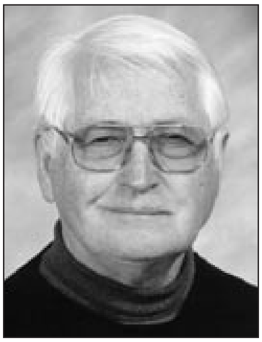
New technologies can lead to quieter mechanisms and materials or unexpected, unpleasant sounds.

Designing Quiet Products



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Sounds made by products can be either pleasing or annoying. Sounds are pleasing when expectations are met and the decision to acquire the product is reinforced (e.g., the familiar sound of a car door closing). Product sounds are annoying when they are unexpected, intrusive, or raise concerns about the function or quality of the product (e.g., a knocking sound in the engine). We tend to refer to sounds in the latter category as "product noise."

This article describes some trends in product design and engineering that have made some products noisier and some quieter. In some cases, quieter mechanisms and materials have replaced noisier ones, but in other cases new technologies have led to unexpected and unpleasant sounds. Psychometric methods that correlate design alternatives and user perceptions are helpful in designing products with sounds that are pleasing to consumers.

Definition of "Quiet"

These days, most product managers understand that the descriptor "quiet" has a broader meaning than "less loud" as measured on a sound-level meter. The sound made by a product must be appropriate to the nature and use of that product, and even small sounds that are inappropriate or distracting should be

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avoided if possible. Designers also realize, however, that appearance, performance, and functionality are also (maybe even more) important than "quietness" to customer satisfaction. Designers must balance the latter attributes, which they understand very well, with the product sound, which is harder to nail down. Unfortunately, some current design trends that work toward satisfying other requirements make designing "quiet" products more difficult.

Quantifying the correspondences between design choices (e.g., materials, geometry, mechanisms, parts layout, and assembly sequence) and the perceptual reactions of people to the sound of that product can seem like an insurmountable task. The complexity of sound-generation processes and the inherent variability in people's perceptions to those sounds creates much "scatter" in predicting user reactions. Nevertheless, through careful experimental design and testing, consistent relationships between design choices and perceptions of acceptability (so-called product sound quality) can be established.

Trends in the development of electric motors have led to noisier products.

Trends That Make Products Noisier

Fifty years ago, an absorption refrigerator was absolutely silent except for the hiss of a small gas flame. Some years later, the hermetically sealed compressor in an electric refrigerator was fairly unobtrusive, although not silent. However, the condenser coils on the back of the refrigerator and the 2 to 3 inches of wall thickness required to accommodate thermal insulation reduced the interior space of the refrigerator; therefore, the condenser coils were moved to the base of the refrigerator, and the wall thickness was reduced to less than 2 inches. As a result, the compressor had to work more often to counteract heat conduction through the walls. In addition, heater coils were placed in the walls of some refrigerators to reduce sweating in humid weather. Refrigerators, which once had no fans, now have two—one for the condenser coils[1] and one for the freezer compartment. As a result, refrigerators are now much noisier than they used to be.

In addition, customer demand for lighter weight, more color options, and interesting shapes and configurations has led to housings for many products made of rigid, low-density plastics. Because these housings are light weight, it is more difficult to isolate them from the forces of the motors and air-handling devices, and, because of their reduced mass, they vibrate more.

Another reason for more product noise is that sound can escape more easily through stiff, lightweight walls. At the same time, the resonance frequencies of the structural modes of the housing increase as the result of the combination of stiffness and reduced mass, thus increasing the radiation efficiency of the structure and moving the sound frequencies into the "loudness and annoyance" range.

Trends in the development of electric motors have also led to noisier products. Induction, universal, and DC-commutator designs are being supplanted by, for example, variable frequency induction, brushless DC, and hysteresis motors, all of which convert a supply voltage to DC, then convert the DC voltage to an AC voltage (single or multiple phase) to control speed and torque, which makes the motor more programmable and can improve energy efficiency and increase performance flexibility. Generally, the AC voltage produced is far from sinusoidal, leading to vibrations at frequencies well above the basic excitation level. Although these small vibrations may not affect the operation of the motor, they do produce audible noise that may be objectionable.

Hysteresis motors are attractive for some applications because of their high starting torque, but this can be accompanied by fluctuating forces that produce vibrations that radiate sound. The forces between rotor and stator can be computed fairly accurately, but the generation of vibrations and the transmission of those vibrations to surfaces that radiate sound can be very difficult to predict.

Even in conventional motors, design trends have increased noise. To improve performance and reduce the size of the overall package, the power density in motors has increased. Current designs for universal motors are a fraction of the weight and size of the electric motors of 50 years ago. Some of the change is attributable to better magnetic materials, but sometimes the motor is excited to the point that the magnetic circuit is driven to saturation, which increases the harmonic content of

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[1] Convection cooling has been tried but does not work well with the new placement of condenser coils.

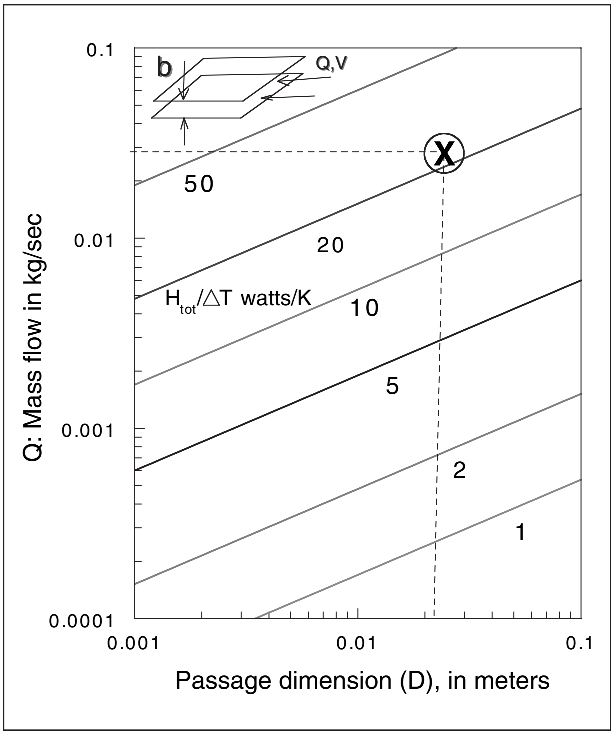

FIGURE 1 The heat transfer for airflow between circuit boards. The location *X* indicates the operating point of a particular design. *Q* = mass flow rate (in kg/sec); *V* = air velocity (in m/sec); *H* = heat flow rate (in jwatts); ΔT = temperature difference, parts to air (in K); *b* = plate to plate spacing (in m); *D = 2b*. Source: Lyon and Bergles, 2006. Reprinted with permission of IEEE.

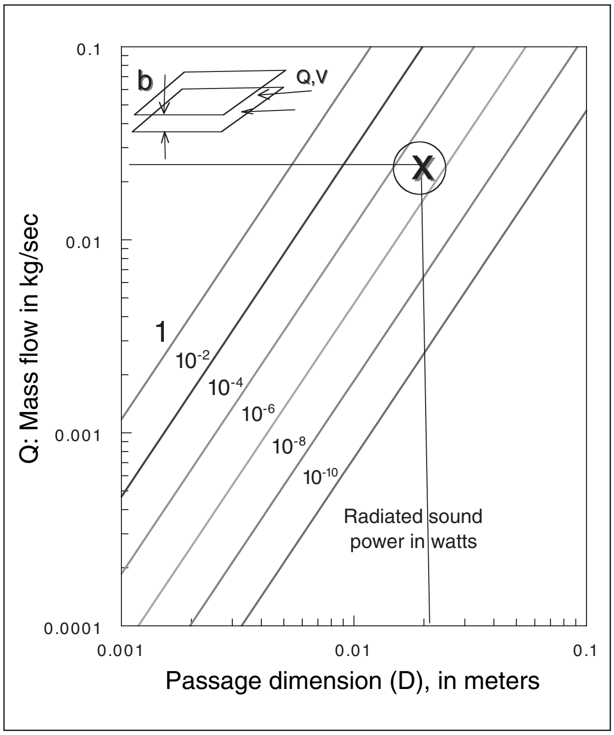

FIGURE 2 Sound generated by the flow of cooling air between circuit boards at the operating point shown in Figure 1. *Q* = mass flow rate (in kg/sec); *V* = air velocity (in m/sec); *b* = plate to plate spacing (in m); *D = 2b*. Source: Lyon and Bergles, 2006. Reprinted with permission of IEEE.

the excitation and causes the magnetic field to balloon around the motor and attract nearby ferrous material. Garage door lift motors, for example, attract the sheet-metal steel frames that support them and produce this kind of product noise.

Another less obvious cause of increased product noise is changes in manufacturing and assembly methods. "Design for manufacture" is a popular theme, but when parts are assembled by a sequence of layering operations, assemblies may have tolerance stack-up problems that lead to more noise (and other problems as well). For example, a popular food-preparation appliance was beset with such problems when new assembly procedures were introduced. Because of the lay-up of shafts and gears in the drive system, the motor could not maintain a constant speed ratio, which led to excessive gear noise (so-called "transmission error").

Irreducible Noise

Electrical and electronic equipment is cooled by passing air over the elements. This airflow is normally turbulent for higher cooling efficiency, and correlations have been developed between airflow parameters (e.g., velocity, turbulence length scales, temperature rise) and passage parameters (e.g., geometry, dimensions, heat release). Balancing heat transport with acceptable temperature rise and pressure drop is a design issue for laptop computers and digital projectors, which are being produced in smaller and smaller packages with the same, or even higher, performance levels.

Turbulent heat transfer inevitably creates a certain amount of noise, which we can label irreducible, because heat-transfer processes and noise generation by turbulent airflow in restricted passages are inextricably linked. As the air flows, the turbulent eddies decay and new ones are created, which produces forces on the components that generate sound and, at the same time, carry heat away from the surface. Thus noise generation is inevitable with turbulent heat transfer. Figures 1 and 2 show the calculation of heat transfer to sound for airflow between banks of circuit boards.

Another aspect of airflow is the pressure drop (or head loss) in the passages, which must be overcome by fan(s). Figure 3 shows the additional sound produced

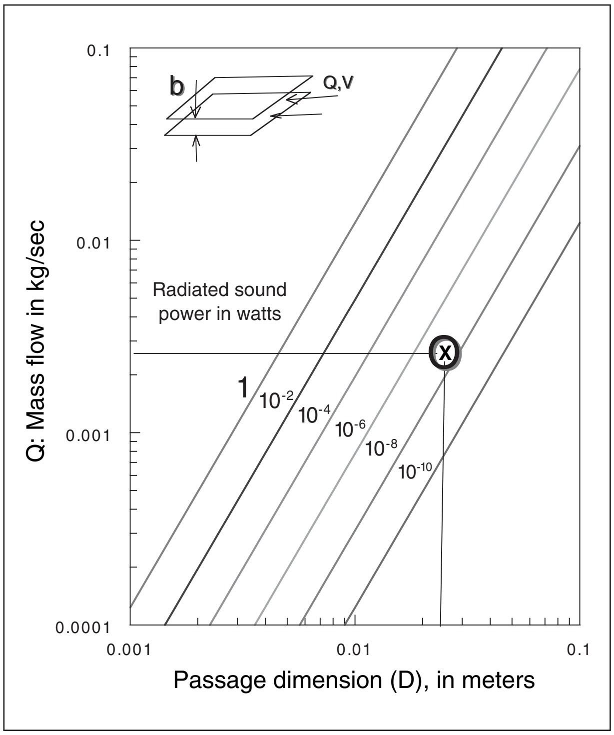

FIGURE 3 Sound generated by a well designed fan that would provide the airflow required in Figure 1. The location *X* indicates the operating point of a particular design. *V* = air velocity (in m/sec); *b* = plate to plate spacing (in m); *Q* = mass flow rate (in kg/sec); *D=2b*. Source: Lyon and Bergles, 2006. Reprinted with permission of IEEE.

by a well designed fan that provides airflow power to overcome this loss. Keep in mind that the actual noise produced by a fan depends on the inlet and outlet flow patterns and the aerodynamics of the blades. A poorly designed fan may produce significantly more noise than is predicted in this figure.

A good part of the noise from rotary lawnmowers arises from airflow around the cutting blades, which are designed to lift the grass by the flow they induce and then cut by impacting the grass at high speed, before it can “get out of the way.”[2] The airflow around the cutting blades radiates sound according to a dipole model of sound generation; airflow noise from grass-cutting blades increases as V^6. This means that a 10 dB reduction in noise requires a 17 percent reduction in speed and a 32 percent reduction in the impact force between the cutting blade and the grass. If noise reduction were achieved by slowing the blades, the mower would no longer cut grass!

New Technologies

One way to make products quieter is to change the technology. For example, printers are quieter because impacting print heads have been replaced by laser beams and ink-jet drops. Hard disk drives are quieter in some products because they have been replaced by solid state memories. The gains were offset a bit because sound made by keyboards had to be increased to provide feedback for the user.

Examples from digital technology are easy to find, but there are also examples in other types of products. The takeoff noise of jet aircraft has been greatly reduced by the advent of high-bypass-ratio jet engines, which increase the scale of turbulence and decrease the speed of the ejected air for a given amount of thrust. The acoustical benefit was not the goal of these changes, however. The goal was to increase fuel efficiency and lower speed thrust, which makes the airplane more “drivable.” Less noise was a happy accidental by-product! In fact, the relationship between higher efficiency and less noise also applies, to a certain extent, to fan-related noise in general.

An example of changes in an industrial process that has reduced noise is the way nails are manufactured. Traditionally, nails were made by chopping wire to a certain length and then holding the cut piece while the head was hammered flat, a noisy procedure. The process also required that the wire be oiled and then that the oil be removed. A machine developed in the Netherlands produces nails much more quietly by replacing chopping and hammering with a rolling method that uses plastic flow of the ductile wire material. A side benefit is that the nails do not have to be oiled, and therefore, degreased at the end of the process.

As these examples show, noise may not be the driving force behind new technologies that result in quieter products. But it is also true that if a product becomes significantly noisier, resistance to using it will be greater, depending on how users and bystanders react to the noise, which brings us again to the issue of human perception.

Good Sounds and Bad Sounds

Why does one car sound sportier or more “aggressive” than another car with a comparable engine and performance? Why do we find noise from one vacuum cleaner less annoying than from another? To answer such questions, and to incorporate the answers into the design of a product, requires product sound-quality engineering,

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[2] In the European Union, a directive was circulated requiring significant reductions in noise produced by lawnmowers used on golf courses and in parks.

a discipline that has arisen in the last 30 years or so. Sound-quality engineers dissect the acoustic signature of products (either existing or virtual), compare them subjectively and objectively, and define ideal (or target) signatures for the product sound.

Because the desired sound involves peoples' reactions, achieving that sound is similar in some ways to determining the right color, surface texture, or shape for the product. For all of these characteristics, objective physical measurements only go so far toward determining the target. Unlike sound, however, the more aesthetic aspects (e.g., color, texture, etc.) are generally independent of other aspects of the product design.

Sound is affected by many of the basic features of a product. The sources of motion, their interconnections, and the structures that hold them in place all contribute to sound generation. Thus the product design must connect the choices for these physical components to the perceptual reactions of consumers.

Sound may enhance or detract from the pleasure of using a product. In addition, sound may indicate how well the product is working. Procedures can be incorporated into the design process so that the positive attributes of the sound are identified and enhanced, and the negative ones are reduced. One approach combines product-sound analysis to identify the major components responsible for the overall sound with jury testing of an array of virtual designs. This procedure can provide specific design goals for the sound of a product in terms that can be specified (e.g., likelihood of purchase, perceived quality, overall acceptability, etc.) and that engineers can address (e.g., a reduction in water-splash noise in a washing machine or changes in the fan-related tonal sound in a vacuum cleaner).

Two types of consumer-oriented "sound studies" (focus-group studies and sound-quality jury tests) can be used to determine the importance of noise to the potential end user of a product, what the consumer expects of the product in terms of noise, and how much extra the consumer might be willing to pay for "improved sound quality."

Focus-Group Studies

A focus-group type of study might be conducted, in which qualified participants are asked to describe the relative importance of sound in relation to all other aspects of a product. The focus group can help identify subjective impressions conveyed by the product sounds that consumers feel are important. These perceptual attributes may include loudness or "strength" of the sound, effectiveness of the product, perceived quality, overall acceptability of the sound, and so on.

Of these, only loudness can be reliably predicted by a physical measurement. Other so-called "sound-quality metrics" that have been developed for an attribute of a single product (e.g., jet aircraft), or sometimes for no specific product, use simple sound stimuli, such as tones, clicks, and bands of noise, designed not to convey connotative meaning. However, meaning cannot be avoided when psychoacoustics are applied to product sounds.[3]

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Sound-Quality Jury Testing

A sound-quality jury test is another method of determining the relationships between possible design changes in a product and consumer responses. The goal of these tests is to quantify consumers' sensitivity to changes in the sounds of specific components and mechanisms in a product, in the context of overall product sound. Ratings for different combinations of attributes are used to determine which modifications optimize "sound quality." For example, even though tones and transient clicks or modulations may not significantly affect the sound level or loudness of a product, they can be audible and thus important in the overall "acceptability" of a product (Cann and Lyon, 1997).

Sound-quality jury studies can be conducted in two ways. First, a jury of consumers/users is presented with the sounds of various "virtual" products based on quantifiable variations in the sounds of the major noise sources in the product; the variations are made using a statistical design-of-experiments approach. After regression analysis of the jury ratings, a numerical relationship is established between a user perception,

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[3] The focus of psychoacoustics has been on how the auditory system assembles and processes acoustic information, peripherally and centrally. Therefore, traditional psychoacoustic methods do not provide guidance for predicting listener responses to the complex, actual sounds of products.

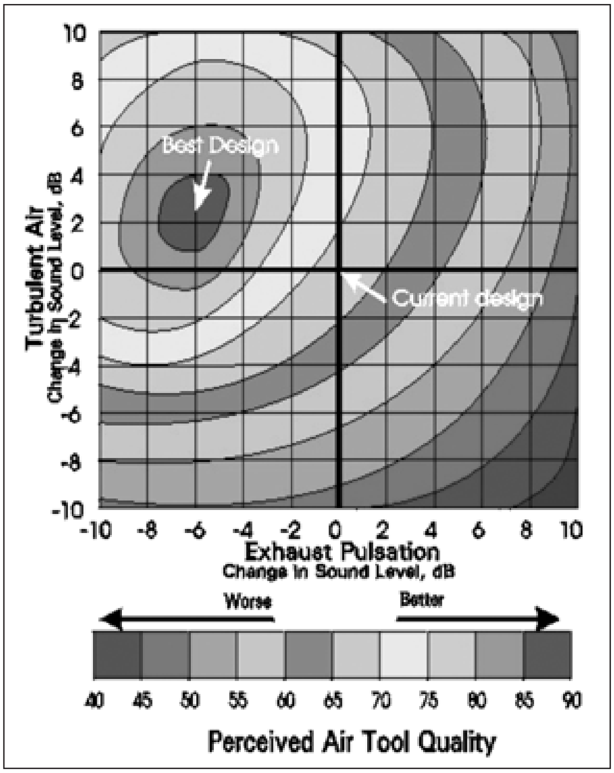

FIGURE 4 Response surface for perceived quality as a function of change in sound levels for two of the noise sources in an air-powered tool. The levels are based on sound-quality jury testing.

such as acceptability of the sound or the likelihood of purchasing the product, and changes in the sounds of the noise-producing components. Figure 4 shows an example of a "response surface" for an air-powered tool. This kind of result indicates different ways of achieving similar levels of improvement in sound quality rather than indicating how to achieve the absolute maximum sound-quality rating.

The second type of jury study involves presenting the sounds of a few products with different degrees of "sound treatment," using an appropriately designed statistical approach. The sounds are either recorded directly from actual products (perhaps competing brands) with different sound treatments or simulate different treatment levels based on recordings made from a standard product (including a few candidate designs based on the first type of jury study, described above). The end result of the second type of jury study is a preference ranking of the sounds (e.g., products).

Once jury ratings have been determined for a type of product, it is often possible to establish a correlation between the ratings and a combination of standard or customized sound-quality metrics, with the aide of statistical methods (e.g., principal components or factor analysis). As long as the product type remains the same, there is no need to reconvene a jury for analyzing the effect of subsequent product modifications.

New Tools

Product design in general has been greatly affected by new computational tools, such as computer-aided design (CAD), computer-aided manufacturing (CAM), and finite-element analysis (FEA). Product-noise analysts and designers also use FEA and other software, such as boundary-element analysis (BEA) and statistical energy analysis (SEA), in addition to a host of software packages, for processing and analyzing experimental data on product prototypes.

With CAD tools, the shape and structure of a product can be designed, and the forces and motions generated by the mechanisms can be analyzed. FEA can then be used to calculate the resulting vibration, flow patterns, and temperature distributions in the product. BEA tools can then be used to calculate the sound radiated from structural vibrations.

Although CAD and FEA work well for analyzing appearance, ergonomics, fluid flow, and temperature, they are less helpful for predicting product sound for a variety of reasons. Take damping, for example, an important parameter in predicting vibration and sound levels that is notoriously difficult to predict. Damping is almost always introduced as a known parameter. Sound radiation is sometimes determined primarily by the dynamic conditions at the edges of structures where FEA may be least reliable.

For these reasons, canonical models (e.g., sound radiation by flat plates or cylinders) and semi-empirical tools (e.g., SEA) have been useful. Although they lack the apparent precision of FEA and BEA methods, they retain parameter dependence in their formulations, and they can predict trends in sound levels as those parameters change.

Self-Image, Demographics, and Economics

People regard some products as utilitarian commodities (e.g., air conditioners, air compressors, paint sprayers, and electric can openers) that have little if any associations with self-image. Other products, such as automobiles, golf clubs, and cameras, have potentially more associations with self-image. For many years, white goods (e.g., refrigerators, dishwashers, clothes washers, and dryers) have been treated as commodities that are purchased primarily on the basis of price and function.

In the last 50 years, the price of an automobile has increased by a factor of 20 to 25, from about $1,500 to $30,000 to $40,000. In the same period, the price of a dishwasher increased by a factor of about 5, from $150 to $750. This has made it much more difficult for manufacturers of white goods to absorb the costs of improvements, particularly in the area of product sound. Indeed, the need for cost reductions in materials and components in white goods has made it difficult to keep product noise from increasing.

For some time, European white goods (a misnomer because many European products have brushed-steel exteriors) have been quieter than comparable U.S. products, but the prices of European products are generally much higher than for their U.S. counterparts. European products are quieter because of heavier construction (stainless steel instead of plastic tubs), more sound-absorbing materials, and better isolation of vibrations from motors, pumps, and water piping.

Recently, however, kitchens themselves, as well as kitchen equipment, have become a matter of pride for many U.S. families. As a result, they are purchasing many more high-end products, which are quieter, not because of breakthroughs in noise-control technology, but because of well-known acoustical principles. These products are available because of marketplace demand and the willingness of consumers to pay higher prices for them.

Conclusion

For the foreseeable future, designing quiet products is likely to remain a combination of analysis, experimentation, and the application of well-known principles in sound and vibration. Product-design teams must include engineers with expertise in computational methods as well as in acoustical technology. But the idea that a designer will draw a CAD model, analyze the product for vibration with FEA, compute the sound radiation with BEA, and then build a prototype with the predicted product sound that has been declared favorable by a psychometric model is a pipe dream, because every one of these tools has deficiencies in areas that are critical for acoustical behavior.

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