PH2233 Fox : Lecture 08
Chapter 16 : Sound

Review:

Vibrating Strings : transverse waves on a medium with $v = \sqrt{F_T/\mu}$. Boundary conditions were that the tranverse displacement had to be ZERO at the ends of the wire, meaning the length of the wire had to be a multiple of $\lambda/2$. For a fixed length L, the wavelengths and frequencies of the standing waves had to be:

$\lambda_N = \frac{2L}{N}$ and
$f_N = N\frac{v}{2L}$
where $\boxed{N = 1, 2, 3, ...}$ and $v = \sqrt{F_T/\mu}$ is the speed of the transverse waves travelling along the wire.

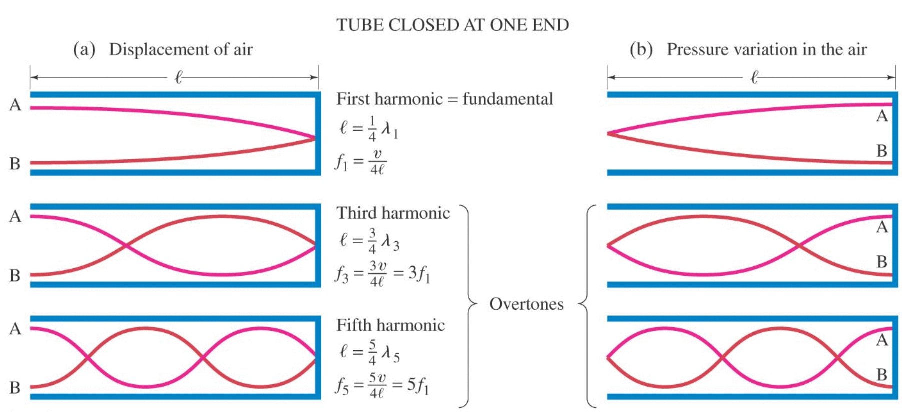
Open Pipe : standing longitudinal (pressure) waves are a solution to the wave equation but now the boundary condition was that the ΔP needed to be ZERO at the ends of the tube since those two locations were in contact with an essentially infinite reservoir of 1 ATM of pressure (i.e. a region where $\Delta P = 0$). This lead to the standing waves possible in a given length tube being such that:

$\lambda_N = \frac{2L}{N}$ and
$f_N = N\frac{v}{2L}$
where $\boxed{N = 1, 2, 3, ...}$ and v is the speed of sound in the medium.

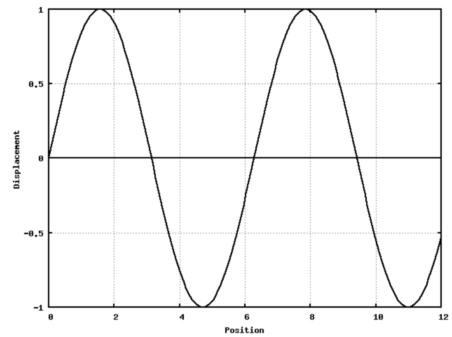
Since the speed of sound depends on temperature, the frequencies will all change as the temperature changes. Wind instruments fix this by including components that can adjust the effective length of the resonating chamber (i.e. the length of the pipe).

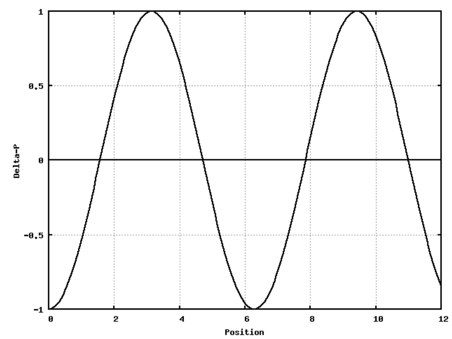
(Stringed instruments are also affected by changes in temperature but in a much more complicated way. As the temperature goes up, the strings get longer so the tension is reduced, but the instrument itself might expand somewhat compensating for that effect.)

Closed Pipe : What happens if we block off one (just one!) end of the pipe? In the figure below, we block off the right end of the pipe but leave the left end open. The standing wave patterns that will 'fit' now have two constraints. At the open end, we need a pressure node since ΔP has to be zero there. On the closed end though, we need a **displacement** node since the atoms there can't move either left or right. (They can't move to the right since there's a wall there; they can't move to the left because that would leave a vacuum behind and that would require a huge force.)



Figuring out the patterns that 'fit' (satisfy our boundary conditions) is a little easier with these figures. The top figure shows the displacement wave pattern and the bottom figure shows the pressure wave pattern.





We need standing waves with a pressure node ($\Delta P = 0$) at the open end of the pipe (the left end in the figure at the bottom of the previous page) and a displacement node ($D = 0$) at the closed end (the right end of the figure on the previous page).

So we'll start by finding a location in the bottom figure where $\Delta P = 0$. Now mark all the spots where $D = 0$ thanks to the top figure. How far apart are those points from our $\Delta P = 0$ location? The first one that works is where $L = \frac{\lambda}{4}$, the next one occurs where $L = 3(\frac{\lambda}{4})$, the next at $L = 5(\frac{\lambda}{4})$ and so on.

So what we're left with is:

$L = (1)(\frac{\lambda}{4})$
$L = (3)(\frac{\lambda}{4})$
$L = (5)(\frac{\lambda}{4})$

and so on.

This pattern is different from what we had before. Basically we have:

$\lambda_N = \frac{4L}{N}$ and
$f_N = N\frac{v}{4L}$

where $\boxed{N = 1, 3, 5, ...}$ and v is the speed of sound in the medium.

NOTE CAREFULLY that for this 'closed pipe' it's only the ODD integers N that are being used.

Example

(a) How long would an organ pipe (CLOSED at one end this time) need to be to resonate at middle C (a frequency of $f = 261.626\ Hz$)?

$f_n = n\frac{v}{4L}$ (with just the odd n's being used) and if this is the fundamental frequency of the pipe then $f_1 = \frac{v}{4L}$.

The speed of sound at $20^o\ C$ is $v = 343\ m/s$ so rearranging:

$L = \frac{v}{4f_1} = \frac{343\ m/s}{(4)(261.626\ s^{-1})} = 0.3278\ m$ (note that's exactly **half** as long as we got with the fully open pipe before).

(b) If we now OPEN UP the closed end, what frequency will this pipe produce?

With an **open pipe**, $f_n = n\frac{v}{2L}$ so it's fundamental would be $f_1 = (1)\frac{343}{(2)(0.3278)} = 523.252\ Hz$ which is exactly twice what it was producing when closed. An exact doubling of the frequency represents exactly ONE OCTAVE so the pipe will now produce another C note that's one octave higher.

Pipe organs exploit this trick. Basically a set of pipes when closed at one of their ends yields one set of notes, but if if we open up that end we get the next octave for free.

TABLE 16–3 Equally Tempered Chromatic Scale†

Note	Frequency (Hz)
C	262
C♯ or D♭	277
D	294
D♯ or E♭	311
E	330
F	349
F♯ or G♭	370
G	392
G♯ or A♭	415
A	440
A♯ or B♭	466
B	494
C′	524

†Only one octave is included.

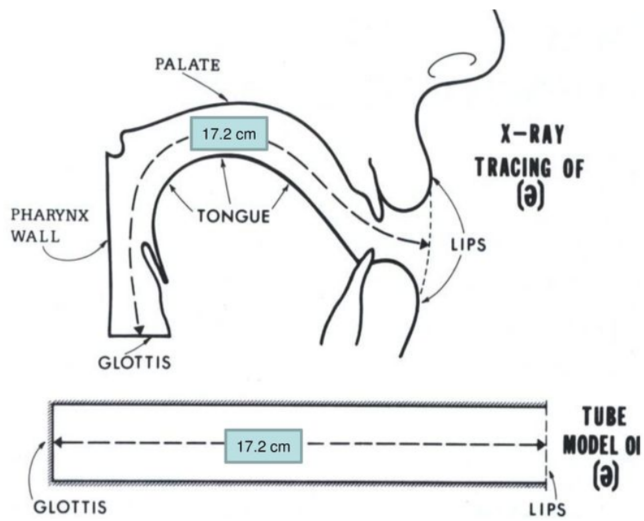
Example : Human Vocal Tract

The human vocal tract is a pipe that extends about 17.2 cm from the lips to the vocal folds (also called 'vocal cords') near the middle of your throat. The vocal folds behave rather like the reed of a clarinet, and the vocal tract acts like a closed pipe.

Estimate the first three standing-wave frequencies of the vocal tract. (The answers are only an estimate, since the position of lips and tongue affects the motion of air in the vocal tract.)

Inside this 'pipe' the air temperature is about 34^oC. The typical human body temperature is about 37^oC but air only stays in the lungs long enough to reach about $34^o\ C$.

$v = 331 + 0.6T = 331 + (0.6)(34) = 351^o\ C$



For a closed pipe, the fundamental frequencies are given by $f_n = n\frac{v}{4L}$ for $n = 1, 3, 5, ...$ The lowest frequency then would be $f_1 = (351\ m/s)/(4 \times 0.172\ m) \approx 510\ Hz$. The next two would be $f_3 = 3f_1 \approx 1531\ Hz$ and $f_5 = 5f_1 \approx 2551\ Hz$.

Try these sites to hear them:

https://onlinetonegenerator.com
https://onlinesound.net/tone-generator
https://www.szynalski.com/tone-generator

(The last one is good since you can enter particular notes too.)

Standing waves would form at these frequencies, meaning there will be specific spots in the vocal tract where pressure antinodes would occur. At those points, the pressure would vary between $\pm\Delta P_{max}$, exerting the largest changes in force on the throat lining, so those frequencies might be more painful for a singer to maintain.

Double-closed Pipe : the book doesn't consider these, noting that 'a tube closed at both ends, having no connection to the outside air, would be useless as an instrument' but that scenario still does exist. An enclosed shower stall is a perfect example. In this scenario, the boundary conditions would be that we need the displacement nodes to be at the boundaries of the chamber.

Consider a shower stall that is closed on all 4 sides (and on the bottom of course) but open at the top. The stall is 1 meter wide, 1 meter deep, and 2 meters from the floor to the **open** part at the top. What (audible) standing wave frequencies will exist in this geometry?

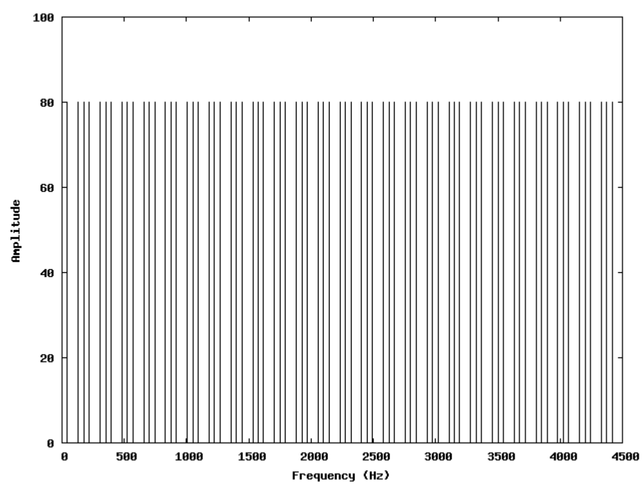
In the **up-and-down direction**, we have a closed pipe (i.e. one that's open at one end and closed at the other) so the frequencies will be $f_N = N\frac{v}{4L}$ with $N = 1, 3, 5, ...$

While taking a shower the air temperature will go up, but let's just keep the temperature at $T = 20^oC$ so the speed of sound is just $v = 343\ m/s$. Then $f_N = (N)\frac{343}{(4)(2)} = (N)(42.875\ Hz)$, again with just odd values for N. The standing-wave frequencies in this direction then would be $42.875\ Hz$, $128.625\ Hz$, $214.375\ Hz$, $300.125\ Hz$, and so on. If you're singing in the shower, those frequencies would create standing waves and sound particularly loud.

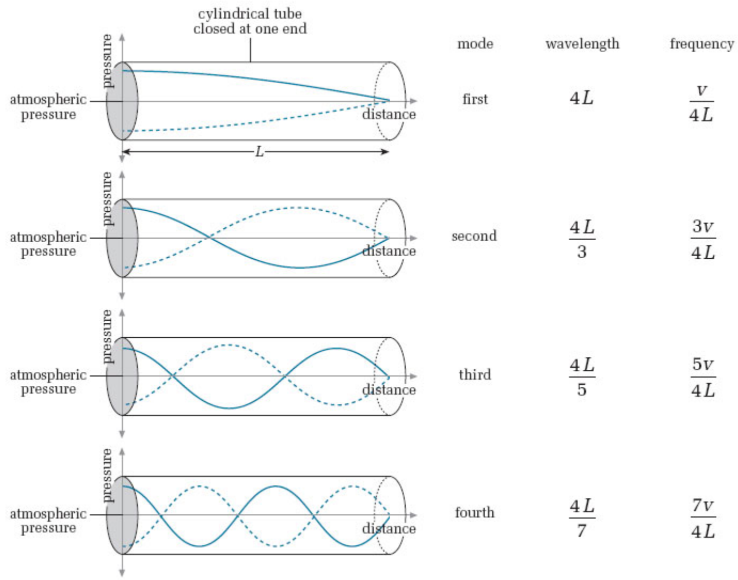
Let's look in the **left-right** or **back-front** directions now. In those directions we have a double-closed scenario. The displacement needs to be zero at each solid surface now. If L is the distance between the two ends (the left wall to the right wall, or the back wall to the front 'wall' or door) then the $D = 0$ points on the graph occur where $L = (N)(\lambda/2)$ for **all** integer values of N (not just the odd ones), leading to $f_N = N\frac{v}{2L}$ with $N = 1, 2, 3....$

With $L = 1\ m$ between the opposing walls, we have $f_N = (N)\frac{343\ m/s}{(2)(1\ m)} = (N)(171.5\ Hz)$ for $N = 1, 2, 3...$ yielding standing wave (i.e. louder) frequencies at $171.5\ Hz$, $343\ Hz$, $514.5\ Hz$, and so on.

For our particular geometry with the height of the shower stall being exactly twice the width or depth there aren't any frequencies that appear in both lists but between $20\ Hz$ and $20,000\ Hz$ there will be hundreds of frequencies creating standing waves, so it sounds like everything is amplified even though it's really only those few hundred special standing wave frequencies...)
This graph covers only up to $4500\ Hz$.

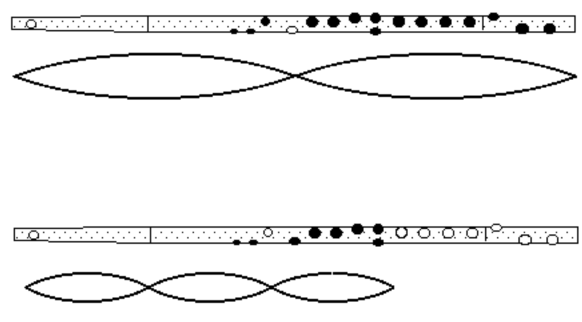


Playing an Instrument : Changing Notes Whether we're dealing with a stringed or wind instrument, we found that the instrument has a series of standing wave modes. Here's another look at a closed pipe (closed on the left end and open on the right in this figure). Lots of modes can exist. The fundamental will likely dominate but some energy will be present in the other modes, leading to the unique sound that each instrument emits, even when nominally playing the identical note.



How do we make an instrument play a different note? In all stringed and wind instruments, it's done by changing the length of the wire or pipe in some way.

Wind Instruments (flute) : the flute has a set of 'holes' drilled into it. If we close off all the holes, it produces the usual fundamental frequency. What happens (top figure) we open up the hole that's in the middle? The existence of that open hole means that $\Delta P = 0$ at that point. The fundamental is no longer a solution. The only modes that can exist now are those that happen to have a pressure node at that point.
Opening different holes eliminates other modes and some other frequency will now be the lowest the instrument can produce.



Stringed Instruments (guitar) : in the case of stringed instruments, the (tranverse) displacement of the string has to be zero at the two ends of the string and it's that length that determines the frequency the string produces. If we alter the length of the string, a different note is produced. In some (most?) stringed instruments, this is achieved by the user pushing down on the string until it contacts a metal(?) bar. That effectively causes a displacement node to move from the end of the string to the location of this 'fret.' The new length then yields a different note when played.

16.3 : Sound Intensity - decibels

The human ear is incredibly sensitive - it can detect intensities as low as $1 \times 10^{-12}\ W/m^2$ and as high as $1\ W/m^2$, at which point the sound is becoming painful (and being exposed for extended periods of time to that intensity can cause permanent damage).

This is such a large **dynamic range**, that intensity is often converted into a **logarithmic** scale called the **bel** or more commonly the **decibel**.
The 'bel' is defined as $log(I/I_o)$ where $I_o = 1 \times 10^{-12}\ W/m^2$ so sound that is just barely detectable is 0 *bel* and the pain threshhold would occur at 12 *bel*. That range (zero to 12) is a bit too coarse, so it's much more common to see sound intensities in units of deci-bels (tenth's of a bel) giving us a range from 0 to 120.
Ultimately then we'll define: $\beta = 10log(I/I_o)$ with β having units of decibels or dB (even though technically it's a unitless quantity).
This table gives some typical sound scenarios with the actual intensities in W/m^2 and the corresponding decibel level.

TABLE 16–2
Intensity of Various Sounds

Source of the Sound	Sound Level (dB)	Intensity (W/m^2)
Jet plane at 30 m	140	100
Threshold of pain	120	1
Loud rock concert	120	1
Siren at 30 m	100	1×10^{-2}
Truck traffic	90	1×10^{-3}
Busy street traffic	80	1×10^{-4}
Noisy restaurant	70	1×10^{-5}
Talk, at 50 cm	65	3×10^{-6}
Quiet radio	40	1×10^{-8}
Whisper	30	1×10^{-9}
Rustle of leaves	10	1×10^{-11}
Threshold of hearing	0	1×10^{-12}

Example : Let's revisit the case of standing $r = 2\ m$ away from a 40 W omnidirectional speaker. Last time we found the intensity was $I = P/S = 0.79577\ W/m^2$. Converting to decibels:

$$\beta = 10log(I/I_o) = 10log(\frac{0.79577\ W/m^2}{1\times10^{-12}\ W/m^2} = 10log(7.9577 \times 10^{11}) = 119\ dB$$

Example : Impact of Doubling the Intensity

Suppose we crank up the speaker from 40 W to 80 W exactly doubling the intensity. What effect does that have on the decibel level? Let's just do this symbolically first:

$$\beta_{new} = 10log(2I/I_o) = 10log2 + 10log(I/I_o) = (3.01\ dB) + \beta_{orig}$$

Doubling the actual W/m^2 intensity results in the decibel version going up by just $+3.01\ dB$. Similarly cutting the intensity in half would REDUCE β 3.01 dB. Basically each time we add 3 to the decibel number, that represents a doubling of the underlying intensity, and each time the decibel number decreases by 3, the intensity has dropped in half.

Arbitrary ratio: suppose $I_2 = (X)I_1$. Then:

$$\beta_2 = 10log(I_2/I_o) = 10log(I_2) - 10log(I_0)$$
$$\beta_1 = 10log(I_2/I_o) = 10log(I_1) - 10log(I_0)$$
$$\beta_2 - \beta_1 = 10log(I_2) - 10log(I_1) \text{ or simply:}$$

$$\Delta\beta = \beta_2 - \beta_1 = 10log(I_2/I_1) = 10log(X)$$

Ratio	Result
$I_2 = 2.0I_1$	$\beta_2 - \beta_1 = 10log(2.0) = +3.01\ dB$
$I_2 = 0.5I_1$	$\beta_2 - \beta_1 = 10log(0.5) = -3.01\ dB$
$I_2 = 10I_1$	$\beta_2 - \beta_1 = 10log(10) = +10\ dB$
$I_2 = 0.1I_1$	$\beta_2 - \beta_1 = 10log(0.1) = -10\ dB$
$I_2 = 100I_1$	$\beta_2 - \beta_1 = 10log(100) = +20\ dB$
$I_2 = 0.01I_1$	$\beta_2 - \beta_1 = 10log(0.01) = -20\ dB$
$I_2 = 1000I_1$	$\beta_2 - \beta_1 = 10log(1000) = +30\ dB$
$I_2 = 0.001I_1$	$\beta_2 - \beta_1 = 10log(0.001) = -30\ dB$

Example : Variation with Distance

$I = P/S$ power per area, so if we're twice as far away, what does that do to the intensity (in real terms, and in dB)?

Assume the sound is spreading out spherically so the area will be $S = 4\pi r^2$ meaning I proportional to $1/r^2$.

Suppose we measure the dB level at some distance r_o. What will the intensity be exactly twice as far away?

$I_{orig} = \frac{P}{4\pi r_o^2}$ and $I_{new} = \frac{P}{4\pi(2r_o)^2} = \frac{1}{4}\frac{P}{4\pi r_o^2} = \frac{1}{4}I_{orig}$

Doubling the distance cuts the (actual W/m^2 value of the) intensity down by a factor of 4. Each factor of 2 represents a drop of 3.01 dB so overall the intensity dropped by $\mathbf{6.02}$ dB.

Moving twice as far away reduces the intensity by about 6 dB, or the other away around: cutting the distance in half results in the dB value increasing by a factor of about 6.

Example : cowbells : I used to live on Nash Street and during a football game I could often hear the cowbells just barely. Let's call that equivalent to a 'whisper', which is an intensity of $\beta = 30$ dB.

(a) How much 'sound power' was being produced by the cowbells?

For this we need to convert from the 'convenience units' of decibels to the actual physical units of W/m^2 first:

$\beta = 10log(I/I_o)$ so $I = I_o 10^{(\beta/10)} = (1 \times 10^{-12}\ W/m^2)10^{(30/10)} = 1 \times 10^{-9}\ W/m^2$.

Converting to power: $I = P/S$ so $P = (I)(S) = (I)(4\pi r^2) = (1 \times 10^{-9}\ W/m^2)(4\pi)(2000)^2 = 0.050265\ W$.

(Now there were probably a thousand cowbells ringing at once, so each one would only be creating much less than a milliwatt of sound power. It's true that very little power is needed to create very loud sounds but we'll see later why this estimate is wrong.)

(b) How loud (in dB) would this sound be to players on the field? The thousand cowbells are all at various distances from the players at the center of the field, but let's use 50 m for a 'reasonable' average distance.

We can shortcut this one and do it separately from the first question. If the player is 50 meters from the source, that means they're 40 times closer than me. We know that each doubling of distance cuts the intensity down by a factor of 6.02 dB or each halving of the distance raises the intensity by that much. How many doublings are in a factor of 40?

$2^x = 40$ and taking the natural log of both sides: $xln(x) = ln(40)$ so $x = ln(40)/ln(2) = 5.32$. That many doublings means a $(5.32)(6.02\ dB) = 32\ dB$ difference. If it sounds like 30 dB at my location, it sounds like $30 + 32 = 62$ dB on the field. Looking at the table above, that should be like somebody talking about a half-meter away. (That seems way too low, and we'll see why..)

Let's check that with an actual W/m^2 approach. We found the total 'sound power' was 0.050265 W so if the listener is only 50 m away from the source(s), $I = P/S = (0.050265\ W)/(4\pi(50)^2) = 1.6 \times 10^{-6}\ W/m^2$.

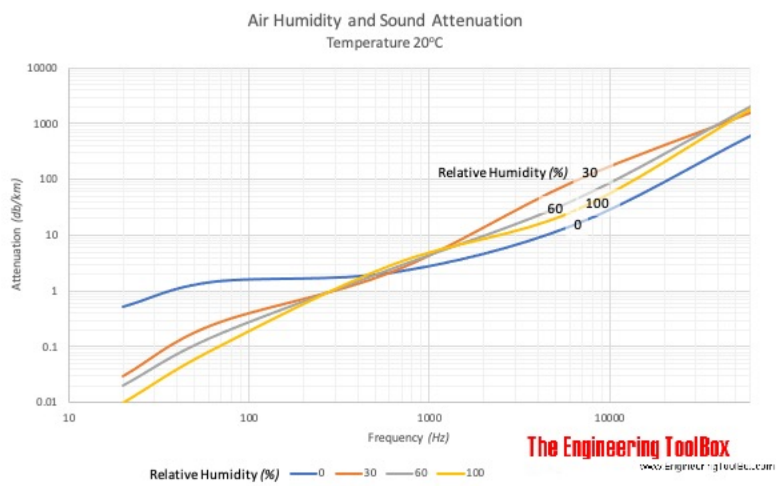
Converting that to decibels: $\beta = 10log(I/I_o) = 10log(\frac{1.6\times10^{-6}}{1\times10^{-12}}) = 62\ dB$.

(continued...)

Why is this wrong? I suspect that to the players on the field, thousands of ringing cowbells probably sounds a lot louder than just being near someone talking. What's missing here is that I'm not accounting for how much sound loses intensity just by passing through the air, an effect called **attenuation**. As a pressure-wave moves through a medium, it's alternately pushing atoms closer together (which raises their temperature) and then farther apart (decreasing their temperature). Thermodynamics is never 100% reversible, so there's always some loss of energy involved as a pressure-wave passes through a medium. This attenuation gets worse as the frequency goes up, the temperature goes up, and as the humidity goes up, so there's no good 'rule of thumb' for this. On a warm day in Starkville for mid frequencies, it's roughly 0.015 dB/m, so 2000 m away from the stadium, this would contribute an additional 30 dB of loss. If there were no losses due to this effect, the sound at my house would have been at 60 dB instead of just 30 dB, so adjusting the calculation above, the sound on the field would be not 62 dB but 92 dB ('truck traffic' according to Table 16-2). That's a bit more likely.

This figure shows the attenuation (in dB per **kilometer**) in air at 20^o C for various humidity values.

Note that higher frequencies are affected much more than lower frequencies.



We'll work through a subset of these in class, but I'll leave them all here in the notes.

Example : Pain Threshhold Pressure Amplitude : What pressure amplitude ΔP does the 'pain threshhold' represent?

$I = (\Delta P_{max})^2/(2\rho v)$ so $\Delta P_{max} = \sqrt{2\rho v I} = \sqrt{(2)(1.2)(343)(1)} = 28.7\ N/m^2$ and when we're recording pressures, the units of N/m^2 is usually called a 'Pascal' (Pa).

You'll often see this quoted as being about 30 Pa. In any event, standard atmospheric pressure here at the surface is about $101,000$ Pa so this painful level of sound is still a minute fraction of one atmosphere.

Example : Jet Engine : For a particular jet engine, a noise level of 140 dB was recorded at $r = 30\ m$ from the engine. How much total 'sound power' is the engine emitting?

$I = P/S$ so $P = (I)(S)$. If the sound is omnidirectional (which it isn't, so this will be an overestimate) $P = (I)(4\pi r^2)$.

From the decibel table, 140 dB represents $I = 100\ W/m^2$, so at 30 m we have about $P = (I)(4\pi r^2) = (100)(4\pi)(30)^2 = 1.13 \times 10^6\ W$ or about 1.13 MW of sound power.

A single engine on a Boeing 777 produced 75 MW of power total, so this is about 1.5%.

Extending the cowbell example, MSU is about 30 km from the GTR airport. Roughly how loud would this jet engine be here on campus?

First, 30 km is 1000 times farther away, and $2^10 = 1024$ so apparently this is almost exactly **10 doublings** and each doubling cuts the intensity by 6.02 dB, so that extra distance would reduce the sound level from 140 dB to $140 - 60 = 80\ dB$. Looking at Table 16-2 on a previous page, that's described as "busy street traffic" and in fact we rarely hear anything taking off that far away.

If we include the effect of attenuation (the absorption of some of that sound as it passes through air), if we lose 0.015 dB/m then over a 30 km distance we'd lose $(0.015)(30000) = 450\ dB$, so now we're down to $80 - 450 = -370\ dB$, and we can't hear anything below 0 dB, so we definitely shouldn't hear anything taking off from GTR.

Reality Check : The jet engine is **not** putting out sound equally in all directions, so if the back end of the jet is pointing our way the initial intensity would be much larger and the attenuation coefficient for **lower frequencies** is much lower (maybe 2 dB/km or 0.002 dB/m). On rare occasion, we can just barely hear this sound (at least the lower frequency rumbling).

Molecular Motion : What is the displacement amplitude of individual air molecules if a sound is at the very lowest end of human hearing? (I.e. $\beta = 0\ dB$.)

Looking at the table, this represents an actual intensity of $1 \times 10^{-12}\ W/m^2$.

$I = (\Delta P_{max})^2/(2\rho v)$ so $\Delta P_{max} = \sqrt{2\rho v I} = 2.878 \times 10^{-5}\ N/m^2$

If we want to convert intensity to amplitude we'll need a frequency, so here we'll punt and use $f = 1000\ Hz$.

$\Delta P_{max} = 2\pi \rho v f A$ so $2.878 \times 10^{-5} = (2)(\pi)(1.2)(343)(1000)(A)$ or $A = 1.1 \times 10^{-11}\ m$ or about $0.1 \times 10^{-10}\ m$. I did that conversion because $1 \times 10^{-10}\ m$ is about the diameter of an atom, so at this extreme end of what we can hear, the molecules of air are only moving about a tenth of their diameter back and forth when they run into the eardrum. (There are a **lot** of them doing so though, yielding a just-barely-noticeable sound.)

Example : Earbuds (I) : how much power do earbuds need to put out to be painful?

The pain threshhold represents an intensity of $I = 1\ W/m^2$, so the total power hitting the eardrum (a roughly circular disk of radius 5 mm) would be $P = (I)(S) = (1\ W/m^2)(\pi 0.005^2) = 8 \times 10^{-5}\ W$ or only about 0.08 *milliwatts*.

With earbuds, nearly all the sound they produce makes it to the eardrum, so they only need to create less than a tenth of a milliwatt of sound power. Assuming they're pretty efficient at converting electrical power into sound power, their batteries should last a very long time.

Example : Ear-buds (II) : Battery Capacity Needed

The Apple airpods pictured here allegedly can play music for 6 hours on a single battery charge. Assuming an 80 dB sound level:

- How much **power** is the speaker putting out?
- How much **energy** (in Watt-hours) is the fully charged battery storing?

Typical ear-bud batteries hold about **0.05 W*h** of energy. Where is the rest of this energy going?

As in the previous ear-bud example, we'll assume all the sound power being created by the speaker directly hits our eardrum.

Converting from dB to W/m^2: $\beta = 10 * log(I/I_o)$ so $I = I_o \times 10^{(\beta/10)} = (1 \times 10^{-12}\ W/m^2) \times 10^8 = 1 \times 10^{-4}\ W/m^2$.

Intensity is power per area: $I = P/S$ so the sound power here is $P = (I)(S)$ where S is the area of the eardrum (circular membrane with a radius of about 5 mm) so:

(a) $P = (0.0001\ W/m^2) \times \pi(0.005\ m)^2 = 8 \times 10^{-9}\ W$.

(b) Putting out that many Watts for 6 hours represents an energy of $(8 \times 10^{-9}\ W)(6\ hours)$ or about $5 \times 10^{-8}\ W \cdot h$.

The battery allegedly stores $0.05 = 5 \times 10^{-2}\ W \cdot h$ of energy, so only about 1 part in a million of this energy is getting converted into sound.

Is the system really this inefficient?

We're missing a lot of other factors involved in this situation. For one, not all the power generated by the speaker actually reaches our eardrum (the insides of our ear absorb some of it).

The most important missing factor is that these earbuds are **wireless**, using Bluetooth radio to receive signals from another device (phone usually) and that process consumes most of the energy here.

Example : Tornado Warning Siren :

The specs for a particular air-raid siren (used more for tornado warnings) are listed as producing 138 dB of sound at a distance of 30 m from the siren. It's also claimed that this siren is powered by a 180 hp diesel motor. Let's see if the given data is consistent.

$\beta = 10log_{10}(I/I_o)$ so $I = I_o 10^{(\beta/10)}$

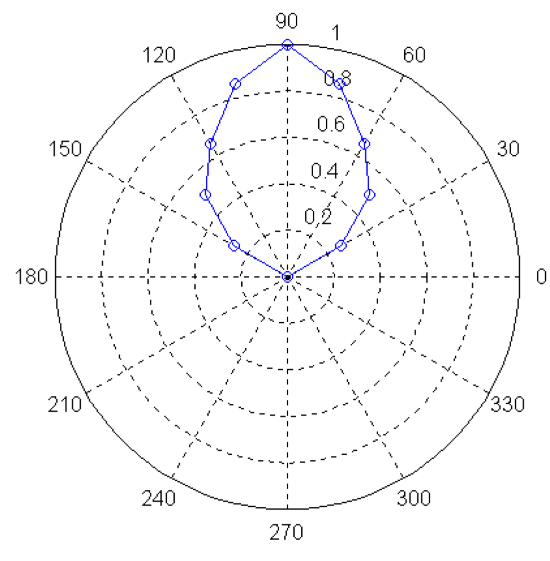
$I = (1 \times 10^{12})10^{(138/10)} = 10^{1.8} = 63.1\ W/m^2$.

If the 'speaker' is **omnidirectional**, spreading the sound out uniformly in all directions equally, $S = 4\pi r^2$, so $P = IS = 714,000\ W$. Now 746 W is 1 hp so this is 960 hp.

That's much higher than the 180 hp motor that was mentioned. What went wrong?

If we look at the design of this 'speaker', it's clearly NOT omnidirectional and is fact designed to send sound out in a cone. S is not the entire spherical surface, but just a small fraction of that. If it's just a fifth of the sphere, we're down to 180 hp.

Tornado Warning Siren



150 Hz

The figure on the right is essentially a polar plot showing how the intensity varies with **angle**, where in this plot the siren is aimed to produce its full intensity at 90^o (i.e. probably pointing straight North). If we move roughly $\pm 45^o$ away from that direction though ($\theta = 90^o \pm 45^o$ in the figure), the intensity has dropped in half, and by $\theta = 90^o \pm 60^o$ relative to north, the intensity is mostly gone.

We'll see plots like these in the context of wireless router antennas later in the course.