

## 8. Room Acoustics

### PURPOSE AND BACKGROUND

An enclosed space has characteristic resonance frequencies for standing waves between walls and other surfaces. We already have discussed the much simpler case of resonating air columns in pipes. The acoustics of a room depends on the volume of the room, the surface area of the walls, the sound absorption properties of the materials, and persons and furniture in the room. When you sing in a shower, you will notice that certain frequencies are enhanced. This is due to resonances in the box-shaped volume of the shower. Resonances may also play an undesirable role in concert halls. These resonances may cause feedback noise if electronic sound amplification is used. In such cases the resonances can be removed from the frequency spectrum with electronic equalizers.

A study of room acoustics includes the frequency analysis and time analysis of sound. The *reverberation time* is the time it takes for the sound intensity to decay by 60 dB or a factor of  $10^6$ .

Large concert halls and churches have reverberation times of up to a few seconds. Our lecture room has a reverberation time of about 0.5 s. Sound travels with speed  $v = 346$  m/s at 25°C. A large concert hall has large distances for sound to travel and consequently a long decay time. The materials from which sound is reflected also affect the reverberation time. Sound absorbing materials such as cloth, egg crating, and acoustical boards greatly absorb sound and have a short reverberation time. Highly reflective materials such as concrete walls and tile floors reflect sound with little absorption and result in long reverberation times. The sound absorption of a material depends on frequency and hence so does the reverberation time. One can “tune” the reverberation time of a room for best acoustics by the choice of materials and their placement.

### I Room Resonances

For the simplest case of a box-like room, with all surfaces constructed of the same material, the resonant frequencies are given by the formula

$$f_{N_x N_y N_z} = \frac{v}{2} \sqrt{\left(\frac{N_x}{L_x}\right)^2 + \left(\frac{N_y}{L_y}\right)^2 + \left(\frac{N_z}{L_z}\right)^2} \quad (1)$$

where  $N_x, N_y, N_z$  are integer harmonic numbers;  $L_x, L_y, L_z$  are the dimensions of the room; and  $v$  is the speed of sound in air. For example, the lowest resonance frequency (fundamental) for the  $x$ -direction is  $f_{100} = v/2L_x$ , with  $N_x = 1$  and  $N_y = N_z = 0$ . This is the same as the fundamental frequency of a vibrating string, where the wavelength was twice the length of the string. Now the wavelength is twice the  $x$ -dimension,  $L_x$ , of the box. The  $y$  and  $z$ -directions have their resonance frequencies as well, calculated in the same way. Many higher resonance frequencies exist for the standing waves in each direction, and also when waves get reflected at an angle with respect to the walls of the box. These frequencies are obtained from equation (1) with more than one of the harmonic numbers  $N_x, N_y, N_z$  equal to 1 or larger.

Our lecture room has a complicated geometry. It is not a “box” and therefore it has a much more complex resonance spectrum than that from equation (1). The room contains furniture, equipment, and people that change the resonances. Nevertheless, we shall assume in a grand simplification that the room is box-like and calculate the lowest resonances.

Measure the length  $x$ , width  $y$ , and average height  $z$  of the music laboratory.

$$L_x = \text{_____}m \quad L_y = \text{_____}m \quad L_z = \text{_____}m$$

Question 1 Calculate the three fundamental resonance frequencies of the room from the formula

$$f = \frac{v}{2L} \quad (2)$$

where  $L$  is any of the lengths  $L_x, L_y, L_z$  and  $v = 346$  m/s at an assumed room temperature of 25°C. (Don't forget to first convert the lengths from feet to meters using 1 m = 3.28 ft.)

$$f_{100} = \text{_____}Hz \quad f_{010} = \text{_____}Hz \quad f_{001} = \text{_____}Hz$$

Question 2 Calculate the first overtones (2nd harmonics) of each of the three fundamentals by doubling the frequencies from the preceding question.

$$f_{200} = \text{_____}m \quad f_{020} = \text{_____}m \quad f_{002} = \text{_____}m$$

Question 3 Write down the range of these first six frequencies.

## II Acoustics Box

Instead of studying the lecture room in more detail, we use a cubical box or “model room” with identical dimensions  $L_x = L_y = L_z \equiv L$ . See Figure 1 for a similar but non-cubical box. The

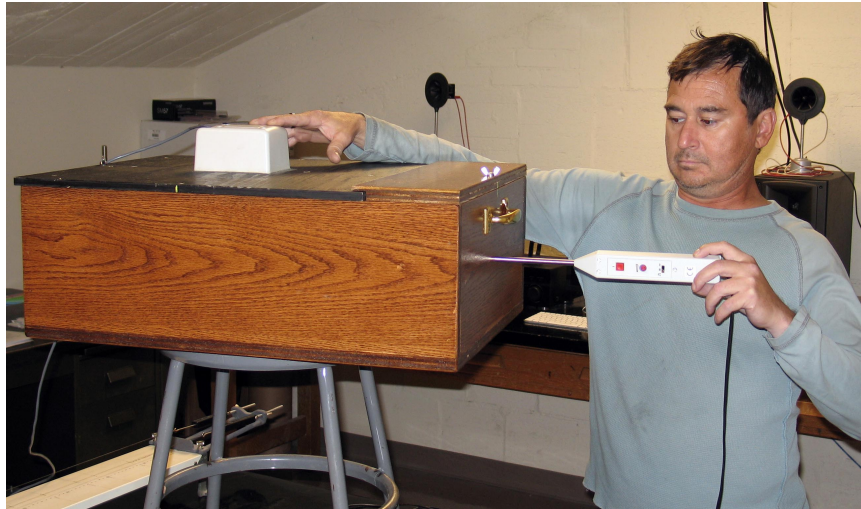


Figure 1: Acoustics box to simulate the acoustics of a room (built by Arnold Fernandez). The small speaker at the top excites box resonances with a swept-sine excitation or white noise. The microphone inserted on the right records the resonances.

frequency spectrum for this cubical “room” is much simpler than for a real room with different dimensions, surfaces, furniture, etc. Equation (1) above simplifies to

$$f_{N_1 N_2 N_3} = \frac{v}{2L} \sqrt{N_1^2 + N_2^2 + N_3^2} \quad (3)$$

The integers  $N_1, N_2, N_3$  in the formula are the mode numbers. For example, the lowest mode with an air resonance in only the  $x$ -direction is  $(N_1, N_2, N_3) = (1, 0, 0)$ . The corresponding resonance frequency is

$$f_{1,0,0} = \frac{v}{2L} \quad (4)$$

For a cubical box, we obviously have the same resonance frequency  $f_{1,0,0}$  for the three modes  $(N_1, N_2, N_3) = (1, 0, 0), (0, 1, 0), (0, 0, 1)$ .

Question 4 Measure the length  $L$  of your box. Calculate the lowest resonance frequency corresponding to modes  $(1, 0, 0), (0, 1, 0), (0, 0, 1)$ .

Question 5 Calculate the next four lowest resonance frequencies above the first resonance frequency and assign the appropriate values of  $N_1, N_2, N_3$ .

Acquire some resonance spectra with the “FFT Analyzer” in the FEaT software. Excite the resonances with white noise or sine sweep and determine which yields the better spectra.

Question 6 Read the five lowest frequencies from the resonance spectra. How do these measured values compare to your calculated values.

### III Calculation of the Reverberation Time

The *reverberation time* is one of the most important characteristics of a room. Just as in the case of the resonant frequencies, the reverberation time depends on the geometry of the room, on the choice of sound absorbing materials, and on the persons and furniture in the room. The reverberation time can be estimated from the formula

$$T_R = 0.050 \frac{V}{A_{\text{sabin}}} \text{ s}, \quad \text{where } A_{\text{sabin}} = aA \quad (5)$$

where  $V$  is the volume of the room in  $\text{ft}^3$  and  $A_{\text{sabin}}$  is the total *effective area* of the room, also called “absorption”, in units of *sabin*,  $a$  the absorption coefficient of the wall material, and  $A$  the physical area square feet.

The unit *sabin* is named after Wallace C. Sabine, founder of architectural acoustics. One sabin is equal to a square foot of perfectly absorbing material. For instance, a  $3 \text{ ft}^2$  hole in a wall is a perfect sound absorber as it reflects no sound and thus corresponds to an effective area  $A_{\text{eff}} = 3 \text{ sabin}$ .

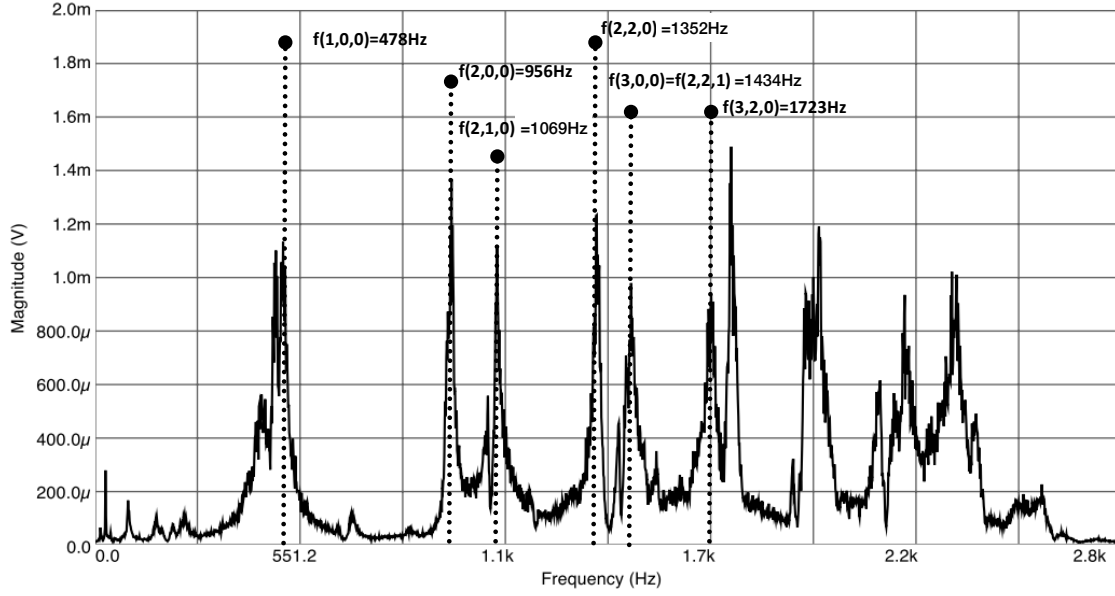


Figure 2: Resonances in a cubical plywood box of inside dimension  $L = 362$  mm. The lowest resonances are clearly seen and the vibrational mode numbers can be identified. The resonances were excited with broadband white noise.

Table 1 lists the absorption coefficients of several common materials. For example, a piece of carpet with an area of  $3 \text{ ft}^2$  at a sound frequency of 500 Hz has an absorption coefficient  $a = 0.3$  and an effective area  $A_{\text{eff}} = aA = 0.3 \times 3 = 0.90$  sabin.

Material	Frequency (Hz)					
	125	250	500	1000	2000	4000
Concrete, bricks	0.01	0.01	0.02	0.02	0.02	0.03
Carpet	0.10	0.20	0.30	0.35	0.50	0.60
Curtains	0.05	0.12	0.25	0.35	0.40	0.45
Acoustical Board	0.25	0.45	0.80	0.90	0.90	0.90
Glass	0.19	0.08	0.06	0.04	0.03	0.02
Plasterboard	0.20	0.15	0.10	0.08	0.04	0.02
Plywood	0.45	0.25	0.13	0.11	0.10	0.09

Table 1: Absorption coefficients  $a$  of various materials. (Values from “The Physics of Sound” by R.E. Berg and D.G. Stork.)

The effective area of an adult person is  $A_{\text{eff}} = 4.2$  sabin.

In order to find the total effective area entering in equation (3), each surface area  $A$  is multiplied by its absorption coefficient  $a$ , resulting in the product  $aA$  for each surface. The total effective area then is the sum over all areas

$$A_{\text{eff}} = a_1 A_1 + a_2 A_2 + a_3 A_3 + \cdots \text{ (in sabin)} \quad (6)$$

Question 7 Calculate the reverberation time of our lecture room, which has approximate length, width, and height  $L_x = 29$  ft,  $L_y = 24$  ft, and  $L_z = 9.5$  ft, respectively. Use the absorption coefficients from Table 1 at 500 Hz for concrete/brick for the walls and floors, and acoustical board for the ceiling. Calculate the effective area  $A_{\text{eff}}$  from equation (6) and the volume from  $V = L_x L_y L_z$ . Finally, use your values for  $A_{\text{eff}}$  and  $V$  in equation (5) to obtain the reverberation time.

$$A_{\text{sabin}} = \text{_____} \text{ sabin}, \quad T_{\text{reverb}} = \text{_____} \text{ s}$$

Question 8 Compare your values with those in the Course Guide (see chapter on “Room Acoustics”).

$$A_{\text{sabin}} = \text{_____} \text{ sabin}, \quad T_{\text{reverb}} = \text{_____} \text{ s}$$

## IV Reverberation Time of The Laboratory Room

Use the signal generator tool and select the Spectrogram Mode in the software. Set the signal generator to 500 Hz or use “white noise”. Record a colored spectrogram, also called a sonogram, where the vertical axis on the display is the frequency, the horizontal axis is time, and the color indicates sound intensity. Run the spectrogram for a few seconds, then turn off the signal generator to stop recording. Observe the time within which the 500 Hz line or white noise fade out. This happens within about one second. This gives a good indication of the reverberation time. You will have to guess on the spectrogram display when the reverberating sound has faded into the background. You may also do this experiment by clapping instead of using a frequency generator or white noise

Question 9 Write down the reverberation time for our laboratory room as obtained from the sonogram:

$$T_{\text{reverb}} = \text{_____} \text{ s}$$

Question 10 Compare this reverberation time with the value you calculated for our classroom (see Questions 7 and 8). Does the classroom or the laboratory room has a shorter reverberation time? Give reasons for the difference.

## V Calculation of the Reverberation Time of the Cubical Acoustics Box

Consider the much simpler case of the cubical acoustics box. Take its length  $L$  to be equal to the box used earlier in the lab.

Question 11 Calculate the reverberation time for the box assuming the absorption coefficient for plywood at 500 Hz in Table 1.

Question 12 What are the least and most sound absorbing materials in Table 1 at 500 Hz? Calculate the reverberation time of the cubical box for those two materials instead of plywood.

Question 13 Based on your results for the previous question, describe how you can adjust the reverberation time of a room with the proper choice of materials.