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Determination of Sound Quality of Refrigerant Compressors

S. Y. Wang
Copeland Corporation
Residents of quiet neighborhoods are often disturbed by the noise radiated from the air conditioning or heat pump units installed in their neighbors' or their own yard. In many cases, the sound of the compressor used in the unit is considered annoying while similar sound radiated from the fan of the same unit can be perceived as acceptable. The annoying sounds of the compressors described by consumers as "metallic", "fluctuating", "not smooth", or "rattling" are not necessarily of high acoustical intensity. Instead, these descriptors are often related to the quality of the sound. This paper reviews the validity of several sound quality parameters such as loudness, roughness, sharpness, tonality, and fluctuation strength when they are applied to compressor noises. Comparisons of these sound quality parameters to a widely used "tone corrected sound power" method in ARI 270-84 are also addressed.

Two distinct types of sound can be identified from the compressor noise. One is the steady state sound and the other is the time varying sound. Among the sound quality parameters examined below, the descriptors of loudness, sharpness, and tonality are applicable to the steady state sound while the roughness and fluctuation strength are related to the time varying sound.

MEASURING THE COMPRESSOR AND HVAC SYSTEM NOISE

Two widely used measurement standards to quantify refrigerant compressor sound and HVAC system sound in the North American market are the ARI 270-84 [2] and ARI 530-89 [3], published by the Air Conditioning and Refrigeration Institute. Used for refrigerant compressors, ARI 530-89 specifies a method to measure the airborne noise radiating from a compressor under a load. The measurement results are reported as sound power levels in one-third octave bands between 100 Hz and 10,000 Hz and as A-weighted sound (power) level. For the outdoor unitary equipment, ARI 270-84 measures the sound power in a very similar manner. But it also attempts to penalize "discrete tones" radiated from the unitary equipment. When a one-third octave band projects above the linear average of the two adjacent bands by 1.5 dB, a "discrete tone" is determined to be residing in this one-third octave band, some amount of penalty is then applied. The penalties for "discrete tones" are often severe; it is not uncommon to see a penalty of 3 to 5 dB added to certain one-third octave bands. In fact, units with an average level of fan noise are often assessed with the penalty of this Standard just because the spectrum shape of their compressors noise is not "smooth" or "flat". The question becomes can the "discrete tone" be heard when these units are running.

The sound of compressors is generally composed of very widely spread multiple tones. A typical narrow band spectrum from a compressor is shown in Figure 1. Many tones (harmonic orders) can be found within a single one-third octave frequency band especially in the high frequencies. On the basis of several laboratory
studies [4] a prominent tone can be effectively detected by instrumentation using a procedure called "tone to noise ratio" computation. The "tone to noise ratio" is defined as the difference in acoustical power between the tone under the examination and all other tones co-existing in the same critical band. The method requires a narrow band (FFT) analysis. Since the ARI 270-84 Standard does not specify the measurement of narrow band information, the effectiveness on detecting a "discrete tone" using the one-third octave band data alone can be questionable. Consequently, the mistakes to penalize some "discrete tones" of none existence may be unavoidable.

Someone might argue that the idea of "discrete tone" referred by the ARI 270-84 Standard is not intended to identify prominent tones but to promote the "sound quality". The method measures the degree of the smoothness or flatness of the one-third octave band spectrum and one might interpret the smooth spectrum as smooth or better quality sound. Unfortunately, this argument may not be a valid one for compressor noises. As discussed below, the compressor noise with a smooth or flat one-third octave band spectrum can be quite annoying and poor on sound quality because it tends to have a higher sharpness level.

LOUDNESS OF THE COMPRESSORS

A refrigerant compressor is a multiple-tone noise source. It is suggested by ISO 532 Standard [5] that loudness level of this noise type be calculated with the Method B ("Zwicker's method") instead of the Method A ("Stevens' method"). Loudness level measured in the unit of Sones simulates the human perceived loudness which can be different from the objective acoustical energy level measured in decibels. Figures 2 and 3 show the one-third octave band spectrum of Compressors A and B, respectively. Although the spectra of these one-third octave bands for Compressors A and B look very different, the difference between the A-weighted sound power levels of Compressors A and B is just 1.3 dBA. The loudness level is calculated as 18.25 Sones for Compressor A and 19.41 Sones for Compressor B, an insignificant 6% difference.

A total of 26 compressors, ranging from 1.5 to 10 tons in capacity, differing from reciprocating piston (two-cylinder and four-cylinder), rotary, to scrolls in design, were evaluated for the loudness levels and the A-weighted sound power levels. Figure 4 shows both the A-weighted sound power level and the loudness level, calculated from sound pressures measured at 2.0 meters distance from the compressors. The results clearly indicate that using the loudness in Sones may not have significant advantages over the currently used A-weighted sound power method of ARI 530-89 in ranking the loudness of the compressor noise.

SHARPNESS OF THE COMPRESSOR SOUND

Clearly, some compressors have a smoother sound than others. Many people may refer this complex auditory sensation as the sensory pleasantness of the sound. Sharpness examines the envelope of the spectrum [6]. The above example of Compressors A and B showed approximately equal loudness and A-weighted sound levels but significantly different sharpness levels were identified because of the different shapes of the spectrum. Sharpness of Compressor A measures 1.55 Acums and Compressor B measures 2.25 Acums, a 45% difference. In this case, the sound of Compressor B is much "harsher" and less pleasant than the sound of Compressor A. This seems to correlate well with the observations made by Zwicker and Fastl [6] that the sensory pleasantness depends more on sharpness than any of the other sound quality parameters such as roughness, tonality, and loudness.

In our second example, illustrated in Figures 5 and 6, Compressors C and D are almost identical in their A-weighted sound power levels and similar on their loudness levels. Compressor D's spectrum is rather flat as shown in Figure 6. But the sharpness of Compressor D measuring 2.05 Acums is worse than that of Compressor C at 1.65 Acums. Interestingly, the sound with a flat spectrum of Compressor D is judged as worse in sound quality than the sound with an uneven spectrum of Compressor C.
ROUGHNESS AND FLUCTUATION STRENGTH OF COMPRESSOR SOUND

Differing in the modulation frequencies, both roughness and fluctuation strength influence the sound quality from the time variation of loudness levels. Based on the work of Zwicker and Fastl [6], the sensation of the fluctuation strength reaches the maximum near 4 Hz frequency modulation. For the compressor noise, the fluctuation is often referred as a "beating" sound. On the other hand, when the modulation frequency increases, the sensation reaches another maximum due to the time variance of the sound at 70 Hz modulation; this is called the roughness of the sound.

One of the concerns about the roughness of the compressor noise is its relation to the cyclic noises generated by gas pulsations. For example, a scroll compressor generates a one per cycle gas pulsation sound while a two-cylinder reciprocating piston compressor generates a noise of two gas pulsations per revolution. The fundamental frequency of gas pulsating noise from the scroll compressor for 60 Hz line frequency is at 58 Hz while the reciprocating compressor is at 116 Hz. Will 58 Hz gas pulsation noise be determined " rougher" than the 116 Hz gas pulsation noise because the 58 Hz is closer to 70 Hz? The answer is, not necessarily. Figure 7 illustrates the radiated noise of a typical scroll compressor and a typical 2-cylinder reciprocating compressor. Analyzing the noise with loudness plots, the roughness of the scroll compressor shows a 0.013 Asper roughness and the reciprocating compressor shows a 0.014 Asper, the reciprocating compressor in this case is insignificantly " rougher" in sound.

The fluctuation strength, on the other hand, might be a good indicator of the beating phenomena generated between the fan noise and the compressor noise in an HVAC system. As shown in Figure 8, the outdoor condensing unit has an audible beating sound and the fluctuation strength was measured as 0.14 Vacils, considerably higher than other smooth sounding units where the fluctuation strength measured in the range of 0.05 to 0.08 Vacils.

CONCLUSIONS

The sound of refrigerant compressors is quite complex. In the frequency domain, it consists of a large number of harmonic tones, and sound energy between harmonic tones is generally small. In the time domain, some compressor sound can be more noticeable due to a higher fluctuation strength. The major conclusions of this paper regarding the sound quality of the compressors are summarized as follows:

a. Using the A-weighted sound power level to measure compressor noise as suggested in ARI 530-89 gives a very good correlation to the loudness level measured in accordance to ISO 532 Standard. To measure the loudness of the compressor noise, A-weighted sound power level is a sufficient indicator.

b. The method of comparing a single one-third octave band data to its adjacent bands on the sound of HVAC systems, as suggested by ARI 270-84, does not sufficiently identify the tonality of the HVAC system sound. Tonality can be determined more effectively with the narrow band analysis data.

c. The most relevant parameter to the sound quality of compressors is found to be the sharpness. A high sharpness reading of the compressor noise generally indicates a poor sound quality and poor sensory pleasantness.

d. The speed of rotation of the compressors and the number of cylinders of a reciprocating compressor do not seem to influence the roughness of the compressor sound significantly.

e. The beating sound of the compressor or the beating sound between the compressor and the fan of the condensing unit can be very noticeable. On these, the fluctuation strength (Vacils) can be a good measure to quantify the beating sound of the HVAC systems.
ACKNOWLEDGMENTS

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REFERENCES


Figure 1. Narrow Band Spectrum of a Typical Compressor.

Figure 2. Spectrum of Compressor A.
Figure 3. Spectrum of Compressor B.

Figure 4. Comparisons of Compressor Noise Measured in A-weighted Sound Power and Loudness Levels

Figure 5. Spectrum of Compressor C.
Figure 6. Spectrum of Compressor D.

Figure 7. Comparison of Time Varying Loudness Levels between a Reciprocating Compressor and a Scroll Compressor.

Figure 8. Time Varying Sound Pressure Levels of an HVAC System When a Beating Sound was Heard.