NOISE CONTROL IN MECHANICAL SYSTEMS

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Week:4

Lecture:19

Lecture 19: Sound Quality

Hello and welcome to the lecture 19 in this course on noise control in mechanical systems with me Professor Sneha Singh. Today's lecture is on sound quality. It's a continuation of our lecture previously which was an introduction to human hearing and the subjective responses to sounds.   to summarize I had given you this that the human ear it's very subjective in nature and it has its own way of perceiving the sound where the hearing and the levels are dependent both on the pressure as well as the frequency of the sound. Being a very complicated frequency selective device and some of the objective measures and some of the and what subjective measures do they relate to with respect to how a human responds to the sound. With the amplitude pressure intensity is typically related to the loudness of the sound and the A weighted levels of the sound.

Summary of previous lecture

Hearing, Levels ≃ pressure, frequency

Objective measures	Subjective measures
Amplitude Pressure Intensity	Loudness A-weighted Levels
Frequency	Pitch
Time – Frequency spectrum	Quality (or "Sound Quality")

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And the frequency is typically related to the pitch which is the how the human here is sort of perceiving the frequency content of the sound. And then the overall frequency spectrum and you can say both the time and frequency spectrum. gives you the overall how the sound is distributed over time and frequency. It gives you what is the quality of the sound or sound quality. we have studied about these in the previous lecture.

Outline

- Sound Quality
- Sound Quality Engineering
  - Objective measures (Psychoacoustics)
  - Subjective measures

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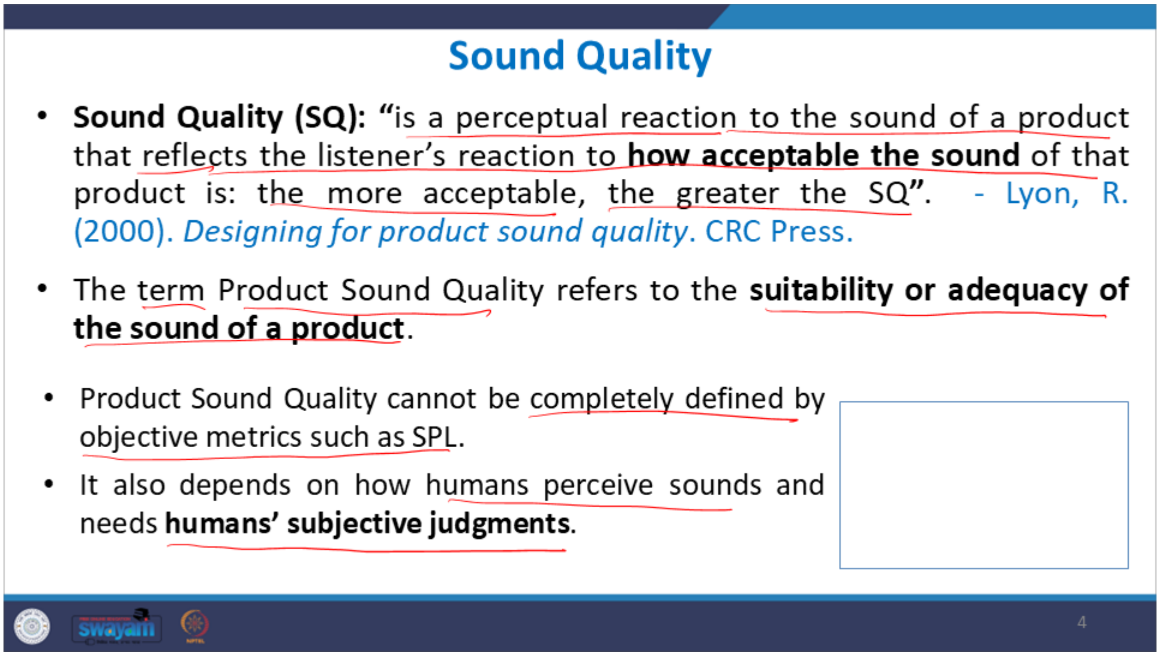
Here we will study about sound quality and then the process of sound quality engineering where, both subjective and objective tests will be introduced and we will study about psychoacoustics as well. let us say what is sound quality, as the name suggests it is like



the quality of some sound, how good the sound is how suitable or appropriate the sound is. it is like this quality of a sound.

Sound quality came because based on, market research and it is closely related to the products. Various products giving out sound and you relate the quality of a sound with respect to the product or the machinery that is emitting that sound. Usually, sound qualities also that products sound quality. The most accepted definition of that is it is a perceptual reaction to the sound of a product that reflects the listener's reaction to how acceptable that sound is for the product. The more acceptable the sound of that product, the greater will be its sound quality. Overall, you can say that the product sound quality refers to the suitability or the adequacy of the sound of a product. And because it is the human that is judging the sound quality. They are saying that this product has a high sound quality which means that the sound emanating from that particular product is very suitable to that product. It suits the product. It is very subjective in nature and the human judgment is involved and hence, it does not get completely defined by the objective metrics alone such as the SPL. Here it also depends on the human perception and the human's subjective judgment.

Let us say this is the image of a car, this car can be of any brand, it can be of some Indian brand such as the Tata Motors, Maruti etcetera or it can be of the different international brands.

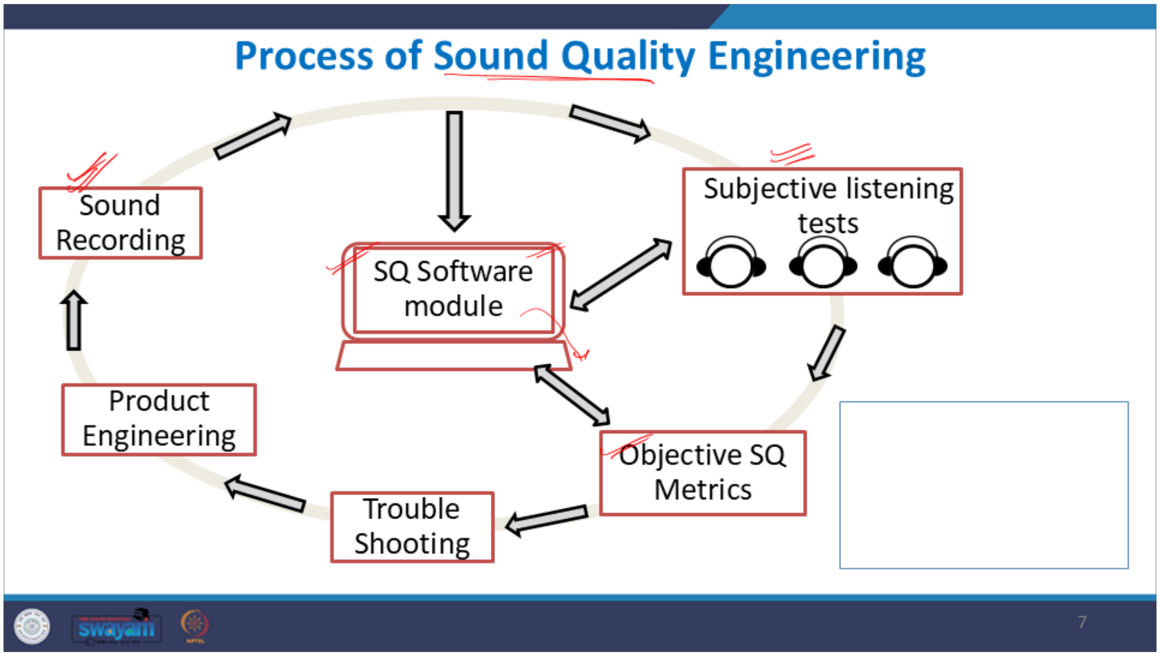
And you would have noticed that, the sound quality plays a major role in automotive industry. You would have noticed that, the sound of different cars are different when a Ferrari goes by, even if you are not looking just by the sound of it you will know that a Ferrari is going by. In the same way, that Harley Davidson bikes that you have if it is going by it has a very unique sound even if you are not looking from far away you can just tell by listening to the sound that it is a Harley Davidson bike. In the same way the sound of, Bentley, Rolls Royce and Ferraris and various other, sports car formula racing cars they have their unique sound signature you don't even need to look at the product just by listening to the sound you can identify that this is not just a car sound it is this particular brand's car so hence sound quality becomes very important for a manufacturer because it can become a means to reinforce the image of the brand. The better the more suited the sound is to the overall product or in this case the overall car and its functionality, the higher becomes its sound quality and hence it improves the overall selling ability of the product. To simplify this what happens let us say, In general, you perceive the sports car to be very racy, very loud, racy and fast. And when they are moving away, the signature of the sound should also sort of reinforce the same image that you have of that car, the same perception that it should be a racy car, very fast, very fast and racy, speedy.

The sound signature should actually reinforce the same thing. A sports car should not sound like, auto rickshaw. It should not sound like that. In the same way, suppose you have got, let us say, an electric or e-rickshaw. You do not expect it to sound like a diesel engine. You do not expect it to sound very machiny or mechanic in nature. In the same way, if you have got a very high-end premium or luxury car, then you do not expect it to sound like a formula racing car which is very high racy and speedy sound it should be more, comforting and more, it should give you a very rich quality it's something very difficult to define but it's just by the sound signature of it you should be able to guess that okay this is a high quality premium car for a very high end customer. Different brands they take special care that the sound signature should be able to reinforce the image they want to give to the consumer.

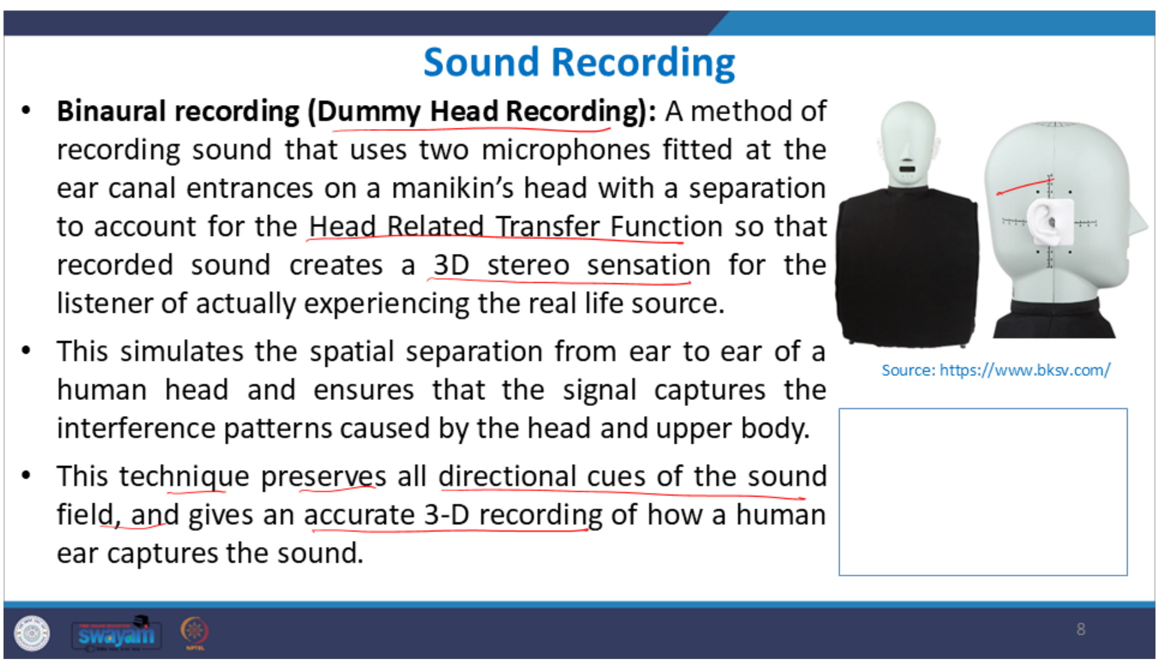
Hence sound quality and sound reinforces the brand image and in the same way sound quality is also enhanced, so that it can provide the information of the operational conditions of a product. For example, let us say, when you are driving a car, you are closed and there would be a sound the interior sounds within the car and that interior sounds should be able to provide the information of the operational conditions of a car and not just that they should be able to enhance the driving experience. By that what I mean is that let us say someone is driving a combustion engine vehicle. As soon as you press the ignition key, you hear a very unique sound. Sometimes the drivers just by the sound of it are able to tell the condition of the car whether the car is running smooth or there is some some issue with the engine or some issue with some component so as you turn the ignition on you hear a very specific sound , that yes the engine has started and the car is idling then as you speed up, from the sound itself you get a feeling that yes the accelerator is moving you have pressed the throttle. And sometimes, you have some very unusual sound, suppose in the same car that you have been driving for many years suddenly you are able to hear some unexpected sound like for example some kind of typical like or something very different from the usual just by the sound of it you can say that, no there is something which is wrong with this car it is not working properly and then you go and get it fixed. The sound here is able to provide you some critical information about the functioning of the car. In the same way in various appliances sound is actually needed for the purpose of safety because it alerts the user that the product is operative. For example, somebody is using a drilling tool. you do not expect the drilling tool to be quiet completely silent at least not in the current times maybe sometime very far down in the future when the technology has evolved, things have changed overall all the machineries have become much quieter then you can expect a quiet drilling tool as well but in the current scenario it is good to have a drilling tool that is making a high noise because drilling tool is a dangerous equipment. When a human being is operating the drilling tool, it is a dangerous equipment. Little bit of here and there and the fingers can be cut. This sound is sort of alerting the user that stay alert, it is a heavy working machinery, it is running at a very high speed and you have to stay alert otherwise it would be dangerous for you. Here the sound is actually required to alert the consumer that, dangerous machinery is being operated.

In the same way, some of the very high metal cutting tools and tile cutting tools, they are very dangerous, just a little bit of mishap and somebody can lose their hand. And hence, sound and a very high pitch, not a very high pitch, sort of high alertive sound or the sound through which the human is becoming alert that, okay, it is some kind of dangerous machinery that is put on. that is required we should not be making these machines required not at least in the current scenario, because they are also alerting the consumers they are also alerting the users that you have to stay alert it is a dangerous machinery that is running and the same goes for various other dangerous machineries like grinding and milling where sound becomes very essential to alert the users. Overall, you can say sound can and sound quality itself is a very important parameter of a product.

Now what is the process of sound quality engineering? Sounds are already inherent and they depend on how it is being generated within that machinery. But sometimes just to make the product more saleable and more appealing to the consumers, the manufacturers they are ready to do slight interventions so as to improve the quality of the sound. So, how it works is that whatever product you have first you make the sound recording and then



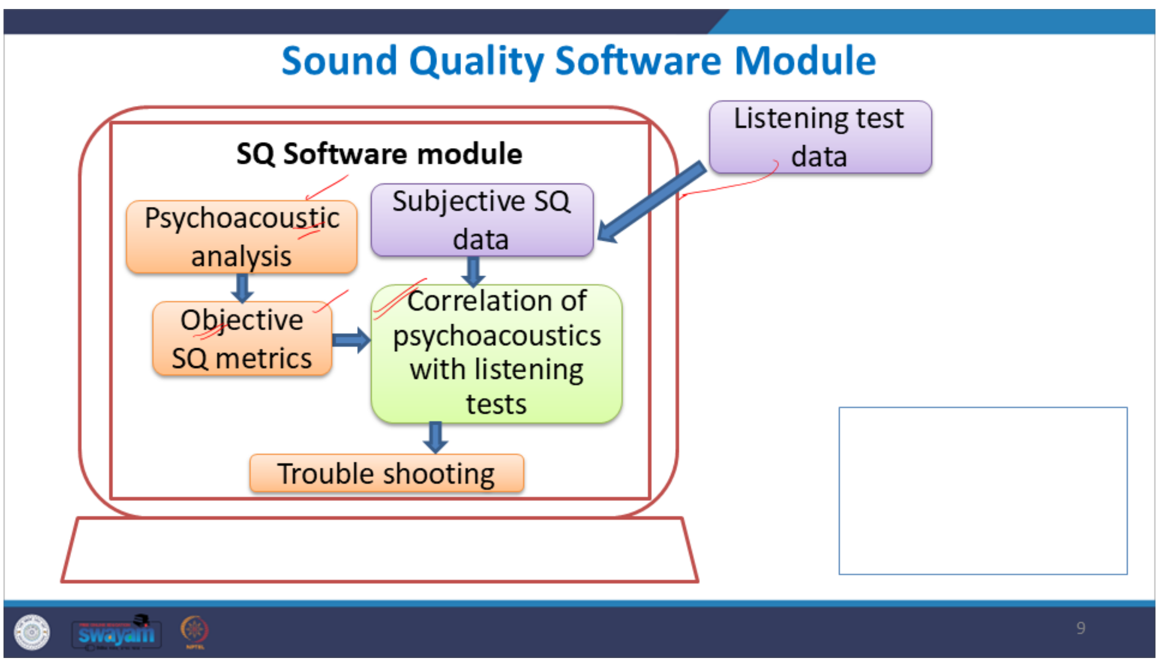
you do both you have because sound quality means it is a subjective judgment you can have a list of consumers or a sample of population listening to that sound and judging them on various parameters then within the software you have, by some means you are calculating some objective matrix you are doing the correlation and then if suppose based on the correlation, you are able to find that okay, these certain metrics relate to this kind of judgment and I want to improve the quality. Maybe I should tweak those metrics, maybe I should make certain interventions and then the same process repeats.



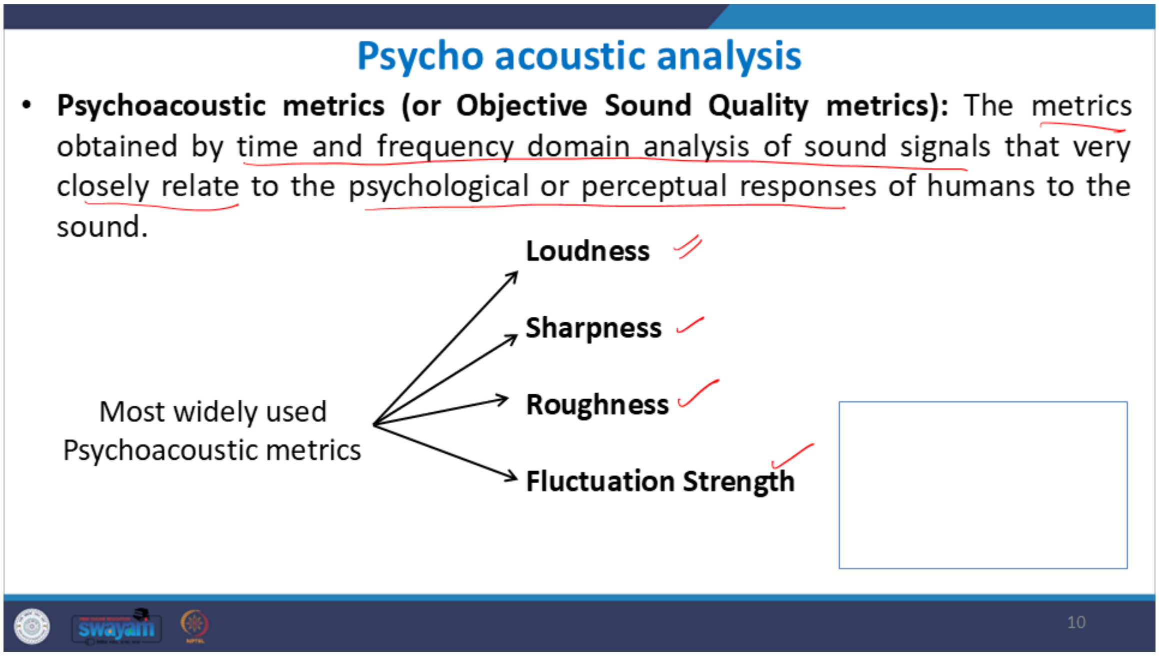
let us go to the first step, sound recording. Usually for sound quality engineering, binaural recording is done, which is also called dummy head recording. What happens here? Here you have a mannequin and you are placing the microphones on the two ears of the mannequin. And they are being recorded. So, the way the sound gets recorded is that, two microphones, they have roughly the same separation as the human ear. The same spatial separation. The sound signal reaching here for the same source would be different from the sound signal reaching this ear because there is a spatial separation between the two points.

And at the same time, we have the head and the torso and the body. And due to the waves hitting and the interference taking place there would be some inherent sort of changes in the spectrum from one end to the other and that is called as the head related transfer function.

When such kind of recording is made, it gives you a more 3d stereo sensation that feels like you are actually experiencing that sound in reality so when this kind of recording is done using a dummy head, this technique perceives the directional cues of the sound field and gives an accurate 3D recording.



You use binaural recording now if you go to the second thing here SQ software module what you do here you do psychoacoustic analysis to obtain the objective matrix you collect the listening data you get some subjective data of how the humans are actually perceiving that sound you do correlation between the two to find that which objective psychoacoustic matrix are affecting how the human perception. This particular matrix is having this kind of effect on the human perception. This is the correlation you want to find so that, when you have to improve the sound quality you will tailor or modify those metrices accordingly.



what are these metrices? These are the psychoacoustic matrices and psychoacoustic analysis is done to get them. These are those metrics which are obtained by some time and frequency domain analysis of sound signals and very closely they relate to the psychological or perceptual responses of humans to the sound. One of these metrics we already saw was the loudness.

It closely relates to how loud a human ear finds the sound. The other metrics we will see in this class is the sharpness, roughness and the fluctuation strength. Let us look at them one by one.

Sharpness means the subjective perception to how sharp or you can say painful or high frequency that sound is. It is basically a comparison of the amount of high frequency content of the sound over the total energy. Overall if a sound in general, if a sound usually has more high frequency content or a greater proportion of the high frequency energies, you call it to be sharper. and this is the formulation of calculating sharpness (refer slide 11).

Sharpness

- **Sharpness:** It is the subjective perception of how sharp (painful or high frequency) is a sound. It is a comparison of the amount of high frequency energy to the total energy, the greater the proportion of high frequency energies, the 'sharper' the sound.
- SI units: **acum**

$$\text{Sharpness: } S = 0.11 \frac{\int_0^{24\ \text{Bark}} N'g(z)zdz}{\int_0^{24\ \text{Bark}} N'dz}$$

N' = *specific loudness as function of critical band rate*

$g(z)$ = frequency dependent weighting function

z = *critical band rate*

We already saw in the previous lecture how to calculate the loudness in the critical band scale and N´ being the specific loudness curve. In that using the same curve you apply a frequency dependent weighting function and, the higher the content higher is the proportion of high frequency content the sharper is the sound. Here just this frequency dependent waiting function. is sort of in a way that the weightage is given to the higher frequencies more and you have a low weightage to the low frequencies and then you apply this weighting to get an altered loudness spectrum or a frequency weighted loudness spectrum you divide it or normalize it by the total loudness and then multiply it with this factor just to get to a manageable number you get the sharpness of the sound.

Fluctuation Strength

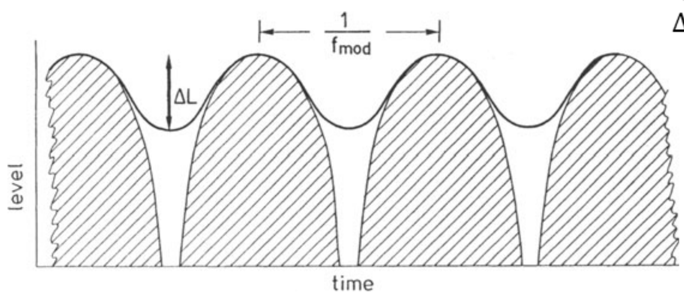
- **Fluctuation Strength:** It is the hearing sensation related to loudness modulations at low frequencies (≈up to 20 Hz) that are discernable individually.
- SI units: **vacil**

$$F = \frac{\Delta L}{\left(\frac{f_{mod}}{4\ \text{Hz}}\right) + \left(\frac{4\ \text{Hz}}{f_{mod}}\right)}$$

F = *fluctuation strength*

f_{mod} = *modulation frequency*

ΔL = *masking depth as function of critical bamd rate*



Source: H. Fastl and E. Zwicker, *Psychoacoustics: Facts and Models*, 3rd ed. Berlin Heidelberg: Springer, 2007.

Fluctuation strength means that it is the sensation of the loudness modulations in the low frequencies. Suppose the sound is being modulated like this, there is a phenomenon called as the masking which means that suppose you have a wave, two waveforms very closely together in time. Then you cannot discern between the two waveforms as two separate waveforms if the difference between their time is very close then to your human ear it sounds like a continuous waveform like this. So, an example of this could be that suppose you had, two machineries you switched one machinery on. And then after 10 seconds, you switch the second machinery on. So, when there's a gap of 10 seconds between the two, you are able to quickly discern that, okay, right now only first machinery has started and then the second one. But what if you switched one machinery and within some fraction of second or within a second you switch the second machinery on. Although they both started at different times, but the difference between the two waveform was so small that to a ear, they were not able to distinguish between these two temporals or temporal distributions and it sounded as the same waveform. It sounded as if both machineries have started together and you could not distinguish. In that way suppose the distribution of a modulated sound is you first find out what would be the sort of inherent after masking how the human is perceiving. All of these metrics could be very confusing because they need a lot of complex calculations based on the hearing research as well. you first find out for that waveform that for a human ear what is the minimum time interval at which they are able to distinguish between two sounds and based on that you find out what is the equivalent masked sound level. Then this particular amplitude becomes the masking depth, and then there is some modulated frequency just like, signals with frequency modulation amplitude modulation. you find out the frequency of the modulation and using this formula you get the fluctuation strength.

Roughness

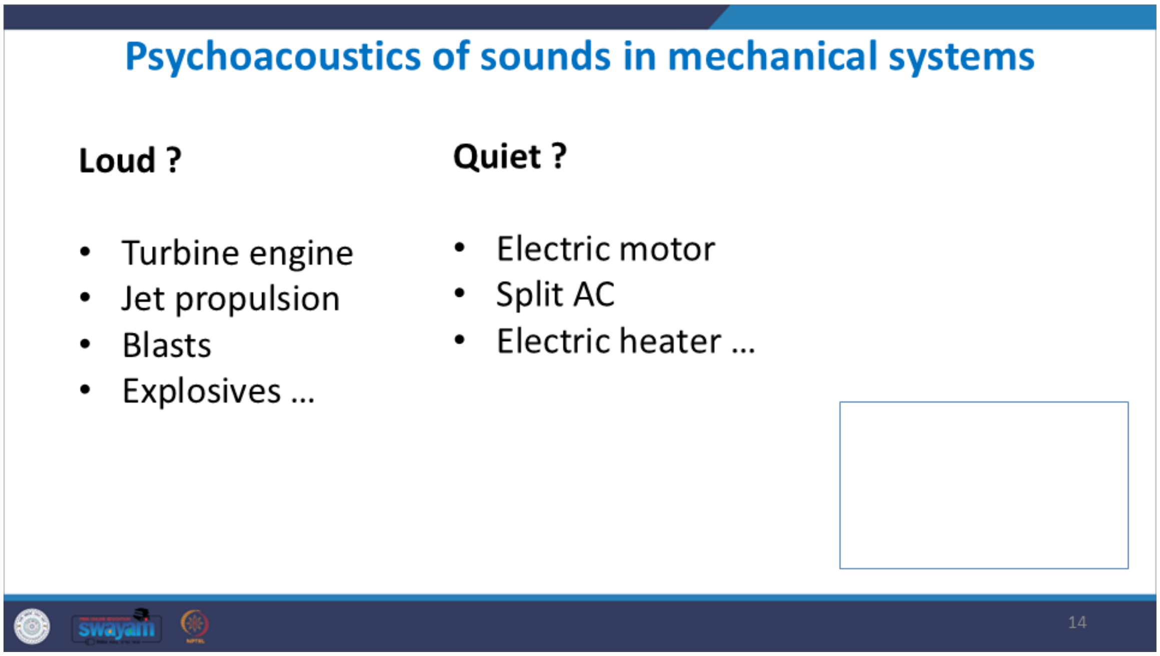
- **Roughness:** It is the subjective perception of roughness or unevenness (annoying quality) of a sound. Roughness quantifies the subjective perception of rapid (15-300 Hz) amplitude modulation of a sound.
- SI units: **asper**

$$\text{Roughness: } R = 0.3\,\frac{\mathrm{f_{mod}}}{\mathrm{kHz}}\int_0^{24\ \mathrm{Bark}} \frac{\Delta \mathrm{L(z)dz}}{\mathrm{dB/Bark}}$$

$\mathrm{f_{mod}} = \textit{modulation frequency}$ $z = \textit{critical band rate}$

$\Delta \mathrm{L} = \textit{masking depth as function of critical band rate}$

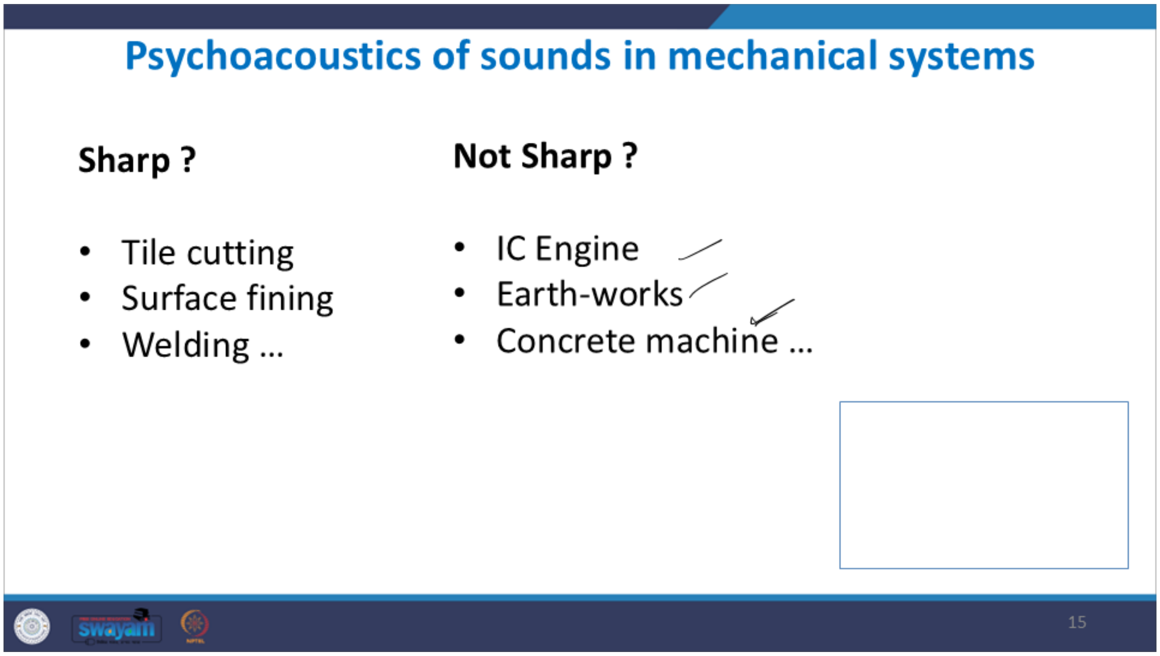
Roughness is same as the fluctuation strength it relates to how rough or uneven a sound is basically it relates to the annoying quality of a sound. Most of the machineries they are said to have a rough sound. Most of the mechanical machineries and this here is the rapid amplitude modulation. The modulation at slightly higher frequencies, and this is the calculation for it.

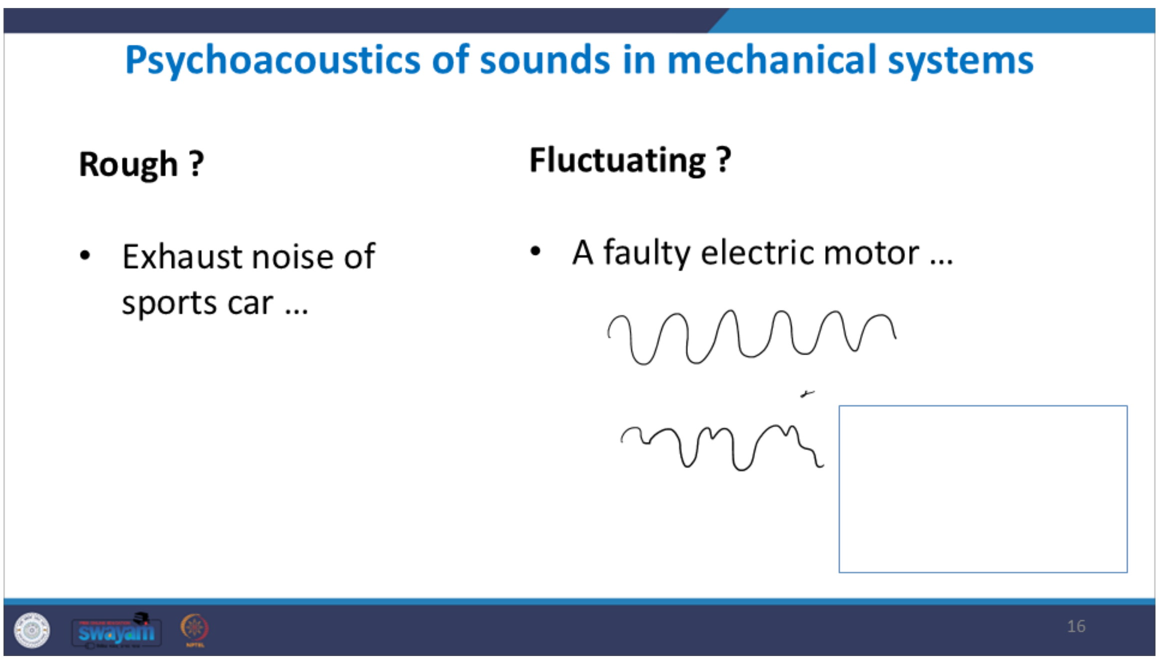


Now, let us see some exercise, psychoacoustics of the sounds in mechanical systems. some of the sounds which typically appear loud to us. Like a turbine engine, then the jet propulsion noise, jet noise is very high when you are close by it. Then the blasts and the explosives. They appear very loud to us.

Some of the quiet sounds Electric motor, A split air conditioner, and Heaters, etc. Most of the electric devices they are actually quiet.

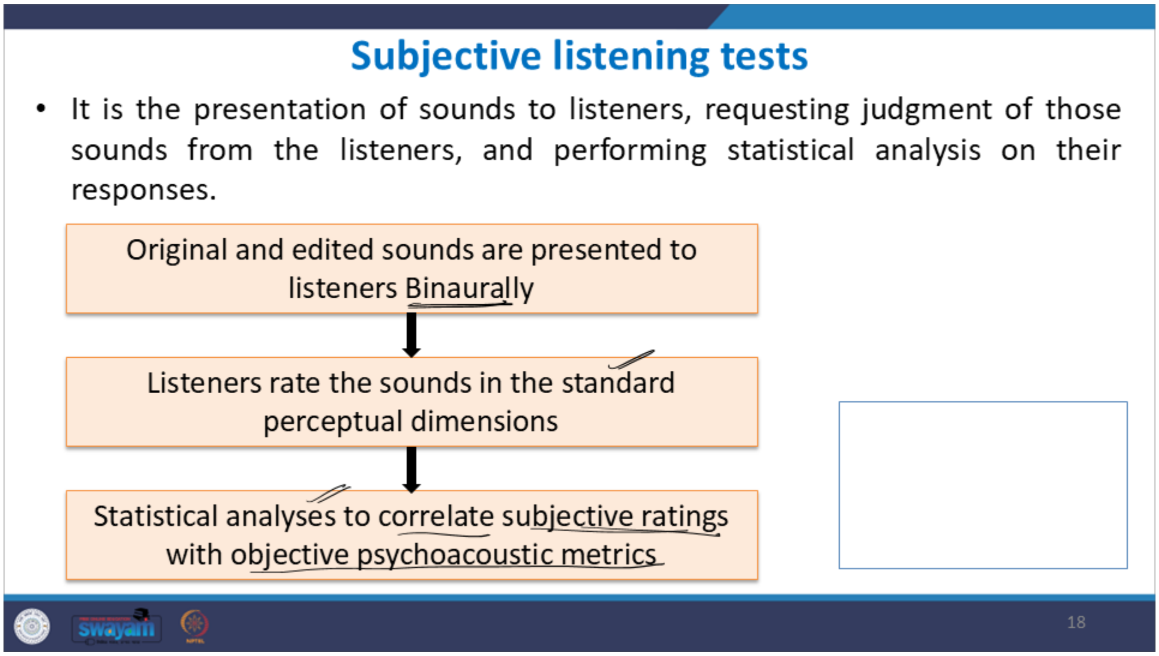
Then sharp sounds, if you see, you would feel that, when you are using this tile cutting machinery it is a very sharp sound, it is itchy and irritating like that. Then the surface fining and the welding these kinds of activities typically to a human these appear as sharp sound and the sound with low sharpness or not sharp could be something like an IC engine, earth working, concrete machinery and so on. Some of the sound which you can say are rough for a human ear, exhaust noise of a sports car, it is a rough sound and it is made to be that way. Then the fluctuating you can say, a faulty electric motor it has a fluctuating quality to it because of the fault inherent in the electric motor if suppose the motor was having some



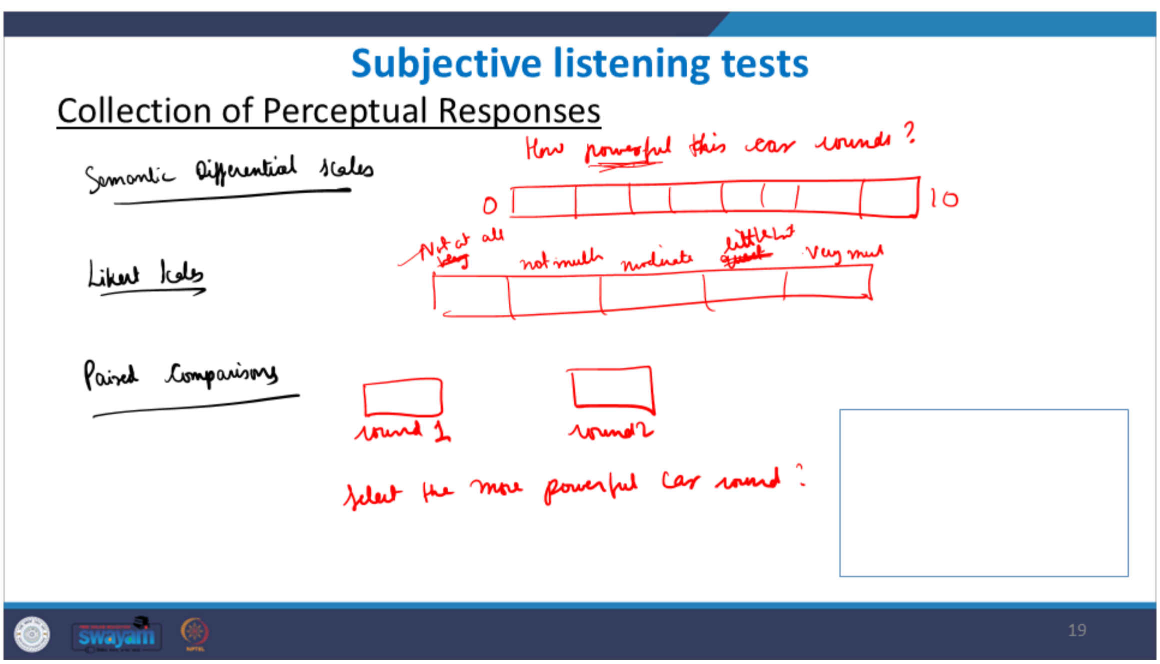


kind of sinusoidal waveform due to the faultiness some additional frequencies have come up maybe and it sounds like modulated and you think of it as a fluctuating noise.

So, we have discussed binaural recording, what happens in sound quality software module. we have discussed about how to obtain these objective sound quality metrics these. Now, we see how to do these listening tests. Very simple, just invite, play the sounds to the listeners in a closed environment so that they are not disturbed by the outside world and



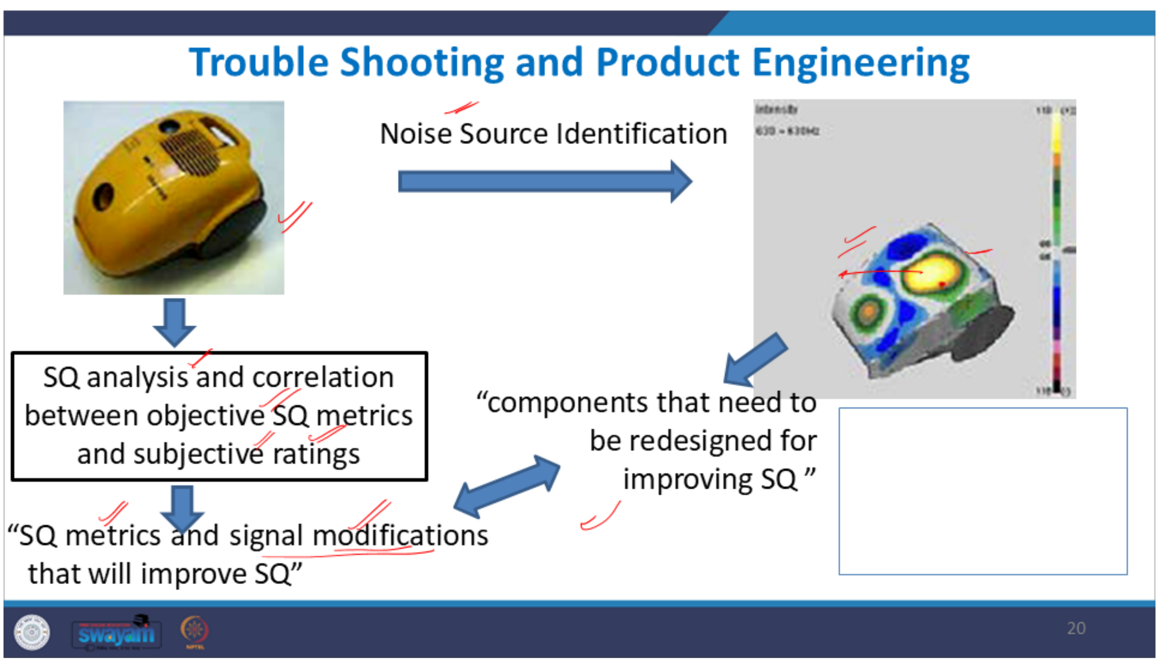
the outside sounds you play them binaurally because you have recorded them binaurally it makes sense to play them again through binaural headphones then the listeners will be asked to rate the sounds in some standard perceptual dimensions you obtain the scores of different sounds just like people, score different products here they are scoring the different sounds and then you do the statistical analysis to correlate their subjective scores with the objective psychoacoustic metrics that you calculated in the previous stage.



How do you collect the perceptual response? You can collect it using some semantic scales, semantic differential scales or through some Likert scales. through paired comparison and there are many others but these are some of the common ones so what does it mean if you see here semantic differential, so let us say we are trying to judge the quality of a car and you can present to the listener you have to rate the sort of powerfulness of the car how powerful the car sounds so you can ask like how powerful this car sounds. And now the listener will be rating the powerfulness of this car sound.

And then you can either have a differential scale which means, from 0 to let us say some 10 and in these definitions, they have to see whether no powerful at all to completely powerful and they have to make their own subjective judgment. Likert scale where, you have the scale but you have words on the top like very, not much. moderate quiet you can see here not at all not much moderate quiet very much like that, so you can have words to supplement rather than having the numbers and then they can rate okay powerful how much not at all or not much moderate quiet little bit. So, these kinds of words you can have or you can just say this is sound one this is sound two, select the more powerful car sound. Usually whenever you do the subjective listening, the listeners are given what product they are rating because the sound quality essentially boils down to how suitable the sound is to that product.

The listeners they need to know what product they are rating and then they are asked certain, questions like how powerful it is, how pleasant it is, how comforting it is and various other, semantic scales and they rate it.



And then finally when you have this you do the troubleshooting, which means that suppose now we will come to the conclusion of the sound quality engineering is that you have a product such as, this vacuum cleaner. You first do the noise source identification and find out what are the various components creating the noise dominant sources of noise. Then you do the sound quality analysis using that steps that we have told and you get the objective metrics you get the subjective ratings from the listeners of these vacuum cleaner. They rate whether it is suitable how powerful the vacuum cleaner sounds how, how modern it sounds you can have various scales , the manufacturer can decide based on what kind of image they want for this vacuum cleaner it should be a powerful, more efficient like that so various , scales can be chosen and the listeners or the consumers, they can be asked to rate the noise of this of the different vacuum cleaners and then based on that you can be able to find out that these particular sound quality metrics like for example sharpness or roughness let us say are more contributing towards the increase of the sound quality.

Then you can think that okay these are the components producing this noise what kind of redesigning I need to do, so that I can enhance the sharpness and the roughness of the sound. Because that is contributing to the increase in the sound quality and based on that the product can be redesigned and so that the signatures they can be improved and overall sound quality improves for the product.

So, I hope you enjoyed this lecture on sound quality and thank you for listening.