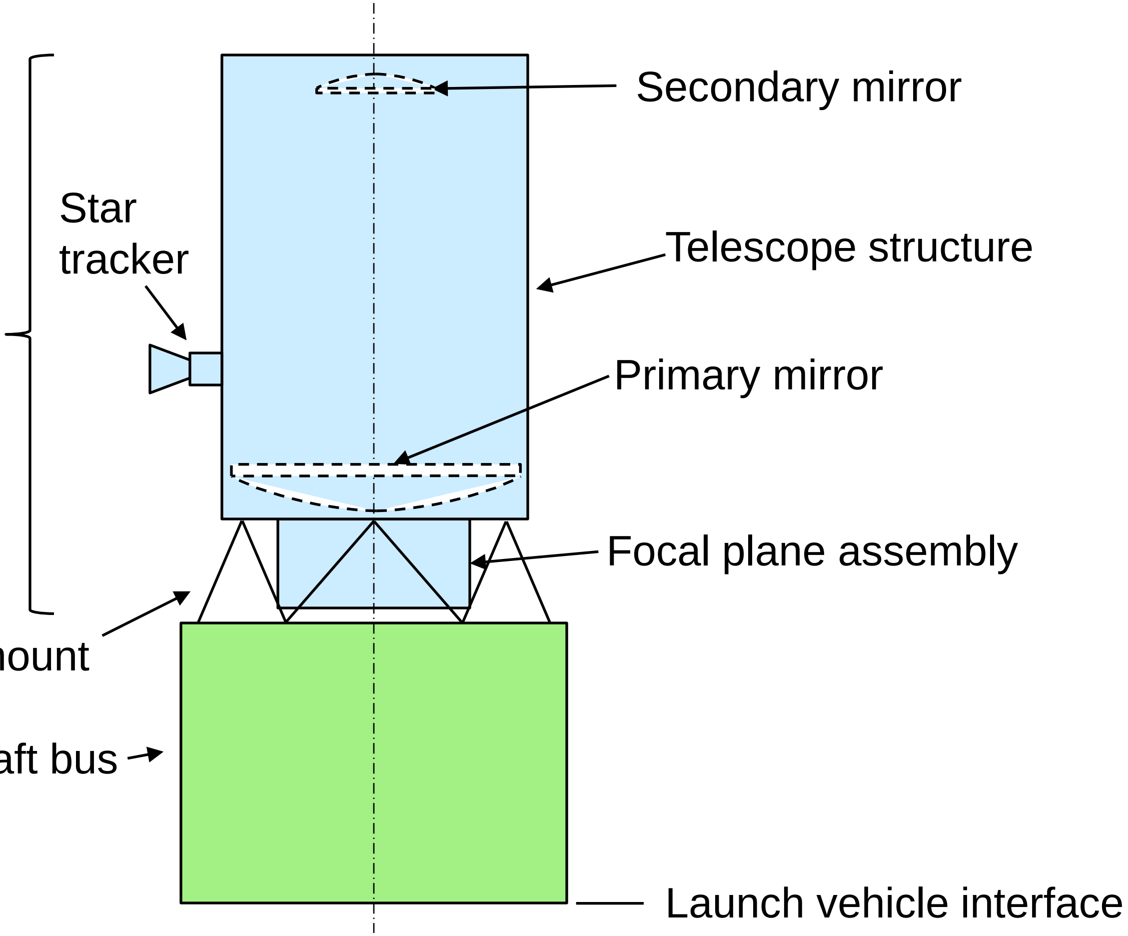
Reasonable goal: off-diagonal terms < 0.05 when diagonal terms are normalized to 1.0

A highly orthogonal (near identity) matrix assures …

- **the reduced mass matrix has adequate fidelity for the target modes**
- **and the selected instrumentation set can adequately define the target mode shapes**

Case History Overview

Simplified configuration



Telescope assembly (TA)
(weighs between 500 and 1000 lb)

Objective: Establish a structural test program for the TA and for the satellite vehicle (SV) assembly (= TA + bus).

Class Exercise

The program needs to design a new test program such that the structure and optical assemblies are stressed at least as severely during TA testing as they will be stressed later, not only during the mission but also during the SV tests, while also protecting against the risk of costly failure from overtest.

Your assignment:

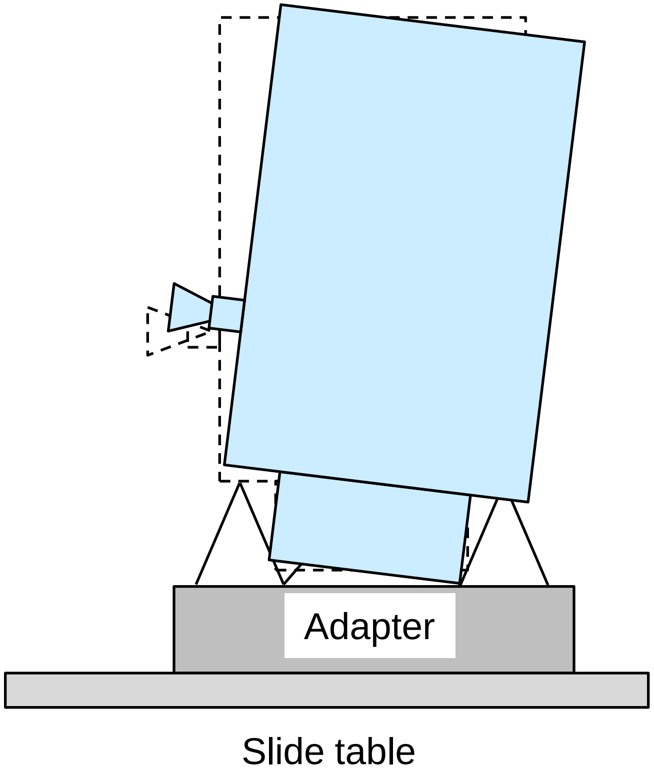
Working in small teams, brainstorm ideas for this redesigned test program.

Address levels of assembly (up to SV level), types of tests, and test levels relative to acceptance (max expected) levels.

Constraints:

- All the flight-hardware designs are complete, and manufacturing is underway
- The optics and the telescope structure have low structural margins of safety and thus cannot tolerate significant over-test
- No time or money available to build qualification hardware
- See special challenges listed on page 8-3

Test Anomaly: Nonlinear Rocking Frequency



	Natural frequency for rocking mode
Low-level sweep	50 Hz
High-level sweep	39 Hz
Low-level sweep (repeated)	50 Hz

Investigation found the nonlinearity to be in the test fixtures (adapter-table assembly), not in the TA.

But the fixtures basically were just chunks of metal.

Any ideas for what caused the nonlinearity?

Unfortunately, this anomaly was discovered only after breaking the test configuration for the first lateral axis and setting up for the second axis.