Acoustical Fundamentals

Part 1: Sound pressure levels and decibel mathematics

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Topics to be covered

- Properties of sound (or noise)
- Mathematics of sound (decibel calculations)
- How properties of sound change as it travels from source to receiver

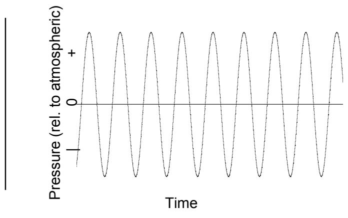
What is sound?

- Pressure disturbance in air
- Travels as wave outward from source
  - Alternating regions of compression and expansion of air molecules
  - Wave has fixed velocity in given medium
    - 344 m/sec in air at STP
    - 1130 ft/sec in air at STP
    - Higher velocity in denser medium

Sound Pressure

- Normal atmospheric pressure
  - 14.7 psi
  - 30 inches Hg
  - 760 mm Hg
  - 101,000 Pascals (Pa)
- Sound pressure fluctuation from normal
  - Alternates above and below normal
  - Very small pressure changes
  - Minimum audible 0.00002 Pa
  - Normal conversation 0.02 Pa

Sound pressure graph



Sound Pressure Level

- SPL = Logarithmic transformation of sound pressure
- Mean pressure = 0
- RMS - root mean square of pressure
- Unit is decibel (dB)
- $dB = 10 \log P^2 + 94$
- $dB = 20 \log P + 94$
- $0\ dB = 20 \log (0.00002) + 94$

Decibel Examples

- 0 dB – Threshold of hearing
- 20 dB – Very quiet room
- 40 dB – Quiet room
- 60 dB – Conversational level
- 80 dB – Loud (traffic, industrial)
- 100 dB – Very loud (power saw)
- 120 dB – Immediate damage potential
- 140 dB – Threshold of pain

Logarithm rules (1)

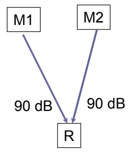
- Two kinds of logs
  - Base 10, common logs
  - Base e, natural logs, ln (e = 2.718…)
- Acoustics, common logs only
- Common log values

log 10 = 1, log 100 = 2, log 1000 = 3
log 0.1 = -1, log 0.01 = -2, log 0.001 = -3
log 1 = 0, log 2 = 0.3, log 3 = 0.5
log 0 is undefined

Logarithm rules (2)

- $\log X^2 = 2 \log X$
- $\log (1/X) = - \log X$
- $\log (XY) = \log X + \log Y$
- $\log 2X = \log 2 + \log X = 0.3 + \log X$
- $Y = \log X$ so $X = \text{inv} \log Y = 10^Y$

Decibel Math



- 90 kg + 90 kg = 180 kg
- 90 dB + 90 dB = 93 dB

- 90 kg + 70 kg = 160 kg
- 90 dB + 70 dB = 90 dB

- Logarithms are the reason!

Decibel Math (2)

- When two sounds add, we add their sound power (energy per second)
  1. Power is proportional to pressure squared
  2. $W_T = P_1^2 + P_2^2$
  3. $dB_1 = 10 \log (P_1^2); dB_2 = 10 \log (P_2^2)$
  4. $dB = 10 \log (P_1^2 + P_2^2)$
  5. $dB = 10 \log (2P_1^2) = 10 \log 2 + 10 \log P_1^2$
  6. $= 10 (0.3) + dB_1 = 3 + dB_1$
- 80 + 80 = 83; 24 + 24 = 27; 72 + 72 = 75

Summing sound pressure levels

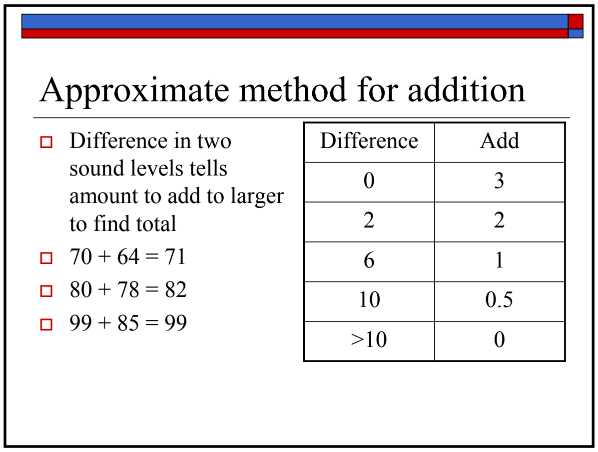
- Power = W, L = sound pressure level
- L = 10 log W
- $W = \text{inv} \log (L/10) = 10^{(L/10)}$

$L_1 + L_2 = 10 \log (W1 + W2)$

$= 10 \log (10^{L1/10} + 10^{L2/10})$

$L_{total} = 10 \log (10^{L1/10} + 10^{L2/10} + 10^{L3/10} + 10^{L4/10})$

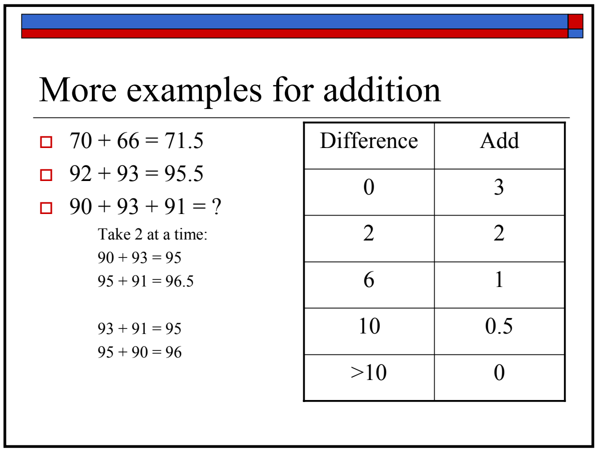
$90 + 93 + 91 = 10 \log (10^{9.0} + 10^{9.3} + 10^{9.1}) = 96.29$



Approximate method for addition

- Difference in two sound levels tells amount to add to larger to find total
- 70 + 64 = 71
- 80 + 78 = 82
- 99 + 85 = 99

Difference	Add
0	3
2	2
6	1
10	0.5
>10	0

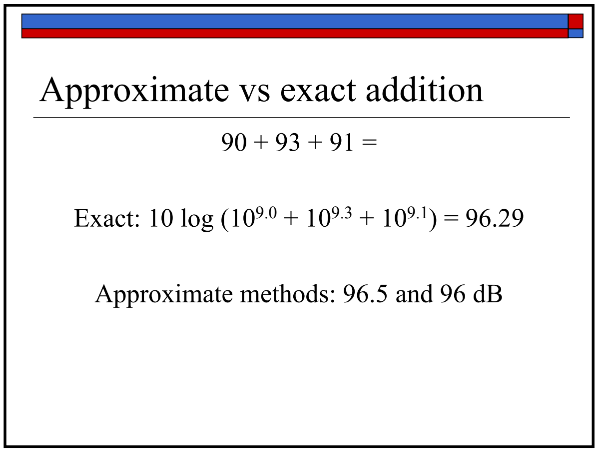


More examples for addition

- 70 + 66 = 71.5
- 92 + 93 = 95.5
- 90 + 93 + 91 = ?
  - Take 2 at a time:
  - 90 + 93 = 95
  - 95 + 91 = 96.5

  - 93 + 91 = 95
  - 95 + 90 = 96

Difference	Add
0	3
2	2
6	1
10	0.5
>10	0

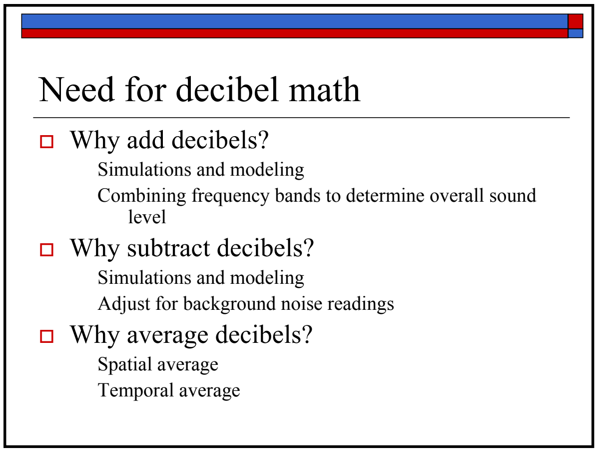


Approximate vs exact addition

90 + 93 + 91 =

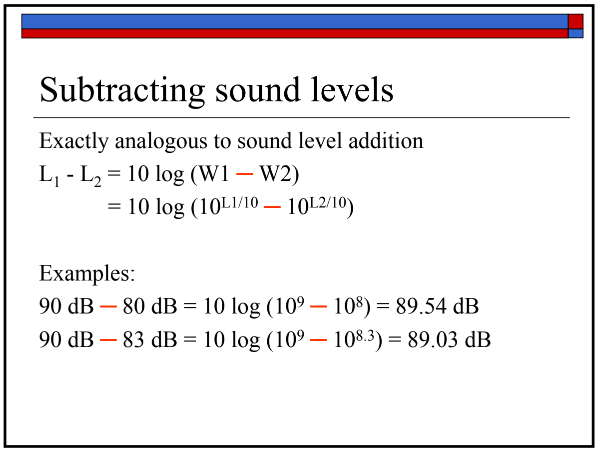
Exact: $10 \log (10^{9.0} + 10^{9.3} + 10^{9.1}) = 96.29$

Approximate methods: 96.5 and 96 dB



Need for decibel math

- Why add decibels?
  - Simulations and modeling
  - Combining frequency bands to determine overall sound level
- Why subtract decibels?
  - Simulations and modeling
  - Adjust for background noise readings
- Why average decibels?
  - Spatial average
  - Temporal average



Subtracting sound levels

Exactly analogous to sound level addition

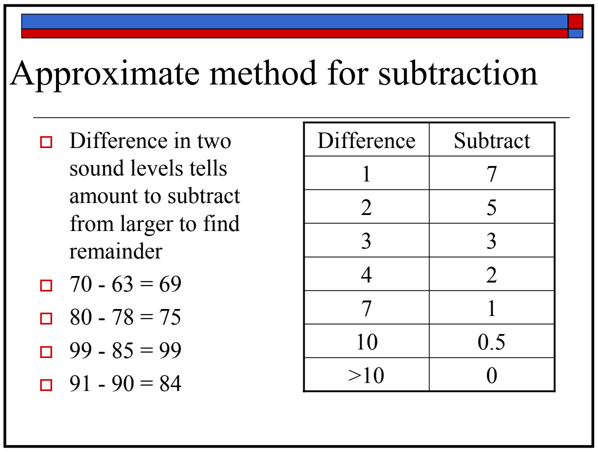
$L_1 - L_2 = 10 \log (W1 - W2)$

$= 10 \log (10^{L1/10} - 10^{L2/10})$

Examples:

90 dB − 80 dB = $10 \log (10^9 - 10^8) = 89.54$ dB

90 dB − 83 dB = $10 \log (10^9 - 10^{8.3}) = 89.03$ dB



Approximate method for subtraction

- Difference in two sound levels tells amount to subtract from larger to find remainder
- 70 - 63 = 69
- 80 - 78 = 75
- 99 - 85 = 99
- 91 - 90 = 84

Difference	Subtract
1	7
2	5
3	3
4	2
7	1
10	0.5
>10	0

Subtraction difficulties

91 - 90 = 84 (approx)
91 - 90 = 84.2 (exact)
91 – 90.5 = 81.4 (exact)

0.5 dB measurement error leads to 3 dB calculation error

Difference	Subtract
1	7
2	5
3	3
4	2
7	1
10	0.5
>10	0

Averaging sound pressure levels

- No simple approximate method
- Exact method: L_{avg} =

$$10 \log[(10^{L1/10} + 10^{L2/10} + 10^{L3/10} + 10^{L4/10} + \dots + 10^{Ln/10}) \div n]$$

- Average 90 and 80 dB =

$$10 \log[(10^9 + 10^8) \div 2] = 87.4 \text{ dB}$$

- Why not 85 dB?

Weighted averaging

- $L_{wtd\ avg} = 10 \log[(w_1 10^{L1/10} + w_2 10^{L2/10} + w_3 10^{L3/10} + w_4 10^{L4/10} + \dots + w_n 10^{Ln/10}) \div (w_1+w_2+w_3+\dots+w_n)]$
- Normally time weighting, often called equivalent sound level, L_{eq}
- 90 dB for 5 minutes, 80 dB for 55 minutes
- $L_{eq} = 10 \log[(5\text{x}10^9 + 55\text{x}10^8) \div 60]$
  $= 82.4$ dB

Weighted averaging - OSHA

- $L_{osha} = 17 \log[(w_1 10^{L1/17} + w_2 10^{L2/17} + w_3 10^{L3/17} + w_4 10^{L4/17} + \dots + w_n 10^{Ln/17}) \div (w_1+w_2+w_3+\dots+w_n)]$
- Calculated average according to OSHA rules, often called L_{osha}
- Actually 16.61, not 17
- 90 dB for 5 minutes, 80 dB for 55 minutes
- $L_{osha} = 81.6$ dB

Summary - sound pressure level

- Logarithmic transformation of RMS acoustic pressure value
- Unit is dB - range 0 to 140 dB
- Decibel units may be added, subtracted, averaged using special rules
- L_p (SPL) is indication of sound power and sound energy (over time)

Acoustical Fundamentals

Part 2 - Sound frequency

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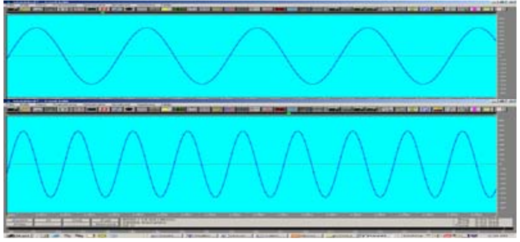
Sound frequency

- Pressure oscillations per second
- Unit Hertz (Hz); 1 Hz = 1 cycle/sec
- Human hearing range 20 - 20,000 Hz
- Infrasound < 20 Hz; ultrasound > 20 kHz
- Peak sensitivity = 2-3 kHz
- Subjective sensation of frequency is pitch

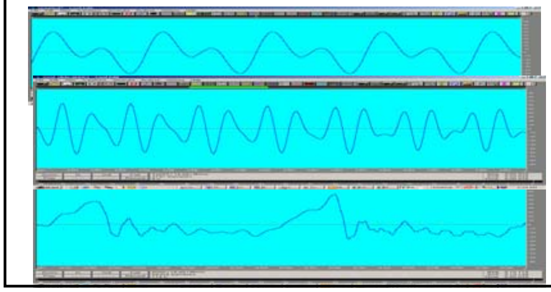
Pure tone sounds

- Single frequency = pure tones



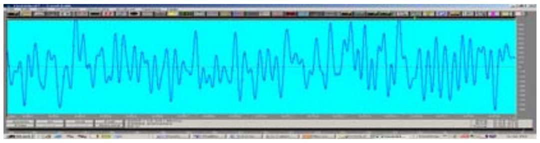
Mixtures of tones

- Musical notes - voices



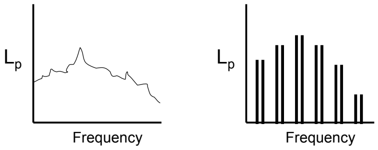
Broadband noise

- Many frequencies mixed together
- Random fluctuation of sound levels
- White noise - all frequencies equal probability
- Pink noise - weighted toward low frequencies



Examples of spectrum display

- Spectrum is display of sound pressure level at various frequencies
  - Graphical
  - Tabular



Frequency Bands

- Constant bandwidth
  - 1 Hz, 10 Hz, 100 Hz, etc
- Constant percentage bandwidth
  - Octave band (0.71 x center frequency)
  - Third octave bands (.235 x center frequency)
  - Others (1/10 or 1/12 octave)
- Octave and 1/3 octave most common

Octave bands

- Upper frequency = 2 x lower frequency
- Center frequency = √Upper X Lower
- Standard center frequencies
  - 16 31 63 125 250 500 1000 2000 4000 8000 16k
- Upper = 1.414 x CF, lower = CF ÷ 1.414
- Example: 1000 Hz band (707 Hz to 1414 Hz)
- Complete coverage, no gaps

Alternative to sound spectrum

- Combination of all levels and frequencies
- Unweighted sound pressure level
- Weighted sound pressure levels
  - Different weights for different frequencies
  - Most common, A weighting
  - Others – B and C weighting

A-weighting

- Used for simplification of measurements
- Correlates reasonably with
  - hearing loss risk
  - annoyance
  - sleep disturbance
  - speech interference
- Weighting factors:

63	125	250	500	1k	2k	4k	8k
-26	-16	-9	-3	0	+1	+1	-1

C-weighting

- Covers full audible spectrum
- Uses
  - Hearing protector assessment
  - A-C difference to estimate frequency
- Weighting factors:

63	125	250	500	1k	2k	4k	8k
-0.8	-0.2	0	0	0	-0.2	-0.8	-3

Weighted sound levels

- dBA, dB(A), L_A = 80 dB
- Example: L_C - L_A = 10 dB
- Predominant frequency = 250 Hz

63	125	250	500	1k	2k	4k	8k
-26	-16	-9	-3	0	+1	+1	-1
-0.8	-0.2	0	0	0	-0.2	-0.8	-3

Loudness of sounds

- Loudness involves L_P and frequency - unit = sone

115 dB - loud sound?

115 dB at 30000 Hz - ultrasound, inaudible

115 dB at 3000 Hz - very loud

115 dB at 30 Hz - less loud

115 dBA - includes both L_P and human hearing response

How is A-weighting done

- Electronically, by sound measuring instrument
- By calculation, from octave bands

63	125	250	500	1k	2k	4k	8k
75	75	70	70	68	66	61	51
-26	-16	-9	-3	0	+1	+1	-1
49	59	61	67	68	67	62	50

Noise Control Example

63	125	250	500	1k	2k	4k	8k	
75	75	70	70	68	66	61	51	
-26	-16	-9	-3	0	+1	+1	-1	
49	59	61	67	68	67	62	50	73 dBA
-5	-6	-8	-10	-12	-14	-18	-20	
44	53	53	57	56	53	44	30	61 dBA

Frequency Summary

- Unit of Hz, range 20 Hz - 20 kHz, maximum sensitivity at 2-3 kHz
- Classification of sounds
  - Pure tones, mixture of tones, random noise
- Spectrum is display of dB vs Hz
- Spectrum analysis often in octave bands
- A-weighting combines L_P and frequency distribution, approximates loudness

Acoustical Fundamentals

Part 3 - Sound propagation

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Sound Propagation

- How does sound change as it moves away from the source?
  - Sound level
  - Frequency
- Factors influencing changes
  - Distance
  - Type of source
  - Atmosphere
  - Intervening objects

Effect of Distance

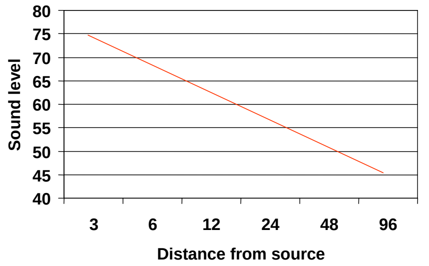
- Point source, free field (no obstacles)
- Power loss is proportional to distance squared

$\Delta L_p = 10 \log (d_1/d_2)^2$

$\Delta L_p = 20 \log (d_1/d_2)$

d_1/d_2	ΔL_p
2	6
4	12
8	18
10	20
100	40

Sound decrease (point source)

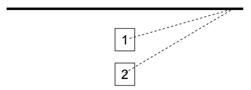


Effect of Distance – Line Source

- Like highway or pipeline
- Loss proportional to distance

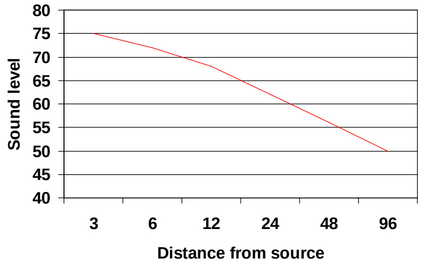
$\Delta L_p = 10 \log (d_1/d_2)$

- Only true while relatively close to line source (d<L/3)



d_1/d_2	ΔL_p
2	3
4	6
8	9
10	10
100	20

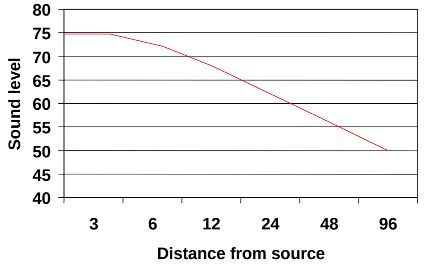
Sound decrease (30m line source)



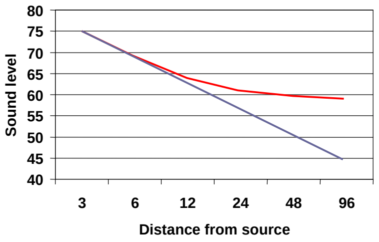
Effect of Distance - Area source

- Objects like side of building with noise source inside
- Assume L x W, where W<L
- No loss while relatively close to source (d<W/3)
- Like line source out to d=L/3
- Like point source beyond that

Sound decrease (area source)



Sound decrease - indoors



Frequency change in propagation

- Geometrical spreading same for all frequencies
- Other mechanisms differ with frequencies
  - Absorption by atmosphere
  - Refraction by atmosphere
  - Interaction with barriers and structures

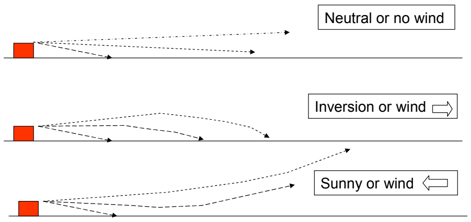
Attenuation by atmosphere

- Significant only for large distances (>100m)
- Variables
  - Frequency
  - Temperature
  - Humidity
  - Distance

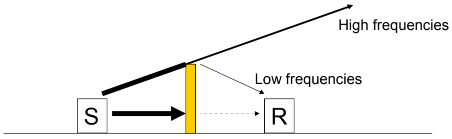
Calculation of attenuation

		Atmospheric Attenuation (dB/1000m)					
Temp C	Rel Hum	125	250	500	1000	2000	4000
	30	0.4	1.5	3.8	6.8	12	32
30	50	0.3	1	3.3	7.5	13	25
	90	0.2	0.6	2.4	7	15	26
	30	0.5	1.4	2.7	5.1	13	44
20	50	0.4	1.2	2.8	5	10	28
	90	0.2	0.8	2.6	5.6	10	21
	30	0.5	1.1	2.9	9.4	32	90
10	50	0.4	1.1	2	4.1	12	42
	90	0.3	1	2.1	3.8	8.1	25

Refraction by atmosphere



Interaction with barriers



Sound interaction with objects