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Structural Dynamics Lunchtime Series #1.5 Shaker Testing Basics

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Topics of this address

(Many addressed in conference paper/magazine article[8])

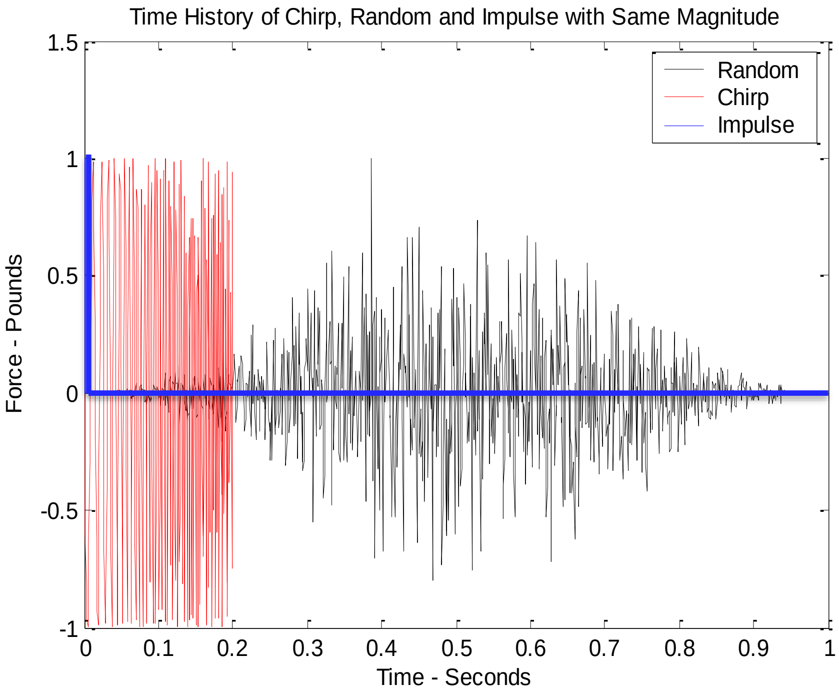
- General advantages of shaker testing over impact testing
- Advantages and disadvantages of step sine, random, burst random, chirp testing, pseudo-random shaker signals
- Shaker setup
- Shaker force gage advantages / gotchas
- Stinger advantages / gotchas
- Fixture considerations
- Obtaining fixed base modal analysis from driven base shaker testing
  - With force measurement
  - Without force measurement

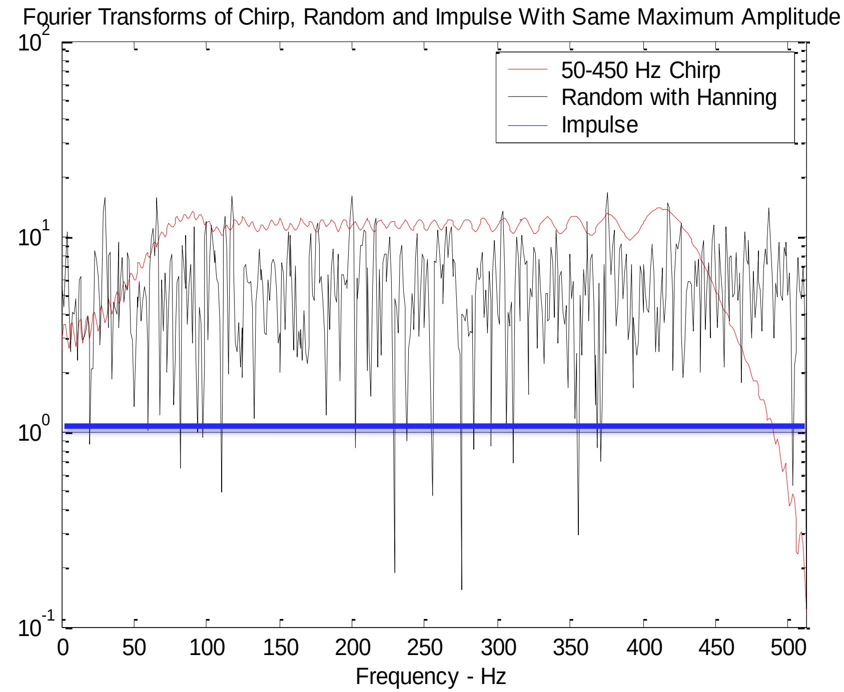
Why would one desire a shaker modal test instead of an impact test?

- Characteristics of a modal test article that will be better served with shaker testing than impact testing
  - The structure is massive with respect to the shaker force gage
  - The structure is slightly nonlinear and you desire the best linear estimate of the modal parameters
  - The channel count is large (so there is a significant amount of setup time) and number of references is at least three
  - The frequency band can be easily covered by a shaker (roughly 1000 Hz)
  - No standard modal test is funded, but a driven base shaker test (think vibe lab) is being performed and model validation modal data (fixed base modal parameters) are desired from the driven base shaker test

General advantages of a shaker modal test over an impact test

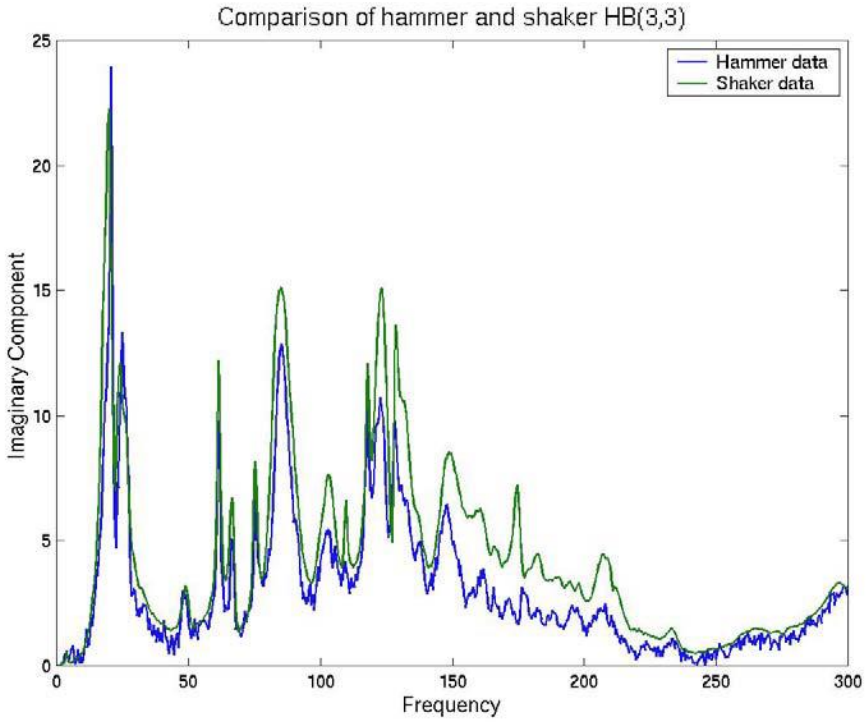
1. Better signal/noise ratio
   - See the figure for comparison of 3 force signals of same maximum amplitude and resulting impact on signal/noise ratio – Random and Chirp give 5 to 10 times better S/N ratio





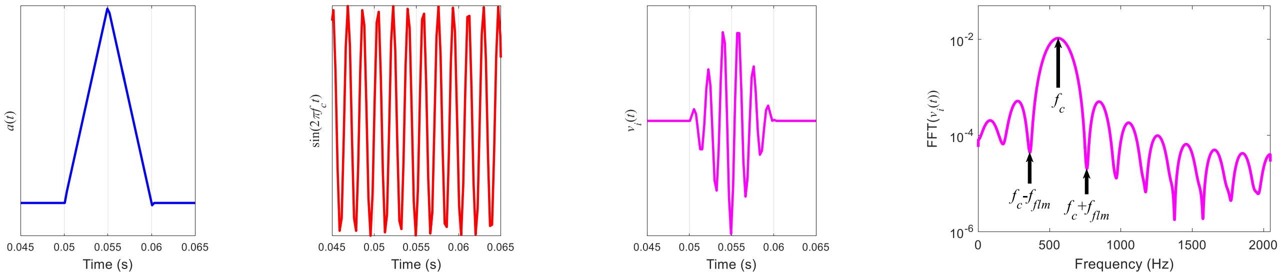
General advantages of a shaker modal test over an impact test

2. Nonlinear response can be minimized for modal extractions
   - Minimizing the maximum force as shown in the previous slide generally (not always) reduced nonlinear response. See FRF from hammer vs shaker for automobile structure below. More linear response usually means better, faster fitting of modal parameters
   - FRFs gathered from random data provide the best linear estimate of the response for modal parameter fitting (per Bendat and Piersol)[2]



General advantages of a shaker modal test over an impact test

3. Controlling the frequency spectrum of the force
   - For a modal test, one usually does not need or want much frequency content below the first elastic modal frequency. Rigid body motion is not usually desired.
   - Frequency content above the max frequency can also be harmful (aliased frequencies excited, nuisance overloads, unrecognized overloads that are filtered out by digital anti-aliasing filter).
     - Filtering the input signals eliminates these hassles/errors. At a minimum, one would like to open the bandwidth to see what the frequency content is.
     - IDEAS DAQ program is not very robust here, putting in flat signal all the way to the Nyquist.
     - Use bandpass options
     - Use external filters – High pass or band pass
     - User defined signals like Matlab Chirp
   - For nonlinear modal identifications one can define arbitrary signals[1] to excite only the modal frequency region of interest (Impact excites all modes and can overload accels)



General advantages of a shaker modal test over an impact test

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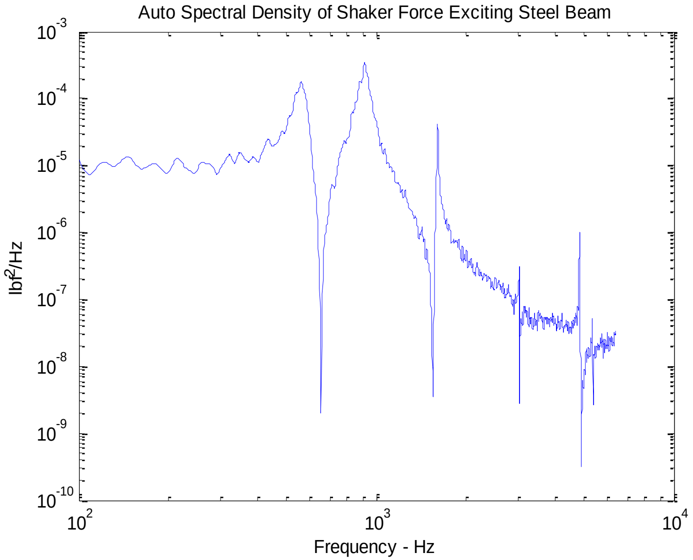
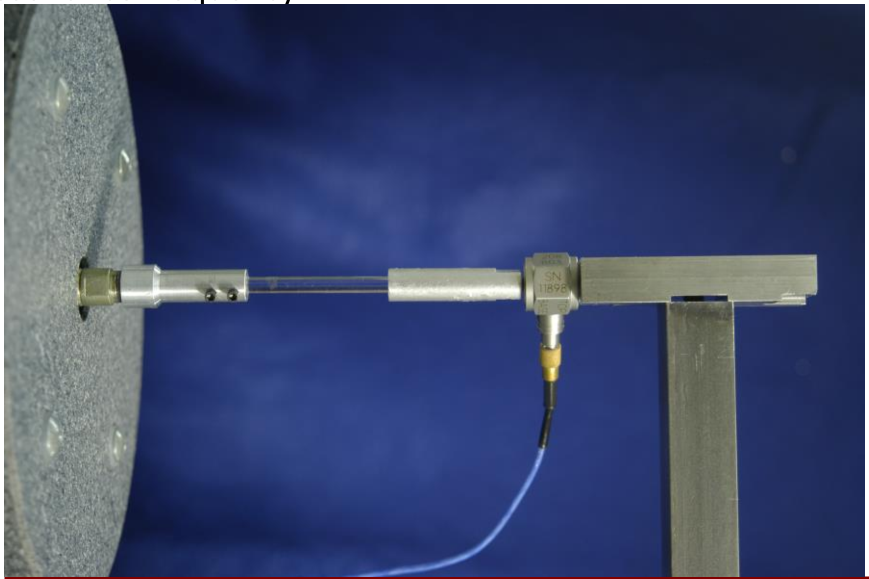
4. Consistent data set from multi-input test data gathered simultaneously
   - Gathering from one reference at a time may allow frequency shifts due to temperature changes, nonlinearities that change with time, boundary conditions that change with time. This is a disadvantage of the laser system with its roving sensor so gather data as quick as possible.
   - Even if one has a poor setup (e.g. boundary conditions that are too stiff for a "free" modal test) the data will be consistent and analyzable
   - Most consistent data usually come with all sensors gathered simultaneously (not roving or switching) and all forces (set at identical levels) gathered simultaneously
5. Time required for multiple input testing is reduced, especially if one has to take the data more than once, which is usually the case since we often cannot set every parameter optimally before we take the data.
6. Force input direction and location are more accurately controlled than with impact testing, which is of great importance for experimental modeling where one needs a very accurate drive point mode shape estimate.

Advantages/Disadvantages of different modal shaker input signals

1. Random input
   1. Advantages
      1. Gives most linearized modal model
   2. Disadvantages
      1. Takes more averages (longer time)
      2. Hann window (colloquial Hanning) distorts FRF (damping estimate) for lower frequencies – the distortion is somewhat correlated to the coherence drop at resonance
      3. Force dropouts especially for lightly damped modes
      4. Some of our smaller shakers put most of their force into the armature resonance frequency, so only use them “below” the armature resonance frequency





Advantages/Disadvantages of different modal shaker input signals

2. Stepped Sine Input
    1. Advantages
        1. Accurate amplitude (and damping)
        2. Can run at various levels and trace out jump phenomenon and hardening or softening springs for nonlinear testing
    2. Disadvantages
        1. Takes an order of magnitude more time than random test
        2. Can only use one reference at a time
        3. Not easy to control – i.e. the dynamic range as one passes through resonances and antiresonances is quite large

Advantages/Disadvantages of different modal shaker input signals

3. Chirp (Fast sine sweep) and Pseudorandom (sum of sine waves at every frequency line w/random phase)
    1. Advantages
        1. Can tailor frequency content
        2. Fast – 5 averages
        3. Note pseudorandom contains every frequency line in every average and is periodic in time window so requires no windowing
        4. Chirp requires no windowing if signal dies out before end of time block
    2. Disadvantages
        1. Nonlinearity is not averaged out as with true random
        2. Can only use one shaker at a time if input signals are highly correlated
4. Burst Random
    1. Advantages
        1. Good for damping estimate
        2. Almost as good at getting “best linear estimate” as pure random
        3. Can use multiple shakers since input signals are uncorrelated
    2. Disadvantages
        1. Needs multiple averages like pure random testing
        2. Signal to noise ratio decreases for whatever time the shaker is turned off in the time window

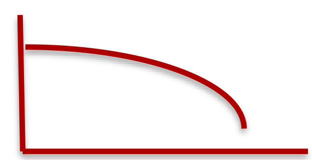
Shaker setup and fixturing

- Fixed shaker or free?
  - The goal is to produce the best alignment possible of shaker with force gage
  - If the test article is fixed, the shaker can be free
  - If the test article is free, the shaker should be fixed
- For free modal tests, a rule of thumb for frequency is :the rigid body modal frequencies due to shaker attachment and bungee supports should be less than 0.1 * first elastic frequency[3] $\omega_{true}^2 = \omega_{measured}^2 - \omega_{rigid\ body\ modes}^2$
- For free test articles, the damping is more sensitive to the rigid body mode damping[3]

$$\zeta_{true} = \zeta_{measured} \frac{\omega_{measured}}{\omega_{true}} \left(1 - \frac{\omega_{rigid\ body\ modes}\zeta_{rigid\ body\ modes}}{\omega_{measured}\zeta_{measured}}\right)$$

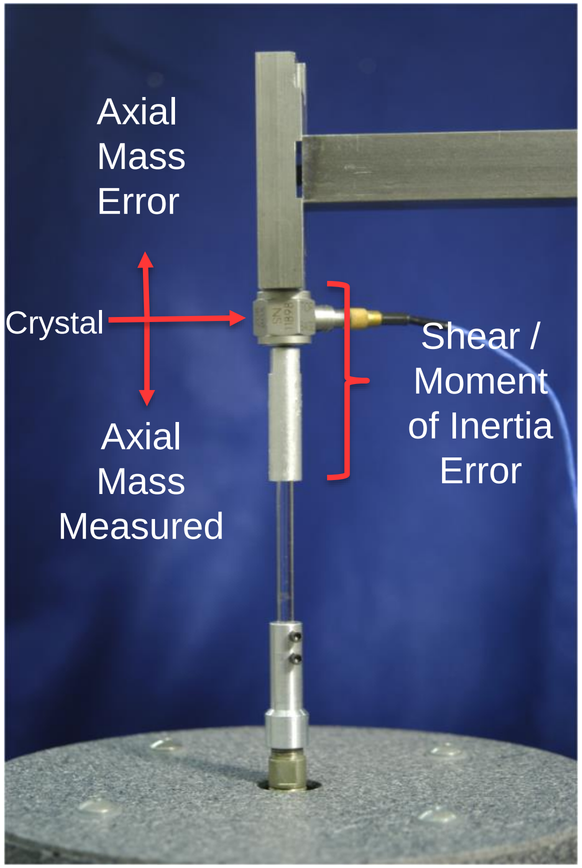
  As an example, suppose the first elastic mode is measured at 100 Hz with 1 % damping. If the bungee cord rigid body mode is 10 Hz with 5% damping, then the true damping would be 0.5 percent (50 percent of what was measured)
- A telltale indication that the force gage is not fully bonded is a Normal Mode Indicator Function that decreases with frequency

NMIF



Shaker force gage advantages / disadvantages

- Shaker force gage advantages
  - Fixtures make the drive point FRF much more likely to be co-linear for experimental model mode shape accuracy compared to impact which may have some angular offsets and a less than co-linear drive point.
  - Sandia fixtures enhance aligned force and drive point accelerometer, but you can still defeat it if you try hard enough.
  - Using as long a stinger as possible minimizes unmeasured lateral/moment loading.
- Shaker force gage disadvantages
  - Fixturing on test article side of force gage adds mass to structure
    - Force measurement accounts for mass on shaker side of crystal for input direction, but not on the test article side.
    - Shear mass and moment mass are NOT accounted for by measurement.
    - For small test articles, these effects can be significant – In the picture, the mass moment of inertia of the short bar is doubled by the mass of the force gage.



Good Shaker Hardware Can Aid Drive Point Alignment/Protect Shaker and Test Article

- Alignment Aids and Protection
  - PCB impedance heads 288C01 and D01 lose fidelity past 500 Hz
  - Modal lab current practice is to use an aluminum cap over the drive point accelerometer
  - PCB collet has been replaced with shaker receivers which allow the stinger to be easily guided into the test article receiver to assure good alignment
  - With well prepared dental cement cap mounts, the stinger setscrews become the weak link and protect both shaker and test hardware
  - 2 set screws gives a static slip force of about 130 pounds
  - 3 set screws gives a static slip force of about 250 pounds
  - Dynamic force slip may occur at about 0.75 times static
  - Set screw torque for #3 screw at 6 in-lbf will not strip threads in our stinger receivers

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Stinger lateral mode resonances

- Stinger lateral mode resonances will pollute FRF data so one should guard against those. In low level tests they may only pollute the local frequency band, but in high level nonlinear testing they ruin the data completely. Above the first lateral stinger mode there will be other lateral dynamics of the shaker introduced that are difficult to predict. For 0.060 inch diameter piano wire, the first lateral mode for a 2 inch long stinger is slightly above 1100 Hz neglecting compressive loading.
- Lateral resonance of the stinger can be approximated with Blevins[7] eqn 8-20 $f = \frac{\pi}{2L^2}(1+\frac{PL^2}{EI\pi^2})^{1/2}(\frac{EI}{m})^{1/2}$
- Another approach to "check" for stinger modes is to just change the stinger length appreciably and overlay the drive point FRFs from two different length stinger runs and see what is different. It can also be compared against a driving point impact FRF to identify stinger modes.

Fixed Base Modal Analysis from Driven Base Test

- Fixed base modes can be estimated from a low level modal test which measures the force from our 250 pound shaker driving the slip table. A sufficient number of accelerometers must be attached to the slip table to constrain out its rigid and elastic modes as given in [5]. $\psi^{+}\Phi_{b}L\{\eta\}=\{0\}$ where ψ are the characteristic mode shapes of the base and Φ_{b} are the mode shapes from the modal test at base DoF.
- One can also make an estimate from transmissibilities calculated to an accelerometer on the end of the slip table (away from the shaker input). These are only good below the first elastic mode of the table. The form of the imaginary portion of the transmissibilities is the same as standard FRFs so one can use the real modes option in SMAC[4] and calculate modal frequency, damping, mode shape. Carne derived this method in [6]. $H(\omega)_{fixed\_base} = T(\omega) - \delta$

where T is transmissibility and δ is 1 in direction of base shake and 0 for orthogonal directions.

References

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- [2] Bendat, Julius S., and Piersol, Alan G., *Engineering Applications of Correlation and Spectral Analysis,* John Wiley and Sons, Inc., Chapter 5, pp.106, 1980
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- [7] Blevins, Robert D., *Formulas for Natural Frequency and Mode Shape,* Robert E. Krieger Publishing Company, pp.144, 1984
- [8] Mayes, Randy L., Gomez, Anthony J., “What’s Shakin’, Dude? Effective Use of Modal Shakers”, *Proceedings of the 33rd International Modal Analysis Conference*, pp. 219-227,, February 2005