Controlling HVAC system noise is essential to the quality of the listening environment in classrooms. The American National Standards Institute Standard S12.60-2002 — *Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools* calls for a maximum background sound level of 35 dBA for classrooms less than or equal to 20,000 ft³ (566 m³), and 40 dBA for classrooms that are greater than 20,000 ft³. These levels are much lower than previously recommended. Careful attention to the design, selection, and detailing of HVAC systems in schools is required to achieve these lower levels.

To control HVAC system noise, individual components of the total noise perceived by a listener must be identified. This noise can be classified as one of five types, each of which can be controlled through good design and construction practice. The types are present in all HVAC systems to varying degrees, and are common problems in schools.

1. **Airborne noise** is radiated from equipment such as air-handling units, fan coil units, heat pumps, through-the-wall heat pumps, etc., the noise is transmitted through the air and directly through walls, windows, doors or ceilings into adjoining spaces.

2. **Self-generated noise** is produced as air moves through a confined duct system. Noise is generated at points of turbulence such as dampers, elbows, T-junctions, and air terminal devices, among others, in the ducted air system. Self-generated noise levels increase with air velocity and the number of turbulent air points within the system.

3. **Duct-borne noise** originates at a noise generating source, such as a fan in an air handling unit, and is carried down the ducted air path to listeners in rooms located remote from the noise generating source. This type of noise can travel through the supply ducts, the return ducts, the ventilation ducts or the exhaust ducts. Rooms closer to the units usually have higher duct-borne sound levels than rooms that are farther from the units.

4. **Structure-borne noise** results from vibrations of rotating or vibrating equipment, such as fans and chillers, that vibrate a part of the building such as a floor slab or structural frame. The vibration is transmitted through the structure, sometimes over great distances, where it vibrates a lighter weight assembly or material such as a ceiling grid or a piece of gypsum board that then re-radiates the sound into a space.

5. **Breakout noise.** The first type of duct breakout noise is noise generated by high speed or turbulent air in ducts that cause the duct walls to vibrate and radiate low frequency noise. The second is low frequency noise from a remote source, such as the fan in an AHU, transmitted down the duct path, through the duct walls, and into a space.

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8 Case Studies

Presented here are acoustical results from eight case studies describing different types of HVAC systems used in schools throughout the southeast United States. Several instances of design approaches that failed to meet the standard also are presented along with potential methods to remedy the situation.

1. Through-the-Wall, Self-Contained Heat Pump Units

Case Study 1 actually consists of several classrooms from schools served by through-the-wall heat pump units. The units have a self-contained refrigeration machine that includes a compressor and condenser section mounted within the unit, an evaporator coil, and a fan to circulate air from the unit to the classroom. The fan must throw the air across the classroom at a relatively high velocity. The combination of high velocity air movement and the major noise making devices, such as the condenser fan, circulating air fan and compressor located on the classroom wall, results in very high noise levels in the classrooms. Noise levels of NC 45 (approximately 50 dBA) to over NC 65 (approximately 75 dBA) were measured in classrooms in Florida with these systems operating. Under no condition, other than off, was this type of unit capable of achieving a 35 dBA background noise level. Many surveyed teachers turned off the air-conditioning units when they tried to speak to the class and ran the units when students were out of the classroom so the noise would not interfere with classroom activities.

2. Modified Through-the-Wall, Self-Contained Heat Pump Units

Case Study 2 consists of a through-the-wall heat pump that was modified by a local school board to reduce the noise associated with these units. The modified installation had short duct runs from the unit to the classroom on the supply and return sides of the unit. The unit was mounted on the exterior concrete masonry unit (cmu) wall of the building. A gypsum board chase wall was built between the cmu wall and the classroom. Interior noise levels of 48 to 51 dBA (NC 45-50) were measured in the classroom. High air velocities at the return air opening and duct-borne noise dominated the noise measured in the classroom. Teachers and administrators commented that the sound levels from the heat pumps were greatly improved compared to the original design. However, they still did not meet the 35 dBA requirement in the acoustical standard.
Case Study 3 consists of an elementary school with classrooms arranged along a central corridor. The corridor has a mezzanine with a concrete floor located above the acoustical tile ceiling that runs the entire length of the building. One water-source heat pump for each classroom is located on the mezzanine. This provides individual temperature control for each room independently of the other classrooms. A fan and a coil are in each heat pump unit. The walls between the classrooms extend to just above the acoustical tile ceiling. A large, open attic/plenum space is above the classroom ceilings. Return air is brought from the classroom into the unit through a very short return duct. A network of supply air outlets is spaced evenly throughout the classroom.

The primary types of noise include airborne and duct-borne noise. Noise from the fan travels through the short return duct and is heard at levels of NC 40 to NC 45 (47–52 dBA) in the room. This is combined with airborne noise that is produced by the fan in the unit. The noise is transmitted through the sheet metal walls of the heat pump into the ceiling plenum, through the acoustical tile ceiling and into the classroom at a sound level almost equivalent to the return air noise. Sound levels propagated through the supply duct are much lower than the return duct and casing radiated noise because of the longer duct run, low air velocities in the supply ducts and small fan sound power level. A background noise level of 35 dBA would likely have been possible if the walls between the heat pumps and the classrooms were of sufficient mass and extended to the roof deck to control the airborne noise, and a greater length of return duct with acoustical lining or a silencer, if necessary, was installed to control the duct-borne noise.

Case Study 4 is a school for profoundly handicapped children. The basic design has a series of buildings consisting of groups of four classrooms arranged around a central corridor. The rooms are air-conditioned by individual fan coil units located in a mechanical room behind each classroom. The mechanical room walls are constructed of painted concrete block extended to the slab above and sealed with caulk at the perimeter to control airborne noise.

The majority of noise sources were addressed. The fan coil units are located so there are adequate lengths of ducts to reduce duct-borne noise, and ducts are sized for appropriate air velocities to reduce self-generated noise. There are also sound attenuators located in both the supply and return ducts to reduce duct-borne noise to the 35 dBA called for in the standard. However, sound levels measured inside the classrooms were 48 dBA, or NC 40, due to a bathroom exhaust fan, with no sound attenuator, added late in design and located directly adjacent to the classroom space with just the bathroom door between the classroom and the loud fan. Relocating the fan in the mechanical room and ducting it to the bathroom with a sound attenuator in the duct was recommended to reduce the noise levels to 35 dBA or less.
Case Study 5 is a two-story school with classrooms lined up on both sides of a double loaded corridor on both the first and second floors. Fan coil units located in a specially designed closet inside each room are used for heating and cooling purposes only. A primary air AHU, located on the second floor above a classroom with ducts running through the corridor provides ventilation air for the individual classrooms. An amount of air equal to the ventilation air is exhausted from each room as well.

The primary air AHU has a silencer in the main supply duct serving each wing to reduce duct-borne sound levels. The unit also has external spring isolators to reduce vibration transmitted to the floor slab. The fan coil units are located in a closet in each room. There is a full return duct with a silencer in it that runs vertically from the bottom of each fan coil unit to a return grille in the ceiling. The supply duct moves through a small silencer into a network of ducts serving each classroom. The walls of the fan coil unit closet are constructed of two layers of 5/8 in. (16 mm) gypsum board on each side of 3-5/8 in. (92 mm) metal studs with 3.5 in. (89 mm) of glass fiber batt in the cavity and sealed at the perimeter with caulk to limit airborne sound transmission into the classrooms and to achieve a nominal sound transmission class (STC) rating of 55. The doors to the closets open into the hallways.

The walls of the mechanical room containing the primary air AHU are constructed of 8 in. cmu (concrete masonry unit) with a separate stud wall held off 1 in. from the cmu wall and consisting of one layer of 5/8 in. (16 mm) gypsum board on 3.5 in. (89 mm) studs with 3.5 in. (89 mm) glass fiber batt in the cavity. The wall is sealed at the perimeter with caulk. This construction is designed to reduce airborne noise from the AHU to the classrooms on either side of the mechanical room to meet the background noise design goal of NC 30. This wall assembly has a nominal STC rating of 64.

The floor of the mechanical room consists of a 4 in. (100 mm) floating concrete floor over the 4in. (100 mm) nominal structural slab with a suspended gypsum board ceiling below to reach a nominal STC rating greater than 65.

Case Study 6 is a school with several two-story buildings that have mechanical rooms located at each end of the buildings with classrooms clustered around the mechanical rooms. The intent of this design concept was to minimize the distance between the AHUs and the classrooms. The main supply and return ducts are routed at high air velocities (2,000 to 2,500 fpm [10 to 13 m/s]) directly from the mechanical rooms to the ceiling space above the adjacent classroom. The only separation between the ducts and the classrooms was the acoustical tile ceiling. Breakout noise from the high velocity air moving through the multiple turns in the ducts was measured at NC 45 to NC 55 (approximately 50 to 60 dBA) in the classrooms nearest to the mechanical rooms. This design concept was repeated on each side of the building, on multiple floors, and in multiple buildings. Rooms farther down the duct path were much quieter.
School HVAC

To reduce the self-generated air velocity noise and the breakout noise, the main ducts had to be enlarged. The ducts could not be enlarged to the extent required to reach 35 dBA, so a mass-loaded vinyl lagging was added to the outside of the ducts to reduce the breakout sound levels. Additionally, a sound attenuator was added in the supply and return ducts to reduce duct-borne sound levels, the branch duct take-offs were moved farther down the duct path to provide more sound attenuation, and additional branches and air terminal devices were installed to reduce self-generated air velocity noise.

Central AHU Systems with Mechanical Rooms Separated from Classroom Buildings
Case Study 7 is a two-story school with classrooms lined up on both sides of a double-loaded corridor on both floors. The mechanical rooms are located in separate buildings in courtyards between the classroom buildings. This provides adequate control of airborne sound transmission between the mechanical room and adjoining classrooms. The ducts were designed to run in the structural area beneath a floating concrete floor slab above the structural floor slab, and a spring mounted gypsum board ceiling was installed in the classroom below, in addition to the acoustical tile ceiling. The AHU's were installed on spring type vibration isolation mounts to reduce structure-borne noise transmission. The terminal units were selected to provide radiated noise levels less than NC 30 in the classrooms. Duct-borne noise is reduced by the length of duct between the AHU and the classrooms and silencers located in the supply and return duct risers. As of the publishing date of this article, measurements have not been made to confirm that actual sound levels achieved in the classroom are less than NC 30.

AHU in Mechanical Penthouse with VAV Terminal Units Over Classrooms
Case Study 8 is a large school in a city near a major interstate highway. The classroom building is three stories tall with a large mechanical room in a penthouse on the roof above a third-floor classroom. Main ducts are run vertically through a large chase that is separated by a cmu wall from the adjoining classroom. Air distribution was through a variable air volume system with terminal units located in the ceiling space of each classroom.

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Acoustical Design Guide

Nine acoustical design guidelines for HVAC systems in schools have been derived from the case studies and recommendations commonly found in the literature. This list is meant to bring attention to aspects of the most important noise and vibration control issues to consider in the design of HVAC systems for schools. Most of the guidelines are neither too elaborate nor too expensive to follow in a school project and are part of the general knowledge within the fields of mechanical engineering, architecture and building construction, so new technology and expensive, uniquely designed items are not required to implement them.

1. Coordinate mechanical equipment selection with space planning. Mechanical engineers have many options for providing conditioned air to classrooms and other spaces in schools. One of the criteria used in selecting one particular system over another should be the noise associated with the equipment. In general, a balance must be struck between the loudness of the source and how far it must be located from the space it is serving to meet the desired background noise. Achieving this balance requires coordination between the mechanical engineer (system selection), architect (space planning), and acoustical consultant (distance and enclosure construction requirements). In general, follow these guidelines for some of the more common systems:

   • Decentralized fan coil units and heat pumps, if located adjacent to a classroom, should be fully enclosed by walls of relatively high mass, and the door to the equipment room should open to a corridor or other non-critical space.

   • Central rooftop units serving multiple rooms should be located over non-critical spaces on concrete roof slabs, and an adequate distance from the rooms they serve.

   • Central systems with VAVs or fan coil units (FCUs) should be installed in mechanical rooms that are separated from classrooms by buffer spaces such as corridors, and an adequate distance from the rooms they serve.

   • Distributed systems should be separated from the classroom by buffer spaces such as corridors, and an adequate distance from the rooms they serve.

   • Self-contained, wall-mounted heat pump units typically cannot be used in their present form and still achieve the 35 dBA requirement in the standard without major noise mitigation design, and even then are still not likely to meet the standard, as demonstrated by Case Study 2.

2. Construct the mechanical equipment room/closet enclosure of sufficient mass to isolate the airborne noise radiated by mechanical equipment from nearby classrooms. Massive wall constructions such as CMU or multilayered gypsum board on each side of single or double metal studs around mechanical rooms/closets should be provided.

   Recommendations for mechanical equipment room sound-isolating construction assemblies can be found in Chapter 47 of the 2003 ASHRAE Handbook—HVAC Applications. The enclosure construction should be based on the sound level of the equipment, the transmission loss characteristics of various wall types, the sound absorbing characteristics of the receiving room, and the background noise criteria in the standard. Enclosure walls must be extended up to the slab above and sealed with caulk. All penetrations through the enclosure must be sleeved and sealed. Doors to the mechanical room/closets should open into corridors or other non-sensitive areas, rather than directly into the classroom.

3. Reduce source sound levels to the extent possible. The first approach to any noise reduction strategy is to reduce the source sound levels, particularly when the source must be located near the receiver. Avoid the use of forward curved fans in large air-handling units, as these fans generate high levels of low frequency sound that is difficult, and costly, to attenuate. Also, design constant volume fans to operate at peak efficiency, and use variable frequency drives to control the fan speed on variable volume air-handling units in lieu of variable inlet guide vanes.

4. Install duct-borne noise control devices as required. In typical school buildings, where AHUs are located in close proximity to the rooms they serve, it will be difficult to meet the background noise level requirements in the standard using only unlined sheet metal ducts. Some combination of sound attenuators, sound plenums, and acoustical flex duct likely will be required to achieve conformance with the standard. Acceptable alternatives to glass fiber duct lining, which is rarely allowed in school buildings today, particularly in the humid southeast United States, might include duct liners with protective coatings, organic fiber duct liners with antimicrobial treatment, double-wall duct with perforated inner liners, film-lined sound attenuators, and sound attenuators with no acoustic media (also known as packless silencers).
Chapter 47 of the 2003 ASHRAE Handbook—HVAC Applications, describes a procedure for determining the extent of duct-borne noise control devices required based on an analysis of the sound levels of the equipment, location of the equipment, and the length of duct between the equipment and the classroom.

5. Follow the guidelines in the literature related to air velocities, airflow, and air balancing for quiet mechanical systems. Larger ducts that allow slower air velocities and a duct system designed to meet ASHRAE and SMACNA guidelines for smooth airflow, are required to limit self-generated noise and meet the 35 and 40 dBA background noise limits in the standard. Self-generated noise from air turbulence can occur at any point in a system, and is most problematic when it occurs close to the space being served. Reference the literature for in-depth discussions of air movement related noise issues.\(^{1,3,5}\) In general, the following should be considered:

- Size ducts not to exceed the air velocities, in feet per minute, given in Table 1, within ±50 fpm (±0.25 m/s).
- Install flex duct without kinks, harsh bends, or offsets. Offsets in flex duct of one-half the duct diameter or more can result in sound levels in the space below that are 12 to 15 dB higher than the manufacturer’s published values.\(^2\)
- Install volume dampers and other balancing and control dampers a minimum of three duct diameters upstream of air terminal devices or design a self-balanc-

**Table 1: Airflow velocity guidelines for HVAC ducts routed to classrooms. Values represent the recommended airflow velocity in fpm, ±50 fpm (±0.25 m/s), at a given distance from the terminal device in the space being served by the duct.**

<table>
<thead>
<tr>
<th>dBA Criteria of Room Served</th>
<th>Supply or Return</th>
<th>Through the Air Terminal Device</th>
<th>Device to 10 ft, Including the Neck</th>
<th>11 ft to 20 ft</th>
<th>21 ft to 30 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>35 dBA</td>
<td>Supply 350</td>
<td>425</td>
<td>550</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Return 425</td>
<td>500</td>
<td>650</td>
<td>800</td>
<td></td>
</tr>
<tr>
<td>40 dBA</td>
<td>Supply 425</td>
<td>500</td>
<td>700</td>
<td>850</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Return 500</td>
<td>600</td>
<td>800</td>
<td>1,000</td>
<td></td>
</tr>
</tbody>
</table>

Advertisement in the print edition formerly in this space.
ing duct system. Avoid opposed blade dampers on air terminal devices if possible.

- Select air terminal devices (grilles, registers, and diffusers) with NC ratings of 18 or less.

6. Avoid common duct routing pitfalls. Well-intentioned designs can result in poor acoustical conditions if these three common mistakes are made:

- **Pitfall 1: Using Unducted (or Plenum) Returns.** Return air should be ducted back to the air moving equipment through ducts of similar length and with similar noise control devices as the supply ducts. In some cases, a ceiling return plenum with sound attenuating transfer ducts to a corridor may be used, but care should be taken to ensure that the overall STC rating of the wall assembly is not affected by the sound escaping through the transfer duct.

- **Pitfall 2: Routing Noisy Ducts Above Sound Sensitive Spaces.** Fan noise in main supply and return ducts from large air handling units routed directly above sound-sensitive spaces, such as conference rooms and classrooms, can break out of the ducts and into the space below. Ducts should be routed above storage rooms, bathrooms, or other acoustically nonsensitive spaces before penetrating the envelope of a classroom or other sound sensitive space. If this is not possible, increasing the sheet metal gauge, using round or flat oval duct, lagging the duct with a mass loaded vinyl wrap, or enclosing the duct in a gypsum board soffit may be required to control breakout noise.

- **Pitfall 3: Routing Common Ducts Above Adjacent Sound Sensitive Spaces.** Unlined supply or return ducts that are routed over adjacent spaces, without branches or splits in the duct, can lead to the crosstalk phenomenon, where sound in one space is transferred to another through the common ductwork. The preferred method for eliminating crosstalk is routing ducts through a common corridor and routing branch ducts separately into the adjacent rooms.

7. Install vibration isolation devices on HVAC equipment. Install vibration isolation devices as recommended in Chapter 47 of the 2003 ASHRAE Handbook—HVAC Applications. At a minimum, this should include vibration isolation devices on all equipment containing rotating or vibrating parts, and flexible connectors on all pipes and ducts connecting to the equipment.

8. Monitor the value engineering process. During the value engineering process, where cost reduction is typically the primary focus, items such as duct liner and sound attenuators often are perceived as luxury acoustical items or “acoustical adds” rather than as integral parts of a standard system design necessary to achieve 35 dBA of background noise in a classroom, and attempts are made to delete these items. This process must be monitored to ensure that the integrity and intent of the design is maintained.

9. Monitor the construction process. The successful implementation of HVAC noise control systems on school projects designed to meet the requirements in the standard requires an attention to details not often seen by contractors on typical projects. Acoustics should be considered during all aspects of the construction process. It is imperative that the design team carefully review submittals related to acoustical items such as vibration isolators, equipment sound levels, duct sizes, duct silencers, duct lining, etc. Also, site reviews should be conducted to ensure that equipment is installed properly, vibration isolators are deflecting properly, penetrations of ducts and pipes through sound critical walls are sleeved and sealed, and unforeseen site conditions have not resulted in modifications to the HVAC system that are detrimental.
to the acoustics. An air balance report should be reviewed to ensure that air velocities in the ducts are as designed.

Conclusions

Designing classrooms with background noise levels that are in conformance with ANSI Standard S12.60-2002 is possible, but requires a team effort that begins at the earliest stages of design when critical decisions are made regarding space planning, system selection, and cost allocation.

Communication among architects, mechanical engineers, structural engineers, and acoustical consultants must take place early in the design process to integrate the HVAC system and the architectural design in such a way as to work in favor of a quiet system design rather than against. Recognition of the primary sources of noise in HVAC systems is essential, and how to reduce or avoid these sources should be considered at all times during the design and construction process.

The case studies presented demonstrate that if each of the recommended design guidelines for HVAC systems in schools are appropriately addressed during the design and construction process, and the detailed recommendations in the literature are followed, the ANSI standard background noise criteria for classrooms can be achieved. Failure to address even one of these guidelines can result in nonconformance with the standard.

References