Foundation of Acoustics

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Acoustics is the science of sound. In the first century B.C., the Roman architect Vitruvius explained in De architectura, his famous 10-volume treatise on architecture, that sound "moves in an endless number of circular rounds, like the innumerably increasing circular waves which appear when a stone is thrown into smooth water ... but while in the case of water the circles move horizontally on a plane surface, the voice not only proceeds horizontally, but also ascends vertically by regular stages". While Vitruvius did not understand everything sound, he was correct about this particular point. Greek mathematician Pythagoras during the 6th century B.C. and Greek philosopher Aristotle during the 4th century B.C. had rudimentary knowledge of sound propagation. The subject has developed enormously during the last four centuries. The term sound implies not only the phenomena in air responsible for the sensation of hearing but also whatever else is governed by analogous physical principles. Thus, disturbances with frequencies too low (infrasound) or too high (ultrasound and hypersound) not to be heard by a normal person are also regarded as sound. In words of Keats, "Heard melodies are sweeter, but those unheard are even sweeter."

The broad scope of acoustics as an area of interest and endeavour can be ascribed to a variety of reasons. Acoustics is one of the most important branches derived from Physics. This is as old as humanity itself. Over the years the development has been wonderfully crafted to make this more an applied technology. Acoustics is a multi-faced discipline that has progressed into an application and has developed into many disciplines. Interesting feature of Acoustics is that we live with sound around us and each sound has a definitive meaning. Mellifluous flow of water, quiet waves, chirping of birds, tuned music of insects and sounds produced by tuned instruments were considered to be acoustics. Advent of technology has found many faceted applications of acoustics and this has been instrumental in having various disciplines of acoustics namely—Architectural Acoustics, Building Acoustics, Environmental Acoustics, Physical Acoustics, Machinery Acoustics, Musical Acoustics, Theatrical Acoustics, Speech Acoustics, etc. Thus in the present days of industrialisation, acoustics in general has wide application to many spheres of activity. Sound may be the means of measurement for diagnosis for one and may also be the means of recognition for another. Subjective nature of this energy is useful in deriving a definitive meaning for speech production and processing in Speech Acoustics. Sound of varied types as a mellifluous form of energy produced by the instruments could be well fused to suit sound of music to make listeners get themselves tuned to life to an escalating beating of drums in orchestrated sound. Also, with the power of spectra, ultrasound techniques have been influential in the science of human body in identification of foreign body to growth of any biological matter inside the same. With the greater emphasis on environmental health and safety, noise—the unwanted sound as put in the right perspective has become a strong source of severe health hazard in most parts of the globe. Specially, developing nations like India has had this pollutant with little or no control. The power of ultrasound, the power of artificial neural network, acoustics emission, signal processing, developments of new treatments, new testing a calibrating facilities are some of the latest contributions to the modern world. New processes and new techniques are being added to the list of the time-tested processes.

In general, sound radiates in waves in all directions from a point source until it encounters obstacles like walls or ceilings. Two characteristics of these sound waves are of particular interest to us in acoustics: intensity and frequency. Intensity is a physical measurement of a sound wave that relates to how loud a sound is perceived to be. We can also measure the frequency of a sound wave, which we perceive as pitch. For example, on a piano, the keys to the right have a higher pitch than those to the left. If a sound has just one frequency, it is called a pure tone, but most everyday sounds like speech, music, and noise are complex sounds composed of a mix of different frequencies. The importance of frequency arises when a sound wave encounters a surface: the sound will react differently at different frequencies. The sensitivity of the human ear also varies with frequency, and we are more likely to be disturbed by medium-to-high frequency noises, especially pure tones. Think of sound as a beam, like a ray of light, passing through space and encountering objects. When sound strikes a surface, a number of things can happen, including:

Transmission— The sound passes through the surface into the space beyond it, like light passing through a window glass.

Absorption— The surface absorbs the sound like a sponge absorbs water.

Reflection— The sound strikes the surface and changes direction like a ball bouncing off a wall.

Diffusion— The sound strikes the surface and is scattered in many directions, like pins being hit by a bowling ball. (Figure 1). Keep in mind that

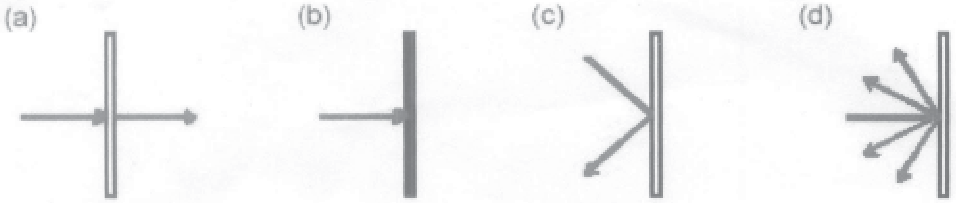

Fig 1: *Sound/Surface Interaction: (a) transmission, (b) absorption, (c) reflection, (d) diffusion*

several of these actions can occur simultaneously. For instance, a sound wave can, at the same time, be both reflected and partially absorbed by a wall.

As a result, the reflected wave will not be as loud as the initial wave. The frequency of the sound also makes a different. Many surfaces absorb sounds with high frequencies and reflect sounds with low frequencies. The Absorption Coefficient (a) and NRC (noise reduction coefficient) are used to specify the ability of a material to absorb sound. A special problem that results from reflected sound is that of discrete echoes. Most people are familiar with the phenomenon of shouting into a canyon and hearing one's voice answer a second later. Echoes can also happen in rooms, albeit more quickly. If a teacher's voice is continuously echoing off the back wall of a classroom, each echo will interfere with the next word, making the lecture difficult to understand. Echoes are also a common problem in gymnasiums. Another type of echo that interferes with hearing is flutter echo. When two flat, hard surfaces are parallel, a sound can rapidly bounce back and forth between them and create a ringing effect. This can happen between two walls, or a floor and ceiling. Sound intensity levels and sound pressure levels can be measured in decibels (dB). In general, loud sounds have a greater dB value than soft sounds. Because the decibel scale is logarithmic rather than linear, decibles cannot be added in the usual way. An important acoustical measurement called Reverberation Time [RT or RT(60)] is used to determine how quickly decays sound in a room. Reverberation time depends on the physical volume and surface materials of a room. Large spaces, such as cathedrals and gymnasiums, usually have longer reverberation times and sound "lively" or sometimes "boomy". Small rooms, such as bedrooms and recording studios, are usually less reverberant and sound "dry" or "dead". The Noise Reduction (NR) of a wall (also expressed in dB) between two rooms is found by measuring what percentage of the sound produced in one room passes through the wall into the neighbouring room (Figure 2). The NR is calculated by subtracting the noise level in dB in the receiving room from the noise level in the source room. Speech intelligibility can be evaluated in existing rooms by using word lists. Several tests are performed wherein one person recites words from a standard list, and listeners write down what they hear. The percentage of words listeners correctly hear is a measure of the room's speech intelligibility.

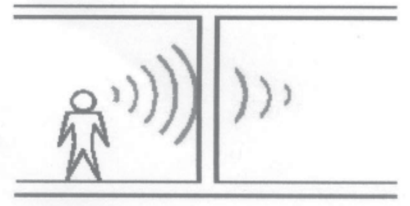

Fig 2: Noise Reduction between two spaces by a dividing wall

Frequency

Frequency is an important factor in most acoustical measurements. Sound occurs when a vibrating source causes small fluctuations in the air, and frequency is the rate of repetition of these vibrations. Frequency is measure in hertz (Hz), where 1 Hz = 1 cycle per second. A young person with normal hearing can detect a wide range of frequencies from about 20 to 20,000 Hz. In order to deal with such a large spectrum, acousticians commonly divide the frequency range into sections called octave bands. Each octave band is identified by its center frequency. For the standard octave bands these center frequencies are: 63, 125, 250, 500, 1000, 2000, 4000, and 8000 Hz. As you can see, the ratio of successive frequencies is 2:1, just like an octave in music. This also correlates with the sensitivity of the ear to frequency, since a change in frequency is more readily distinguished at lower frequencies than at higher ones. For example, the shift from 100 to 105 Hz is more noticeable than the shift from 8000 to 8005 Hz. Higher-frequency octave bands contain a wider range of frequencies than lower-frequency octave bands, but we perceive them as approximately equal. To obtain a more detailed indicator of the spectrum of sound power, measurements are often made in the one-third octave frequency bands. Standard center frequencies for the one-third octave bands are: 50, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800 and 1000 Hz, etc. Note that an octave band contains the one-third octave band at the standard band center frequency plus the one-third octave bands on each side.

Decibels

The most common measure of a sound's level is Sound Pressure Level, or SPL, expressed in decibels, abbreviated dB. Decibels are not typical units like inches or pounds in that they do not linearly relate to a specific quantity. Instead,

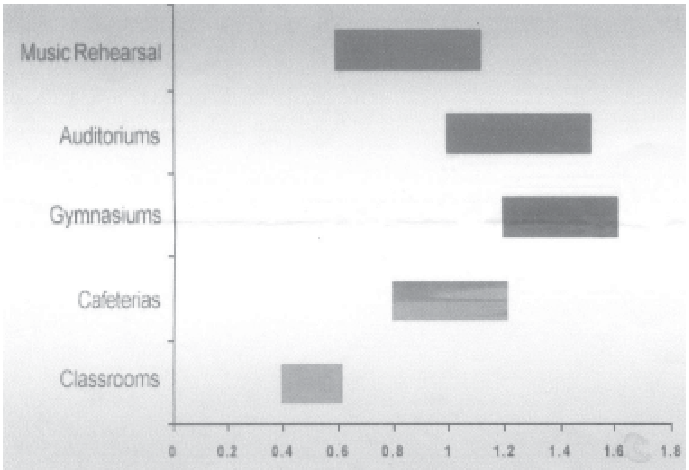

Fig 3: *Suitable Reverberation Times (in seconds) for various rooms typically found in educational facilities.*

decibels are based on the logarithmic ratio of the sound power or intensity to a reference power or intensity. Sound power and intensity are not easy to measure. However, sound pressure is easily measured with a sound level meter. Sound pressure may also be expressed in dB since sound pressure squared is proportional to sound power or intensity. We use dB instead of the actual amplitude of the sound in units of pressure because its logarithmic value represents the way our ears interpret sound and because the numbers are more manageable for our calculations. Most sounds fall in the range of 0 to 140 dB, which is equivalent to waves with pressures of 20 to 200,000,000 micropascals (or 2×10^{-10} to 2×10^{-2} atm). To help you get a feeling for sound pressure levels (in dB), the approximate SPLs of some common sound sources are given in Figure 4.

Source	***SPL (dBA)***
Faintest audible sound	0
Whisper	20
Quiet residence	30
Soft stereo in residence	40
Speech range	50–70
Cafeteria	80
Pneumatic jackhammer	90
Loud crowd noise	100
Accelerating motorcycle	100
Rock concert	120
Jet enjine (22.5m away)	140

Fig. 4: *Sound Pressure Levels of common sound sources.*

A simple sound level meter combines sound pressure levels over all frequencies to give the overall SPL in dB. More complex meters have filters that can measure the SPL in each octave band or one-third octave band separately so we can identify the level in each band, thus identifying the spectrum of the sound. Sound level meters can also "weight" the sound pressure level by adjusting the level in different frequencies before combining the levels into a weighted overall level. For example, A-weighting reduces the level of sounds at low frequencies to stimulate the variations in sensitivity of the ear to different frequencies. A-weighting slightly reduces the dBA to differentiate them from unweighted dB levels. Similarly, C-weighted values are labeled dBC. C-weighting slightly reduces the level of sounds below 50 and above 5000 Hz, but is nearly flat in between, and can be used to approximate an unweighted reading on sound level meters that only offer A- or C-weighting. Comparing A- and C-weighted levels for a noise source can provide a rough estimate of its frequency distribution. If the two levels are within 1 or 2 dB, most of the noise is above 500 Hz. If the two levels vary by more than a few dB, a significant amount of the noise is in the lower frequencies. To convert unweighted octave band sound pressure levels into weighted A or C levels, add or subtract the amounts noted in Figure 5 from the corresponding frequency bands. Next, sum the octave band levels (two at a time as explained below) to arrive at the overall dBA or dBC value.

	Octave Band Center Frequency (Hz)								
	31	63	125	250	500	1000	2000	4000	8000
A-weighting	-40	-26	-16	-9	-3	0	+1	+1	-1
c-Weighting	-2	0	0	0	0	0	0	-3	

Fig. 5: *Frequency Discrimination in dB for A and C weighting.*

As mentioned earlier, calculating the SPL of two sources together is not as simple as adding their individual decibel levels. Two people speaking at 70 dBA each are not as loud as a jet engine at 140 dBA. To combine two decibel values, they must be converted back to pressure squared, summed, and converted back to decibels. The mathematics may be approximated by using Figure 6.

Difference between two decibel values	Amount added to higher value
0 or 1	3
2 or 3	2
4 to 9	1
10 or more	0

Fig. 6: *Decibel "Addition"*

If one sound is much louder than the other, the louder sound drowns out the softer sound, and the combined decibel level is just the level of the louder sound. If the two sounds are equally loud, then the combined level is 3 dB higher. More than two sources can be combined, but they must be considered two at a time. For example, an unbuilt classroom is expected to have 34 dBA of mechanical system noise, a computer that generates 32 dBA of noise, and an overhead projector that generates 43 dBA. What will be the total sound pressure level from the three noise sources? The difference between the first two decibel values is: 34–32=2, so add 2 dB to the higher value: 34+2=36 dBA. Then combine this with the projector noise: 43–36=7, so add 1 dB to the higher value: 43+1=44 dBA total from the three noise sources. If the SPL of the teacher's voice is 55 dBA, what is the signal-to-noise ratio in the room? 55–44=+11 dB, which is sufficient for good speech intelligibility. How much louder is the total 44 dBA than each of the individual noise sources? Due to the response of our ears, we can just notice a different of 3dB. An increase of 10 dB sounds approximately twice as loud, and an increase of 20 dB sounds about four times as loud.

Reverberation Time

Over 100 years ago, a Harvard physics professor named Wallace Clement Sabine developed the first equation for reverberation time, which has since been named after him and is still used today. Reverberation time is defined as the length of time required for sound to decay 60 dB from its initial level. Sabine's simple formula is:

$$RT\ (60) = 0.05V\ /\ (?S?)$$

Where:

RT(60) = reverberation time (sec)
V = room volume (ft^3)
S = surface area (ft^2)
? = absorption coefficient of material(s) at given frequency
? indicates the summation of S times ? for all room surfaces

To use this formula, the volume of the room, surface area of each material in the room, and absorption coefficients for those materials must be known. Absorption coefficients are measured in specialized laboratories, and represent the fraction of sound energy (not sound level-dB) the material will absorb as a decimal from 0 to 1. A commonly used one-number rating called NRC (Noise Reduction Coefficient) is simply the average of the absorption coefficients at 250, 500, 1000 and 2000 Hz. This simple, one-number rating can be useful for comparing the relative absorption of two materials; however, examining absorption coefficients in each octave band gives a better idea of the performance of a material at various frequencies. Reverberation time is often calculated with the room unoccupied. Since people and their clothing provide additional sound absorption, an unoccupied room is the worst-case scenario, though not an unreasonable one, since occupancy of most classrooms varies. In a complete analysis, this calculation should be performed for each octave band, as the RT can vary widely at different frequencies. However, for a quick estimate, the RT of a classroom can be calculated for just one octave band representative of speech frequencies, such as 1000 Hz. If this RT is acceptable, then the RT throughout the speech range will likely be acceptable.

Speech Intelligibility

There are many methods for measuring or predicting speech intelligibility, ranging from a simple A-weighted sound level to the complex Speech Transmission Index (STI). Speech intelligibility can be predicted from reverberation time and signal-to-noise ratio. Speech intelligibility tests can be used to measure intelligibility in existing rooms. Such tests can take many forms. Typically, a speaker reads nonsense syllables, monosyllabic words, or sentences, and listeners record what they hear, or choose from a list of possible alternatives. The percentage of test items correctly heard is a measure of speech intelligibility. Standardized tests have been developed that outline test procedure, selection of listeners, training of speakers and listeners, and so on. Also available are recordings or standardized word lists that can be reproduced instead of having a speaker read from a list. This eliminates lip reading cues and variations in different speakers' speech characteristics and speech levels. Before beginning actual testing, listeners should practice taking the tests in a quiet environment until they are familiar with the procedure and their scores reach a stable level (Words used are randomly chosen from a standardized list so listeners cannot simply memorize the order of the words). If speech intelligibility in a classroom is less than 90 per cent, acoustical treatments should be implemented to reduce reverberation and/or improve signal-to-noise ratio.

Noise Criteria Rating

The noise level in a space can be effectively described with a single-number rating called the noise criteria (NC) rating. The NC rating is determined by measuring the sound pressure level of the noise in each octave band, plotting these levels on a graph, and then comparing the results to established NC curves. The lowest NC curve not exceeded by the plotted noise spectrum is the NC rating of the sound. On most graphs, NC curves are shown in intervals of 5 to save space, but the NC rating can be given as any whole number in between, not just as a multiple of 5.

Sound Level vs. Distance

We all know that sound level decreases as the distance from a sound source increases. This decrease in sound level is quantified by the inverse square law. That is, the sound energy decrease is proportional to the square of the distance increase. For example, if the listening distance from a sound source is increased by a factor of 2 (doubled), the direct sound energy is decreased by a factor of 4 or 2 squared (2 times 2). This translates to a 6 dB reduction in the sound intensity level and the sound pressure level of the direct sound for each doubling of the distance from the sound source.