



APPLICATION GUIDE

Sound from Rooftop Units

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Introduction

This Application Guide describes the ways in which rooftop HVAC units can create sound and how that sound is transmitted both indoors and outdoors. It offers suggestions on how to avoid unnecessary sound within the built space and in the surrounding environment. This information, properly applied, will guide the designer toward an optimally quiet air conditioning system installation.

A large, packaged rooftop unit by the nature of its size, components, and location can generate unwanted sound within and around the built environment. In the process of designing the environmental system for a building, acoustical goals should be set, and an acoustical review should be conducted.

One common approach to addressing acoustical concerns is to repeat a fixed set of design practices for every job. This approach can work well to eliminate sound problems. However, it may unnecessarily inflate the installed cost of some projects while providing insufficient sound control on others. This is especially true for new HVAC products whose sound levels are different from equivalent predecessors. On projects where the sound environment is critical, the most successful approach is to conduct an acoustical analysis early in the design process. Even a relatively simple acoustical analysis can help achieve occupant satisfaction while minimizing installed cost.

To support the designer's acoustical analysis, indoor sound from packaged rooftop units is rated in accordance with the ANSI/AHRI Standard 260 "Sound Rating of Ducted Air Moving and Conditioning Equipment" (AHRI 2012) and outdoor sound is rated in accordance with the ANSI/AHRI Standard 370 "Sound Performance Rating of Large Air-cooled Outdoor Refrigerating and Air-conditioning Equipment" (AHRI 2015b). The acoustical impact of each selectable feature at the desired unit operating conditions is available to the system designer.

Indoor Sound from Rooftop Units

The simplest way to understand HVAC sound in the built environment is the Source/Path/Receiver model. The source generates sound energy, that energy flows along several different paths, and it eventually ends up indoors where it is heard by the occupants (receivers). Each of these elements is described next in more detail.

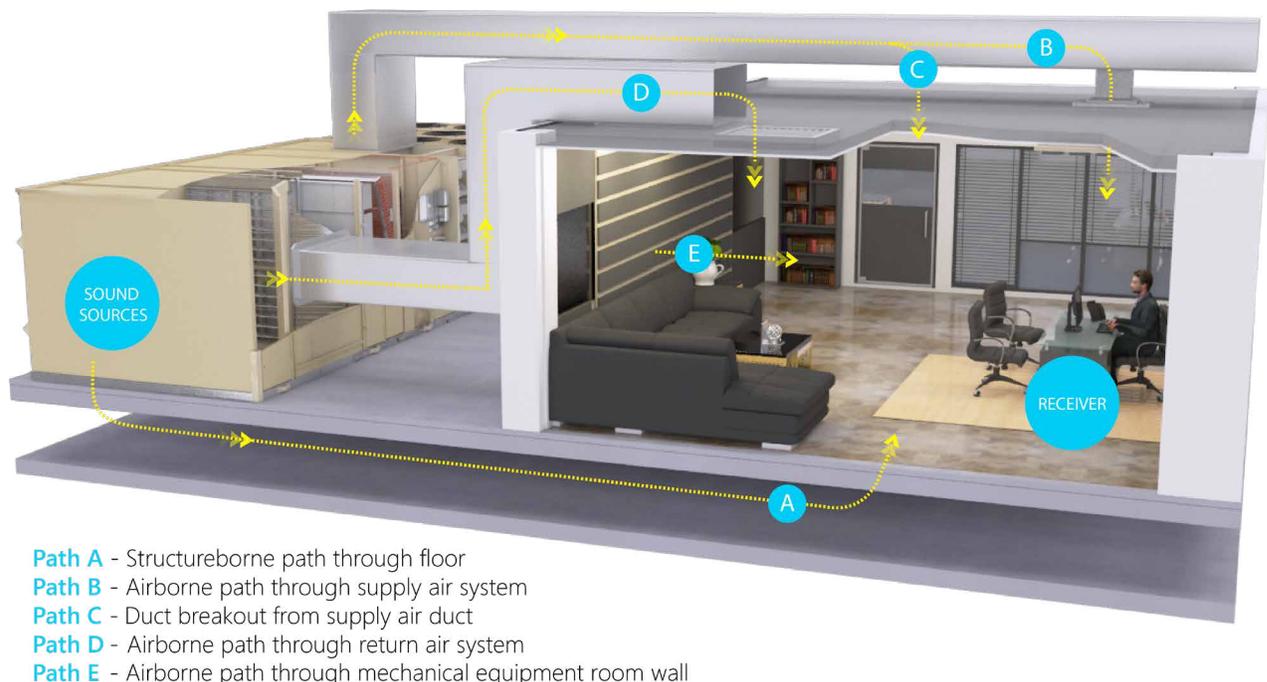
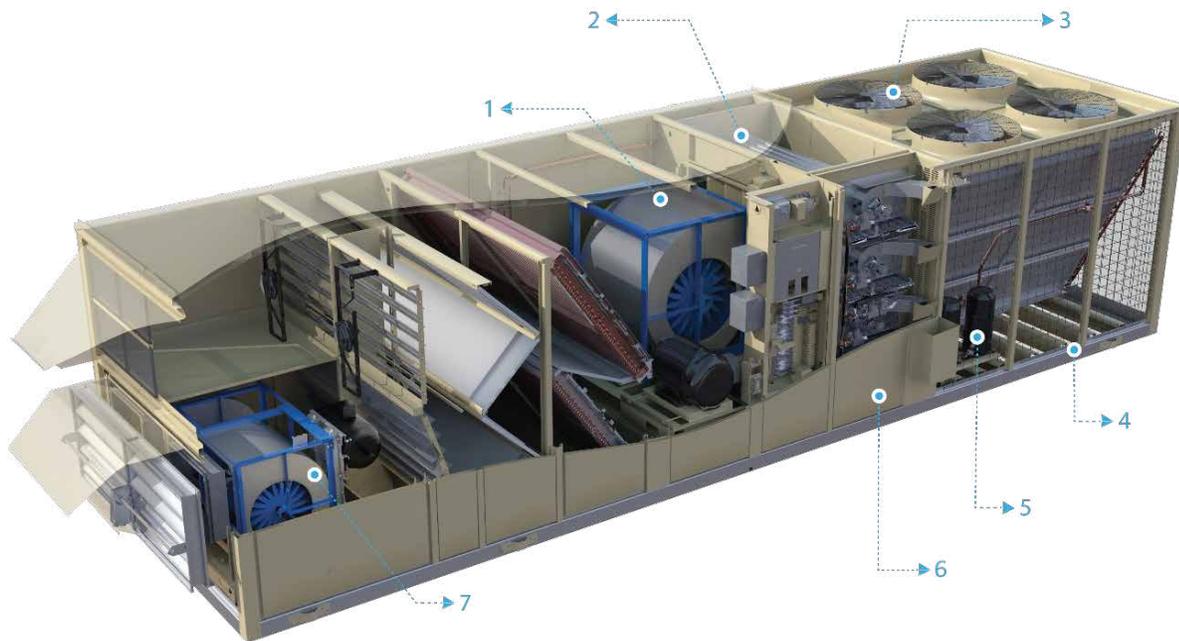


Figure 1: Notional Source-Path-Receiver Diagram for an HVAC Unit

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Figure 2: Schematic of Large Rooftop Unit with Indicators Pointing to Major Sources of Sound Emission

Sources of Sound

The source is the physical generator of the sound. Large, packaged rooftop units contain several sound sources. Each source has a unique sound quality and level, but all of them play a role in determining the sound the receiver hears within the built environment. The basic sources of sound associated with a rooftop installation include, but are not limited to:

1. Supply fan
2. Gas heaters
3. Condenser fans
4. Structural vibration generated by compressors and fan assemblies
5. Compressors
6. Flow noise generated at duct fittings outside the unit (elbows, reductions, diffusers, etc.) and at dampers within the unit
7. Exhaust or return fans

An accurate acoustical analysis for a building application starts with, and depends on, accurate sound data for the packaged rooftop unit. The manufacturer recognizes the importance of providing ducted sound power levels (*ducted discharge* for the supply discharge and *ducted inlet* for the return). The manufacturer continues to increase the depth of its product lines whose sound emissions are measured in accordance with the latest edition of AHRI Standard 260. When measured to this standard, designers can be confident that published sound data for the unit accurately reflects the contributions of all the internal sound sources, accounts for all of the appurtenances inside the unit and the cabinet itself, and covers the necessary range of operating conditions.

Paths Traveled by Sound

The paths are all of the routes along which sound energy can travel from the sources to the receivers. Sound may follow more than one path from a source to a receiver location. For example, sound from the supply fan travels inside the supply ductwork and enters the occupied space through the supply-air diffuser. Supply fan sound also travels through the walls of the supply duct (known as breakout noise), and then through the ceiling into the occupied space.

The following paths are typically the most important for rooftop unit sound:

- **Airborne:** Sound follows the airflow path inside the ductwork. Supply airborne sound emanates from the discharge and travels in the same direction as the supply air, from the rooftop unit down the supply air path. Return airborne sound emanates from the inlet and travels against the direction of airflow, from the rooftop unit back through the return air path. In variable air volume (VAV) systems, the discharge sound from the terminal units contributes to the supply airborne path.
- **Breakout:** Some of the sound traveling inside the ductwork passes through its walls. This is known as breakout sound. From there, the sound travels into the ceiling plenum, and then through the ceiling and into the occupied space.
- **Roof Transmission:** Sound can pass through the roof deck (either within or outside of the roof curb) and into the plenum space, and then through the ceiling into the occupied space.
- **Structure-Borne:** The framework of the building, as well as the walls and floors, can transmit vibration which is then radiated as sound into the occupied space. Vibrational energy may come directly from the vibration of the rooftop unit, or it may be the unit's airborne sound that is transferred into the structures.

The sources of sound and the transmission paths are generally similar for all types of HVAC systems. Since rooftop equipment is not enclosed by an equipment room, the added sound reduction offered by walls and floor slabs is not available.

Receivers of Sound

The ultimate receiver of packaged rooftop unit sound is the ear of the occupant. For the purposes of this Application Guide, the receiver is the location (or space) where the sound will be heard and judged against some defined criteria. This could be a private office, a conference room, an open office area, a theater, etc. A single installation may have several receiver locations with varying acoustical requirements.

Estimating Indoor Sound from Rooftop Units

While estimating the sound resulting from installation of a rooftop unit is not simple, it is straightforward. The following five steps provide guidance, and they are detailed next:

1. Set sound goals for the finished spaces.
2. Determine the source sound levels for the rooftop unit(s) of interest.
3. Identify each sound path and its elements.
4. Analyze the contribution from each path.
5. Sum up all of the paths: total acoustical performance.
6. Compare results with sound goals, and evaluate them against the budget.

Note: As the complexity of an installation increases, so does the value of a qualified acoustical consultant.

Step 1: Set Sound Goals for the Finished Spaces

At the outset of any HVAC project, realistic acoustical goals must be established for the occupied spaces. Every HVAC project brings with it implicit, often subjective, expectations, and it is much easier to satisfy these expectations when they are understood by everyone involved before designing the system. Without quantified sound goals, there cannot be agreement about the installed performance (or lack thereof) of a rooftop unit.

Sound goals will vary depending on how the space is used. Once the sound goals are understood, they can be quantified using an appropriate descriptor, such as A-weighted sound level (dBA), noise criteria (NC) or room criteria (RC). Choosing the right descriptor for the job depends on the criticality of the sound performance, whether a sound quality assessment is preferred, and what resources are available to assess the installation. *Table 1* compares the capabilities of these three descriptors.

Table 1: Comparison of Sound Rating Descriptors

Descriptor	Use For	Assesses Sound Quality	Requires Frequency Band Information
dBA	Components & Systems	No	No
NC	Components	No	Yes
RC	Systems	Yes	Yes

As a rough guide, typical ranges of NC are listed for various occupied spaces in *Table 2* below. For the purposes of such a guide, RC ranges are similar for each type of space.

Table 2: Ranges of Preferred Noise Criteria (NC) for Occupied Spaces

Type of Occupied Space	NC (Range)
Private residences, apartments, condominiums	25–35
Hotels/Motels	
Individual rooms or suites	25–35
Meeting/banquet rooms	25–35
Halls, corridors, lobbies	35–45
Service/support areas	35–45
Office Buildings	
Executive and private offices	25–35
Conference rooms	25–35
Teleconference rooms	25 max
Open plan offices	30–40
Circulation and public lobbies	40–45
Hospitals and Clinics	
Private rooms	25–35
Operating rooms	25–35
Wards	30–40
Corridors	30–40
Public areas	30–40
Performing Arts	
Concert and recital halls	See NOTE
Drama theaters	25 max
Music teaching studios	25 max
Music practice rooms	25 max

Type of Occupied Space	NC (Range)
Laboratories	
Testing/research, minimal speech communication	45–55
Research, extensive speech communication	40–50
Group teaching	35–45
Churches, Mosques, Synagogues	
Worship spaces	25–35
With critical music programs	See NOTE
Schools	
Classrooms up to 750 ft ²	40 max
Classrooms over 750 ft ²	35 max
Lecture rooms for than 50	35 max
Libraries	30–40
Courtrooms	
Unamplified speech	25–35
Amplified speech	30–40
Indoor Stadiums and gymnasiums	
School and college gymnasiums and natatoriums	40–50
Large seating capacity spaces	45–55

NOTE: An experienced acoustical consultant should be retained for guidance on any sound-critical space (below NC 30) and for all performing arts centers.

When defining the desired sound levels for occupied spaces, remember:

- For a given level of HVAC performance, lower sound levels usually cost more to achieve.
- Not every space within the building must have the same acoustical requirements. Bathrooms, hallways, storage areas, and non-occupied spaces do not need to be as quiet as offices and conference rooms. A quiet but cost-effective installation takes advantage of this.
- Successful acoustical results require a team effort, including the owner, the architect, the design engineer, the installation contractor, and the equipment manufacturer.

Step 2: Determine the Source Sound Levels

For packaged rooftop units, the primary indoor sound sources are related to the supply and return. As sound sources, these are rated according to AHRI Standard 260. The descriptors are octave-band (frequencies) sound power levels in decibels sound power. These rated levels can be used as the sound sources for indoor sound.

Note that sound power level ratings measured in accordance with AHRI Standard 260 are measured when the rooftop unit is operating at the Conditions for Standard Rating (AHRI 2012). This condition may differ from the conditions expected for the installed unit, and corrections may be necessary to determine the changes in the unit's sound power levels. Consult with your sales engineer, who can determine those changes for the packaged rooftop units.

Step 3: Identify Each Sound Path and Its Elements

Sound transmission paths are defined by their end points: the sound source and the receiver location. There may be many receiver locations depending on the installation, but their number can be reduced by determining which are *acoustically critical*. Critical receivers include conference rooms, executive offices, and classrooms. Music and speech performance spaces are considered highly critical, and an acoustical consultant must be included in the design and evaluation of the conditioning system.

After the critical receiver locations are defined, the sound paths from the source to each receiver can be identified. For each path, enumerate the elements along that path. For example, for the supply fan airborne path, all of the ductwork and the fixtures (bends, reductions, dampers, outlets, etc.) must be accounted for.

In general, sound diminishes with distance away from the source. That means that the space directly below the rooftop unit will typically be the loudest. If adjacent spaces have sound goals that are well below those established for the space directly under the unit, evaluate these spaces as well.

Step 4: Analyze the Contribution from Each Path

Once each path has been identified, individual elements can be analyzed for their contributions to the sound in each space. For example, the supply airborne path includes various duct elements (elbows, straight ducts, junctions, diffusers, etc.) and a room-correction factor. Algorithms available from ASHRAE can be used to calculate the acoustical effect of each duct element. The effect of changing an element, such as removing the lining from a section of ductwork or adding turning vanes to an elbow, can be estimated.

Step 5: Sum Up All of the Paths: Total Acoustical Performance

Once the sound contributions to each of the individual paths for a particular receiver location are calculated, they must be added together to determine the total sound at the receiver. This process must be repeated for each critical receiver location whose contributing paths will vary accordingly.

Software tools are available that collect and evaluate all of the path elements pertaining to each acoustically critical receiver. Such software can simplify path analysis, especially for larger jobs with many different paths. For very complex arrangements, a qualified acoustical consultant should be retained.

Step 6: Compare with Sound Goals, Evaluate Budget

The sum of the sound paths leading to a particular receiver location is an estimation of the sound level at that location. If the sum is lower than the sound goal for that receiver location, the design does not need to be changed, although it may be reviewed for potential cost reductions. If the estimate exceeds the sound goal, review the paths to determine which are making dominant sound contributions. Then make alterations to the sources and/or the path elements to reduce the sound at the receiver location.

This is typically an iterative process, comparing the acoustical effect of various alterations. Once a design meets the sound goals for the project, it must be reviewed to understand the work and costs required to implement the design. Where cost is an issue, system layout alternatives or equipment options should be explored.

Note: The earlier an acoustical analysis is performed in the project timeline, the more options are available to achieve the sound goals. Waiting until construction is underway—or worse, finished—severely limits the scope of remedies and puts the project at risk.

Outdoor Sound from Rooftop Units

Rooftop units generate sound in the outdoor environment as well as the indoor environment. This sound may or may not be of concern to the designer, but in most communities, sound emission is becoming increasingly regulated and must be addressed. The most common regulation occurs at the property line of the source or at an adjacent building.

Sources of Sound

The primary sources of outdoor sound from packaged rooftop units are the condenser fan(s) and the refrigerant compressor(s). In most cases, the sound from the condenser fans exceeds that of the compressors in overall sound level. However, since they contribute sound in very different frequency bands (lower for fans, higher for compressors), they are both important to the overall sound emissions.

For large rooftop units, the condenser fans and compressors are located at one end, and at the other end, there will be openings to supply fresh air to the building. Inside the plenum fed by these openings, there may be either exhaust fans or return air fans. The sound from these fans is typically less than that from the condenser equipment. However, depending on how the unit is oriented, this return air equipment may face critical receivers and should be taken into consideration.

As with indoor sound, an accurate sound assessment starts with, and depends on, qualified sound data for the rooftop equipment. Manufacturers provide outdoor sound power levels for their rooftop products, measured in accordance with AHRI Standard 270 (for units of capacity less than 40 kW or 11.4 tons) or AHRI Standard 370 (for units of capacity greater than 40 kW or 11.4 tons). Note that sound power level ratings measured in accordance with AHRI Standard 270 or 370 are measured when the rooftop unit is operating at the Conditions for Standard Rating (AHRI 2015a, 2015b).

Paths Traveled by Sound

The path traveled by outdoor sound is more simplified relative to the situation for indoor sound. Fundamentally, outdoor sound from rooftop units propagates in nearly straight lines through the air. Complications arise when units are installed next to walls rising above the rooftop that cause additional reflections. These reflections have the effect of creating *image sources*, almost as if additional units had been installed there.

Sound tends to decay at a rate of about 6 dB for each doubling of distance from the source outdoors. Therefore, a sound source that generates 80 dB at 10 feet will be about 74 dB at 20 feet, 68 dB at 40 feet, 62 dB at 80 feet, and so forth. However, this propagation rule of thumb is weakened when reflections occur or when the prevailing breeze bends the sound toward a critical receiver. On the other hand, air itself absorbs some of the sound, especially at high frequencies.

Sound from rooftop units does not emerge equally in every direction. In particular, sound from the condenser fans is largely directed upwards. This is an advantage to many installations, but it is a serious detriment when receivers are located above the unit. The latter is commonly the case in urban environments. It is also typical of installations on multi-story buildings, where a rooftop unit is located below occupants on higher floors. In these cases, the sound sources are essentially aimed right at the receivers; because the sound is directive, it does not decay as rapidly over distance.

Intervening structures can help block the sound substantially if they lie in the path between the source and the receiver. This can include the rooftop itself if its edge blocks the line-of-sight from a critical receiver on the ground to the unit on the rooftop. Note however that sound diffracts around structures, so the reduction along any blocked path is never complete.

Receivers of Sound

The receivers of outdoor sound are the neighbors adjacent to the rooftop unit's installation. The most critical receivers are residents, schools, places of worship, and performing arts buildings. Because so many local ordinances regulate sound at the property line, that line itself becomes the receiver of interest for acoustical analyses.

Table 3 lists noise limits commonly found in many municipal ordinances.

Table 3: Typical Municipal Ordinance Noise Limits at the Property Line

Type of Zone	Maximum Sound Pressure Level (dBA)	
	Day (7:00 AM to 7:00 PM)	Night (7:00 PM to 7:00 AM)
Residential - Single Family	50	45
Residential - Multi-Family	55	50
Commercial	60	55
Industrial	70	70

General Recommendations for Rooftop Units: Indoor Sound

No single, generalized list of acoustical practices can achieve the indoor sound goals in every installation. Many of these practices introduce increased costs that may or may not be justified by the specific acoustical requirements. For this reason, a thorough acoustical analysis is recommended in order to meet the acoustical goals at the lowest cost. This section introduces typical methods of sound attenuation that can be deployed as needed during the system design and acoustical analysis.

Quieting the Sources

Recalling the Source-Path-Receiver model previously described, one of the most effective methods of lowering sound at the Receiver location is to generate less sound at the source. Unit options such as quieter fans or an additional plenum section are examples of quieting at the source.

It can be difficult to translate a given change in unit sound power level to a change in the resulting room NC, because a change to the unit configuration will impact not only the overall sound level but the shape of the sound spectrum, as well. (It is the shape of the sound spectrum that affects the color, timbre, or quality of the received sound.) How a given specification translates to a change in room NC depends on how the unit is to be installed.

For information on the quieting options available for the packaged rooftop units, see *Specific Recommendations for the Packaged Rooftop Units* on page 20.

Fan Selection

Large rooftop units can be configured with supply fan only (barometric relief), supply and exhaust fan, or supply and return fan. Each choice has a unique impact on sound produced by the unit. If the unit's configuration has not been pre-selected by the customer, check all allowable configurations to find the one that is quietest for the application. In general, for a given flow and pressure drop, a larger fan selection lowers the sound level. However, there is a risk that use of a larger fan may also move the fan closer to a region where *acoustical stall* occurs, resulting in more generated sound. (Refer to the section *Fan Operating Points: Avoid Acoustical Stall* on page 10.)

The generalized acoustical model indicates that both the discharge and return paths must be considered in order to obtain the best acoustical performance.

A supply fan only unit has higher sound levels at the discharge opening than at the return opening. However, some sound attenuation may be introduced by the heat section in the supply plenum and by the mixing and return sections in the return path.

Adding an exhaust or return fan creates higher sound levels at the return opening. However, by shifting the required operating point of the supply fan, doing so may lower the sound level at the discharge. Switching to a supply and exhaust fan configuration may increase the sound in the occupied area below the rooftop by approximately 3 NC points. Switching to a supply and return fan configuration may result in an increase of up to 11 NC points.

Supply Fan

The dominant source of indoor sound from rooftop units is the supply fan. Low-frequency sound generated by the fan easily transmits to the conditioned space both down the ductwork (supply-side airborne noise) and through the duct walls (known as duct breakout noise).

To help attenuate the discharge sound from the supply fan, consider using the *Standard CFM*, or the largest supply fan available in a given tonnage size. Larger fans run at a lower speed to achieve a given operating condition. For example, a larger fan is typically quieter by about 10 dB in the 250 and 500 Hz octave bands at 32,000 CFM and 5 inwg of fan static pressure.

Unit sound data is dependent both on fan type and fan operating point. It is best to check all available fan selections for a particular operating point. Note that in some cases, it may be more cost effective to reduce noise from the unit/installation by another method.

Return or Exhaust Fan

The greatest sound impact resulting from adding a return or exhaust fan comes from the sound transmitted through the return air opening. Sound radiated from the return opening is the sum of the supply fan inlet sound plus the exhaust or return fan sound. Adding a return fan may result in the return airborne and breakout sound paths dominating the sound levels in the occupied space. Also, adding a return or exhaust fan changes the discharge sound from the supply fan. The change in discharge sound depends both on the type and operating point of the return or exhaust fan used.

In general, return fans result in higher sound levels in a space than do exhaust fans because the inlet to the return fan is mounted directly above the return ductwork. Exhaust fans are mounted on a wall of the return plenum section, not directly to the return ductwork. This allows for some attenuation of the exhaust fan sound by the volume of the plenum. Also, different fan types and operating points are used for the two fans, so the sound created will be unique to each fan at each operating point.

To reduce the sound being transmitted through the return air opening, consider the following:

1. Review the sound data for return vs. exhaust fan for the required conditions. Determine which configuration results in the lowest sound levels. Explore all fan options for each configuration. Changing the supply and return fan size, and by extension the required fan speed, results in moving the blade passage frequency so the sound levels of some octave bands may increase and some may decrease. In any case, moving to a larger fan can have a significant effect.

2. Consider using a horizontal connection (if one is available for the configuration) for the unit return and running the return duct over the roof before penetrating the building. The advantages of a horizontal run of ductwork are detailed in the section *Supply Air: Airborne Path* on page 11.

Design the System to Meet the Requirements

It is more common to overestimate system static pressure requirements to achieve a design airflow than to underestimate them. This results in the installation of larger motors and/or higher speed drives than is required to overcome the actual installed static pressure. To compensate for the resulting additional airflow, the air terminal devices' balancing dampers must be set to be more restrictive than necessary. These *over-aired* systems waste energy and cause the units to generate excess sound.

In acoustically sensitive installations, take extra care to evaluate the system pressures as closely as possible to minimize unnecessary sound.

Fan Operating Points: Avoid Acoustical Stall

With increasing restriction, fans enter a region of *acoustical stall* prior to entering true aerodynamic stall. The fan reliably moves air when operating in the *acoustical stall* region, but the low-frequency sound produced by the fan is inconsistent and highly variable. When the fan is operating in this region, even small changes to the fan operating condition can produce unpredictable changes in the low-frequency sound level.

The Selection Navigator tool does not force the designer to avoid the *acoustical stall* region since it is not possible to provide accurate, representative acoustical data for this condition. When acoustical performance is an important consideration, do not select fans so that they operate in the *acoustical stall* region. Likewise, note that a fan operating above the *acoustical stall* region can periodically unload so that it falls back into that stall region. Check the selection at partial load conditions to avoid this problem.

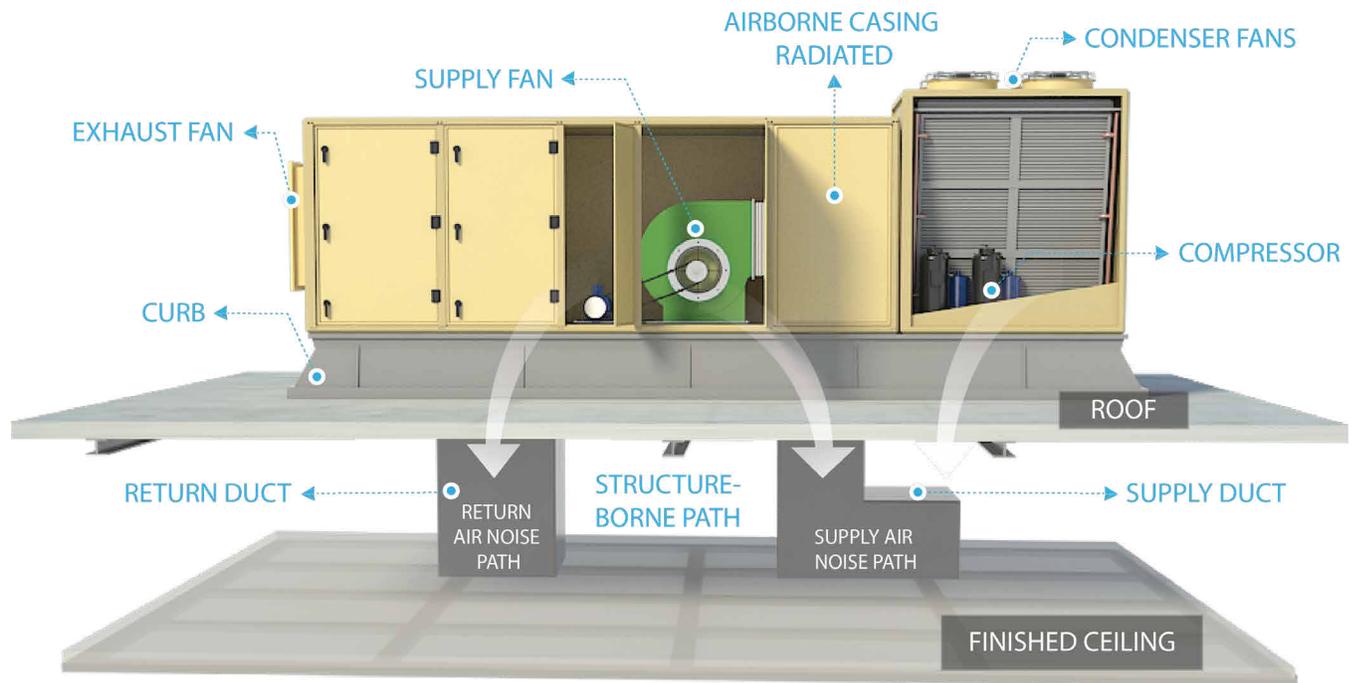
Operate the Unit as Designed

For minimum noise, operate the rooftop system at the lowest possible pressure within the duct. After installing the rooftop unit and its associated air distribution system, it must be properly air-balanced by qualified technicians using calibrated air measuring devices. The airside system should be balanced to achieve the desired airflow at all terminal outlets while maintaining the lowest possible fan speed and system static pressure.

Mitigating the Paths

After selecting the lowest-sound unit capable of delivering the required air performance, if the sound levels in the occupied space are predicted to remain above the sound goals, it is necessary to provide additional sound reduction along the paths of sound transmission.

As rooftop unit size increases, building and duct construction details play an increasing role in determining the resulting sound levels in the occupied space. For large rooftop applications, the critical sound paths are (1) supply airborne, (2) return airborne, (3) supply breakout, (4) return breakout, and (5) structural vibration. If the acoustics of the installation are not considered, an application can have sound levels that are unsatisfactorily high. With proper attention both to unit selection and to application details, acceptable sound levels in the occupied space can be achieved.



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Figure 3: Notional Schematic Showing Major Sound Paths for Rooftop Units

Locating the Unit

The single most effective recommendation to prevent noise problems within a building is to locate the rooftop unit over an area that is not considered critical for acoustical performance. Such areas include those with little-to-no human occupation, such as copy rooms, rest rooms, storage rooms, and other similarly unoccupied areas of the building. Consider locating the unit over a non-sound sensitive area, even if this results in running the supply and return ducts across the roof. The added expense of the external ductwork may likely be less than the expense of quieting a unit placed over an occupied space. In addition, the external runs of duct can provide attenuation of the supply and return airborne sound before the roof penetration is made.

Locating a large rooftop unit over a sound-sensitive area may either

- A. Result in unacceptably high sound levels in the occupied area, or
- B. Require considerable cost in order to prevent the sound produced by the unit from reaching the occupants.

Never locate a rooftop unit directly over, or in close proximity to, sound-sensitive areas such as conference rooms, executive office spaces, libraries, surgical theaters, performance spaces, or other spaces that require high speech intelligibility or prolonged mental focus.

Supply Air: Airborne Path

1. Two-inch (5 cm) thick, exposed duct lining is a good silencer. The length of duct that should be lined depends on how much attenuation is necessary. However, a general rule of thumb is to line a run of at least 20 feet (6 m).
2. Size supply ducts for maximum airflow velocities not to exceed 900–1,000 feet per minute (fpm). If the flow velocity is too high, elbows, junctions, and insufficiently rounded inside corners generate additional turbulence sound.
3. In-line duct silencers can be very effective sound attenuators. Keep in mind that:
 - a. They can add static pressure loss, which makes the fan work harder and generate more sound, and
 - b. Their performance (both pressure drop and attenuation) is affected by inlet and outlet conditions.
4. Take advantage of the horizontal supply option and route the supply duct horizontally above the roof for a span of 15–20 feet (4.5–6 m) before penetrating the building envelope. Use 2-inch (5 cm) internal duct lining on this run to attenuate high frequency sound. This provides very significant attenuation. The lining absorbs the higher frequency sound, while some of the lower frequency sound breaks out of the duct above the roof line.

5. If horizontal ducting above the roof is not an option, elevate the unit to provide 7–8 feet (2–2.5 m) of straight vertical drop above the roof. This provides supply airflow more distance to smooth out and allow for some noise breakout above the roof. Although not as effective as the horizontal ducting approach, this method can provide significant sound attenuation.

Return Air: Airborne Path

The ductwork carrying return air also hosts sound emanating from the rooftop unit, even though the flow is out of the building. This is especially true when return fans are used to support higher return air static loads. The techniques for quieting return ducts are the same as those for supply ducts.

1. Two-inch (5 cm) thick, exposed duct lining is a good silencer. The length of duct that should be lined depends on how much attenuation is necessary. However, a general rule of thumb is to line a run of at least 20 feet (6 m).
2. Size all return air ducts for maximum air velocities not to exceed 900–1,000 fpm. If the flow velocity is too high, elbows, junctions, and insufficiently rounded inside corners generate additional sound.
3. To take advantage of duct end reflection losses, the return duct should terminate within the ceiling plenum.
 - a. Do not install obstructions (such as diffusers or grilles) on the ends of the inlets.
 - b. Allow four equivalent duct diameters of unobstructed straight run following the duct inlet.
 - c. Duct end reflection loss increases as the duct size decreases, so splitting the return duct into multiple, smaller ducts improves the attenuation. Each leg of the return ductwork should be 3–5 duct diameters long.
 - d. More low-frequency attenuation can be achieved by end reflection loss than by adding duct silencers. Splitting the duct into a *T* or *H* configuration provides additional attenuation due to the added length of lined ductwork and increased distance between adjacent duct openings.
 - e. Add a *T* onto a *T* if necessary to get a sufficiently small final inlet cross sections. See *Figure 4*.
 - f. Install internal linings in the termination ductwork for additional attenuation. Use heavier gauge sheet metal to inhibit breakout noise.

4. In-line duct silencers can be very effective sound attenuators. Keep in mind that:
 - a. They can add static pressure loss, which makes the fan work harder and generate more sound, and
 - b. Their performance (both pressure drop and attenuation) is affected by inlet and outlet conditions.

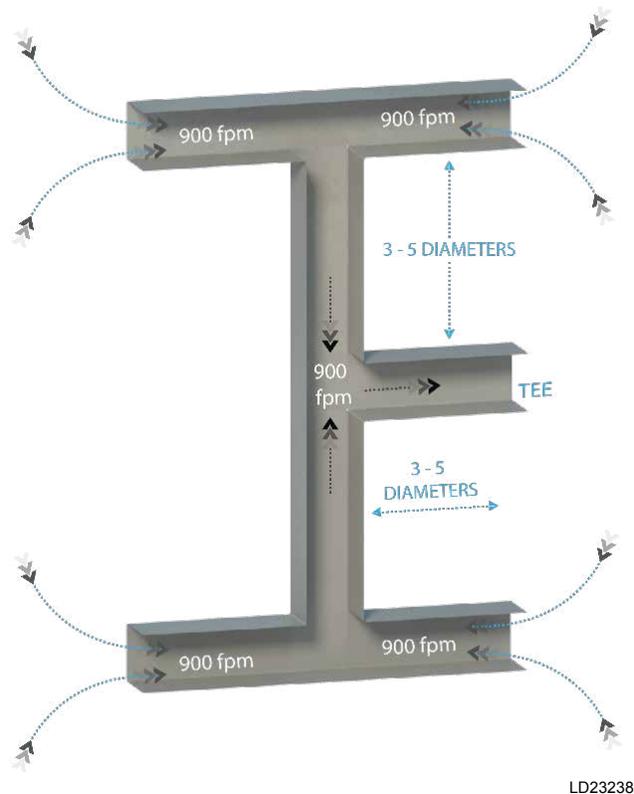


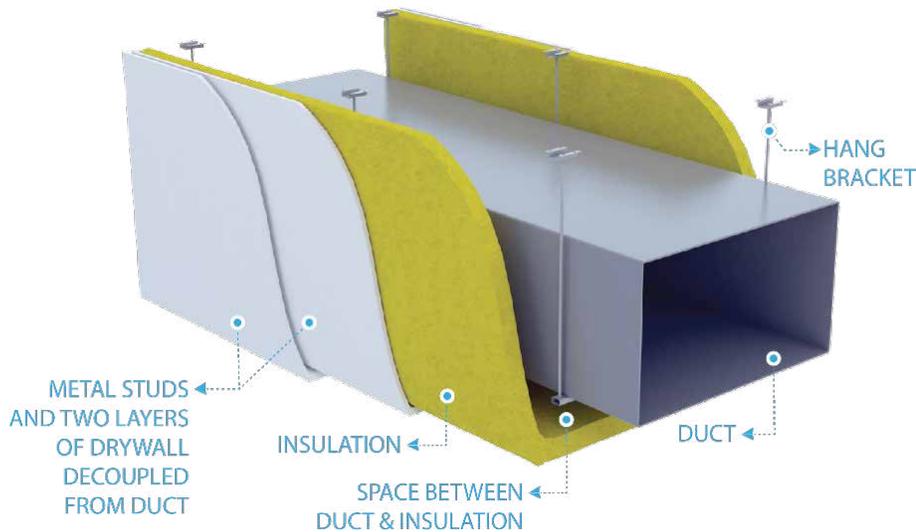
Figure 4: Notional Schematic of T and H Ducts to Split Intake Noise

Supply Air and Return Air: Duct Breakout Path

Even though ductwork is typically made of some solid material, part of the sound traveling within the duct passes outward through its walls. In many cases, the amount of sound that breaks out from the duct in this manner is quite substantial. The following are guidelines for mitigating breakout sound.

1. Place main duct runs, branch runs (when possible), and VAV terminal units above hallways and other non-sensitive areas (rest rooms, copy rooms, etc.) to help attenuate the sound radiated into the occupied spaces. In order to reduce or eliminate the sound radiated to adjacent areas, the walls around these unoccupied spaces may need to be extended from the floor the underside of the roof and be sealed to both.

2. If possible, run supply and return air ductwork horizontally across the roof for some distance before penetrating the roof, as previously discussed. This allows some of the low frequency sound to breakout to the outdoors before the duct enters the building.
3. Use spiral-seam cylindrical duct (internally lined) for the supply air. Round duct has a very high sound transmission loss compared to rectangular duct. Spiral-seam round duct is far superior to rectangular duct in containing low frequency sound (particularly at the 16 and 31.5 Hz octave bands). Note that use of round supply duct requires a properly designed transition immediately following the rooftop unit discharge.
 - a. A two-piece mitered round elbow with turning vanes may be used when space is very limited. If the available plenum height is limited, install multiple, smaller round ducts in parallel. With the ducts running in different directions, there is the added benefit of reducing the duct breakout in any single location. Again, a properly designed transition should be located immediately following the rooftop unit discharge.
 - b. If the unit is located above an occupied space, it is important to make the proper rectangle-to-multiple-round transition in order to prevent noise breakout from the transition into the building space. The flat portions of the transition permit noise to break out. The transition should be fabricated of heavy gauge sheet metal (#14 to #16 gauge). In addition, it is recommended that gypsum board lagging be placed around the transition and extended up to the roof decking, extending both upstream and downstream of the transition section. (See Item 4.)
 - c. Since the high frequency sound is contained within a round duct and transferred down the duct, adding 2-inch (5 cm) internal absorptive lining is recommended. The lining helps attenuate high frequency noise.
4. Rectangular duct is not well suited to resisting the breakout of internal sound. When rectangular ductwork must be used, heavy gauge sheet metal (#14 to #16 gauge) is recommended for the first 20–30 feet (6–9 m) of duct. Add lagging to the outer surfaces of the ductwork. Lagging is any dense material, such as gypsum board, that increases the transmission loss of the duct wall. The effectiveness of the lagging depends upon 1) the material selected, and 2) the method, skill level, and experience of the installer. Three types of lagging are considered to be effective and are listed here from most effective to least effective:
 - a. **Gypsum board isolated from the duct.** Two layers of 5/8-inch (16 mm) gypsum board are supported on a frame that surrounds but does not contact the ductwork. Glass fiber insulation is added between the duct and the gypsum board, but this insulation must not bridge the internal gap. Doing so would destroy the vibration isolation from the duct. See *Figure 5 on page 14*.
 - b. **Mass-loaded acoustical barrier wraps.** A flexible acoustical barrier having an areal mass of at least 1 pound per sq. ft. (5 kg/m²), including an inner layer of acoustical foam or fiber blanket, increases the resistance to duct breakout. Such materials are often referred to as *mass-loaded vinyl barrier*. Refer to the barrier manufacturer's literature for installation details.
 - c. **Gypsum board tight to duct.** Two layers of 5/8-inch (16 mm) gypsum board over a 1-inch (25 mm) thick glass fiber blanket, screwed tight to the duct, provides an acoustic barrier and some vibration damping. No attempt is made to keep the gypsum board isolated from the duct's vibrations.
5. Install a gypsum board ceiling rather than drop-in acoustical tiles. This increases the sound transmission loss of the ceiling, helping to block noise breaking out of the ducts. However, since painted wallboard has lower sound absorption than acoustical tile, sound within the occupied space itself cannot be absorbed.



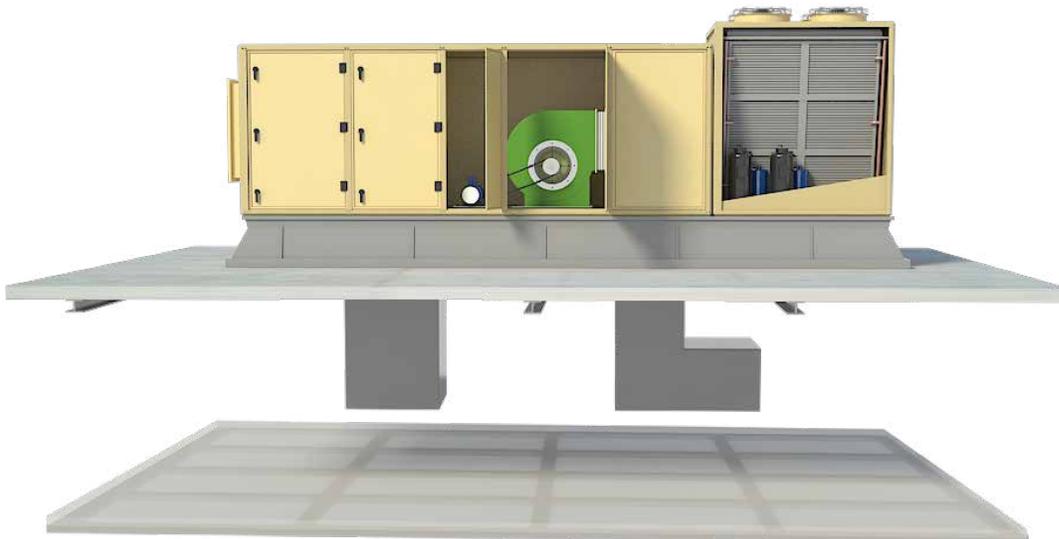
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Figure 5: Notional Schematic of Drywall and Insulation Duct Barrier

Positioning the Unit over Duct Chases

Often a large rooftop unit serves several floors of a building with supply and return ducts running in a duct chase between the floors. Properly positioning the unit over the chase can have a dramatic effect on the sound levels in the occupied areas near the unit. It is best to use an offset-plenum curb that prevents line-of-sight between the discharge plenum and the supply duct, and the inlet plenum and return duct.

Figure 6 shows a construction that provides a high level of path attenuation. Notice that a short run (height of one floor) of return duct is installed inside the chase. This provides some additional return breakout transmission loss, which lowers the sound levels in the chase. Return air openings at the floors include a properly sized silencer and a short run of lined return duct to provide additional attenuation and to move the return airborne sound away from the chase wall. Round duct is used for the supply to reduce duct breakout near the chase wall.



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Figure 6: Notional Schematic of Good Rooftop Installation Practice for Reduced Noise

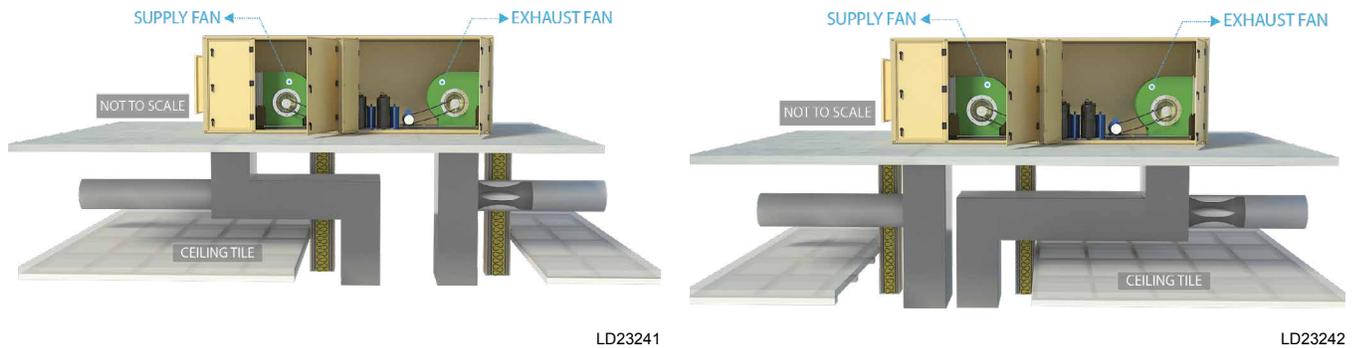


Figure 7: Notional Schematics of Poor Duct Installations for Rooftop Units that Increase Noise

Removing the short run of return duct from the configuration shown in *Figure 6* on page 14 may result in an increase of up to 10 NC for a supply fan only unit and up to 12 NC for a unit with both supply and exhaust fans.

Locating either the supply or return opening over the chase and then ducting the other opening to the chase is not recommended (see *Figure 7*). An exception to this guidance is provided for jobs where a poured concrete roof curb is used. Poured concrete roof curbs are typically used in conjunction with a concrete roof slab to minimize roof transmission. Where a concrete curb is used, the supply opening should be located over the chase, and the return duct should run inside the concrete curb to the chase.

In all applications using a duct chase, it is important that the chase is run all the way to the roof deck and is sealed to the roof deck with acoustical mastic. Supply and return air ducts should not directly touch the penetrations through the chase wall, and the penetrations must be sealed to prevent sound from leaking out of the chase.

Proper Duct Design

In order to successfully meet the acoustical goals for an installation, all sources of sound must be considered. The fans in the rooftop unit are not the only sources of sound in an HVAC system. Aerodynamic noise generates at duct fittings such as elbows, diffusers, dampers, and takeoffs. The sound power levels generated at these fittings depend primarily on the airflow velocity and the fitting geometries, each of which strongly influences airflow turbulence.

To minimize aerodynamic noise, refer to the the ASHRAE handbooks listed in *References* on page 21, as well as the book *A Practical Guide to Noise and Vibration Control for HVAC Systems* when designing a quiet HVAC system (Schaffer 2005).

Avoiding Duct Rumble

Careful duct design is especially important at the discharge of the rooftop unit. Air leaving rooftop units tends to be turbulent. Improper duct design generates very low-frequency rumble. The 2015 ASHRAE Handbook discusses this:

“Duct rumble is low-frequency sound generated by vibration of a flat duct surface. The vibration is caused when an HVAC fan and its connected ductwork act as a semi-closed, compressible-fluid pumping system; both acoustic and aerodynamic air pressure fluctuations at the fan are transmitted to other locations in the duct system. Rumbling occurs at the duct’s resonance frequencies (Ebbing et al. 1978), and duct rumble levels of 65–95 dB in the 16–100 Hz frequency range have been measured in occupied spaces...The very low resonant frequencies at which duct rumble occurs means that the sound wavelengths are very long (10–70 feet), and the rumble can exert sound energy over long distances. Lightweight architectural structures such as metal frame and drywall systems near a source of duct rumble can easily vibrate and rattle in sympathy to the rumble” (Wang and Wise 2015).

The primary cause of turbulence that results in rumble is a large, sudden decrease in static pressure in the duct, usually at an elbow or fitting. The resulting stall regions form and release large, energetic eddies that pulsate against the thin duct walls.

The following are some general recommendations for reducing duct rumble:

- Size rectangular ductwork in such a way as to produce low air velocities. Round duct can be sized for medium velocity airflow.
- Avoid ductwork with large aspect ratios (much wider than tall), especially near the fan.

- Avoid abrupt decreases in static pressure at turns and fittings.
- Avoid abrupt changes in duct direction, especially close to the fans. Use radius bends or turning vanes and angled splits. Never turn to horizontal directly below the unit.
- Stiffen rectangular ductwork sufficiently to avoid its resonant vibration.
- Allow smooth airflow to develop by providing a run length of at least three duct diameters between any duct fittings.
- Choose the most efficient fittings. The greater the pressure drop across a fitting, the greater the flow-generated sound.

For further insight into the causes and solutions of duct rumble, refer to the *ASHRAE Journal's* "Understanding Duct Rumble" (Paulauskis 2016, 40–45). Specific procedures for estimating sound power as generated by various fittings are detailed in the *ASHRAE Handbook—Heating, Ventilation and Air-Conditioning Applications* (Carnes et al. 2007, 701–50).

Roof Airborne Transmission Path

Some of the outdoor sound from a rooftop unit penetrates through the roof itself. The best way to avoid that sound is to locate the unit over an area that is not sound sensitive. If the unit is located directly above a sound sensitive area, additional sound reduction measures will be required.

1. It is important to carefully seal all openings around the ducts with non-hardening acoustical caulk or mastic. A leakage area of approximately 1% results in a 40% reduction in the effectiveness of the acoustical barrier.
2. If the rooftop unit is installed on a curb, minimize the amount of roof that is cut away inside the curb, and fill the remaining gaps with non-hardening acoustical caulk or mastic. Additional mass can be added inside the curb to provide even greater attenuation. Fill the curb with several layers of gypsum board, stagger and seal the joints between sheets, and seal the joints around the duct and between the duct and the curb.
3. Raise the rooftop unit up on supports to lift it further above the roof surface. The supports must be vibration isolated from the roof support structure. Seal all openings around any roof penetrations with non-hardening acoustical caulk or mastic, or if appropriate, use properly sized boots that match and seal to the roof membrane.

4. Increase the mass density of the roof deck. Lightweight, built-up roofs provide very little sound attenuation. It may be necessary to pour a concrete slab in the area under and around the rooftop unit. As general rule-of-thumb, the slab should extend out past the edges of the unit by 1.5 times the height of the unit.
5. It is difficult to predict the sound contribution coming from the base pan of a rooftop unit, because the strength of that particular sound source is not measured as part of any rating standard. A conservative approach is to treat the portion of the roof under the curb in the same manner as the roof surrounding the unit. For example, if a concrete slab surrounds the unit, concrete should also be used inside the curb.

Structure-Borne (Vibrational) Paths

The structure-borne path is unique because the source of the sound is vibration that travels through the building elements and then radiates into occupied spaces. The fans and compressors inside the rooftop unit generate vibrations that are transmitted to the frame of the unit. A fraction of this vibrational energy is then transmitted to the structure of the building. From there, the vibration follows various paths and is then re-radiated into the occupied space as audible sound.

As with airborne paths, it is possible to predict what is required to prevent structure-borne vibration from being a problem. However, structure-borne paths are often difficult to identify, and the calculations are complex. Since structure-borne vibration is less likely to be a problem than airborne sound, it is common to follow a few general best practices rather than do a complete analysis.

The first line of defense against transmitted vibrations is the use of properly-sized isolation mounts under the unit's base rails. In most installations, this provides enough vibration reduction to prevent structure-borne noise issues. The amount of additional isolation required between the mainframe and the building is largely dependent on the building's structure where it supports the unit.

Guidelines on vibration isolation are provided in *A Practical Guide to Noise and Vibration Control for HVAC Systems*:

"The roof structure should be stiff enough to deflect no more than 1/4 inch (0.6 cm) under the combination of the dead load and the operating load of the unit. This may require 20-foot (6 m) column spacing in the vicinity of the unit" (Schaffer 2005).

For equipment larger than 20 tons (70 kW) of cooling capacity, the guide goes on to recommend:

“For installations over noise sensitive areas, mount the unit on high-deflection spring isolators resting on grillage that is supported 2–3 feet (0.6–0.9 m) above the roof line by extensions of the building columns” (Schaffer 2005).

Note: Although rare, the use of both internal and external vibration isolation can cause the system to experience resonance conditions. Such conditions can contribute to indoor sound and, in extreme cases, may result in damage to unit components.

Finally, an *ASHRAE Transactions* article entitled “Sound and Vibration Considerations in Rooftop Installations” suggests the following guidelines for static deflections of installed isolation springs:

“A rooftop unit mounted on a good, stiff roof can use an isolation system with 1–2 inch (2.5–5 cm) static deflection on the springs. But a unit on a flimsy roof may require 3–5 inches (7.5–12.5 cm) of static deflection to achieve adequate vibration isolation because of the lower natural frequency of the flimsy roof” (Harold 1991).

Proper installation of the springs is just as important as proper specification of them. Spring effectiveness can be virtually eliminated by *mechanical short circuits*. These happen as the result of any of the following installation mistakes:

- Attaching an electrical conduit (or pipe) to the rooftop unit and then to the roof (or curb) without flexible connectors.
- Placing any material (roofing tar, scraps of wood, etc.) between the bottom of the unit and the top of the curb.
- Applying horizontal pressure to the unit (usually through misalignment) that causes the spring guides to make continuous contact.
- Attaching ductwork to the unit without flexible connectors.

Proper isolation to eliminate vibration transmission is only possible if the building structure is sufficiently rigid to serve as a base for the mechanical equipment. To help isolate the unit from the building, consider the following:

1. Locate the unit over an unoccupied area of the building (such as a storage room, rest room, or hallway) and over vertical supports. This minimizes the roof deflection and vibratory transmission. Do not locate the unit in the middle of a horizontal beam. Avoid large column spans!

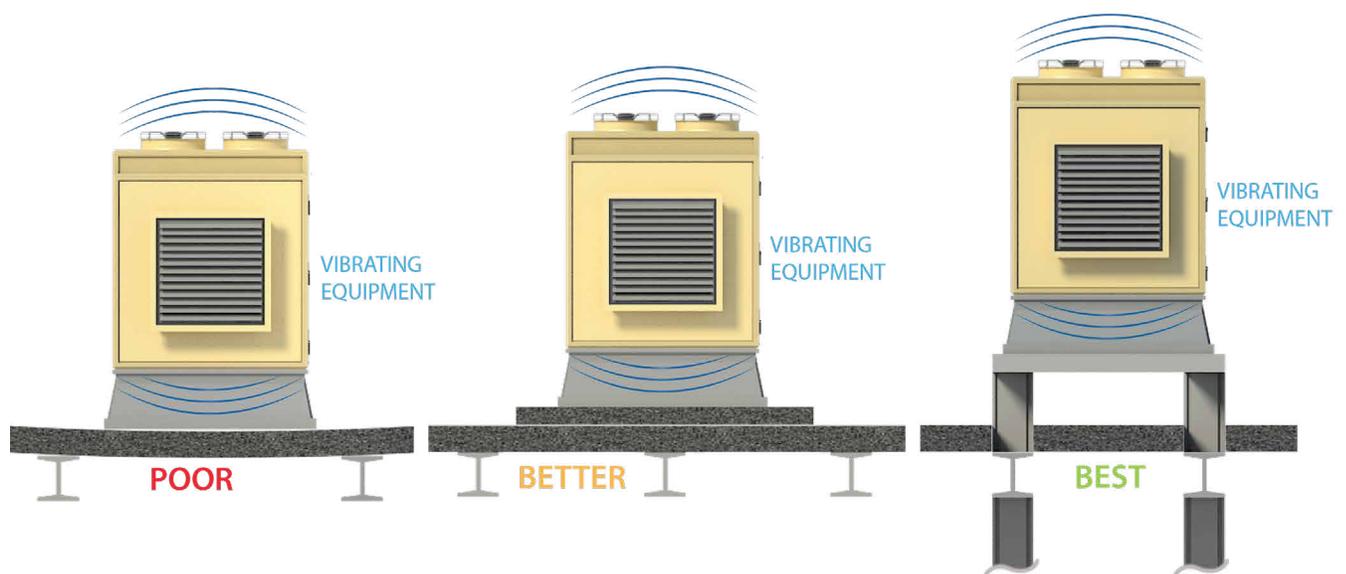


Figure 8: Schematic of Poor Rooftop Installation, Use of Reinforcing Slab, and Direct Mounting on Building Columns

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2. Use an inertial base or solid concrete pad as a base for the rooftop unit. This mass, when properly supported, impedes vibration and prevents low frequency noise from breaking through the roof directly below the unit. It also provides a stiff foundation under isolation springs, so that they can perform their function as designed.
3. Isolate the unit on spring isolation rails selected to match the characteristics of the roof structure.

Note: Do not allow large rooftop units to be installed on buildings with a lightweight roof structure unless column supports are provided that are independent of that roof structure. Otherwise, the entire lightweight roof structure in the vicinity of the unit can vibrate, and this vibratory motion then transmits throughout the entire building structure.

4. Always use an approved, fire-resistant, flexible canvas connector when connecting supply and return ducts to the rooftop unit or curb.
5. After penetrating the building envelope, and especially when dropping the duct through a vertical chase, do not allow the duct to come into direct contact with chase walls or to be rigidly attached to any structural members of the building. Use properly sized and installed hanger isolators and do not allow ductwork to be mounted in direct contact with the walls or any part of the building structure.

Additional guidance is available in the following publications:

1. The *ASHRAE Transactions* article “Sound and Vibration Considerations in Rooftop Installations” addresses sound control from the full-system viewpoint (for example, building structures, air distribution systems, and the rooftop equipment) (Harold 1991).
2. The *ASHRAE Journal* article “Practical Guide - Controlling Noise from Large Rooftop Units” (Guckelberger 2000, 55-62).
3. Additional reference materials listed at the end of this publication.

General Recommendations for Rooftop Units: Outdoor Sound

As is the case with indoor sound, no single, generalized list of acoustical practices can achieve the outdoor sound requirements in every installation. Some of these practices introduce increased costs that may or may not be justified by the specific acoustical requirements. For this reason, a thorough acoustical analysis is recommended, in order to meet the acoustical goals at the lowest cost. This section introduces typical methods of sound attenuation that can be deployed as needed during the system design and acoustical analysis.

Quieting the Sources

Fan Selection and Speed

As discussed in the section on outdoor sound, the condenser fans are often the dominant contributors. There is less flexibility in selecting condenser fans for packaged units than in selecting the supply, return, and exhaust fans.

The first rule of fan noise is *slower is lower*. Sizing the unit so that the fans can run at a lower speed can have significant benefits in radiated sound. Likewise, selecting units with variable speed fan motors helps.

Another option is the selection of purpose-built, low noise fans. These fans feature blades that move air with increased efficiency and lower sound levels, especially the tones related to the blade rate. For critical applications, low noise fans may be necessary in order to meet requirements.

Compressor Covers and Blankets

Compressors, by their nature, are vibrationally energetic, and their shells radiate sound. While the sound radiated by compressors is almost always less than that from the condenser fans, there are cases and applications where reduction of the compressor sound can be beneficial.

The most common approach is a “path” treatment applied directly to the compressor. These come in the form of mass-loaded covers or *blankets* that enclose the compressor shells. Drop-on blankets are typically of marginal effectiveness, providing 1–3 dB reduction in sound. This is because they do not seal around the entire compressor, and the majority of sound energy can still escape. Closed, fitted blankets can provide better reduction from 2–5 dB.

Besides the added cost of covers and blankets, they provide thermal insulation, as well. This can potentially reduce the life of the compressor, which is designed assuming that a certain amount of internal heat can radiate away from the shell. Check with the compressor manufacturer before installing closed, fitted blankets.

Despite the drawbacks of compressor covers, there are situations in which the higher-pitched harmonics from the compressors, while not necessarily of dominant overall sound level, are particularly annoying to neighbors. In these cases, covers can provide a modicum of relief.

Mitigating the Paths

Mitigating the outdoor sound transmission paths for rooftop units is challenging. By their nature, the units must be exposed to the atmosphere in order to operate. This limits the effectiveness of most mitigation strategies. The key strategies include distance and blocking line-of-sight.

Locating the Unit

Along with the constraints imposed by the requirements for locating rooftop units relative to the indoor spaces, one must also consider the effect of placement on outdoor sound propagation.

Firstly, the most benefit can be gained if the unit is located as far from critical receivers as possible. If an installation is fortunate to have one or two directions with distant or non-critical receivers, those areas should be favored. It is very typical of commercial and retail buildings that they back onto residential areas. Placing rooftop units all the way to the rear of the roof for aesthetic reasons will put those receivers at additional risk. If the site is surrounded by critical receivers, or if a requirement is imposed around the entire property line, the best location is in the center of the roof.

Secondly, avoid locating the unit close to additional vertical structure that extends above the roof, unless that structure is shading critical receivers. Any receiver that is in line to receive reflection from the vertical structure will experience increased sound levels.

Lastly, do not place the unit directly beneath occupied spaces, especially if there are windows overlooking the unit.

Positioning the Unit

As mentioned previously, sound from large rooftop units does not propagate outwards equally in all directions. For units with barometric relief or return fans operating at a relatively light load, orienting the return section of the unit toward the most critical receivers can be beneficial.

Adding Sound Barriers

The single most common strategy for mitigating rooftop unit outdoor noise is the addition of sound barriers. There are many manufacturers, types, and styles of barriers available. Key considerations to barrier selection are height, mass, coverage, absorption, and the unit's requirements for airflow.

The primary consideration for a barrier is its height. The barrier must block line-of-sight to the critical receivers in order to be effective. However, sound can still diffract over the top, so additional height is needed. A common rule of thumb is that the barrier should be at least 30%, and preferably 50%, taller than the height of the condenser fans.

A barrier is not effective if it does not block sound from the sides as well. The best approach is to surround the unit. If there are one or more sides that are not critical, then the barrier need not intervene on those sides. But it must either wrap around toward those sides or extend beyond the unit, again by at least 30% and preferably by 50% of the unit's length.

A barrier must have considerable mass in order to block sound from passing through it. A commonly seen mistake is to think that decorative fencing constructs a sound barrier. Properly manufactured barriers carry sufficient mass to block sound effectively. Similarly, even small gaps in a barrier defeats its purpose; it must be closed. A gap can remain at the bottom of the barrier to allow airflow, but it must be blocked by the extension of the rooftop. For example, a gap on the edge of a roof defeats the barrier in that direction.

The best-performing barriers are those that are *absorptive*. That is, they can absorb sound on the unit side. Such barriers cost more per foot than non-absorptive types, but they have come into such common use that the cost differential has been reduced significantly.



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Figure 9: Barrier System Around Rooftop Unit

Finally, the barrier must allow the unit to continue functioning to its full capacity. This can be a major constraint on the barrier. As previously mentioned, if the unit is sufficiently away from the edge of the roof, there can be a gap at the bottom of the barrier to allow air to flow to the unit. If the geometry of the site is such that the barrier must seal to the roof all the way around, then relief must be installed in the form of absorptive louvers. Several manufacturers supply such louvers for a large range of flow requirements.

Properly designed sound barriers introduce very significant weight and wind loads to the roof and building structure. In new construction, it is best to design for this consideration. In retrofit construction, structural modification is likely necessary. Though costly, it often has the added benefit of stiffening the roof and support near the unit, as discussed above in the section on structural vibration.

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