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Acoustics in HVAC System

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Abstract

Acoustics can be a complex issue, but HVAC acoustics can be successfully evaluated for many typical applications. How sound behaves in different conditions and environment is to be studied. Also a study of different rating methods has been established, which can be used in many applications. For many complex applications, we can combine the different rating methods to get the proper acoustical environments. Different methods to improve acoustics in rooms of new buildings and also to improve the performance of existing buildings can be learned.

Keywords: *Acoustics, sound, Noise, rating methods.*

INTRODUCTION

CHAPTER: 1

1. SOUND BASICS

Sound is defined as a disturbance in an elastic medium that can be detected by the human ear. The medium can be gas, liquid or solid. Noise is undesirable sound or sound without value. The pressure waves (or sound) act on the inner ear, which is what we hear. The best sound is not necessarily no sound. In an open office concept, background sound offers privacy for conversations. The quality of sound is also important. Tonal sounds are usually not desirable. The following list will help better understand sound.

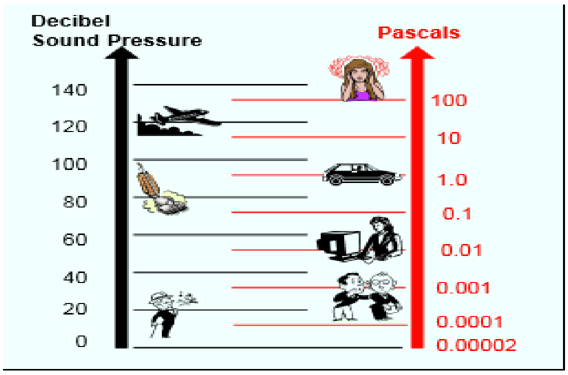


Figure 1: Typical Sound Pressure Levels (Ref No. 3).

Important Points

1. The amplitude of the sound wave represents the loudness and is measured in decibels (Pascals). The louder the sound, the larger the amplitude. The loudest atmospheric sound has zero atmospheric pressure at the low point and two times atmospheric pressure at the high point. This is 194 dB.

2. The frequency of sound represents the pitch and is measured in Hertz. The higher the frequency, the higher the sound. The human hearing range is from about 16 Hz to 16,000 Hz. below 30 Hz, sound can be felt as well as heard.

3. The wavelengths for sound can vary from 70 feet (21.3 m) at 16 Hz to 0.07 feet (0.02 m) at 16,000 Hz. This is important because sound absorbing materials tend to work well when their dimensions are close to the wavelength. Therefore, a 1-inch (25 mm) ceiling tile is effective at absorbing higher frequency sounds, but low frequency sounds are much more difficult to attenuate.

4. The human ear can respond to very wide range of sound levels. At the low end, the ear is sensitive to sound pressure waves as little as 0.00002 Pa. At the high end, the human ear can hear about 20

Pa without pain, which is 1,000,000 times louder. This is a key reason why Decibel logarithmic scales are used.

5. The speed of sound is dependent on the density of the medium it is travelling through. The lower the density, the slower the sound wave. At standard atmospheric conditions, the speed of sound (Mach 1) is 764 miles per hour (1120 feet per second, 341 m/s).

6. Sound waves do not actually pass through walls or other solid objects. Instead, they impinge on the exterior surface of the wall or object, causing it to vibrate. This, in turn, causes the air molecules in the space to vibrate. What is actually happening is that the sound wave is making move.

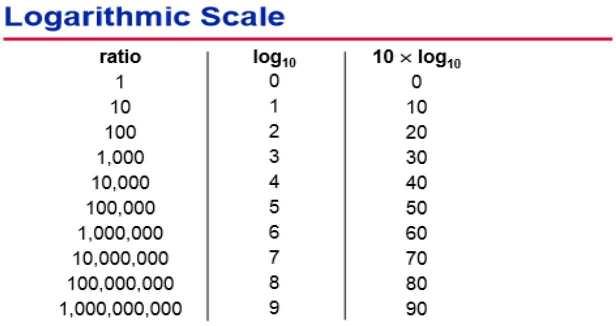
Wavelength and Frequency

The wavelength of sound in air is given by;
Eq. 1 $\lambda = co / f$

Where λ is the wavelength in feet (m). co is the speed of sound, which is 1120 feet per second (341 m/s) at sea level. f is the frequency in Hz.

Decibels

The very large range in sound pressure makes a logarithmic scale more convenient. Decibels (dB) are always referenced to base signal. Knowing the base reference is critical because the term "decibels" in acoustics is used for sound pressure and sound power. In the case of sound pressure, the reference is 0.00002 Pascals, which is the threshold of hearing.



Logarithmic Scale

ratio	$\log_{10}$	$10 \times \log_{10}$
1	0	0
10	1	10
100	2	20
1,000	3	30
10,000	4	40
100,000	5	50
1,000,000	6	60
10,000,000	7	70
100,000,000	8	80
1,000,000,000	9	90

Table 1: Logarithmic Scale (Ref No.3).

Eq. 2 Lp = 20Log(P/0.00002)

Where Lp is the sound pressure in Decibels (dB) P is the sound pressure in Pascals.

For sound power the reference is 10-12 Watts.

Eq.3 Lw = 10Log (W/10-12)
Where Lw is the sound power in Decibels (dB) W is the sound power in Watts

Decibel Addition and Subtraction

Since Decibels are logarithmic, they cannot simply be added. For instance, 40 dB + 40 dB is not 80 dB, it is 43 dB. Decibels can be added as follows:

Ls = 10Log(10L1/10 + 10L2/10+10L3/10+....) Decibels can be quickly added together with an accuracy of about 1 dB by using the relationship shown in Table 1- Decibel Addition Chart.

Decibel Example Calculate the loudest possible sound at standard atmospheric pressure (101.3 kPa)

Lp = 20Log(101,300/0.00002)

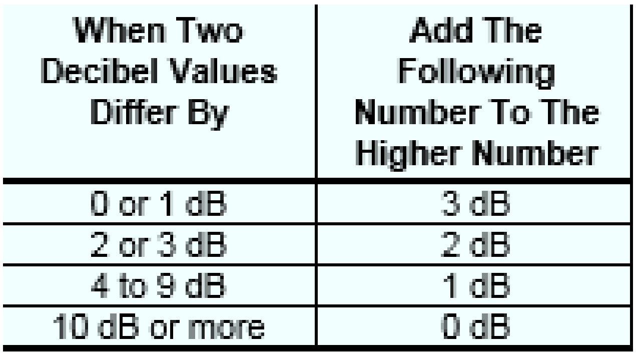
= 194 dB RE 20μ Pa

Note: 20μ Pa is another way to write 0.00002 Pa.

Decibel Addition Example Add the follow values together; L1 = 80 dB L2 = 82 dB L3 = 84 dB L4 = 93 dB L5 = 72 dB

LTotal = 10Log(1080/10 + 1082/10+1084/10 + 1093/10+1072/10) = 94 dB

Using Table 1- Decibel Addition Chart Between L1 and L2, there is a difference of 2 dB so add 2 dB to L2 for a total of 84 dB. Between 84 dB and L3, there is a difference of 0 dB so add 3 dB to 84 dB for a total of 87 dB. Between 87 dB and L4, there is a difference of 6 dB so add 1 dB to L4 for a total of 94 dB. Between 94 dB and L5, there is a difference of 22 dB so add 0 dB to 94 dB for a total of 94 dB.



When Two Decibel Values Differ By	Add The Following Number To The Higher Number
0 or 1 dB	3 dB
2 or 3 dB	2 dB
4 to 9 dB	1 dB
10 dB or more	0 dB

Table 2: Decibel Addition Chart (Ref No.2).

Decibel subtraction is accomplished as follows:

Eq. 5 Ls = 10Log (10L1/10 - 10L2/10-10L3/10-....)

2. SOUND PRESSURE VS. SOUND POWER

What you hear is sound pressure. It is the fluctuation in the atmospheric pressure that acts on your eardrum. However, sound pressure is dependent on the surroundings, making it a difficult means to measure the sound level of equipment. Sound power is the sound energy released by a sound source. It cannot be “heard”, but it can be used to estimate the sound pressure levels if the space conditions are known. Sound pressure and sound power are best explained with an example.

Consider a 5 kW electric baseboard heater. The 5 kW rating is a clear, definable measure that can be used to compare one heater against another. This is the equivalent of Sound Power. However, it not possible to know whether a 5 kW heater is sufficient to keep the occupant warm and comfortable unless the temperature of the space is known. The temperature of the space is the equivalent of sound pressure. If the 5 kW heaters are used in a small, single room addition to a house, it will probably provide a comfortable temperature. If the heater is used in the Toronto Skydome, it is unlikely to offer any comfort to occupants. In each application the same size heater (or sound power level) provides very different thermal comfort results (or sound pressure level).

Knowing the Sound Power levels for a piece of equipment (e.g. a fan coil) will allow a fair and direct comparison of two models. It will not, however, indicate whether the sound level will be acceptable until the space is defined. Knowing the sound pressure of a piece of equipment (e.g. a cooling tower) will allow two models to be compared (assuming the same conditions were used for testing both units). However, unless the actual space where the product is used has the same properties as the test conditions, the sound pressure level provided will not be what the occupant experiences. In this manual, Sound Pressure will be indicated by Lp RE 20µ Pa and Sound Power will be indicated by Lw RE 10-12 W.

Broadband Sound

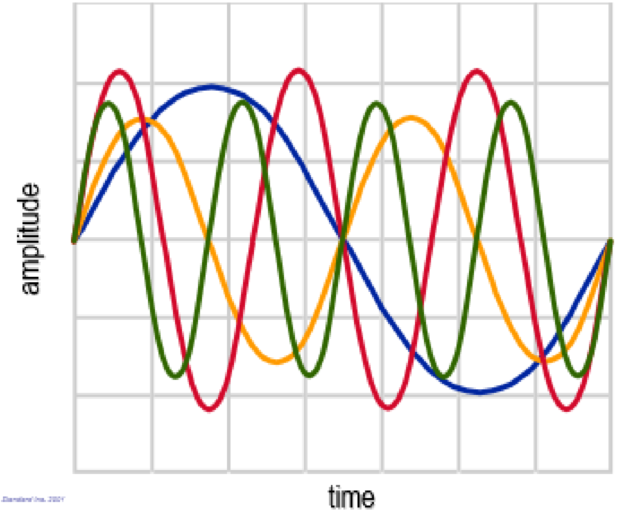


Figure 2: Sinusoidal wave form (Ref No. 1).

A pure sinusoidal wave form, however, is very rare in HVAC acoustics. Typically, sounds are of a broadband nature, meaning that the sound is composed of several frequencies and amplitudes, all generated at the same time. Figure represents the components of broadband sound.

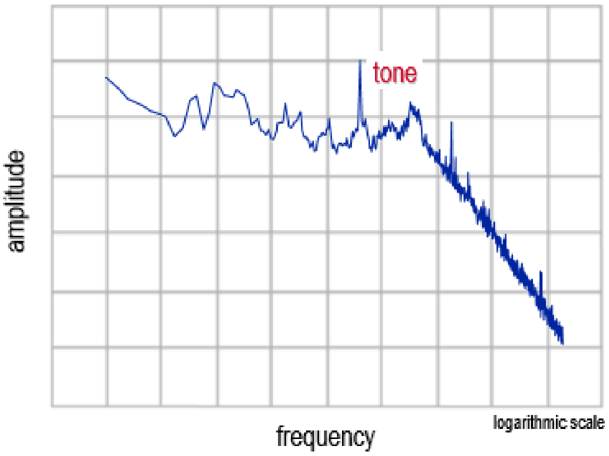


Figure 3: Amplitude vs Frequency (Ref No. 1).

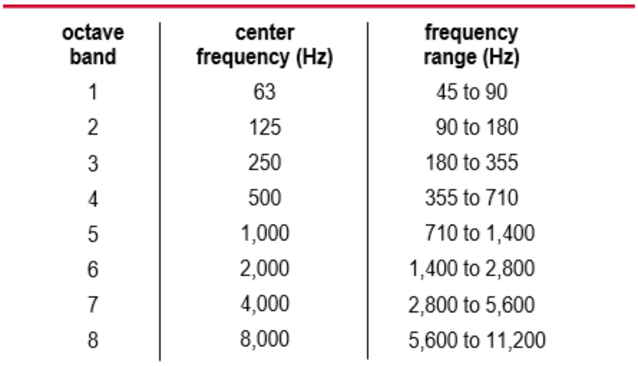
Alternatively, plotting the amplitude (vertical axis) of each sound wave at each frequency (horizontal axis) results in a graphic of the broadband sound that looks like this. As you can see from this example, the sound energy is greater at some frequencies than at others.

Again, a pure tone has a single frequency. If a sound in a narrow band of frequencies is significantly greater than the sound at adjacent frequencies, itwould be similar to a tone. Tones that stand out enough from the background sound can be objectionable. Many of the sounds generated by HVAC equipment and systems include both broadband and tonal characteristics.

3. TONAL SOUNDS

A pure tone is the sound pressure or power associated with a single frequency. For example, there is often a 60 Hz sound component when based on 60 Hz electric frequency. Identifying a pure tone can help in acoustic analysis. For example, if there was a 60 Hz pure tone and only octave band analysis is considered, then the 60 Hz pure tone energy would be included in the 63 Hz octave band. It would not be evident that the sound energy in this band was due the electric frequency.

Octave Bands



octave band	center frequency (Hz)	frequency range (Hz)
1	63	45 to 90
2	125	90 to 180
3	250	180 to 355
4	500	355 to 710
5	1,000	710 to 1,400
6	2,000	1,400 to 2,800
7	4,000	2,800 to 5,600
8	8,000	5,600 to 11,200

Table 3: Octave Band (Ref No. 3).

Equipment such as fans, compressors and pumps can produce tonal sounds. Caution should be taken when evaluating tonal products because they are not modeled well by octave band analysis. For instance, a tonal product such as a double helix screw compressor cannot be evaluated using the processes described in this manual or by the Acoustic Analyzer. Refer to the ASHRAE article, Addressing Noise Problems in Screw Chillers.

Because sound occurs over a range of frequencies, it is considerably more difficult to measure than temperature or pressure. The sound must be measured at each frequency in order to understand how it will be perceived in a particular environment. The human ear can perceive sounds at frequencies ranging from 20 to 16,000 Hz, whereas, HVAC system designers generally focus on sounds in the frequencies between 45 and 11,200 Hz. Despite this reduced range, measuring a sound at each frequency would result in 11,156 data points. For some types of analyses, it is advantageous to measure and display the sound at each frequency over the entire range of frequencies being studied. This is called a full-spectrum analysis and is displayed like the example shown in Figure 7. To make the amount of data more manageable, this range of frequencies is typically divided into smaller ranges called octave bands. Each octave band is defined such that the highest frequency in the band is two times the lowest frequency. The octave band is identified by its center frequency, which is calculated by taking the square root of the product of the lowest and highest frequencies in the band.

3.1 Centre Frequency=Square Root Of (Lower Frequency * Upper Frequency)

The result is that this frequency range (45 to 11,200 Hz) is separated into eight octave bands with center frequencies of 63, 125, 250, 500, 1,000, 2,000, 4,000, and 8,000 Hz. For example, sounds that occur at the frequencies between 90 Hz and 180 Hz are grouped together in the 125 Hz octave band.

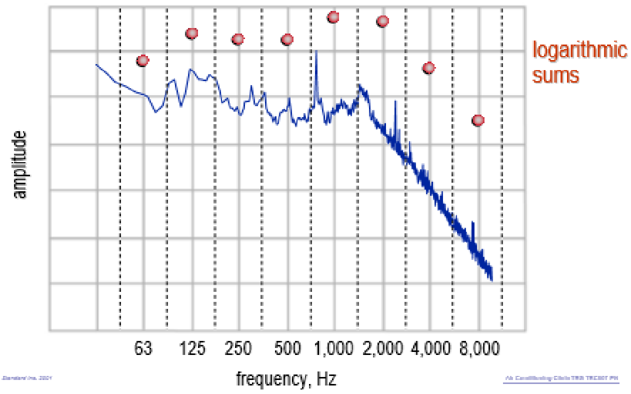


Figure 4: Effect of Octave Band (Ref No. 1).

Octave bands compress the range of frequencies between the upperand lower ends of the band into a single value. Sound measured in an octave band is the logarithmic sum of the sound level at each of the frequencies within the band.

Unfortunately, octave bands do not indicate that the human ear hears a difference between an octave that contains a tone and one that does not, even when the overall magnitude of both octaves is identical. Therefore, the process of logarithmically summing sound measurements into octave bands, though practical, sacrifices valuable information about the “character” of the sound.

CHAPTER: 2

1. SOUND PERCEPTION AND RATING METHODS

The study of acoustics is affected by the response of the human ear to sound pressure. Unlike electronic sound-measuring equipment, which provides a repeatable, unbiased analysis of sound pressure, the sensitivity of the human ear varies by frequency and magnitude. Our ears are also attached to a highly arbitrary evaluation device, the brain.

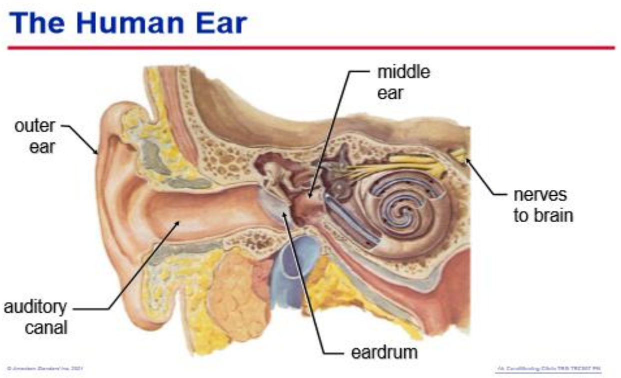


Figure 5: Human Ear (Ref No. 1).

Human Ear Response

The ear acts like a microphone. Sound waves enter the auditory canal and impinge upon the ear drum, causing it to vibrate. These vibrations are ultimately transformed into impulses that travel along the auditory nerve to the brain, where they are perceived as sound. The brain then analyzes and evaluates the signal.

2. LOUDNESS CONTOURS

The sensation of loudness is principally a function of sound pressure; however, it also depends upon frequency. As a selective sensory organ, the human ear is more sensitive to high frequencies than to low frequencies. Also, the ear’s sensitivity at a particular frequency changes with sound-pressure level. Figure 20 illustrates these traits using a set of contours. Each contour approximates an equal loudness level across the frequency range shown.

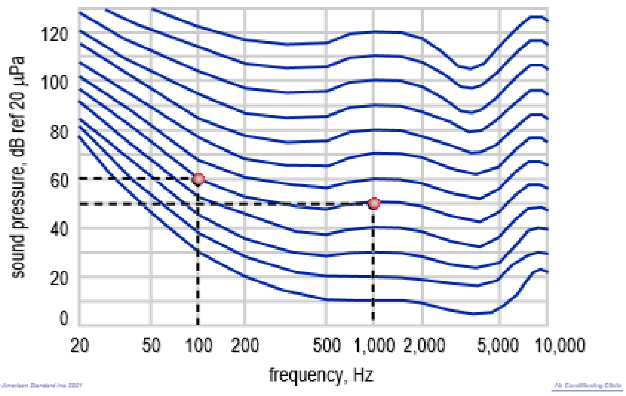


Figure 6: Loudness Contours (Ref No. 3).

For example, a 60 dB sound at a frequency of 100 Hz is perceived by the human ear to have loudness equal to a 50 dB sound at a frequency of 1,000 Hz. Also, notice that the contours slant downward as the frequency increases from 20 to 200 Hz, indicating that our ears are less sensitive to low-frequency sounds. The contours are flatter at higher decibels (> 90 dB), indicating a more uniform response to “loud “sounds across this range of frequencies.

As you can see, the human ear does not respond in a linear manner to pressure and frequency.

Response to Tones

Additionally, tones evoke a particularly strong response. Recall that a tone is a sound that occurs at a single frequency. Chalk squeaking on a blackboard, for example, produces a tone that is extremely irritating to many people.

3. SINGLE-NUMBER RATING METHODS

The human ear interprets sound in terms of loudness and pitch, while electronic sound- measuring equipment interprets sound in terms of pressure and frequency. As a result, considerable research has been done in an attempt to equate sound pressure and frequency to sound levels as they are perceived by the human ear. The goal has been to develop a system of single-number descriptors to express both the intensity and quality of a sound.

With such a system, sound targets can be established for different environments. These targets aid building designers in specifying appropriate acoustical requirements that can be substantiated through measurement. For example, a designer can specify that “the background sound level in the theater shall be X,” where X is a single-number descriptor conveying the desired quality of sound. The most frequently used single-number descriptors are the A-weighting network, noise criteria (NC), and room criteria (RC). All three share a common problem, however: they unavoidably lose valuable information about the character, or quality, of sound. Each of these descriptors is based on octave-band sound data which, as noted earlier, may already mask tones.

Further, the process of converting from eight octave bands to a single number overlooks even more sound data. Despite this shortcoming, the single-number descriptors summarized in this clinic are valuable tools for defining sound levels in a space, and are widely used to specify the acoustical requirement of a space.

A-B-C Rating

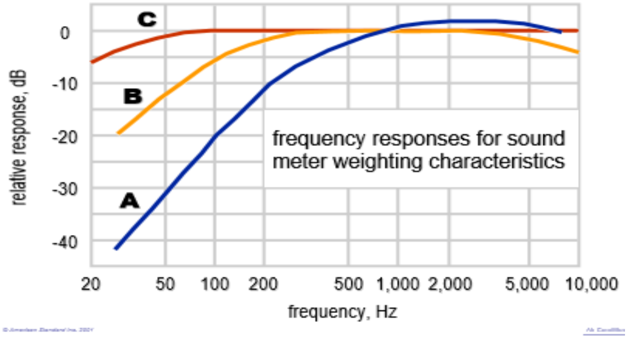
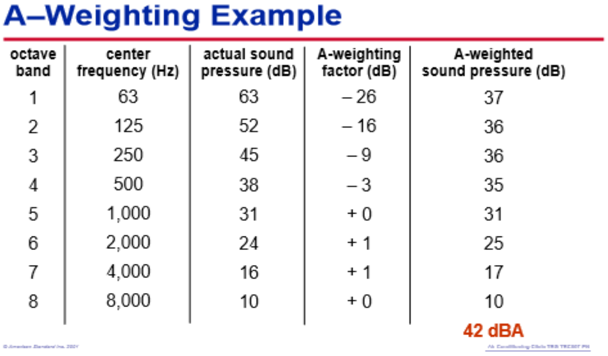


Figure 7: A-B-C Rating (Ref No. 1).

One simple method for combining octave-band sound data into a single-number descriptor is A-, B-, or C-weighting. The weighting curves shown in Figure 23 compensate for the varying sensitivity of the human ear to different frequencies.

A-weighting, which is most appropriately used for low-volume (or quiet) sound levels, best approximates human response to sound in the range where no hearing protection is needed. B-weighting is used for medium-volume sound levels. C-weighting is used for high-volume (or loud) sound levels where the response of the ear is relatively flat.



A–Weighting Example

octave band	center frequency (Hz)	actual sound pressure (dB)	A-weighting factor (dB)	A-weighted sound pressure (dB)
1	63	63	– 26	37
2	125	52	– 16	36
3	250	45	– 9	36
4	500	38	– 3	35
5	1,000	31	+ 0	31
6	2,000	24	+ 1	25
7	4,000	16	+ 1	17
8	8,000	10	+ 0	10
				42 dBA

Table 3: A-Weighting Example (Ref No. 1).

The following steps describe how to calculate an A-weighted value

1. Starting with the actual sound-pressure levels for the eight octave bands, add or subtract the decibel values represented by the A-weighting curve shown in Figure 23. These weighting factors are also listed in the table in Figure 24. Subtract26 dB from the 63 Hz sound-pressure level, 16 dB

from the 125 Hz level, 9 dB from the 250 Hz level, and 3 dB from the 500 Hz level. Then, add 1 dB each to the sound-pressure levels in the 2,000 Hz and 4,000 Hz octave bands.

2. Logarithmically sum all eight octave bands together to arrive at an overall A- weighted sound-pressure level. This value is then expressed using the units of dBA. For the sound-pressure data in this example, the A-weighted sound-pressure level is 42 dBA. Most sound meters can automatically calculate and display the A-weighted sound-pressure level, providing a simple and objective means of verifying acoustical performance. However, as mentioned earlier, one of the drawbacks of a single-number descriptor is that data about the relative magnitude of each octave band is lost when the eight octave bands are combined into one value. Therefore, even if the target dBA level is achieved, an objectionable tonal quality or spectrum imbalance may exist.

Applications

A-weighting is often used to define sound in outdoor environments. For example; local sound ordinances typically regulate Dba levels at property lines.

Hearing-related safety standards, written by organizations such as the Occupational Safety and Health Administration (OSHA), also commonly refer to A-weighted sound-pressure levels when determining whether hearing protection is required in a certain environment.

To avoid confusion, we recommend that A-weighting be applied to only octave-band sound- pressure data, not to sound-power data. Also, A-weighting should be limited to expressing a single-number descriptor. Displaying sound data in all eight octave bands in terms of A- weighted sound pressures should be avoided.

NC Curves

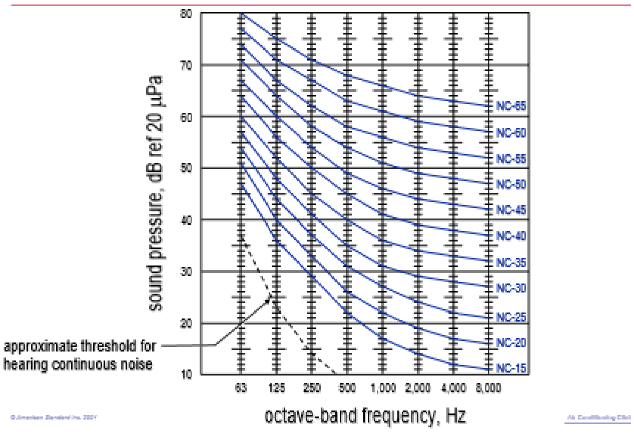


Figure 8: NC Curves (Ref No. 1).

Noise criteria (NC) curves are probably the most common single-number descriptor used to rate sound-pressure levels in indoor environments. Like the equal-loudness contours on which they are based, the loudness along each NC curve is about the same. Each NC curve slopes downward to reflect the increasing sensitivity of the ear to higher frequencies.

It should also be noted that NC charts do not include the 16 Hz and 31.5 Hz octave bands. Although HVAC equipment manufacturers typically do not provide data in these bands (because it is very difficult to obtain reliably), these octave bands do affect the acoustical comfort of the occupied space. Nevertheless, these octave bands can be measured in a space that is already built and may provide useful diagnostic information.

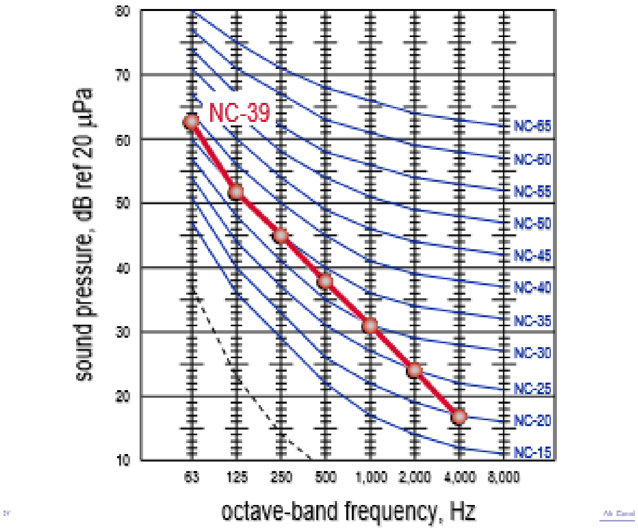


Figure 8.1: NC Curve (Ref No. 1).

The following steps describe how to calculate an NC rating.

1. Plot the octave-band sound-pressure levels on the NC chart.
2. The highest curve crossed by the plotted data determines the NC rating.

Although the NC curves are popular and easy to use, they do have few shortcomings. Specifically, they do not account for the tonal nature and relative magnitude of each octave band. Figure 27 shows octave-band data measured in an open-plan office space and plotted on an NC chart. The resulting value, NC-39, is generally considered to be acceptable for this type of environment. Notice that this NC value is set by the 63 Hz octave band and the sound drops off quickly in the higher octave bands. In this particular example, sound generated by the air-handling unit travels through the ductwork, breaks out through the duct walls, and radiates into the office area. To achieve the desired NC level, two layers of sheet rock were added to the exterior surface of the duct to block the low-frequency sound

. Unfortunately, because high-frequency sounds are much more easily attenuated than low-frequency sounds, the upper octave bands are now over- attenuated. Although an objective analysis deems the resulting NC-39 sound level acceptable in this type of open-plan office space, most listeners in the space would probably perceive this unbalanced spectrum as having an annoying rumble.

RC Curves

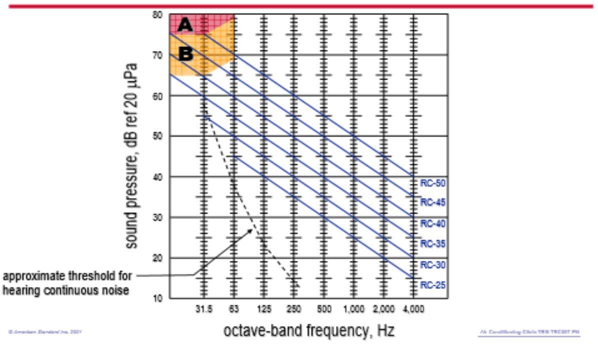


Figure 9: RC Curve (Ref No. 1).

Room criteria (RC) curves are similar to NC curves in that they are used to provide rating for sound-pressure levels in indoor environments. The major difference is that RC curves give an additional indication of sound character.

As discussed in the previous example, sound spectrums can be unbalanced in ways that result in poor acoustical quality. Too much low-frequency sound results in a rumble, and too much high-frequency sound produces a hiss. RC curves provide a means of identifying these imbalances. An RC rating consists of two descriptors. The first descriptor is a number representing the speech interference level (SIL) of the sound.

The second descriptor is a letter denoting the character of the sound as a subjective observer might describe it.

- N identifies a neutral or balanced spectrum
- R indicates a “rumble”
- H represents a “hiss”
- RV denotes perceptible vibration

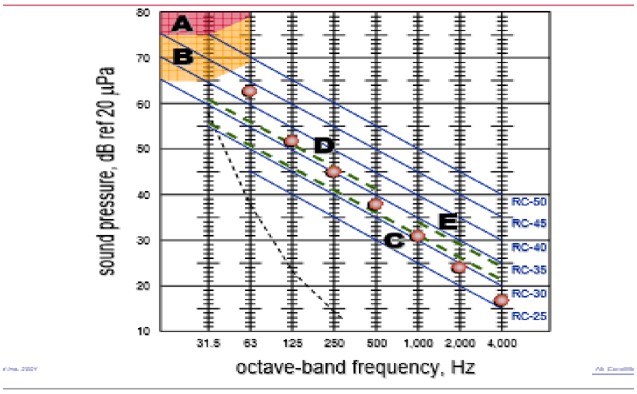


Figure 9.1: RC Curve (Ref No. 1).

Calculating an RC value from octave-band sound-pressure data is not quite as easy as determining an NC value, but it is still fairly simple. The RC value is based on sound- pressure data from the eight octave bands between 31.5 and 4,000Hz. Note that these are different than the octave bands included on the NC chart.

The following steps describe how to determine an RC rating

1. Plot the octave-band sound-pressure levels on the RC chart.
2. Determine the SIL by calculating the arithmetic average of the sound-pressure levels in the 500 Hz, 1,000 Hz, and 2,000 Hz octave bands. In this example, the arithmetic average of 38 dB, 31 dB, and 24 dB is 31 dB.
3. Draw a line (C) with a slope of –5 dB per octave that passes through the calculated SIL at the 1,000 Hz octave band. This is the reference line for evaluating the character of the sound spectrum.
4. Between 31.5 Hz and 500 Hz, draw a line (D) that is 5 dB above the reference line (C). Between 1,000 Hz and 4,000 Hz, draw a second line (E) that is 3 dB above the reference line (C). These two boundary lines (D and E) represent the maximum permitted deviation to receive a neutral (N) rating.
5. Judge the character of the sound quality by observing how the sound spectrum deviates from the boundary lines drawn in Step Four. Use the following criteria to choose the appropriate letter descriptor that characterizes the subjective quality of the noise.

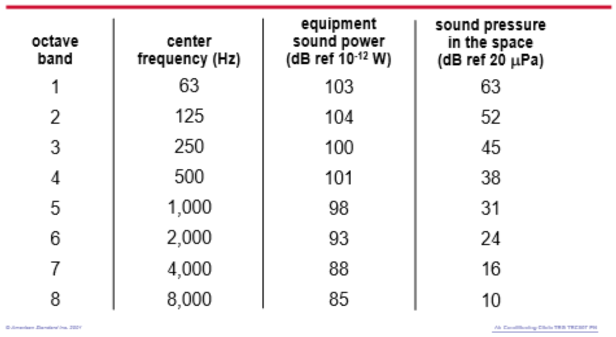
- Neutral (N): The sound level in each of the octave bands between 31.5 Hz and 500 Hz is below line D, and the sound level in each of the octave bands between 1,000 Hz and 4,000 Hz is below line E.
- Rumble (R): The sound level in any octave band between 31.5 Hz and 500 Hz is above line D.
- Hiss (H): The sound level in any octave band between 1,000 Hz and 4,000 Hz is above line E.
- Perceptible vibration (RV): The sound level in either the 16 Hzor 63 Hz octave bands falls in the shaded regions (A and B). These regions indicate sound-pressure levels at which walls and ceilings can vibrate perceptibly— rattling cabinet doors, pictures, ceiling fixtures, and other furnishings in contact with them.

Region A: High probability that noise-induced vibration levels in lightweight wall and ceiling constructions will be felt. Anticipate audible rattles in light fixtures, doors, windows, and so on.

Region B: Noise-induced vibration levels in lightweight wall and ceiling constructions may be felt. Slight possibility of rattles in light fixtures, doors, windows, and so on.

The RC rating for the sound is the numerical SIL value calculated in Step Two and the letter descriptor determined in Step Five.

Octave Band Rating Method



octave band	center frequency (Hz)	equipment sound power (dB ref 10^{-12} W)	sound pressure in the space (dB ref 20 µPa)
1	63	103	63
2	125	104	52
3	250	100	45
4	500	101	38
5	1,000	98	31
6	2,000	93	24
7	4,000	88	16
8	8,000	85	10

Table 5: Octave Band Rating Method (Ref No. 1).

Octave-Band Rating Method A more useful method of rating sound level is to use the octave bands discussed earlier. While octave-band data is not as simple to interpret as a single-number rating, it provides much more information about the character of the sound.

Both sound-power levels and sound-pressure levels can be presented in octave-band format. When equipment sound data is provided in terms of sound-power level in each octave band, an "apples to apples" comparison can be made between various pieces of equipment. In addition, this sound-power data can be converted to sound-pressure levels when the details of the environment are known. This type of analysis will be discussed further in Period Three.

Sound-pressure levels in each octave band, whether predicted from sound-power data or measured in an existing environment; reveal much more about the character of sound than any of the single-number rating methods. It is important to note that any of the single-number ratings described in this section can be calculated from octave-band sound- pressure data. However, octave-band data cannot be derived from any of the single-number ratings.

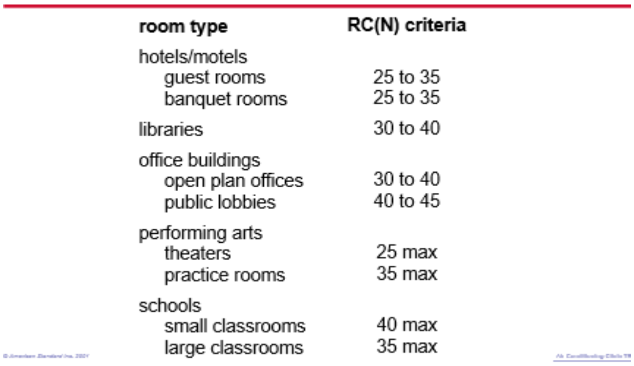
CHAPTER 3

1. ACOUSTICAL ANALYSIS

The primary acoustical design goal for an HVAC system is to achieve a background noise level that is quiet enough so that it does not interfere with the activity requirements of the space and is not obtrusive in sound quality.

What is considered "acceptable "varies dramatically with the intended use of the space? Obviously, a factory has less stringent acoustical requirements than a church, while an office has a different set of requirements altogether. Therefore, the acoustical design goal depends on the required use of the space.

Setting a Goal



room type	RC(N) criteria
hotels/motels	
guest rooms	25 to 35
banquet rooms	25 to 35
libraries	30 to 40
office buildings	
open plan offices	30 to 40
public lobbies	40 to 45
performing arts	
theaters	25 max
practice rooms	35 max
schools	
small classrooms	40 max
large classrooms	35 max

Table 6: Octave Band Rating Method (Ref No. 1).

The first step of an acoustical design is to quantify the goal. Period Two introduced several single-number descriptors that designers commonly use to define the acoustical design goal for a space. Each descriptor has its advantages and its drawbacks.

In general, when defining the acoustical design goal for an interior space, either an NC value or an RC value is used. To aid HVAC system designers, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) recommends target RC ratings for various types of spaces, and encourages the use of the RC rating method whenever the space requires a neutral, unobtrusive background sound. Figure 34 includes an excerpt from the ASHRAE Handbook—Applications (Table 43 in Chapter 46 of the 1999 edition).

As mentioned earlier, A-weighting is also used in many hearing-protection safety standards for industrial environments. These standards generally take the form of a maximum A- weighted sound-pressure level at a specified distance from the piece of machinery.

When defining the acoustical design goal for an outdoor environment, to meet a local noise ordinance for example, the A-weighted scale is typically used. This generally takes the form of a maximum A-weighted sound-pressure level at the lot line of the property.

More-sophisticated noise ordinances may specify maximum sound-pressure levels for each octave band and possibly a restriction on other characteristics of the sound. For example, a sound ordinance may define that a tone is present when the sound-pressure level in any one-third octave band exceeds the arithmetic average of the sound-pressure levels in the two neighboring one-third octave bands by 5 dB or more.

2. SOURCE–PATH–RECEIVER ANALYSIS

Achieving the desired acoustical characteristics in a space, however, requires more than selecting an appropriate single-number descriptor. Including a single-number descriptor in a HVAC system specification means that someone must perform an acoustical analysis to determine if the proposed HVAC system and equipment will satisfy the space acoustical requirements. To make such a prediction, the analysis must convert the sound-power level of the source (the fan in the air handler in this example) to the sound-pressure level in the occupied space, assessing the effect of installation and environmental factors along the way.

Sound that reaches the occupied space will be altered by ductwork, wall and ceiling construction, room furnishings, and many other factors. The validity of an acoustical analysis, therefore, depends on the analyst’s familiarity with construction details.

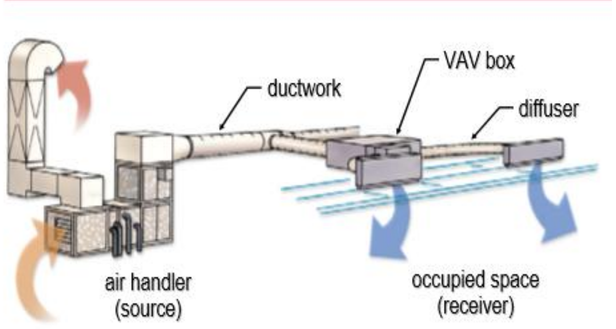


Figure 10: Sound-Path-Receiver Analysis (Ref No. 1).

Predicting the sound level in a given space requires making a model of the system. A source–path–receiver model provides a systematic approach to predict the acoustical characteristics in a space. As the name suggests, this modeling method traces sound from the source to the location where we want to predict the sound (the receiver). How the sound travels between the source and the receiver, and everything it encounters as it travels along the way, constitutes the path.

In the example shown in Figure, the source is the fan in the mechanical room. The receiver is the person working in the adjacent office space. The supply duct provides one of the paths for sound to travel from the source to the receiver.

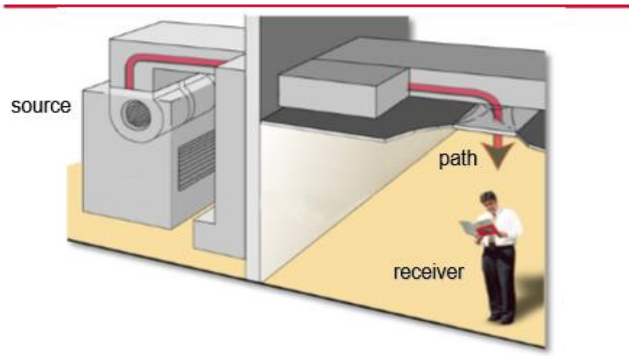


Figure 11: Source-Path-Receiver Model (Ref No. 5).

Using such an analysis, the designer can determine the effect of the paths on the sound emanating from the source, and can specify the maximum allowable equipment sound power that will not exceed the sound-pressure target for the space.

2.1 Typical Sound Paths

The work, and art, of an acoustical analysis is in identifying and quantifying the various paths that sound travels from the source to the receiver.

There are primarily three different types of sound paths.

- Airborne: This is a path where sound travels with, or against, the direction of airflow. In a HVAC system, sound travels along this type of path through the supply ductwork, return ductwork, or an open plenum.
- Breakout: This type of path is typically associated with sound breaking out through the duct walls and into the space.
- Transmission: This is a path where sound travels through walls, floors, and ceilings. In its simplest form, this path involves sound traveling directly through the air from the source to the receiver.

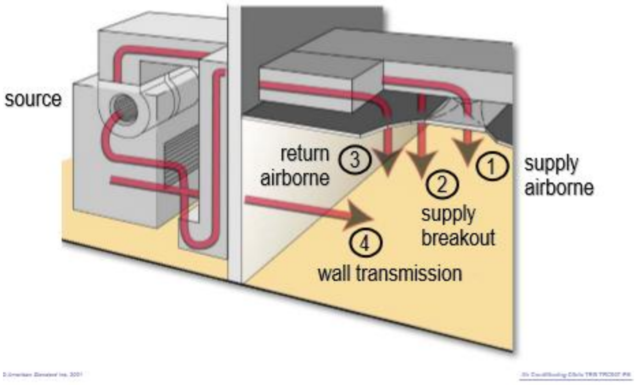


Figure 12: Transmission of sound in different ways (Ref No. 5).

In other cases there may be several paths for sound to travel from a source to the receiver. This particular example shows the paths associated with an air handler that is installed in a mechanical equipment room adjacent to an occupied space. Only one sound source is included in this analysis, the fan located in the air handler. The receiver is the person working in the office. The sound travels from the source to the receiver along four separate paths:

1. Supply airborne through the supply ductwork and diffusers and into the space 2.
2. Supply breakout as the sound travels through the walls of the supply ductwork, through the ceiling tile, and into the space 3.
3. Return airborne through the air-handler intake, return ductwork and grilles, and into the space 4.

4. Wall transmission as the sound travels through the adjoining wall and into the space.

These paths are typical of most centralized air-handling equipment, including packaged rooftop and self-contained air conditioners. Most other equipment types have a subset of these paths.

There are a few important points to remember when identifying sources and paths for a source–path–receiver acoustical analysis.

- One piece of equipment may contain several sound sources. For example, a packaged rooftop air conditioner (shown in Figure) contains supply and exhaust (or return) fans, compressors, and condenser fans.
- Sound may travel from a single source to the receiver along multiple paths. This was demonstrated with the previous example.

2.1 Sound-Path Modeling

When all the paths have been identified, they can be individually modeled to determine the contribution of each to the total sound heard by the receiver. Sound-path modeling studies how sound from a source changes on its way to a receiver. The pieces that make up the path from source to receiver can be called elements of the path.

Returning to the air-handler example, one path that sound travels from the air-handling unit (source) to the person in the office (receiver) is to follow the conditioned air supplied to the space. In addition to the source and receiver, the elements of this path include the components of the air distribution system, such as straight pieces of duct, possibly duct silencers, elbows, junctions, and diffusers. The path also includes the acoustical characteristics of the occupied space, such as its size, floor coverings, furnishings, and wall construction.

Modeling of Sound Paths on the Graph

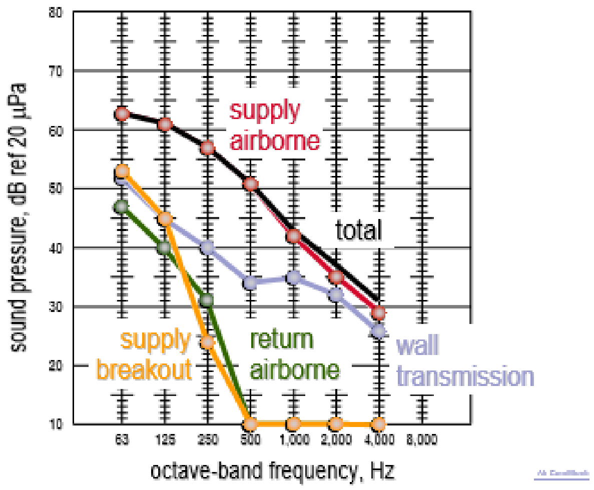


Figure 13: Modeling of sound Path on Graph (Ref No. 5).

As mentioned previously, the total sound heard by the receiver is the sum of sounds from multiple sources, following multiple paths. After each path is modeled to determine its contribution to the sound-pressure level at the receiver location, the paths must be summed to complete the model. While separating the individual paths is necessary for modeling, a secondary benefit is that the magnitude of the various paths can be compared.

In this example, sound travels from a single source to the receiver along four separate paths: supply airborne, supply breakout, return airborne, and transmission through the adjacent wall. By modeling these four paths independently, you can see that the supply airborne path contributes to the total sound-pressure level in the space much more than the other three paths. In fact, when the sounds due to all four paths are logarithmically summed, the total sound heard by the receiver is nearly the same as the sound due to the supply airborne path alone.

This would indicate that, if the sound-pressure level in the space is too high, the designer should focus first on reducing the sound due to the supply airborne path. Reducing the sound due to the return airborne path, without addressing the supply airborne path, would have no effect on the total sound-pressure level heard in the space.

3. COMPUTER ANALYSIS

Solving these algorithms manually can be tedious and time consuming, especially when one or more paths need further attenuation and the calculations have to be repeated. Fortunately, computer software tools are available to spare analysts from the calculation- intensive equations.

Also, computer programs make it easier to perform trade off, or “what if?”, analyses. Examples may include determining the effects of using a duct silencer, changing the construction of the equipment-room wall, adding absorptive materials to a ceiling, or placing a barrier wall between an outdoor sound source and the property lot line.

Sound Transmission

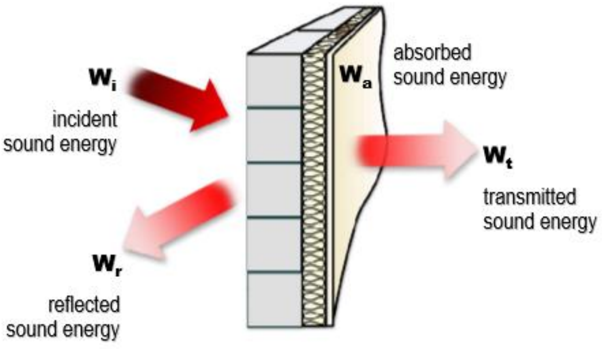


Figure 14: Sound Transmission through Wall (Ref No. 5).

The total sound energy that strikes a surface (Wi) is either reflected (Wr), absorbed by the material (Wa), or transmitted through the material (Wt).

A material provides a barrier to the incident sound energy (Wi) when it reduces the amount of sound energy that is transmitted through the material (Wt). There are a number of factors that affect the amount of sound transmitted through the wall, including the type and thickness of material, frequency of the sound, and quality of construction.

Materials that are dense (such as masonry block or wallboard) or stiff (such as glass) are generally better at reducing transmitted sound than materials that are lightweight or flexible. Increasing the thickness of a material reduces the amount of sound transmitted through it. Finally, the ability of a material to reduce transmitted sound depends on frequency. High- frequency sound is more easily reduced than low-frequency sound.

The ability of a material to reduce transmitted sound is most commonly referred to in terms of its insertion loss, noise reduction, or transmission loss. Insertion loss and noise reduction are both based on actual sound-pressure measurements and are expressed in terms of dB reduction.
Insertion loss (IL) is the difference in sound pressure measured in a single location with and without a noise-control device located between the source and receiver. Using the air- handler example, assume there is a door installed in the wall separating the equipment room from the office space. The difference in the sound pressure measured in the occupied space with the door open versus with the door closed is the IL of the door.

Noise reduction (NR) is the difference between sound-pressure measurements taken on each side of a barrier. For example, the NR for this same door can be determined by measuring the sound-pressure level inside the office space, with the door closed, and on the other side of the door inside the equipment room. The difference in these measurements is the NR of the door.

Transmission loss (TL) is proportional to the ratio of the sound-power level on the receiver side of a barrier to the sound-power level on the source side. Using the same door example, the transmission loss of the door is determined by the manufacturer by taking measurements in a special laboratory and expressing the results as sound power. It is also expressed in terms of dB reduction.

Receiver sound correction, also called room effect, is the relationship between the sound energy (sound power) entering the room and the sound pressure at a given point in the room where the receiver hears the sound. This reduction in sound is due to a combination of effects, including distance and the absorptive and reflective properties of the surrounding surfaces. In an outdoor environment, such as a field or parking lot, the absorption of sound is nearly perfect. Sound leaves the source in all directions and diminishes as it travels away from the source. Only the portion of the sound that travels in a direct line from the source ever reaches the receiver. In this environment, the receiver sound correction is mainly a function of distance between the source and receiver. In contrast, sound entering a room bounces off walls and other surfaces. Therefore, the receiver will hear sound reflecting off the surfaces, as well as the sound coming directly from the source. The amount of sound that reaches the receiver is dependent on the size of the room and the absorptive and reflectivity of the surfaces in the room. For example, in a completely “hard” room (with concrete walls and floors and no furnishings) the room effect is very small. Conversely, in a “soft “room (with carpeted floors and wall coverings) the room effect can be quite substantial. Receiver sound correction will nearly always result in a reduction in sound level in each octave band. Sound spreading refers to the reduction of sound energy as a listener moves away from the sound source. It is a factor in room acoustics and, typically, is the primary factor in outdoor sound calculations.

CHAPTER 4

1. SOLUTIONS TO THE PROBLEMS

Sound travels from one area to another through:

- Closed doors and windows
- Walls
- Ceiling and floor
- Heating, ventilation and air-conditioning (HVAC) system ducts and vents
- Cracks and openings

Door and Window Checkpoints

Check the basic structure for problems — Are your doors too thin? Are they hollow? Do your doors have louver panels? Are windows constructed with a single pane of glass? How thick is the glass?

- Check tightness — Are door and window jambs without seals or gaskets, or are the gaskets worn out, torn away or out of alignment? Check seals by closing the door or window on a piece of paper. If the paper is easily pulled through the jamb, and you feel little or no resistance, your seals are not as good as they should be. Anywhere you can feel air movement or see light shine through is also a trouble spot.
- Check the sweep-seal at bottom of door — does the door bottom seal tightly over threshold? Again, the paper test works well.
- Look in your building's design and construction documents to see if you can find any acoustic specifications for the doors and windows. Be sure they were followed.

To provide effective sound isolation, doors need to be solidly built with sufficient mass. Most doors are 13/4" thick and not built for adequate sound isolation. They also must seal tightly around the jamb and over the threshold to contain sound. Windows can provide effective sound isolation if they are constructed with two isolating panes. It is best if each pane is a different thickness over 1/4" so they do not resonate at the same frequency. Also, separating the panes with an absorptive air space of at least 2" greatly improves the sound isolation. Windows that open should also seal tightly with gaskets.

Door and Window Solutions

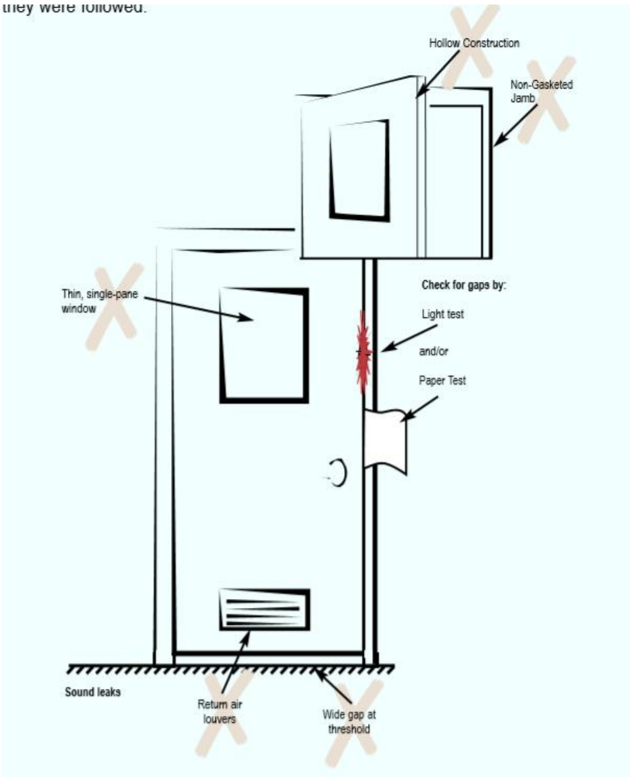


Figure 15: Door Problem (Ref No. 4).

If your doors or windows are not sound-rated, replace them with sound-rated products (STC 43 minimum, see glossary). See that they are installed and sealed properly.

- For poorly constructed doors, it is possible to increase the sound isolation ability by adding mass with materials like 3/4" plywood or sheet metal applied to both sides. Evaluate how this may interfere with the leverset, hinges and jamb. For this solution we recommend working with a carpenter. Also, evaluate the costs of this compared to installing a new door.
- To eliminate sound leaking through a single pane of glass, consider adding a second pane of laminated glass. Use glass that is at least 1/4" thick and separate the two panes as far apart as possible. Make sure your alterations do not compromise fire codes and again compare the costs to installing new window units.
- If your doors and windows do not have seals, or they are torn or missing, add new seals. Magnetic seals work the best but, if they are not an option, make sure to choose a dense, flexible material like neoprene. When the door or window is shut, the seals should be in line with, and compress against, a flat clean surface. The goal should be an air tight connection.
- Many doors will have a drop-down sweep seal that seals against the threshold when the door is shut. Often these are simply out of alignment and can be adjusted with a screwdriver. If there is no sweep seal, have one installed. Typically they consist of a sweep-seal closure and threshold plate. They will require frequent checking to ensure proper alignment.
- For window panes that are loose in their mountings, re-glaze the openings or seal panes to be airtight.
- Evaluate the need for each door and especially windows. In some cases, you may be able to do without them. If you can wall them in, be sure to check building and fire codes for compliance.
- You can increase the sound isolation of your doorways by adding a second door in front of your original door — similar to the double doors common between adjoining hotel rooms. This is easiest if your door is recessed or in a slight alcove. Again the input of an acoustic expert and carpenter are necessary.
- Louvers in a door can simply be taken out and the remaining hole insulated and surfaced with solid boards. Make sure to check with a mechanical engineer or your building maintenance supervisor to be sure return air circulation will not be interrupted.

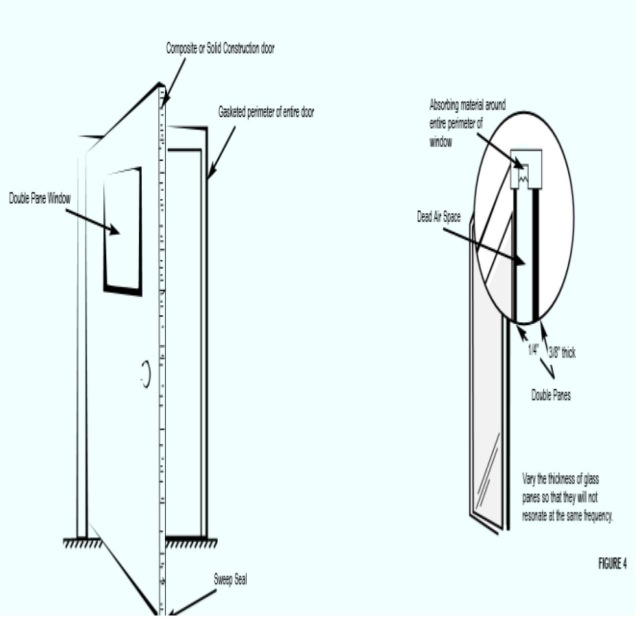


Figure 16: Door Solution (Ref No. 4).

1.1 Wall Solutions

While walls are impenetrable visual barriers, they are often poor sound barriers. And keep in mind it doesn’t take much to compromise the isolation effectiveness of a wall. In fact if you had a solid 4' x 8' wall and put a tiny hole in it the size of a quarter, you would reduce the effectiveness of the wall by 80%. Identifying the trouble spots will require some thorough checking. The walls you probably want to focus on are interior walls, especially those that are shared with adjoining classrooms or office spaces. To provide adequate sound isolation, walls need to have a great deal of mass, seal at the floor and ceiling deck, and contain a space of dead air and insulation.

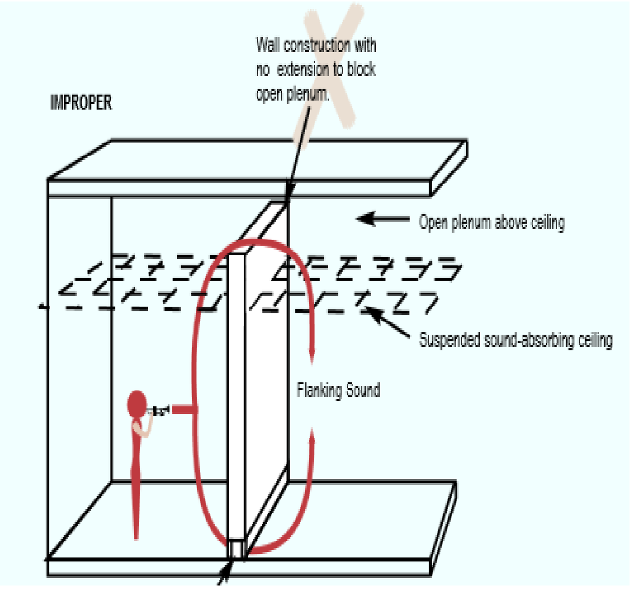


Figure 17: Wall Problem (Ref No. 4).

If you have a wall that is just too thin, look into adding another wall in front of it or even tearing it out and building a correct, sound isolating wall (figure 8). If you go to this extreme you will also be able to address other issues like adding insulated, off-set electric boxes and cable runs. We recommend that you consult with an acoustician to create the proper specifications for reconstructed walls.

- Sealing your walls at the ceiling, floor and around window and door frames is very important and often overlooked during construction. These gaps can be as large as few inches or just a fraction of an inch and are often hidden under trim strips. For large gaps, use a material that will be dense and solid — like gypsum board as opposed to just stuffing the space with fiberglass. For small gaps the only solution may be a silicone caulking.
- Correcting improper wall construction (figure 5) is absolutely critical for adequate sound isolation. It will require a skilled carpenter to extend the wall to the ceiling deck and seal it correctly. Another option you can look into is a loaded vinyl sheet plenum barrier. Make sure any work is in keeping with current fire and building codes.
- Back-to-back electrical boxes and cable runs that leak sound can be fixed by horizontally offsetting the boxes and adding fibrous insulation. Again, hire a professional to do the work. We recommend offsetting the boxes by a minimum of two feet to assure that at least one stud separates the boxes.

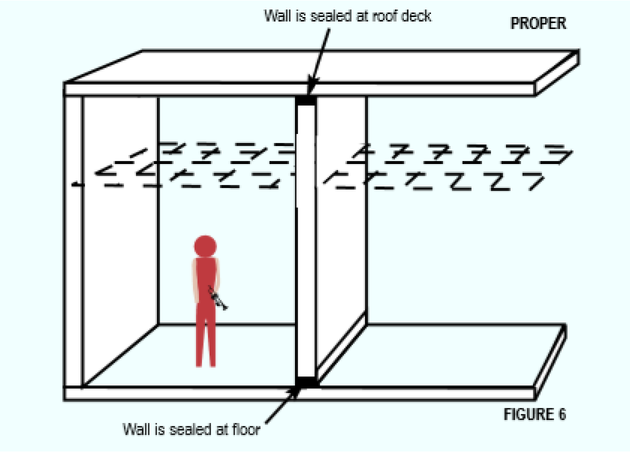


Figure 18: Wall Solution (Ref No. 4).

2. CEILINGS AND FLOORS

Like a wall, the ceiling and floor must have sufficient mass to isolate sound. Ceilings that are roof decks are often too thin or constructed with corrugated steel. And if the ceiling in your room is the floor for a room above, you may hear significant sound transfer. Holes cut into floors and ceilings for ductwork, electrical and plumbing can also cause problems unless correctly detailed.

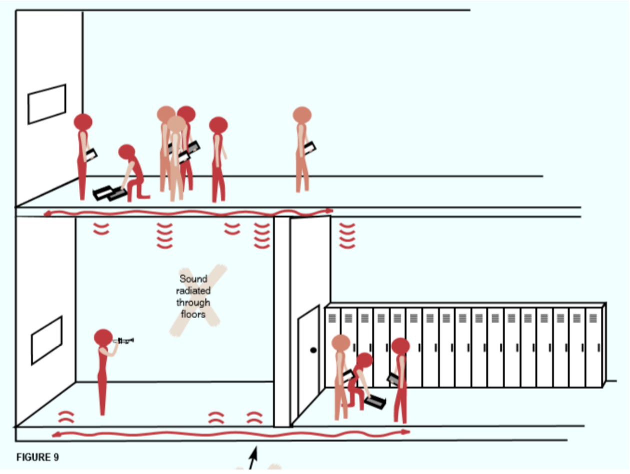


Figure 19: Ceiling and Floor Problem (Ref No. 4).

2.1 Ceiling and Floor Solutions

- If you suspect your ceiling does not have enough mass and you are hearing noise like airplanes or rain, add a suspended sound-isolating ceiling supported by acoustical hangers (figure 10) to increase the overhead sound isolation. Bring in an acoustician to evaluate your situation.
- Metal roofs are often corrugated and not sealed to the walls (figure 11). Trusses are another typical trouble spot for isolation. Make sure common openings between rooms are sealed.
- If you are experiencing sound transmission coming into your room from the floor, you may need to consider installing a floated floor (figure

10). Again, this is an expensive and complex solution that will require the input of an acoustician or architect.

- To seal holes around pipes, conduit, vents, etc., patch opening with gypsum board or other heavy material and caulk perimeter joint at penetration with an acoustical sealant.

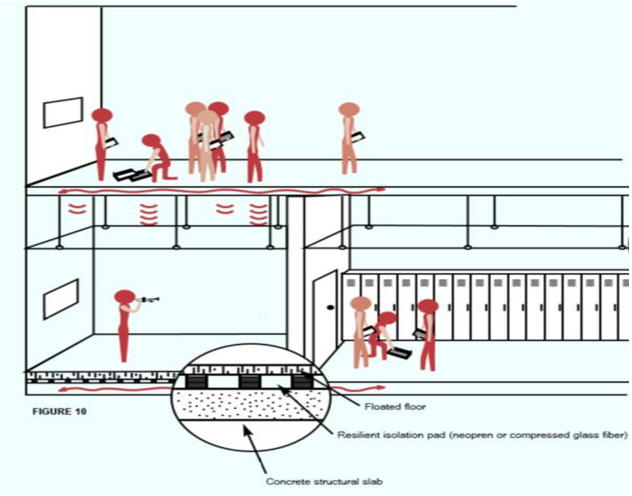


Figure 20: Ceiling and Floor Solution (Ref No. 4).

1. MATERIALS TO AVOID

Don't use thin drapes, foam, carpet or thin panels to absorb sound. These materials just do not have the physical properties necessary for broad-range musical sound absorption. In fact, when used they are almost guaranteed to create more problems than they solve. Remember, solutions that work in lecture-based class rooms may not work in music areas.

1.1 Loud Room Solutions

A loud room is one of the most common complaints in rehearsal areas. Usually this is a result of small rooms that do not provide adequate cubic volume. Hard, reflective surfaces in your room may also contribute to excessive loudness Find a way to increase the cubic volume of your space. This can be done in a number of ways such as removing a portion of your suspended ceiling. If you have closed risers, see if they can be removed and rehearse on a flat floor or on portable open riser units that connect the cubic volume underneath to room. Remove a wall and expand your room (figure 14). No matter how you increase cubic volume, we first recommend the consultation of an acoustician. For any structural modifications, work with your architect.

- If your space is too small and can't be made larger, you will be limited in what can be done to reduce loudness. Look into other larger areas in the facility where you might be able to relocate rehearsals.
- Remove whatever you can to make more room for sound. Relocate cabinets, desks, marching band equipment, etc.
- If your room is surrounded by individual practice rooms, open their doors when they are not being used to increase the acoustic volume of your rehearsal room.
- Sound absorption panels, when properly applied, are another way to quiet a room. To be effective across a broad frequency range they should be at least 3" thick (figure 16). Absorptive panels are also used to treat a number of other acoustic problems and must always be used in conjunction with diffusive surfaces. Consult an acoustician or a company experienced in acoustical panel solutions.
- Heavy curtains can also provide acoustic absorption when properly applied. Use 18 oz. velour curtains hung at 100% fullness, about 12" in front of a reflecting wall. This trapped air space is critical to enhancing the low-frequency absorption effect of the curtain (figure 15).
- As a last resort, you can consider reducing sound energy by splitting rehearsal times and reducing your group sizes.

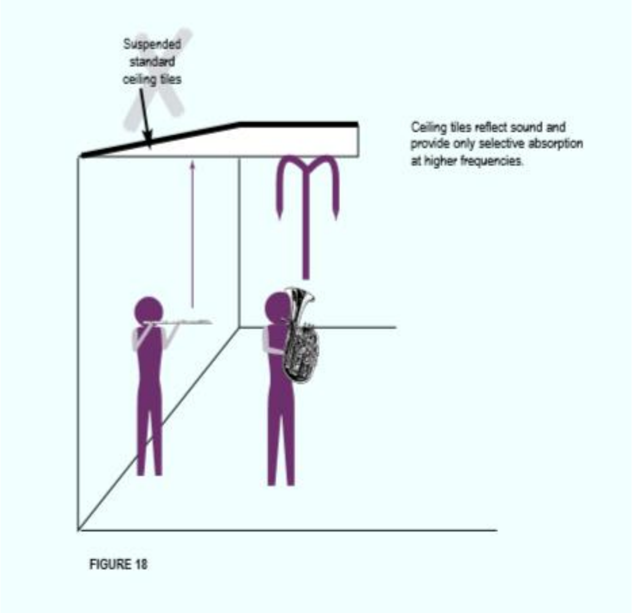


Figure 21: Bass-Heavy Room Solutions (Ref No. 4).

1.2 Boomy, Bass-Heavy Room Solutions

- Remove thin curtains and carpet (especially on walls) and replace with materials that will provide effective absorption across a broad frequency range.
- Apply absorption panels at least 3" thick. The thicker the absorber, the more the loudness of bass frequencies is reduced. These solutions may require the involvement of acoustic professionals.
- Replace reflective ceiling tiles with 1" thick acoustically absorptive (rated at NRC 0.95 or higher) fiberglass panels (figure 19). Remember the more space above these panels, the better the low frequency absorption.

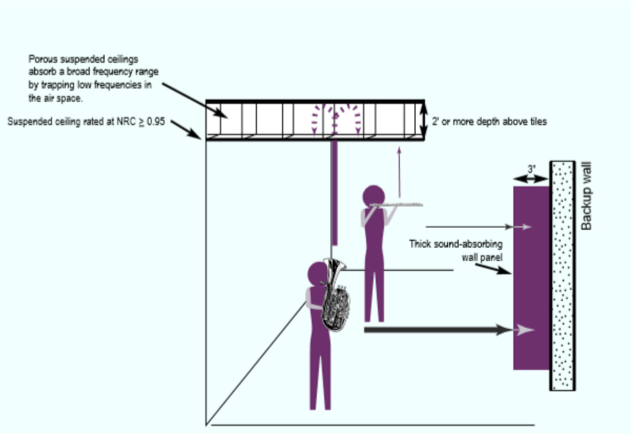


Figure 22: Echoes and Standing waves solution (Ref No. 4).

1.3 Echoes and Standing Waves Solutions

- The primary goal is to minimize parallel, reflective paths between the surfaces in your room. This is best accomplished with a combination of diffusive and absorptive treatments. These are easily applied to walls and ceilings. Again, we recommend the consultation of professionals experienced in rehearsal room acoustics and treatment solutions.
- To treat large glass surfaces, add heavy, velour drapes over sections of the windows.
- Walls may be splayed or angled but to be effective this must be done on two planes.

2. MECHANICAL NOISE SOLUTIONS

- Remember, office rooms need nearly twice the rate of fresh-air exchange as a classroom of equal size due to the physical activity of making music. As a result, vent openings need to be large with open grillwork (figure 28). Work with your building engineers to solve the problem of small vents and heavily screened grills.
- If the HVAC system mechanical rooms are too close to your room the best solution is to relocate them. If this is not a possibility, contact an acoustic professional and determine what type of sound isolators could be installed to resolve the problem. Often, springs and neoprene isolators can "decouple" the equipment from the surrounding structure (figure 26).
- Ductwork that is channeling sound can be quieted with sound absorptive linings or baffles (called “sound attenuators’”). Again the help of an acoustical professional and your building engineer will be necessary.
- Squeaks and rattles are usually an indication that HVAC systems need some maintenance. Ask your building engineer if lubrication, new bearings and belts or any other procedure might quiet the system.
- Quieting noisy light transformers and ballasts is easy and saves energy. Electronic ballasts with an "A" sound rating are quiet and consume less energy. Work with your building engineer to get your lighting systems updated.

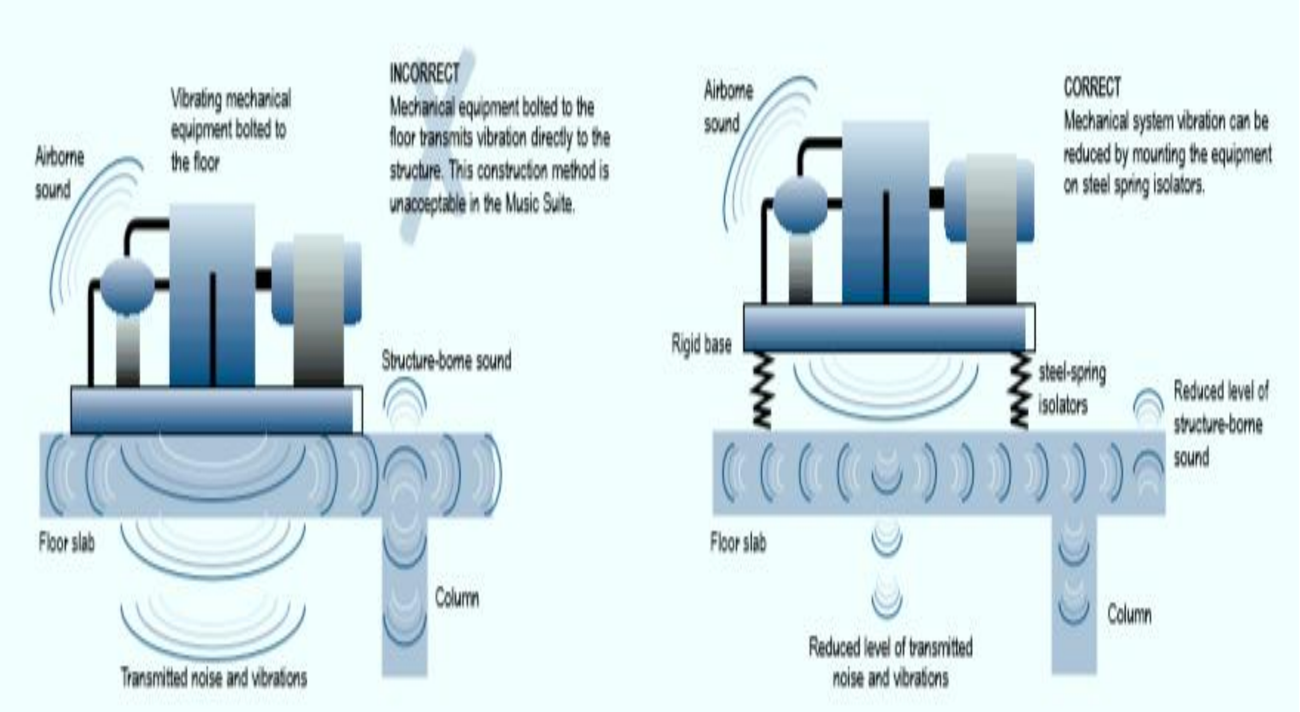
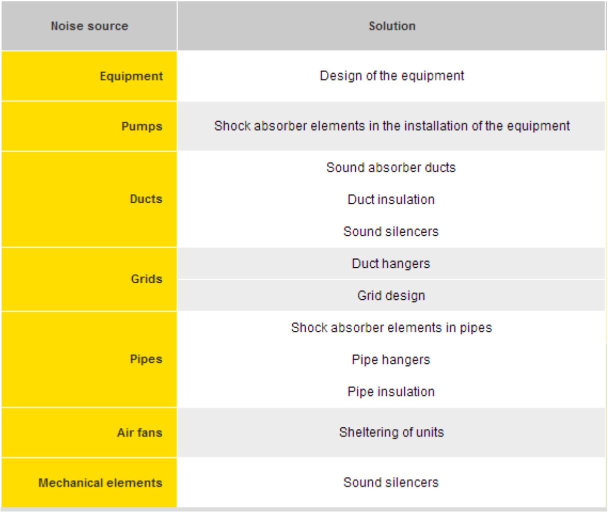


Figure 23: Mechanical Noise Solutions (Ref No. 4).

Solutions Related to Equipments of Hvac



Noise source	Solution
Equipment	Design of the equipment
Pumps	Shock absorber elements in the installation of the equipment
Ducts	Sound absorber ducts Duct insulation Sound silencers
Grids	Duct hangers
	Grid design
Pipes	Shock absorber elements in pipes Pipe hangers Pipe insulation
Air fans	Sheltering of units
Mechanical elements	Sound silencers

Table 7: Sound Related to Equipments of HVAC (Ref No. 4).

CONCLUSION

- Acoustics can be a complex issue, but HVAC acoustics can be successfully evaluated for many typical applications. From the report we understand how sound behaves in different conditions and environment.
- Also a study of different rating methods has been established, which can be used in many applications. For many complex applications, we can combine the different rating methods to get the proper acoustical environments.
- We also have learnt different methods to improve acoustics in rooms of new buildings and also to improve the performance of existing buildings.

REFERENCES

[1] ASHRAE, 1999. Applications Handbook. American Society of Heating, Refrigerating and Air- conditioning Engineers.

[2] ASHRAE, 2013, Journal.

[3] HVAC acoustics guide, mcquay International.

[4] Acoustic problems & solutions, wenger limited.

[5] Fundaments of Sound Energy.