Carnegie Mellon Acoustics — Electrical & Computer Engineering

**Electroacoustics (18-493)**
**Fall Semester, 2004**

# PROBLEM SET 8

**Issued:** 12/1/04
**Due:** 12/10/04

**Reading:** This material reviews topics on room acoustics, following material in Secs. 10.1 through 10.15. Classes during the last week will be concerned with acoustics in sound recording studios and in stadia.

**Reminder:** The final exam will be take place on Friday, December 17, and will include material up through this problem set. The exam is closed book, but you may bring in three sheets of notes.

**Problem 8.1:**

A uniform tube of circular cross-section and length $l$ is closed at both ends by a material having an absorption coefficient of $\alpha$. The tube is of diameter $d$, with $d$ much smaller than $l$, but not so small that waves in the tube will be attenuated by viscous friction with the sidewalls.

It is desired that the fundamental normal mode of the tube exhibit a bandwidth $\Delta\omega$. Assume that this normal mode is of high $Q$. What must be the value of $\alpha$? (Note that $\alpha = 1 - |\Gamma|^2$)

**Problem 8.2:**

A tube of length $l$ has a material with absorption coefficient $\alpha_1$ at one end and a material with absorption coefficient $\alpha_2$ at the other end. Derive an expression for the absorption coefficient $\alpha$ of a material which if used to replace the materials at both ends of the tube would yield approximately the same decay rate for large times. Explain any approximations you make in arriving at the result. Assume sound propagation only along the length of the tube.

**Problem 8.3:**

In class we obtained the following expression for the number of normal modes $N$ in a rectangular room with frequencies less than $f$:

$$N = \frac{4\pi f^3 V}{3c^3}$$

where the volume $V$ is the volume of the room.

The reverberation time of a particular room for the frequency of 500 Hz is 0.7 sec.

(a) What is the approximate bandwidth for the normal modes of the room in this frequency range? The dimensions of the room are 20 feet by 25 feet by 12 feet. (Assume the bandwidth associated with simple exponential decay.)

(b) How many normal modes occur, on the average, within a frequency range equal to the bandwidth of a normal mode at this frequency?

**Problem 8.4:**

A certain room in a CMU dormitory measures 12 feet high by 20 feet wide by 30 feet long with walls of painted concrete, linoleum floor, and smooth plaster ceiling. It is desired to make a tape recording of a woodwind quintet in this room. Assume that the members of the quintet will be sitting on wooden chairs and refer to the information on absorption coefficients in Table 10.1 in Beranek.

(a) Calculate the reverberation time in this room at frequencies 125, 500, and 2000 Hz.

(b) Using your intuition or Figure 13.25 in Beranek, what is a preferred reverberation time for this situation at 500 hz?

(c) You have a choice of doing the following to improve conditions:

1. cover the floor with a carpet ($\alpha = 0.25$)
2. hang up four 10’ by 12’ rugs on the walls ($\alpha = 0.3$)
3. invite up to 20 people to listen to the performance (you only have 20 more wooden chairs)
4. any combination of the above

Show that your solution will reduce reverberation time at 500 Hz to a desired amount.

**Problem 8.5:**

Consider a room with the following parameters:

- Room dimensions are 10 feet by 14 feet by 16 feet
- Average sound absorption coefficient of the interior surfaces is $\bar{\alpha} = 0.1$ at 10 kHz

(a) Find the reverberation time of this room at 10 kHz, neglecting the effects if air absorption.

(b) What is the reverberation time of the room at 10 kHz if one includes the effects of air absorption? Assume that the air in the room is at 40% relative humidity and at a temperature of 68 degrees Fahrenheit.

**Problem 8.6:**

A plane wave of SPL 100 dB and frequency 1000 Hz is normally incident upon a fully open window of a large irregular room. The area of the window is 1 square meter.

The interior of the room is very sparsely furnished (as in some dormitories), so that to a first approximation we may consider only the interior surfaces of the room in examining the sound field within the room. These surfaces are as tabulated below:

| **Type of surface** | **Area of Surface** |
|---|---|
| Wood floor, on solid foundation | 25 $m^2$ |
| Plaster, gypsum, scratch and brown coats on metal lath, on wood studs (walls) | 50 $m^2$ |
| 3/8-inch thick wood panelling with a 3-inch air space behind (ceiling) | 25 $m^2$ |

(a) What is the SPL observed within the room's reverberant sound field? **Note:** assume that all of the energy of the incident plane wave enters the room *(i.e.* that there are no reflections at the window).

(b) The window is now partially closed so that an area of only 0.001 square meters remains open. The transmission loss (often abbreviated TL) is defined for a wall as

$$TL = 10\log_{10}\left[\frac{\text{acoustic power in normally-incident plane wave}}{\text{acoustic power in transmitted wave}}\right]$$

In this room, the transmission loss of the windowpane is 60 dB. What is the SPL of the reverberant field now, with the window now partially closed, as described above?

(c) Now assume that the window is fully open again as in part (a). A wool pile rug (with underpad) 25 square meters in area is placed on the floor), and a total of 25 square meters of 1/2-inch thick perforated acoustic tile with five hundred 5/32-inch holes per square foot is placed upon the walls of the room. What now is the SPL within the reverberant field of the room if a plane wave of frequency 1000 Hz and SPL 100 dB is normally incident upon the (open) window? What is the SPL within the room's reverberant field if the frequency of the incident plane wave is changed to 125 Hz, its SPL remains 100 dB, and the window remains fully open?

**Problem 8.7:**

It is desired to determine the steady state power **radiated** from a loudspeaker as a function of frequency by making appropriate measurements in a large reverberant irregular room. First the reverberation time $T(f)$ of the room is measured as a function of the frequency *f*. Then a measurement is made of the spatial average of the time mean square value of the pressure standing waves set up by the speaker as a function of the excitation frequency *f*. (The notation for this average in the text is $|P_{avg}|^2$**.)**

Derive an expression for the power $W(f)$ radiated by the speaker in terms of the room volume *V* and the measured quantities $|P_{avg}|^2$ and $T(f)$. Neglect air absorption and make the approximation of small absorption coefficient, *i.e.*, $\bar{\alpha} \ll 1$ which is appropriate for many rooms with hard walls.

**Problem 8.8:**

Suppose you are going to make recordings of an orchestra in Boston's Symphony Hall, a hall that is widely renown for its good acoustics. You wish to position your pressure-sensitive microphones so that they receive a substantial portion of the direct sound pressure radiated by the orchestra, thereby avoiding the problem of "double reverberation". This problem would occur if in recording you placed the microphones entirely within the reverberant field of the concert hall. The play-back of such a recording would then sound unclear and very diffuse when heard in the reverberant field of a listening room. The music would have been entirely subjected to the normal mode structures of both the concert hall and the listening room.

On the other hand, if your microphones are placed too close to the orchestra, entirely within the direct field of the instruments, it is observed that the resultant sound is harsh or unnatural.

You desire to know the approximate distance $r_0$ at which the sounds pressure level due to the reverberant field equals that due to the direct field. Although there is at present no way of precisely determining optimum microphone positions, this knowledge will at least enable you to avoid gross errors in microphone placement.

(a) Calculate $r_0$ at midband (500-1000 Hz) given the following information:

- *T*, the reverberation time that is valid in the frequency band 500-1000 Hz, is 1.8 seconds (when the hall is occupied by people).
- *V*, the volume of the hall, is approximately 662,000 cubic feet.
- *S*, the total interior surface area of the hall is about 80,000 square feet, assuming that the interior surfaces of Symphony Hall are plane surfaces.

(b) For those of you who have actually been inside Symphony Hall:

Might you expect the value of $r_0$ calculated in part (a) to be a little too high or a little too low? Explain your answer.