An Appliance Noise Tutorial

Let’s review the basic concepts of acoustics and the design of quiet products.
After a long and arduous design process, it can be frustrating to learn that a product has a “noise problem.” Perhaps Marketing has determined that the product may not fare well against the competition, especially internationally where noise standards are higher. Maybe sales are sluggish even though the product has superior performance. Fortunately, these scenarios can be avoided by incorporating low noise components and noise reduction treatments within the product design during development. Applying noise reducing “Band-Aids” after a product has been designed is always possible although typically difficult, as options may be limited due to constraints imposed by mechanical reliability and function as well as weight, size and cost.

This article will review the basic concepts of acoustics and the design of quiet products. The first point to realize is that acceptability of sound is not as simple as loudness. Other contributing factors include the frequency spectrum of the sound (more on this below) and its temporal variability. The second important observation is that noise is unwanted sound. If not extremely loud or annoying, a very obvious sound can be an asset that connotes product quality or power, such as with vacuum cleaners where sound associated with a strong airflow through the nozzle can mean robust cleaning is occurring. Context can also be important.

A noisy blender in a lab or kitchen can be an annoying distraction but a noisy blender in a beach bar is an entirely different matter. Overall, the relationship between sound and perceived product value can be roughly divided into product sound quality, the relationship between sound of a product and its subjective perception—positive or negative, and product noise, wherein unwanted sound has no positive connotation and simply compromises product acceptability. The former is a fascinating enterprise drawing on the sciences of perception, psychology and marketing. (For more, see the appliance DESIGN August 2011 article by David Bowen.) This tutorial will focus on the latter.
Let’s define the basic quantitative descriptors of sound in simplest terms. Sound is a small time-varying fluctuation in air pressure measured on a logarithmic scale in decibels. Many people are unfamiliar and often uncomfortable with this measure, which is somewhat ironic as it is based on the physiology of our own sensory systems. Although we are unaware of it, we perceive differences in sound proportionally rather than linearly, which is another way to say logarithmically. (We also perceive light this way. The ancient astronomical scheme for assigning visual magnitudes of stars turns out to be a logarithmic scale as well.) The advantage of logs and decibels is that values stretching over many orders of magnitude can be compressed into a much smaller range for our consideration.

To be precise, the measure of sound pressure level (SPL) in decibels (dB) for a root mean square of acoustic pressure $P_{\text{rms}}$ measured in Pascals (Pa) in the metric system is $10 \log \left( \frac{P_{\text{rms}}}{P_{\text{ref}}} \right)^2$ where $P_{\text{ref}}$ is a standard reference pressure, 20 $\mu$Pa, an estimate of the lowest threshold of human hearing. Figure 1 illustrates some typical sound levels using the slightly different measure dBA that is defined below. Some interesting facts: This scale allows us to describe over five decades (a factor of $10^5$) in sound pressure using a scale of 0 to 130; Our ears can usually distinguish a 3 dB difference; A difference of 10 dB is typically perceived as a doubling of the loudness of the sound; 90 dB is the greatest workplace noise level permissible by OSHA for a worker during an 8 hour shift.

Decibels cannot be directly added or subtracted; simple logarithmic arithmetic is needed to combine them. To do so, decibels have to be converted back to squared pressure levels—which can be combined linearly—and then the result is converted back to decibels. Thus to add levels A and B dB we need to perform the operation $10 \log \left[ \frac{10^A}{10} \right] + 10 \log \left[ \frac{10^B}{10} \right]$ which is almost never anything like $A + B$. Setting $A = B$ we can easily conclude that adding two equal sounds increases the SPL by 3 dB and that reducing noise by a factor of two is equivalent to reducing SPL by 3 dB irrespective of what the levels were initially.

While sound is often measured by a single number like SPL, it is obvious that this cannot be a complete description as all sounds consist of a combination of many frequencies added together. To show this, sound pressure is often plotted in terms of its frequency spectrum showing pressure, in dB, as a function of frequency. More precisely, the sound pressure is plotted in terms of frequency ranges or bands. Popular sets are known as octave bands, in which the uppermost frequency of a band is twice that of the lower. For example the 16-Hz octave band contains the sound power between 11 and 22 Hz. Other types of bands are also used, including 1/3-octave
bands (three of which make up one octave band). Even more narrow bands with constant bandwidth, including those with a 1-Hz bandwidth, are useful in identifying narrowband noise. To obtain a single value for the overall SPL, the sound pressures in all of the bands are added up logarithmically as described above.

While a spectral plot can characterize how the levels of the different components of a sound are distributed in frequency, it only approximates how that sound is perceived. The human auditory system responds to frequencies between about 20 and 20,000 Hz, but not equally. The response of the auditory system is highest in the 1 – 3 kHz range and drops off on either side. Thus, to characterize a perceived sound, corrections known as “A weights” are applied that effectively reduce the relative pressure in the frequency bands away from this range to create an A-weighted spectrum. The sum of pressures in this spectrum, the overall A-weighted SPL denoted by dBA, is the standard measure of sound as perceived by the human ear. As a consequence, equal pressure in bands at the high and low ends of the audio spectrum contribute less to the perceived level than those in the middle, so quieting in this frequency range is usually very important.

Figure 2 shows a narrowband noise spectrum of a vacuum cleaner (with A weighting applied), and illustrates two types of noise. There is a wide hump with a maximum from about 400 to 2,000 Hz that is typical of broadband noise from, in this case, the exhaust airflow. This type of broadband noise, in which power is spread more evenly across a portion of the spectrum, can sound like a waterfall, HVAC noise or “white noise.” It can be inoffensive and possibly soothing unless excessively loud. Superimposed on this curve are a series of narrow peaks representing tonal noise generated by the brush rollers and the fan impeller. The latter are examples of sounds that can be particularly annoying.

Product Noise Description and Culprits

A classic acoustic paradigm frames problems in terms of a noise source and a path (or paths) from the source to the third element, the receiver. Means to reduce noise at the receiver, whether incorporated into a design from the beginning or added afterwards, require reductions of the noise generated by potential sources, and weakening or interrupting the paths within the product or to the receiver. For appliances, the receiver is the consumer, whose sensitivity to noise is, if anything, increasing due to closer living arrangements and exposure to quieter versions.

Sources of product noise fall into three categories as listed below. A good summary of means to control these sources and paths can be found in a previous appliance DESIGN article from July 2013 by Gladys Unger.
Airflow

Almost all airflow through products is turbulent, and air turbulence creates noise. This includes inlets, exhausts, and all internal airflow channels in between. Impingement of the flow with surfaces can result in significantly greater noise being generated, with path properties such as surface roughness and tight-turn radii increasing turbulence and noise. Airflow can also excite vibrations that produce radiated noise when they reach the product surface, acting as a loudspeaker. This noise tends to be broadband but interactions with certain geometries (e.g. lips or protruberances) can generate more tonal components as in wind instruments. Means to control generation of this type of noise include reducing the flow speed, smoothing flow surfaces, inserting screens or other dissipative elements (e.g. foam) in the airflow. Mufflers can always be added to inlets or exhausts when weight, space and cost permit.

Fans and other rotating elements

Fans tend to produce broadband noise as well as tonal noise at the blade passage frequency as a result of turbulence and blade interactions with housings and airflows. The latter tends to be a greater problem for fans operating at higher speeds. There has been extensive work designing quieter fans with good efficiency, but these modifications are not always incorporated in smaller, cheaper fans. Fan noise is typically a strong function of rotation and airflow speeds, and trading flow volume for speed can be an effective noise reduction strategy. Location of fans beyond line of sight to a user can sometimes be effective.

Motors and gears

These elements can produce noise that propagates through the air and/or vibrations that find their way to outer surfaces of a product which then radiate noise. Housings for motors and gears are often large, lightweight contiguous panels that respond to vibration from internal sources with greater vibration levels and are also efficient radiators of noise. Manufacturers of motors and gears have become more sensitive to the relationships between component build quality and noise, and one should investigate available noise data to gauge tradeoffs between cost and potential noise implications before selecting components. Sometimes an ounce of prevention is cost effective.

Quieting of Noisy Products

Remediation of noisy products begins with a “noise audit” consisting of the identification and rank ordering of all noise sources present. A common approach is to separately operate various components of the product under realistic conditions of load and measure the resulting noise. An
alternative is the “window” method, wherein the product is operated normally but all potential noise sources except one are blocked or attenuated by means of passive enclosures (e.g. covered with noise barriers such as lead sheets, mufflers, etc.), and the resulting noise is attributed to the unmitigated source, i.e. the open “window.” Vibration-related sources can be simulated by using a shaker to create radiation from surfaces. Airborne transmission of noise generated within a product can be simulated through the use of a small speaker placed within the product. With only the speaker turned on the noise level is measured inside and out, and the resulting ratio measures how much noise is transmitted to the outside.

When complete, the noise audit consists of a series of frequency spectra of the component noise contributions due to individual sources and paths within the product which when properly summed yield the overall product noise spectrum. This is the roadmap for reducing the noise, which proceeds by replacing noisy sources, mitigating paths, moving components, shifting frequencies of tones by slowing or replacing fans, and so on, while not compromising the performance, weight, size and cost of the product. While this can often be a challenge, making use of a methodical approach offers the best chance of achieving success.

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