Reducing Compressor Noise While Considering System Interactions

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ABSTRACT

Refrigerant compressors can be a primary noise source in residential air conditioning and heat pump systems. When evaluating the contribution of a compressor to the total noise, it is necessary to consider how the compressor couples to the condensing unit. Compressors typically couple to the condensing unit via three different types of noise paths. First, the compressor couples structurally to the base pan, refrigerant tubing, and electrical wiring. Also, the compressor is coupled acoustically to the system via the refrigerant gas in the tubing and condenser coils. Finally, sound waves radiating from the compressor housing interact with the acoustic environment in and around the condensing unit. Often, the most effective noise reduction solution addresses the coupling of the compressor to the system rather than the compressor as an exclusive noise source.

This paper offers design guidance while summarizing the results of a program to reduce the sound and vibration of a residential air conditioning - heat pump unit. An approach is demonstrated for reducing compressor noise while considering system interactions. Techniques are discussed for identifying and ranking the noise transmission paths. Results are presented of an experimental modal analysis conducted on the condensing unit cabinet. The modes of vibration that contribute to system noise are identified; and solution methods for alleviating the effects of the resonance modes are presented. Also, an approach is discussed for quantifying and reducing the contribution of discharge pressure pulsations to condensing unit noise.

INTRODUCTION

Low noise operation is an increasingly important design requirement of residential air conditioning and heat pump (AC-HP) systems. As air conditioning becomes available to more of the world’s communities, the intrusiveness of noise from AC-HP systems becomes less acceptable. Moreover, the condensing unit represents the primary source of noise in a residential AC-HP system. Condensing units are typically located outside an exterior wall and may expose neighboring residences to unwanted sound. In urban settings and other efficient living areas, excessive noise from AC-HP condensing units has become a community issue.
A typical residential AC-HP condensing unit consists of a set of condensing coils and tubing, a sheet metal cabinet and framing, a base pan, a fan, and a refrigerant compressor. Since the compressor supplies the fluidic power to drive the refrigeration circuit, it is usually the focus of noise reduction initiatives. In order to control system variables and separate the sources during noise evaluations, the compressor is typically removed from its condensing unit and operated via remote calorimeter. Indeed, ARI Standard 530 outlines a method for rating the sound and vibration of refrigerant compressors [1]. Unfortunately, using sound and vibration data from a compressor operating independent of its condensing unit as the sole method for quantifying compressor noise completely neglects system interactions. The condensing unit will amplify or attenuate sound and vibration generated by the compressor. Therefore, the most effective noise reduction solutions must consider system interactions.

**COMPRESSOR – CONDENSING UNIT COUPLING**

**Acoustic Control Volume**

Before discussing the coupling of the compressor to the condensing unit, the study should be framed by looking at the condensing unit installation. Most residential condensing units in the U.S. are placed on massive foundations (slabs) lying on the ground outside. In these cases, the transmission path for structural energy from the compressor is assumed to terminate at the condensing unit – slab interface. Gaining in popularity among installation technicians, however, is the use of lightweight, prefabricated slab materials. Slabs manufactured from these materials will readily accept structural energy and radiate that energy as sound. In urban settings and in vertical housing construction, condensing unit installations on building sides or rooftops is more common. Thus, the assumption is no longer valid that structural energy flow originating at the compressor terminates at the condensing unit base pads.

In order to evaluate compressor – condensing unit coupling, imagine an acoustic control volume enclosing the compressor, Figure 1. Noise energy flow paths through the control volume are categorized as structural or fluidic. Structural transmission consists of energy flow through the mounting feet into the base pan, flow along the intake and discharge tubing, and flow through the electric cables. The fluidic transmission paths include dynamic pressure pulsations propagating downstream on the discharge side and upstream on the intake (suction) side. For this discussion, radiation of sound from the compressor housing is also considered a fluidic path.

In addition to evaluating each of the transmission paths separately, the balance between the energy flow paths must also be considered. One low order assumption sometimes applied in noise control engineering is that a machine produces a specified amount of acoustic energy as a function of its performance parameters such as energy consumed. Indeed, many noise control textbooks describe methods for estimating the sound power produced by electric motors, fans, and pumps using the electric power consumed normalized by the mass of the device. These methods generally assume low levels of structural damping or acoustic absorption. But, even for the case of significant damping, energy dissipation is treated as just another flow path. Thus, any reduction in the transmission of energy along one path may actually increase the flow of energy across another path.
Structural Transmission Paths

Structural energy flow from the compressor mounting feet into the base pan is a primary concern for condenser noise control [2]. Elastomeric grommets are typically placed between the feet and the base pan to provide vibration isolation. The design goal in selecting the grommets is an isolation frequency well below the frequency of compressor rotation (2800 to 3500 rpm). Two design criteria in selecting isolation grommets are often overlooked, however. First, isolation to low frequency requires low-durometer grommets. But, the weight of the compressor can preload the grommets to the point of rendering them ineffective. So, grommets must be selected with sufficient material to allow the compressor plenty of dynamic displacement. Second, the vertical direction is not the only structural transmission path through the grommets. A strong lateral vibration component is inherent to most compressor designs. Another consideration in designing effective isolation is to place the compressor mounting feet at locations on the base pan with high structural impedance. To this end, some manufacturers attach additional plates to the base pan adjacent to the compressor feet.

Another structural transmission path of significance for noise control is the flow of energy along the refrigerant tubes on both the discharge and suction sides. In an effort to conserve on the cost of copper, many manufacturers are designing tube routings short and straight to reversing valves, condenser coils, and other mounting hardware. These short tube runs provide for efficient transmission of structural energy. Any cost savings in materials are then eroded by the cost of noise control activity. The preferable design to minimize structural energy transmission is generous on tube length and applies gradual radii at bends. Loops in the tubes add compliance to the compressor mounting system and enhance vibration isolation.

Structural resonance is another concern in designing refrigerant tubes. Care should be taken to insure that resonance modes of the tubes do not align in frequency with pressure pulsation. The pressure pulsation frequencies are typically harmonics of the compressor rotation speed. Resonance frequencies can be predicted using finite element analysis or can be measured using experimental modal analysis. If a natural frequency of a refrigerant tube is found to coincide with a pulsation frequency, it is preferable to shift the resonance frequency downward.
by adding length or mass to the tube. By shifting the resonance frequency downward, the mode will be less efficient at radiating sound.

One structural transmission path regularly overlooked is the path along electrical cables. Every child at some time has fabricated a telephone from tin or aluminum cans tethered by string. When the string is pulled tight, the device becomes an efficient transmitter of structural energy along the string. The same type of structural transmission can occur from a compressor through taut electrical wires. Therefore, power cables and other electrical wires routed to the compressor should be sufficiently long to prevent transmission via wire tension.

**Fluidic Transmission Path**

The refrigerant fluid provides two transmission paths for noise energy from the compressor to the condensing unit. Dynamic pressure pulsation can propagate downstream from the compressor’s discharge and upstream from the compressor’s intake (suction) [3]. Though, dynamic pressure pulsation in the suction gas is rarely manifested as sound radiating from the condensing unit. On the other hand, pressure pulsation in the refrigerant discharging from the compressor into reversing valves or the condenser coil can cause sound to radiate from the condensing unit. Mufflers in the discharge line adjacent to the compressor are the most direct and common method for addressing this noise issue.

Acoustic standing waves (resonance) can form in the refrigerant downstream of the compressor discharge. Standing waves are most likely to occur in straight tubes terminated in sharp bends. If the acoustic resonance frequency coincides with the frequency of a harmonic of compressor rotation, high dynamic pressure levels in the tube will result. These high dynamic pressures may then cause a high level tone to radiate from the condensing unit. To prevent standing waves from forming, straight refrigerant tubes should be avoided, and tube bends should be designed using gradual radii. If an acoustic standing wave forms in a tube, the length of the tube should be increased by a quarter wavelength of the standing wave. A quarter wavelength will shift a dynamic pressure maximum point to zero. For example, the length of a standing wave at 120 hertz in R22 refrigerant (speed-of-sound equal to 7200 in/sec) is 60 inches. Fifteen inches added to the length of the tube will shift the standing wave a quarter wavelength.

Finally, sound waves radiating from the compressor housing interact with the acoustic environment in and around the condensing unit. Many manufacturers enclose the compressor in a compartment of sheet metal. To minimize noise transmission for these designs, the enclosure walls should be as massive as reasonable. Layers of acoustic material attached to the inside walls will add mass and increase acoustic absorption in the enclosure. Care should be taken to avoid structural contact between the compressor and enclosure. As an alternative to a structural enclosure, some manufacturers place acoustic blankets over the compressor. These blankets should be massive, well sealed, and loose fitting with a layer of acoustic absorption on the inside.

**NOISE REDUCTION CASE STUDY**

Cylinder disengagement-type compressors operate on fewer cylinders when the capacity demands are less. For instance, two-cylinder reciprocating compressors operating on just one cylinder offer greater energy efficiency and user comfort during low system demand. These types of compressors are commonly installed in condensing units with mature designs and
existing hardware. However, systems using this technology produce a different sound quality. During single-cylinder operation, the compressor generates 50/60 Hz discharge pressure pulsation rather than the 100/120 Hz pulsation common to two-cylinder operation. Unfortunately, if compressor-condensing unit coupling in the 50/60 Hz frequency range is given insufficient consideration, undesirable sound or vibration may occur.

An investigation was conducted to reduce the sound and vibration from a condensing unit developed for the Middle East market. The system offered both air conditioning and heat pump capability, and a cylinder disengagement compressor was installed in the unit. The condensing unit included a triple-layer coil and a swept-blade fan. The unit was sized for four tons of air conditioning capacity. The condensing unit cabinet offered low profile geometry for mounting on the building sides. In a field test installation, the unit produced unacceptable sound and vibration, particularly when operated in one-cylinder mode. Because of the mounting configuration, both sound and vibration from the unit intruded into building living spaces.

The results of an experimental modal analysis conducted on the unit cabinet revealed a structural resonance at 48 Hz. When driven by the single-cylinder, 50 Hz pulsation frequency, the structural resonance produced high-level vibrations that propagated throughout surrounding structure. The mode shape associated with the resonance is described by large displacements in the top and compressor-side panels of the cabinet, Figure 2. A method for shifting the resonance to a frequency much higher than the pulsation frequency was demonstrated using angle-iron stiffeners, Figure 3. The result of shifting the resonance frequency was to lower the vibration response of the cabinet to pressure pulsations at 50 Hz.

In order to reduce dynamic pressure pulsations in tubing downstream of the compressor discharge, various inline muffler designs were studied. A search of the available refrigerant mufflers produced no off-the-shelf muffler that was effective for a 50 Hz pulsation frequency. The mufflers that were claimed to address low-frequency pulsation did so at a sacrifice to system performance by choking the flow. Consequently, a reactive muffler of sufficient volume to
attenuate 50 Hz pulses was designed and fabricated. The muffler was then installed in the condensing unit at a location between the compressor and the reversing valve, Figure 4. The muffler served to reduce peak-to-peak pressure pulsation to about half the original level.

Although the muffler reduced pressure pulsation in the refrigerant tubes, structural vibration continued to be transmitted by the compressor during single cylinder operation. The compressor foot grommets were found to also be insufficient as low-frequency isolators. So, a study was conducted of vibration isolation mounts. After several iterations, it was concluded that coil springs provided the most effective isolation, Figure 5.
The condensing unit was modified per the above discussion and reinstalled at the field test site. Sound and vibration measurements were conducted to evaluate the changes. The sound pressure level was measured inside the building adjacent to the condensing unit. Vibration levels were measured on the steel frames supporting the unit. Figure 6 shows that the overall sound level was reduced by seven decibels. The peak vibration level was reduced in half, Figure 7.

**CONCLUSIONS**

Low noise operation is an increasingly important design requirement of residential air conditioning and heat pump systems. Since compressors supply the fluidic power to drive these refrigeration circuits, they tend to be the focus of noise reduction programs. As the industry moves toward alternate refrigerants and energy efficient systems, the gas pressures will increase. As a result, the dynamic forces in the compressor will increase. These trends will heighten the need for comprehensive approaches to compressor noise control. The most effective methods for compressor noise control must consider how the compressor couples to the system.

**REFERENCES**