Acoustics
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Module-7 Sound in Public Spaces & Noise Management
Lecture 03
Absorption coefficient, and irregular rooms

So earlier we had covered reverberations in rooms which were of regular shapes, parallel walls they could be 1-D long rooms or 2-Dimensional rooms or we had also talked about 3-Dimensional rooms. A lot of rooms however take auditoriums, concert halls and lot of lecture theatres they are not of regular shapes. So what we will cover today is how does sound behave if it gets propagated inside large but irregular room.

So couple of things for large irregular rooms, one that because the walls are not perfectly parallel to each other so the reflections keep on happening for and you will have standing this for virtually any frequency and that virtually any angle of incidence because things are not very nicely parallel to each other.

Second thing at any given point sound moves in all directions in parallel rooms if you have a forward going planer wave then it will nicely behave and reflect and it will move in straight lines so the propagation will not necessarily be in all directions but in irregular rooms these reflections could happen (not reflec) because of the nature of reflections the propagation of sound at any given point could be in all directions.

Third thing the number of modes in these rooms and the number of natural frequencies in these rooms is extremely large it is even larger compared to some other 3D rooms examples which we had seen. So at virtually any given frequency if you move from one point to other point within a very small distance you will see moving from one node to other node to other node.

In last class we had seen because it is like a more or less or rectangular room, for low frequencies the distance between two nodes at least in this room which has parallel walls, nice rectangular boxy room at low frequencies the distance or separation of nodes at low frequencies 125 Hertz we had seen is not very small but in irregular rooms that may not necessarily be the case.

So if you combine all these 4, 5 effects which I had mentioned then the sound field in such a room is called a diffused field is called a diffused field.

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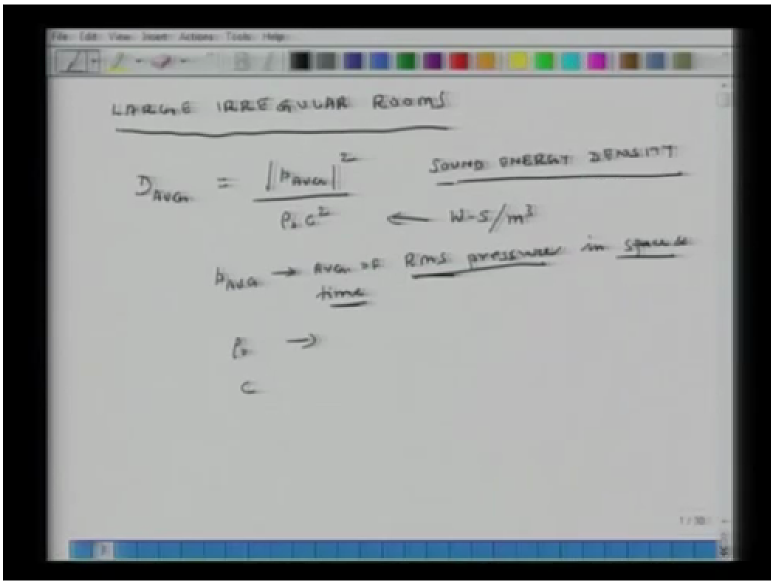

So we will develop some relations how sound behaves in these kind of enclosures, so it is large irregular rooms. So what I will do is I will introduce a couple of terminology. So the first concept I will introduce is develop a relation between energy density in the room energy density and the sound pressure level and this I have taken from some of the earlier class notes with just a mapping.

So I will define a term D average is p average square over Rho not c square and this is sound energy density is D average. So the units of (())(4:12) Watt second Watt second is energy or joules and because of its density it is for every cubic meter couple of things to note p average is the average of RMS pressure in space and time what does that mean? If I have a microphone when I am playing music where people are talking the microphone is sensing some pressure level.

So I position microphone at a point and I record data for let us say few minutes 1 minute, 2 minutes and then I take the average RM at the average of the different RMS values. So for first one tenth of a second I find the RMS, second one tenth of a second I find in the RMS and then I average it out. So that is averaging the RMS pressure in time in time. Now I move my microphone to slightly different location and then I do the same exercise so then I am averaging it in space.

So this guy is average in both space and time, so you measure for a little longer periods or time at couple of locations and then you get the (())(5:47) and it is again the average of RMS pressure, it is not the peak pressure, it is not the minimum pressure, it is the average of RMS pressure and of course Rho not is a density and c is velocity of sound (())(6:04) that is my sound energy density.

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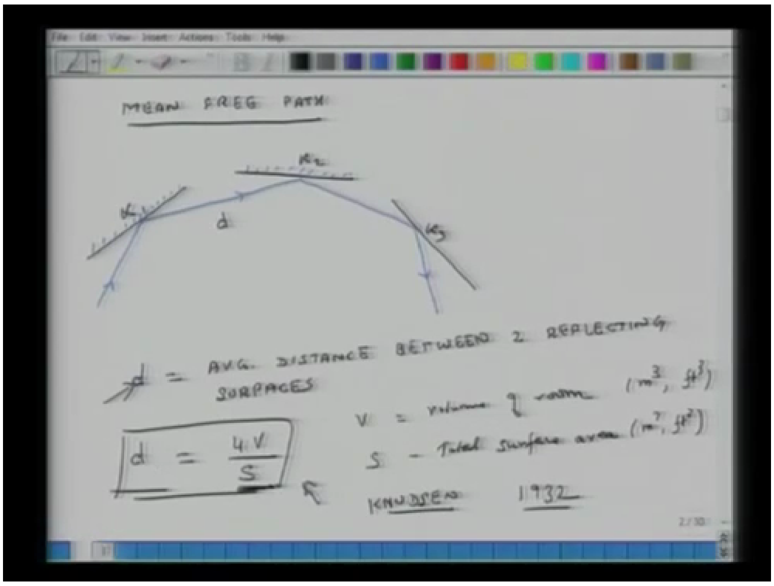

The second concept I will introduce and this is a new concept mean free path. Let us consider couple of walls in an enclosure I have incident sound it gets reflected by this surface. So it comes and hits another surface, it gets again reflected and it gets again reflected and so on and so forth. The mean free path I will define it as letter d and this is average distance between two reflecting surfaces, so this distance could be d, this is reflecting surface 1 of absorption coefficient alpha 1, we will define and explain what these alphas are later alpha 2, alpha 3.

So between two reflecting surfaces average distance through which the sound travels is d and if I have to compute the value of d it is 4 V over S, how did we get this? So V is volume of room, S is total surface area I mean reflecting area this is this could be in meter cubes or feet cubes, this could be in meter square or feet square. So the first time there was a Acoustician his name was Knudsen.

So in 1932 he did some experiments he computed experimentally the value of d so he design 10, 12 different types of closed spaces all these closed spaces were irregular in shape and they were very significantly different from each other. So it is not that they were slightly different they were very significant and what he found was that the value of d is comes to 4 V over S. Later based on some statistical principles people also did some studies and from a theoretical stand point validated the same expression.

So this this expression d equals 4 V over S has an experimental basis and also has statistical basis. The value of d could be either in feet or in meter cubes meters but you have to be just consistent but reason I am saying that is that because it is a relation based on statistics and experiments we have to be careful about it. So we have talked about D average, second concept we introduce is mean free path which is d.

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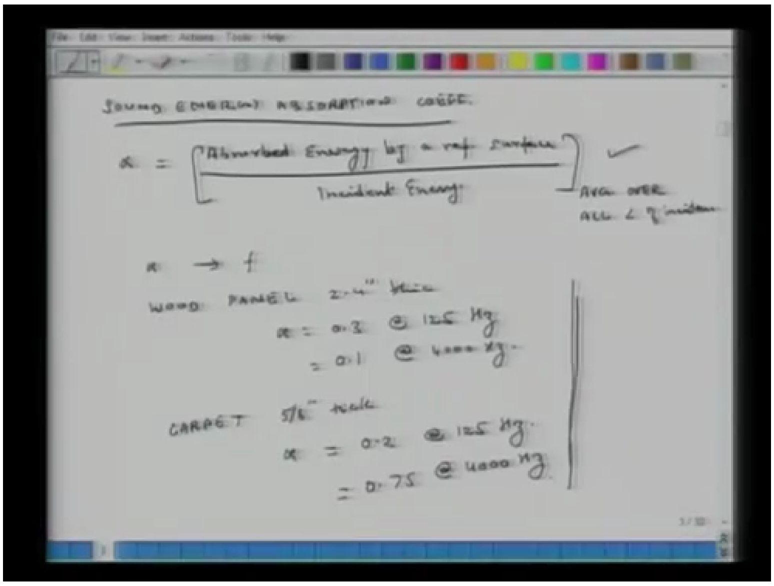

Now we will introduce another thing called sound energy absorption coefficient, okay and this is alpha, alpha is absorbed energy by a reflecting surface divided by incident energy and this I average it over all angles of incidence because the absorption coefficient will change as by angle of incidence is changing. So whatever energy is being absorbed for different values of incident angles I average them up and I get value of alpha this is an experimentally.

So you find this value alpha for different materials through experiments, the other thing you may want to know is that this value of alpha is strongly dependent on frequency it changes with frequency, I will give you two examples. So the hand out which you have today extracted these two pieces of data for example this wood panel which is 2 to 4 inches thick alpha equals 0.3 at 125 Hertz and same thing goes down to 0.10 at 4000 Hertz, so they change significantly with frequency and then I will give you another counter example Carpet it could be 5 over 8 inch feet, alpha is 0.2 at 125 Hertz and in this case it is going up at 4000.

So whenever we talk about alpha the natural question is alpha at what frequency there are some materials where alpha is more or less constant over the frequency rate most of the material they have very strong frequency dependent behaviour. So alpha always has to be talked in context of a frequency number. In general when people do not specify alpha then you may assume with a little bit of latitude that it is may be for 500 cycles per second.

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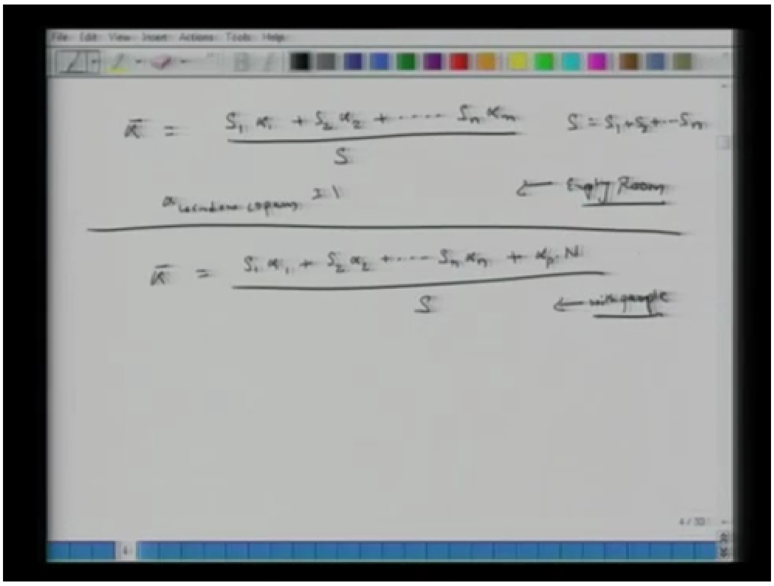

Third thing I wanted to mention is that this is the ratio of energies it is not a ratio of pressures, okay it is a ratio of energies. So if I have a irregular room which has lots of reflecting surfaces and for that room I can compute an average alpha and I can do that in such a way that I take S 1 is the first reflecting area alpha 1 plus S 2 alpha 2 the answer (())(13:20) S n over total reflecting area in the room, where S equals S 1 plus S 2 plus S n, question what would be the alpha or reflection coefficient of a window open window. So if you have windows in your rooms you should still account for those by prescribing in appropriate value if it is close then you have to or if it is open then you have to make it 1.

So alpha window if there is a room, so this if for an empty room, okay if there is a room with people sitting in it then again the hand out which you have it provides values of alpha for individuals whether they are sitting or standing or they are on the chair so on and so forth. So if there are people sitting in it then we can say average alpha would be S 1 alpha 1 plus S 2 alpha 2 till alpha n plus alpha person times number of people sitting in the room or standing or whatever over S so this is with people typically alpha p exceeds 1, 1.5 sometimes goes upto 7.

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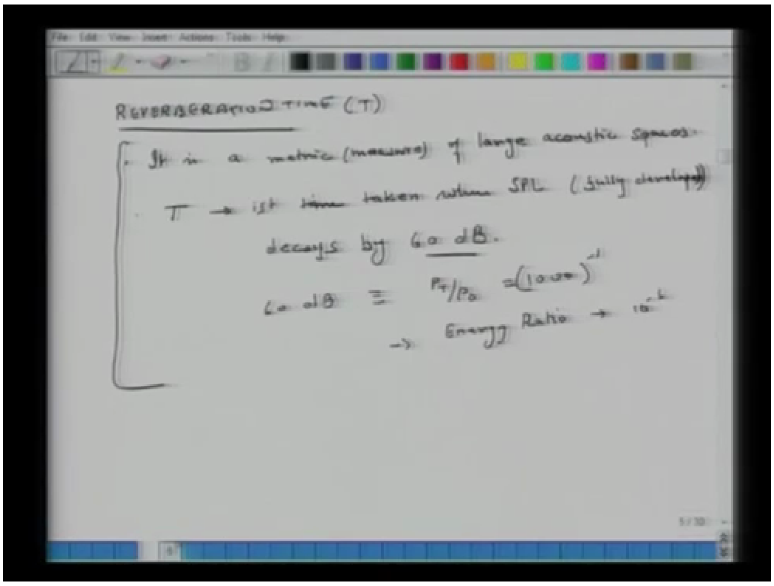

So we have talked about three concepts sound energy density, mean free path, sound energy absorption coefficient a lot of times it is also called sound absorption coefficient so just be away. So using these three concepts we will develop a property of a room which is large and irregular and this property is called reverb time reverberation time and we will designate it by a letter capital T couple of points it is a matrix one of the matrix measure of large acoustics spaces to figure out whether an auditorium sounds good or bad this is one way objectively calibrating yourself and saying that yes this room sounds good, this room does not sound good.

Second thing T is the time taken when SPL that is the sound pressure level which is fully developed decays by 60 dB, what does this mean? You have an auditorium or lecture theatre L 7 and you start the sound system there or people are talking let that start happening and at a particular point you place a microphone and you will see that after a certain period of time the sound pressure level will stabilize, once it has stabilized then you turn of the source and then sound pressure level will start decreasing very fast.

So the time it takes to start from that P not condition so P not minus 60 dB that time is called reverberation time of that room, what is 60 decibels in pressure 2 pressure values are off by 60 decibels it means what is the ratio of pressure in absolute 1000, 60 dB corresponds to P T over P not is 1000 and if I am computing the ratio of energies ratio is 10 to the power of minus 6 using this understanding we will start now doing some math.

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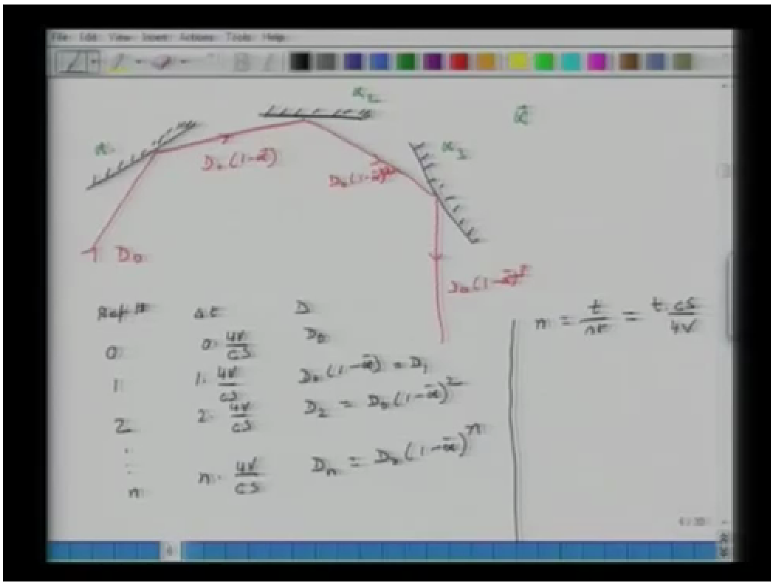

So again we will draw three surfaces all these three surfaces are reflecting and they also do absorb some sound. So let us say that is absorption coefficient of this surface is alpha 1, this surface is alpha 2, this surface is alpha 3 such that the overall rooms absorption coefficient is alpha bar that is my incident sound it gets reflected, gets reflected again, gets reflected again the intensity of incident sound is D not what will be the intensity of sound after it gets first reflection D not times alpha got absorbed what is remaining? (one minute) this guy becomes D not 1 minus alpha square, this is D not 1 minus alpha cube these are the so in a statistical sense, okay.

So these are alpha, this is the average alpha for the room, in a more precise yes you are right it will be D not times 1 minus alpha 1 times 1 minus alpha 2 and so on so forth but in a statistical sense I am just using alpha average alpha bar, what we will do is construct a simple table first column time, second column delta t, third column value of t, okay at t equals 0 delta t is 0 times 4V over CS D 0, this is D 1 equals D 0 that is for v over c at first reflection so actually this is my reflection number, okay at first reflection delta t is 1 times 4V over CS, this is D not times 1 minus alpha bar, this is D 1.

Second reflection delta t is 4V over CS and this is D 2 equals D not 1 minus alpha bar whole square (())(20:37) nth reflection it is n times 4V over CS D n equals D not 1 minus alpha bar n. Now we know that we can also write n as total time elapse which is t over delta t and that is t times CS over 4V.

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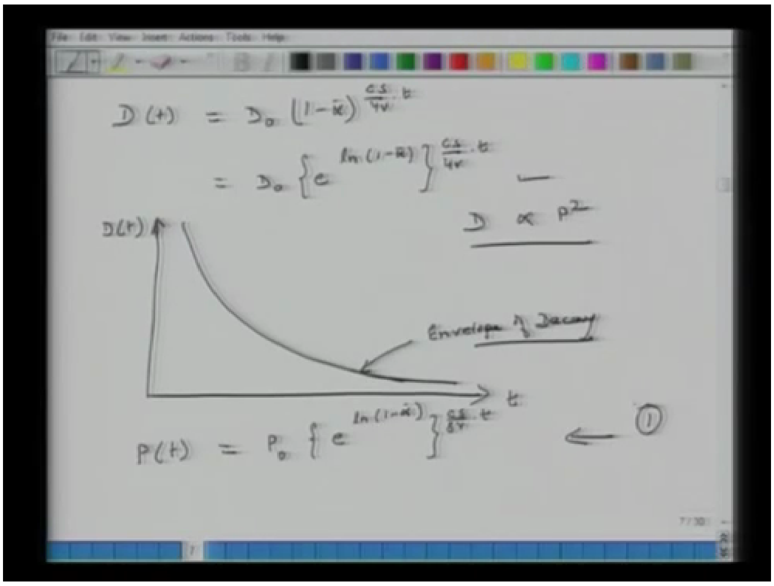

So with that understanding I can express at any given time sound energy density is D t equals D not 1 minus alpha bar times CS over 4V times t, I can again reframe it as exponent log 1 minus alpha bar. So if I plot D t with respect to time I get this kind of a relationship in exponential (())(21:57). So this is in regular rooms we have developed a relation for envelope of decay in this case the envelope of decay is also giving you the exact value of pressures at different times of sound intensity at different times because reflections are happening all the time and the overall field in the room is diffused.

The other thing is we made this jump n equals t over delta t and this is because again the room is irregular so the values of delta t do not increase in you know quantum they are continuously changing so this is also a continuous variable in the earlier case where we had parallel walls this t was changing from you know this reflections per happening and t was progressing in one quantum, second quantum, third quantum and so on so forth here it is a continuous variable so that is my envelope of decay.

We know that D is related to energy so it is directly proportional to P square pressure square. So I can also say that pressures will pressure in the room will also decay in a similar exponential factor such that is P not e log 1 minus alpha but what will be the value of CS here CS 8V t so instead of 4 I am putting an 8 here because the relationship between D and P is a square relationship so I label this expression as 1.

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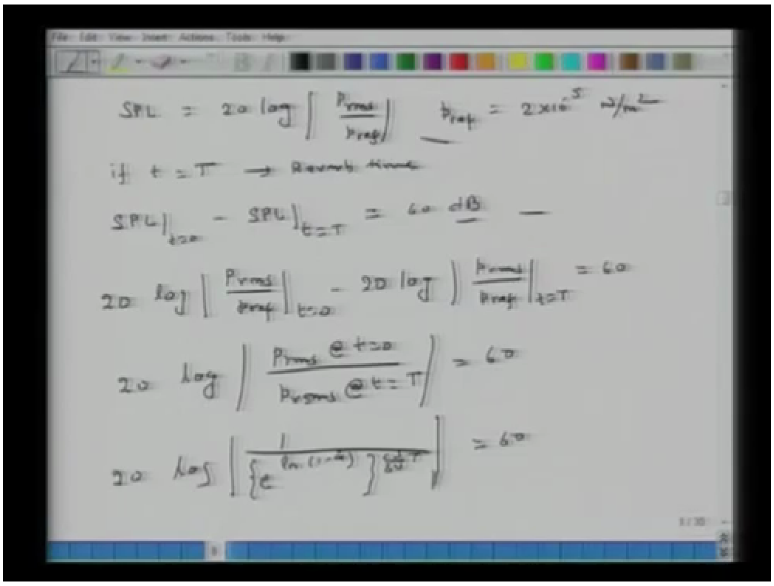

We know that sound pressure level in decibels is 20 log in base 10 P rms over p ref where p ref equals to 2 into 10 to the power of minus 5 Newtons per square meter. So what is it that we are trying to do in through this entire exercise we are trying to develop an expression for reverberation time so you do not have to forget that. So if t equals T which corresponds to reverb time than SPL at t equals 0 minus SPL at t equals T what is the difference 60 decibels.

So I put this relation in this equation and what I get is 20 log P rms over p ref at t equals 0 minus 20 log p rms over p ref at t equals T equals 60 dB and I can rearrange this as 20 log P rms at t equals 0 divided by p rms at t equals T is 60 dB, what is P rms at t equals 0 P not what I get is 20 log so basically what I get is this e ln 1 minus alpha bar and the whole thing is raise to the power of 8V times T can everyone read this I read some micro writing there it could be read, okay.

So just to make sure that you have read it correctly 20 log 1 over exponent natural log 1 minus alpha in parentheses whole thing raise to the power CS over 8V T.

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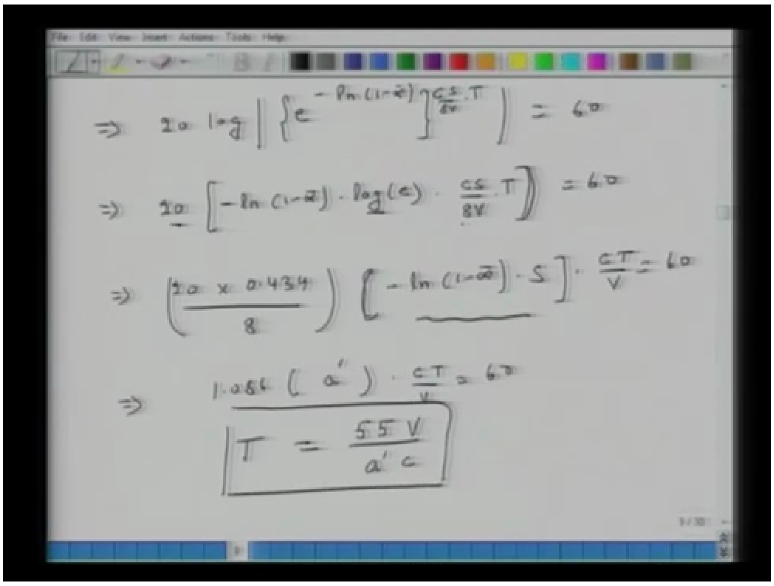

So now I do some mathematical manipulations I get 20 log e minus ln 1 minus alpha CS over 8V times T equals 60. So now I take the log and what do I get 20 I take log of this guy though I get minus ln 1 minus alpha times log of e times CS over 8V T equals 60. So I get 20 log of this is log is in log 10 base 10 so log of times 0.434 that is log of e divided by 8 I am pulling these three together times minus ln 1 minus alpha times S times CT over V equals 60.

So this entire thing becomes 1.086 times this entire expression times CT over V equals 60 and I call this expression as a prime is a prime a positive number or a negative number here 1 minus alpha is less than 1, so this a prime is positive. So essentially what I get is reverb time equals I can move everything on the right side 55 over V divided by a prime c.

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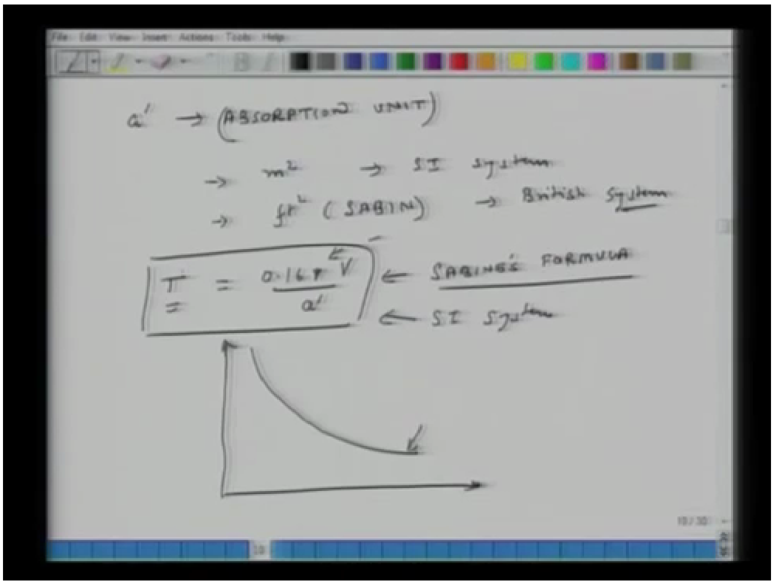

And a prime is called absorption unit the name is absorption unit it is not a unit of the name is absorption unit and the unit of this absorption unit quantity is meter square in SI system and feet square but more popularly it is also called Sabin in British system and a prime is called absorption a prime is a property of the room because what is it? It is basically S times a function of alpha and essentially what it tells is how much sound is overall in an overall sense getting absorbed by the say that T is 50 times V over a prime c and we can rewrite because c we know the value of c.

So we can rewrite the same equation as T equals 0.161 V over a prime and this is a very famous equation in the architecture acoustics it is called Sabine's formula it is named after a person obviously Sabin in 1898 in Boston he measured coefficients this reverb time of this formula should work in both so you have to change it yes so this is for SI system yes you are right but you can change it this constant will change but the formula will be still be called Sabin, so what Sabin did is hold on what Sabin did is that he took an axis you know and he was computing with respect to he was essentially plotting this V over a ratio you know and what he found was this is a hyperbolic relationship so from that he said that okay I can extract this value of T he was doing that numerically.

Now he probably not playing with this 0.161 parameter that comes out naturally once you plot this entire hyperbola then that thing comes out. This is a very it looks very simple relation only three terms in it T, V and a and it looks very deceptive but it has a lot of substance in it.

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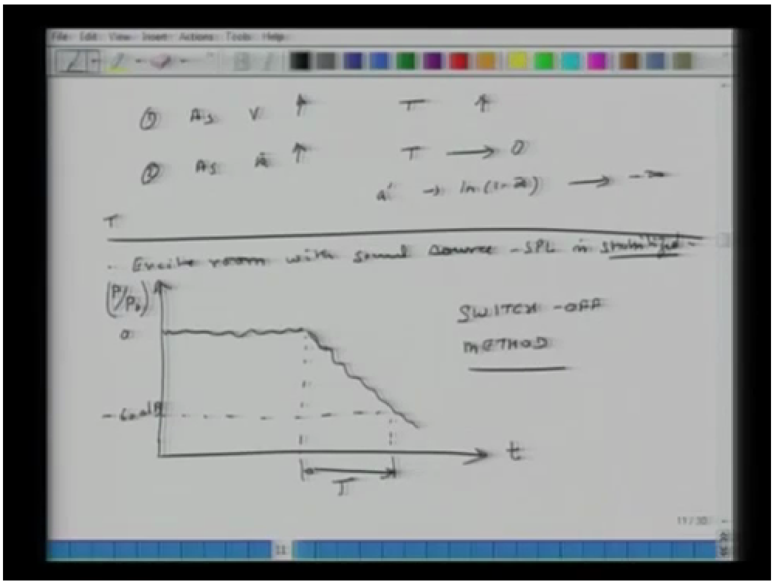

So one thing is that as V goes up T goes T will go up, second as alpha goes up what happens to T? It goes towards 0, why because you have in this a prime you have logarithm 1 minus alpha. So this goes towards minus infinity, the third thing remember that this relation is dependent on frequency so each room will have different reverb constants for different (()) (32:16) so do not forget that.

In this entire analysis we have only assumed that sound is getting absorbed only on the reflecting surfaces as it moves from one surface to other surface during the movement of sound from one surface to other surface nothing is getting absorbed but in reality air also does (())(32:42) the overall sound pressure level. So this formula needs a little bit of calibration to account for absorption of air but even without that it is really good relation.

So we had talked about how do you measure T first thing is you excite a room with some sound source you know till SPL is stabilized it takes a little bit of time for the sound pressure level to convergent become flat and then you switch it off the sound source. So what you get is something like this, so here if I am plotting P over P not in decibels then when I am exciting it becomes stable after a while and then I switch this thing off and sound pressure level decrease something like this.

So if this is my reference which is 0 dB I am recording data and this is minus 60 dB and this value of time is my reverb and this approach of measuring T is called switch off method do not make couple of qualifications in this entire discussion (())(34:27) one is that this theory is good to the extent that sound is sound field is what diffuse it is well distributed throughout the room that is one that we need to have a diffuse field.

Second thing is that the room should not only be irregular but it should not also have focusing elements, what do I mean by focusing element for instance I have let us say light you know and then I have a concave mirror which will focus light in the particular field. Similarly I can have surfaces which focus sound at particular locations. So I do not want to have any focusing elements in the room with that will yield the smoothness of SPL distribution into it I do not. There could be even be a little bit but the equation overtly focused in one particular area or zone.

Third thing is that the total absorption coefficient should be small or moderate what does that mean that if my alpha bar is fairly large if alpha bar is fairly large then it does not take a lot of reflections for the sound to decay very to a level which is not measurable. So alpha has to be not too large it could be fairly small also but it does not have to be large. For instance there is a room and all the windows are open and it only has windows in practical sense then this reverb time and all this discussion becomes meaningless.

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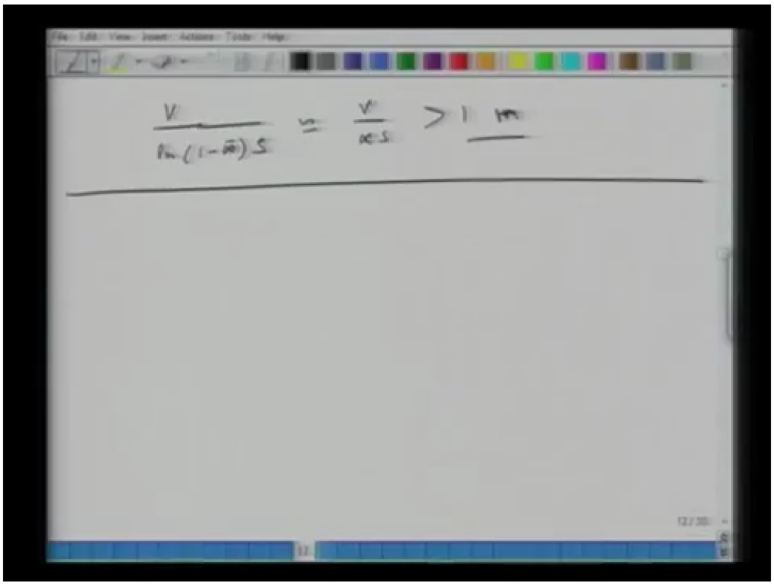

So one way to quantify that the rooms absorption characteristics are moderate or small is that V over log minus 1 minus alpha S is V over alpha S is greater than 1 meter (())(36:40). If you go to lecture hall complex you listen you hear a lot of echoes especially in L 1 or some other larger room whenever a professor is teaching the sound is not clear and I think the biggest challenge is there is the reverb time is too large.

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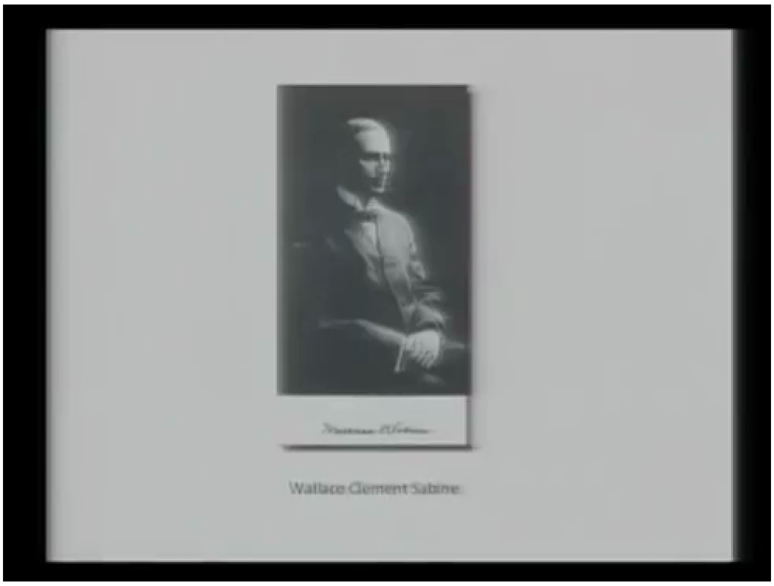

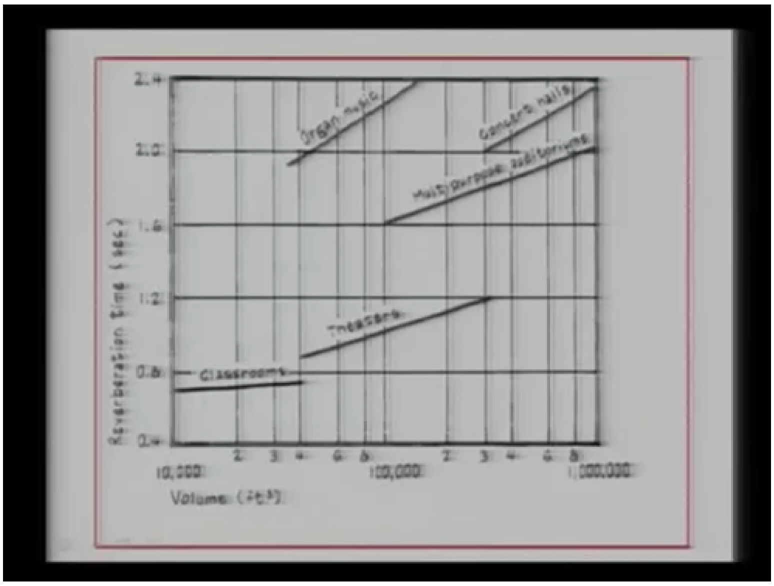

What I also wanted to show you is couple of slides which will be helpful just for record is the picture of Mr Sabin what you are seeing here on this plot typical recommended reverb times for different applications. For instance a class room where most of the frequency content is in the bandwidth of speech about 0.8 seconds is the optimum time. If we have a classroom where reverb time is significantly larger than this than the speech will not necessarily be intelligible will not be understood easily.

Similarly theatres where you have a mix of music and speech they need a little larger reverb time and then concert halls where you want to have a good amount of reverberation the time is in access of two seconds so and so forth.

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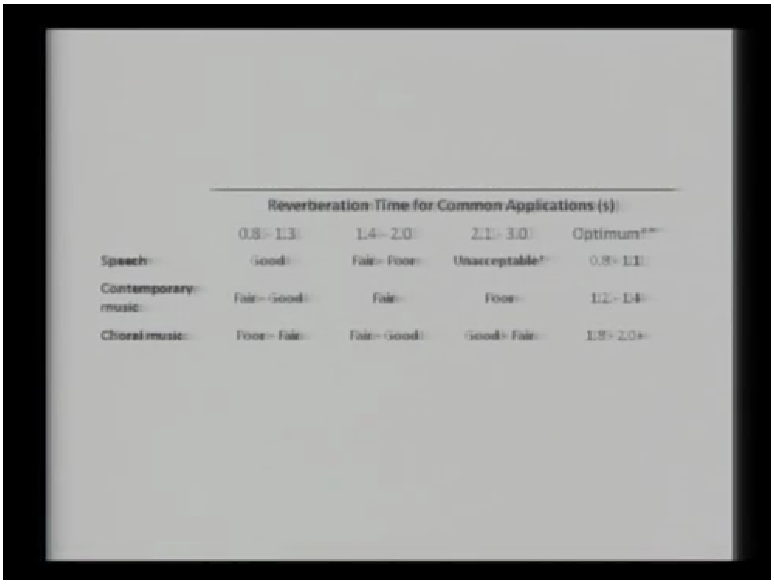
Reverberation Time for Common Applications (s)

	0.8 - 1.3	1.4 - 2.0	2.1 - 3.0	Optimum**
Speech	Good	Fair - Poor	Unacceptable*	0.8 - 1.1
Contemporary music	Fair - Good	Fair	Poor	1.2 - 1.4
Choral music	Poor - Fair	Fair - Good	Good - Fair	1.8 - 2.0+

So this is another chart it shows in some quantifiable ways speech 0.8 to 1.3 is a good reverb time, 2 seconds is certainly unacceptable even if I am in 1.4 to 2 it may be poor or fair and for pure music I need a little higher reverb time if it is if the reverb time is too low than sound does not excite the human (())(38:38) you can have it could be only the (())(38:53) you could have because the point is that because you have irregular room so even regardless whether it is omnidirectional or unidirectional at the end of the day sound will be moving in all directions at all frequency.

Student is asking: In case window is open and after some reflections it go through the window if a unidirectional surface, so when that case what will be the (())(39:15) reverberation time.

So again because of the nature of irregularity of the room by the time it reaches unless you are directly projecting sound towards the window that is totally different case, by the time it reaches by that time the sound field should have become diffuse enough. So there is no very hard objective cut off that but this is an approximate answer to you. What happens if the reverb time is too low, let us say I am talking we are talking in this room and if the reverb time is too it is let us 0 seconds what does that mean basically what that means is that the person who is speaking he has to make more effort in making himself or herself heard. So you also need some reverb time, 0 is not good because that requires more power for the person of or the sound system. But if it is too high then if I say cat by the time I am saying ta c will also overlap with ta so it will become confusing.

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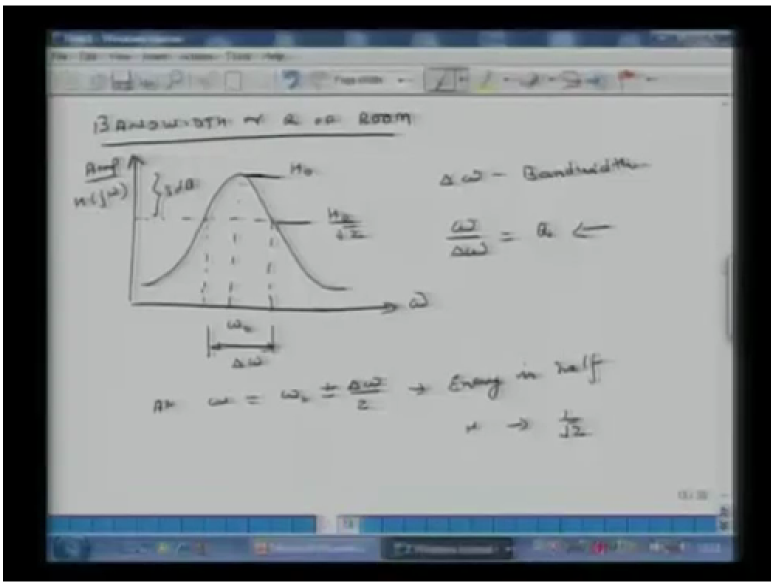

Another parameter which we can extract is we know the reverb time of a room is called bandwidth or Q of a room and we will talk about it. Let us say we have a spring mass damper system f equals ax plus cx dot plus mx dot dot and if I plot the response of that kind of a system I get something like this, where this is my omega and this is my amplitude, right this could be some transfer function which is a function of this point is got natural frequency.

So bandwidth of this kind of a system is defined as a range of frequencies between which the power goes down or the value of H goes down by a factor of 3 dB's so this is 3 dB and this is let us say H not then this will be what H not over root 2. So associated with this is a parameter called delta omega delta omega is called bandwidth omega over delta omega is called Q it is a industry standard term even in vibrations you hear this term Q what is the Q of the system.

So if there is no damping in the system what does Q become infinite Q becomes infinite when there is no damping process, right. So Q is also kind of a reflection of how damp the system is at omega equals omega not plus minus delta omega over 2 my energy is half the direct variable H which could be pressure or velocity or displacement H is 1 over root 2, this is the bandwidth.

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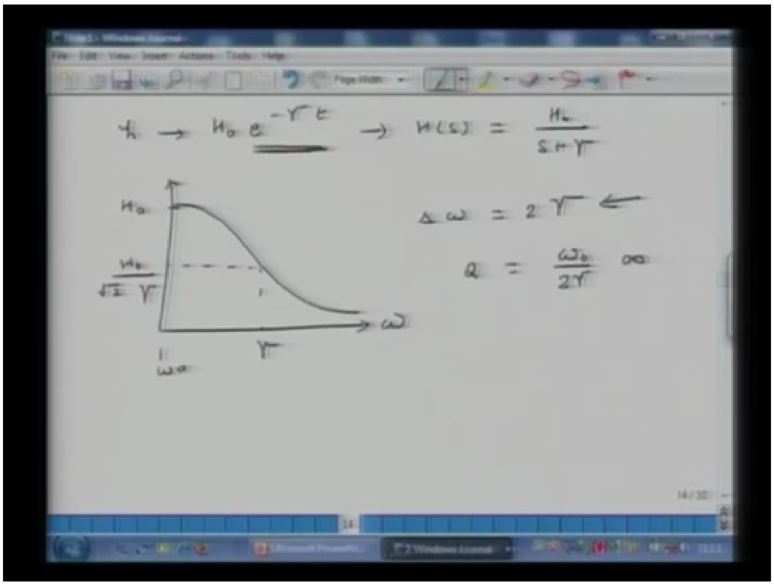

Now the question is that if I have a room and there is a diffuse field in it what is Q of that room? So we will try to use this concept and also the idea of T and try to figure out what is the value of Q of so there is intermediate step to get to that answer. So let us say you have a signal H not e minus gamma t, the Laplace of it will be H S equals H not over S plus alpha so we will plot this and we get something like this, this is my H not, this is my if this is H not over root 2 alpha and this is alpha then bandwidth is 2 alpha and Q oh I am sorry this should be gamma, this is also gamma so Q is what omega not over 2 gamma in this case it is infinity because omega not is 0 this is my omega not but the point is that if I have an exponential decay form then my bandwidth is 2 gamma.

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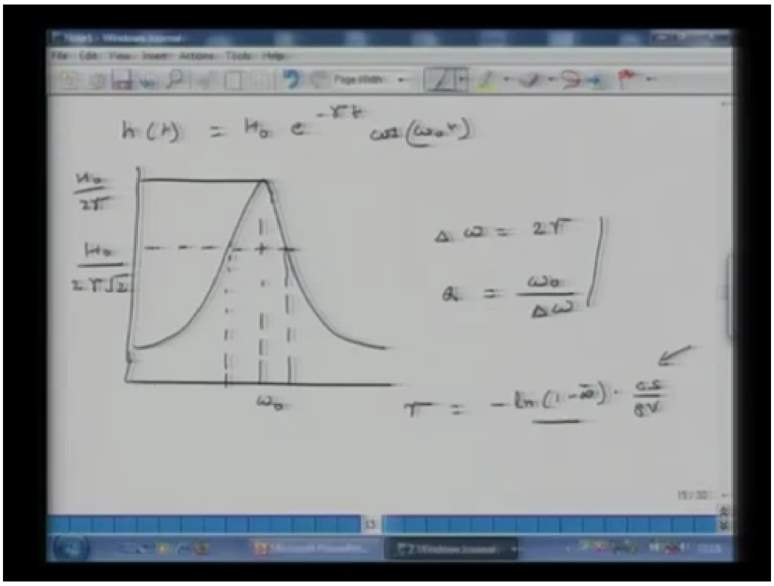

So now we go to a diffuse room and in a diffuse room my H t signal is essentially we had developed it, right this H not e minus gamma t Cosine omega t, what this means is that if I am I have a room and if I started playing a tone of omega not in that room till it became stabilized and then I turned it off, right then the signal in the room will decay in such a way, it will still be Cosine omega t but it will decay over a period time in an exponential way e to the power of minus gamma t that is what it mean this should be a little not that sharp.

So my centre frequency is omega not and this is H not over 2 gamma root 2, this is H not over 2 gamma, so essentially my bandwidth of a room is 2 gamma and Q associated with the frequency which is getting excited in the room is now in case of a room we know that gamma is what minus ln 1 minus alpha bar times CS over 8V remember it is 8 because we are not plotting in this case the energy we are plotting the fundamental variable pressure or displacement (())(46:27). So I can use this and these to figure out the overall Q of the room, we will do a very quick example.

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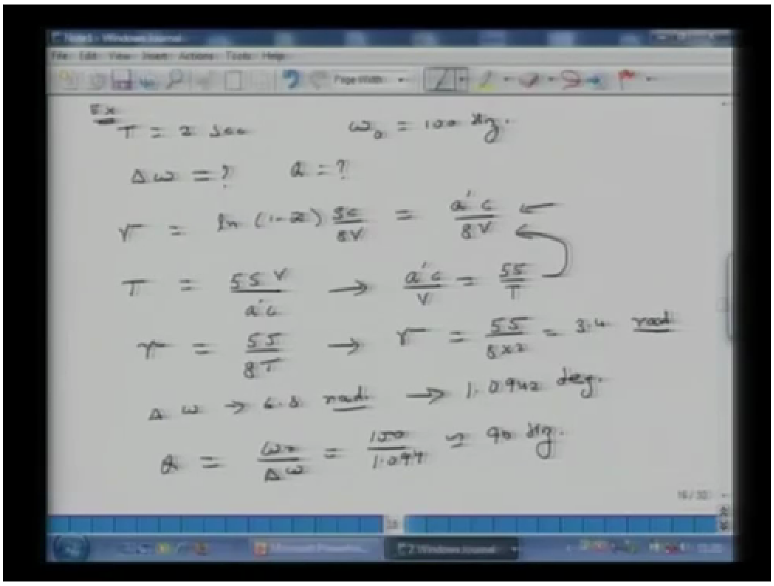

So let us say my T equals 2 seconds for example, omega not is 100 Hertz then what is bandwidth and what is Q, we know that gamma is ln 1 minus alpha bar SC over 8V this is basically a prime c over 8V we also know that T is 55V over (8T) a prime c so this gives me a prime c over V which I will later introduce here a c over V is 55 over T. Now I put this here and gamma is 55 over 8T and that gives me gamma equals 55 over 8 into 2 equals the number comes 3.4 seconds so gamma is 3.4 seconds and delta w was 2 gamma is 6.8 seconds gamma is radius and that translates to 1.0942 degrees so Q equals omega not over delta w equals 100 over 1.094 that is approximately 90 Hertz, what it physically means that between 90 Hertz and 110 Hertz the room will sound variational if I play a tone a room will.

The decay of energy will be by a factor of 2 between 90 and 110 Hertz that is what it means. So if this band is very thin then the room will be variational that band if we will pick up then it will be variational if this band is a little bit wide then it will be very smooth transition of (())(49:24) that is what it, we will do three examples of reverb time how it is used in industry applications.

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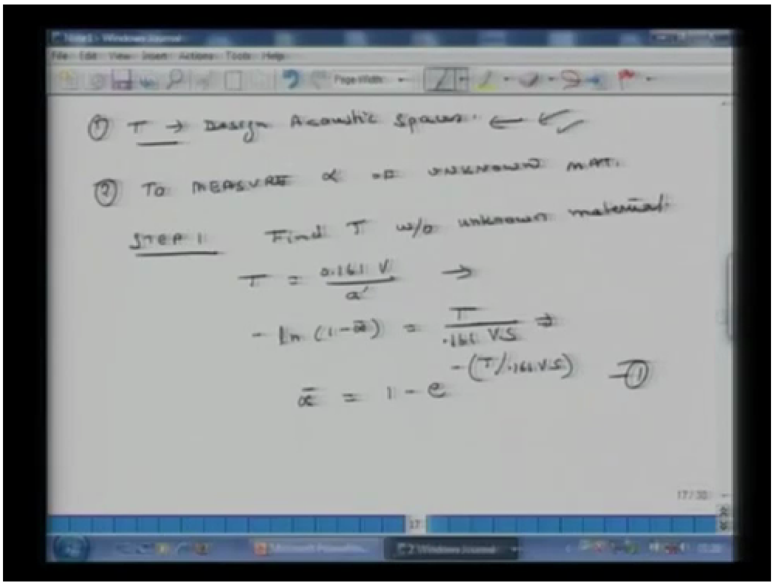

So one is we already talked about finding constant of a room and using a constant to design a room accordingly. So T helps us in designing acoustic spaces in your assignment this one question where you will be expected to tune the characteristics of a particular room such that you acquire a T of I think it is like 0.7 seconds. So if you have a target value then you can architect your room accordingly so that you hit your target value of T so that is one.

Second one is okay so in this context again dependent on frequency this no reverb time which works for all frequency ranges but you have to design for a particular frequency or a set of frequency. Second thing is has to be irregular room, has to be fairly large enough and if it is not large if it is a small quote and quote regular room then the Sabine's approach it does not work that well. So in that case there are some other approaches where they take ratios of reflected energy and direct energy then they try to optimize that particular parameter but in large irregular rooms where the sound field is fairly diffused reverb time does a fairly good work in terms of optimising the acoustic of (())(51:21).

The second thing is you can use T to measure alpha of a particular material, how do you do that? So way back in the course we had talked about 1-dimensional long tube which has known reflective no unknown reflective impedance and using the (())(51:44) approach we could figure out the reflectivity or reflection coefficient of this material, right and also the phase of the material by swiping the microphone along the length of the cube but that approach is good only if your sound is hitting in what direction? In normal direction my surface this and hitting like that then that is the way to develop get reflective coefficient of the material.

If I have to develop an understanding for different incident angles or in an overall average sense what is the reflection coefficient of the material then we can use T to find out the value of alpha. So we will quickly cover that aim is to measure alpha of unknown material so step 1 we take a fairly diffused room is does not have a high absorption characteristic and then find the reverb time of that room without this material in it, okay. So find T without a known material.

So T equals 0.161 V over a prime and if I do the math I get minus ln 1 minus alpha bar equals T over 0.161 VS, S is the surface area I know surface area of the room so I can get log alpha from this relation and I can also get alpha bar for the room without the material and that is basically 1 minus e minus T over 0.161 VS, okay. So I know alpha bar for this one, from T I can figure out the alpha bar for this.

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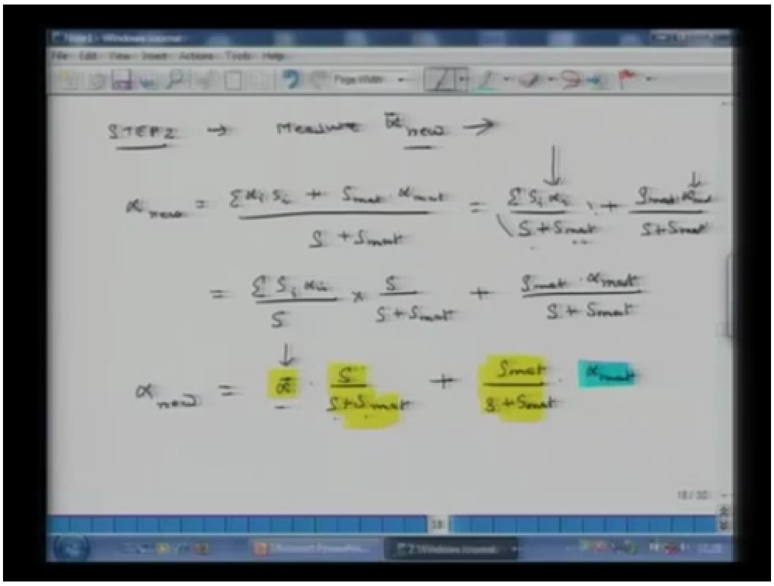

Then step 2 I do the same measurement and I find alpha new, so in the same room now I place this material, I know the surface area of the material and I find alpha new. So from alpha new and from alpha I can extract the value of alpha of the material, how do we do that? So that is what exactly what we will do, so alpha new is basically alpha i S i plus S of the material, i is only for the room alone, S material alpha material and divided by S plus S mat so this is basically S i alpha i over S plus S mat plus S mat times alpha mat over S plus S mat, I do not know alpha mat I know everything else also I do not know this quantity as one single entity I do not know this also, right.

I know alpha i but I do not know this entire thing by itself because this is different than the alpha of the room what I do is S i alpha i over S times S over S plus S mat plus S mat times alpha mat over S plus S mat this is what is this term alpha bar times S over S plus S mat. So I know this S mat over S plus S mat times alpha mat. So now I know everything I know all these blocks and this is the only guy which I do not know so I can figure out alpha in this way.

So this is another application the reverb time has usage in terms of designing architectural spaces, also characterising materials, also developing targets for different types of rooms once again it is dependent on frequency and the choice of what is the right reverb time for a particular acoustic space it depends on how we are going to use that space. So if I have a room where I will use it only for purposes of talking then I have to shoot for one particular value of T, if I have to use it only for music and I have to use may be another value of T, if I have to use for mixture of applications then my target (())(57:54). So that is all I wanted to cover today and then we will (())(58:00).