9. Electrical Energy and Work, Acoustical Power

PURPOSE AND BACKGROUND

Electricity is one of the most important energy forms. Here we study electrical energy, work, power, voltage, current, and resistance. We will compare the power consumption of a conventional incandescent light bulb with more efficient compact fluorescent and light-emitting diode light bulbs (CFL and LED light bulbs for short). We will determine the energy and dollar savings of using a CFL or LED light bulb instead of an incandescent light bulb. We will also investigate the acoustic power radiated by a loudspeaker by finding the sound intensity in front of the speaker. The speaker efficiency then follows from the acoustic power divided by the electric power. We judge how loud a speaker sounds for a given acoustic power and find out how acute our sense of hearing is.

I Some Theory Concerning Power, Energy, Work, and Electricity

Energy is the ability to do work.

Example: 1 gallon of gasoline contains energy to do work. An automobile engine does work and moves a car 30 miles with this energy.

Unit of energy and work: 1 Joule (J)

Power is the rate at which work is done:

$$\text{Power} = \text{Work/Time Interval} \quad \text{or} \quad P = W/\Delta t \tag{1}$$

$$\text{Work} = \text{Power} \cdot \text{Time Interval} \quad \text{or} \quad W = P\,\Delta t \tag{2}$$

Unit of power: 1 J/s = 1 Watt (W)

Ohm's law of electricity:

$$V = IR \tag{3}$$

where V is the voltage across a load (for instance a light bulb or loudspeaker) in volt (V); I is the current through the load in Ampere (A); and R is the resistance of the load in Ohm (Ω).

Electric power:

$$P = VI \quad \text{or, equivalently,} \quad P = I^2 R \quad \text{and} \quad P = V^2/R \tag{4}$$

Common unit of energy: 1 kilowatt-hour (kWh)

Conversion: $1\ \text{kWh} = 1000\ \text{W} \times 3600\ \text{s} = 3,600,000\ \text{W} \cdot \text{s} = 3,600,000\ \text{J} = 3.6 \times 10^6\ \text{J}$

Example: A sedentary person consumes 2000 kcal (kilocalories) of food energy per day. The conversion is $1\ \text{kcal} = 4184\ \text{J}$. Therefore $2000\ \text{kcal} = 8,370,000\ \text{J}$. This amount of energy is consumed in a time interval $\Delta t = 24\ \text{hr} = 86,400\ \text{s}$. Hence the rate of energy consumption is $P = W/\Delta t = 8,370,000\ \text{J}/86,400\ \text{s} = 97\ \text{J/s} = 97\ \text{W}$ or about 100 W. This is typical for the resting metabolic rate of a person. You may know this rate as "2000 kcal per day" rather than 100 Watt. When we sit around doing little, we burn food energy at the rate of 100 W, i.e., about the same as an old-style 100 W incandescent light bulb consumes in the form of electrical energy.

II Power and Energy Consumption in Light Bulbs

An incadescent light bulb, CFL, and LED light bulb are connected to a triple light bulb fixture, which supplies a household voltage $V = 120$ volt to each bulb. The power rating of the three bulbs are $P = 40$ W, 9 W, and 6 W, respectively, but the bulbs are equally bright.

1. Suppose you turn the light bulbs on for 5 hours each day. Calculate the energy used by each bulb in a 30-day month. Express your answers first in Joules, and then convert to kWh.

2. Electricity costs about 13 cents/kWh. What is the monthly electric bill for each of the light bulbs?

3. An incandescent light bulb costs \$0.75 (if still available), a CFL \$1.50, and an LED light bulb \$5.00. How long does it take to make up for the extra initial cost of the CFL and LED light bulbs over the incandescent light bulb? (Hint: The number of months needed to make up the extra initial cost is equal to the difference in their initial costs divided by the difference in their monthly costs.)

4. How much money is saved over the lifetime of 10,000 hours of a CFL and 20,000 hours of an LED light bulb, compared to the 2000 hours for an incandescent light bulb? Include in your calculation the number of incandescent light bulbs you would need during the lifetime of a CFL and LED light bulb. Hint: Use the formula

$$\text{savings (in dollars)} = \$0.75 \left(\frac{T}{2000 \text{ hr}} \right) - C_{\text{initial}} + \frac{\$0.13}{1000 \text{ W} \cdot \text{hr}} (40 \text{ W} - P)\, T \tag{5}$$

   where $T = 10,000$ hr, $C_{\text{initial}} = \$1.50$, and $P = 9$ W for a CFL; or $T = 20,000$ hr, $C_{\text{initial}} = \$5.00$, and $P = 6$ W for a LED light bulb.

5. What are the energy savings in percent when using a CFL and LED light bulb instead of an incandescent light bulb? (Hint: Compare the wattages of the three bulbs.)

III Electric Power to a Loudspeaker

A sine-wave signal generator is connected to a loudspeaker as shown in Figure 1. A multi-meter, set to the ammeter mode, is connected in-line between the loudspeaker and the signal generator, and another multi-meter, set to the voltmeter mode, is connected in parallel to the speaker inputs. When the amplitude of the signal generator is adjusted to produce a comfortable loudness at 500 Hz, one observes a current $I = 0.3$ Ampere and voltage $V = 5$ volt.

1. Calculate the power to the loudspeaker from the formula $P = IV$.

2. Loudspeakers of hi-fi systems often are rated at 100 W or higher. How does your answer for our loudspeaker compare with such ratings?

3. Do you think a power of several hundred Watt is necessary? Why or why not?

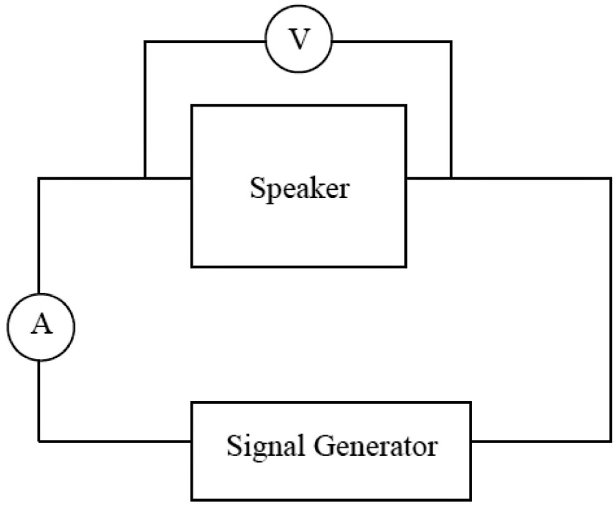

Figure 1: Schematic of the speaker connections to a signal generator, voltmeter, and ammeter.

IV Resistance or Impedance of a Loudspeaker, Power Continued

The reaction of a loudspeaker to an applied alternating current (AC) voltage is called *impedance*, labeled with the letter Z. Impedance is not the same as resistance because it also includes capacitance and inductance. But we will ignore this distinction here and use resistance and impedance interchangeably. This means that we will use Ohm's law $V = IR$ to calculate the resistance from $R = V/I$, and then use this value of R to get an estimate of the impedance Z.

1. Obtain the impedance of the loudspeaker from the voltage V and current I given in Part III above. Compare this with the specification of $16\ \Omega$ on the loudspeaker enclosure.

2. Obtain the power to the loudspeaker from the expression $P = I^2R$. Compare your answer with the result from Part III, Question 1.

V Acoustical Power and Loudspeaker Efficiency

Using a sound level meter in setting "A" (which corresponds to the response of the human ear), we can measure the sound loudness level (in phon) at various locations in front of and close to the speaker. Averaging these measurements at a distance of 1 m from the speaker, we find an average loudness level of 90 phon.

1. Consulting the Fletcher-Munson equal loudness curves in Figure 2, what is the sound intensity I in $\mathrm{W/m^2}$ corresponding to an average loudness level of 90 phon at a frequency of 500 Hz?

2. To calculate the total acoustical power $P_{\text{acoustical}}$ radiated by the loudspeaker, we need to know the area into which the power is radiated. Assume that this area is the base of a cone in front of the speaker with area $A = 0.6\pi r^2$, where $r = 1\ \mathrm{m}$. Given this area, calculate the acoustical power using the formula $P_{\text{acoustical}} = IA$.

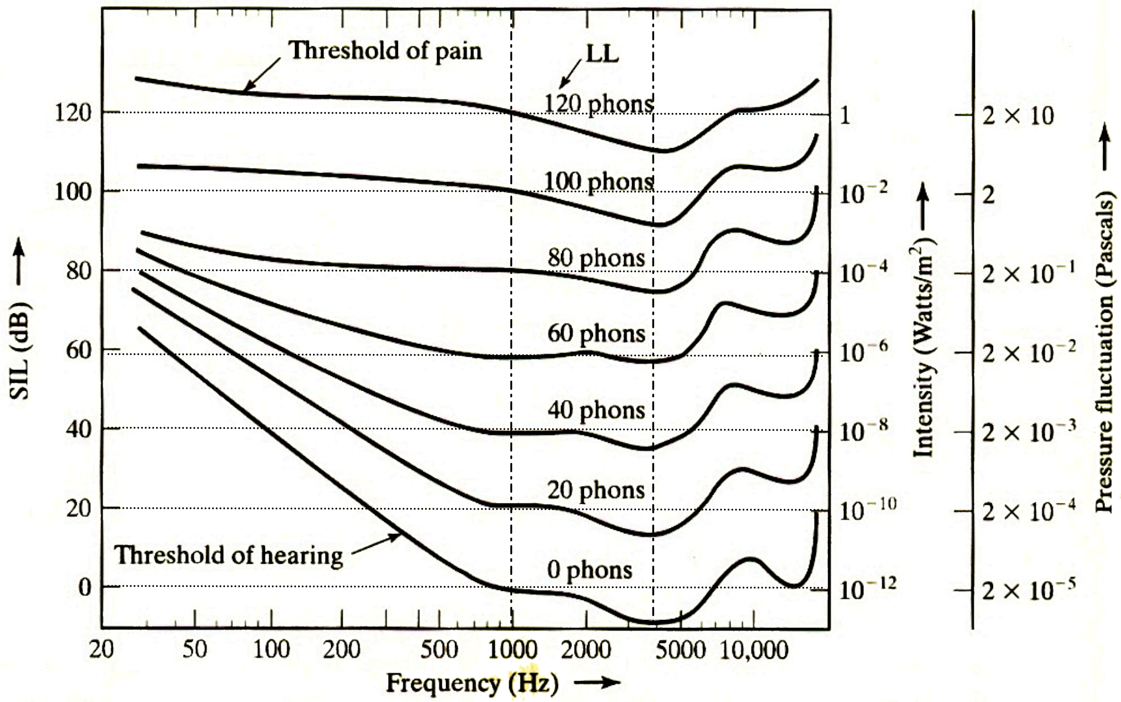

Figure 2: Fletcher-Munson curves of equal loudness. (From "Physics of Sound," by R.E. Berg and D.G. Stork.)

3. Using the above answer for $P_{\text{acoustical}}$ and your result from Part III, Question 1 for the electrical power $P_{\text{electrical}}$ to the speaker, calculate the *loudspeaker efficiency* $(P_{\text{acoustical}}/P_{\text{electrical}}) \times 100\%$.

4. Based on your answer to the previous question, comment on the conversion of electrical power to acoustical power.

5. Compare the acoustical power output from a speaker with the light power output from a CFL. Do this by assuming that the same electrical power (e.g., 9 W) goes into both the speaker and the CFL. For the CFL assume a conversion efficiency of 20% from electrical power to light power, so $P_{\text{light}} = 0.20\, P_{\text{electrical}}$. For the acoustical power, you will need to increase the value that you found in Question 2 above by a factor of $9/1.5 = 6$ to take in account the increase in electrical power from 1.5 W to 9 W. (You should find that the emitted acoustical power is much lower than the light power output from a CFL.)