**FUNDAMENTALS OF INDUSTRIAL HYGIENE, 6TH ED.**

**HOMEWORK #4**

**INDIVIDUAL MEASUREMENT OF SOUND**

**Objective:** Students will become familiar with the measurement of sound, including sound power levels, sound pressure levels, sound damping, and the determination of sound levels resulting from single or multiple sources.

**Background:** In physics, sound is a vibration that propagates through compressible media (gas, liquid, or solid) as a typically audible mechanical wave of pressure and displacement. In this arena, sound waves are often described and characterized by the generic properties of: frequency, wavelength, amplitude, sound pressure, sound intensity, speed of sound, and direction of sound. Although representing only a minor change in overall atmospheric pressure, excessive sound levels have the ability to cause trauma to delicate structures within the ear, leading to temporary (if stressed), partial (if damaged), or permanent (if destroyed) hearing loss.

In physiology and psychology, sound is the reception of vibration waves and their perception by the brain. The physical reception of sound in any organism capable of hearing is limited to a range of frequencies. Humans normally hear sound frequencies between approximately 20 *Hz* and 20,000 *Hz*. Other species have a different range of hearing. Dogs, for example, can perceive vibrations higher than 20,000 *Hz*, but are deaf to vibrations below 40 *Hz*. Physiological and psychological effects of extreme sound levels vary depending on the frequency, and include chest wall vibration, respiratory-rhythm changes, and mild nausea and gagging (low frequency), to tickling sensations and heating of air-filled cavities (medium to high frequencies), to heating of air cavities, hair, and textiles (at high frequencies).

As a signal perceived by one of the major senses, sound is used for detecting danger, navigation, predation, and communication. Virtually any physical phenomenon, such as fire, wind, rain, surf, earthquake, or flood, produces and is characterized by its unique sounds. Earth organisms evolved under a regime of naturally occurring low frequency (wind, surf, waterfalls) and high frequency (bird chirps/cheeps, mosquito wings, elk bugle) sounds. However, the advent of the industrial revolution has resulted in a dramatic change in the acoustic ecology and subsequent effects on society and the individual.

**Decibels and Levels**

Even though the weakest pressure perceived as sound is a small quantity, the range of sound pressure perceived as sound is extremely large (20 – 20,000 *Hz*).

The weakest sound that can be heard by a person with very good hearing is known as the *threshold of hearing*.

At a reference tone of 1000 *Hz*, the threshold of hearing is taken to be a sound pressure of 20 *μPa*.

The *threshold of pain*, or the greatest sound pressure that can be perceived without pain, is approximately 10 million times greater.

It is, therefore, more convenient to use a relative scale of sound pressure rather than an absolute scale.

For this purpose, the *bel*, a unit of measure in electrical-communications engineering, is used.

The *decibel (dB)* is the preferred unit for measuring sound.

One *decibel* is one-tenth of a *bel* and is the minimum difference in loudness that is usually perceptible.

The decibel is a dimensionless unit used to express the logarithm of the ratio of a measured quantity to a reference quantity.

In acoustics, the decibel is used to describe the level of quantities that are proportional to sound power.

**Sound Power Level (*LW*)**

*Sound power* (*W*) is the amount of energy per unit time that radiates from a source in the form of an acoustic wave.

*Sound power level* (*Lw*), is *expressed in decibels* relative to the reference power of 10-12 watts (*W0*) (threshold of hearing) and expresses the total amount of sound power radiated by a sound source.

where: *W* = sound power

*W0* = reference power (10-12)

log10 = a logarithm to the base 10

**Table 1: Sound Power Table**

**sound power (*W*) *dB* equivalent source**

0.000000000001 (10-12) 0 threshold of hearing (reference power level)

0.00000000001 (10-11) 10 human breath, rustling leaf

0.0000000001 (10-10) 20 whisper, very calm room

0.000000001 (10-9) 30 quiet conversation

0.00000001 (10-8) 40 normal conversation

0.0000001 (10-7) 50 quiet office

0.000001 (10-6 ) 60 busy restaurant, washing machine

0.00001 (10-5) 70 noisy office (\*EPA-identified maximum for disruption)

0.0001 (10-4 ) 80 alarm clock

0.001 (10-3) 90 heavy traffic

0.01 (10-2) 100 lawn mower, jack hammer

0.1 (10-1) 110 chain saw

1 120 sonic boom (\*risk of instantaneous hearing loss)

10 (101) 130 machine gun (\*threshold of pain)

100 (102) 140 jet at takeoff

1000 (103) 150 jet engine at 1*m*

1000000 (106) 170 stun grenade

1000000000 (109) 210 Saturn VII rocket at liftoff

**Example Problem: Sound Power Levels**

A source radiates an acoustic wave with a *sound power level* of 0.000006 watts.

What is the decibel level of the sound when measured at the source (i.e., distance from source = 0)?

where: *W* = sound power (in *watts*)

*W0* = reference power (10-12 *watts*)

log10 = a logarithm to the base 10

Note: Refer to Table 1: *Sound Power Table*.

Does the calculated value appear to “fit” with the information on the table?

**Example Problem: Sound Power Levels**

A source radiates an acoustic wave with a *sound power level* of 73 watts.

What is the decibel level of the sound when measured at the source (i.e., distance from source = 0)?

where: *W* = sound power (*watts*)

*W0* = reference power (10-12 *watts*)

log10 = a logarithm to the base 10

Note: Refer to Table 1: *Sound Power Table*.

Does the calculated value appear to “fit” with the information on the table?

**Sound Pressure Level (*LP*)**

Sound power (i.e., total energy radiated over time) cannot be measured directly.

It is possible to measure sound intensity (i.e., energy per square meter), but the instruments are expensive and must be used carefully.

Sound pressure can be measured more easily, so *sound level meters* are built to measure sound pressure level (*LP*) in decibels.

The sound level meter directly indicates sound pressure level referenced to a sound pressure of 20 *μPa* (threshold of hearing, also equal to 0 *dB*).

The equation for sound pressure level is:

which can be rewritten

where: *p* = measured Root-Mean-Square (RMS) sound pressure (in *μPa*)

*p0* = reference RMS sound pressure (20 *μPa*)

Note: With the *sound pressure level*, the multiplier is 20 and not 10 as in the case of the sound power level equation.

This is because sound power is proportional to the square of sound pressure and because 10  log10 *p2* can be rewritten as 20  log10 *p*.

Example: 6300 *μPa*

10  log10 (6300)2 = 20  log10 (6300)

10  log10 (39690000) = 20  log10 (6300)

10  7.6 = 20  3.8

76 = 76 {True}

**Table 2: Sound Pressure Table**

**sound pressure (*μPa*) *dB* equivalent level**

20 0 threshold of hearing (reference power level)

63 10 human breath, rustling leaf

200 20 whisper, very calm room

630 30 quiet conversation

2000 40 normal conversation

6300 50 quiet office

2 60 busy restaurant, washing machine

6,0 70 noisy office (\*EPA-identified maximum for disruption)

200,000 80 alarm clock

630,000 90 heavy traffic

2,, 100 lawn mower, jack hammer

6,300,000 110 chain saw

2 120 sonic boom (\*risk of instantaneous hearing loss)

63,000,000 130 machine gun (\*threshold of pain)

200,000,000 140 jet at takeoff

630,000,000 150 jet engine at 1*m*

6,300,000,000 170 stun grenade

200,000,000,000 200 Saturn VII rocket at liftoff

**Example Problem: Sound Pressure Level**

The acoustic wave radiated by a source is measured some distance away from the source and is found to generate a sound pressure level of 156 *μP*a.

What is the decibel level of the sound wave at the point where it was measured?

where: *p* = measured Root-Mean-Square (RMS) sound pressure (in *μPa*)

*p0* = reference RMS sound pressure (20 *μPa*)

Note: Refer to Table 2: *Sound Pressure Table*.

Does the calculated value appear to “fit” with the information on the table?

**Example Problem: Sound Pressure Level**

The acoustic wave radiated by a source is measured some distance away from the source and is found to generate a sound pressure level of 45,563,000 *μP*a.

What is the decibel level of the sound wave at the point where it was measured?

where: *p* = measured Root-Mean-Square (RMS) sound pressure (in *μPa*)

*p0* = reference RMS sound pressure (20 *μPa*)

Note: Refer to Table 2: *Sound Pressure Table*.

Does the calculated value appear to “fit” with the information on the table?

**Sound Intensity Level (*LI*): Damping of Sound Level with Distance**

Hearing is directly sensitive to sound pressure.

As sound power is radiated from a point source in free space, the power is distributed over a spherical surface, so at any given point there exists a certain sound power per unit area (i.e., sound intensity).

The sound pressure level (*Lp*) (in *dB*) depends on the distance (*r*) between the sound source and the place of measurement.

Note: Reporting the sound pressure level without the given distance to the sound source greatly compromises the utility of collected data.

Unfortunately, this error (unknown distance) occurs quite often.

**Inverse Distance Law**

In physics, an inverse-square law is any physical law stating that a specified physical quantity or intensity is inversely proportional to the square of the distance from the source.

In acoustics, the sound pressure (in *dB*) of a spherical wavefront radiating from a point source decreases by 50% as the distance (*r*) is doubled.

Note that the decrease is 6 *dB*, since *dB* represents an intensity ratio.

The equation for calculating sound intensity levels with distance from the source is:

where: *L*P1 = sound pressure level at location of first measurement (in *dB*)

*r*1 = distance from source of first measurement (in *meters*)

*r*2 = distance from source of second measurement (in *meters*)

**Example Problem: Sound Intensity Level**

A piece of machinery radiates a sound measured at 100 *dB* at a distance of 1 *m* (*r*1 = 1) from the source.

What would the sound pressure level be at *r*2 = 2 *m*?

where: *L*P1 = sound pressure level at location of first measurement (in *dB*)

*r*1 = location of first measurement (in *meters*)

*r*2 = location of second measurement (in *meters*)

**Example Problem: Sound Intensity Level**

A piece of machinery radiates a sound measured at 117 *dB* at a distance of 9 *m* (*r*1 = 9) from the source.

What would the sound pressure level be at *r*2 = 78 *m*?

where: *L*P1 = sound pressure level at location of first measurement (in *dB*)

*r*1 = location of first measurement (in *meters*)

*r*2 = location of second measurement (in *meters*)

**Assessing Multiple Sound Emissions**

Because decibels are logarithmic values, it is not proper to add them by normal algebraic addition . . . 60 *dB* plus 60 *dB* does not equal 120 *dB*, but only 63 *dB*.

The equation for calculating combined sound power levels is:

which can be rewritten

The equation for calculating combined sound pressure levels is:

which can be rewritten

Note: Both the multiple sound power level and the multiple sound pressure level calculations entail a three-step process.

**Example Problem: Combining Multiple Sound Power Levels**

Two sources are radiating noise in a free field (unobstructed area).

One source has a sound power level of 123 *dB* and the other source has a sound power level of 117 *dB*.

What is the combined power level of these two sources?

which can be rewritten

1) Calculate the individual sound powers (*W1 and W2*) of the devices operating at 123 *dB* and 117 *dB*.

2) Next, add the individual sound powers (*W1 + W2*) of the devices operating at 123 *dB* and 117 *dB*.

3) Lastly, use this new ‘combined sound power’ value to calculate the resultant output in *dB*.

*dB*

**Example Problem: Combining Multiple Sound Pressure Levels**

The sound pressure level of each of three individual noise sources is measured at a point such that with only the first source running, the *LP* = 86 *dB*; with only the second source running, the *LP* = 84 *dB*; and with only the third source running, the *LP* = 89 *dB*.

What will the sound pressure level (*LP*) be with all three sources running simultaneously?

or

1) Calculate the individual sound pressure levels of the three devices (86 *dB*, 84 *dB*, and 89 *dB*).

2) Next, add the individual sound powers (*LP1 + LP2 + LP3*) of the devices creating sound pressures of 86 *dB*, 84 *dB*, and 89 *dB*.

3) Lastly, use this new ‘combined sound pressure’ value to calculate the resultant output in *dB*.

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**Name:**

**EXERCISES:** Perform the calculations identified below. Show your work neatly and clearly in a manner similar to the examples provided above (i.e., write the formula, define each variable in the formula, show steps of your calculations).

**Part I: Calculation of Sound Power Level**

Calculate the sound power level (*W0*) (in *dB*) for each of the following sound powers (*W*): 10, 20, 40, and 80 watts.

***10 watts*** *(5 points)*

Formula:

where:  =

=

=

Calculations:

***20 watts*** *(5 points)*

Formula:

where:  =

=

=

Calculations:

***40 watts*** *(5 points)*

Formula:

where:  =

=

=

Calculations:

***80 watts*** *(5 points)*

Formula:

where:  =

=

=

Calculations:

Notice that each of the values given represents a doubling in power output from the previous value (e.g., 10, 20, 40, 80).

What is the relationship in sound power levels (*LW*) and decibels (*dB*) based on your calculations?

*When the sound power is doubled, the sound power level increases by dB. (1 point)*

**Part II: Calculation of Sound Pressure Level**

Calculate the sound pressure level (*Lp*) (in *dB*) for each of the following sound pressures: 2000, 4000, 8000, and 16000 *μPa*.

***2000 μPa*** *(4 points)*

Formula:

where:  =

=

Calculations:

***4000 μPa*** *(4 points)*

Formula:

where:  =

=

Calculations:

***8000 μPa*** *(4 points)*

Formula:

where:  =

=

Calculations:

***16000 μPa*** *(4 points)*

Formula:

where:  =

=

Calculations:

Notice that each of the values given represents a doubling from the previous value (e.g., 2000, 4000, 8000, 16000).

What is the relationship in sound pressure levels (*L0*) and decibels (*dB*) based on your calculations?

*When the sound pressure is doubled, the sound pressure level increases by dB.**(1 point)*

**Part III: Calculation of Sound Intensity Level**

Given a source radiating a sound pressure level of 96 *dB* measured at a distance of 2 meters from the source, calculate the sound pressure level (*Lp*) (in *dB*) at each of the following distances from the source: 5, 10, 20, and 40 meters.

***5 m*** *(5 points)*

Formula:

where:  =

=

=

Calculations:

***10 m*** *(5 points)*

Formula:

where:  =

=

=

Calculations:

***20 m*** *(5 points)*

Formula:

where:  =

=

=

Calculations:

***40 m*** *(5 points)*

Formula:

where:  =

=

=

Calculations:

Notice that each of the values given represents a doubling from the previous value (e.g., 5, 10, 20, 40).

What is the relationship between distance from the source and decibels (*dB*) based on your calculations?

*When the distance from a sound source is doubled, the sound pressure is decreased by dB.**(1 pt.)*

**Part IVa: Assessing Multiple Sound Power Emissions**

A workplace has three pieces of equipment in operation each of which individually radiates sound power levels of *LW1* = 87 *dB*, *LW2* = 112 *dB*, and *LW3* = 93 *dB*.

What is the resultant combined sound power level *LW(total)* (in *dB*) if all three devices operate concurrently?

Formula: *(1 point)*

1) Calculation of individual sound powers (*W1, W2, and W3*) of the devices.*(3 points)*

***W*1** ***W*2** ***W*3**

2) Addition of the individual sound powers (*W1 + W2 + W3*) of the devices.*(1 point)*

3) Use of the new ‘combined sound power’ value to calculate the resultant sound power output (in *dB*).

*(2 points)*

Formula:

Calculation:

**Part IVb: Assessing Multiple Sound Pressure Emissions**

When measured in isolation from the same location, the sound pressure level of each of three noise sources are: *LP1* = 83 *dB*; *LP2* = 96 *dB*; and *LP3* = 68 *dB*.

What will the sound pressure level (*LP(total)*) be if all three sources run simultaneously?

Formula: *(1 pt.)*

1) Calculation of individual sound pressures (*P1, P2, and P3*) of the devices.*(3 points)*

***P1 P2 P3***

2) Addition of the individual sound pressures (*P1 + P2 + P3*) of the devices.*(1 point)*

3) Use of the new ‘combined sound pressure’ value to calculate the resultant sound pressure output (in *dB*).*(2 points)*

Formula:

Calculation: