SOUND QUALITY EVALUATION OF COMPRESSORS

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ABSTRACT

Sound Quality is becoming a product differentiator in the consumer and appliance industries. This is creating new challenges in the compressor design and evaluation process. This paper describes the measurement and data post-processing methods implemented at one compressor manufacturer to assess and evaluate the sound quality of compressors.

INTRODUCTION

Historically the compressor industry has used sound power as the standard measure of the noise of its products. Compressor and appliance manufacturers have over the years equipped their noise and vibration laboratories with facilities and instrumentation to measure their products' sound power in a repeatable and consistent fashion. The beauty of the sound power level 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. In more recent years, however, there has been an increased demand not just for efficiency and low noise but also for better sound quality. In this paper, we will discuss the need for metrics other than sound power to quantify the sound quality of compressor and appliances. We will also describe some of the work done at Tecumseh Products to account for sound quality during the compressor development process.

SOUND POWER AND SOUND QUALITY

Sound power is the time-averaged acoustic power output of a source. Sound quality is the auditory perception of the source based on customer's expectation. From these definitions, it is clear that sound power characterizes the noise source regardless of the receiver (the customer), while sound quality characterizes how the noise source is perceived and depends on both source and receiver. A correct sound quality measure therefore has to quantify the relation between the objective noise output of the source and the subjective judgement of that source on the part of the receiver.

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 averaged over a certain measurement 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 averaging process is aimed at reducing the impact of local and transient phenomena.

However, these phenomena may be objectionable and considered annoying by the final customer. In order to verify whether the sound power spectrum can be used to represent the annoyance of compressor sound, a study was carried out at the Tecumseh Products Research Laboratory to compare the subjective perception of noise signals with identical power spectra but different phase spectra.

Let us consider, as an example, the sound power spectrum, displayed in Figure 1, of a small single cylinder refrigeration compressor. The test was performed in an anechoic room using a hemispherical microphone measurement surface according to ISO 3745 (1). The sound power frequency spectrum of Figure 1 was inverse-Fourier transformed to obtain a time history, displayed in Figure 2. Before performing the inverse-Fourier transform, a random phase angle was assigned to each frequency line of the linear spectrum. The resulting time history was then subjectively compared to the actual recordings made at some of the microphones on the measurement hemisphere. While no formal jury test was conducted, all engineers who listened to the sounds agreed that actual recordings and the time history of Figure 2 sound quite different.

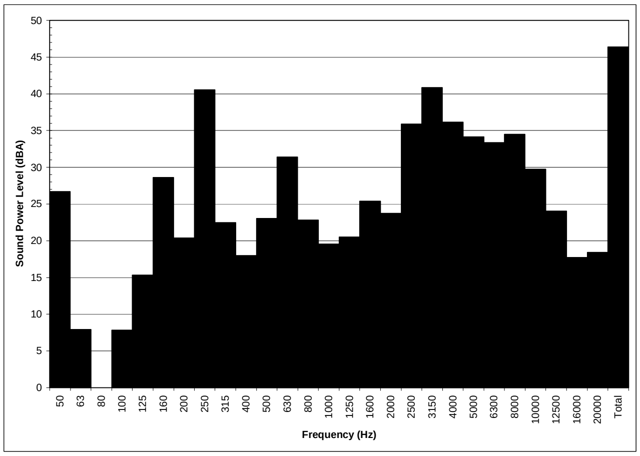

Figure 1. Sound Power spectrum of small single cylinder refrigeration compressor

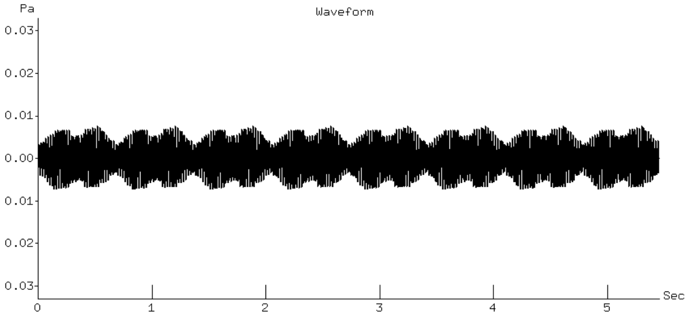

Figure 2. Time history resulting from inverse Fourier Transform of sound power frequency spectrum

There are several reasons, which help to explain this result. First, 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. Furthermore, sound quality is affected by both frequency and time characteristics of the noise signal. The time (or phase) information of the compressor noise is lost during the temporal and spatial averaging required computing the sound power spectrum. A recent study (2) shows the insufficiency of any frequency-weighted noise metric, such as the power spectrum, as a predictor of annoyance. The study compares the judged annoyance of pairs of signals of identical power spectra but of different phase spectra. The results of the formal jury test reported in the article indicate clearly that the sound quality of these sounds differ substantially. This conclusion is in agreement with the results of the study conducted by the authors of this paper.

Another important factor from a sound quality standpoint is the presence of transient phenomena. The alignment of gas dynamics effects (temperature, pressure) and mechanical resonances may induce a periodic increase and decrease in level of a particular frequency. This is especially evident when testing the compressor in the application and it may or may not be accounted for during the test depending on the duration of the tone and its directivity. If the tone has short duration (short compared to the measurement time at each microphone location), its presence will not affect the overall A-weighted sound power level. An example of the effect of an intermittent tone is shown in Figures 3 and 4. The original recording of a residential refrigerator exhibited an intermittent high frequency tone, which, at a certain condition, occurred approximately once every 3 seconds, with a duration of about 1 second. The tone was objectionable and considered annoying. The original recording was modified, using sound quality analysis software (3), by normalizing the loudness of the unsteady tone to a constant and not annoying level. Figure 3 shows the average 1/3 octave sound pressure spectrum of the original noise recording (dashed line) and the modified signal (solid line). The two spectra overlay perfectly except at 2500 Hz band, where there is a difference of 2.5 dB. The overall level remains the same (51.1 dB (A)). Neither the spectra nor the overall level however provide any indication of the temporal nature of the tone.

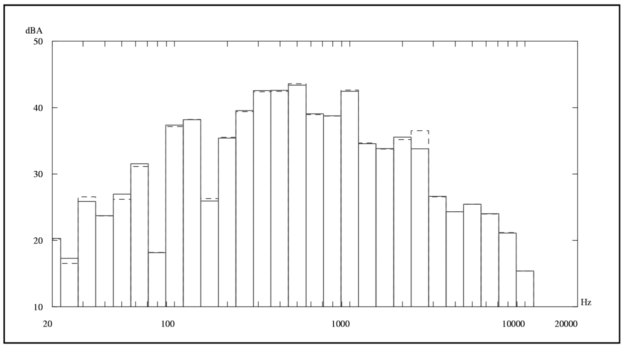

Figure 3. A-weighted 1/3 octave spectrum of refrigerator noise with (dashed)
And without (solid) intermittent tone

More meaningful appears to be the comparison of the loudness functions versus time, as shown in Figure 4. The dashed line shows higher level of loudness at two different instances in time, with each event lasting about 1 second. This agrees well with the subjective evaluation of the sound.

Based on these data, it was concluded that sound power cannot be used as a measure of sound quality. The sound power test procedure was therefore modified to allow for the acquisition of time histories at all microphone positions. The time histories are necessary to compute sound quality metrics.

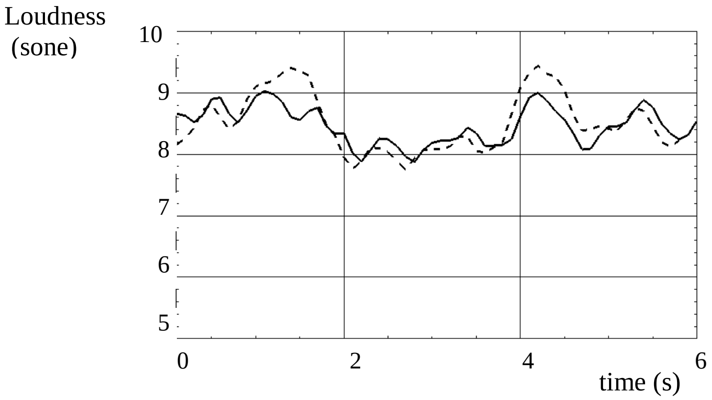

Figure 4. Loudness function (sones) versus time
with tone (dashed) and without it (solid)

SOUND QUALITY METRICS

The metrics that are commonly used to characterize the sound quality of a product can be divided in three groups:

1) metrics which describe physical quantities and therefore are independent from the human hearing. Examples of these are the overall RMS, linear level in dB, crest factor, peak-to-peak value and statistical parameters of the time history (skewness, kurtosis, percentile levels, etc.)
2) metrics based on the above, but corrected by using simplified human hearing models (such as the A-weighting curve) or “annoyance” penalization factors based on experiments (such as the Sound Rating of the Air-Conditioning and Refrigeration Institute (4))
3) metrics computed by using a mathematical model of the human hearing. These are the so-called psychoacoustic metrics. Some of the most commonly used psychoacoustic metrics are (5):
   - Steady-state and transient Loudness, to quantify the perception of loudness
   - Fluctuation Strength and Roughness, to quantify the perception of modulation, beating and roughness
   - Tonality and Pitch Strength, to quantify the perception and annoyance of pure tones.

At the Tecumseh Research Laboratory, we have started to develop a database of sound quality compressor metrics. During the sound power test in the anechoic chamber, time histories of the sound pressure are acquired at each measurement microphone by using a multi-channel Agilent VXI front-end with 48 kHz sampling frequency on each channel. A set of sound quality metrics is then automatically computed for each microphone and saved in ascii format. Currently, since no sound quality target has yet been identified, several metrics are computed and their values stored in the database.

This new test procedure clearly 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 system in parallel to the measurement of the average spectra, on the other hand much more additional disk space is required to store the data related to each test. Time history and metric files need then to be stored in a relational database where they are associated to each test and to the sound pressure spectra.

For each compressor and each test condition, the metrics computed for all microphone positions are generally put in a matrix. Statistical parameters such as median, maximum, minimum and standard deviation are then computed to qualify the distribution of the metrics and their variation. Sound quality metrics polar patterns are also generated, to identify possible concerns due to directivity. Examples of sound quality metric polar plots for a compressor are shown in Figure 5, with loudness values on the left plot and tonality values on the right plot. Loudness is measured in sones and plotted on a 10 to 15 sones scale. Tonality is expressed in dimensionless units, with 1 being the tonality of 1kHz tone at a 60 dB level. Tonality values in Figure 5 are plotted between 0 and 0.5.

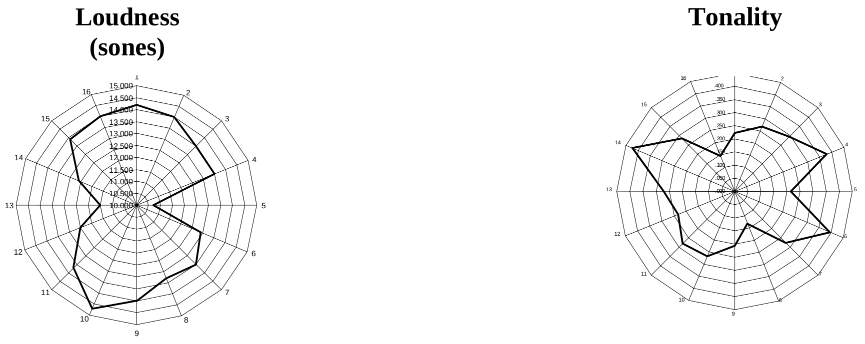

Figure 5. Polar plot of loudness (left) and tonality (right)

THE DEVELOPMENT OF A COMPRESSOR SOUND QUALITY TARGET

As discussed earlier, compliance with non-sound quality targets, such as sound power, often does not guarantee good sound quality. Therefore a separate target has to be developed to account for sound quality during the product development process.

Sound quality targets have been successfully developed in the automotive industry by following rigorous test and analysis methods borrowed from the behavioral science and sensory testing fields (6). A block scheme of the procedure is shown in Figure 6.

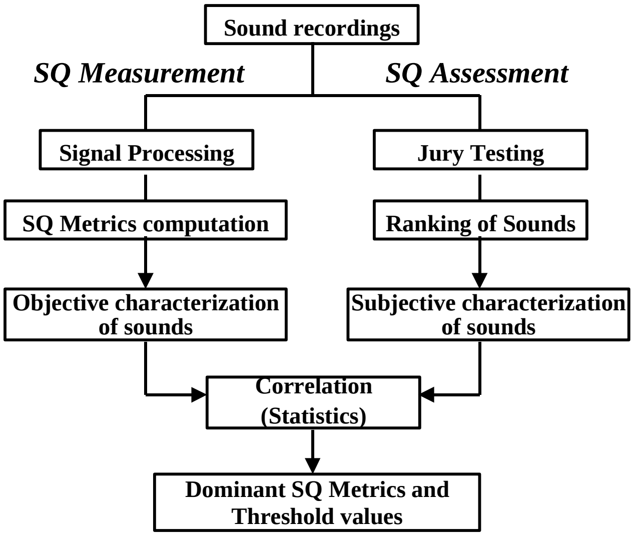

Figure 6. Compressor Sound Quality target development process

Sound quality is measured by computing metrics, which represent the objective data. In parallel, sound quality is subjectively assessed by performing jury tests where different compressor sounds are presented to jurors who are asked to express a preference. The jury study can be conducted following different possible approaches, however if the results are to be correlated to objective sound quality metrics, it is recommended to perform a controlled experiment, where jurors and answers can be checked for consistency and repeatability. A very good practical guideline for performing jury tests and analyzing jury test results has been prepared by specialists in the automotive industry (7). The same approach can be used to assess the sound quality of other products.

CONCLUSIONS

Compressor sound test procedures at the Tecumseh Products Research Laboratory have been modified to allow for the measurement of sound quality metrics. The objective is to gather a database of compressor sound quality metrics that can be used to establish internal sound quality targets.

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