Damping of The Room LF Acoustics

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Outline: LF Room Acoustics

- Rooms excessively amplify sound at certain frequencies
  - Dictated by room size and geometry
    - Standing waves (acoustic resonances/modes)
      - Waves whose oscillation is continuously reinforced by their own reflections
    - Rooms have many resonances
      - The LF resonances are
        - » discrete
        - » distinct
      - Typically, the first resonant mode accommodates most of the acoustic energy build up in the room
      - In a typical listening room the resonant frequencies of standing waves fall in the bass frequency region

Outline: Solutions

- Dissipative remedies, using sound absorbing material, are ineffective at low frequencies
- Reactive devices (bass traps) are commonly used for absorbing LF acoustic energy
  - Different passive and active bass trapping techniques will be talked about
    - Their advantages/disadvantages discussed
- Damping measurement/quantification
  - Different techniques for low and high frequencies
- The tutorial will conclude by comparing/contrasting damping with equalizing

Wave Propagation

- Acoustic waves
  - Pressure (and particle velocity) distribution that propagates through any medium
    - Particles moving back and forth creating regions of compression and refraction
    - Produces the sensation of sound
    - 3-dimensional wave motion
      - Spherical
        - » Planar
    - Spatial and time dependant
      - Wave equation:
        - » In Cartesian coordinates

$$\frac{\partial^2 p}{\partial t^2} = c^2 \nabla^2 p$$

$$\frac{\partial^2 p}{\partial t^2} = c^2 \left(\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} \right)$$

Standing Waves

- With no obstacle/boundaries impeding the propagation of acoustic waves, they moves in one direction only
  - Free field propagation
- In presence of boundaries, i.e., impedance change, a percentage of the wave energy gets reflected back
  - Percentage: between 0 to 100%
    - Depending on how much absorption occurs at the boundary
  - Common in enclosed spaces
- At certain discrete frequencies, the reflected wave overlaps the original wave, exactly, creating a standing wave/acoustic resonance
  - Occurs at all frequencies, **low**, mid and high
  - The wavelength of the standing waves between two parallel walls
    - λ_1=2L, λ_2=L, λ_3=.66L, ….
    - f= c/λ

Mode Shapes and Frequencies

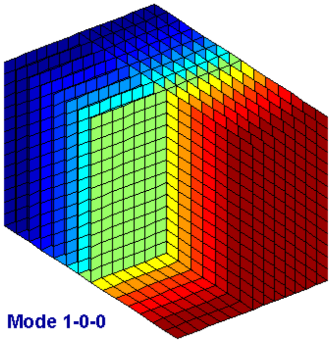
- For a rectangular shoe-box room, with rigid walls the natural frequencies and the shape of the modes can readily be evaluated
  - Excel, Matlab,…

$$freq = \frac{c}{2}\left[\left(\frac{n_x}{l_x}\right)^2 + \left(\frac{n_y}{l_y}\right)^2 + \left(\frac{n_z}{l_z}\right)^2\right]^{\frac{1}{2}}$$

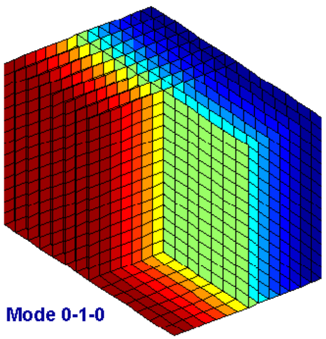
$$shapes = (\cos k_x x)(\cos k_y y)(\cos k_z z)$$

$$k_x = \frac{n_x \pi}{l_x},\quad k_y = \frac{n_y \pi}{l_y},\quad k_z = \frac{n_z \pi}{l_z}$$

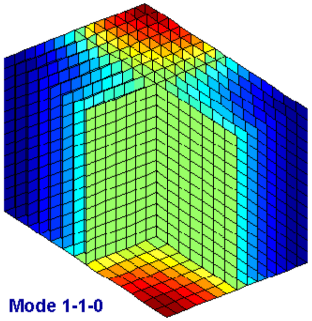
$$where\;\; n_x, n_y, n_z = 0,1,2,\ldots$$



Mode 1-0-0

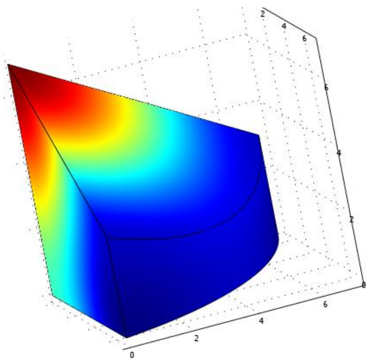


Mode 0-1-0



Mode 1-1-0

- For more irregular rooms numerical tools are used to find the frequencies and mode shapes



Finite Element Analysis

- FEA tools can be used in analyzing the modal response of a room with
  - Any geometry
  - Any boundary condition
  - Any obstacle/equipment in the room
- Prior to having the room built
  - Such analyses will aid in
    - Proper dimensioning of the room
    - Placement of LF acoustic treatments
    - Placement of audio equipment

Analysis Steps

– Model the space geometry

– Mesh the model

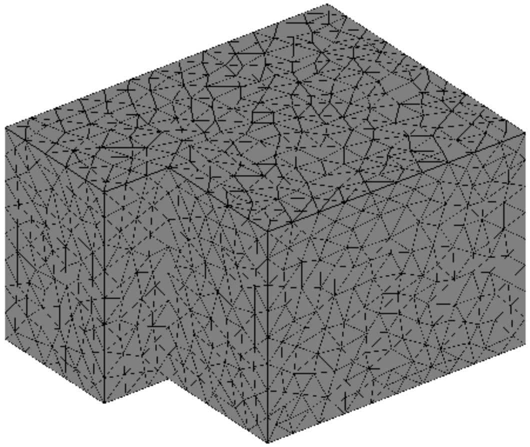
  - Discretize it to many small pieces (finite elements)

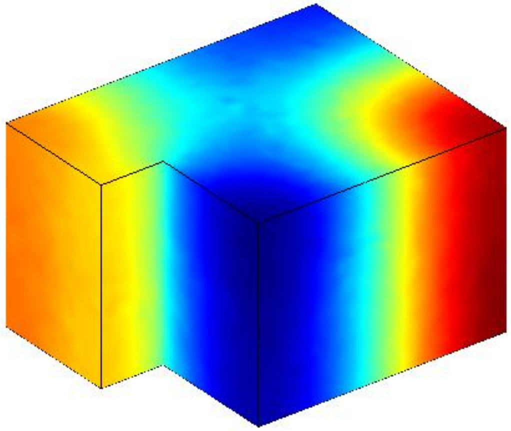
– Apply boundary conditions

– Solve

  - Modal analysis
  - Frequency response analysis

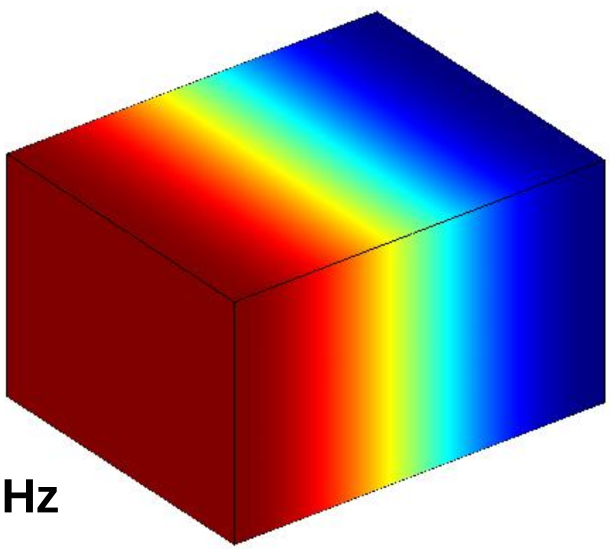
– Post-process the results



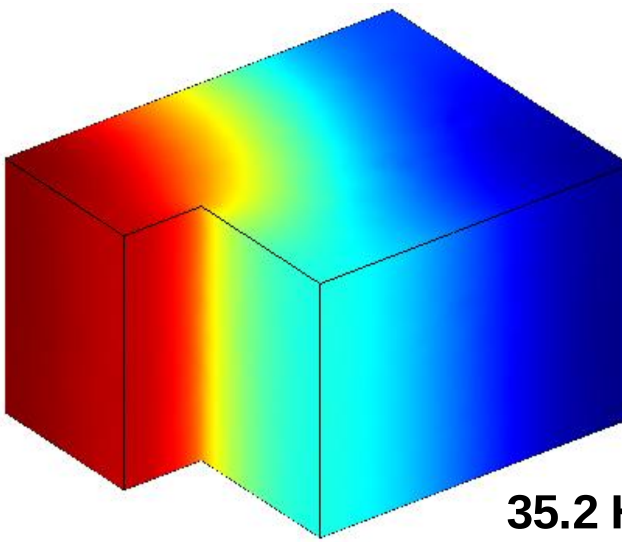


Irregular Rooms

- Irregularities in a room change the shapes and frequencies of the standing waves/modes



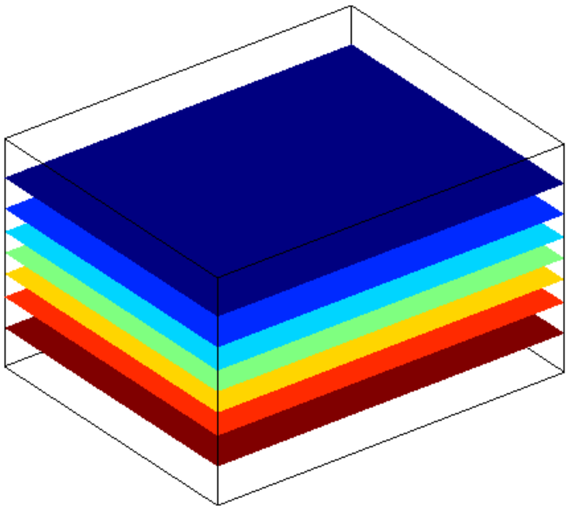
34 Hz

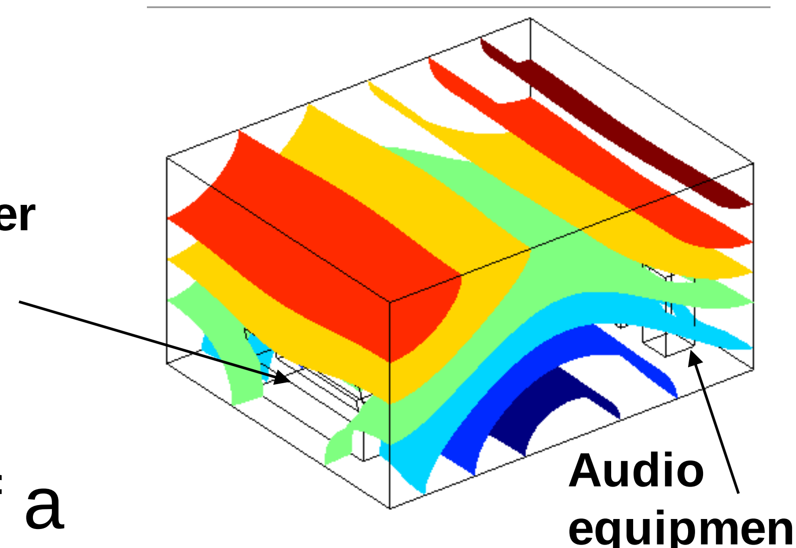


35.2 Hz

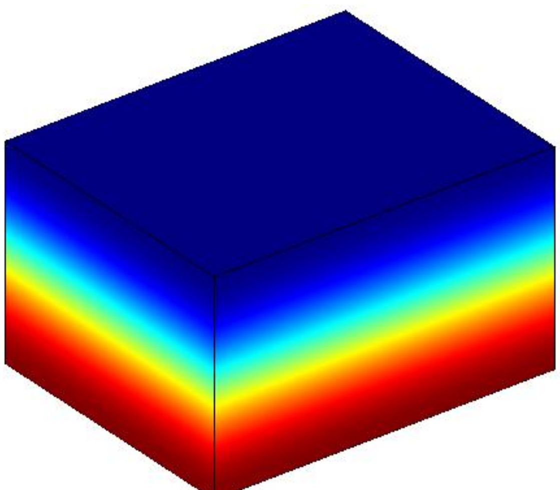
Mode 1

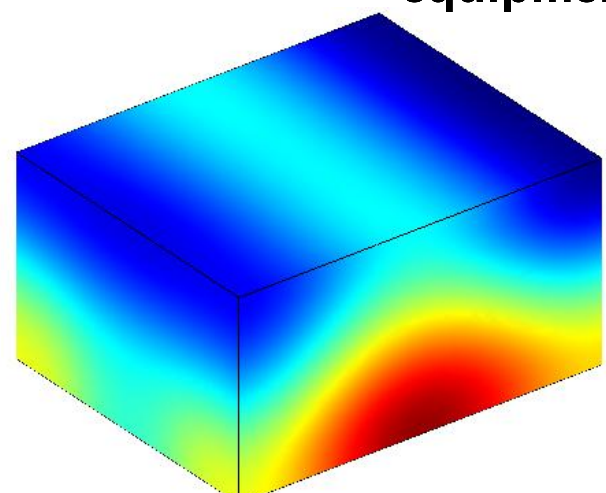
Obstacles/Equipment in a Room





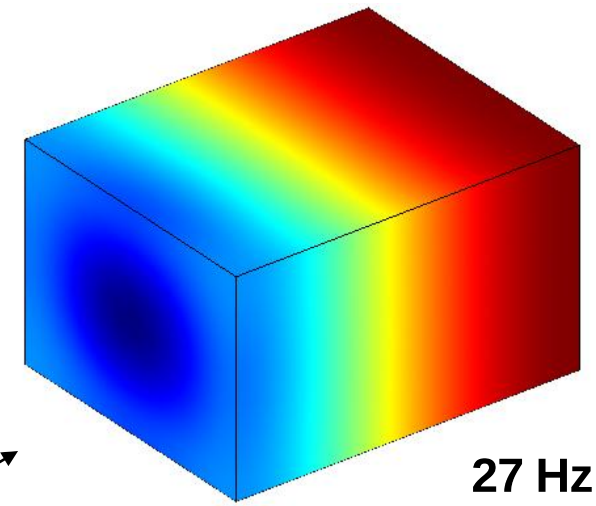
Mode 4 of a room without and with furniture/ equipment

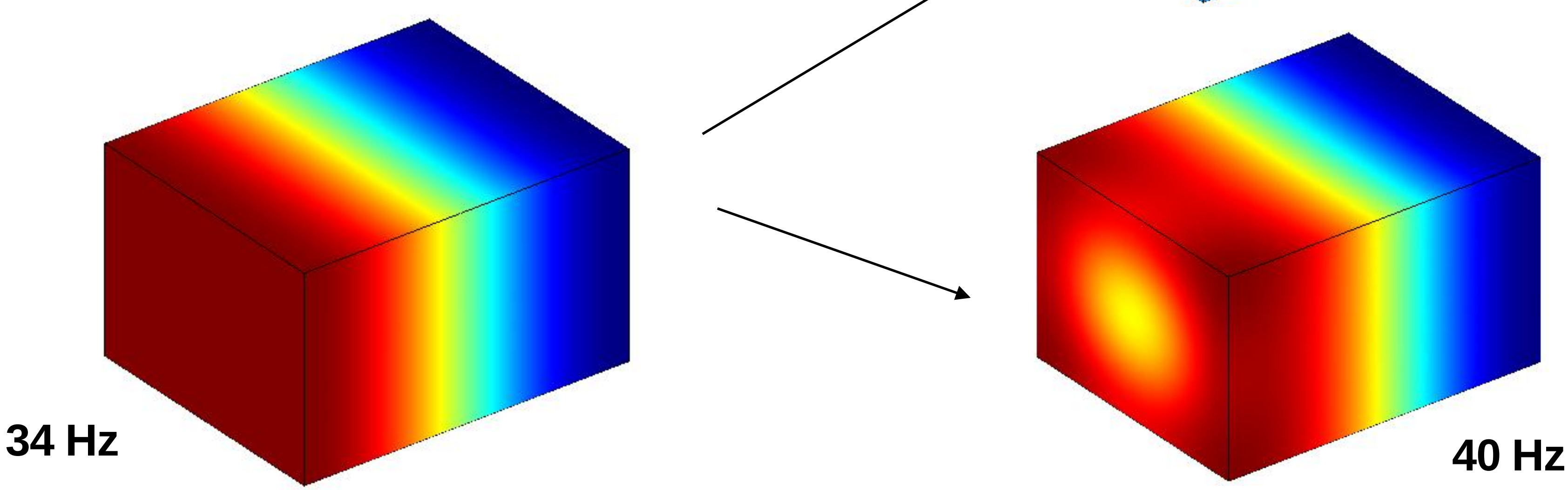




Resonating Walls

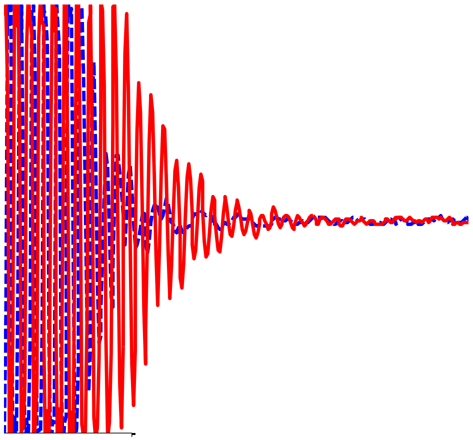
- A resonating wall can affect the modal character of the room
  - With no damping built into the resonating wall, it can split an acoustic mode into 2 modes
    - 34 Hz mode is split into 27 and 40 Hz modes
  - Incorporating some damping into the resonating wall, turns the wall into a tuned absorber
    - This is the principle behind panel absorption





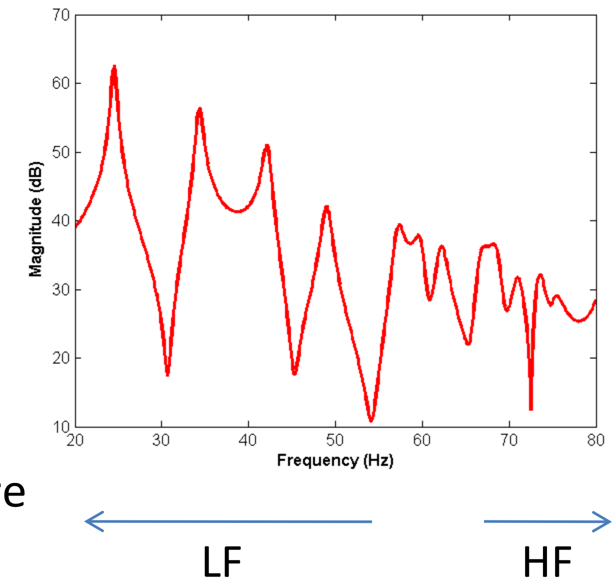
The Effects of Standing Waves

- Standing waves (acoustic modes) make a room to accommodate the excessive reverberation of sound at certain frequencies.
  - This results in the *reinforcing* and *lingering* of certain tones, long after they should have ceased
  - This is because the original oscillations of standing waves are continuously reinforced by their own reflections
  - standing waves are discrete at low frequencies
    - Lower modes normally carry most of the energy
      - The wavelength of these modes match the dimensions of smaller rooms
        - Resonant frequencies: 20 to 80 Hz
    - Lower modes alter the natural sound at these frequencies dramatically making the sound *boomy* and tonal



Frequency Response Function (FRF)

- Most commonly used tool in identifying room modes
  - **Definition:** output/input over various frequencies in any linear system is called frequency response function
    - – Also called transfer function by practitior
    - – Measured at steady state
      - A complex quantity
        - – Magnitude
        - – Phase
    - – In acoustics
      - Output: pressure or particle velocity
        - – Measured by a microphone or hot wire
      - Input: rate of change of volume velocity
        - – Normally created by a loudspeaker
    - – Commonly used in low-frequency acoustics
      - Peaks in FRF indicate resonances



FRF Evaluation Techniques

- Analytical
  - Used when an analytical model (partial differential equation) for the system is available
- Numerical
  - Used when a numerical (e.g., finite element) model for the system is available
- Experimental
  - Most commonly used technique
    - Requires the measurement of the output and input
      - Fast Fourier Transform (FFT) algorithm is used in evaluation of experimental FRFs

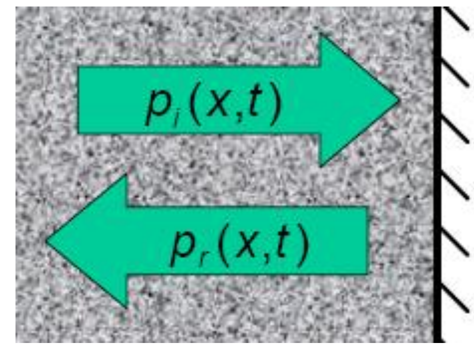
$$\mathrm{FRF}(\omega) = \frac{\mathrm{FFT}(O)}{\mathrm{FFT}(I)}$$

$$\mathrm{FRF}(\omega) = \frac{P_{oi}(O, I)}{P_{ii}(I)}$$

Dealing with LF Resonance

- Note that resonance is caused by reflection of a wave upon itself

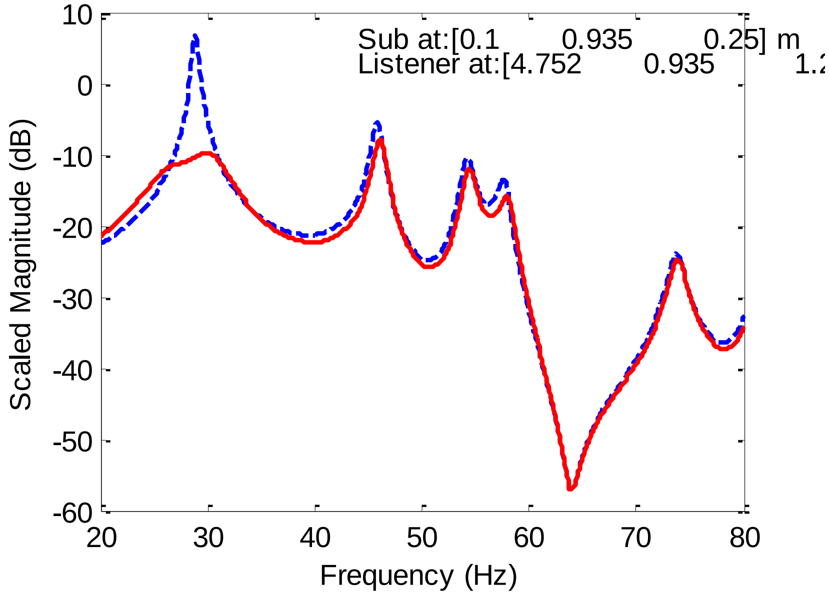
  $P_i + P_r = P_i + R * P_i$, where R is the reflection coefficient



- R=0 eliminates the resonance
  - Walls need to be removed!
    - This is why resonance exists in enclosed, not open, spaces
- Next best solution is making R small
  - Reflection=1-|Absorption|^2
    - Increasing absorption abates the resonance
      - Dissipating acoustic energy
        - » **Acoustic damping**

Frequency Response and Damping

- Peaks in a frequency response is an indication of acoustic resonances (standing waves)
  - The sharpness of a peak indicates lack of damping in that standing wave (mode)
  - Normally the first mode is the one in need of most damping
    - Absorbing the energy of the first mode lowers the boominess and lingering of sound associated with that mode
      - Addition of damping to that mode is exhibited by flattening it in the frequency response

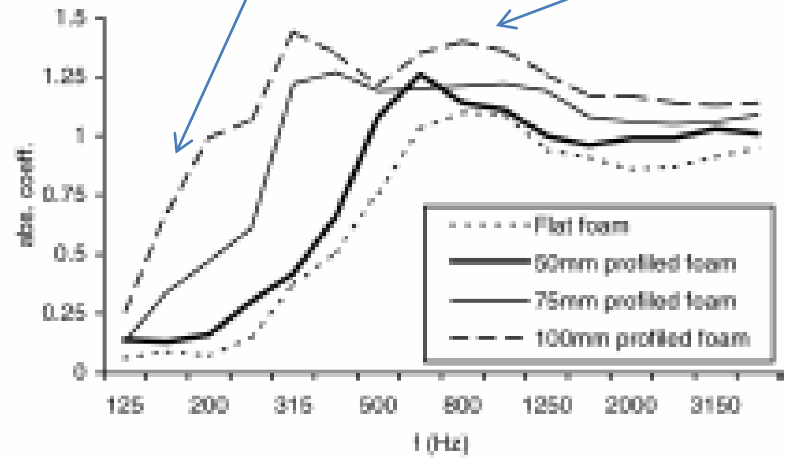


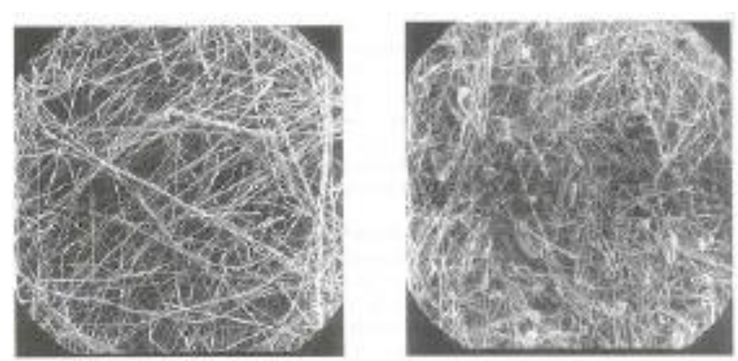
Sound Absorption/Damping

- Acoustic energy
  - Kinetic energy, KE
    - Particle velocity
  - Potential energy, PE
    - Acoustic pressure
  - Total Energy
    - KE+PE
      - Where one is maximum the other one is zero
  - Sound absorbing material absorb KE energy
    - Their fibrous nature entangles the sound, dissipating its KE
      - To be effective they need to be placed in the region of high particle velocity
    - Edge effect also contributes to absorption

low at low frequencies

$\alpha>1$





Sound Absorbing Material Effectiveness

- Facts:
  - Acoustic modes have zero velocity at the walls
    - Their velocity is maximum ¼ wavelength away from the walls

Middle of the room for the first mode

  - Sound absorbing material, the main element n dissipative absorbers, are normally installed on the walls
    - To have space left in the room, the thickness of sound absorbing material should be reasonable
- Although very effective at high frequencies, dissipative absorbers are not good dampening the LF standing waves of a room

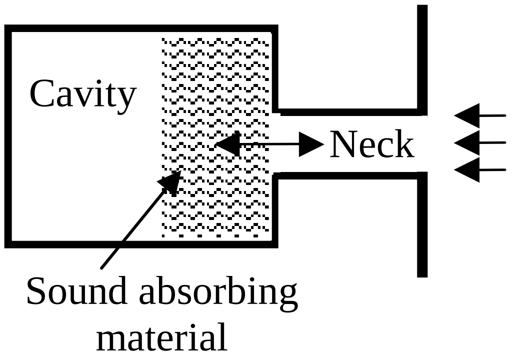
Note that the wavelength of a 25 Hz resonance is around 50 ft

Reactive Absorbers

- Absorbers of any kind are commonly placed close to or on the walls/surfaces
  - That is where velocity is zero/small but pressure is maximum/large
- Reactive absorbers are damping mechanism that
  - Convert PE energy (pressure) to KE (velocity)
  - Dissipate KE
- Commonly used reactive absorbers
  - Helmholtz resonators
  - Quarter wave tubes
  - Panel absorbers

Helmholtz Resonator

- Cavity
  - acting as spring
- Neck/throat
  - acting as mass
- Dissipation
  - Turbulence in the neck and neck to cavity transition
  - Sound absorbing material
    - Placed next to the neck in the cavity



- HR is similar to a spring mass dashpot system
  - Resonate at single frequency; a tuned device
    - Whistle caused by blowing in a bottle is a tone at this frequency

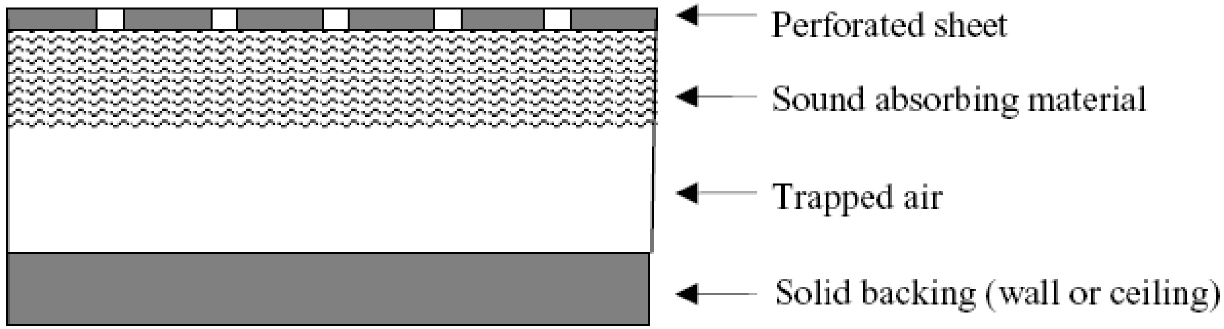
$$\omega_n = \sqrt{\frac{1}{IC}}$$

I =(air density)*(neck length)/(neck area)

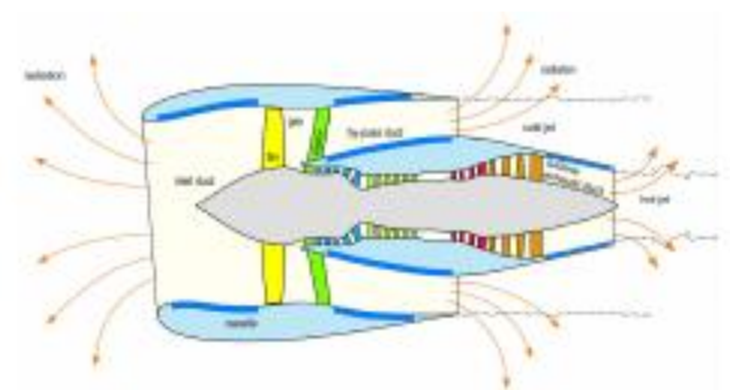
C=(cavity volume)/[(air density)(speed of sound)^2]

Cavity Backed Perforated Panels

- A number of Helmholtz resonators with individual necks and common cavity



- The backing volume acts as the cavity
- The perforations act as necks
- A tuned device
  - Similar to a Helmholtz resonator, perforated panels can be viewed as a single resonance device
    - Acceptable assumption up to a certain frequency
  - Commonly used in aircraft engines

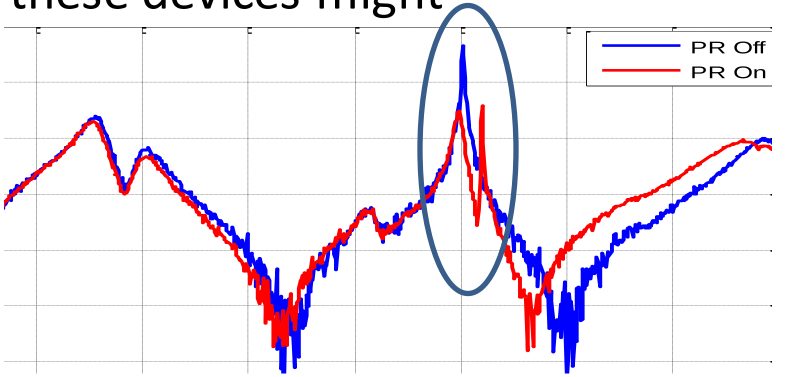


Panel Absorbers

- Panels/plates have many structural resonances
  - Sheet metal, plywood, etc.
  - Backed by a cavity, to add stiffness
    - Cavity houses sound absorbing material
- The first structural resonance of the panel is tuned to a target acoustic mode of a room
  - The acoustic pressure pulsation causes the panel to vibrate at resonance
    - The panel convert the acoustic PE into acoustic KE
      - KE is dissipated in the sound absorbing material

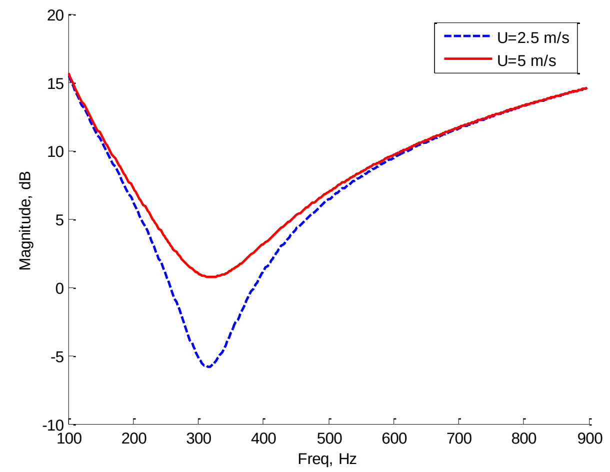
Issues with Reactive Absorbers

- The tuning of such devices is half the story
- The other half is the size of such devices
  - A tiny Helmholtz resonator and a very large one can have the same resonant frequency
    - This does not mean that they both have the same effectiveness
  - The low frequency resonance of standing waves requires large reactive devices
    - Bulky when tuned to low frequencies
  - Once designed and tuned to a room, can not be used in another room with different geometry
  - The higher order resonant frequencies of these devices might introduce undesirable effects
- Mode splitting
  - With not enough damping in the reactive absorber, the target mode gets splitted
    - Energy is not dissipated, just re-distributed



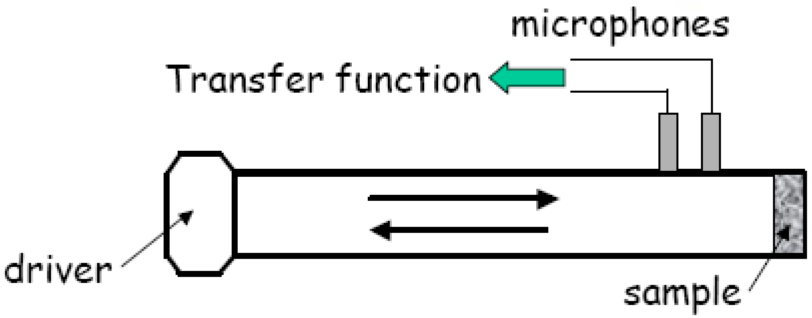
Impedance of an Absorber

- Acoustic impedance of a surface $$Z = \frac{p}{q} = \frac{p}{uA}$$
  - Specific acoustic Impedance $$z = \frac{p}{u} = ZA$$
    - Complex
    - Frequency dependant
- Semi-empirical impedance models
- Measured impedance



  - Pressure-Velocity measurem
    - PU probe
      - In-situ measurement

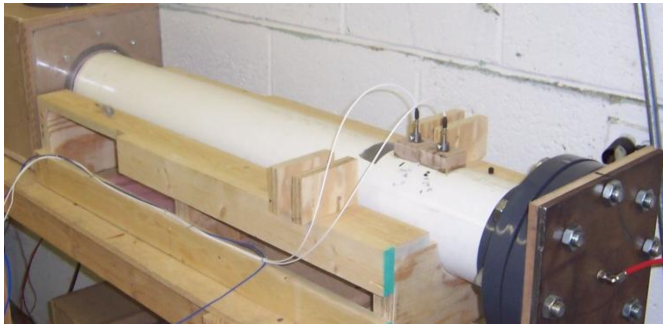
  - Pressure-Pressure measurement
    - 2 microphone technique



- Impedance can be used as the
  - Measure of sound absorption
  - Boundary condition in finite element model of the room

Absorption Measurement

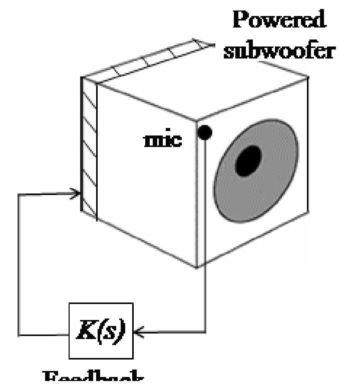
- Random incidence (reverberant field) measurement
  - Measurement is done in a reverberant room with non-parallel walls in which diffused sound field is generated
    - Standards such as ASTM C423 are used
  - Suitable for characterizing mid to high frequencies absorbers

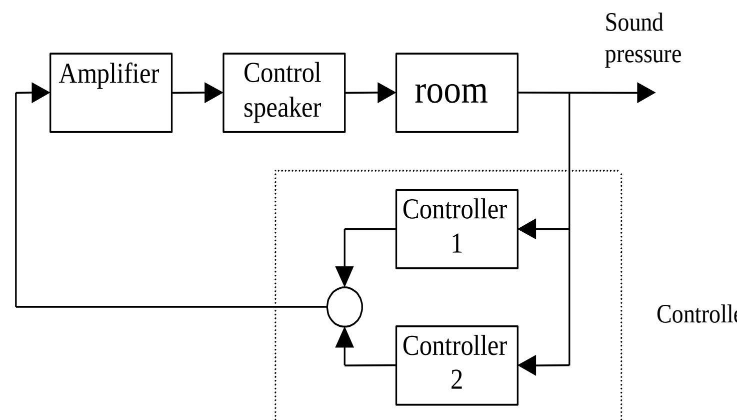


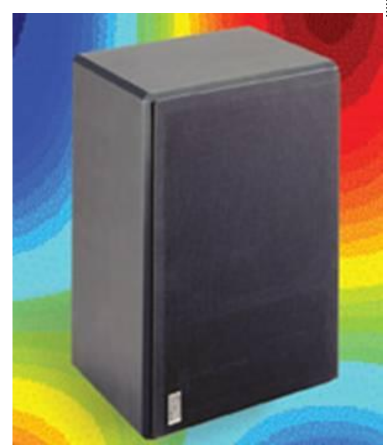
- Normal incidence measurement
  - Measured by placing the face of the absorber at one end of an impedance tube with planar, 1D wave propagation
    - Standards: ISO 10534-2, ASTM E-1050 and JIS 1405-2
      - Hardware and software for measuring the frequency-dependent absorption coefficient , reflection coefficient, and acoustic impedance
  - Suitable for characterizing low-frequency absorbers

Active Acoustic Absorbers

- Reactive tuned absorbers are commonly used to add damping to LF modes
  - Large in size
  - Not re-tunable
- Active reactive absorbers
  - A powered subwoofer radiating in response to the measured pressure
    - Nearly-collocated feedback control
    - A small microphone as sensor
    - Targets one (or two) LF mode(s)
- Size of a small, subwoofer
  - Low power demand
  - Robust, low-order, tunable and re-tunable
- Placement
  - Where it couples effectively with the target mode(s)
    - At a high pressure location of the target mode
- A true damping solution
  - Not equalization







Simulation of a Small Room

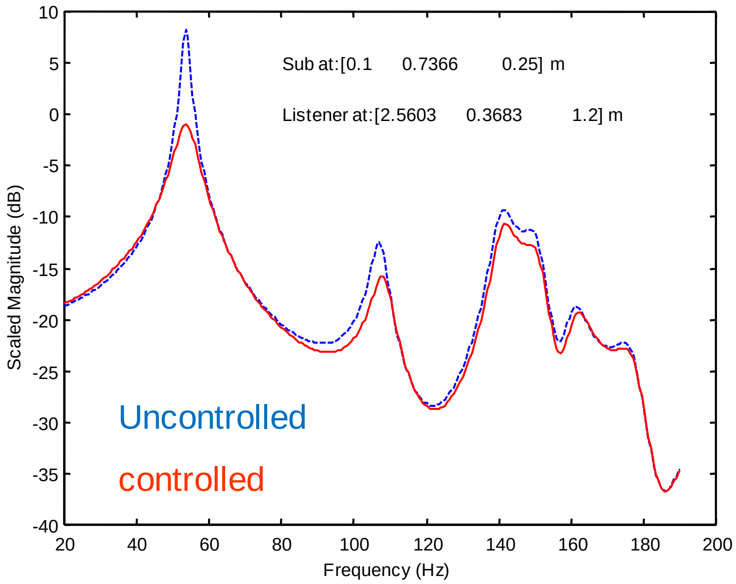
- At low frequencies the modes are discrete
  - The modal density increases with frequency

Resonant Frequencies

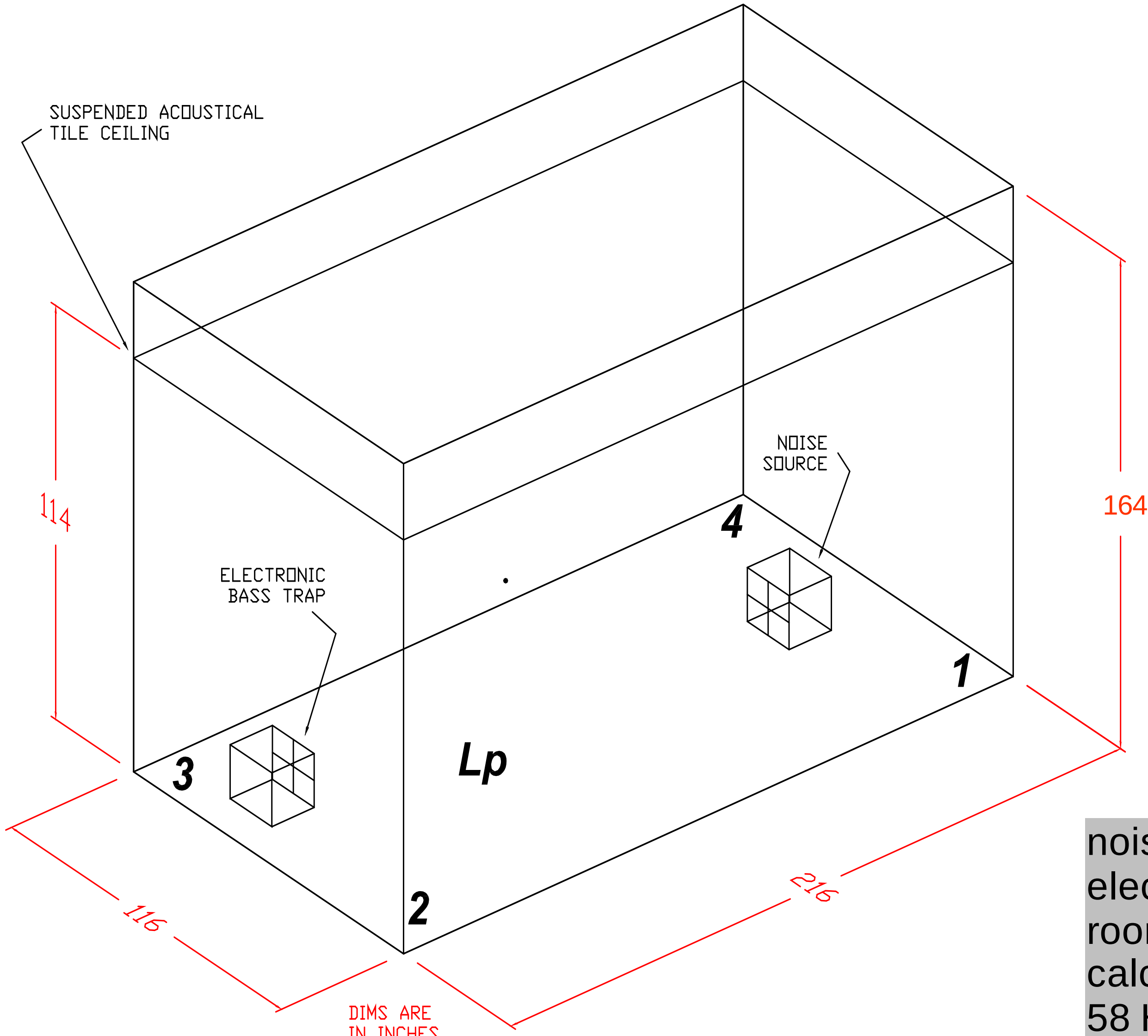
Mode index			Frequency
L	**W**	**H**	**Hz**
1	0	0	54
2	0	0	107
0	1	0	116
1	1	0	128
0	0	1	141
1	0	1	151
2	1	0	158
3	0	0	161
2	0	1	177
0	1	1	183

2 modes in 20 to 110 Hz range

8 modes in 110 to 184 Hz range



A Test Room

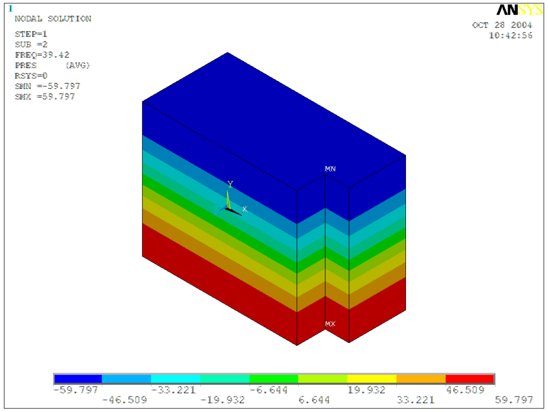


noise source at wall 1,4
electronic bass trap at wall 2,3
room dims 18 x 9.7 x 13.6 feet
calculated modes 31, 39, 50, and 58 Hz

FE Modal Analysis

Resonant
frequencies

1 31 Hz
2 39
3 50
4 58.3



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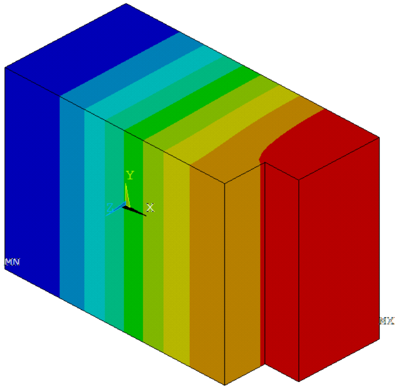

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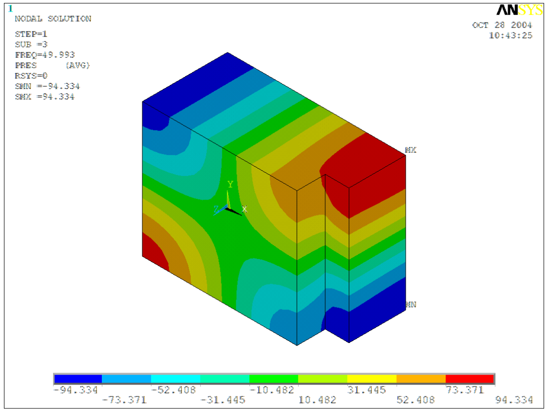

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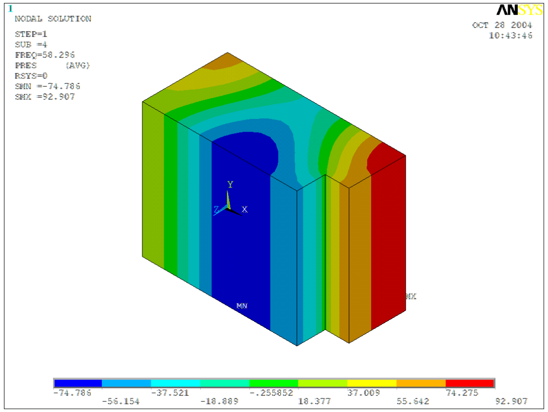
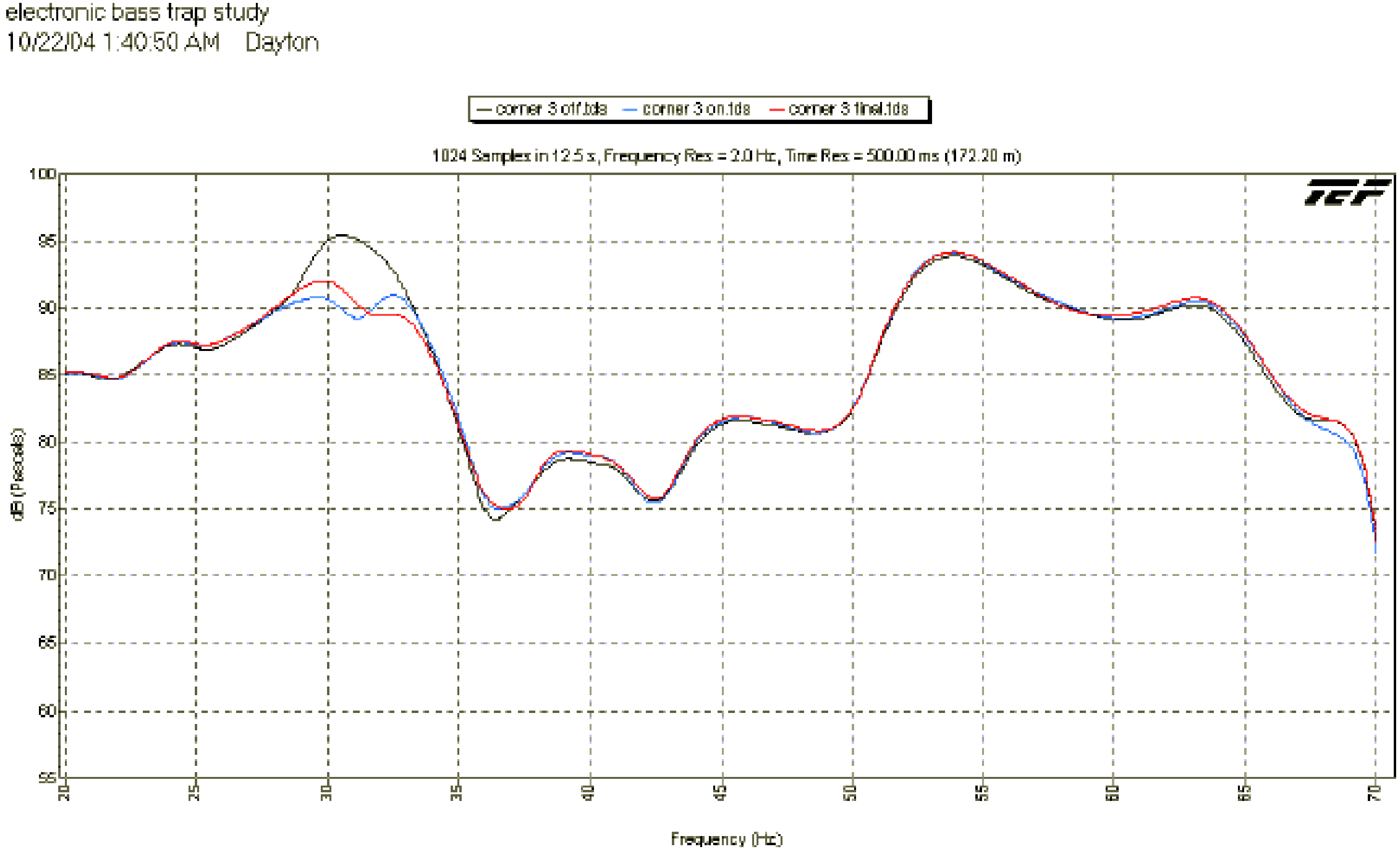


4

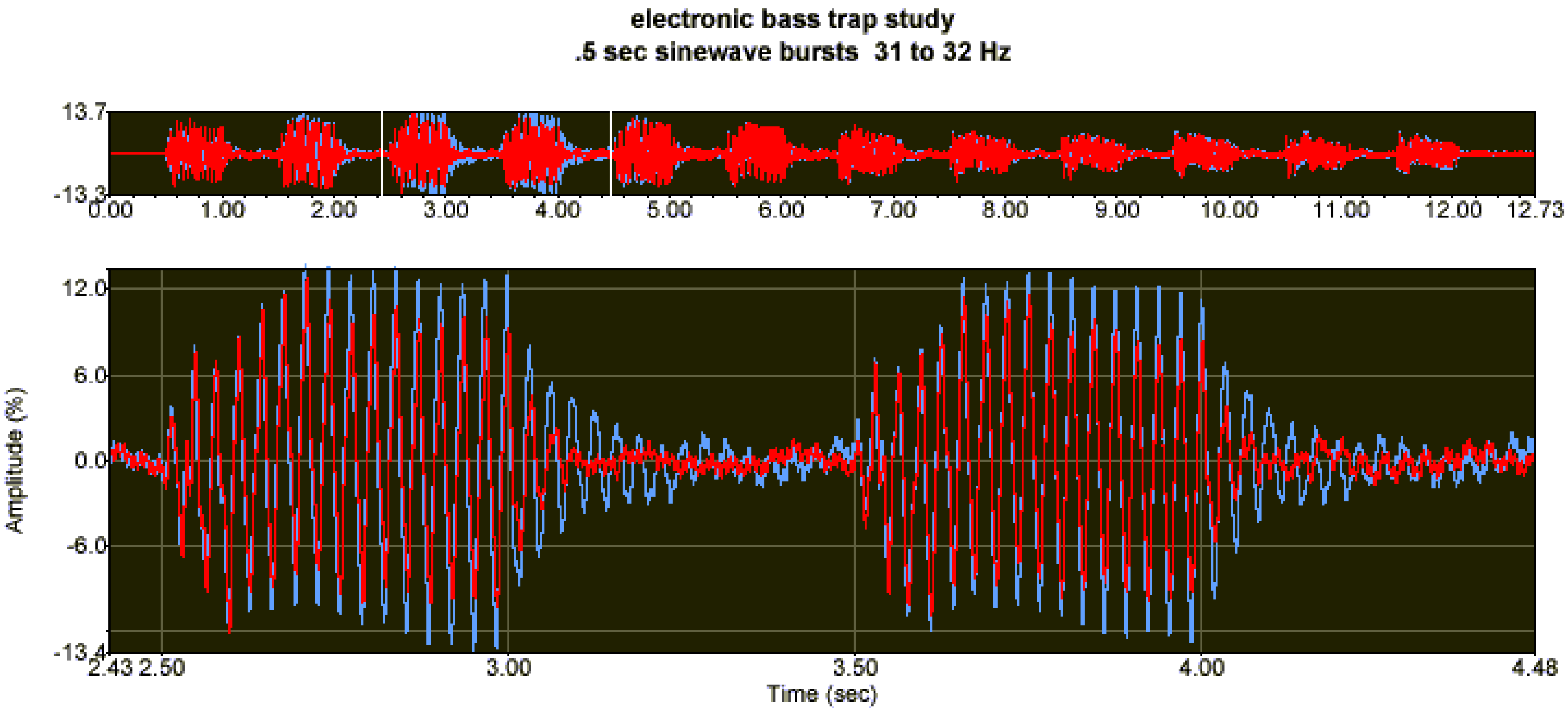
Corner 3

BLACK - CONTROLLER OFF
BLUE - CONTROLLER ON OPTIMIZED
RED - CONTROLLER ON OPTIMIZED FOR CORNER 2



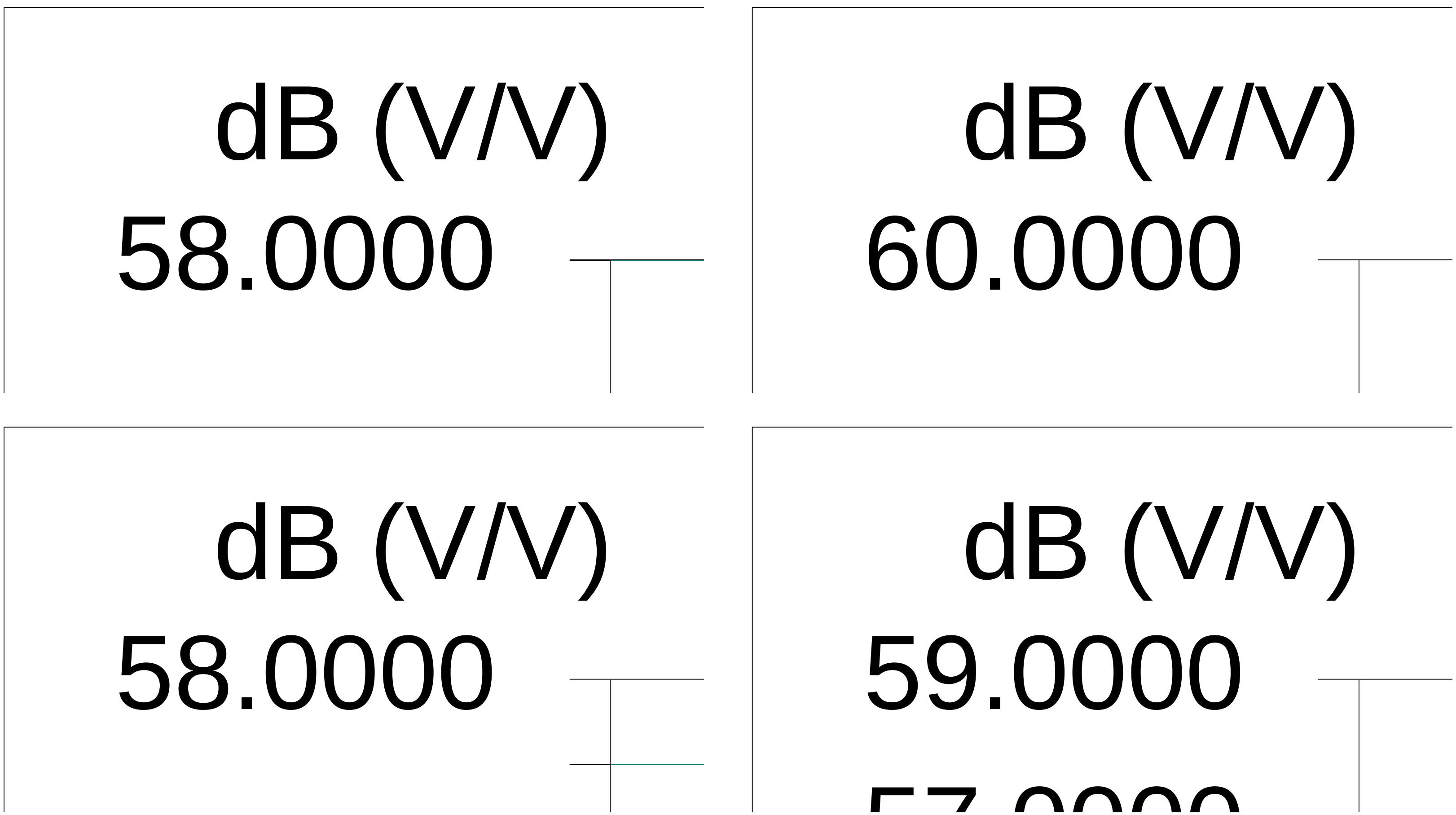
Time Domain Data

BLUE - CONTROLLER OFF
RED - CONTROLLER ON
MIC AT LISTENING POSITION



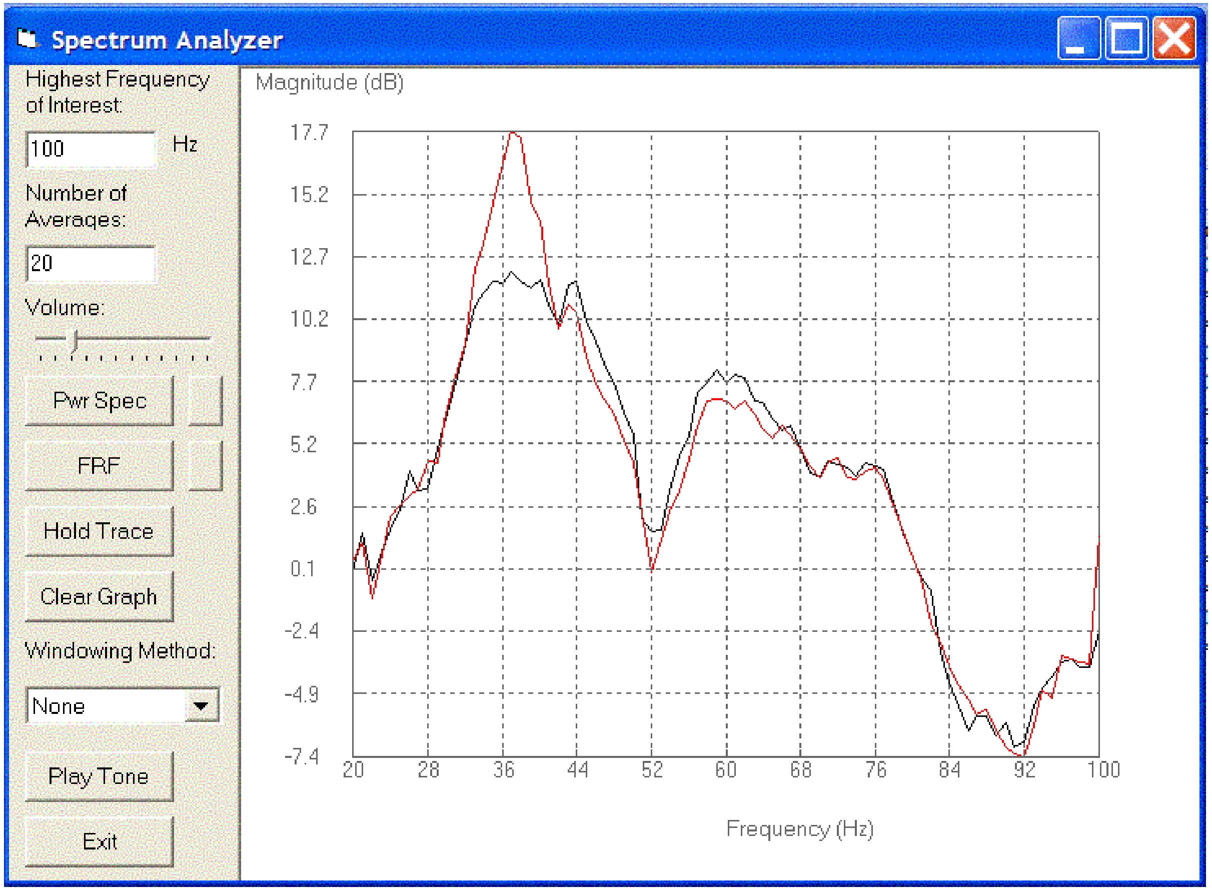
More Measurements

Blue: off Red: on



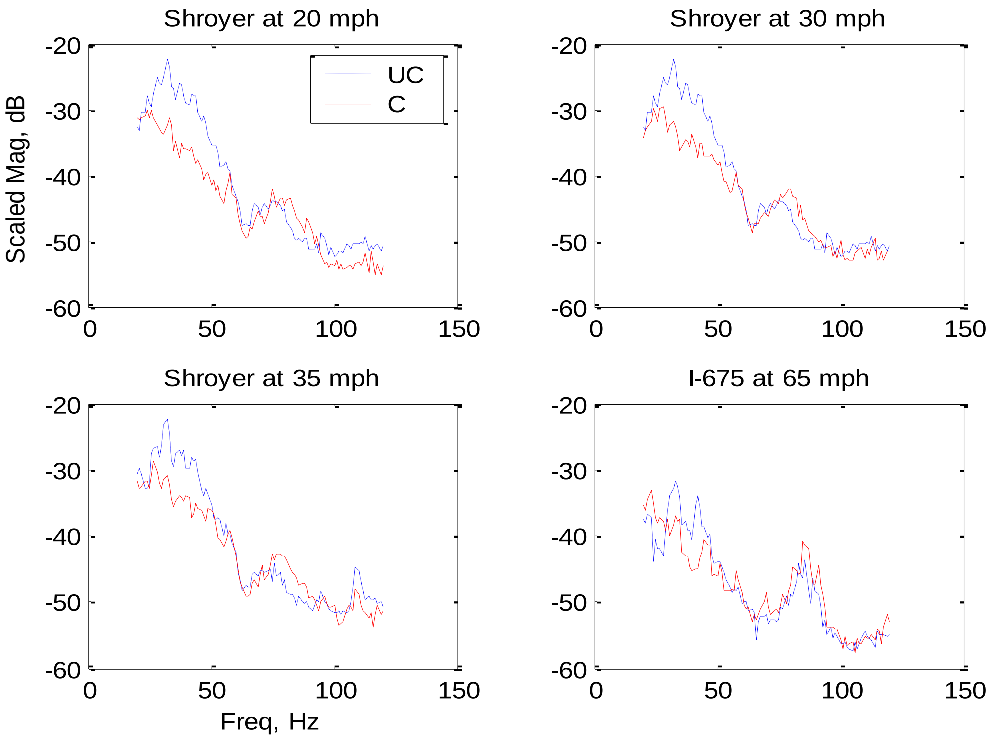
Software Tool

- Dynamic signal analysis
  - Uses the sound card
    - Plays the excitation noise thru the speaker output
    - Acquires the measured sound thru the mic input



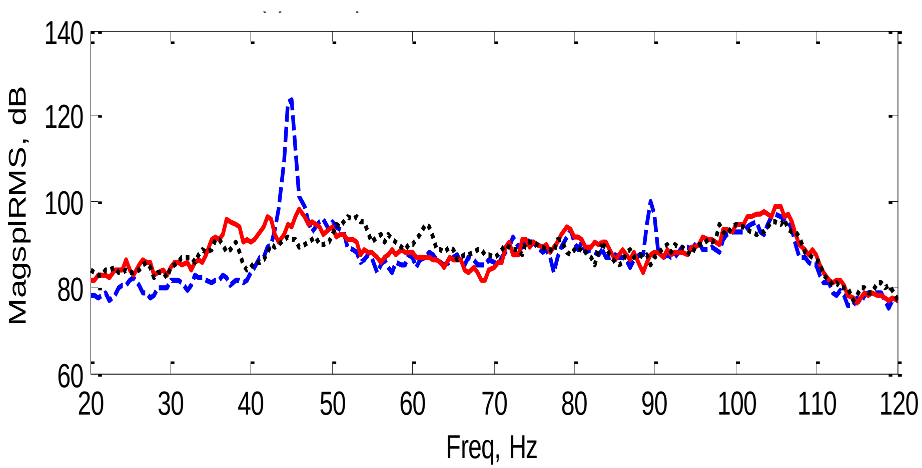
Other Applications

- Vehicular applications
  - Can be used both as a bass trap inside large vehicles (SUVs and minivans) to
    - Abate boom noise
    - Enhance the listening experience
- Passive absorbers for addressing LF modes in a vehicle would be too large



Other Applications

- Industrial application
  - Acoustic resonance in an enclosed industrial combustor



Damping vs. Equalizing

- Damping dissipates energy
  - Flattening a peak in the frequency response **is because** energy is being removed from the system at that resonance
    - Lowers ringing/lingering of sound at the target mode
  - Damping is a parameter of the system
    - Energy removal affects all the locations the same way

- EQ is a narrow-band volume control
  - Flattening a peak in the frequency response **is not because** energy is being removed from the system at that resonance
    - Does not affect the ringing/lingering of sound at the target mode
  - Not effective in room with live music

Summary

- Rooms excessively amplify sound at certain frequencies
  - Dictated by room size and geometry
    - Standing waves (acoustic resonances/modes)
      - Tonal lingering of sound
- Passive tuned acoustic damping
  - Helmholtz resonator, panel absorbers, quarter wave tube, etc.
- Active tuned acoustic damping
  - Small, and effective way of adding tuned damping to a room
    - Abates severe bass coloration
  - Tunable and re-tunable
  - Occasional and low power demand
  - One (or two) controllers can be tuned to add damping to one (or two) acoustic mode(s) of the room
    - Multiple controllers (circuits) are cascaded in parallel and share resources
  - Other applications
    - Vehicular and industrial
- Quantifying the absorption of LF dampers
  - Impedance tube measurement