NOISE CONTROL IN MECHANICAL SYSTEMS

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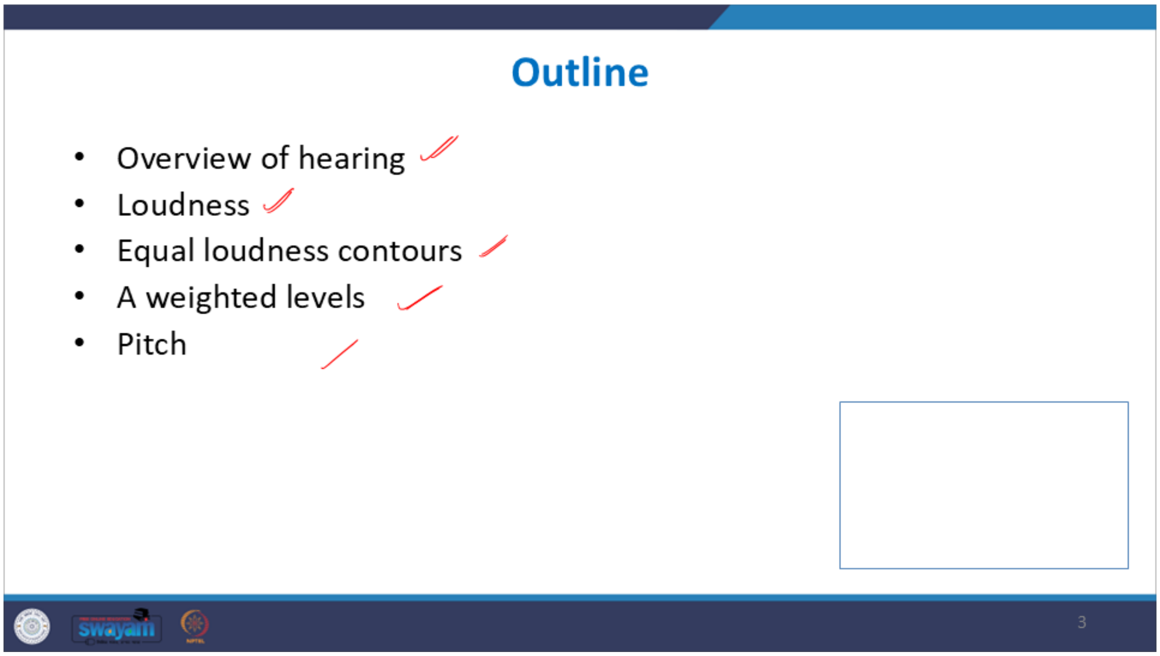
Week:4

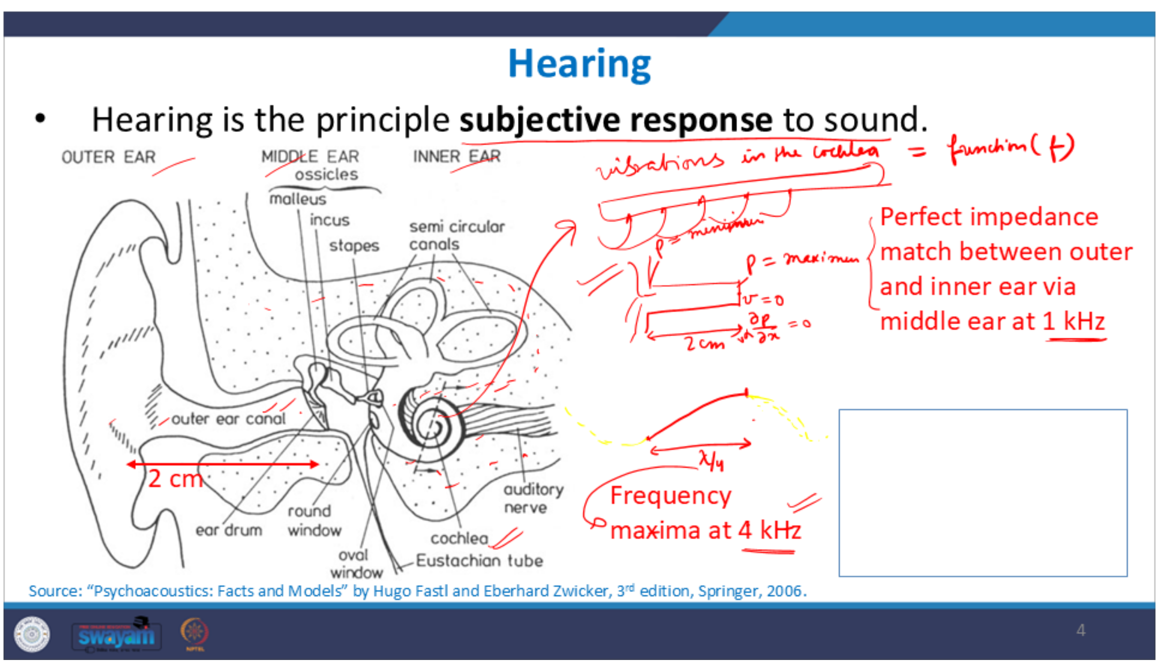
Lecture:18

Lecture 18: Introduction to human hearing

Welcome to the lecture 18 in this course on noise control in mechanical systems and in this lecture, we will be starting a new module in this course which would be a module on human response to noise. And to discuss about the human response to noise, we will study about various aspects such as what do you mean by human hearing? How do the humans hear and perceive the sounds? And what are some of the subjective metrics through which we can correlate how the human is perceiving the sound? We will also study how the sound affects the human. We will have both auditory effects of sound as well as non-auditory effects of sound and a very common industrial hazard which is noise induced hearing loss will be introduced in this module and then finally, we will see about once we have understood and taken a grasp of how noise affects the human beings. Then we come to know and understand that regulations are imperative in order to control the noise. The noise regulations already being enforced worldwide and in India will also be discussed. So, let us begin the very first lecture within this module which is the lecture 18 overall. This is the lecture on introduction to human hearing.



Here we will study, we will take an overview of what is the hearing mechanism. Then we will see some of the perceived metrics such as loudness and the equal loudness contours, the A weighted levels and the pitch.



Hearing is what? Sound is a physical phenomenon which relates to the pressure fluctuations traveling in the longitudinal wave fashion in the fluid medium. This then hits our ear, our ear then starts vibrating and transmits this information to finally the brain in the form of fluctuations in electric signals and then our brain responds to this particular phenomenon. This response or overall, this receiving of the sound by the human ear and the response to this sound becomes hearing which is the subjective response to sound. Over here you can see a brief overview of how a human ear looks like anatomically (refer slid 4) you have an outer ear then you have a middle ear and then you have the inner ear.

The purpose of the outer ear is to collect the noise it is like an antenna trying to collect as much of sound waves hitting it as much as possible and then whatever sound waves are hitting it, they are traveling through the outer ear canal and reaching the middle ear. If you see here a length of this outer ear canal for a typical adult human ear is approximately 2 centimeters. and here it is acting like a rigid long tube which is closed at one end and open into an infinite baffle which is the atmosphere. It is like a tube closed at one end and then opens up into an infinite baffle of the atmosphere and this length is 2 centimeters. Whenever we have got a closed boundary on the tube the sound waves are flowing and suddenly a rigid wall is there which means that the particles cannot flow through.

In that case the velocity at this end would become 0 the particle velocity. So, which means that the pressure velocity, which is, directly proportional

$$\frac{\partial P}{\partial x} = 0$$

So, p is maximum. And here which finally ends up meeting the atmosphere and diffusing P becomes minimum or reaches the minimum value. So, which means that here the waveform can look like this. If P is a sinusoidal wave this is a sinusoidal wave of pressure variation, then here we have the minima so it is the other way around and here we reach the maxima. Now if you think about it in the overall waveform suppose this is your overall waveform like this a complete sinusoidal wave this part is a quarter of the wavelength $\lambda/4$. And this $\lambda/4$ is 2 centimeters. If you solve it, you know, $\lambda/4$ is equal to 2 centimeters.

$$\frac{\lambda}{4} = 2$$

$$\lambda = 8$$

$$\lambda = \frac{c}{f} = 8\ cm$$

$$f = \frac{345}{0.08} \approx 4kHz$$

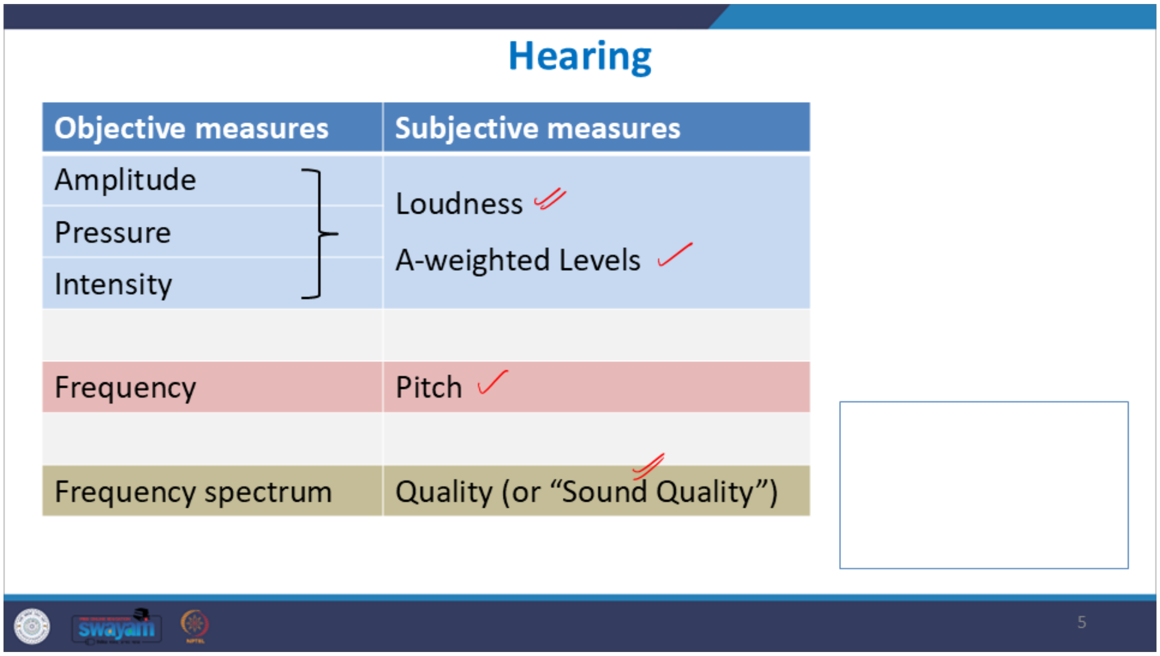
C as, you know, 343 or 345 meters per second ultimately when you solve it what you will get so let me erase this bit over here what you get ultimately is that the frequency maxima occurs so the lambda corresponding to this so the frequency corresponding to this lambda is approximately 4 kilohertz and which is what is observed that in the human ear you know they are most sensitive to the sound at 4 kHz.

The sound wave is collected from the outer ear and reached into the through the ear canal into the middle ear. What is the middle ear doing now? Middle ear is sort of like a transition phase between outer and inner ear and then it sort of tries to match the impedance. So, here we have air media. and here we have entirely you know brain fluid kind of a media and the nerve cells. From here to here, there would be a lot of difference in the impedance of the two media and this tries to match it. The impedance for continuity of flow and this perfect impedance match happens at 1 kilohertz. So, once again the human ear is sensitive at 1 kHz. So, this is the range within which the ear is usually sensitive.

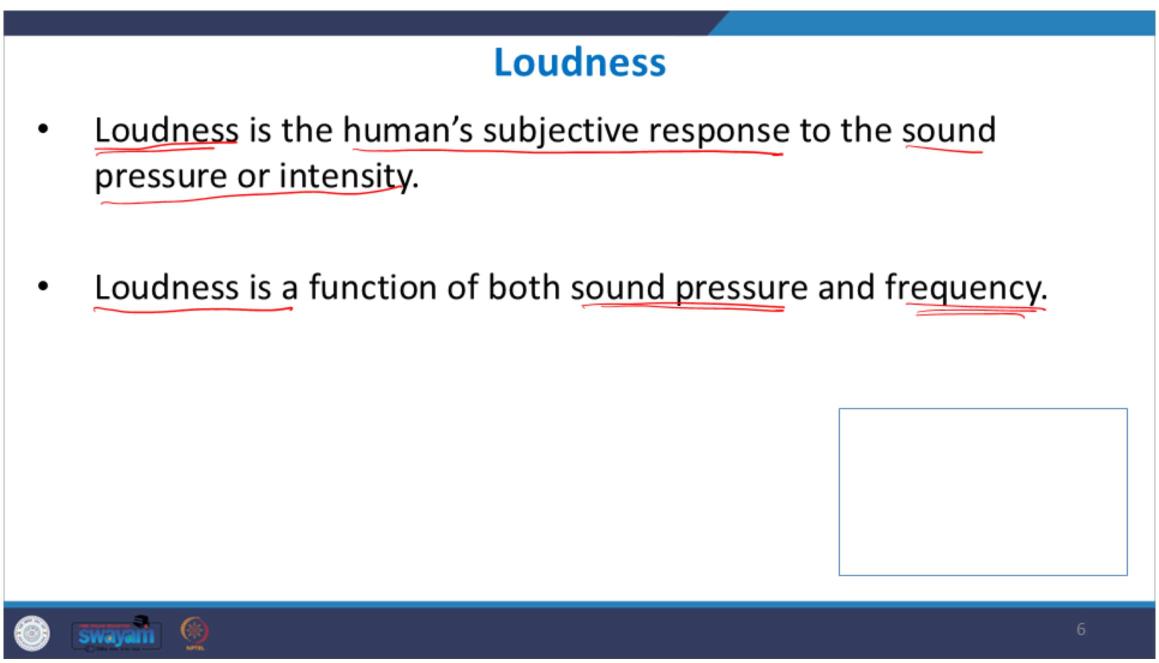
Finally, whatever you know sound waves they are hitting, they are getting converted into the vibrations of the fluid surrounding this particular in the inner ear. These fluid vibrations and then finally it goes through a very unique cell shaped structure called the cochlea. In cochlea what happens is that, when the sound wave is hitting depending on where it is hitting the cochlea a different level of vibration is generated. In this membrane if you sort of unstretch this particular cochlea into a long tube. So, depending on which region of cochlea the vibrating waves are hitting you are getting a different level of vibrations and the distance at which they are hitting depends on what is the wavelength of the sound wave.

So, which means that ultimately you know the vibrations in the cochlea are a function of of the frequency of the incident wave. Ultimately whatever sound which reaches our ear our ear and the hearing mechanism it acts like a frequency selective filter. So, we have a very complex frequency selective filter and we hear the sound.

Now we have in order to quantify, how a human ear is perceiving this you know so called objective sound pressure levels, we have some measures that have been devised. So, these some of these measures which closely relate to how a human ear is perceiving.

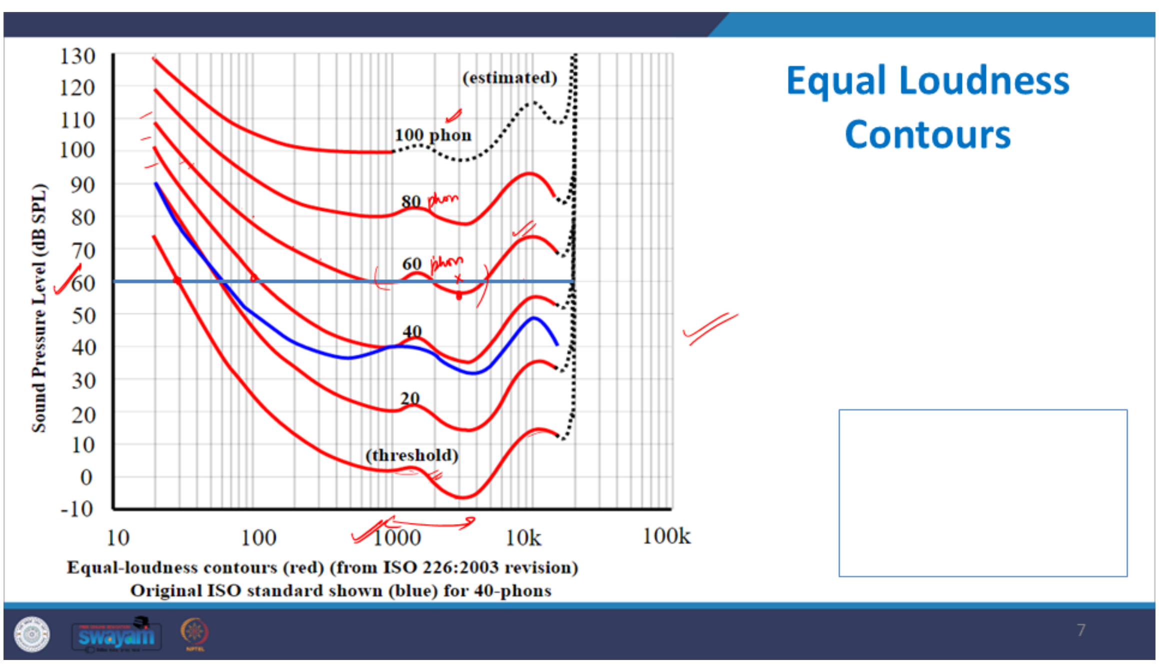


Loudness a weighted levels, pitch and then the quality or the sound quality. So, loudness and the A weighted levels they typically correlate or they are sort of like the subjective version of what is the amplitude or the pressure or the intensity of the sound. And then pitch closely relates to what is the frequency of the sound or the frequency content and sound quality well it is both time and frequency distribution so it is the overall spectral distribution of the sound.



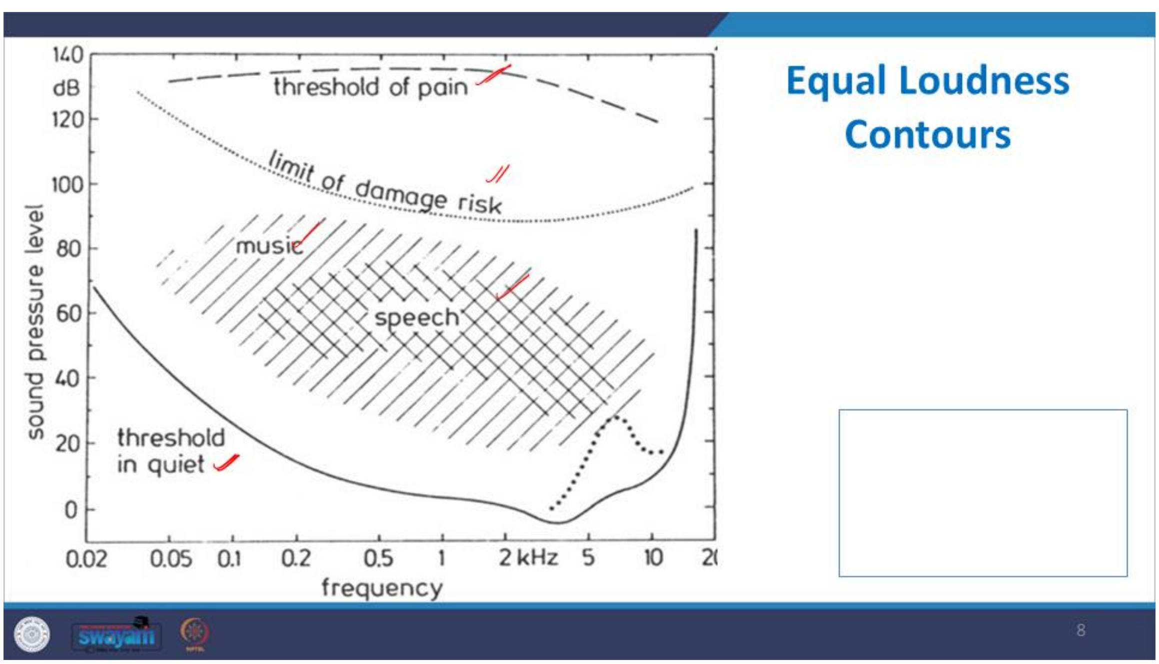
Let us start with the very first matrix which is the sound loudness so what happens how do you define the loudness so think about it suppose you have some speaker is playing and as a listener you say that oh please turn that off it's too loud and then suddenly some good music is coming up and you say, it is very quiet, turn the volume up, let the sound become slightly more louder or you say that.

That person is talking loudly or that machinery is too loud. This is a very common terminology we usually use for noise or sound that something is loud or quiet. So, what does this loudness mean? It is the human's subjective response to the sound pressure or the intensity that is hitting them. And, if it was some objective measure like, the SPL or the decibels, then you will directly say that, okay, so that means that loudness should be directly proportional to the acoustic pressure or the intensity. But that is not the case, loudness is not always proportional. directly proportional to the acoustic pressure of the intensity it is it depends on the pressure of the intensity but there is more complexity to it because why? Because of this fact that we are hearing it through this entire mechanism and in this hearing, the brain signals generated by the different sound waves, they do not just depend on the acoustic pressure of the sound they also depend on the frequency. So, hence may be there are two sounds of the same decibel levels which are hitting us in one sound the frequency content is something different. Let us say one sound is somewhere around 4 kHz and then there is another sound of the same decibel, but the frequency is at let us 20 Hz or 50 Hz, then to our ear The 4 kHz sound will actually sound much louder than the sound at 50 Hz and so on. Although they both may be having the same SPL because our hearing is also dependent on the frequency. So in the same way the loudness is a function of both. the sound pressure of the wave as well as the frequency of the wave.



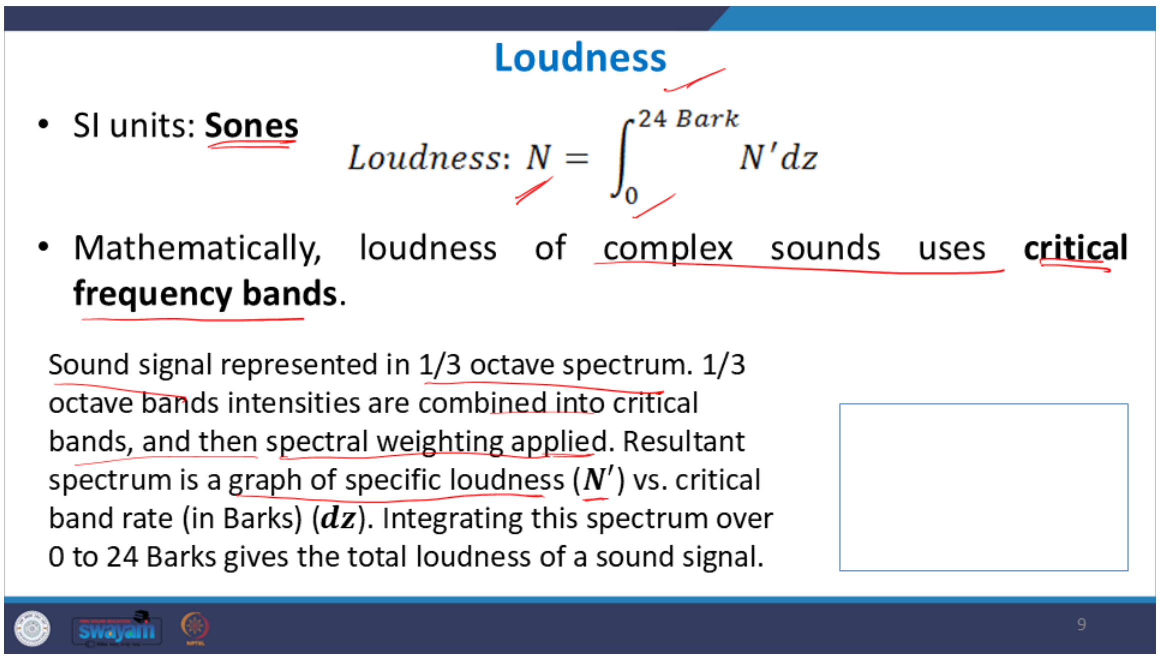
Based on a lot of accumulated research on human hearing and listening tests where people were given stimuli with different levels and the sound stimuli at different frequencies and numerous such studies were conducted and people were asked to judge the loudness of the sound whether this is louder than this or that. And based on that finally over years and years of research this equal loudness contours were made. What do they show is that these are the lines of equal loudness which is felt by a human being. If you look here at one particular level let us, say at 60 dB.

Let us say we are giving the human ear a sound of 60 dB. If that sound is close to somewhere around 4 kHz, so it sounds that 60 dB sounds at 4 kilohertz it sounds greater than 60 dB and similarly in some of the in this entire region, if you see that same 60 level sound will sound like 60 decibels or greater. But if you shift towards a lower frequency then what happens that same 60 dB sound will actually sound lower. This is a 60-decibel sound here this means it is just barely audible at this frequency, and the same 60 dB sound as you go higher. So, suppose say at 100 Hz it corresponds to a loudness of 40 the same 60 dB hertz at this here is barely visible which is at 40 hertz is barely audible here but over 100 hertz it is almost close to 40 loudness and then as you go up towards this more frequency sensitive zone it becomes louder and then again as you come towards the high frequency zone again that same sound would be of less loudness. Basically, if you see or observe the pattern of this curve here the dip indicates that this the dip indicates that the human ear is more sensitive to that particular frequency zone and that is why it is more sensitive. So, this is the equal loudness contour. So, even at lower frequencies you get higher loudness in this level and here even at higher spl you get the same loudness.

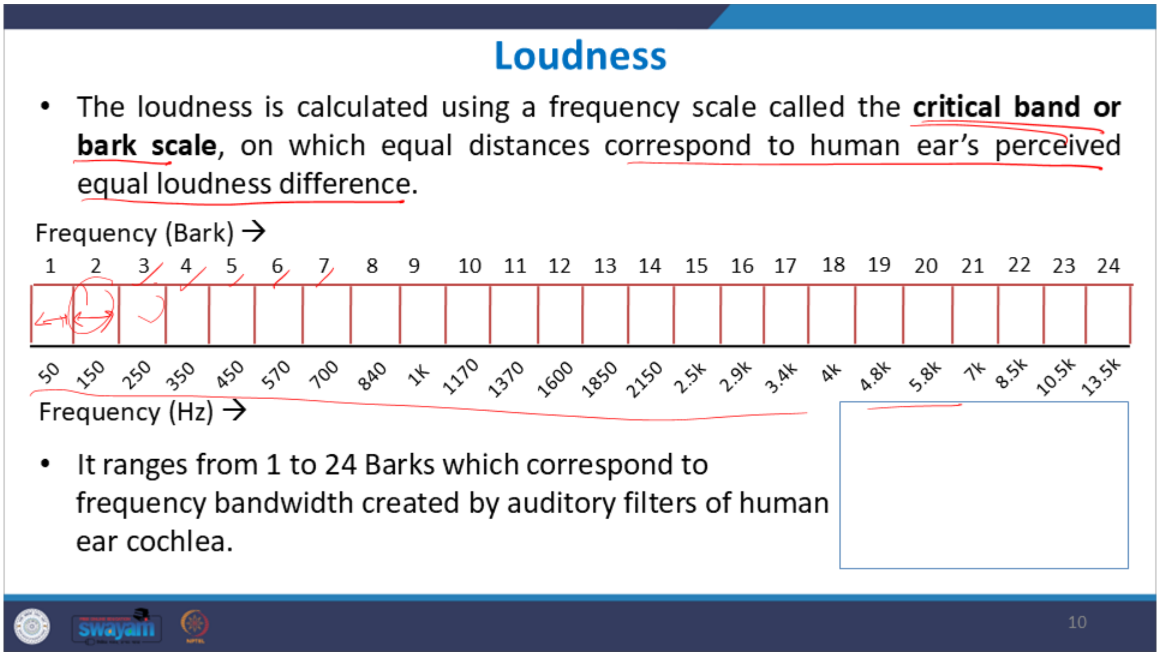


In fact, most of the you know human hearing is based on this equal loudness contour this shows a graph so this is like a typical threshold of hearing, below which human ear is roughly insensitive and they are not able to hear the sound.

So, this becomes a threshold of hearing which is also called as the threshold of quiet and this upper one is the threshold of pain and in between there are sounds at different ranges like the speech, the music and this is the limit where the damage happens. That is what you mean by you know loudness that is how loud the human is judging the sound to be. And it is a function of both the SPL as you saw here, and the frequency, this loudness.

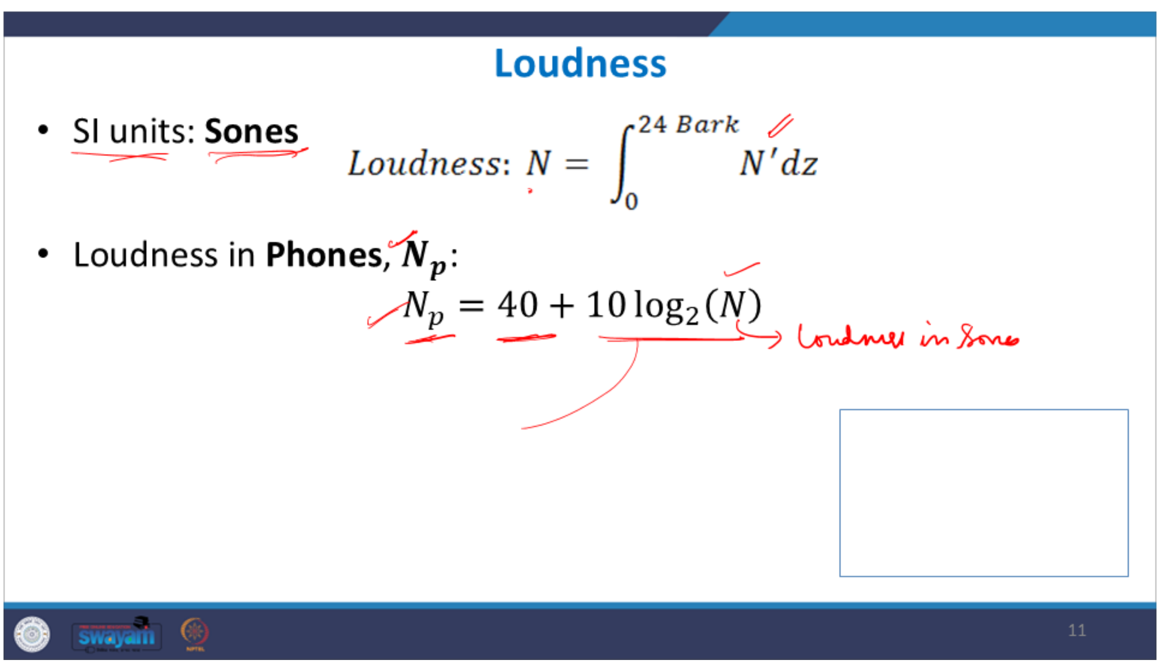


So, how do you in order to quantify this loudness, sones are proposed. These are a certain unit to quantify the loudness. For that you use a different frequency scale which is called as the critical frequency band. This shows the critical frequency band or the Bark scale. This is a scale which corresponds very much to the human cochlea where the different frequency bands are there and equal distances within these frequency band they correspond to the human ear's equal loudness difference. As you jump from one band to another band in this bark scale, it's like jumping from one loudness to another loudness value so it is like showing a scale where loudness is increasing linearly this is like a scale. So what happens in this critical scale you simply integrate so first of all you represent the sound signal in the one-third octave spectrum, this is the one-third octave spectrum and then you combine them into critical bands so you obtain a new bark scale.



And then in the bark scale some special kind of spectral weighting is applied it is a complex algorithm and these algorithms are available online as well which you can go and search So, the spectral weightings are applied and all of that has been determined based on the hearing research and after applying the spectral weighting on that that sound spectrum represented in the Bark scale you get a graph of specific loudness which is like loudness per critical band or the loudness increase with increase in the critical band.

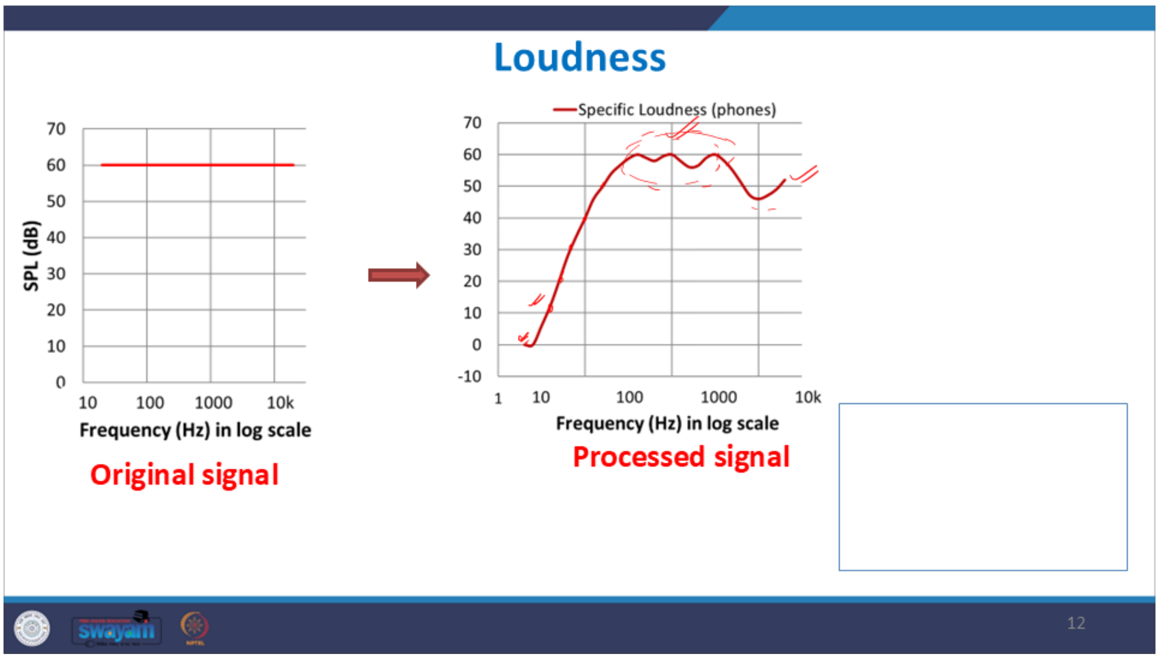
So, you get the specific loudness. and when you integrate it over the entire bark scale you get the total loudness N.



So, this formula gives you the loudness in zones which is the SI unit of loudness, but the more typical or commonly used unit is also called as phones as you see here the equal loudness contours will first be devised with phones in mind. So, this was the phones which was an older unit of loudness and how are sounds and phones related using this formulation here. So, this is the loudness in phones which is,

$$N_p = 40 + 10\log_2(N)$$

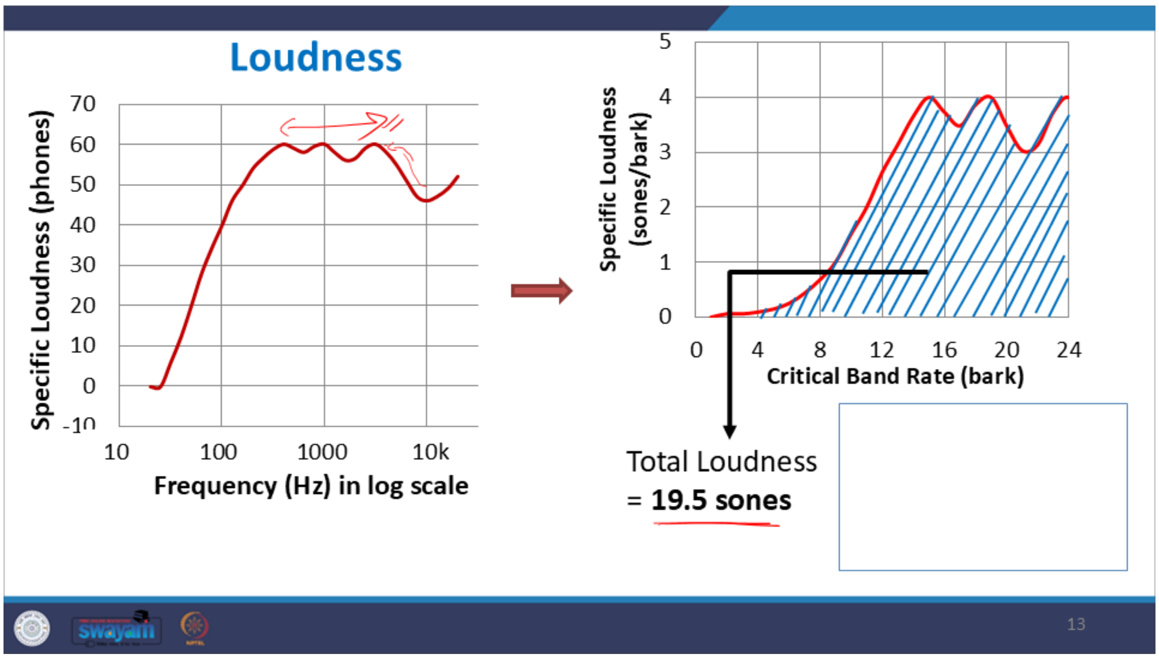
where here N is the loudness in sounds.



So, let us say this is one graph that I had made in excel where, I had a sound signal. So, basically, I had some pressures points at different frequencies all having the same intensity which is 60 dB. And then when I applied the loudness algorithm to it which is available online as well, it is too complicated to show in this introductory lecture and hence I have kept it out of scope of this course. But when you apply that particular spectral masking and the various algorithms, you get this as the specific loudness in phones. So, if you see here this curve it looks a bit familiar what is this?

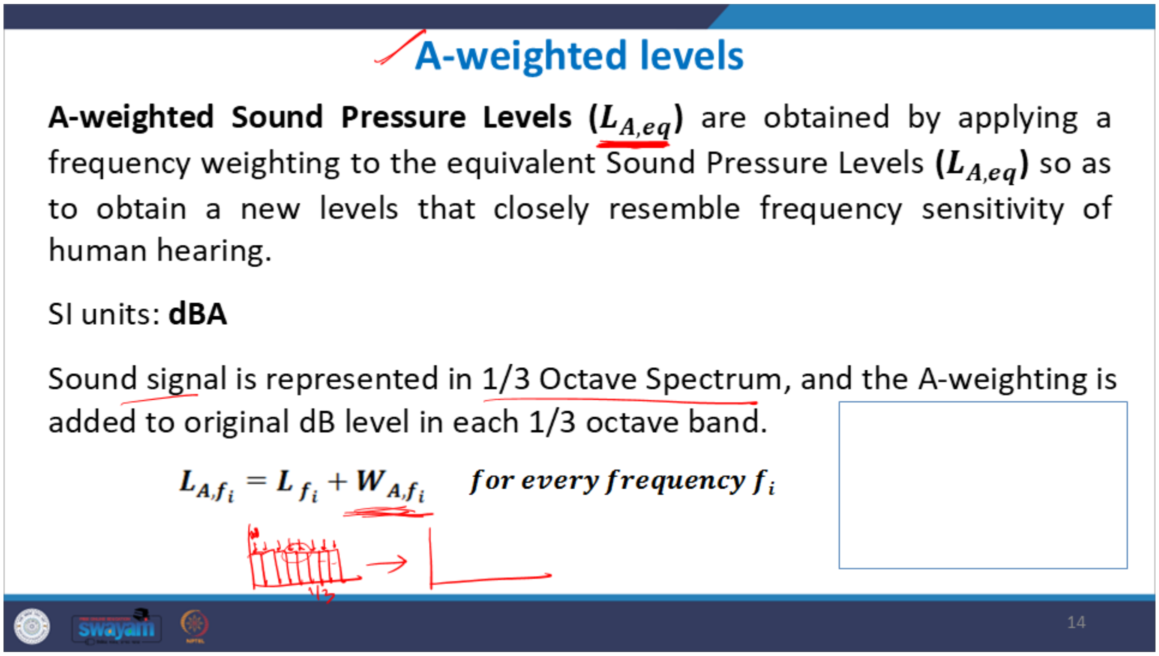
If you come here this curve is the inverse of the equal loudness contour (refer slide7). So, that simply means that a 60 dB sound when passed, it will be barely audible at 10 that same this. So, it might be having same 60 dB at 10. frequency, but it would be barely audible, it will feel like it is just 0 loudness in phones. And then as you increase or go up in the frequency, the perceived loudness of this noise will start to rise. And then within this sensitive zone, it will sound same as a 60 dB sound, it will be of 60 phones loudness. then once again once the frequency goes beyond this value, the perceived loudness decreases

This shows how sensor even though I am passing a signal of 60 dB throughout all the frequencies our ear hears it like this, it hears it as a sound similar to 60 dB, only within this sensitive zone which is this frequency here between 1000 Hertz to 4 kHz, and Below that the same thing the loudness decreases so that it is barely audible below 10 or 50 Hz and then suddenly the loudness also drops at some higher frequencies.



And now that you have this graph in phones if you apply this formulation here (refer slide 11) and you have this in phones, if you convert it back to sounds you get this specific loudness in sounds. This is your N dash in zones that you are getting and if you integrate it to get the total loudness. So, once you integrate it the area under this curve becomes your total loudness which is 19.5 sones. Although I passed a 60 dB noise at all the frequencies ultimately it boiled down to being 19.5 sones overall.

Another matrix that we use same as loudness is the A weighted levels in fact this is a more common choice by the noise control engineers and researchers. Just like the equivalent sound pressures are represented by $L_{equivalent}$ or L_{eq}, the A weighted sound pressure level is given by $L_{A,eq}$ and how it is obtained? Let us say you have the sound spectrum in one third octave,



you apply some spectral masking or that is means you apply a spectral weighting to this sound and convert it into A levels and then combine them together so what do you do you represent the sound in the one third octave and then you apply a frequency selective filter to it. How how should this filter look like?

It is like you are applying some weight to every level at every frequency band so if this is your original waveform let us say, in the one-third band. Now you add some factors to each level these w_i to each frequency band so that it should mimic the human hearing and this is what the human hearing is like, it is more sensitive towards this one to four kHz frequencies drop sharply at the low frequencies and again has a small drop at the higher frequencies so this is how the human ear hears the sound so that is the same type of frequency weighting you have to apply. What it means is that at the lower frequencies you need to have this w_i should be a high negative term you are sort of subtracting the levels because to a human ear at these low frequencies they will sound very low, but they will sound the same level at these middle frequencies and again their perceived levels will decrease at higher frequencies. So, you have to apply these weights.

This is the generic function to get the weight at every, one third octave band level. Then you use the formula of combining all these levels to get your final $L_{A\ equivalent}$. So, this shows us the weight. So, as you see here and as already, anticipated at lower frequencies, we are reducing the actual levels to get how the human ear perceives.

A-weighted levels

A-weighting for a frequency f is given by:

$$W_A = 2 + 20log_{10}\left(\frac{12194^2 \cdot f^4}{(f^2+20.6^2)(f^2+12194^{2^2})\sqrt{(f^2+107.7^2)(f^2+737.9^2)}}\right)$$

$$L_{A,eq} = 10log_{10}\left(10^{\left(\frac{L_{A1}}{10}\right)} + 10^{\left(\frac{L_{A2}}{10}\right)} + \cdots 10^{\left(\frac{L_{An}}{10}\right)}\right)$$

A-weighted levels

1/3 Octave Band	A-weighting
20 Hz	-50.5
25 Hz	-44.7
31.5 Hz	-39.4
40 Hz	-34.6
50 Hz	-30.2
63 Hz	-26.2
80 Hz	-22.5
100 Hz	-19.1
125 Hz	-16.1
160 Hz	-13.4

Because it is not very sensitive at these frequency ranges. So, we are adding these high negative terms the highest at the lowest frequency and then slightly decreasing as we go ahead and it keeps decreasing. and then from here onwards we have the sensitive zones. So, are you know the decrease in the level the factor by which we are decreasing the actual level keeps reducing and at 1000 Hertz it is 0, no decrease and then it is more sensitive at this range. So, instead of decreasing we are now increasing the levels.

A-weighted levels

1/3 Octave Band	A-weighting
200 Hz	-10.9
250 Hz	-8.6
315 Hz	-6.6
400 Hz	-4.8
500 Hz	-3.2
630 Hz	-1.9
800 Hz	-0.8
1000 Hz	0
1250 Hz	0.6
1600 Hz	1
2000 Hz	1.2

sensitive zone

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So, from here onwards whatever was the actual levels we add a positive weight to actually increase it because our ear is in the sensitive zone where this zone over here these sensitive zones (Refer slide13) where the sounds are perceived much louder. So, again we reach the sensitive zone. we add small values to it we keep doing that for these sensitive zones.

A-weighted levels

1/3 Octave Band	A-weighting
2500 Hz	1.3
3150 Hz	1.2
4000 Hz	1
5000 Hz	0.5
6300 Hz	-0.1
8000 Hz	-1.1
10 kHz	-2.5
12.5 kHz	-4.3
16 kHz	-6.6
20 kHz	-9.3

sensitive zone

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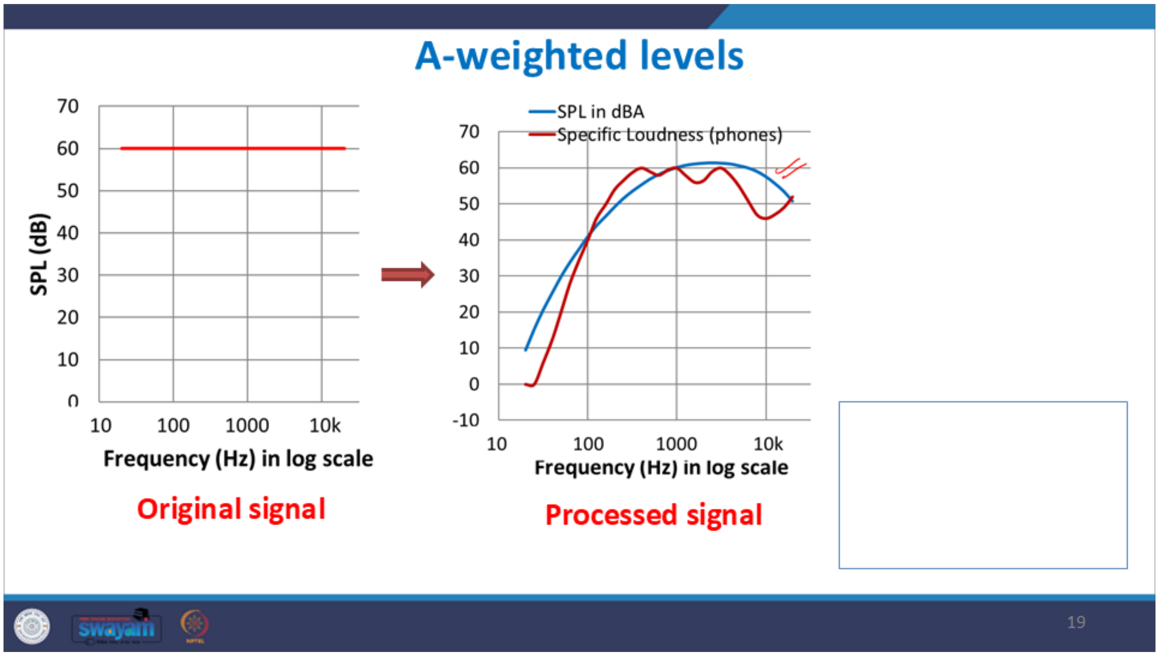
And then slowly as we move away into higher frequencies, again we start reducing the amplitude because then again, the sensitivity reduces. If you can see it in this graph, again when we reach a certain level (refer slide 13), this perceived loudness slowly drops. So, we will reduce the actual levels like this.



So, suppose I have the same signal 60 decibel in all the frequencies and now I already obtained the graph of the specific loudness in phones. Now, let us also obtain the graph of this in dBA. So, what I did was to these levels in the various bands I have added these factors. So, this is how I have added these factors to 60 dB. So, in the 20 hertz, it would be 60 minus 50.5, In 25 hertz, the level would become 60 minus 44.7, In 31.5, this level would be, you know, 60 minus 39.4 and so on.

So, this modified level will give you a graph like this. So, you see that this A weighted graph is very close to the human's loudness perception. So, this is a very close indicator of how the human ear is actually perceiving the loudness.

Now t for this lecture the last measure is the pitch, which corresponds very much to the frequency of the sound so this is what this is the subjective perception or the subjective response to the frequency so low frequency sound means for a human it is like low pitch and a high frequency for the human it seems like it is the high pitch sound Some examples I can give you, like the pitch of a female voice is usually perceived as higher than males.

When the female is talking, we say that, oh, that's a high-pitched noise. And when a male is talking, in most of the cases, you say that it's a low-pitched noise. In the same way, in a

Pitch

- Pitch is the human's subjective response to the frequency.
- Low frequency sounds: Low pitch
- High frequency sounds: High pitch
- E.g. Pitch of female voice usually perceived higher than males
- Mechanical machinery perceived to have lower pitch than electronic machinery.

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machinery or in a mechanical system, the mechanical machineries they usually have more of the low frequency content compared to a high frequency content. So, to us you know the pitch sound it sounds like the mechanical machinery are low pitch whereas the electronic machinery they have a higher pitch or more kind of high frequency tone.

Pitch

Typical sounds	Frequency range
Range of Human Hearing	20 Hz to 20 kHz
Speech intelligibility (speech that can be understood)	600 to 4800 Hz
Female voice	700 Hz
Male voice	350 Hz
Speech privacy range (speech that most intrude into adjacent areas)	250 to 2500 Hz
Typical small table radio	200 to 5000 Hz
Rotating machinery noise	20 to 10000 Hz

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This is the typical range of frequencies and some of the typical sounds. Like the rotating machinery the table radio the speeches male and female voice where female voice is almost double the frequency so sounds like double the pitch and so on.

I think you know with this i would like to close this lecture so thank you for listening.