Building Services III
Lecture 10

Fundamentals of Acoustics

Let's define acoustics first. Acoustics is usually very broadly defined as 'the science of sound'. In this lecture, we will concentrate on the room's acoustics, the shaping and equipping of an enclosed space to obtain the best possible conditions for faithful hearing of wanted sound and the direction and the reduction of unwanted sound. This is called the room acoustics. Room acoustics deal primarily with the control of sound which originates within a single enclosure, rather than its transmission between rooms. What is a sound wave? A sound wave is a pattern of disturbance caused by the movement of energy travelling through a medium, it might be air, water or any other liquid or solid matter, as it propagates away from the source of the sound. The source is some object that causes a vibration such as a ringing telephone, or a person's vocal chords. There is an analogy or a comparison to the movement of water in a ripple with the movement of sound waves. The pattern of the disturbance creates outward movement in a wave pattern like waves of seawater on the ocean. The wave carries the sound energy through the medium, usually in all directions and less intensely as it moves further from the source.

Next, we come to the definition of frequency. Frequency is defined as vibration cycles per second. It is expressed in Hertz (Hz). The wave length is defined as the distance between identical points on a wave. As you can see in this graphic, the wave has a certain pattern and then the wave length is measured when the same pattern repeats again. That is the difference between the identical points and identical patterns on a wave. Next comes the, Sound Magnitude. In sound magnitude we have two aspects; sound power/ acoustic power and sound intensity/ acoustic intensity. The sound power is the rate at which the sound energy is emitted, reflected, transmitted or received per unit time. The SI unit of sound power is the watt (W). You would have seen denoting the speaker volume in watts; 500 watts, 1000 watts, etc. This is what they mean by watt, the sound power of that particular speaker. When it comes to sound intensity, it is defined as the sound power per unit area. The SI unit of sound intensity is the watt per square metre (W/m square). Sound energy passing per second through a unit area held perpendicular to the direction of propagation of sound waves is called intensity of sound.

Next is the Measure of Sound. Sound is measured using a unit called 'decibel'. The decibel (dB) is a logarithmic unit used to express the ratio of two values of physical quantity, often power or intensity. One of these values is often a standard reference value in which case the decibel is used to express the level of the other value related to this reference. One is a constant value and the other is expressed as a relative effect. While power is measured in watts, the most used acoustic measurement for intensity is the decibel and the word decibel is derived in honor of Alexander Graham Bell, a decibel = 1/10 of a Bel. A decibel is a logarithmic measurement that reflects the tremendous range of sound intensity our ears can perceive and closely correlate to the physiology of our ears and our perception of loudness.

Here is a graph or a decibel scale which shows a green line that denotes the threshold of hearing which refers to the minimum sound level a human can hear. The red line depicts the threshold of pain i.e the maximum sound, one can hear, after which it causes pain. All the music and speech happens between these two threshold limits of hearing and pain.

Now, we move on to the Sound Pressure Level. This is a relative thing. As we saw in the graph on the previous slide, it also has a threshold of hearing upto the threshold of pain. Here, we have a graphic description of various activities and objects emitting sound and which are the sounds within the threshold of hearing and how certain sounds reach threshold of pain. Here is a picture of of a noise isolating earphones that are usually used at construction sites, in order to the prevent this threshold of pain affecting the workers. From the previous definitions, we understood that sound is transparent in terms of waves and it needs an object to vibrate and further transmit the sound across the distance. Here in this graphic chart, you can see a source. Here, we have a vibrating object, the guitar and the vibration variables are as follows; Conductor, rate of vibration, number and relative energy of harmonic vibrations and Total energy of vibration. The resulting wave characteristics from the conductor are; velocity, the rate of vibration decides the frequency, the number and relative energy of harmonic vibrations decide the wave shape and the total energy of vibration decides the pressure of sound and in turn this velocity and frequency put together decides the wavelength of sound. When it comes to the perceptions of the ear, this frequency decides the pitch at which we hear the sound. The wave shape is the reason for the timbre or quality of sound, the pressure translates into the amplitude of sound and based on the pitch and timbre, we identify the tone of a particular instrument or a human voice. This is the path or a flow chart which shows the mobility of sound in a step by step manner. First it creates a physical disturbance from the sound source, then it turns into pressure waves - compression and rarefaction wave and then when it hits the conductor or the vibrating medium, it at times is transparent to the human ear as a direct sound from the vibrating medium. In the space, in the air or in the volume of the room, it attracts or changes as reflections, resonance, reverberation, diffusion, diffraction and finally absorption and then it reaches the human ear. It goes through all these aspects in a particular space. Let us define the reverberation now. A reverberation or a reverb is created when a sound or signal is reflected causing a large number of reflections to build up or decay as the sound is absorbed by the services of objects in this space which would include furniture, people, etc. The time interval between reflections is usually so short that distinct echoes are not heard. Instead, this series of reflections will bend with the direct sound to add 'depth'.

Reverberation is a basic acoustic property of a room. It can enrich speech and music in all areas - or it can slur speech and generate high noise levels throughout a room, depending upon the room volume, timing and absorption. This picture talks briefly about the various parameters or aspects that define the acoustics of that space. This is a picture of a concert hall where you see a performance on stage and the audience seated on their seats and the roof profile. The roof material, the false ceiling materials, the acoustic materials play a very major role in improving the acoustic performance of this particular space. Next, would be the shape of the space itself, shape of the false ceiling, the shape profile and the plan of the space. The entire volume also has a very great impact. What happens when a performer is performing on stage and the sound is transmitted from the stage? Sometimes it goes as a direct sound and the sound also gets reflected and then gets absorbed by the audience. As mentioned in the earlier picture, the shape of a space determines the sound path within the space. The earlier picture we had a convex type of a ceiling which reflects the sound. Here, you see a concave profile. This convex profile reflects the sound in different directions and it distributes the sound whereas the concave profile concentrates the sound on a particular point. Here you see another graphic or a picture showing a rectangular room or a squarish room which has parallel wall surfaces. Parallel reflective surfaces generates unwanted reverberation. It is better to avoid such kind of a shape when designing concert halls and auditoriums.

Reverberation

Reverberation as we defined earlier is the multiple reflections from the various points of the space and then later absorbed by the audience, objects and whatever furniture there is, in the room. Finally the decay of sound. Here, there is a direct sound from the performer, multiple reflections from the roof and then finally it reaches the audience.

Once we have defined reverberation, the next important aspect we have is reverberation time. Reverberation time must match the room function. Pure speech requires short reverberation time. Symphony blends notes with long reverberation time. Here we have a graphic showing the different reverberation times depending on the volume of the room. Here, there is a red band. The y axis denotes the reverberation time in seconds and x axis is the volume of the room in cubic feet. The lower part of the band is best for rooms intended primarily for speech which means lower reverberation time. The upper part is better for music rooms, this is the upper part. Studies based on audibility of speech and music reveal that the most desirable reverberation types generally fall within the ranges shown below. These values are based on a sound frequency of 500 Hz (appropriate pitch of male speech). For speech like in small offices, classrooms, lecture rooms and work rooms, the reverberation time range in seconds is between 0.50 seconds to 2 seconds. For music performances, the range of reverberation time is from 0.80 to 2.25 seconds depending on the use of the rooms.

The reverberation time plays a crucial role in the quality of music and the ability to understand speech in a given space. When the room surfaces are highly reflective, sound continues to reflect or reverberate. The effect of this condition is described as a live space with a long reverberation time. A high reverberation time will cause a buildup of the noise level in a space. It is difficult to choose an optimum reverberation time in a multi-functional space, as different uses require different reverberation times.

Let us look at the requirements for speech. The aim here is for good speech intelligibility at all seats within the space, such that each spoken syllable is heard separately and not blurred together, and that the speaker is loud enough to be heard without strain. The sound heard by an auditor is a blend of direct sound straight to the seat, early reflections from the walls and ceiling, and reverberant sound which results from multiple longer term reflections within the space. Direct sound is a function of the distance between the speak and seat and will be louder when the distance is reduced. Reverberant sound has been traditionally measured in terms of the time it takes for the sound to fall by 60 dB (i.e to one millionth of its initial value). This time period is usually independent of speaker-seat distance, depending instead on the volume of the space and the sound absorbing properties of its surfaces and contents, it also varies with frequency. If you read the last point, you can relate it to the picture shown earlier. Irrespective of the speaker - seat distance, the factors or parameters like the volume of the space, the sound absorbing properties like the materials used in the space, like a false ceiling, the wall panelling, the flooring, the seats in the auditorium etc, all these decide the reverberation time and the clarity of a particular speech or music.

Research shows that a reverberation time (RT) of around 1.1 seconds at mid-frequencies is appropriate for speech in small to medium spaces. The RT should not rise too much at low frequencies as this lowers intelligibility by an effect known as 'masking'. With good early reflections, this figure becomes more flexible. An audience's expectation regarding the actual quality of the speech signal is usually not too critical, as long as the speaker's voice and accent are clearly recognizable and any vocal information is understandable.

Now, let us look at the requirements for music. The definition for a pre-requisite for speech is with music we expect more blend with a separate burst of sound. On the contrary to music, speech has only one particular frequency or a single person talking. But here,when it comes to a music performance, you have a lot of people singing, music instruments singing and a lot of other things, that is why they say people expect more blend with separate bursts of sound. People expect excessive clarity in music auditoria to give the subjective impression of brittleness or dryness and accentuates unwanted bowing or fret noise, making the musicians job even more difficult. One immediate conclusion from this is that rooms for music will be expected to have longer reverberation times than rooms for speech, naturally. Reverberation times of up to 2.4 seconds happen in large concert halls and the value of 2 seconds is typical in recent work. The currently accepted optimum range is 1.8 - 2.2 seconds. Another difference is that music can consist of a great range of frequencies (20 Hz to 20 kHz) whilst speech is basically a narrow band signal (500 Hz to 4 kHz).

Site Selection

Next we will move on to Site section for best acoustical performances. How do we select the site of a particular building? Say for example, a space for an office room or a space for an auditorium. The basic understand, the basic criteria which decides this is we have to separate a zone or the spaces accordingly or locate the site based on surrounding factors. For example, if you have a noisy road or a highway and then you are going to select a site nearby, you have to see how you can mass the sound or create barriers, man-made or natural barriers to reduce the impact of the noise affecting the space. Here, we have shown a small graphic, there is a noisy space, a quiet space and you create an artificial barrier. Within the campus itself, you zone the space as noisier space, non-critical areas and then you bring the critical areas. You have to consider acoustical sensitivity of activities.

Here are a few graphics which depict how can do site selection. You have to take maximum advantage of the distance from the source of noise. You can create natural or man-made Berms which act like sound barriers. You can create man-made, artificial, acoustical barriers. You can if its a big campus, you can place buildings that act as buffers between the space where acoustical performance is happening and the noise source. It is also best to locate buildings at a higher elevation than the noise source. Next comes, orientation. Say for example, you have a site by the highway or the main road and the shape or orientation of the building with respect to the highway has a great impact on the acoustical performance or the noise control within the site. These are very self explanatory graphics which can be understood based on the shape of the building, how the acoustical performance happens. When it comes to campus planning, you can orient your buildings or create buffer spaces so that the noise from the main road or the noise source doesn't affect their activity. Say for example, if we take a school abitting a mainroad or a highway, you can put a huge open space like a playground which will take care of noise transfer. Similarly in a factory, a parking lot can take care of the noise from the road and it will not affect the office space.

Next, comes the Shape. The shape of the room or the space. Let us look in detail about shape, taking the auditorium as an example. For more than 2500 years, the historical development of the theatre interior has been marked by close functional relationship of these structures with their user's needs. Natural acoustics have always been a characteristic feature of these buildings. It is still important today, when most halls are equipped with loudspeaker systems, often computer controlled. Figure 1 shows the floor plans for three halls, illustrating successive development stages of the theatre building architecture.

The first shape we take into consideration is the rectangular shape. Halls with rectangular plans have side walls that ensure short first reflection times but the large parallel surfaces often result in acoustic defects, such as flutter echoes and standing waves. It is not advisable to not go ahead for a rectangular plan, especially for an auditorium. Next is the fan shaped. Halls with a fan-shaped plan make is possible to accommodate a large audience while providing good visibility and acoustics. The shape of the hall prevents the formation of flutter echo by side walls, though the sound reflected from the rear wall can reach the front of the auditorium with significant delay. This can be prevented by covering the rear wall with a sound diffusing or absorbing structure.

The next shape is a 'horseshoe' plan. This ensures good visibility, a sense of proximity to the sound source and mutual eye contact between the spectators. A large number of boxes and rich interior decor contribute to sound dispersion, which help conceal the possible acoustic defects and ensure the proper ratio of direct to reverberated sound. The large number of listeners and the presence of boxes can result in excessive attenuation of the hall, thus preventing the recommended reverberation time from being attained.

Next parameter is the volume. Here, there is a section of an auditorium showing the balcony arrangement, the balcony heights and the reflection from the sound source, from the speakers and then the reflection from the false ceiling and other surfaces. Classic auditorium is shaped to convert harmful late reflections into helpful early reflections and reverberation. When it comes to design of a balcony, it is important that the depth of the balcony is always lesser than the height of the balcony. Why is this so? It is because we keep the opening height greater than the overhead depth. People at the rear of the under balcony need to be able to see the ceiling above the front of the stage, that's why we have to do this. People at the rear seats of the balcony need to be able to see the first 6 rows of seats on this main floor. People on the balcony should be able to see first 6 rows of the main row. The distance from balcony face to ceiling should be greater than balcony face to the rear wall of the balcony.

Next we shall delve into the treatment of interior surfaces. Basically, there are three types of surfaces. One is the floor surface, the wall surface and the ceiling surface. Usually we use wood or the concrete as the default material to construct floors. Of course we can use a lot of panels, fabric coverings, curtains as treatments to walls. For the ceilings we can use baffles and clouds.

What are baffles and clouds? This is nothing but the profile or type of acoustical panelling or false ceiling done in concert halls and auditoriums. An examples of baffles is shown in the image here. Baffles are nothing but strips of acoustic panels hanging from the ceiling, this is really useful for greater reverberation times. We can also use false ceiling like clouds, with a mixture of a flat false ceiling and some hanging false ceilings covered with acoustic fabrics or panels. The treatment also encompasses the occupancy of the space, like number of people on the seats.