

# NOISE CONTROL IN MECHANICAL SYSTEMS

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Week:03

Lecture:15

## Lecture 15: Frequency domain analysis of sound signals: 1

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**Noise Control in Mechanical Systems**  
**Lecture 15**  
**Frequency domain analysis of sound signals-1**

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Hello and welcome to the lecture 15 in the series on noise control in mechanical systems with myself Professor Sneha Singh from IIT, Roorkee. So, we have started recently with the new module that is sound signal analysis within this course where We are seeing what happens when the same sound waves which we initially studied as a physical phenomenon now is being recorded by the means of some acoustic transducer and it is converted into discrete values of pressure or discrete values of corresponding voltages. Then what kind of analysis we can do? So, previously we saw some time domain analysis that can be done. as in where we see how it is varying over time. So, a waveform in

analog form becomes something like this where this is the time scale, this is the pressure and in the digital form when recorded via some any kind of instrumentation device the same thing you know comes across as a collection of points sampled at some time delta  $t$  let us say okay so this is the discrete data and then we do analysis on these points such as you know kurtosis skewness RMS values the equivalent levels and percentile levels and these things like SPL, SIL and SWL.

### Summary of previous lecture

Time domain analysis

Analog

Time  $\rightarrow$

Discrete

$\Delta t$

Kurtosis  
Skewness  
RMS  
Equivalent Levels  
Percentile

SPL, SIL, SWL

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So, in this lecture now we will continue on this topic and now we will see first of all that what are some of the common types of sounds based on their temporal features. So, typical sounds having different kind of temporal distributions in mechanical systems and then the frequency domain representation of sound signals or the spectrum.

## Outline

- Sound classification based on their temporal features
- Temporal distribution of sounds in mechanical systems
- Frequency domain representation of sound signals
  - Spectrum

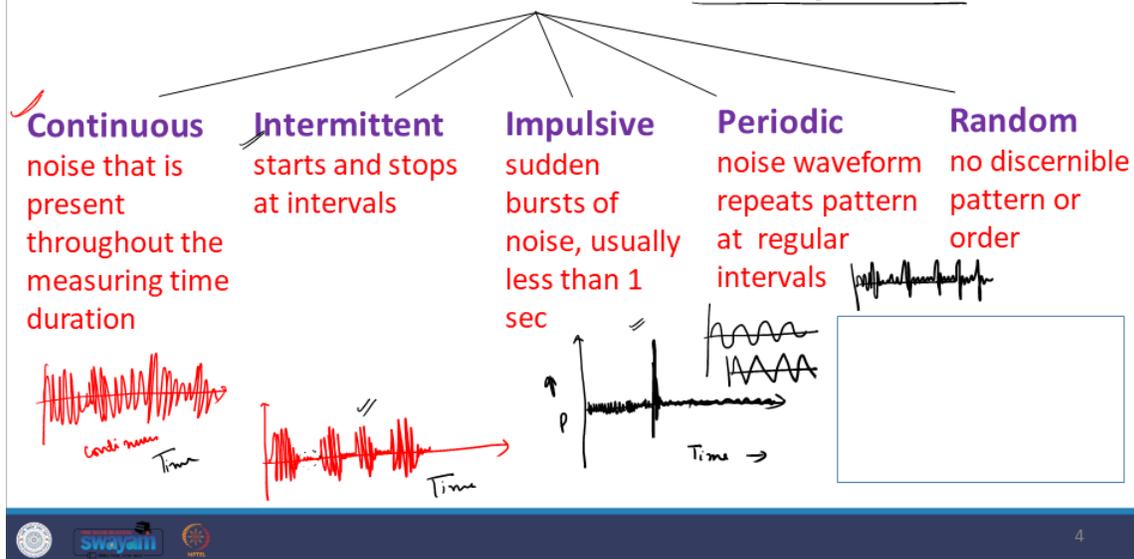


So sound classification based on their temporal features, how do we classify them? Some of the general and broad category of classification can be, we can say it is a continuous sound which means that, so over here noise and sound I am using synonymously because it is a series on noise control. So here the continuous noise is simply a noise or a waveform that is present throughout the measuring time duration. So suppose I pressed the instrument at some time  $t$  equals to 0, I recorded for like 30 seconds and I got a certain length of signal or pressures, pressure values and throughout that the sound waveform was almost present. So here we are distinguishing that if you think about it, you know there is some sound in the atmosphere at all times we do not have absolute zero so that does not mean that that is a continuous sound so let us say we have some waveform like this which is continuous over time with small variations of fluctuations throughout the measurement time that becomes continuous however So, this is quite relatively we take what is continuous what is not. If you are recording the same thing and suddenly there is an absence of some dominant sources and only some minimal background noise is available. Then we say so over here you will see that even in this portion will never achieve an absolute zero, there is nothing like absence of sound till you are there in the fluid medium in the atmosphere. But on the relative scale the waveform that we are measuring and suddenly there is a drop and we go to a very ground zero level with very minimal amount of relatively very less amount of SPL or very less amount of acoustic pressure and it varies like that, then that we do not call it as continuous. So, in

that case this kind of waveform where you know suddenly there is a drop and you go to the background level and then there is some again dominant noise sources acting which are increasing the pressure level and then again it is going down to a zero not the absolute zero, but it is going down to some minimum background level again rising up because of some secondary sources appearing or primary sources appearing and then it is again going down to the background reference level to some kind of minimum background level so there is fluctuation in the sound as if it feels like you know the sources, the noise sources are there and then they are not there, they are there and they are not there.

So, the sound waveform from these kinds of sources is not continuous in your measurement time duration. So, that kind of waveform is called as intermittent. So, always remember that even if it is intermittent sound, there will always be noise, there will always be some acoustic pressure present because there is no never absolute zero, but we are talking on a relative scale. that there is some source and then suddenly there is a significant drop in the pressure level and then again there is a rise in the pressure level and so on. So, that is continuous and intermittent over time. Similarly, you have impulsive sound what it means is that it is for those kinds of sources that are of very high intensity, but they occur for a very small duration of time fractions of seconds. For example, let us say you have metal work where you have an iron smith, he is working on a hot iron plate and then he drops the hammer. So, the hammer is impacting, there is a sudden blast of sound waves and then it is just for like very few seconds, even for a fraction of second there is an impact and blast of sound waves and again it drops back. So, if we have this kind of waveform where is there is a sudden burst in the noise and then it is usually less than for 1 second and then again it comes down to some reference background level then we call it as impulsive noise. Let us say so the waveform could be like this we could have something this is time. this is the acoustic pressure, then we can be having some background noise level and suddenly there is a burst of sound waves for a very small time and again you are getting some minimal background sound level. So, this kind of a waveform could be called impulsive in nature, periodic where the noise waveform repeats at regular intervals. So, it could be like this, it could be like this any kind of pattern it can follow or it could be something like this. It is repeating over regular intervals. So, this becomes periodic and random becomes Where you do not have, when a noise waveform that you are getting which is not following, which is neither impulsive in nature, neither it is periodic in nature and you cannot discern any pattern or order within it. It is very random as the name suggests and you call it as a random sound.

## Sound classification based on their temporal features

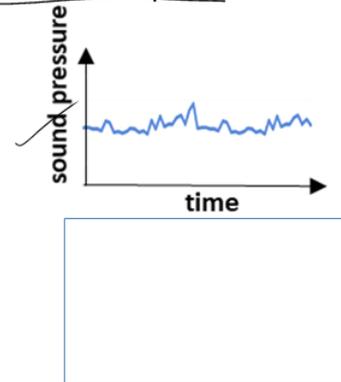
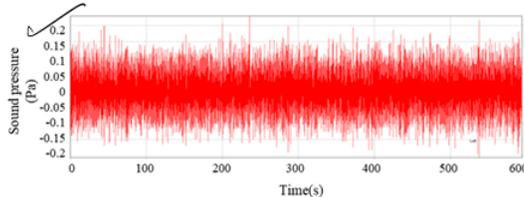


So, let us see you know because it is the course on you know noise control in mechanical systems. So, let us see how are the typical machinery and various mechanical systems, what are their noise like and how are they distributed temporarily or how they are distributed over time. if you see here most of the noise made by the machinery that keeps running without any interruption such as you know an air conditioner a fan or something so most of these noise they are continuous in nature when the machinery is running constantly at a steady state it's not like you're suddenly increasing and decreasing the speed of this machinery or increasing and decreasing the RPM or any kind of sudden change in the operating condition, you are not changing the operating condition, you are keeping it constant and the machinery is running smoothly, you will obtain a continuous waveform, something like this, okay.

# Temporal distribution of sounds in mechanical systems

## 1. Continuous Noise

- Examples: noise by machinery that keeps running without interruption.



and then, intermittent noise could be, you know, especially the machineries that do not usually run over a long period of time. Let us say for example a mixer grinder in typical Indian household the practice is that we do not run the mixer grinder continuously for a long time because it heats up. Whenever we operate this mixer grinder machinery how do we operate it?

We just switch it on. for a few seconds and switch it off again we see how the mixture is or the blend is then we switch it on again then we switch it off after a few seconds so we follow an intermittent pattern while using this mixer grinder machinery so there you get an intermittent noise because the machinery is being switched on for a few seconds and then switched off again then switched on and then switched off again in the same way let us say you have these you know various metal work like a welding sparks or gas metal arc welding most kind of these welding processes where the spark is being generated these machineries also because they heat up so quickly you cannot run it continuously for a long time in contrast to running an ac or a fan which can run for a long period of time so here also the general practice is that you operate the machinery you do the welding for a few seconds and then you stop and then again you adjust your tool you see how it is and then you restart the welding and then you stop after a few seconds you don't run it for a long time so in general the practice is that you use the machinery of the welding for a few seconds you stop again you weld it after a few seconds then you stop and it doesn't run continuously so here also this becomes like an intermittent noise similarly in the case of drilling very same pattern when you are drilling a hole you don't drill the hole for like minutes and hours like that drilling just takes a few seconds you drill it for a few seconds

then you see how the hole is if you need to increase your hole diameter etc so you then drill again just to readjust and then you stop it you don't keep running the drilling machine continuously you go to any factory floor any kind of construction site there would be some machineries that might be running continuously for example let's say if it's a cement mixer then it takes time to mix the cement that runs that you can say that more or less it is a continuous sound source whereas these welding metal cutting, drilling they only happen for a short duration in scattered over different times. So, they become the intermittent noise source.

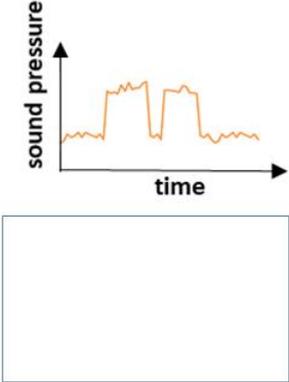
## Temporal distribution of sounds in mechanical systems

### 2. Intermittent Noise

- Examples: Vehicle pass-by, Train pass-by, Drilling, Hammering, Stamping machine, Metal works, Welding, Speech.



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Similarly, impulsive noise again if you come to mechanical systems various kind of gunshots and explosives. Obviously, when you are doing a gunshot have you ever seen that somebody continuously is doing the gunshot it is it is in the form of impulse you know suddenly there is a gunshot a blast of sound waves. In a fraction of second, the bullet goes. In the same way, there could be tanks that are firing cannonballs. Again, it's for a fraction of second, suddenly there's a blast of sound waves when the sort of explosive is fired or a cannonball is fired and then there's again coming back to the ground level so they don't happen continuously neither they happen intermittently like they're happening for a few seconds and stopping then again happening for a few seconds

and stopping it's not like that they are very impulsive in nature which means that there's a sudden burst of sound energy and then there's again zero for a long time in the same way in any case when there is two heavy rigid bodies impacting together shot in the impacting together at you know it and then they're moving apart so they're impacting and moving apart so whenever there's any kind of machinery where you have two rigid solid bodies they come into close contact for a fraction of second impact and then move apart whenever you have this kind of mechanism you will have an impulsive noise waveform let us say for example here the metal working where the iron spit is just impacting and trying to shape the metal. In the same way you can have you know these stamping machines that are trying to shape and make steel plates or coins etc. So all of this here the bodies are impacting and then moving apart. So they are generating impulsive noise which could look like this.

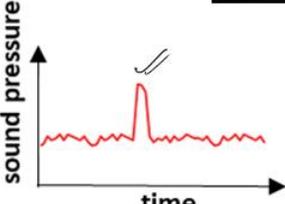
### Temporal distribution of sounds in mechanical systems

#### 3. Impulsive Noise

- Examples: Explosives, Gun shots, Hammering, Stamping, etc.



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Then periodic noise if you think about it you know most of the machineries or the device where rotation or reciprocation is happening at a constant rate. So, in most of the mechanical device you will see that usually there is a component that is rotating or reciprocating and is generating some motion. And if they are rotating or reciprocating, so either it could be a rotating motion or it could be some mechanism that is doing a reciprocating motion and it is being done at a constant rate, then that mechanism itself is

going to produce some noise waveform. And because it is some, because that mechanical, you know that phenomenon which is generating the noise waveform here. it is periodic in nature so let's say for example it's some it's the rotation of let's say a gearbox the gearbox here the gears are rotating and the shaft is rotating at a constant rate and the gears are meshing and they are moving at a constant rate and you are not changing the gear ratio you are keeping it moving at a constant rate then the phenomenon repeats at fixed intervals of time this phenomenon is generating the noise so by default the noise it's generating will also be repeating whatever noise waveform it's generating it will repeat over time in the same fashion as the phenomenon or the mechanism is repeating over the time in the same way let us say you have these machinery such as fans any kind of fans or blades and you run them at a constant RPM or a constant speed. Again, the mechanism that is generating the noise here which is the blades cutting the air and moving that mechanism is generating the noise and the mechanism is repeating after some fixed interval of time. So, the noise waveform that is being generated by the mechanism it will also be repeating after fixed intervals of time. Similarly, compressors, the very primary example being of a pendulum clock that repeats its motion. That's a simple harmonic motion with a period of one second. It's repeating its motion. Compressors, these road rollers. where you know if they are moving at a constant speed the roller is rotating and generating a periodic waveform. Sometimes even you will it is very fascinating to see some of the sometimes when the wood carpenters they are working on the saw they also have almost a periodic motion while trying to cut the wood. It is not perfectly periodic, but it is very fascinating to see that how they you know the way they cut the wood when you see a carpenter working at the wood you will see that they are you know following this periodic pattern of cutting the wood and that is also generating roughly a periodic waveform.

## Temporal distribution of sounds in mechanical systems

### 4. Periodic Noise

- Any machinery/ device featuring rotation or reciprocation at a constant rate.
- Examples: Clocks, Saw, Road rollers, Automotive engine, Tuning forks, Compressors, fans, blowers, electric motors, etc.

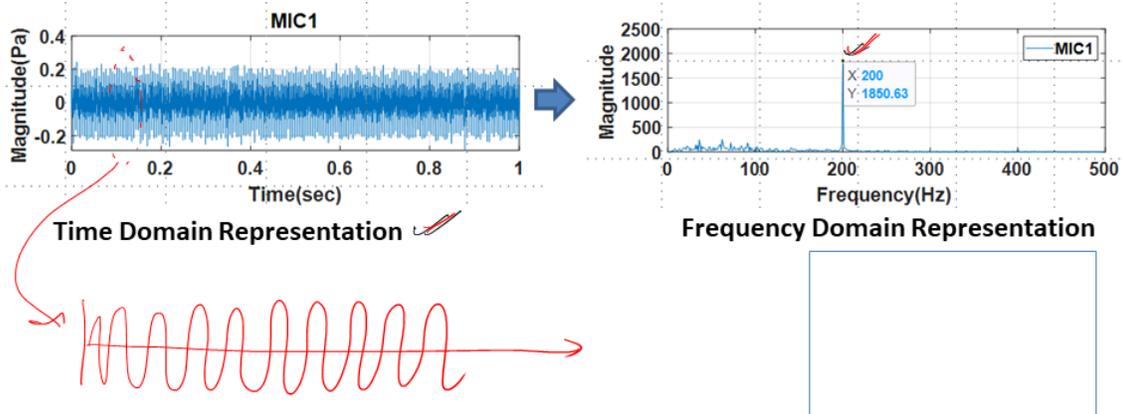


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So, this is an example of the periodic waveform from one of our research here in my group and this is the time domain representation of a periodic signal. So, over here you know obviously we have taken it for over a period of one second and so from a distance you will not notice something like it's a sinusoidal wave okay it doesn't look like this but it is actually a sinusoidal wave and you know it's compressed so Within 1 second, there are many cycles happening. So, this is a periodic waveform. So, it is being compressed. So, you are not able to discern whether it is a sinusoidal wave. When you do a frequency domain representation, you find that it has got a very sharp single peak at 200 Hz frequency. So, it is a sinusoidal, it is comprising mainly of a sinusoidal waveform of 200 hertz. So, it is periodic in nature, it is harmonic sound. And suppose you zoom into this particular waveform, let us say we are zooming into this one and you see this, it over expanded scale, this is what it will look like. It will look like a sinusoidal wave that is repeating, okay, like that.

## Temporal distribution of sounds in mechanical systems

### 4. Periodic Noise



Now, the last type of noise which is the aperiodic or random noise as I said there is no discernible pattern or order very unpredictable in nature and they do not repeat in any kind of a way. So, for example, you know the noise due to excavators, bulldozers, loaders where you know they are generating the random noise because it depends on what task they are doing the kind of load conditions ground conditions then moving this lot of random things it's not like it's doing something fixed you know the noise waveform depends on how much load is there and then how much load is being unloaded and so on so over a period of time it's not periodic in nature neither it is following an impulsive waveform this is a random noise similarly one of the most common example which is quite known for being notorious for noise control engineers is the noise due to turbulent air flows. So, whenever there are turbulent air flows such as you know jet noise or the jet fuel mixing noise. So, wherever there are turbulent flows involved or let us say any kind of HVAC machinery or a blower fan that is sort of operating at a very high speed and the air flow is through a complicated path then after a certain speed from laminar it becomes turbulent the flow becomes turbulent in nature and then it becomes all unpredictable. In fact, turbulence is very tricky subject both for the fluid mechanics people and researchers as well as for the noise control engineers because there is no fixed way to deal with it. We do not know what is the we cannot model the waveform in any simplistic way for the turbulent noise neither we can have a fixed way of controlling it.

## Temporal distribution of sounds in mechanical systems

### 5. Aperiodic or Random Noise

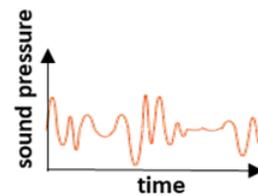
- Sound that has no discernible pattern or order; it is unpredictable and does not repeat in any regular way.
- Examples: excavators, bulldozers, and loaders produce random noise depending on the task, the load, and the ground conditions.
- Jet noise, noise produced by turbulent flows



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Now for any general machinery noise what you see is that other than you know various machineries that can follow a particular pattern in most of the cases the machineries they have both random and periodic components such as a canister vacuum cleaner. It can have both these components because in a complex machinery it's not just it has one single part right. Suppose we have got a car and I was giving you the example of you know a gearbox making a noise when it's running at a constant RPM but automotive or a particular car does not just have gearbox. It has a lot of other components. Some components may generate a periodic noise whereas some other components may generate an aperiodic or random noise. So, a machinery in totality can have both random and periodic components. For example, in this vacuum cleaner what you see is we have the periodic noise it is being produced by the centrifugal blower because it is rotating at a constant. So, here you have to specify that whenever the centrifugal blower is running you are not you know it is running at a steady state it is not like the user is constantly changing the RPM and the operating conditions the user is keeping the operating conditions fixed in the measurement time running at constant RPM and operating condition, then it will generate a periodic waveform this blower because and that waveform will have the frequency same as the blade passage frequency. You can see what this term is and see for yourself what this means. Then the same vacuum cleaner can also have a component that may generate random noise. For example, you know produced by the airflow through the motor. So, the blower when it is rotating by the virtue of its rotational mechanism, it is generating the noise which is periodic in nature, but when it is rotating, it is it sort of you know creating a suction mechanism for the airs

to flow and when the air flow happens and they go through this complicated passage way at high speeds they become turbulent in nature and they take a random noise waveform

## General Machinery Noise

**Usual machinery noise has both random and periodic components**

**Canister Vacuum Cleaner**

- Periodic noise: produced by centrifugal blower <sup>running at const. RPM & operating condition</sup> at blade passage frequency.
- Random noise: produced by air flow through motor.



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Ok so now you know that some of the temporal distribution of sounds let us get back to so there are two ways so over here I told you that you know this is we representing the times the sound signals as it is varying with time.

But there is also a way in which we can represent the same sound signal on how it is varying with respect to frequency and we can see whether it is harmonic in nature, what kind of frequency components it has. So, this lays the foundation for spectral distribution or frequency domain analysis. So, before I begin what is frequency domain analysis, I will give you the theorem that is the fundamental basis of frequency domain analysis that is the Fourier's theorem. So, what does the Fourier's theorem say?

It says that any sound signals whether it is periodic, aperiodic any kind of sound signal, it can always be expressed as a superposition of harmonically related pure tones of varying amplitudes and phases. So, mathematically if  $P(t)$  is the acoustic pressure of any waveform here  $P(t)$  can be periodic in nature it can be composed of various periodic components or it can be a completely random noise also, but any kind of generic you

know pressure signal can be expressed as a summation of pure tone components where they are harmonically related which means that here it can be expressed as you know comprising of frequencies where the first frequency is the fundamental frequency and then the summation of the successive frequencies where the successive frequencies are integral multiples of whatever fundamental frequency you are taking ok. So, here  $f_2$  would be twice of  $f_1$ ,  $f_3$  would be thrice of  $f_1$ . So, it is a summation of different periodic different pure tones of varying amplitude where first pure tone is a fundamental has a fundamental frequency and then the other tones, they are integer multiples of that particular frequency.

$$p(t) = A_1 \sin(2\pi f_1 t + \phi_1) + A_2 \sin(2\pi f_2 t + \phi_2) + A_3 \sin(2\pi f_3 t + \phi_3) + \dots \dots$$

### Fourier's Theorem

Any sound signal (periodic/ aperiodic) can be expressed as superposition of harmonically related pure tones of varying amplitudes and phases.

$$p(t) = A_1 \sin(2\pi f_1 t + \phi_1) + A_2 \sin(2\pi f_2 t + \phi_2) + A_3 \sin(2\pi f_3 t + \phi_3) + \dots \dots$$

- $f_1 = \text{Fundamental frequency} = \text{first harmonic}$
- $f_2 = 2f_1 = \text{second harmonic}$
- $f_3 = 3f_1 = \text{third harmonic}$

All frequency component are integer multiples of fundamental.

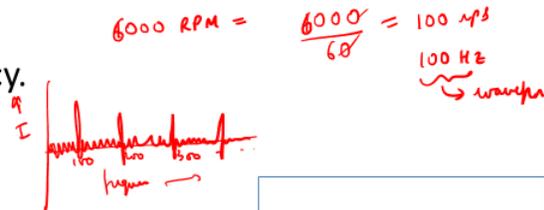

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So, how do you apply this to the mechanical systems because you know that mechanical device rotating at constant speed it can be expressed as a sum of the harmonically related pure tones where the fundamental frequency is the rotational frequency. So, if you would observe and just by some way measure the waveform or the sound signal of an engine an IC engine.

So, the engine is rotating at a particular speed you know the engine it is doing its phenomenon at a particular rpm and a particular speed. So, you should be able to generate a waveform that has let us say for example, one engine is rotating let us say at 100 or let us say 1000 rpm right. So, which means how many cycles it is doing per second it is 1000 revolutions per second. So, 1000 per minute sorry 1000 per minute then 1000 by 60 becomes the number of cycles per second that that engine is doing. So, this will become the frequency whatever this value is ok, it should be somewhere close to 16.67. So, that becomes its fundamental harmonic. So, the engine is having a particular rpm which belongs to a certain number of cycles per second and because that mechanism is repeating in that many times per second it is generating a waveform which should have the same frequency right. So, whatever that frequency let us take something which is easier to you know calculate. So, let us say 6000 RPMs it is a big turbo engine and 6000 revolutions per minute. So, which means that per second we get 100 revolutions per second or 100 hertz should be the waveform, but when you usually measure it what you see is that let us say this is your frequency and this is the intensity. that you are measuring what you will see is that it may have the waveform this is 100, 200, 300 and so on. So, usually what you will observe is that the waveform could be like this like this. So, what is happening here is that the mechanical device is rotating at a particular speed, but it is generating the fundamental frequency and also its successive harmonics. So, again you are you can represent it using this Fourier series.

## Fourier's Theorem in Mechanical Systems

- Sound produced by mechanical device rotating at a constant speed may be expressed as a sum of harmonically related pure tones.
- Fundamental – Rotation frequency.



So, now let us come and directly jump to you know frequency domain representation of sound signals. till now whatever analysis we did was for the sounds with a single frequency we call the sounds that have a single frequency as tones so any harmonic plane wave having a single frequency not even harmonic plane wave it could be a spherical or a cylindrical wave front just having a single frequency it becomes a tone but most of the sounds as seen in daily life they may have may various tones it is not like the sounds in daily life would be composed only of a single tone or having a single frequency due to the complex mechanism they could be you know multiple frequencies that are coming together to get the overall sound waveform and in that case Acoustic intensity for most of these sounds is non-uniformly distributed over various frequencies and time. Now, human ear it is audible in a frequency range of 20 to 20 kilohertz and in the next module you will come to know that our ear is a very frequency sensitive device. So, we perceive the sounds based on what frequencies are present in it. So, sounds at certain frequencies may appear louder to us compared to the sounds at certain other frequencies, sounds at certain frequencies may appear more appealing and pleasant to us compared to the sounds at certain other frequencies. So, our perception is very frequency dependent. and hence because we are doing noise control for us for us humans and humans, they are very frequency dependent when it comes to you know perception of the sound hence noise for noise control how to control the noise the knowledge of what frequencies are present becomes very essential because humans, they are sensitive and they like a certain frequencies and they don't so that is why Frequency content knowledge is very important.

## Frequency domain representation of sound signals

- Till now, theoretical analysis was done for sounds of single frequency, i.e. “tones”.
- Most of the sounds of daily life contain many tones of different amplitudes. Acoustic intensity for commonly observed sounds is non-uniformly distributed over frequency and time.
- Audible frequency range is 20 Hz to 20kHz. Human hearing and sound perception is highly frequency sensitive, therefore knowledge of frequency content is essential for noise control applications.

So, let us come to the fact what is a sound spectrum? It is a representation of sounds as a distribution of its acoustic intensities over frequencies. Okay So very simply if you had one axis for the frequency and one axis for the acoustic intensity. and some distribution that shows this, how this intensity is varying over the different frequencies, you will get the spectrum. Now, here an important term is which is called as a spectral density. What is a spectral density? It is the magnitude of the acoustic intensity over a particular frequency.

### Sound Spectrum

- **Spectrum:** Representation of sounds as a distribution of its acoustic intensities over frequencies is called a sound spectrum.
- **Spectral density ( $\zeta$ ):** of a sound is the magnitude of its acoustic intensity over a particular frequency.





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So, let us see from this example. Let us say we are Now again here it's not possible to practically measure the acoustic intensity in every frequency because you know if you take a real scale we can have a frequency at 20 Hz then 20.0001 Hz, 20.002 Hz so again we are not taking analog signals so we can only measure the intensities at fixed intervals of time in the same way due to the limitations in data computation itself we able to gather the intensity data at only certain frequency points so if suppose we start and we measure what is the overall intensity at 20 Hz and then what is the overall intensity at 21 Hz and then 22 Hz and so on till the last limit of audible frequency range. So, at every range within a gap of 1, 1 Hz we are measuring what is the intensity of the sound wave only within that frequency. okay So, that is a spectral density which is the magnitude of the acoustic intensity over a particular frequency.

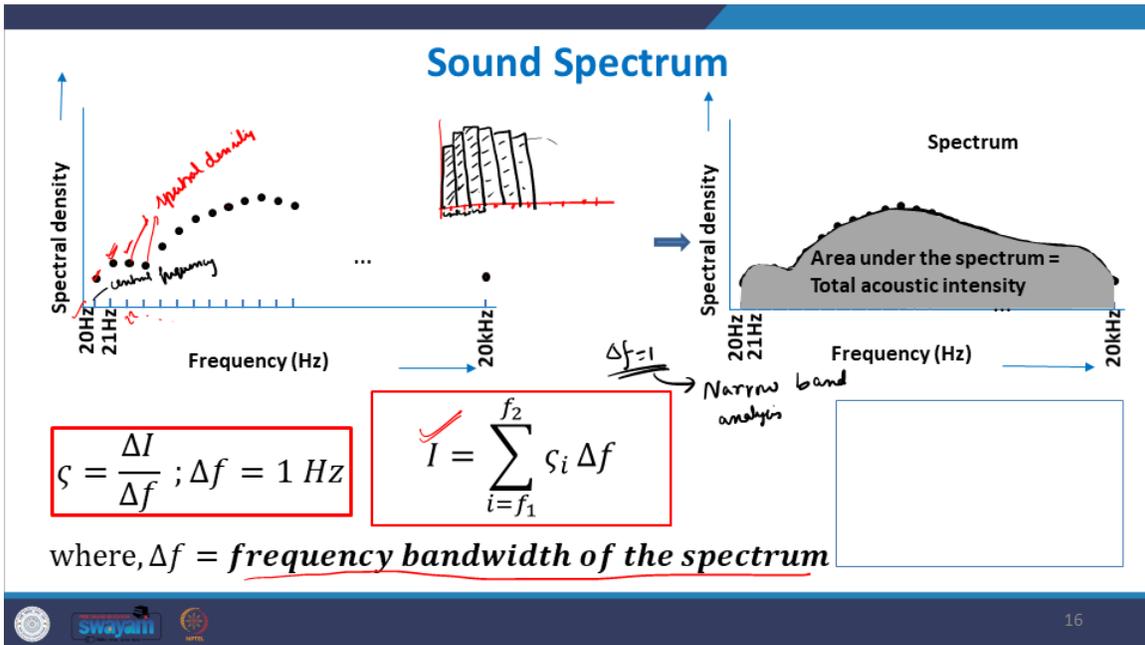
So, all of this individually become what? They become your spectral density.

okay and you can you get a collection of points and then suppose you find out the area under this points that should give you the total acoustic intensity because the spectral density which is these points okay spectral density versus frequency is what it is the that small  $\Delta i$  that is present within a small  $\Delta f$  the small band of frequency over which we are measuring the amount of intensity and if you want to you know find the total intensity then we sort of sum up that okay within this band this is the amount of intensity then within this band this is the amount of intensity and you successively sum up the intensities over all the bands and within all the audible range and you would be able to get the total intensity within the audible range by summations.

$$\zeta = \frac{\Delta I}{\Delta f} ; \Delta f = 1 \text{ Hz}$$

$$I = \sum_{i=f_1}^{f_2} \zeta_i \Delta f$$

So, this is equivalent to the area under the curve. Now, over here this  $\Delta f$  which is the difference between the frequencies of two bands is called as the frequency bandwidth of this spectrum ok. So, it looks like this you know suppose you have a spectrum and you are measuring at certain fixed intervals in frequencies then you can assume something like that that over this band you have a certain frequency then here you have got a certain frequency may be here you have got a certain frequency here you have got a certain frequency like this and then you are to find out the total intensity you are just summing up the intensities over these bands like that. And when this bandwidth is equal to 1,  $\Delta f$  is equal to 1, we call it as narrow band analysis because we are almost analyzing over every frequency.



So, within this frequency spectrum each band over here, this is these are the various bands so here this is what these are the central frequencies in a band okay and this is the band so you will have a central frequency so once again over here let us say in each band you will have an upper frequency a lower frequency a central frequency and a bandwidth

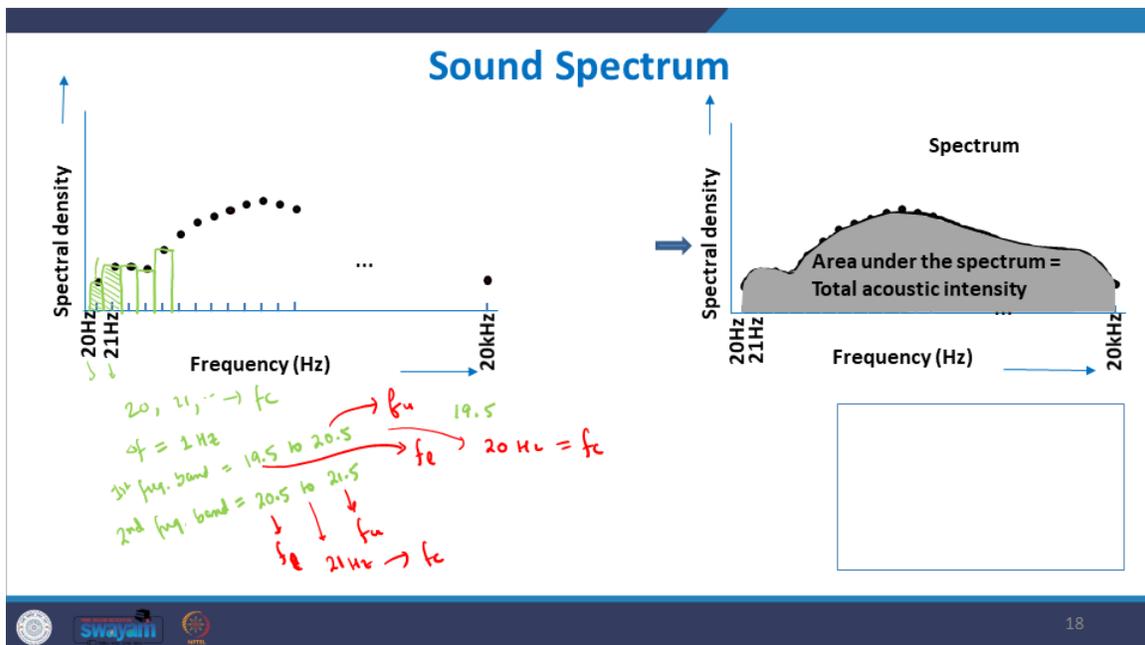
### Sound Spectrum

- Any general sound can be described as acoustic intensities distributed over narrow frequency bands. Such distribution is called a **spectrum** or **frequency spectrum**.
- Each band is characterized by:
  - Upper frequency ( $f_u$ )
  - Lower frequency ( $f_l$ )
  - Central frequency ( $f_c$  or  $f$ )
  - Bandwidth ( $\Delta f$ )

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let us explain through this one so let us find out the frequency bands here which i'll represent it using this light color so let's say So, I am constructing the frequency bands. So, here these frequencies 20 hertz, 21 hertz are the central frequencies within a particular band.

So, what I am saying is that whatever this value is, this is I am saying that this is the spectral density over this entire range, over this entire band of frequency. Then what I am saying is that this is the spectral density over this entire band of frequency and so on. So, here 20 hertz, 21 hertz they are all central frequency of that band, but there is a lower limit and an upper limit. So, here let us say we have made a band with a bandwidth as 1 hertz. So, the first band could be like this. could be from 19.5 to 20.5 with the central frequency at 20 and we are saying that within this entire range this is our intensity in the second in the same way we can have second frequency band where it can start from 20.5 to 21.5 and we say that within that band this is the range of frequency this is the intensity so we are building up these bands so here this 19.5 so here this one here in the first band so in every band in this band this is the lower frequency this is the upper frequency and 20 hertz in this case is the central frequency. In the same way in this band, this becomes the lower frequency, this becomes the upper frequency and 21 Hz becomes the central frequency and so on. So, this is how the bands are made up of. Okay.



So there are various common types of sound spectrum. We have linear spectrum, octave spectrum and one third octave spectrum. Okay. So, what is a linear spectrum? In the linear spectrum what happens that see spectrum is always you know distribution of spectral density over frequency. If you have the frequency in a linear scale, it becomes a linear spectrum. If the frequency is in logarithmic scale, it can be either octave or one-third octave spectrum. And this we will discuss in detail in the subsequent lecture, not here. So, let me just discuss the linear spectrum. So, in the linear spectrum, what happens? Let us say this  $f$  means the central frequency. So, every new central frequency would be the previous central frequency plus some constant. So, which means that all the bands they have constant width in the linear frequency range.

So, the  $\Delta f$  which is  $f_u$  minus  $f_l$  is always a constant

$$\Delta f = f_u - f_l = \text{constant}$$

and the next central frequency can be got by simply adding that constant over the previous central frequency and so on. okay and if this  $\Delta f=1$  as I told you it becomes a narrow band frequency or a narrow band analysis.

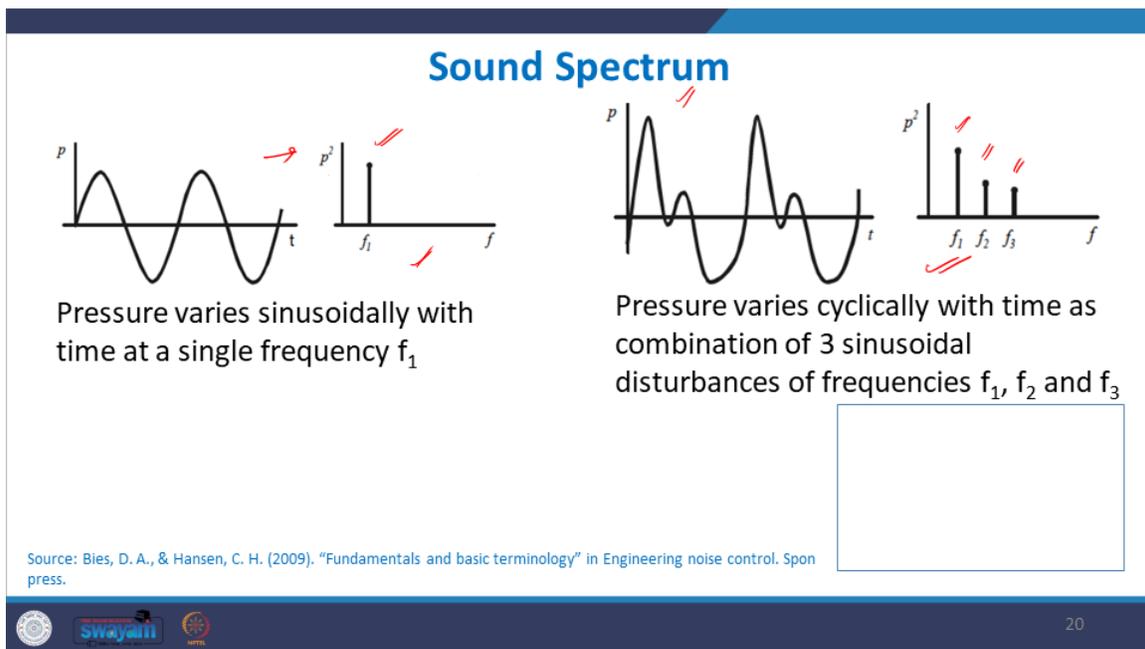
### Sound Spectrum

- Common types of sound spectrum:
  - Linear spectrum
 
$$f_i = f_{i-1} + \text{const}; \Delta f = f_u - f_l = \text{const}; f_c = \frac{f_u + f_l}{2}$$

$\Delta f = 1$ , Linear spectrum is also called Narrow Band spectrum/ Narrow Band Analysis
  - Octave spectrum
 
$$f_u = 2f_l; f_c = \sqrt{f_u f_l}; f_i = 2f_{i-1}$$
  - One-third octave spectrum
 
$$f_u = 2f_l; f_c = \sqrt{f_u f_l}; f_i = 2f_{i-1}$$

So, let us see over here this waveform now if we convert it into the frequency now if we convert it and we get the frequency we do the frequency analysis and represent the intensity over frequency. So, over here it has a particular frequency with which the wave front is repeating. Let us say that is  $f_1$

So, our FFT, our frequency representation will look like this because there is a single frequency. It is a pure sinusoidal wave. but over here it doesn't look like a pure sinusoidal wave but you can definitely see that it is repetitive in nature so what is it actually composed of it is a summation of three sinusoidal waveforms at three different frequencies but with three different magnitudes as well.



Okay so we do the spectrum analysis or the frequency analysis which is converting a time varying signal to the frequency components like this We do the frequency analysis and we come to know what are the frequency components and what is the magnitude of intensity in those frequency components. And the methods used are Fourier analysis and various kind of its variants. And it's useful for noise control application because our hearing is highly frequency dependent.

## Spectrum analysis

- **Spectrum analysis or Frequency analysis:** is the process of converting a time varying signal to its frequency components.
- Methods used for frequency analysis are Fourier analysis and its variants.
- It is useful for all noise control applications as human hearing is highly frequency dependent. So, noise control criteria and its solutions are also frequency dependent.

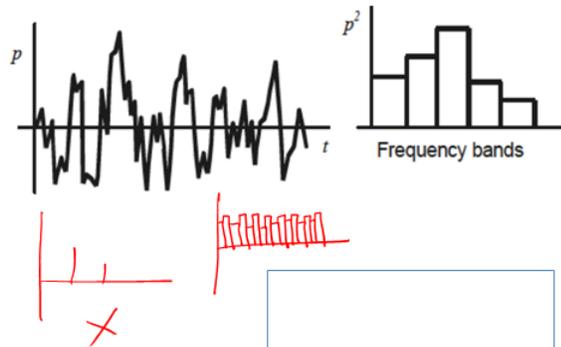


Even if suppose we have a random waveform like this, over here I don't see any repetitive pattern. It seems very random. But as you go back to your Fourier theorem, it says that whether a signal is periodic or non-periodic, it can always be expressed as a summation of the harmonically related pure tones. So, in this case, it was fully sinusoidal, so a single frequency. Here it was a summation of three different sinusoidal waveforms but here which is very random it can be thought of as composed of infinite number of frequencies okay to get to this very random waveform so which means that the spectral density will look like this it will have some intensity over all the frequency ranges okay so the waveform would not look like this or like this it would look like you know having intensities whether low or high over all the frequency bands. So, the more random the signal, the more intensities you have over all the frequency bands and with the Fourier's theorem you can still represent this waveform having composed of these frequencies.

## Sound Spectrum of random noise

Pressure varies erratically and randomly with time. No periodic component.

Using Fourier series this random sound wave can be represented as collection of harmonic waves of all frequencies.



Source: Bies, D. A., & Hansen, C. H. (2009). "Fundamentals and basic terminology" in Engineering noise control. Spon press.

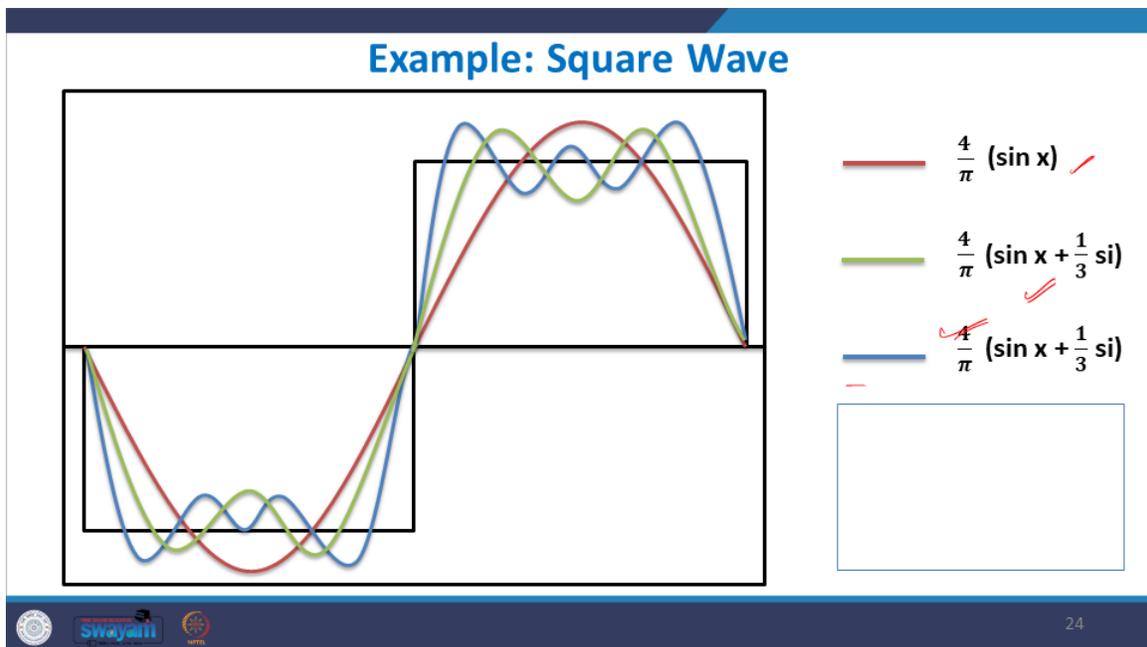
In the same way, this is another random signal. If you do the energy content versus frequency, you would see that it has some energy content over all the frequency bands. Okay.

## Sound Spectrum of random noise



Energy content at every frequency within a certain range. Sound has energy content over a continuous range of frequencies not at a finite set of frequencies as in periodic sound.

This is an example of a square wave. This is also repetitive in nature and this is just to explain to you what is a Fourier's theorem. if you add the first term you get the sinusoidal wave. if you add the second term of the Fourier theorem you get this green wave which is coming closer to square wave. If you add the third term you get this blue wave which is even closer to the square wave and then you keep successfully add successively adding the Fourier series terms and you get very close to the square wave. So, ultimately you know Any form of signal can be represented using summation of various harmonic tones and it can have a frequency intensity over various frequencies.



So, with this I would like to end this lecture. Thank you for listening.

**Thank You**



**Swajati**

