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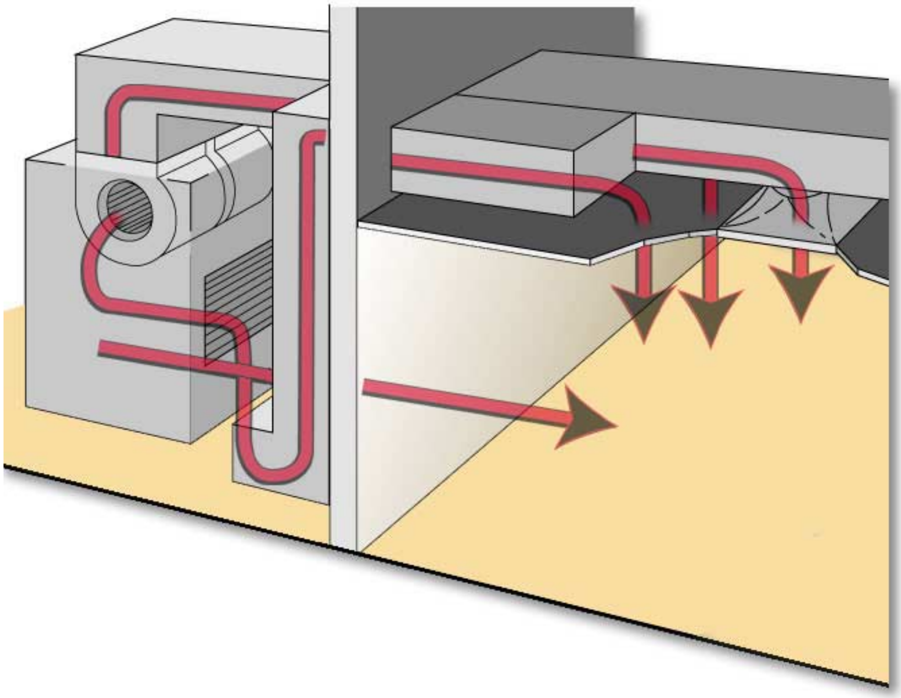
Fundamentals of HVAC Acoustics

One of the Fundamental Series



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Level of detail (circle one) Too basic Just right Too difficult

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Fundamentals of HVAC Acoustics

One of the Fundamental Series

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Preface

Fundamentals of HVAC Acoustics

A Trane Air Conditioning Clinic

Figure 1

Trane believes that it is incumbent on manufacturers to serve the industry by regularly disseminating information gathered through laboratory research, testing programs, and field experience.

The Trane Air Conditioning Clinic series is one means of knowledge sharing. It is intended to acquaint a nontechnical audience with various fundamental aspects of heating, ventilating, and air conditioning (HVAC). We have taken special care to make the clinic as uncommercial and straightforward as possible. Illustrations of Trane products only appear in cases where they help convey the message contained in the accompanying text.

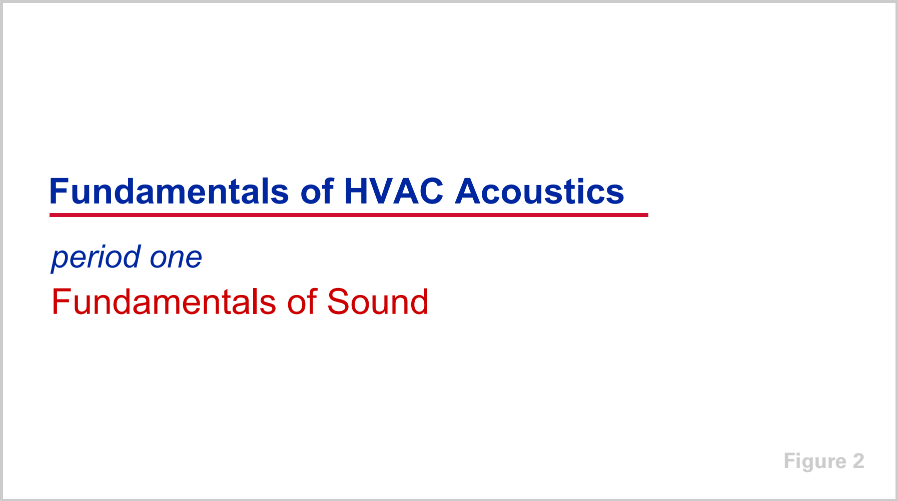
This particular clinic introduces the reader to the **fundamentals of HVAC acoustics**.

Contents

period one

Fundamentals of Sound

notes



Fundamentals of HVAC Acoustics

period one

Fundamentals of Sound

Figure 2

People have become increasingly conscious of acoustics as a component of a comfortable environment. Sound levels, both indoor and outdoor, can be affected to varying degrees by HVAC equipment and systems.

The degree to which the HVAC system affects the sound at a particular location depends on the strength of the sound source and the environmental effects on the sound as it travels from that source to the listener.

period one

Fundamentals of Sound

What is Sound?

- Audible emissions resulting from vibration of molecules within an elastic medium
- Generated by vibrating surface or movement of a fluid
- In buildings, it may be airborne or structure-borne
- Noise is unwanted sound

Figure 3

What is Sound?

Sound is the audible emissions resulting from the vibration of molecules within an elastic medium. It is generated by either a vibrating surface or the movement of a fluid. In the context of building HVAC systems, this elastic medium can be either air or the building structure. For structurally-borne sound to become audible, however, it must first become airborne.

Noise is different than sound. Sound is always present, but is not always obtrusive. **Noise** is defined as unwanted sound. Generally, people object to sound when it interferes with speech, concentration, or sleep.

period one

Fundamentals of Sound

notes

Sound Wave and Frequency

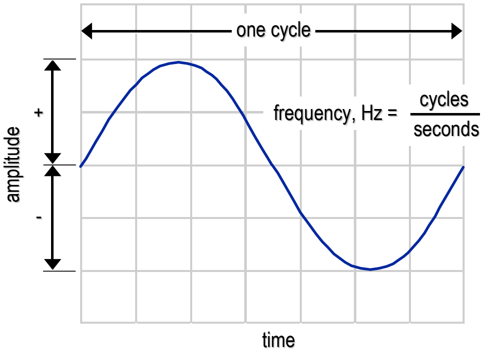


Figure 4

Airborne sound is transmitted away from a vibrating body through the transfer of energy from one air molecule to the next. The vibrating body alternately compresses and rarefies (expands) the air molecules. The pressure fluctuations that result from the displacement of these air molecules take the form of a harmonic, or sine, wave. The amplitude of the wave depicts pressure. The higher the amplitude, the louder the sound.

This transfer of energy takes time. Each complete sequence of motion (compression and rarefaction) constitutes a cycle, and the time required to complete one cycle is the cycle period. The **frequency** of the periodic motion is the number of cycles that occur in a second. The unit of measure for frequency is the hertz (Hz). One hertz is equal to one cycle per second.

$$\text{frequency, Hz} = \frac{\text{cycles}}{\text{seconds}}$$

The terms pitch and frequency are often (incorrectly) used interchangeably. Frequency is an objective quantity that is independent of sound-pressure level. **Pitch,** however, is a subjective quantity that is primarily based on frequency, but is also dependent on sound-pressure level and composition. Pitch is not measured, but is described with terms like bass, tenor, and soprano.

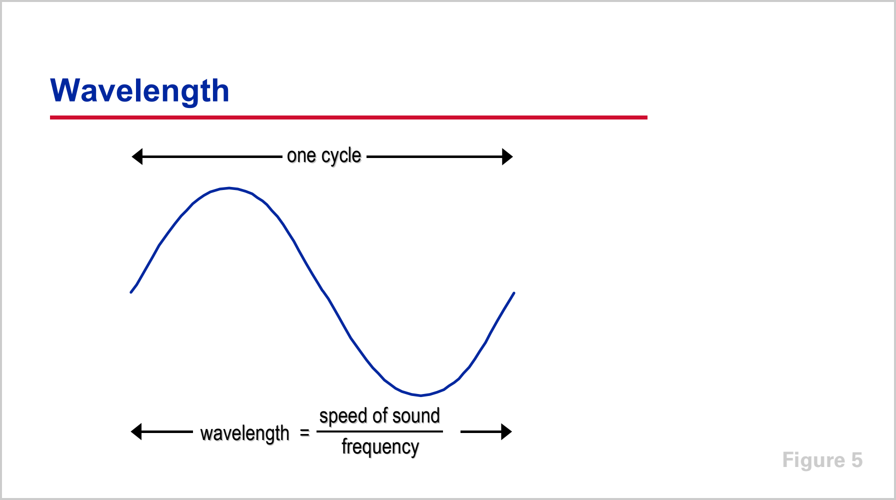


Figure 5

The **wavelength** of the sound is the linear measurement of one complete cycle. The wavelength and frequency of a sound are related by using the following equation:

$$\text{wavelength} = \frac{\text{speed of sound}}{\text{frequency}}$$

The speed of sound transmission is a physical property of the medium. For air, the speed varies slightly with temperature change. Because the temperature range encountered in the study of HVAC acoustics is relatively small, the speed of sound can be considered a constant 1,127 ft/s (344 m/s). For example, sound traveling through the air at a frequency of 200 Hz has a wavelength of 5.6 ft (1.7 m).

$$\text{wavelength} = \frac{1{,}127\ \text{ft/s}}{200\ \text{Hz}} = 5.6\ \text{ft}$$

$$\left(\text{wavelength} = \frac{344\ \text{m/s}}{200\ \text{Hz}} = 1.7\ \text{m}\right)$$

notes

Broadband Sound

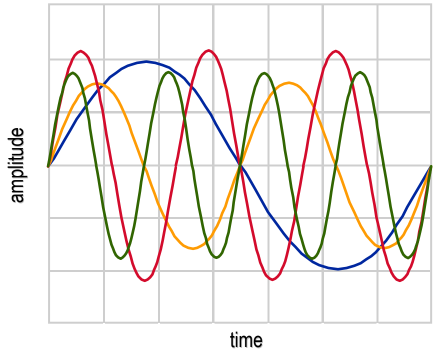


Figure 6

The wave form shown in Figure 5 represents sound occurring at a single frequency. This is called a **pure tone**.

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 6 represents the components of broadband sound.

Broadband Sound and Tones

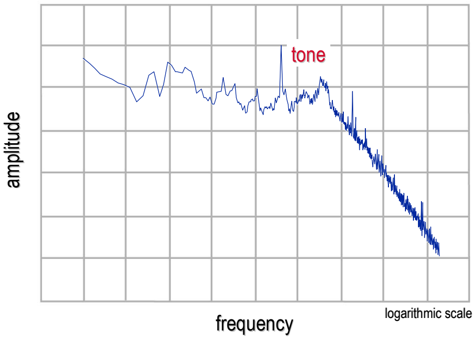
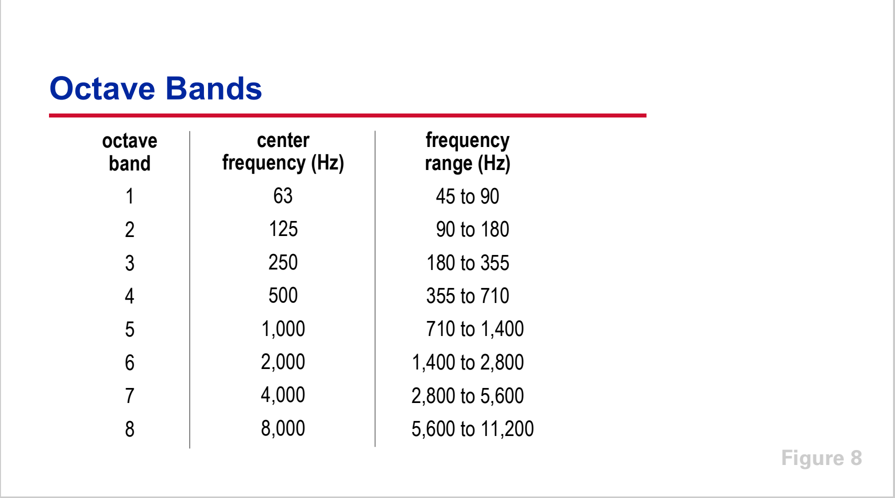


Figure 7

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, it would 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.



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

Figure 8

Octave Bands

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.

$$\text{center frequency} = \sqrt{\text{lowest frequency} \times \text{highest frequency}}$$

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.

notes

Octave Bands

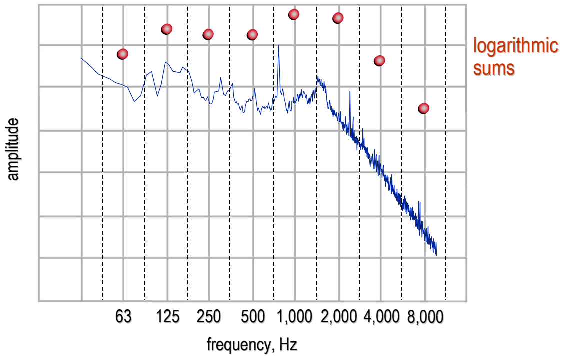


Figure 9

Octave bands compress the range of frequencies between the upper and 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.

notes

One-Third Octave Bands

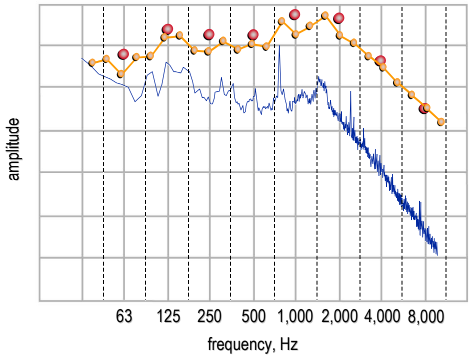
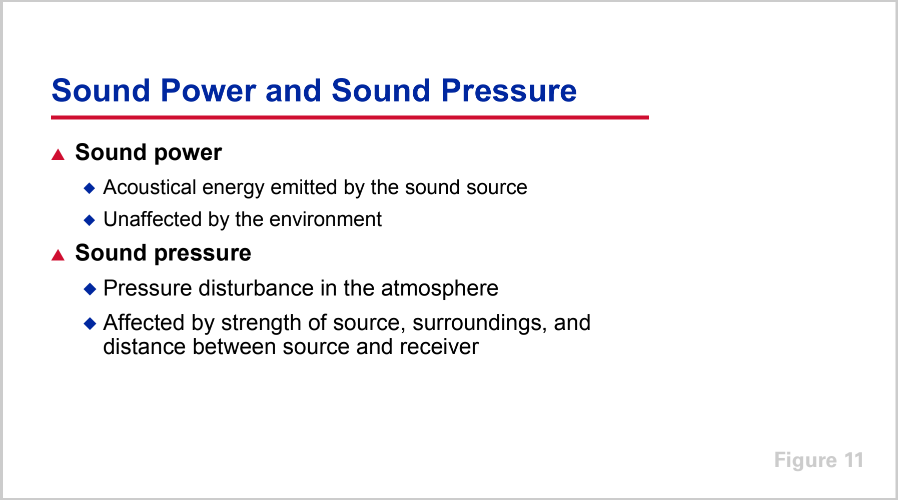


Figure 10

Middle ground between octave-band analysis and full-spectrum analysis is provided by one-third octave-band analysis. **One-third octave bands** divide the full octaves into thirds. The upper cutoff frequency of each third octave is greater than the lower cutoff frequency by a factor of the cube root of two (approximately 1.2599). If tones are contained in the broadband sound, they will be more readily apparent in the third octaves.

The use of octave bands is usually sufficient for rating the acoustical environment in a given space. One-third octave bands are, however, more useful for product development and troubleshooting acoustical problems.



Sound Power and Sound Pressure

- **Sound power**
  - Acoustical energy emitted by the sound source
  - Unaffected by the environment
- **Sound pressure**
  - Pressure disturbance in the atmosphere
  - Affected by strength of source, surroundings, and distance between source and receiver

Figure 11

Sound Power and Sound Pressure

Sound power and sound pressure are two distinct and commonly confused characteristics of sound. Both are generally described using the term decibel (dB), and the term "sound level" is commonly substituted for each. To understand how to measure and specify sound, however, one must first understand the difference between these two properties.

Sound power is the acoustical energy emitted by the sound source, and is expressed in terms of watts (W). It is *not* affected by the environment.

Sound pressure is a pressure disturbance in the atmosphere, expressed in terms of pascals (Pa), that can be measured directly. Sound pressure magnitude is influenced not only by the strength of the source, but also by the surroundings and the distance from the source to the listener. Sound pressure is what our ears hear and what sound meters measure.

While sound-producing pressure variations within the atmosphere can be measured directly, sound power cannot. It must be calculated from sound pressure, knowing both the character of the source and the modifying influences of the environment.

An Analogy

- **Sound power**
  - Correlates to bulb wattage
- **Sound pressure**
  - Correlates to brightness

Figure 12

The following comparison of sound and light may help illustrate the distinction between these two properties. Think of sound power as the wattage rating of a light bulb. Both measure a fixed amount of energy. Whether you put a 100-watt light bulb outdoors or in a closet, it is always 100-watt light bulb and always gives off the same amount of light.

Sound pressure corresponds to the brightness, from the light emitted by the light bulb, in a particular location in the room. Both sound pressure and brightness can be measured with a meter, and the immediate surroundings influence the magnitude of each. In the case of light, brightness depends on more than the wattage of the bulb. It also depends on how far the observer is from the light bulb, the color of the room, how reflective the wall surfaces are, and whether the light bulb is covered with a shade. These other factors affect how much light reaches the receiver, but do not affect the wattage of the light bulb.

Similarly, sound pressure depends not only on the sound power emitted by the source, but also on the characteristics of the surrounding environment. These might include the distance between the sound source and the listener, whether the room is carpeted or tiled, and whether the room is furnished or bare. Just as with light, environmental factors like these affect how much sound reaches the listener.

Decibel

$$\text{dB} = 10\log_{10}\left[\frac{\text{measured value}}{\text{reference value}}\right]$$

Figure 13

Sounds encompass a wide range of volumes, or levels. The loudest sound the human ear can hear without damage due to prolonged exposure is about 1,000,000,000 times greater than the quietest perceptible sound. A range of this magnitude makes using an arithmetic scale cumbersome, so a logarithmic scale is used instead.

The measurement of sound level is expressed in terms of **decibels (dB)**, a dimensionless quantity. A decibel is a calculated value based on the ratio of two quantities. It is defined as ten times the logarithm to the base ten ($\log_{10}$) of the measured quantity divided by the reference quantity. The reference quantity must be specified to prevent confusion regarding the magnitude of the ratio.

$$\text{dB} = 10\log_{10}\left[\frac{\text{measured value}}{\text{reference value}}\right]$$

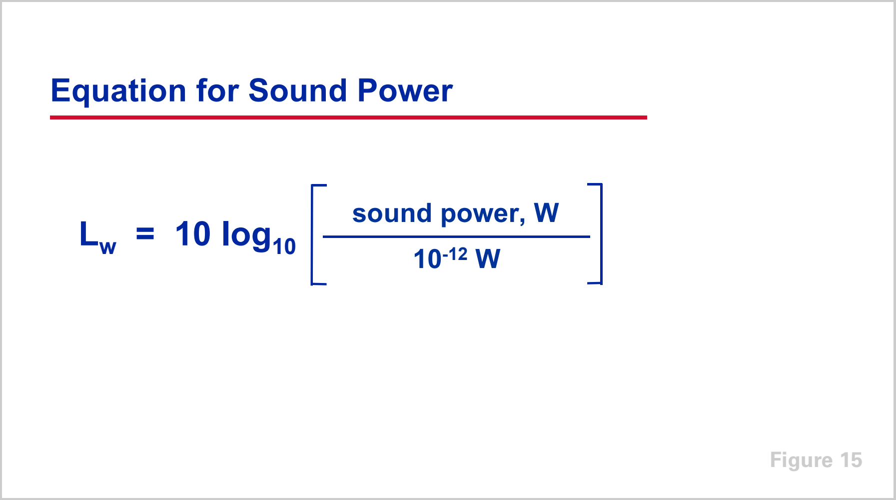
Logarithmic Scale

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

Figure 14

A logarithm is the exponent power of the base. In this case, the base is ten. For example, the $\log_{10}$ of 10 (or 10^1) equals 1, the $\log_{10}$ of 100 (or 10^2) equals 2, and the $\log_{10}$ of 1,000,000,000 (or 10^9) equals 9.

As mentioned earlier, the loudest sound the human ear can hear without damage due to prolonged exposure is about 1,000,000,000 times greater than the quietest perceptible sound. If we use the quietest perceptible sound as the reference value, this ratio would range from 1 to 1,000,000,000. Converting this arithmetic range to a $\log_{10}$ scale yields a range of 0 to 9. This unitless result is described in terms of bels. Multiplying by ten results in the more-commonly used broader range of 0 to 90 decibels (dB).



Equation for Sound Power

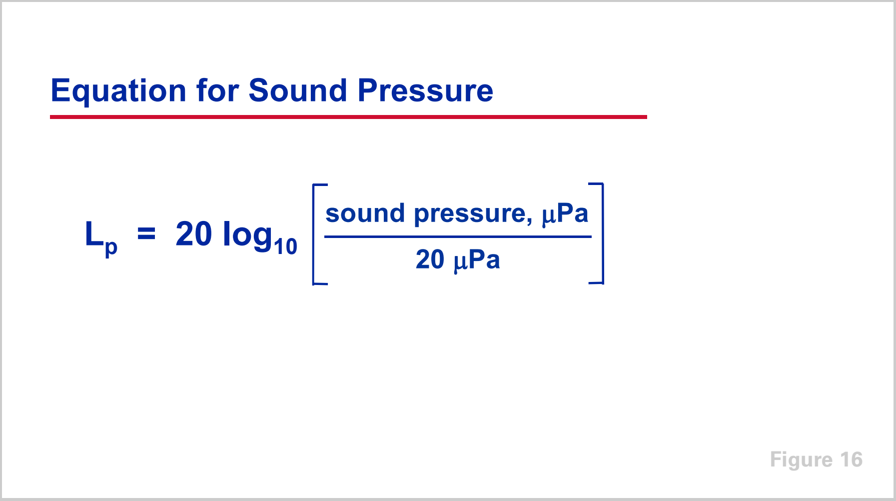
$$L_w = 10 \log_{10} \left[\frac{\text{sound power, W}}{10^{-12}\ \text{W}} \right]$$

Figure 15

When a reference value is established and placed in the denominator of the ratio, the dB can be calculated for any value entered into the numerator.

The reference value used for calculating sound-power level is 1 picowatt (pW), or 10^{-12} watts. Therefore, sound-power level (L_w) in dB is calculated using the following equation:

$$L_W = 10 \log_{10} \left[\frac{\text{sound power, watts}}{10^{-12}\ \text{watts}} \right]$$



Equation for Sound Pressure

$$L_p = 20 \log_{10} \left[\frac{\text{sound pressure, } \mu\text{Pa}}{20\ \mu\text{Pa}} \right]$$

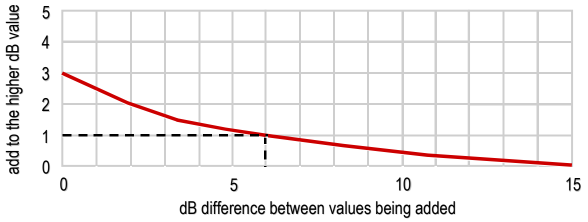
Figure 16

The reference value used for calculating sound-pressure level is 20 micropascals (μPa), or 2 ×10^{-5} Pa. Therefore, sound-pressure level (L_p) in dB, is calculated using the following equation:

$$L_p = 20\log_{10}\left[\frac{\text{sound pressure, μPa}}{20\text{ Pa}}\right] \text{ or } 10\log_{10}\left[\frac{\text{sound pressure, μPa}}{20\text{ Pa}}\right]^2$$

Again, these reference values can be considered the threshold of hearing. The multiplier 20 is used in the sound-pressure level equation instead of 10 because sound power is proportional to the square of sound pressure.

Logarithmic Addition of Decibels



50 dB + 44 dB = 51 dB

Figure 17

Measuring sound using a logarithmic scale means that decibel values cannot be added arithmetically. Instead, logarithmic addition must be used to add two or more sound levels. This involves converting the decibel values into ratios of sound intensity, adding these ratios, and then converting the sum back into decibels. The mathematics become rather involved—the graph in Figure 17 has been developed to simplify the procedure.

To demonstrate the use of this figure, consider the example of adding a 50 dB sound to a 44 dB sound. The difference between these two sounds is 6 dB. Therefore, 1 dB is added to the higher of the two sounds (50 plus 1) to arrive at the logarithmic sum of 51 dB.

Also, notice that the logarithmic sum of two sounds of equal magnitude (0 dB difference) results in a 3 dB increase. Therefore, adding two 50 dB sounds would result in a combined sound level of 53 dB.

period two

Sound Perception and Rating Methods

Fundamentals of HVAC Acoustics

period two

Sound Perception and Rating Methods

Figure 18

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.

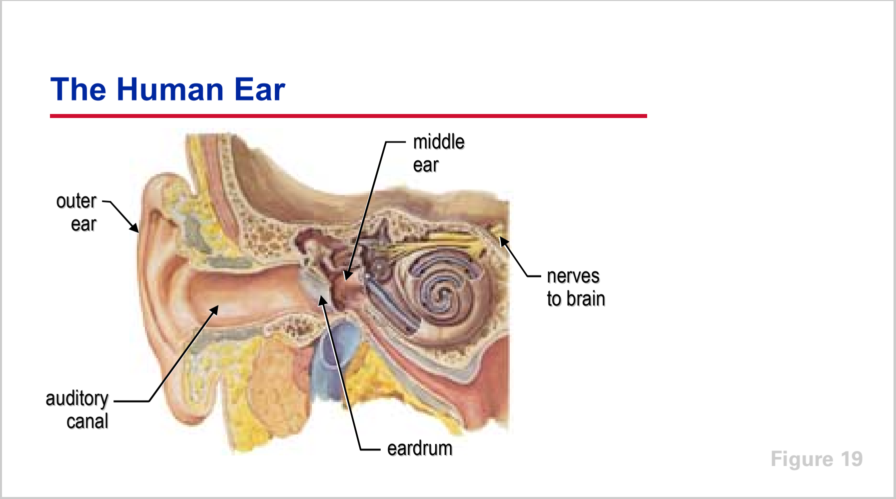


Figure 19

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.

period two

Sound Perception and Rating Methods

notes

Loudness Contours

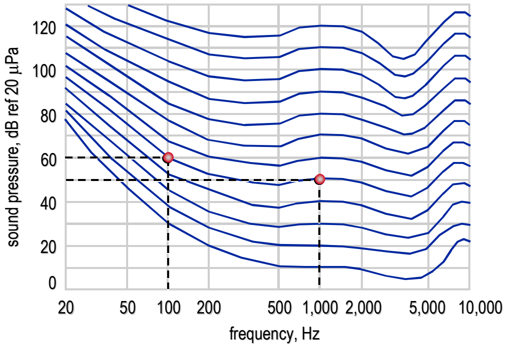


Figure 20

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.

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.

period two

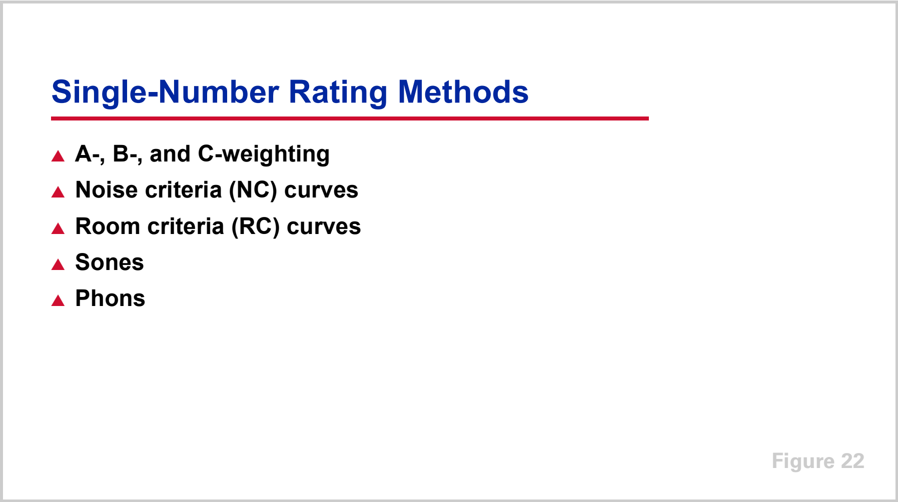
Sound Perception and Rating Methods

notes

Response to Tones

Figure 21

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.



Single-Number Rating Methods

- **A-, B-, and C-weighting**
- **Noise criteria (NC) curves**
- **Room criteria (RC) curves**
- **Sones**
- **Phons**

Figure 22

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 Weighting

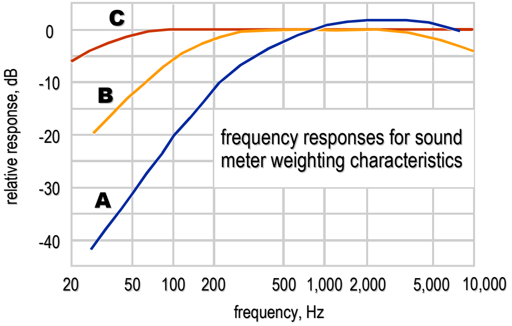
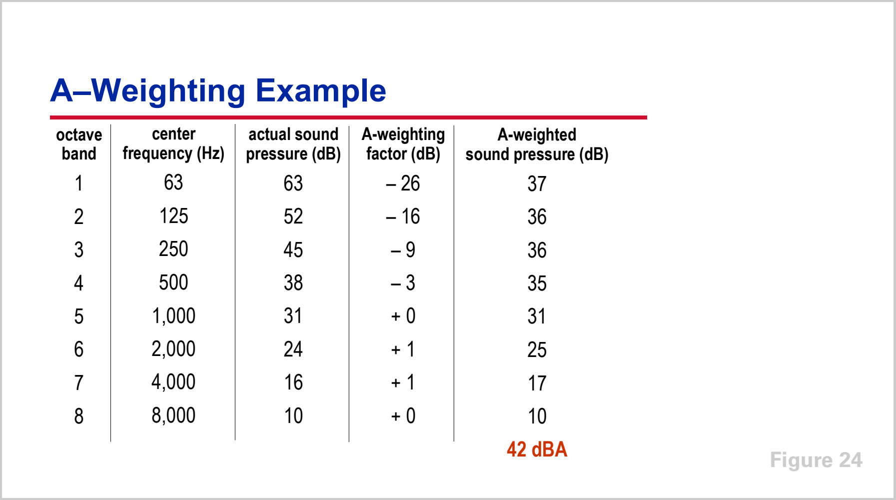


Figure 23

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

Figure 24

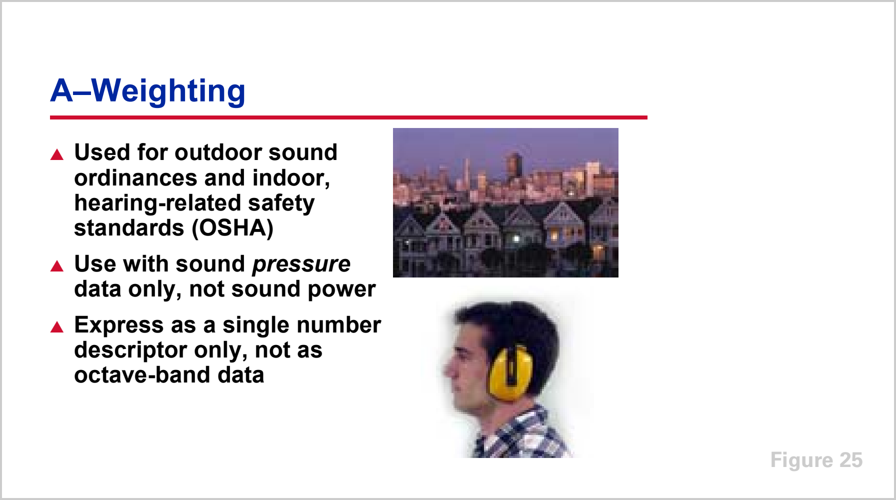
The following steps describe how to calculate an A-weighted value.

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. Subtract 26 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.



A–Weighting

- Used for outdoor sound ordinances and indoor, hearing-related safety standards (OSHA)
- Use with sound *pressure* data only, not sound power
- Express as a single number descriptor only, not as octave-band data

Figure 25

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 only to 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.

Noise Criteria (NC) Curves

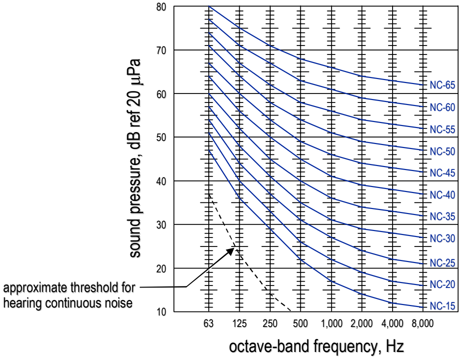


Figure 26

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 effect 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.

period two

Sound Perception and Rating Methods

notes

Noise Criteria (NC) Curves

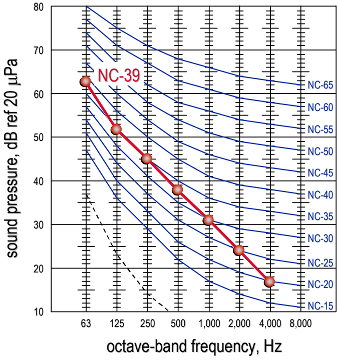


Figure 27

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 a 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.

period two

Sound Perception and Rating Methods

Room Criteria (RC) Curves

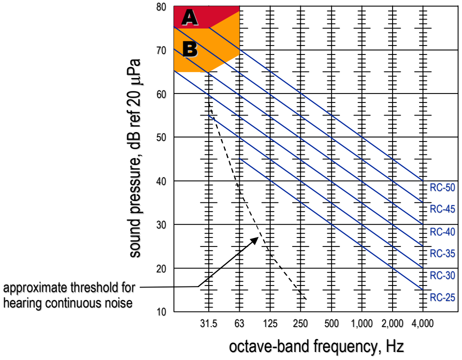


Figure 28

Room criteria (RC) curves are similar to NC curves in that they are used to provide a 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

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 Hz and 4,000 Hz. Note that these are different than the octave bands included on the NC chart.

Room Criteria (RC) Curves

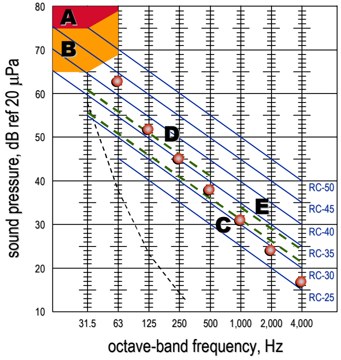


Figure 29

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 the octave bands between 16 Hz and 63 Hz 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.

Room Criteria (RC) Curves

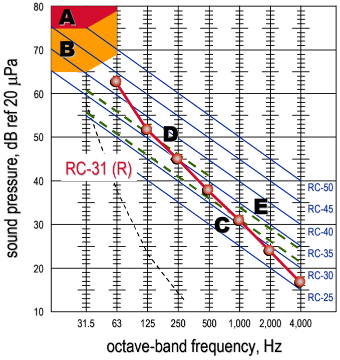


Figure 30

If we plot the acoustical data for our example office space on the RC chart, we find that it results in a rating of RC-31(R). The SIL is 31 and the sound-pressure levels in the 63 Hz and 125 Hz octave bands are above line **D**, indicating a rumble characteristic of the sound.

This time, our objective and subjective analyses lead to the same conclusion. Although the space is quiet enough, the background noise is perceived as having a rumble. A sound spectrum that falls in the RC neutral category would be judged as excellent by most observers. It is this conformity of analysis results that makes the RC rating method a better tool than the other single-number descriptors for specifying acoustical requirements indoors. Despite the advantages of the RC rating system, it is less widely used than other single-number descriptors.

Finally, accurate determination of sound-power levels for the 16 Hz and 31.5 Hz octave bands requires a very large reverberant room. Most HVAC equipment manufacturers do not provide sound data in these two octave bands due the cost of constructing such a large test room and the difficulty in qualifying it. This makes it difficult to predict sound-pressure levels in these octave bands.

notes

Phon and Sone

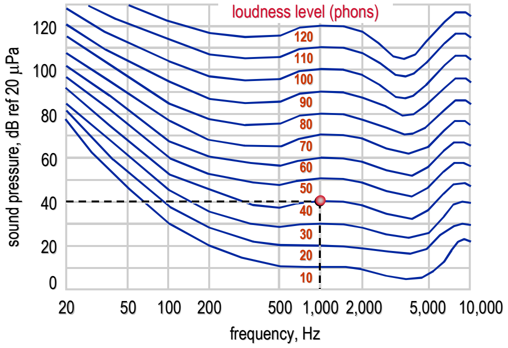
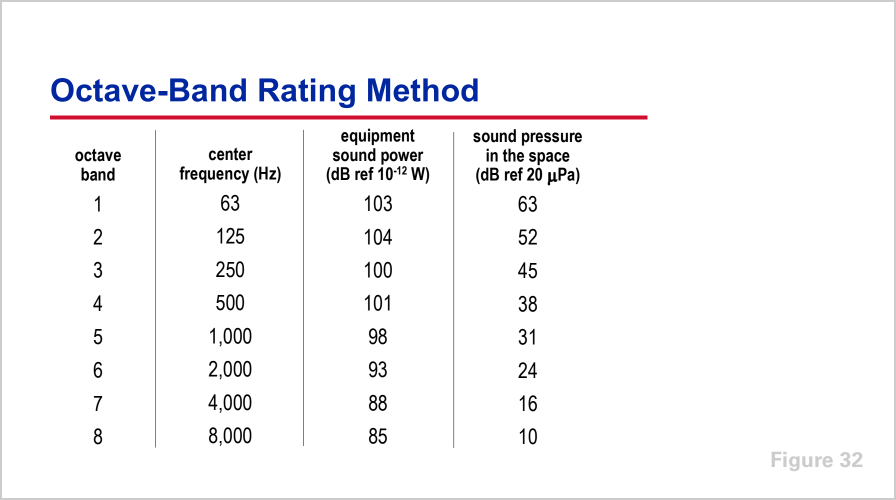


Figure 31

The **phon** is another descriptor used to indicate loudness with a single number. The loudness of a sound, expressed in phons, is equal to the sound- pressure level of a standard sound, at 1,000 Hz, that is considered equally loud. For example, a sound pressure level of 40 dB at 1,000 Hz is considered to have a loudness of 40 phons. Any sound that falls on this same loudness curve, at any frequency, would also be described as having a loudness equal to 40 phons.

While the phon scale is logarithmic, the **sone** is the linear equivalent to the phon. In principle, the sone scale is linear when compared to the response of the human ear. For example, two sones is twice as loud as one sone, and half as loud as four sones.

While the phon and sone scales are not widely used, some HVAC equipment, primarily non-ducted fans and power ventilators, is still rated in sones. AMCA Standard 301, *Methods for Calculating Fan Sound Ratings from Laboratory Test Data*, provides a method for calculating the sone rating from octave-band data. Use caution when comparing equipment based on sones. Multiple methods exist for calculating a sone rating, and they provide different results.



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

Figure 32

Octave-Band Rating Method

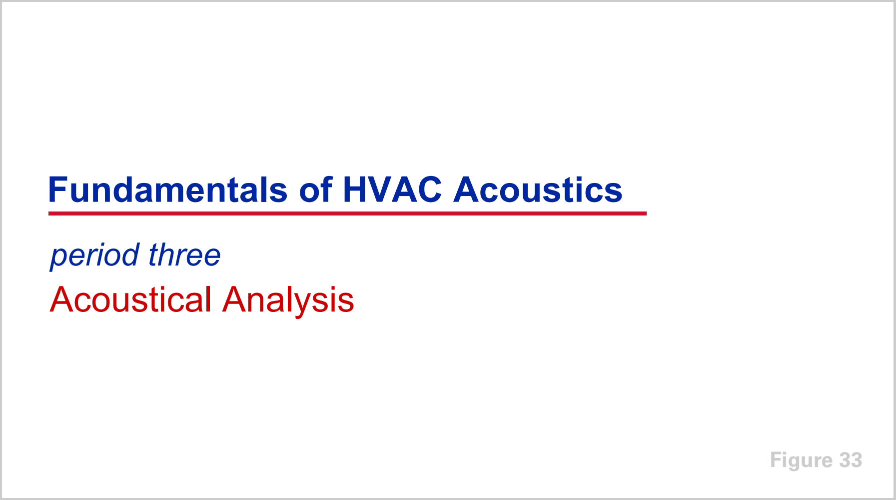
A more useful method of rating sound level is to use the octave bands discussed earlier. While octave-band data is not as simple to interpret as a single-number rating, it provides much more information about the character of the sound.

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.

period three
Acoustical Analysis

notes



Fundamentals of HVAC Acoustics

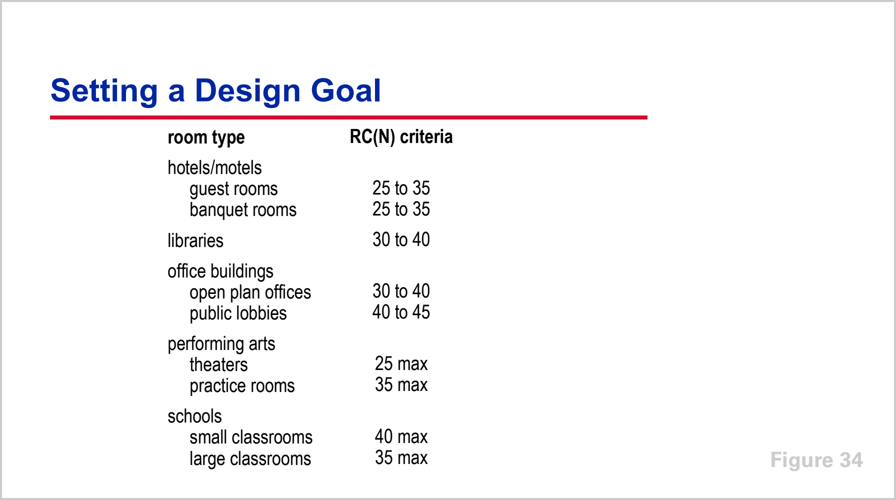
period three

Acoustical Analysis

Figure 33

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 Design 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

Figure 34

Setting a Design Goal

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 its and 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.

notes

Setting a Design Goal

Figure 35

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.

period three

Acoustical Analysis

Acoustical Analysis

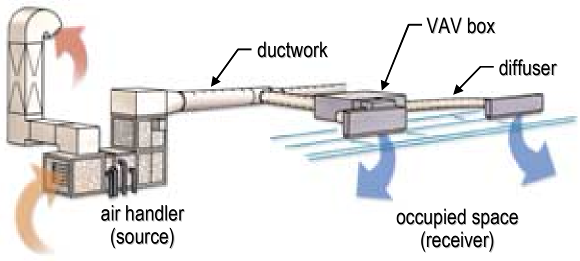


Figure 36

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.

Source–Path–Receiver Model

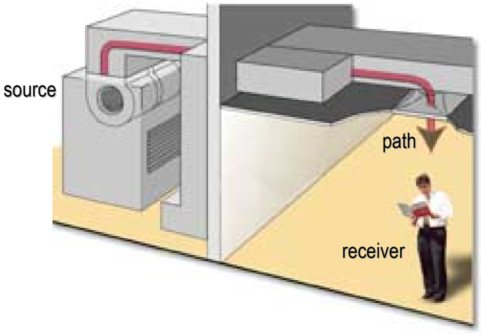


Figure 37

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.

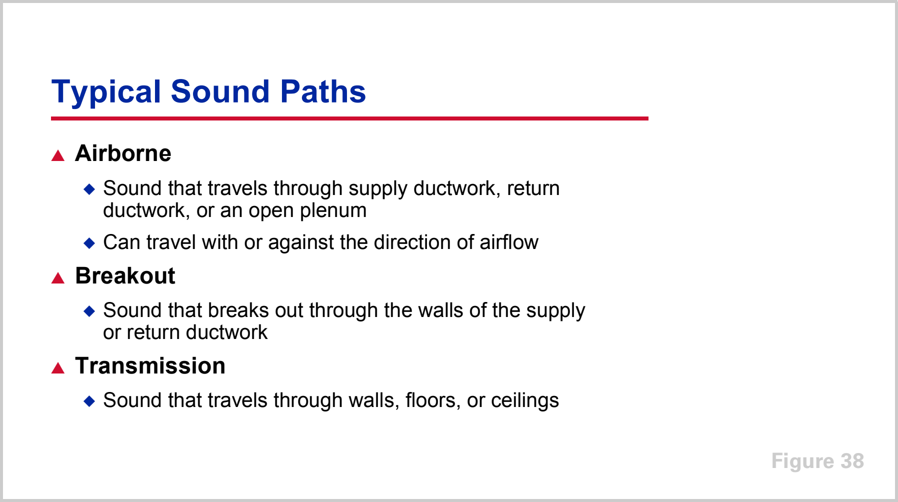
In the example shown in Figure 37, the source is the fan in the mechanical room. The receiver is the person working in the adjacent office space. The supply duct provides one of the paths for sound to travel from the source to the receiver.

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.

period three

Acoustical Analysis

notes



Typical Sound Paths

- Airborne
  - Sound that travels through supply ductwork, return ductwork, or an open plenum
  - Can travel with or against the direction of airflow
- Breakout
  - Sound that breaks out through the walls of the supply or return ductwork
- Transmission
  - Sound that travels through walls, floors, or ceilings

Figure 38

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.

period three

Acoustical Analysis

notes

Examples of a Single Sound Path

Figure 39

Sound can travel between a single source and the receiver along one or multiple paths. In the case of an air-cooled chiller sitting on the roof of a building, and a receiver located across a parking lot at the edge of the property, sound travels along only one path.

Another example is a fan-coil unit installed under a window in an office. Sound travels primarily along one path, from the fan-coil to the receiver in the same room.

Example of Multiple Sound Paths

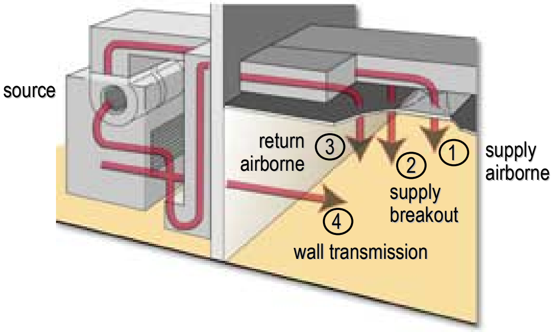


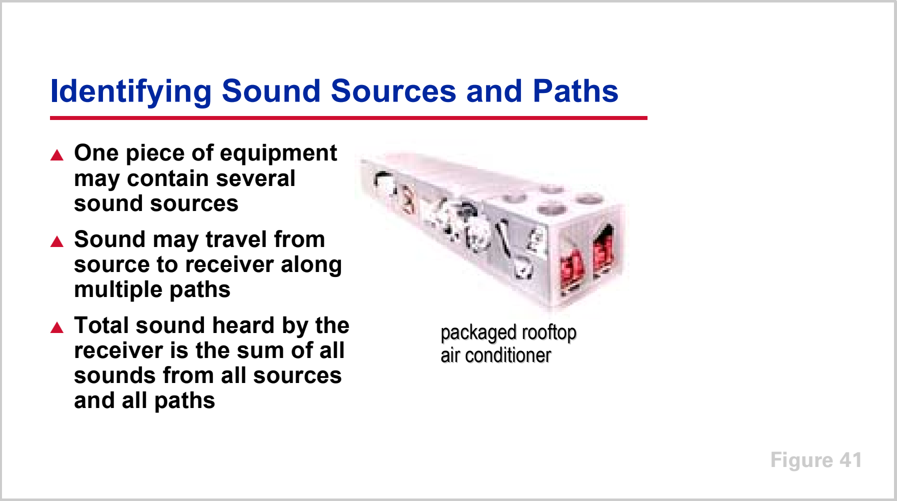
Figure 40

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:

notes

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



Identifying Sound Sources and Paths

- One piece of equipment may contain several sound sources
- Sound may travel from source to receiver along multiple paths
- Total sound heard by the receiver is the sum of all sounds from all sources and all paths

Figure 41

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 41) 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.
- The total sound heard by the receiver is the sum of all the sounds from various sources that travel along several paths.

Modeling Sound Paths

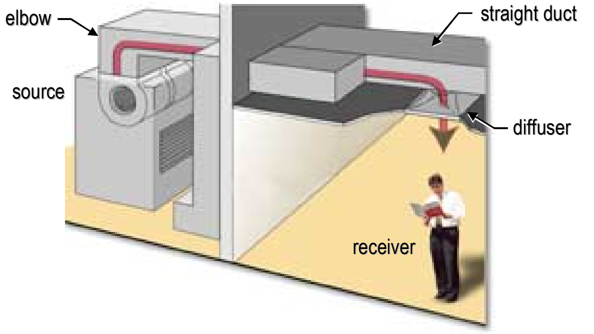


Figure 42

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.

Example of Multiple Sound Paths

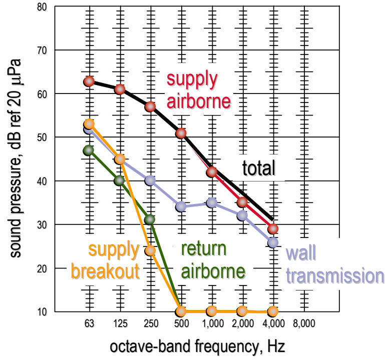
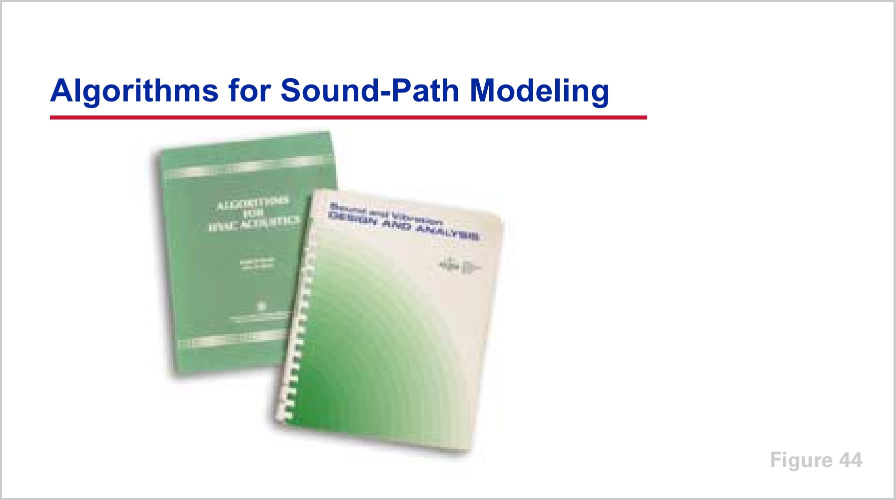


Figure 43

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.



Algorithms for Sound-Path Modeling

Figure 44

Theoretical equations aid the analysis of some path elements, but prediction equations based on test data and experience prevail. For example, an acoustical lab may have measured the attenuation and regenerated sound from a number of different types of duct elbows at various airflow rates. Data recorded from tests is used to generate an equation that can be used to model the test data.

ASHRAE collected and developed numerous prediction equations for path components in HVAC systems, and subsequently published them in their *Algorithms for HVAC Acoustics* handbook. Similar information can be found in the National Environmental Balancing Bureau (NEBB) publication titled *Sound and Vibration Design and Analysis*.

ASHRAE algorithms are widely used and generally provide good results. When using the algorithms, it should be remembered that they mainly come from test data. As a result, if they are used to extrapolate beyond the test conditions, the accuracy of the algorithms will diminish.

notes

Computerized Analysis Tools

Figure 45

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 tradeoff, 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.

Attenuation and Regeneration

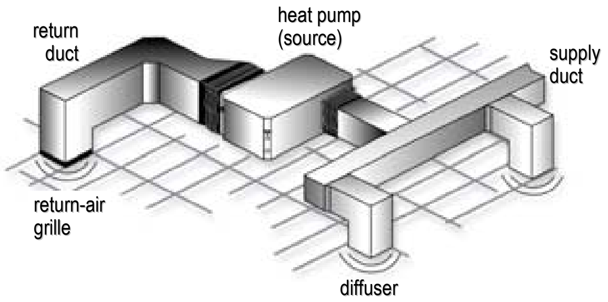


Figure 46

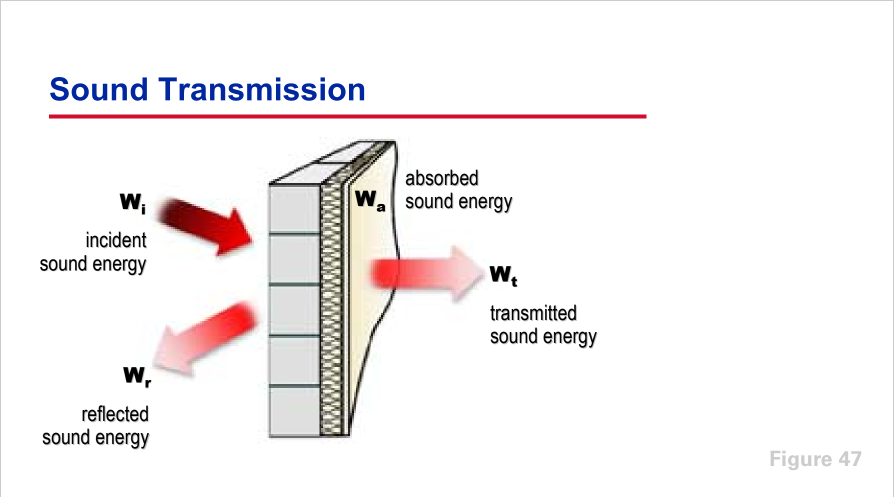
Terms Used in Sound-Path Modeling

This section introduces several terms that are fairly specific to the science of acoustics.

Attenuation refers to the reduction in sound level as sound travels along the path from a source to a receiver. It is typically used to refer to the reduction of sound as it travels through a duct system. Straight ducts, elbows, junctions, and silencers are examples of elements that attenuate sound.

Regenerated sound results from components of the duct system that create turbulence in the air stream. Turbulence is caused by an abrupt change in airflow direction or velocity with a corresponding static-pressure loss. Regenerated sound increases with air velocity or when the air is forced to make sharp turns. Elbows, junctions, diffusers, silencers, and dampers are all examples of elements that regenerate sound.

Notice that some elements can both attenuate and regenerate sound. For example, as air makes a 90-degree turn in a rectangular duct elbow, some of the sound is reflected back upstream, attenuating the airborne sound downstream of the elbow. At the same time, however, the turbulence created by the air turning the sharp corner causes some regenerated sound.



Sound Transmission

Figure 47

The total sound energy that strikes a surface (W_i) is either reflected (W_r), absorbed by the material (W_a), or transmitted through the material (W_t).

A material provides a barrier to the incident sound energy (W_i) when it reduces the amount of sound energy that is transmitted through the material (W_t). 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.

Sound Transmission

- Insertion loss (IL)
- Noise reduction (NR)
- Transmission loss (TL)

Figure 48

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 (Figure 42), 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.

Absorption

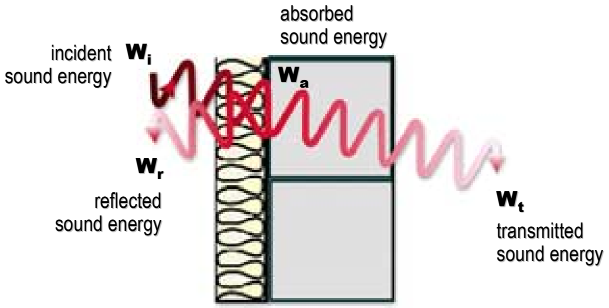


Figure 49

Absorptive materials work by converting acoustical energy into heat energy. The absorbed energy (W_a) is the portion of the incident sound energy (W_i) that is neither transmitted through the material nor reflected off the material.

The absorptivity of a material depends on several factors, including thickness, frequency of the sound, and whether there is a reflective surface located behind the absorptive material. Materials that are porous (such as open cell foam) or fibrous (such as fiberglass insulation) are more absorptive than materials that are smooth and dense (such as sheet metal or gypsum board). Increasing the thickness of a material, and installing a reflective surface behind the material, both increase its absorptivity. It is also important to note that absorption is dependent on frequency. High-frequency sound is more easily absorbed than low-frequency sound because it has a shorter wavelength and more cycles occur within the thickness of the absorptive material.

The absorptivity of a material is typically described in terms of an **absorption coefficient**. The absorption coefficient is the ratio of sound energy absorbed by the material to the sound energy incident upon the surface of the material. Preferably, absorption coefficients are reported for each octave band, but may also be expressed in terms of a single **Noise Reduction Coefficient (NRC)**. The NRC is simply the arithmetic average of the absorption coefficients for the 250, 500, 1,000 and 2,000 Hz octave bands.

notes

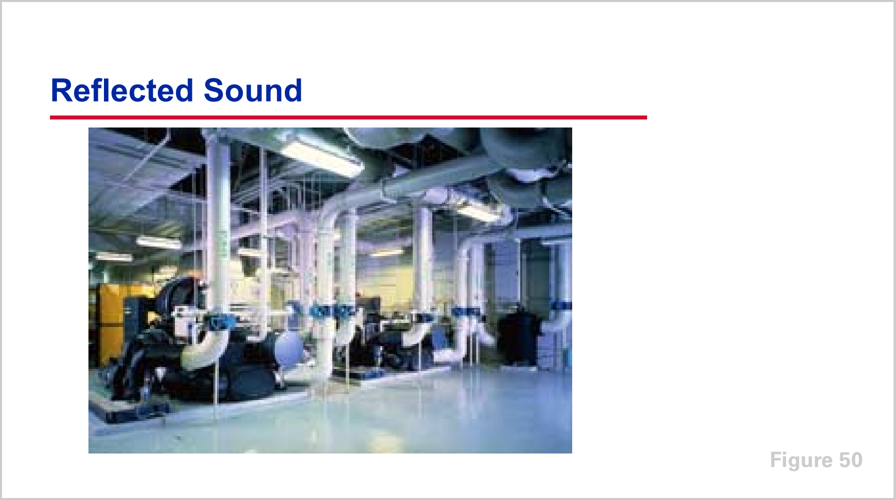

Reflected Sound

Figure 50

Finally, some of the incident sound energy (W_i) bounces off of (or is reflected from) the material. Reflected sound becomes especially important when the sound source and the receiver are located in the same room.

Consider a mechanical equipment room that contains a water chiller, pumps, and other sound sources. Often the walls of the equipment room are constructed of masonry—either cement block or poured concrete. Neither of these materials absorb or transmit very much of the incident sound energy, so most of it is reflected back into the room. The reflected sound adds to the sound coming from the source, greatly increasing the sound level in the room. The best way to reduce reflected sound is to add an absorptive material to as much of the walls, floor, and ceiling as possible.

On occasion, reducing reflected sound may also lower the sound levels in adjacent spaces. Using the equipment room example, reducing the reflected sound energy lowers the sound level in the equipment room. Given a fixed transmission loss for the walls, this will result in a decrease in sound that travels to the adjacent space. Said another way, if it is quieter in the equipment room, it will be quieter in the adjacent spaces.

notes

Receiver Sound Correction

Figure 51

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 absorptivity 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.

period four

Equipment Sound Rating

notes

Fundamentals of HVAC Acoustics

period four

Equipment Sound Rating

Figure 52

As explained in Period One, sound *pressure* can be directly measured, however, sound *power* cannot. Because sound pressure is influenced by the surroundings, the most accurate sound data that can be provided for a piece of equipment is sound power.

Sound-power levels are determined by measuring sound-pressure levels in an environment with known acoustical characteristics, and adding back any effects attributed to the surroundings.

Free Field

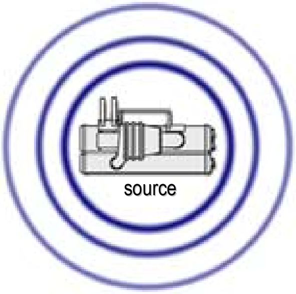


Figure 53

Fields of Measurement

To measure sound pressure correctly, it is important to understand the behavior of sound in various environments, or fields.

In theory, a **free field** is a homogeneous, isotropic medium that is free from boundaries. In practice, an example of a free field over a reflecting plane would be a large open area void of obstructions, like a parking lot or meadow.

An ideal sound source, that is, one that radiates sound equally in all directions, placed in a free field generates sound-pressure waves in a spherical pattern. At equal distances from the source, the sound pressure is same in all directions. As the sound waves travel farther away from the source, the area of the sphere increases. Doubling of the distance from the source spreads the sound over four times as much surface area.

notes

Distance Correction in a Free Field

$$L_{p2} = L_{p1} - 20 \log_{10} \left[\frac{r_2}{r_1} \right]$$

Figure 54

This type of relationship between distance and surface area provides the following simple mathematical model for estimating how sound will change as the distance from the source increases.

$L_{p2} = L_{p1} - 20 \log_{10} [r_2 / r_1]$

where,

L_{p2} = sound-pressure level at distance r_2

L_{p1} = sound-pressure level at distance r_1

r_1 = distance from the source where L_{p1} was measured

r_2 = distance from the source to where the sound pressure (L_{p2}) is desired

Using this expression, it can be shown that doubling the distance from the sound source results in a 6 dB reduction in the sound-pressure level. This is a handy fact to know when making estimates of outdoor sound levels.

$L_{p2} = L_{p1} - 20 \log_{10} [2 / 1] = L_{p1} - 6$

Distance Correction in a Free Field

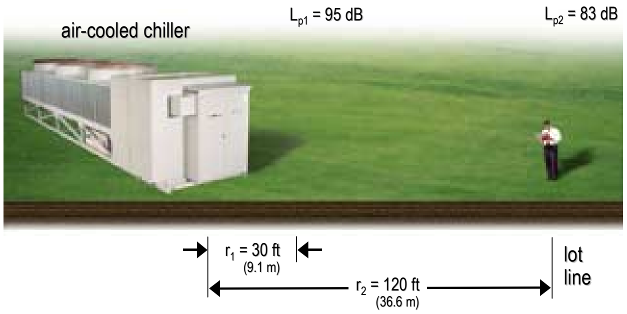


Figure 55

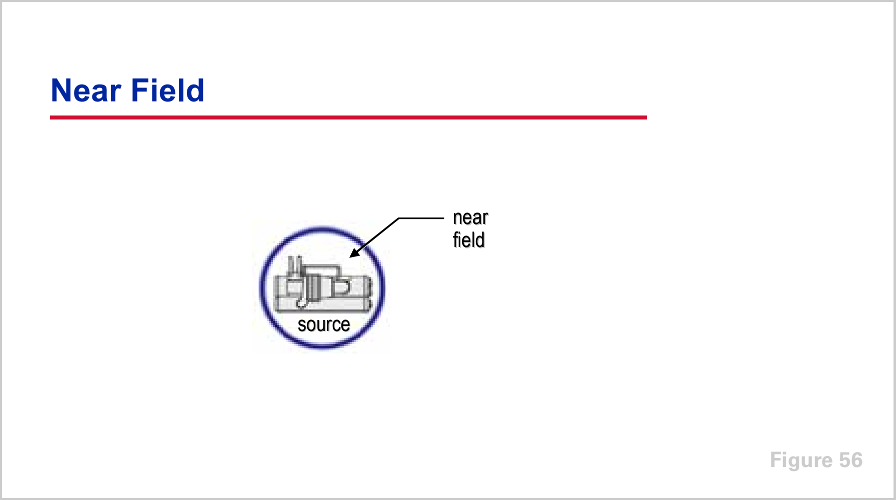
In practice, this equation is commonly used to determine how loud a piece of equipment will be at a given distance. For example, the manufacturer of an air-cooled chiller lists the sound-pressure level of the chiller as 95 dB at a distance of 30 ft (9.1 m) from the chiller. This equation can be used to estimate the sound-pressure level at a lot line, which is 120 ft (36.6 m) from the chiller. In this example, the sound-pressure level at the lot line is 83 dB.

$$L_{p2} = 95\text{ dB} - 20 \log_{10} [120\text{ ft} / 30\text{ ft}] = 83\text{ dB}$$

$$(L_{p2} = 95\text{ dB} - 20 \log_{10} [36.6\text{ m} / 9.1\text{ m}] = 83\text{ dB})$$

This equation is only valid for sound pressure. It cannot be used to convert sound power (L_w) to sound pressure (L_p). Also, it is only valid in a free-field environment.

notes



Near Field

Figure 56

The **near field** is an area adjacent to the source where sound does not behave as it would in a free field. Most sound sources, including all HVAC equipment, do not radiate sound in perfectly spherical waves. This is due to the irregular shape of the equipment and different magnitudes of sounds radiating from the various surfaces of the equipment. These irregularities cause pressure-wave interactions that make the behavior of the sound waves unpredictable.

Sound-pressure measurements should not, therefore, be made in the near field. The size of the near field is dependent on the type of source and dimensions of the equipment.

notes

Reverberant Field

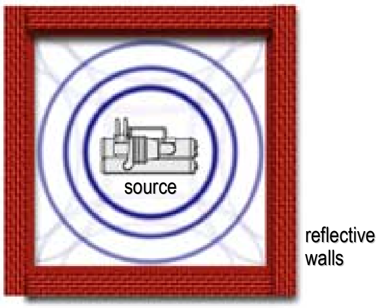


Figure 57

A **reverberant field** is nearly the opposite of a free field. Reverberant fields exist in rooms with reflective walls, floors, and ceilings. When a sound source is placed in an enclosed room, the sound waves from the source bounce back and forth between the reflective walls many times. This can create a uniform, or diffuse, sound field. In a perfectly reverberant room, the sound-pressure level is equal at all points within the room.

Special reverberant rooms are designed, built, and qualified for the purpose of measuring the sound emitted by a piece of equipment. This type of facility will be discussed later in this period.

notes

Semireverberant Field

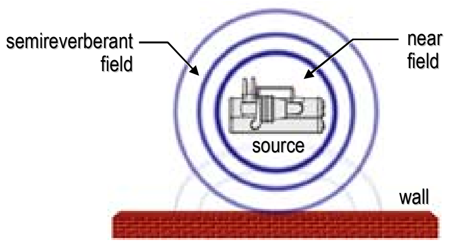


Figure 58

Most rooms in buildings are somewhere between a free field and a reverberant field environment. Called a **semireverberant field**, these spaces have some characteristics of both free field and reverberant field environments. The walls, floor, and ceiling prevent the sound from behaving as it would in a free field. These surfaces are not, however, perfectly reflective. Some of the sound is reflected by these surfaces, but a portion of the sound is absorbed or transmitted.

An understanding of how sound behaves in a semireverberant field is important when taking sound measurements. The characteristics of the sound field change with distance when a small sound source is placed in the center of a room. Close to the source, in the near field, sound measurement is unpredictable. Near the wall, in the reverberant field, the reflected sound begins to add to the sound coming directly from the source. The reduction in sound level due to the distance from the source tends to be cancelled out by the addition of the sound reflecting off the wall. This results in a near-constant sound-pressure level near the wall.

In the semireverberant field, sound behaves similarly to how it would in a free field. The sound level will decrease as the distance from the source increases, but not as much as it would in an ideal free field.

The construction of the room plays a significant role in determining what portion of the room behaves as a reverberant field, and what portion behaves as a semireverberant field. Small rooms with hard, reflective surfaces behave similarly to reverberant rooms. This description often fits a mechanical equipment room that is constructed of concrete and is small with respect to the size of the sound source.

notes

Rating HVAC Equipment

Figure 59

HVAC Equipment Sound Rating

As mentioned earlier, because sound pressure is influenced by the surroundings, often the best way for an equipment manufacturer to provide sound data is to provide sound-power levels.

Sound-power levels for many types of HVAC equipment are determined in an acoustics laboratory, usually by the manufacturer. Sound-power levels are determined by measuring sound-pressure levels in a test facility with known acoustical characteristics, and adding back any environmental effects attributed to the surroundings. Formal written standards qualify such test facilities and methods, in order to promote uniformity of data between different manufacturers across the industry. This allows for objective comparisons of similar equipment.

The two most common methods of determining the sound power of HVAC equipment are the reverberant-room and free-field methods.

notes

Reverberant-Room Method

Figure 60

The most common test method for HVAC equipment is the **reverberant-room method**. The objective of a reverberant room is to create a uniform, or diffuse, sound field by reflecting and mixing the sound waves. The walls, floor, and ceiling of the reverberant room are hard, in order to cause multiple reflections of sound waves. In this environment, the sound pressure is essentially the same at all locations within the room.

Sound-pressure levels are measured in the reverberant room and used to calculate sound-power levels for the piece of equipment. The reverberant-room method is commonly used to determine the sound power of fans, air handlers, compressors, in-room air conditioners, terminal equipment (such as fan-coils and VAV boxes), and diffusers.

notes

Free-Field Method

Figure 61

The **free-field method** is commonly used for HVAC equipment that is too large to be tested in a reverberant room. This includes water chillers, cooling towers, and the outdoor sound from packaged rooftop air conditioners and air-cooled condensers.

This type of equipment is placed on a hard surface in an anechoic (or sound-absorbing) room or on a large parking lot outdoors. This approximates the characteristics of sound in a free field above a reflecting plane. That is, the sound-pressure waves travel evenly in a hemispherical pattern, away from the equipment. Sound-power levels are determined by measuring sound-pressure levels on an imaginary hemispherical surface surrounding the equipment.

Figure 62

Formal standards are written by industry organizations to promote uniformity of data between different manufacturers. Air-Conditioning & Refrigeration Institute (ARI), the Air Movement and Control Association International (AMCA), and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) are three such organizations.

However, methods for predicting sound data may still vary from manufacturer to manufacturer, hampering comparisons of similar equipment. Done properly, collecting accurate sound data for an entire line of products is an expensive and time-consuming endeavor. A single product line may consist of many models, and each model may come in a range of sizes with various options that alter the sound generated by the equipment.

(The ARI, AMCA, and ASHRAE logos are registered trademarks of their respective organizations.)

period four

Equipment Sound Rating

notes

Ducted Air-Handling Equipment

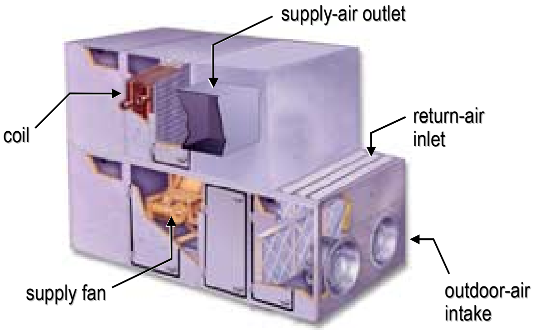


Figure 63

One of the best examples to demonstrate the complexity of gathering complete and accurate sound data is air-handling equipment. This involves any type of HVAC equipment that contains a fan and is used to condition and move air through a duct system.

Consider that each fan in an air-handling product line may run at multiple speeds and within a range of flow and static-pressure conditions. The fact that each type of fan (forward-curved, backward-inclined, and so forth) has a different operating characteristic further complicates testing.

A fan performs differently inside an air handler than it does in a stand-alone application. The air-handler casing generally changes the airflow patterns at the fan inlet and discharge openings, which can change the sound power for a given flow and static-pressure condition.

Additionally, an air handler may have only one source of sound or it may have several. For example, a ducted, packaged rooftop air conditioner has multiple sources. It contains a supply fan, refrigeration compressors, air-cooled condenser fans, and possibly an exhaust or return fan.

Finally, sound may leave the air handler in multiple ways. In the case of the indoor air handler, sound travels along with the conditioned air into the supply duct system. It also travels back out the return-air inlet, against the direction of airflow. Finally, sound is also radiated by the casing of the air handler into the equipment room. In order to properly design the HVAC system, the designer needs to know the sound power from all of these paths.

Air Handler Test Configurations

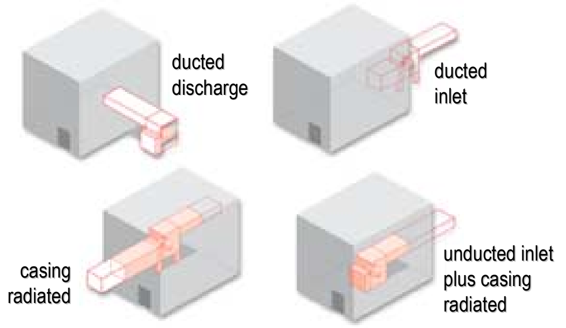


Figure 64

In order to isolate these different paths, the air handler must be tested using a number of different configurations. For example, to determine the portion of the sound that is discharged with the air into the supply ductwork, the air handler is installed outside of the reverberant room with the supply air ducted into the room.

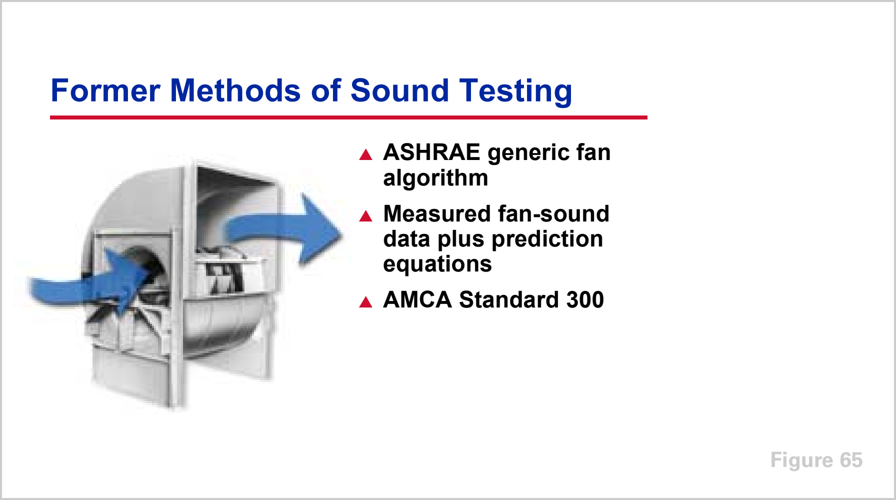
In order to determine the sound that travels back down the return duct in a ducted inlet application, the air handler is again installed outside of the reverberant room, but the return air duct is connected to the reverberant room.

In order to determine the portion of the sound that is radiated by the casing, the air handler is installed inside the reverberant room with both the return and supply air ducted outside of the room.

Finally, in cases where the return air travels back to the air handler through an open plenum and into the open equipment room, the combined “free” (or open) inlet plus casing radiated sound level must be known. Therefore, the air handler is installed inside the reverberant room with a free inlet and the supply air is ducted to outside of the room.

period four

Equipment Sound Rating



Former Methods of Sound Testing

- ASHRAE generic fan algorithm
- Measured fan-sound data plus prediction equations
- AMCA Standard 300

Figure 65

Historically, there have been several methods used to generate sound data for air handling equipment.

Though increasingly less common, there are still cases where fan-sound levels are based on prediction equations such as the generic fan algorithm published long ago by ASHRAE. Using this algorithm is much less costly than using an acoustic test facility, but results in much less accurate data. In 1995, after tests proved that sound levels predicted by the algorithm could vary from actual measured readings by as much as 10 dB in a given octave band, ASHRAE removed the fan prediction algorithm from the handbook, stating that:

The sound power generated by a fan performing at a given duty is best obtained from manufacturers' test data taken under approved test conditions.

[1999 *ASHRAE Handbook–Applications,* Chapter 46, page 4]

Another sometimes-used rating method measures actual sound data for the fan by itself, then uses acoustical equations to predict the effects of the cabinet, coils, filters, and other components that make up the air handler. These prediction algorithms vary from manufacturer to manufacturer, and since they are usually proprietary, it is difficult to judge their accuracy. This prevents designers from effectively comparing data between manufacturers or applying that data in an analysis.

AMCA Standard 300–1996, *Reverberant Room Method for Sound Testing of Fans*, defines the test methodology for collecting fan-only sound-power data. However, it has also been used to test entire air handlers. Just because the data was "taken in accordance with AMCA 300" does not indicate whether the sound data is for the fan only or for the entire air handler. This leaves the designer to determine whether the data reflects the entire air handler or, as intended, just the fan by itself.

period four

Equipment Sound Rating

notes

ARI Standard 260

- **Uses reverberant-room method**
- **Tests entire air handler, not just fan**
- **All common configurations and components included**
- **Includes effects of secondary sound sources**


2001
STANDARD for

SOUND
RATING OF
DUCTED AIR
MOVING AND
CONDITIONING
EQUIPMENT

ARI
AIR-CONDITIONING & REFRIGERATION INSTITUTE

Standard 260

4301 NORTH FAIRFAX DRIVE • ARLINGTON, VIRGINIA 22203

Figure 66

The objective of ARI Standard 260–2001, *Sound Rating of Ducted Air Moving and Conditioning Equipment*, is to deliver sound data that accurately represents the acoustical impact of the air-handling equipment after it is installed.

This standard uses the reverberant-room method to measure the sound generated by the entire air handler, not just the fan. As mentioned, a fan performs differently inside an air handler than it does in a stand-alone application. The air-handler casing generally changes the airflow patterns at the fan inlet and discharge openings. This effect is the major reason for the difference between fan-only sound data and the actual sound produced by the air handler after it is installed.

To eliminate such inaccuracies, ARI 260 requires that the entire air handler be tested in all of the configurations in which the equipment is commonly applied in the field. This involves the four test configurations discussed in Figure 64, as well as various combinations of options such as inlet and discharge plenums, different types of filters, dampers, coils, and so forth.

Unlike the other methods, ARI 260 requires that secondary sound sources, such as return or exhaust fans and compressors, be tested to determine their acoustical impact on the air handler. Any secondary source that alters the sound spectrum of the supply fan must be included in cataloged ratings.

In summary, ARI 260 addresses a wide range of air-handling equipment with a consistent test method. It ensures accurate, verifiable sound data, and focuses on the entire air handler in all of its common installation arrangements. ARI 260 enables designers to make equitable product comparisons, and to more accurately predict sound-pressure levels for occupied spaces.

period four

Equipment Sound Rating

notes

Sound Power by Octave Band

octave band	center frequency (Hz)	equipment sound power (dB ref 10^{-12} W)
1	63	103
2	125	104
3	250	100
4	500	101
5	1,000	98
6	2,000	93
7	4,000	88
8	8,000	85

Figure 67

Depending on the type of equipment, sound ratings for HVAC equipment are typically given as sound-power levels by octave band or as a single dBA rating.

Outdoor equipment, such as an air-cooled chiller or condensing unit, may be rated in terms of A-weighted sound-pressure level (dBA) at a specific distance from the equipment. This generally assumes a free-field environment and may be useful for comparing equipment from various manufacturers. Nevertheless, the sound-pressure level by octave band should still be available from the manufacturer for use in an acoustical analysis.

As mentioned, air-handling equipment is typically rated in terms of sound-power level per octave band. Typically, this data is given for the octave bands from 63 Hz through 8,000 Hz. The availability of accurate, tested sound data for HVAC equipment is vitally important to any acoustical analysis.

period five
Review

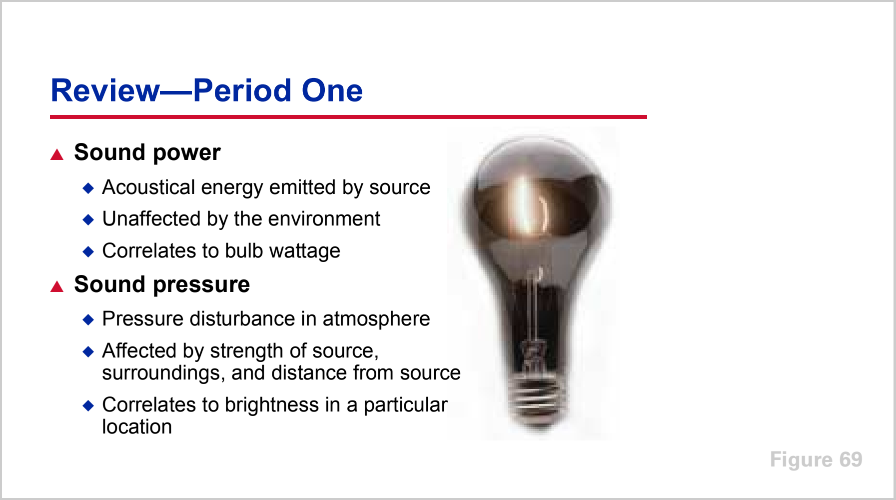
Fundamentals of HVAC Acoustics

period five

Review

Figure 68

We will now review the main concepts that were covered in this clinic on the fundamentals of HVAC acoustics.



Review—Period One

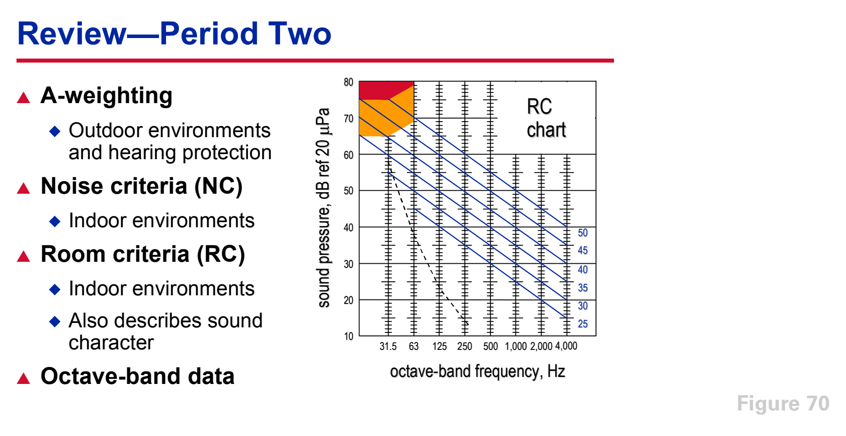
- **Sound power**
  - Acoustical energy emitted by source
  - Unaffected by the environment
  - Correlates to bulb wattage
- **Sound pressure**
  - Pressure disturbance in atmosphere
  - Affected by strength of source, surroundings, and distance from source
  - Correlates to brightness in a particular location

Figure 69

Period One explained some of the basic concepts of sound. Sound is the audible emissions resulting from the vibration of molecules within an elastic medium. It is generated at many different frequencies at the same time. Noise is defined as unwanted, or obtrusive, sound.

Sound power and sound pressure are both terms that are used when describing sound. Sound power is the acoustical energy emitted by the sound source and is *not* affected by the environment. Sound pressure is a disturbance in the atmosphere and can be measured directly. Its intensity is influenced not only by the strength of the source, but also by the surroundings and the distance from the source to the listener. Sound pressure is what our ears hear and what sound meters measure.

notes



Review—Period Two

- **A-weighting**
  - Outdoor environments and hearing protection
- **Noise criteria (NC)**
  - Indoor environments
- **Room criteria (RC)**
  - Indoor environments
  - Also describes sound character
- **Octave-band data**

Figure 70

Period Two discussed how the human ear perceives sound. As a selective sensory organ, the human ear is more sensitive to high frequencies than to low frequencies. The sensitivity of the human ear at a particular frequency also changes with loudness.

Many single-number rating systems have been developed over the years and each has its advantages and drawbacks. This clinic focused on some of the more commonly used rating systems, including A-weighting, Noise Criteria (NC), and Room Criteria (RC). A-weighting is typically used to describe the sound in outdoor environments, and for determining whether or not hearing protection is required in certain industrial environments. Noise Criteria and Room Criteria are used to describe the sound in indoor environments. The RC method has the added feature of describing the character, or quality, of the sound, as well as its loudness. However, because most HVAC equipment manufacturers do not have sound-power data for the 16 Hz and 31.5 Hz octave bands, it is difficult to predict the sound-pressure levels in these octave bands.

Finally, both sound-power levels and sound-pressure levels can be described using either full or one-third octave bands. Octave-band sound-power data is commonly used for describing the sound generated by HVAC equipment. It can also be used to describe the sound in either indoor or outdoor environments.

period five

Review

notes

Review—Period Three

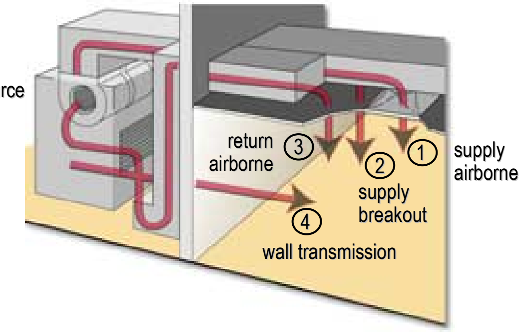


Figure 71

Period Three walked through the steps of an acoustical analysis, including setting the design target for the indoor or outdoor environment, and performing a source–path–receiver analysis. This method of analysis 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.

Remember:

- One piece of equipment may contain several sound sources.
- Sound may travel from a single source to the receiver along multiple paths.
- The total sound heard by the receiver is the sum of all the sounds from various sources that travel along several paths.

Computer software analysis tools are available to aid in performing this type of calculation-intensive analysis.

Review

notes

Review—Period Four

Figure 72

Period Four introduced two common methods used by HVAC equipment manufacturers to provide accurate sound data. Because sound pressure is influenced by the surroundings, the most useful sound data that can be provided for most pieces of equipment is sound power.

Sound-power levels are determined by measuring sound-pressure levels in an environment with known acoustical characteristics, and adding back any effects attributed to the surroundings. The most common method uses a special acoustical testing facility called a reverberant room.

The availability of accurate, tested sound data for HVAC equipment is vitally important to any acoustical analysis. ARI Standard 260–2001 is one example of an industry standard for rating the sound level of equipment. This standard addresses a wide range of air-handling equipment with a consistent test method. It assures accurate, verifiable sound data, and focuses on the entire air handler in all of its common installation arrangements. As with other existing sound standards, ARI 260 enables designers to make equitable product comparisons and to more accurately predict sound levels for occupied spaces.

period five

Review

notes

An American Standard Company

Figure 73

For more information, refer to the following references:

- *Acoustics in Air Conditioning* Applications Engineering Manual (Trane literature order number FND-AM-5)
- Trane Acoustics Program (TAP™)
- ASHRAE Handbook – Fundamentals (chapter 7, 2001)
- ASHRAE Handbook – Applications (chapter 46, 1999)
- *A Practical Guide to Noise and Vibration Control*, ASHRAE, 1991
- *Application of Manufacturer’s Sound Data*, ASHRAE, 1998
- *Algorithms for HVAC Acoustics*, ASHRAE, 1991
- *Sound and Vibration Design and Analysis*, National Environmental Balancing Bureau (NEBB), 1994

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Quiz

Questions for Period 1

1 What unit of measure is used to describe frequency?

2 Define a tone.

3 Sound _______ (power or pressure) is what our ears hear and is influenced by the surroundings.

Questions for Period 2

4 Which of these two single-number descriptors, A-weighted sound pressure level or Noise Criteria (NC) rating, is better for describing outdoor sound?

5 Which of the above mentioned descriptors is better for describing sound in an office space or classroom?

6 What is the NC rating of a space with the following sound-pressure levels?

octave band	center frequency (Hz)	measured sound pressure (dB ref 20 μPa)
1	63	48
2	125	47
3	250	45
4	500	39
5	1,000	35
6	2,000	27
7	4,000	19
8	8,000	14

Quiz

notes

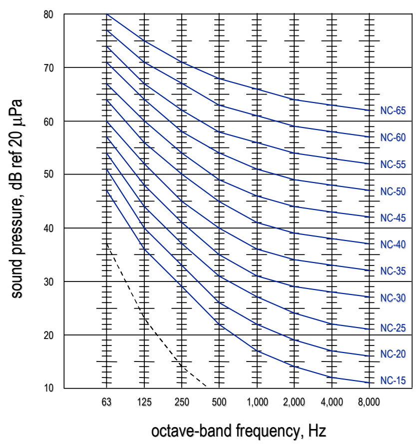

Figure 74

Questions for Period 3

7 True or False: Sound can only travel from a source to the receiver along one path.

8 True or False: One piece of HVAC equipment may contain several sound sources.

9 What term is used to describe the reduction in sound that enters a room as it travels to the receiver? It is influenced by distance and the absorptive and reflective characteristics of the surfaces and furnishings in the room.

Questions for Period 4

10 A _______ (free or reverberant) sound field is characterized by a uniform, or diffuse, sound field where the sound pressure is equal at all points in the field.

11 What recent ARI standard, which rates the sound due to ducted air moving and conditioning equipment, requires testing of the entire air handler, not just the fan?

Answers

1 Hertz (cycles per second)

2 A sound at a single frequency. A sound at a narrow band of frequencies that is significantly greater than the sound at adjacent frequencies would be similar to a tone.

3 Sound pressure

4 A-weighted sound-pressure level is better for describing outdoor sound

5 Noise Criteria rating is better for describing sound in an office or classroom

6 NC-35 (see Figure 75)

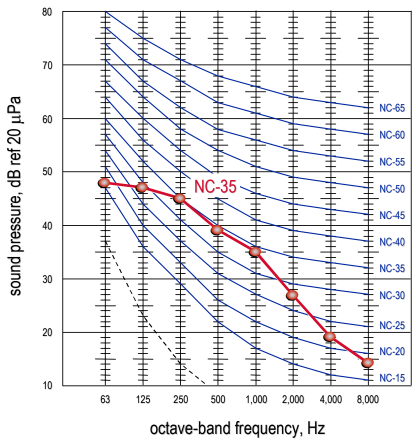

Figure 75

7 False

8 True

9 Receiver sound correction (or room effect)

10 Reverberant

11 ARI Standard 260–2001, *Sound Rating of Ducted Air Moving and Conditioning Equipment*

Glossary

absorbed sound Sound energy that strikes a material and is converted from sound energy to heat energy within the material.

absorption coefficient The ratio of the sound energy absorbed by the material to the total sound energy incident upon the surface of that material.

AMCA Air Movement and Control Association International (www.amca.org)

ARI Air-Conditioning & Refrigeration Institute (www.ari.org)

ASHRAE American Society of Heating, Refrigerating and Air Conditioning Engineers (www.ashrae.org)

attenuation The reduction in the sound level as it travels along the path from a source to the receiver.

A-weighting A single number used to describe sound. It uses weighting factors, by octave band, to approximate human response to sound in the range where no hearing protection is needed. It is most appropriately used for low-volume (or quiet) sound levels and is expressed as dBA.

broadband sound Sound energy that occurs at many frequencies, usually covering the entire audible range.

center frequency Single frequency used to identify an octave band. It is calculated by taking the square root of the product of the lowest and highest frequencies in the octave band.

decibel (dB) A dimensionless ratio of two quantities that is used to describe both sound power and sound pressure. It is defined as ten times the logarithm to the base ten ($\log_{10}$) of the measured quantity divided by the reference quantity.

dynamic insertion loss The sound insertion loss of a duct silencer with air flowing through it.

free field A homogeneous, isotropic medium, free from boundaries. An example of a free field over a reflecting plane would be a large open area void of obstructions, like a parking lot or meadow.

free-field method A common method for testing HVAC equipment that is too large to be tested in a reverberant room, such as water chillers and cooling towers. The equipment is placed on a hard surface on a large parking lot outdoors to approximate the sound conditions in a free field above a reflecting plane. The sound pressure waves travel evenly in a hemispherical pattern away from the equipment. Sound-power levels are determined by measuring sound-pressure levels on an imaginary hemispherical surface surrounding the equipment.

frequency The number of cycles, or oscillations, per second of a wave in periodic motion. Expressed in hertz.

Glossary

hertz (Hz) The unit of measure for frequency. One hertz is equal to one cycle per second.

insertion loss (IL) The difference in sound pressure measured in a single location, with and without a noise control device (installed between the source and receiver) in place.

near field The area adjacent to the source where sound does not behave as it would in a free field, due to the fact that the source does not radiate sound equally in all directions.

NEBB National Environmental Balancing Bureau (www.nebb.org)

noise Unwanted or obtrusive sound. Generally, people object to sound when it interferes with speech, concentration, or sleep.

noise criteria (NC) A single number used to describe sound in a room. It uses a series of curves for plotting sound pressure by octave band and determining the NC value.

noise reduction (NR) A term used to measure the effect of a barrier on reducing the amount of transmitted sound. It is the difference between sound-pressure measurements taken on each side of a barrier.

noise reduction coefficient (NRC) A single number used to describe the sound-absorbing characteristics of a material. It is the arithmetic average of the absorption coefficients for the 250, 500, 1,000 and 2,000 Hz octave bands.

octave band A range of frequencies that 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.

phon A unit of measure, using a logarithmic scale, used to describe the loudness of a sound.

pitch A subjective quantity used to describe a sound. It is primarily based on frequency, but is also dependent on sound-pressure level and composition. Pitch is not measured, but is described with terms like bass, tenor, and soprano.

receiver sound correction 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 is due to a combination of effects, including distance and the absorptive and reflective properties of the surrounding surfaces. Also called *room effect*.

reflected sound The sound that bounces off, or is reflected by, a barrier back toward the source.

regenerated sound The noise caused by turbulent flow in air and water systems.

Glossary

reverberant field A uniform, or diffuse, sound field that is the opposite of a free field. In a perfectly reverberant field, the sound-pressure level is equal at all points.

reverberant room A specially constructed room with reflective walls, floors, and ceilings. When a sound source is placed in this room, the sound waves bounce back and forth between the reflective walls many times. In a perfectly reverberant room, the sound-pressure level is equal at all points in the room.

reverberant-room method A common method for testing HVAC equipment. It uses a specially-constructed room to create a uniform, or diffuse, sound field by reflecting and mixing the sound waves. The walls, floor, and ceiling of the reverberant room are hard in order to cause multiple reflections of sound waves. In this environment, the sound pressure is essentially the same at all locations in the room. Sound-pressure levels are measured in the reverberant room and used to calculate sound-power levels for the piece of equipment.

room criteria (RC) A single number used to describe sound in a room. It uses a series of curves and reference lines for plotting sound pressure by octave band and determining the RC value and a descriptor of the sound quality (i.e., hiss, rumble).

room effect See *receiver room correction*.

semireverberant field A sound field that is somewhere between a free field and a reverberant field. The walls and ceiling of a room prevent the sound from behaving in a free field manner, however, these surfaces are not perfectly reflective. Some of the sound is reflected by these surfaces, but a portion is absorbed.

sone A unit of measure, using a linear scale, used to describe the loudness of a sound. A sone is the linear equivalent to a phon.

sound Audible emissions resulting from the vibration of molecules within an elastic medium. It is generated by either a vibrating surface or the movement of a fluid. In the context of building HVAC systems, this elastic medium can be either air or the building structure. For structurally-borne sound to become audible, however, it must first become airborne.

sound power The acoustical energy emitted by the sound source. It is not affected by the environment.

sound pressure An audible pressure disturbance in the atmosphere that can be measured directly. Its magnitude is influenced not only by the strength of the source, but also by the surroundings and the distance from the source to the listener. Sound pressure is what our ears hear and what sound meters measure.

source–path–receiver model A systematic approach to analyzing the sound in a space. It 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.

tone A sound in a single frequency. A sound in a narrow band of frequencies that is significantly greater than the sound at adjacent frequencies would be similar to a tone.

transmitted sound The sound that travels though a barrier.

transmission loss (TL) A term used to measure the effect of a barrier on reducing the amount of transmitted sound. It is the ratio of sound power on the receiver side of a barrier to the sound power on the source side.

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