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IMPLEMENTATION OF SOUND QUALITY MEASUREMENTS IN COMPONENT RATING TESTS

Gabriella Cerrato-Jay[(1)]
Doug Collings, P.E.[(2)]
David Lowery[(1)]
[1]Tecumseh Products Research Laboratory, 3869 Research Park Drive, Ann Arbor MI 48108 USA
[2]Tecumseh Products Company, 100 E. Patterson Street, Tecumseh MI 49286 USA

INTRODUCTION

In recent years, in the consumer and appliance industries there has been an increased demand not just for efficiency and low noise but also for better sound quality. Traditionally, in this industry, products have been acoustically labeled by using their sound power level, and noise and vibration laboratories around the world are equipped with application-specific testing rooms and instrumentation dedicated to the measurement of the sound power spectrum. However, the recent market demand for better sound quality poses new challenges for the refrigeration engineering community. The first challenge is to understand if existing testing facilities and techniques can be adapted to measure sound quality along with sound power. The second challenge is to find the right metrics to describe the sound quality of the compressor by itself and in the final application. In this paper, we will discuss some of the techniques adopted in the noise and vibration laboratories of Tecumseh Products to evaluate the sound quality of compressors.

THE TRADITIONAL MEASUREMENT OF SOUND POWER

In many laboratories, sound power is calculated from measurements of sound pressure at specific microphone locations, either in a reverberant or in an anechoic chamber. At each microphone location, the third-octave spectrum of the sound pressure is measured over a certain time, then the sound pressure spectra measured at all locations are averaged together with some weighting coefficients which are a function of the measurement surface. The resulting sound power spectrum is therefore the result of temporal and spatial averages.

The noise targets most commonly used in the refrigeration industry are based on either the A-weighted sound power spectrum or the Sound Rating Number (SRN) of the Air-Conditioning and Refrigeration Institute (ARI)[(1)]. The SRN is based on the A-weighted sound power spectrum in third-octave bands with level corrections in dB which penalize the presence of tonal components. In previous versions of this standard (1967 and 1975), the sound power spectrum was first corrected for the presence of tones then it was converted to sound rating indices by using weighting factors based on equal loudness curves. In these earlier implementations, the Sound Rating resembled closely the calculation of loudness for broad-band sounds according to the Stevens method implemented in the ISO 532A standard. The latest version of the ARI standard, however, omits the conversion of the sound power levels in each third-octave band to rating indices proportional to loudness. The Sound Rating now is simply based on the A-weighted sound power level spectrum corrected for the presence of tones.

While the A-weighted sound pressure level is certainly correlated to loudness, several jury studies conducted with several types of automotive sounds have shown that loudness almost always correlates better to our subjective perception of the intensity of the sound [(2)]. Furthermore, in an extensive comparative study published in 1994, the A-weighted sound pressure level in dB is compared to the loudness in sones calculated using Zwicker's method as standardized in ISO 532B [(3,4)]. Numerical analyses, conducted to quantify differences between the two descriptors, indicated that the ratio of maximum to minimum loudness in sones for a particular A-weighted sound pressure level can be dramatic. In other words, spectra with identical A-weighted sound pressure levels may have very different values of perceived loudness. As an example, at an A-weighted level of 70 dB, the range in loudness extends from 2.2 to 45 sones. In addition, extensive jury studies were conducted and the conclusion of the investigation was that “loudness calculation via ISO 532B is indeed a better engineering tool for estimating changes in loudness than A-weighted sound pressure level”. Another more recent study shows the inadequacy of any frequency-weighted noise metric, such as the power spectrum, as a predictor of annoyance [(5)]. In the study, the judged annoyance of pairs of signals of identical power spectra but of different phase spectra was found to be quite different, indicating that the “historical” physical characteristics of the sound, such as level and spectral content, do not uniquely determine its annoyance.

As for the tone correction in the ARI standard, it is applied whenever the sound power level of any third-octave band exceeds the average of the two adjacent bands by more than 1.5 dB. In this case, the measured level is increased by a table look up value. The adjustment factor increases with the center frequency of the third-octave bands, up to a maximum of 6 dB at 10 kHz. Low frequency tones are therefore much less penalized than high frequency tones, and their annoyance may be underestimated especially in the application. It has also already been pointed out that the perception of the tonality of compressors would be better quantified by looking at narrow band frequency data [(6)].

The Air-Conditioning and Refrigeration Institute has recently acknowledged the need for sound quality metrics other than the current SRN and it is investigating alternative descriptors better correlated with loudness. In a study commissioned by ARI, it was concluded that the current SRN metric does not distinguish between signals that are differentiated by subjective perception [(7)]. The work described in this paper agrees with this conclusion.

SOUND POWER AND SOUND QUALITY

Sound power is the time-averaged acoustic power output of a source. The beauty of sound power is that it is an objective product label and it is transportable, that is, it is independent from test setup and procedures, assuming identical product operating conditions. Sound quality, on the other hand, is the auditory perception of the source based on the listener’s expectation. From these definitions, it is clear that sound power characterizes the noise source regardless of the receiver, while sound quality characterizes how the noise source is perceived and depends upon both source and receiver. The averaging processes used in the measurement of sound power are aimed at reducing the impact of local and transient phenomena. However, these are the same phenomena that may be objectionable and considered annoying by the final listener. Therefore, from a sound quality standpoint, these phenomena cannot be neglected.

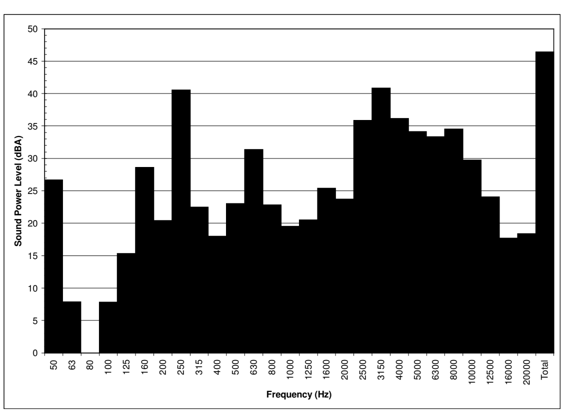
In order to verify whether the sound power spectrum could be used to represent the annoyance of compressor sound, a study was carried out to compare the subjective perception of the time history derived from the sound power spectrum of a compressor and of the actual recordings at a number of microphone positions.

Figure 1 shows the test setup in the anechoic chamber at the Tecumseh Products Research Laboratory in Ann Arbor, MI. The compressor is positioned in the center of the room and the test is performed in accordance with the ISO 3745-1977 standard [(8)]. The measurement microphones are mounted on a 1.5m radius arc driven by a stepper motor. During the test, the sound pressure is measured at each microphone for each arc angle, for a total of 65 microphones distributed on a hemispherical surface surrounding the compressor. At each microphone position, the time history of the sound pressure is sampled at 48 kHz and recorded to disk for 10 seconds.

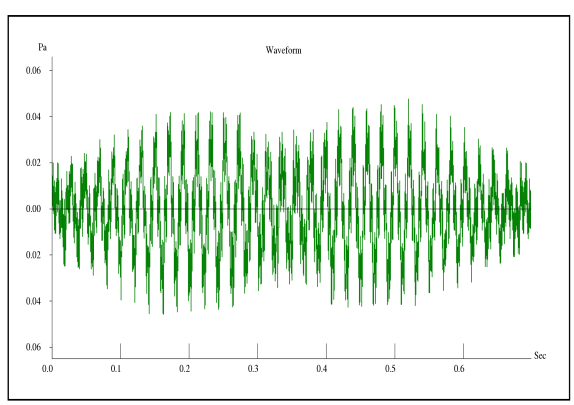
Figure 1: Sound Power Test of compressor in the anechoic room
at Tecumseh Products Research Lab

Figure 2a shows an example of the third-octave sound power spectrum of a small single-cylinder refrigeration compressor. The sound power spectrum was computed in both third-octave bands using digital filters (Fig. 2a) and in narrow frequency bands. A random phase angle was attributed to each frequency line of the linear narrow band spectrum which was then inverse-Fourier transformed. The loudness of the resulting time history, shown in Figure 2b, was first equalized to the median loudness of the 65 measured signals. Then the time history was played back and compared to a few of the actual recordings. This approach was used for different compressors of different sound power spectrum and level. In all cases, while no formal jury test was conducted, all engineers who listened to the sounds agreed that actual recordings and the time history extracted from the sound power spectrum sounded quite different.

An additional factor that helps in understanding these subjective differences is that compressors are, in general, directive noise sources with strong tonal content. Therefore, there may be several locations on the measurement surface where the actual noise is considerably different from its spatial average. In addition, the alignment of gas dynamics effects and system mechanical resonances may induce changes in level of a particular frequency. This is especially evident when testing the compressor in the application; this may or may not be accounted for during the sound power test depending on the duration of the tone and its directivity.



(a)



(b)

Figure 2: third-octave sound power spectrum (a) and time history from inverse-Fourier transform (b)

For all these reasons, it was concluded that since the sound power spectrum seems to be a poor indicator of sound quality, other descriptors should be measured in order to quantify the sound quality of compressors.

THE CHALLENGE OF MEASURING SOUND QUALITY

In this section we will discuss the main issues of concern when trying to include sound quality measurements in compressor rating tests.

Test Data. In order to be able to compute sound quality metrics, it is necessary to acquire and store time histories of the sound pressure. This is a major departure from the standard sound power test and it poses new challenges to the organization of the test laboratory. While the acquisition of the time histories does not slow down the test since it is done with a multichannel data acquisition system in parallel with the measurement of the average spectra, on the other hand much more disk space is required to store the data related to each test. Since time histories are sampled at 48 kHz to get the full audible frequency range, the size of the file containing all recordings related to one test is 169 Mb. Archive and backup procedures have also to be updated to account for this massive amount of data

Single Microphone Versus Binaural Head. In the automotive industry, which has pioneered the application of sound quality techniques to mass-product engineering, the standard sound quality transducer is a binaural head. The complexity of the sound field created by different sources and paths in the vehicle interior cannot be faithfully reproduced by single microphone measurements. In our case, however, there is only one source (the compressor under test) and the radiation of noise satisfies free-field conditions since the test is performed in an anechoic chamber. The first question therefore is whether to use a binaural head to acquire time histories of sound pressure that will be used to compute metrics and will be played back to jurors. As for calculating the sound quality metrics, they should be computed from binaural signals which have been equalized to the response of a single microphone in the same acoustic field. Therefore, at least in the first stages of this project, we will assume that sound quality metrics computed from signals acquired by the microphones on the measurement hemisphere are representative. In fact, it has been demonstrated that this is a correct assumption at least for loudness. A study conducted by Zwicker concluded that measuring loudness with a single microphone at the place where the listener's head or the binaural head would be seems to approximate well the actual loudness [9].

As for the quality of the sound reproduction, this is strongly affected by the transducer and using a binaural head guarantees much more realistic playback. As part of the on-going sound quality investigation, we have measured the frequency response function between a single microphone and the left and right microphones of a binaural head during a compressor noise test in the anechoic room. As illustrated in Figure 3, the transfer function TF_1 between the single microphone M_1 and the reference microphone M_0 was measured, along with the transfer functions TF_L and TF_R between M_L, M_R and M_0. The ratios $TF_{L1} = TF_L / TF_1$ and $TF_{R1} = TF_R / TF_1$ represent the transfer functions between the single microphone and each microphone of the binaural head. A binaural signal was recreated by convolution of the time history recorded at the single microphone with the transfer function between the microphone and the binaural head at the same position. The resulting synthesized binaural signature sounds almost identical to the real binaural signal and the sound quality metric values of real and synthesized signals are also very close. If it can be demonstrated that "virtual" binaural head signals generated from real single microphone signals provide faithful sound reproduction, then sound quality can be measured during the sound power test with no need for additional transducers.

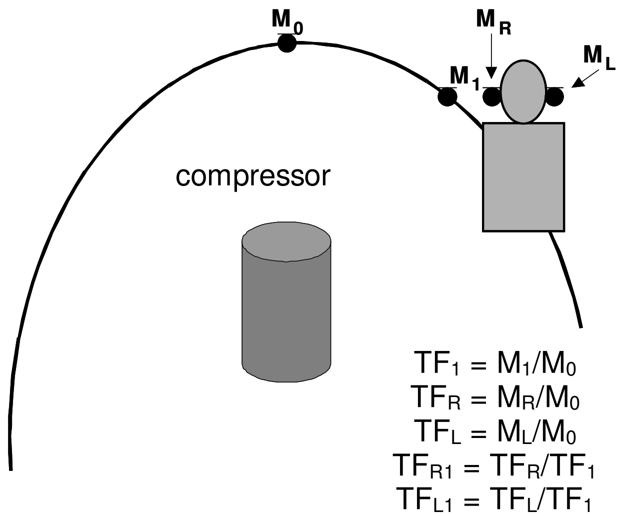
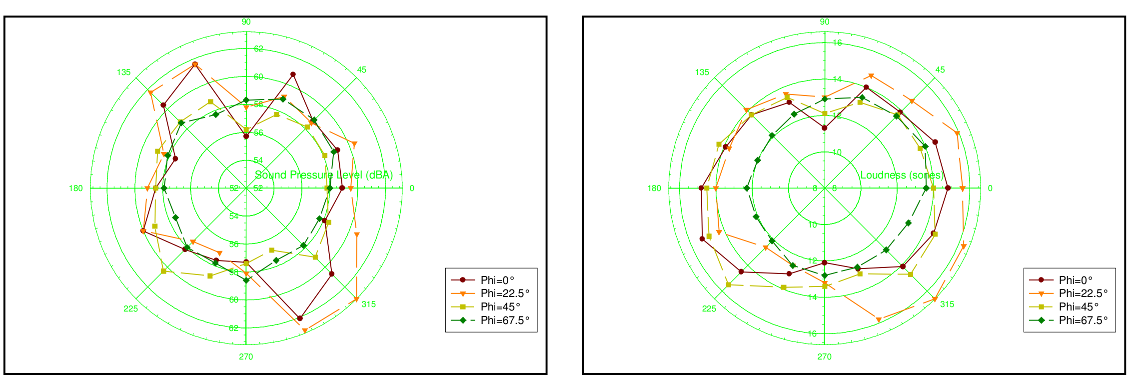


Figure 3: Measurement of transfer function between single microphone and binaural head

Sound Quality Metrics. As for most other products, the most important sound quality feature for compressors is likely to be loudness. A well acknowledged fact in the compressor community is that "the most pleasing compressor is the one that you cannot hear". While this does not necessarily require a super-quiet compressor but rather a compressor whose noise blends with the other sources, low loudness is a good starting point. To quantify loudness, the following loudness-related metrics are currently computed for the compressors tested at the Research Lab: Zwicker Loudness (ISO532B), linear, A- and C-weighted SPL, Speechband and Speech Interference Level. To quantify other sound quality features we compute kurtosis, sharpness, tonality, roughness and fluctuation strength. For each compressor and each test condition, the sound quality metrics for all microphones on the measurement hemisphere are automatically computed using a commercial software package [10] and stored in matrix form in an Excel spreadsheet. Statistical parameters such as maximum, minimum, median, standard deviation and percent of change are then computed to qualify the distribution of the metrics and their variation.

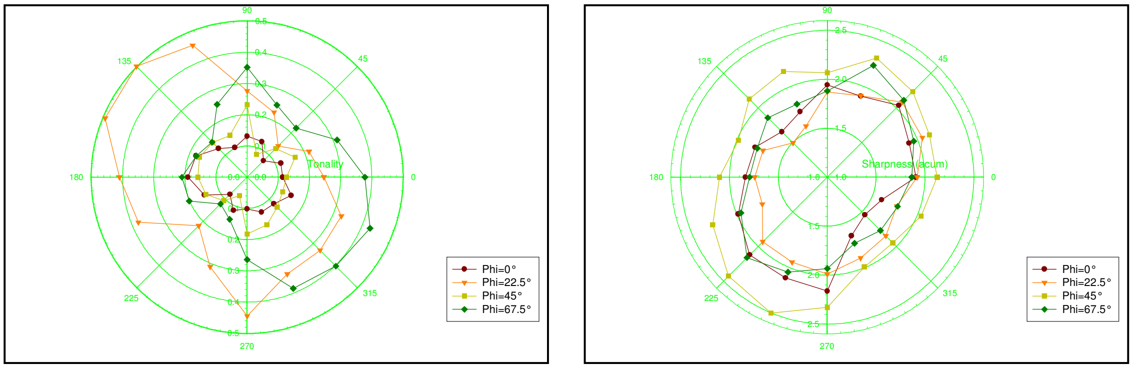
Polar patterns of sound quality metrics are also generated, to identify possible concerns due to directivity. Examples of sound quality metric polar plots for two different compressors are shown in Figures 4 and 5. The four curves on each plot refer to the four elevations (horizontal planes) of the microphones on the measurement hemisphere.



(a) (b)

Figure 4. Polar plot of A-weighted SPL (a) and Zwicker Loudness (b)

Figure 4 shows the polar patterns of A-weighted sound pressure level (dB) on the left and Zwicker loudness (sones) on the right for a two-cylinder reciprocating compressor. In this case, Zwicker loudness and A-weighted SPL do not correlate well, since their spatial distribution is quite different. Figure 5 shows the polar patterns of Tonality (dimensionless) on the left and Sharpness (acum) on the right for a different compressor. The two patterns are consistently different suggesting the orthogonality of the Sharpness and Tonality metrics for this compressor.



(a) (b)

Figure 5. Polar plot of Tonality (a) and Sharpness (b)

CONCLUDING COMMENTS

The results of our tests confirm the conclusions of previous studies that sound power seems to be a poor indicator of overall compressor sound quality. It has also been the experience of the authors that compliance with non-sound quality targets, such as sound power, often does not guarantee good sound quality in the application. Compressor sound quality metrics should be computed in addition to the A-weighted sound power spectrum. Current efforts at Tecumseh Products are focused on modifying the sound power test procedures to allow for the additional measurement of sound quality metrics. The objective of future sound quality activities will be to develop a one- or multiple-metric sound quality model which can be used to establish sound quality targets for the application and for the compressor.

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