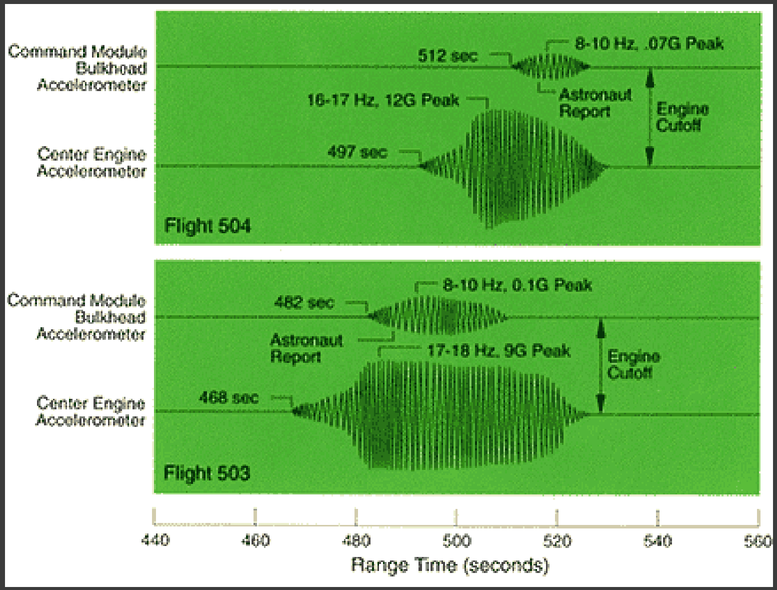
Rocket Vibration

- http://www.youtube.com/watch?v=-rASHRBo9Rg&feature=player_embedded
- **HEAT1X-Tycho Brahe inaugural flight / Pilot's POV – 9Hz oscillation**

Saturn Rocket Vibration



- “Pain was directly associated with motion of the eyeballs and testicles, as well as from internal heating that resulted from sloshing of the brain and viscera. The vibration frequency was also in the range of normal brain waves, adding confusion to decision making, hand and arm movement, and even speech.” –Jim Fenwick on Pogo oscillations

http://www.pwrengineering.com/articles/pogo.htm

Space Shuttle Main Engine Turbopumps

- “The high-pressure pumps rotated at speeds reaching 36,000 rpm on the fuel side and 24,000 rpm on the oxidizer side. At these speeds, minor faults were exacerbated and could rapidly propagate to catastrophic engine failure.”
- “…the vibration spectral data contained potential failure indicators in the form of discrete rotordynamic spectral signatures. These signatures were prime indicators of turbomachinery health…”

March 2012

- “While the lower stages of the North Korean rocket continued to function for several minutes, resonance at the top of the launch vehicle resulted in ‘**catastrophic disassembly** of the third stage at Max Q,’ said Charles Vick, senior technical and space policy analyst at GlobalSecurity.org. ‘The vibrations just tore it apart.’”

http://www.eetimes.com/electronics-news/4370955/Severe-vibrations-likely-brought-down-N--Korean-rocket

What can cause rocket vehicle vibration?

Causes of vibration

- Thrust oscillations
- Noise (pressure waves) due to the motor or engine (liftoff, transonic, max dynamic pressure)
- Pyroshocks (explosive bolts and such)
- Fluid flow phenomena (aerodynamic stress)
  - Winds
  - Turbulence
  - Vortex shedding
- Turbomachinery (liquid propellant engines)

Why do we care?

Why do we care?

- Human bodies have natural frequencies
  - 5 to 10 Hz seems particularly bad
  - Need to consider this for vehicles with humans in them
    - Ares 1-X vehicle was expected to vibrate such that the pilots would not be able to read the displays (google for clever fix to this)

Why do we care?

- Severe vibration has structural implications
  - Fatigue, overstressing
  - Malfunction of components
  - Control system coupling
  - Propulsion system coupling
  - “Catastrophic disassembly”, “Catastrophic engine failure”
- Can affect where we decide to place certain things (equipment, sensors)
- If vehicle has a payload, we need to pay attention to how vibration affects the payload
  - Vibration isolation

Vibration Testing

- Lab tests
  - Vibration tests
    - Shaker tests, impact hammer modal tests
    - https://www.youtube.com/watch?v=o8H_NT7Ziao
    - https://www.youtube.com/watch?v=PDlrdNK5EyQ
    - https://www.youtube.com/watch?v=pCXTZDfTdG0
    - http://www.youtube.com/watch?v=XkmgMkDKAyU
  - Acoustic tests
- Field tests
  - Static firings
- Flight tests

Vibration Analysis

- Need to determine loading (what is causing the vibration?)
- Mathematical Model
  - Lumped parameter (E59 lumped elements)
  - Distributed parameter
    - For simple structures, we have classical solutions (beams, shells, plates, domes)
- Verify model with experimental data

Beam vibration (transverse)

- https://www.youtube.com/watch?v=kun62B7VUg8

Longitudinal, axial, torsional

- https://www.youtube.com/watch?v=v_ab5PHarCA

Euler-Bernoulli Beams

- Lateral motion assumed here
- We will be interested in the mode shape of the beam (displacement)
- Also interested in the frequencies at which the various modes occur

Boardwork

- $EI\frac{\partial^4 y}{\partial x^4}$+$\rho A\frac{\partial^2 y}{\partial t^2}$=0 (apologies for the sign error in lecture)
- $\rho = mass\ density\ of\ the\ beam$
- A= area
- I = inertia
- E = Young’s modulus
- y = lateral displacement

The transcendental Eq. (5) has infinite solutions, it can be solved numerically, the first five values are reported here:

Mode order n	$k_n L$
0	0
1	4.7300
2	7.8532
3	10.9956
4	14.1371
5	17.2787

Putting these values back in Eq. (5) gives the modeshapes corresponding to the natural frequencies ω_n that can be calculated from the characteristic Eq. (2). The mode shapes are given by the following:

$$w_n(x) = [\sinh(k_n x) + \sin(k_n x)] + \frac{\sin(k_n L) - \sinh(k_n L)}{\cosh(k_n L) - \cos(k_n L)}[\cosh(k_n x) + \cos(k_n x)] \qquad (6)$$

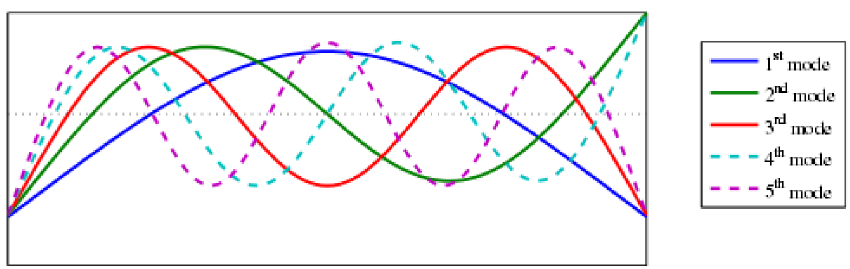


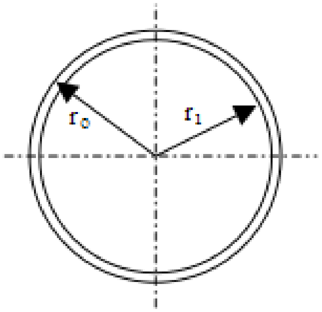
Figure 1. First 5 mode shapes for a free-free beam

http://140.116.155.39/2012%E8%AA%B2%E7%A8%8B/%E6%8C%AF%E5%8B%95%E5%8A%9B%E5%AD%B8/Beam_vibration.pdf

Why do we care about displacement?

- If we have a mathematical model, we might be interested in placing sensors at particular places on our vehicle
  - Avoid dead spots (why?)
  - Validate the model

Appendix 1: Calculation of beam's cross sectional properties



Cross section of a hollow cylinder

$$A = \pi(r_o^{\,2} - r_i^{\,2})$$

$$I = \frac{1}{4}\pi(r_o^{\,4} - r_i^{\,4})$$

http://www.eng.hmc.edu/NewE80/PDFs/DynamBeamAnalyticalModes.pdf

Flutter

- https://www.youtube.com/watch?v=OhwLojNerMU