

IH&S 527: Noise Control Engineering

Chapter 2: Physics of Sound and Vibration

by

Steven E. Guffey, PhD, CIH

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1

Noise

- Defining noise
 - Common definition: unwanted sound
 - Information theory context: Noise is "that auditory stimulus or stimuli bearing no informational relationship to the presence or completion of the immediate task"
 - For hearing conservation, it is sonic energy in frequency ranges and amounts that can affect hearing deleteriously

2

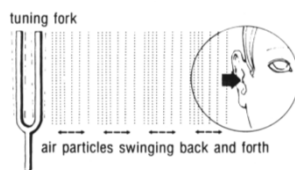
Physics of Sound

- Parameters:
 - Frequency or pitch
 - Wavelength
 - Pressure (Loudness)
 - Amplitude Intensity (Power)
- Units of measure
 - Frequency
 - cycles per second
 - Pressure
 - Loudness
 - Bells and decibels (A, B, and C scales)

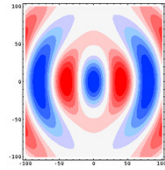
3

Sound

- Oscillations in pressure in a medium with elasticity and viscosity.
- Radiates as waves from the source.




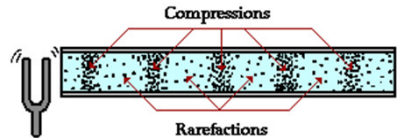
tuning fork
air particles swinging back and forth



The sound source vibrates and affects air particles, which strike the ear drum.

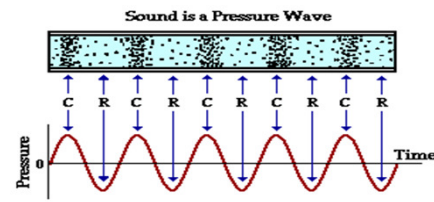
4

Sound variations

5

Sound is a pressure wave:



NOTE: "C" stands for compression and "R" stands for rarefaction

Amplitude of pressure wave : distance from the stationary position to the extreme position on either side and is measured in meters (m). The intensity of vibration depends on amplitude.
"Sound Pressure": RMS amplitude.

6

Speed of Sound for Air

$$c = \sqrt{\gamma R T_{abs}}$$

Where: γ = ratio of specific heat = 1.401 for 0-100 C
 R = gas constant = 286 m²/s²/°K
 T = abs temperature = 273.15 + T_c

- Change of 10F before significant temperature effect

$$c = 330.7 \sqrt{\frac{273.15 + T_c}{273.15}}, \text{ m/s}$$

7

Speed of Sound In Air

at 20 C and 30% R.H.

c = 1126 ft/sec
 = 343.74 m/sec

8

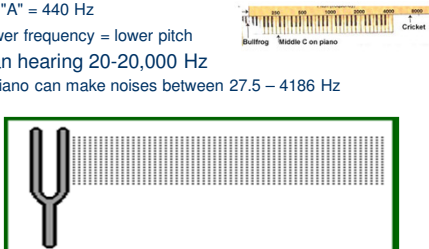
Speed of Sound (c = speed of sound)

Gases		Solids	
Material	v (m/s)	Material	v (m/s)
Hydrogen (0°C)	1286	Diamond	12000
Helium (0°C)	972	Pyrex glass	5640
Air (20°C)	343	Iron	5130
Air (0°C)	331	Aluminum	5100
		Brass	4700
		Copper	3560
		Gold	3240
Liquids at 25°C		Lucite	2680
Material	v (m/s)	Lead	1322
Glycerol	1904	Rubber	1600
Sea water	1533		
Water	1493		
Mercury	1450		

9

Frequency

- Inverse of time for one compression and rarefaction
- Unit of measurement: = cycles per second (Hz)
- Pitch= musical label for particular frequencies:
 - ex/ "A" = 440 Hz
 - Lower frequency = lower pitch
- Human hearing 20-20,000 Hz
 - A piano can make noises between 27.5 – 4186 Hz



10

Frequencies for the Notes of the Even-tempered Scale for the Octave Above Middle C*

C	261.63	F#	369.99	C	523.25
C#	277.18	G	392.00		
D	293.66	G#	415.30		
D#	311.13	A	440.00		
E	329.63	A#	466.16		
F	349.23	B	493.88		

*A-440 is used as the standard, and the interval between each note is 2^{1/12} = 1.05946.

11

Frequency and the human ear

- Human speech: 1,000 - 4,000 Hz
- Humans lose sensitivity at:
 - <1,000 Hz, and
 - >4,000 Hz
- Threshold of Pain = 120 dB

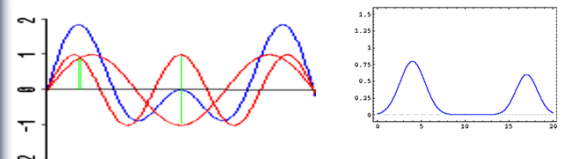
12

Frequency Characteristics of Noise

- Pure Tones Are a Single Frequency
 - Rare in industrial noises
 - Some in music
 - Musical notes when played have harmonics, so not truly pure
- Complex Tones
 - Real noises are typically complex, consisting of many frequencies, including harmonics of dominant frequencies
 - Powerful pure tones may be heard against the background in some types of jet engine noise. In machinery noises that are nominally pure tones and which sound musically pitched, harmonics also occur
- Time Characteristics of Noise
 - "Continuous" — actually varying about a mean
 - "impulse" — very short, very loud sounds

Combined Frequencies

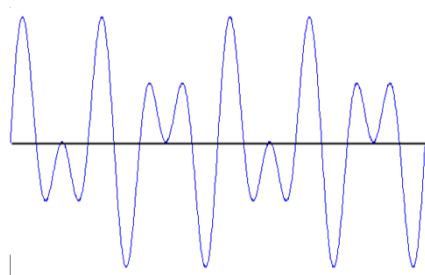
- Industrial exposures are a combination of many frequencies.



Superposition of two waves

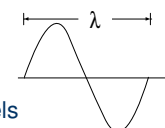
14

Combined Frequencies




15

Wavelength (λ)



- Wavelength is distance wave travels in one complete cycle:
 - $\lambda = c/f$
 - c = speed of sound at 20C and 30% R.H.
 - = 1126 ft/sec
 - = 343.74 m/sec
 - f = frequency, Hz
 - λ = wavelength, ft or m
 - ex/: The wavelength of a 100 Hz wave is 11.28 feet




16

Bandwidth

- Acoustical energy typically widely distributed across frequencies
- Therefore: break range into smaller ranges
- Frequency band of one octave:
 - $F_{upper\ end} = 2 \cdot F_{lower\ end}$ (2.3)
- Frequency band of 1/3rd octave:
 - $F_{upper\ end} = 2^{1/3} \cdot F_{lower\ end}$ (2.4)
- Center frequency = geometric mean of the upper and lower band-edge frequencies:
 - $F_{center} = 2^{1/3} \cdot (F_{upper\ end} \cdot F_{lower\ end})^{1/2}$ (2.5)

17

Homework, due next class.



- Compute wavelengths for all the notes of the musical scale shown on a previous slide.
- Compute wavelengths for the range of human *hearing* given earlier:
 - Low end of range and high end of range
- Compute wavelengths for the range of human *speech* given earlier:
 - Low end of range and high end of range
- Compute frequencies for wavelengths matching each of the dimensions of a box:
 - 12" wide 14" deep 36" high
- If you see lightning strikes a tree 3 km away from you, how long before you will hear it (assume sea level, 20C, 30% rel hum).

18

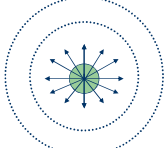
Power and Pressure

- Use RMS sound pressure:
 - $$p_{rms} = \sqrt{\frac{1}{T} \int_0^T p(t)^2 dt} \quad \dots (2.6)$$
- Sound power (W):
 - total acoustical output of a source
 - measured in watts (w)
 - computed with sound pressure
- Sound power level (PWL or L_w):
 - $L = 10 \log(A/B) \text{ dB} \quad \dots (2.7)$
 - $L_w = 10 \log(W/W_0) \text{ dB, re } 10^{-12} \text{ watt} \quad \dots (2.8)$

19

Sound Power and Point Sources

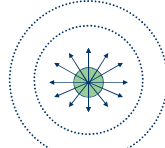
- Acoustical power uniformly radiates in all directions in an expanding sphere
 - Cannot be measured directly
 - Does not vary with distance
 - Power is energy per time. If steady-state, power is "conserved."
 - Power same regardless of volume containing it because the amount of energy is fixed at any given time.



20

Illustration of Power and Intensity

- Intensity = Sound Power per unit area
 - Value passing the surface of the sphere at a particular radius
 - Intensity proportional to pressure squared
 - Relationship of surface area to radius forces intensity to fall 6 dB every doubling of distance from the source
 - Difficult to measure intensity directly. Pressure easy to measure.

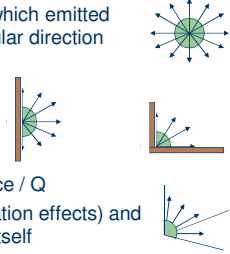


- Conversely: Sound Power = Intensity x Area

21

Directivity


- Measure (Q) of the degree to which emitted sound is channeled in a particular direction (instead of uniform sphere)
 - Sphere: Q = 1
 - Hemisphere: Q = 2
 - 1/4 Sphere: Q = 4
 - 1/8 Sphere: Q = 8
- Surface area = spherical surface / Q
- Due to reflecting surfaces (location effects) and to directionality of the source, itself
- Typically increases with frequency



22


Directivity -- continued

- Q = ratio of observed to expected sound pressure
 - Expected: if spherically radiated
 - Observed and expected at same distance, r
- Directivity index:
 - $DI = 10 \log(Q) \text{ dB} \quad \dots (2.9)$
- Example: for hemispherical (Q=2)
 - DI = 3 dB higher than if spherical (Q=1)



23

Homework, due next class.



- If all the power in your 100 watt stereo system was converted to sound power, what would the sound power be in dB?
- If the speaker was placed 30 ft from, what would the sound intensity in dB at your location if the speaker was located on a:
 - flat, hard field
 - flat hard field against a high, long concrete wall in the middle of its length
 - flat hard field in the corner created by two high, long concrete walls
- You measure an average sound intensity of 80 dB at 11 m from a speaker suspended well above ground outdoors. What is the sound power of the speaker?

24

Sound Pressure Level

- Abbreviation = SPL or L_p
- 20 μ Pascals = nominal hearing threshold @ 1000
- Threshold of pain occurs at approximately 100 Pascals
- Range of more than a million to 1
- Ear responds not linearly but logarithmically

25

The Decibel Scale

- Must use log scale. Bel = \log_{10} .
- One tenth of a Bel = decibel
- Sound Pressure Level = $10 \log_{10} (P/P_{ref})^2$
- $SPL = L_p = 10 \log_{10} (P/P_{ref})^2$
- $SPL = 20 \log_{10} (P/P_{ref})$
- where: P = sound pressure measured
- $P_{ref} = 20 \mu Pa$
- Note: $(P/P_{ref})^2 = 10^{SPL/10}$
- Zero decibels not absence of noise. It is simply the reference level.

26

Perception and dB

Equal-loudness contours (red) (from ISO 226:2003 revision)
Original ISO standard shown (blue) for 40-phon

dB	Perception
3	just perceptible
5-6	clearly perceptible
10	sounds twice as loud

27

Weighting scales

- Definition: adjustments to measured values
- Flat or linear: no weighting
- A scale (dBA)
 - Approximation of responses of human ear
 - Required by OSHA and EPA
- B scale is rarely used (dBB)
- C scale (dBC)
 - Weights frequencies equally
 - Sometimes used in noise control
- 1000 unweighted on all scales
- All scales ignore very high and very low frequencies

28

Typical noise levels

WHEN IS NOISE TOO LOUD?

Jet Engine (near)	140	Shotgun firing
Jet takeoff (100 feet)	130	Rock concerts
Boom Box	120	Chain saw (gas)
Jackhammer	110	Radio headset
Arcade Game Parlor	100	Lawnmower (5 feet)
Motorcycle	90	Hair dryer
City traffic noise	80	Vacuum cleaner
Dishwasher	70	Normal Conversation
Inside car windows up	60	Quiet office
Refrigerator humming	50	Living room
Broadcasting studio	40	Whisper
Hearing test booth	30	Rustling leaves
Sounds just audible	0	Normal breathing

NOISE LEVEL (dB SPL)
Decibel Sound Pressure Level

29

Some examples

Some Examples of sound measurements
Taken by NIOSH

Source: <http://www.cdc.gov/niosh/hp0.html>

30

Example of A-Weighting

Description	63	125	250	500	1k	2k	4k	8k
Lp	74	88	83	82	81	77	72	58
A-weighting, dB	-26	-16	-9	-3	0	1	1	-1
Lp, dB, A-wt	48	72	74	79	81	78	73	57

31

Adding sound levels

For "n" random, uncorrelated sounds

$$\text{For pressure} = \frac{P_{total}^2}{P_{ref}^2} = \sum_{i=1}^n \frac{P_i^2}{P_{ref}^2}$$

$$\text{Since: } SPL = 10 \log_{10} (P^2/P_{ref}^2) \quad \text{Then: } 10^{\frac{SPL}{10}} = \frac{P^2}{P_{ref}^2}$$

$$\text{Therefore: } 10^{\frac{SPL_{total}}{10}} = \sum_{i=1}^n 10^{\frac{SPL_i}{10}}$$

$$\text{Taking logs of both sides: } SPL_{Total} = 10 \log_{10} \left[\sum_{i=1}^n 10^{\frac{SPL_i}{10}} \right]$$

32

Adding unequal sound levels

Example: Given $SPL_1 = 75$ dB and $SPL_2 = 74$ dB

$$\begin{aligned} SPL &= 10 \log_{10} \left(10^{\frac{SPL_1}{10}} + 10^{\frac{SPL_2}{10}} \right) \\ &= 10 \log_{10} \left(10^{7.5} + 10^{7.4} \right) \\ &= 10 \log_{10} (10^{7.5} + 10^{7.4}) = 77.54 \text{ dB} \end{aligned}$$

33

Adding two equal sound levels

$$\begin{aligned} SPL_{total} &= 10 \log_{10} \sum_{i=1}^n 10^{\frac{SPL_i}{10}} \\ &= 10 \log_{10} \left(10^{\frac{SPL_1}{10}} + 10^{\frac{SPL_1}{10}} \right) = 10 \log_{10} \left(2 \times 10^{\frac{SPL_1}{10}} \right) \\ &= 10 \log_{10} \left(10^{\frac{SPL_1}{10}} \right) + 10 \log(2) \\ &= SPL_1 + 10(.301) = SPL_1 + 3 = 60 + 3 = 63 \text{ dB} \end{aligned}$$

34

Adding four equal sound levels

$$\begin{aligned} SPL_{total} &= 10 \log_{10} \sum_{i=1}^4 10^{\frac{SPL_i}{10}} \\ &= 10 \log_{10} \left(4 \times 10^{\frac{SPL_1}{10}} \right) \\ &= 10 \log_{10} \left(10^{\frac{SPL_1}{10}} \right) + 10 \log(4) \\ &= SPL_1 + 10(.602) = SPL_1 + 6 = 60 + 6 = 66 \text{ dB} \end{aligned}$$

35

Finding an unknown source when total and others known

$$SPL_1 = 10 \log_{10} \left[10^{\frac{SPL_{total}}{10}} - 10^{\frac{SPL_2}{10}} - \dots - 10^{\frac{SPL_n}{10}} \right]$$

Example: Given $SPL_{total} = 75$ dB and $SPL_2 = 74$ dB

$$SPL_1 = 10 \log_{10} \left(10^{\frac{SPL_{total}}{10}} - 10^{\frac{SPL_2}{10}} \right)$$

$$SPL_1 = 10 \log(10^{7.5} - 10^{7.4}) = 68 \text{ dB}$$

36

Adding & Subtracting 2 Sources (Table)

$$\Delta SPL_{total} = 10 \log_{10} \left[10^{\frac{SPL_2}{10}} + 10^{\frac{SPL_1 + \Delta SPL}{10}} \right] - SPL_1$$

$\frac{SPL_2 - SPL_1}{SPL_1}$	$\frac{SPL_{total} - SPL_1}{SPL_1}$	$\frac{SPL_2 - SPL_1}{SPL_1}$	$\frac{SPL_{total} - SPL_1}{SPL_1}$
0	3.01	9	0.51
1	2.54	10	0.41
2	2.12	11	0.33
3	1.76	12	0.27
4	1.46	13	0.21
5	1.19	14	0.17
6	0.97	15	0.14
7	0.79	16	0.11
8	0.64	17	0.09

37

Another Abbreviation: $L_p = SPL$

$$L_p = 10 \log \left[\sum_{i=1}^N 10^{\frac{L_{p_i}}{10}} \right], dB$$

38

Homework

Condition	SPL_1	SPL_2	SPL_3	SPL_{total}
2 sources	85	85	0	
2 sources	100		0	103
2 sources	89	88	0	
2 sources		101	0	102
2 sources	100	89	0	
2 sources	102	80	0	
3 sources	75	80	81	
3 sources	75	68	79	
3 sources	75	67	61	
3 sources	75	66	78	
3 sources, 2 the same	75			80

39

Finding dBlin and dBA

Description	63	125	250	500	1k	2k	4k	8k	dBlin	dBA
Lp	74	88	83	82	81	77	72	58	90.8	
A-weighting, dB	-26	-16	-9	-3	0	1	1	-1		
Lp, dB, A-wt	48	72	74	79	81	78	73	57		85.2

$$SPL_{Total} = 10 \log_{10} \left[\sum_{i=1}^{n=8} 10^{\frac{SPL_{n_i, dB}}{10}} \right], dBlin$$

$$SPL_{Total} = 10 \log_{10} \left[\sum_{i=1}^{n=8} 10^{\frac{(SPL_{n_i} - A_{w_i}), dB}{10}} \right], dBA$$

40

HW: Compute dBlin and dBA

Due next class

Problem	Lp Value at Frequency								Fill Blanks	
	63	125	250	500	1k	2k	4k	8k	dBlin	dBA
1	60	65	79	87	86	81	80	67		
2	82	82	82	82	82	82	82	82		
3	60	68	78	84	82	85	76	65		
4	86	85	78	80	85	79	79	79		
5	74	88	83	82	81	77	72	58		

41

The End Questions?

42