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

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

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. The approximate length, width, and height of the room are $L_x = 29$ ft, $L_y = 24$ ft, and $L_z = 9.5$ ft, respectively.

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

$$f = \frac{v}{2L} \tag{2}$$

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

2. Calculate the first overtones (2nd harmonics) of each of the three fundamentals by doubling the frequencies from the preceding 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 $L_x = L_y = L_z = 362\ \mathrm{mm} \equiv L$. See Figure 1 for a similar but non-cubical box. The frequency spectrum for this cubical "room" is much simpler than for a real room with

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.

different dimensions, surfaces, furniture, etc. Equation (1) above simplifies to

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

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

$$f_{1,0,0} = \frac{v}{2L} \tag{4}$$

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

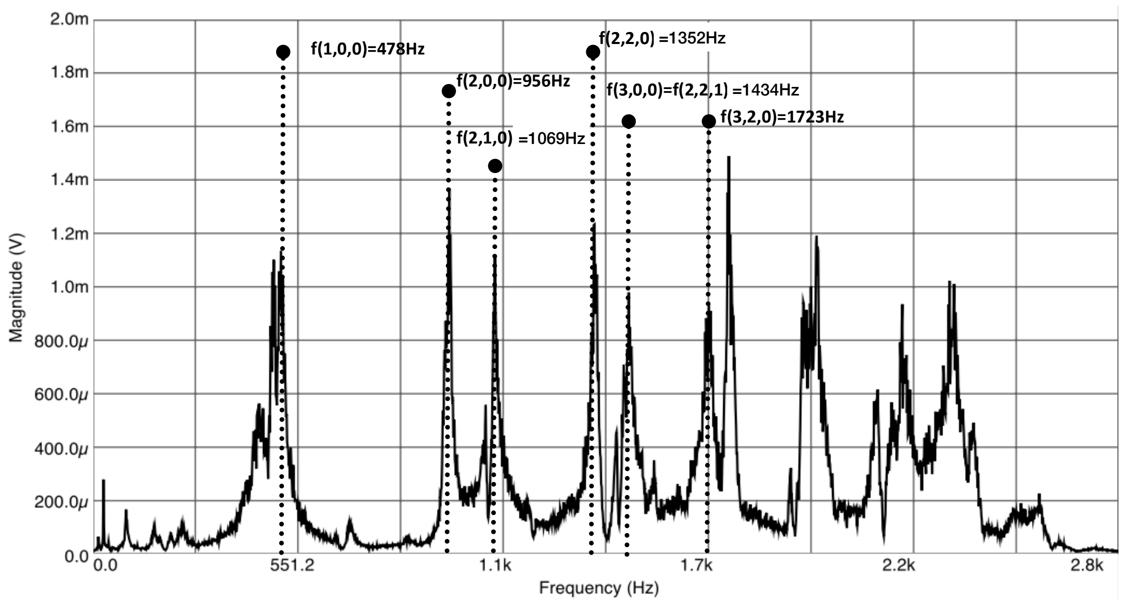

Figure 2: Resonances in a cubical plywood box of inside dimension $L = 362$ mm. The lowest resonances are clearly seen and the vibrational mode numbers can be identified. The resonances were excited with broadband white noise.

By exciting the acoustics box with either a swept-sine wave or white noise, we are able to obtain a "room spectrum" from the cubical box as shown in Figure 2.

1. Verify that the frequencies of the peaks in Figure 2 agree with the frequencies calculated from equation (3) using $L = 362$ mm and the appropriate values of N_1, N_2, N_3.

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

$$T_{\mathrm{R}} = 0.050 \, \frac{V}{A_{\mathrm{sabin}}} \, \mathrm{s} \tag{5}$$

where V is the volume of the room in ft^3 and A_{sabin} is the total *effective area* of the room, also called "absorption", in units of *sabin*.

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 ft^2 hole in a wall is a perfect sound absorber as it reflects no sound and thus corresponds to an effective area $A_{\mathrm{eff}} = 3$ sabin. Table 1 lists the absorption coefficients of several common materials. For example, a piece of carpet with an area of 3 ft^2 at a sound frequency of 500 Hz has an absorption coefficient $a = 0.3$ and an effective area $A_{\mathrm{eff}} = aA = 0.3 \times 3 = 0.90$ sabin. The effective area of an adult person is $A_{\mathrm{eff}} = 4.2$ sabin.

	Frequency (Hz)					
Material	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.)

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 $a\,A$ for each surface. The total effective area then is the sum over all areas

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

1. Calculate the reverberation time of our lecture room, which has approximate length, width, and height $L_x = 29\,\text{ft}$, $L_y = 24\,\text{ft}$, and $L_z = 9.5\,\text{ft}$, 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_{eff} from equation (6) and the volume from $V = L_x L_y L_z$. Finally, use your values for A_{eff} and V in equation (5) to obtain the reverberation time.

2. Compare your values with those in the Course Guide (see chapter on "Room Acoustics").

IV Calculation of the Reverberation Time of the Cubical Acoustics Box

Consider the much simpler case of the cubical acoustics box, which has length $L = 362$ mm for all three dimensions.

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

2. 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.

3. 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.