Sound Quality Guidelines for Non-Automotive Products

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The field of sound quality is very advanced in the automotive industry. In recent years it has also become an important marketing and engineering factor in other industries. The biggest differences in SVQ (Sound/Vibration Quality) perception between passenger vehicles and other products lie in the human machine interface and the modality of the interaction. Both factors strongly impact expectation. When driving, we fully "experience" the vehicle, since we are immersed in it through multiple and distributed interfaces that make our perception truly multimodal. Furthermore, the driving experience is, in almost all conditions, very interactive in nature. Instead, when we use a vacuum cleaner or we install an air purifier in a room, our interface with either product is simpler, often limited to our aural perception of its noise and only at times supplemented by a tactile dimension, as in the case of the vacuum cleaner. Additionally, with many consumer products, our experience is intrinsically passive, because we do not interact with the product other than turning it on or off, as is the case with appliances, air conditioners, generators, etc.

Various considerations help us understand the different expectations that we, as users, have for automotive versus other products. In terms of objectionable features, however, many concepts from automotive sound quality still apply to consumer, medical and off-highway products. The same psychoacoustic features, such as loudness, pitch, modulation, etc. combine to create our holistic perception of the sound. A high-level, low-frequency tone is annoying whether it is a vehicle boom phenomenon or the blade-passing frequency of a fan in a room air conditioner.

Another interesting human factors concept that is mainly peculiar to consumer and especially medical products relates to the need of the user for some sort of reassuring feedback (tactile or audio). In the case of an appliance, we typically expect something to happen (action or motion of a part), with some noise associated to it, as a consequence of our interaction with the machine (such as pushing a button to close a door). For the user of a medical device, such as a dialysis machine, some level of compressor noise and valves that circulate fluids and deliver drugs is reassuring, since it means that "everything is working as it should," but it should not be too loud to interfere with sleep and comfort.

These concepts and others relating to the SVQ of consumer and medical products and of industrial and off-highway equipment are briefly summarized in this article.

Sound Quality Concepts

From a historical perspective, most of the industries being discussed here have implemented noise and vibration testing to some degree. For example, within the consumer product market, and to some degree the medical industries, it is common to test products and components for sound power level (SWL) based on an accepted standard, such as ISO-3744.[1] Vibration requirements are often evaluated according to an applicable vibration exposure standard, such as ISO-5349, the ISO hand transmitted vibration standard.[2]

Industrial products and off-highway industries often test for SWL as well as adhere to noise exposure requirements (OSHA noise exposure standard 1910.95[3]) and whole-body vibration requirement discussed in ISO 2631-1:1997.[4] In addition, the off-highway industry is often required to adhere to European driver noise level standards (European Directive 77/311/EEC[5]). The noise and vibration limits that are applied are based on health risks or community annoyance issues, or in some cases product-specific requirements.[5] but do not consider the perceived quality or expectation of the sound and/or vibration emissions of a product. The distinction in this case is focused on the possibility that a product noise or vibration signature may be below the prescribed threshold, based on health or community annoyance, but still be perceived as having poor quality. Because sound/vibration quality is a function of level, frequency, and temporal (in terms of impulsive or changing) characteristics, specifications such as SWL, which average both spatial and temporally in one-third octave bands, do not correlate well with subjective preference or perceived quality.

An example of this is discussed by Cerrato[6] where an icemaker, which met the manufacturer's specification for A-weighted SWL, was identified as having a sound quality concern described as a low frequency moan. In this case the objectionable moan was due to a tone in the 250 Hz one-third octave band. Although the tone could be clearly identified because it stood out from its adjacent one-third octave bands, it had a much lower level than some of the higher frequency bands and did not affect the overall A-weighted SWL. Similar experiences have been observed in products that exhibit unwanted impulsive, modulating, changing, or tonal characteristics. For this reason, it is necessary to consider sound or vibration quality analysis as being independent from nonperceived quality specifications, such as noise or vibration exposure levels or pass-by requirements.

When one considers sound and vibration quality, it is helpful to first categorize the sound or vibration according to their functions. One approach is to classify them as passive, running, action, or signal events. Passive events refer to the acoustic or tactile feedback that can be observed during interaction with the product when it is not operating. This includes button pushes or door closures where the operator may expect some feedback such as an audible or tactile click. The challenge associated with passive sounds involves finding the compromise between the operator's expectation for clear feedback that conveys a high quality yet is not excessive or overpowering. This is discussed in the context of automotive door closures in a previous *Sound & Vibration* article[7] and in more detail later in this article.

Running (or operating) events refer to the sounds/vibrations that occur during the operation of the product as it relates to comfort and reliability. The events in this category generally contribute to the operator's impression of quality or annoyance but do not convey specific information. Running events are generally used to quantify the sound or vibration quality during a typical or specific operating condition. In contrast, action events relate informational feedback to the operator. The feedback is seldom intended to be a specific piece of information but rather a general indicator that something has changed. An example of this is the sound change that occurs when a product switches from one part of a cycle to the next. In most cases, action events are subtle indicators that something (expected) has changed but do not provide such a strong feedback to become annoying.

Finally, signal events provide informational feedback to the operator. As opposed to action events, which are subtle indicators, signal events are intended to be clear and sometimes unignorable (alarms, for example). A signal event may be as simple as an alarm that indicates the end of a cycle, or much more complex, as in multiple alarms indicating different states and with different levels of operator action required. Simple signal events are commonly found in the consumer product industry, while more complex multi-tiered signal events are often used in medical devices.

Consumer Products

Although the consumer products industry has historically evaluated noise and vibration characteristics through "standards" such as SWL and hand-arm vibrations, the idea of using sound quality as a product differentiator is not new.[8-12] The concept of product differentiation through sound quality is presented by each of the authors in different ways and in context of various products, but in all cases the overall goal is to identify the characteristics (or dimensions) of the sounds in terms of their merit and function. The common theme is the understanding that each of the characteristics can serve a specific function, described as passive, running, action, and signal events in the previous section, and either detract or bolster the event's effectiveness at performing its function.

While delving into some of the typical issues that are seen within the consumer products industry, it is helpful to first understand that although there is a wide variety of products that could be considered consumer products, many of the products have very similar noise generating mechanisms. For example vacuum cleaners, air purifiers, lawn mowers, refrigerators, icemakers, leaf blowers, and air conditioners all have motors/engines and fans to move air. Therefore, they will all share common characteristics of having a broadband component from the air flow and a tonal component from the fan blade pass and the motor/engine harmonics. It is important to note that although the dimensions of the sounds may be similar, the preference is expected to change based on the expectation of the operator. For example, a consumer will likely be willing to accept a higher loudness and tonal content in a vacuum cleaner or leaf blower than they would in a refrigerator.

Passive Events

As mentioned earlier, passive events are acoustic or tactile events that occur during non-operating interactions with the product. The most typical case of a passive event is the opening or closing of a door or cover on a product. In general a consumer expects to receive a certain level of feedback during the event; that is, some noise is to be expected as a refrigerator seal is cracked or a door latch clicks into place. This feedback gives the operator confidence that, in the two examples; the refrigerator was properly sealed, and the door is properly closed. But even while some noise is expected, the noise will still be used to provide a perception of quality. Hatano and Hashimoto[13] studied the sound quality of the noise emitted as the paper tray for a printer was operated manually. The goal of this study was to optimize the sound of the event with a focus on making it less annoying for surrounding people located near the printer in a typical office environment.

An example of a passive event is shown in Figure 1. The data shown in this figure are the sound pressure measured while a refrigerator door is opened. The event, which occurs at about 0.5 seconds, is a scrapping sound of two parts of a hinge rubbing together. For this particular example, it is likely that the consumer may expect some noise as long as it is representative of the seal around the door breaking, but a scrapping sound would not be preferred.

Running Events

As discussed in the first part of this section, a large number of consumer products contain a motor/engine and fan of some type, and in most cases this indicates that the sound will contain broadband and tonal components. The broadband component can often be described by its overall level, or loudness, and spectral content. The loudness can be described in terms of one of the loudness metrics, such as DIN45631,[14] and is often one of the most important characteristics in defining the perceived quality of a product during running events. In addition to loudness, the broadband component can also be represented in terms of spectral content.

A generic example of the spectral content that can be present in broadband noise is the comparison of pink noise compared to white noise, which subjectively is perceived as broadband noise with a different pitch. Figure 2 shows the frequency spectra for two different vacuum cleaners with the same overall loudness levels but different frequency spectral content. In this case, one of the vacuum cleaners has more low-frequency content, while the other has more high-frequency content. The difference in frequency spectral content results in a difference in perceived pitch.

A second example of the spectral content of a broadband noise changing the perceived pitch is shown in Figure 3. In this case, the one-third octave spectra for two lawnmowers are compared.

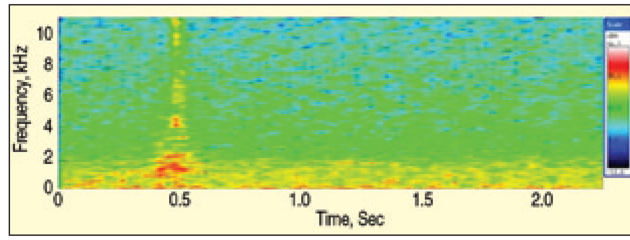

Figure 1. Scraping noise heard during opening of refrigerator door.

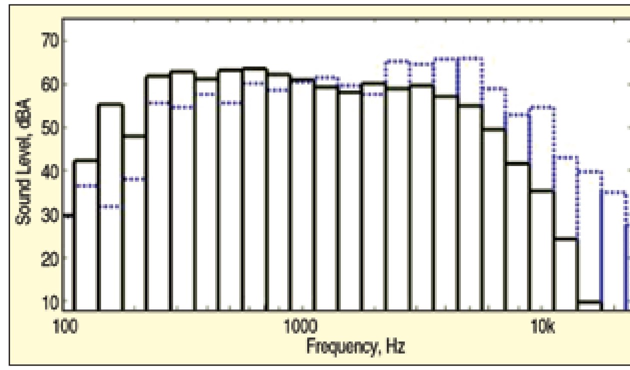

Figure 2. One-third octave spectra for two vacuum cleaners with similar loudness but different spectral content, resulting in a difference in perceived pitch.

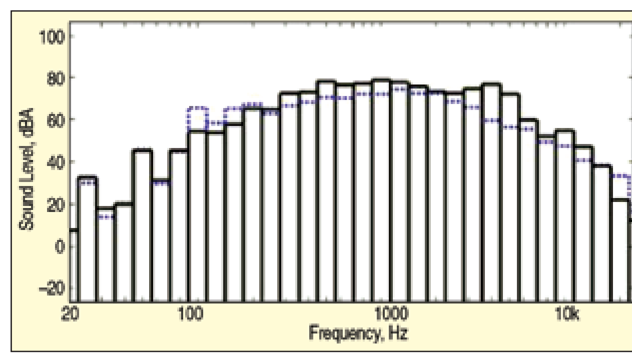

Figure 3. One-third octave spectra for two lawn mowers with similar loudness values and different spectral content.

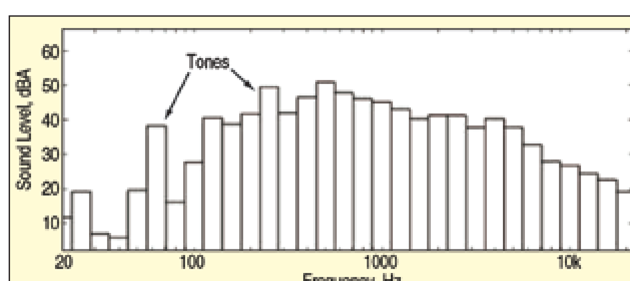

Figure 4. One-third octave spectrum measured near a refrigerator.

There are various metrics that can be used to represent the spectral content in signals, some of which are discussed in References 15 and 16.

Another common sound quality issue encountered during operation of many consumer products is tonality. Tonality, in general, is the degree to which a single frequency stands out from the adjacent frequency bands and can be measured using multiple metrics including, tonality, prominence ratio, or tone-to-noise ratio. Tonality is generally considered a negative attribute. An example of a tonal sound is shown in the one-third octave spectrum of the sound measured near a refrigerator, shown in Figure 4. The first tone indicated in the plot is the fan motor frequency, and the second tone is the fan blade pass.

A second example of a tonal noise is shown in Figure 5. The figure shows the sound measured near a sink during the operation of a food grinder. In this case, a strong second-order vibration was generated by the grinder motor and excited a stainless steel sink. The combination of the vibration from the motor and the sound radiation efficiency of the sink resulted in a strong tonal noise.

Products that contain multiple tones can also exhibit a roughness to their perceived character, which is often referred to as a growl sound. The rough or growly sound occurs if there are two tones that have spacing of 20-300 Hz but is most sensitive to spacing of about 70 Hz. Generally, the spacing of the tones is such that they appear as a single tone in a one-third octave spectrum, so octave-based measurements are not able to identify the presence of the two tones. Figure 6 shows a one-third octave spectrum measured near a refrigeration compressor for a residential air conditioning unit. This figure shows that two tones that are spaced 59 Hz apart show up in the one-third octave spectrum as a single tone in the 630 Hz band, demonstrating that standards (or metrics) based on one-third octave spectra cannot identify sounds with a roughness characteristic.[15]

A combination of some or all of these characteristics, including modulation, that will be described later are used in the sound quality evaluation of various products including small fans,[17] notebook inlet grilles,[18] refrigerators,[19] gas boiler pumps,[20] and vacuum cleaners.[21]

A second type of mechanism that can be found in a wide range of consumer products is an electric motor that drives a gear set and possibly a ball screw or chain. A few examples of these types of mechanisms include garage door openers, electric can openers, and automatic doors. The dominant characteristics that these types of mechanisms exhibit are motor whine from the electric motor and tonal noise and modulations from the gear sets or mechanisms. Motor whine tends to contain strong tonal content that in most cases can be described in terms of loudness, spectral content, tonal strength and roughness similar to the earlier discussion. The gear sets, ball screws, or chains tend to have loudness, tonal content and modulations. These can be classified as either frequency or amplitude modulations and are often caused by variations in torque or load on the motor. These mechanisms closely relate to the seat track and window regulator discussion included in Reference 7. Reference 22 discuss the sound quality of sewing machines and found that roughness, sharpness, loudness and fluctuation all play a role in perceived sound quality.

An example of amplitude modulation is shown in the recording of two automatic garage door openers (Figure 7). This figure clearly shows one opener as having a significant amount of amplitude modulation and the second as having a much lower level. Discussions regarding modulation can be found in References 15 and 23.

A final class of events commonly seen in the consumer products industry are impulsive types of sounds, such as door closings[24] or bearing transient events.[25] This class of sound ranges from impacts that occur during the operation of products such as an automatic stapler, a defective refrigerator fan, or a baseball bat or a golf club striking a ball. The nature of the product and impulsive noise along with the consumer expectation tend to govern the perception. For example, a consumer would not expect to hear any transient during the operation of a refrigerator or an air purifier. In contrast, an automatic stapler would be expected to make an impulsive noise during operation, so a complete lack of noise during operation may be disconcerting and may cause the user to question whether the stapler is working. While the consumer may expect to hear some noise during the operation of the stapler, the noise and possibly feel of the impulsive event may be used to judge the quality of the product. In this case, a "solid" or "strong" sound would be preferred, and a "rattle" sound may convey the image of poor quality.

Similar to the stapler, sporting equipment like baseball bats and golf clubs are expected to generate impulsive noises and tactile events when the ball hits the bat or club. The impulsive events often provide two levels of feedback to the user; the first is a subjective impression of the quality of the equipment, and the second is an impression of the quality of the hit. For example, Figure 8 compares the impulsive sound when a ball is struck by two different golf clubs.

The time history shown in the figure clearly shows that one club "rings" longer than the other. The duration of the impact affects the golfer's impression of the club quality. If the impulse is too short the golfer feels that the club head is "dead," but if the impulse is too long the golfer feels that it rings too much and it doesn't transfer enough energy to the ball. Reference 26 covers an effort to relate the feel of a golf shot to its impact sound. In the study, the subjective impression of the shot was recorded along with the sound pressure at a typical golfer's head location. During the study, the authors found that there was a strong correlation between the golfers subjective impressions and objective ratings for SPL(A), Zwicker loudness, and Sharpness.

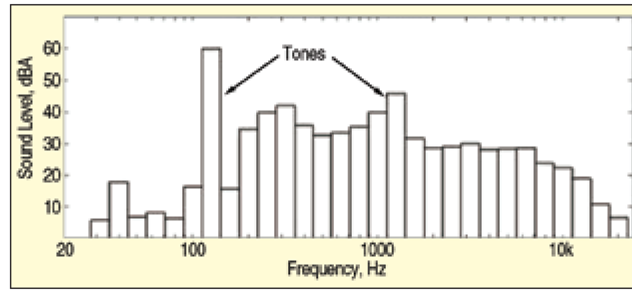

Figure 5. One-third octave sound pressure spectrum measured near a food grinder.

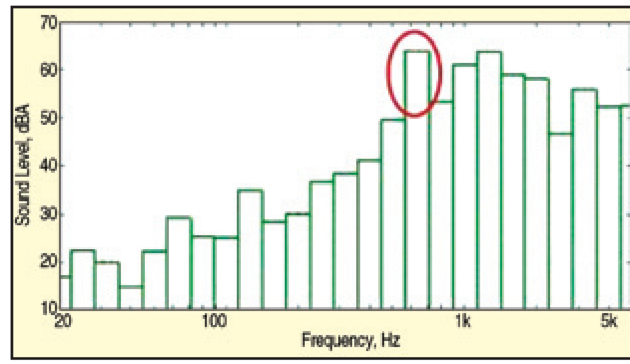

Figure 6. One-third octave spectrum for a refrigeration compressor for a central air conditioning unit; sound exhibits rough nature.

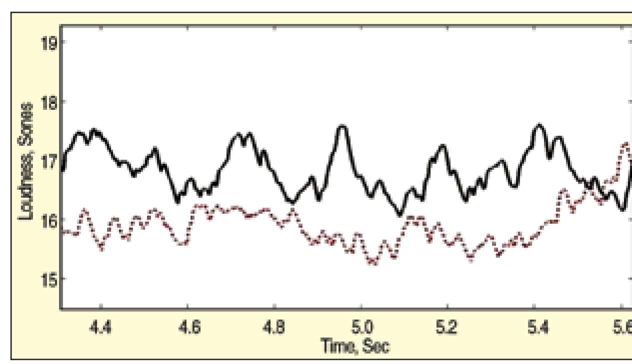

Figure 7. Time-varying loudness for two garage door openers during door lift.

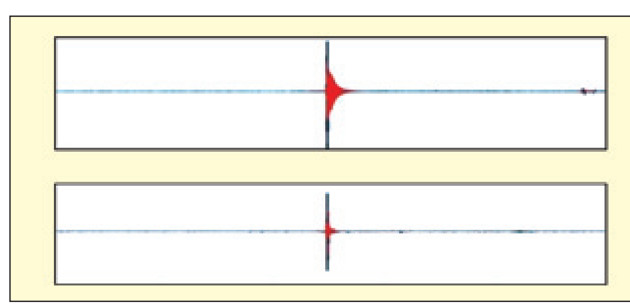

Figure 8. Comparison of impact sound when ball strikes two different golf clubs.

Action Events

Action events as discussed earlier refer to events or changes in running events that indicate a product is functioning properly. In a

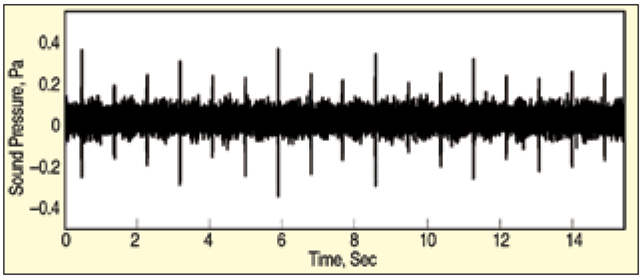

Figure 9. Sound pressure time history near a check-sorting machine.

general sense, the sound/vibration quality aspects of action events are closely related to those of running events, with the caveat that action events are part of the consumer's expectation. Reference 27 discusses the operating sounds of a copy machine with a focus on the transient events that occur as the machine picks up, conveys and ejects the paper. During this study, the effect of the timing of the transients were studied with an effort to optimize the timing for pleasantness.

To help illustrate the idea of action events, consider the time history of the operating sound of a desktop check sorter (see Figure 9). This figure shows a recorded time history during the operation of a desktop check sorting machine, which consists of an electric motor that drives a serpentine belt to pull the paper checks past various scanning and printing devices. The overall sound of the device has a tonal nature, as the belt rolls over the drive gear and idler pulleys, with various impulsive sounds that occur as the check is routed through the scanning and printing devices. The impulsive "clicks" that are generated by the scanning and printing functions give an overall impression that the machine is operating as expected. The action events are expected – and even preferred – by the consumer as long as they are not annoying or overpowering.

Signal Sounds

As opposed to the previously discussed events, signal events are intended to convey information to the consumer. Within the consumer product industries, signal events are most typically designed to act as indicators, such as a clothes washer buzzing when a cycle is done, or water cooler beeping to indicate that the water jug should be replaced. Because the number of signal events tends to be low for consumer products, the actual signal does not have to be especially refined, but rather the signals tend to be designed to be noticeable. In contrast, the medical industry commonly uses acoustic alarms as indicators to convey much more information including state of the machine or patient, and urgency. Therefore a more detailed discussion of signal sounds will be made under the medical industry discussion.

Issues Specific to Medical Equipment

The concepts of SVQ within the medical industry contain many of the same concerns as consumer products, especially for products that include DC motor mechanisms or motor fan assemblies. These concerns may include loudness, tonal content, modulations, sharpness, and transients and are often viewed in the same way. Despite the similarities in many of the products, there are some concerns that are unique to the medical industry.

Three examples of unique concerns for medical equipment in terms of the area where the priority may be highest include:

- *Hospital equipment* – Sound and/or vibration cues are needed to carry specific information, often regarding the state of the machine and/or the patient, with cues regarding the urgency of action.
- *Wearable devices* – Sound and/or vibration of the machine should provide "comforting" feedback to the patient/user; that is, action events that indicate everything is running normally while not compromising the privacy of the patient.
- *Home Care* – Sound and/or vibration of the machine should be minimally invasive from the point of view of sleep disturbance.

Because all three concerns are important to each type of medical equipment, despite differences in priorities, the remaining portion of this section will focus on each of these major concerns: signal/alarm sounds, action sounds with a focus on privacy, and sleep disturbance.

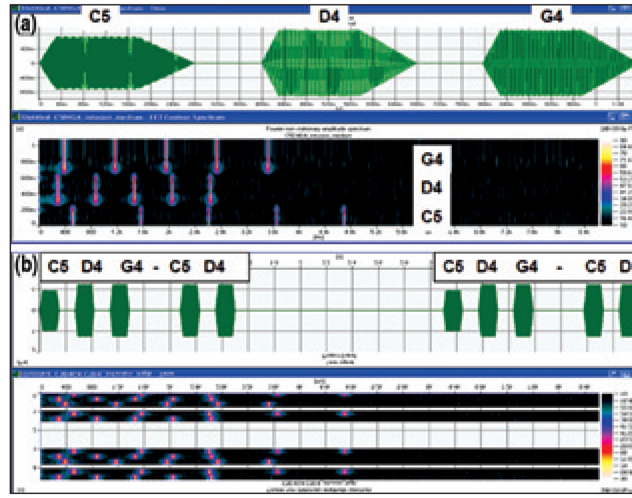

Figure 10. Medium and high alarm for drug delivery equipment (IEC 60601-1-8).

Alarm Sounds and Noise in Hospitals

For medical equipment, the need for acoustic cues carrying information about the state of the machine or the patient is particularly vital. The information to be conveyed is often much more complex and multidimensional than that provided to signify the end of the washing cycle of a dishwasher. In fact, the subject of alarm sounds of medical equipment is under a lot of scrutiny by human-factors groups at major manufacturers and by international standard organizations, since current alarm strategies perform well below their optimal level.

Alarm sounds of medical equipment need to be easily identified, localized and interpreted regardless of the surrounding soundscape. This translates into much more complex requirements than "good sound quality." This means that the alarm sound needs to be not only "audible," that is, discriminated from background noise, but also it needs to be clearly identifiable to convey specific and unequivocal information about the clinical state of the patient. Manufacturers of medical equipment need also to ensure that the alarm and its meaning can be learned and retained by clinical and nursing staff.

In 2000, researchers from the anesthesiology department of the University of Arkansas proposed a new set of alarm sounds for anesthesia monitors that had performed well for audibility, learnability and urgency mapping.[19] The sounds were grouped by type of physiological measurement or instrument situation: ventilation, perfusion, infusion, cardiac performance, oxygenation, power failure and temperature. This new set of sounds originally created for anesthesia monitors were then adopted in 2005 as international standard, IEC 60601-1-8 "General Requirements and Guidelines for the Application of Alarms in Medical Electrical Equipment."[20]

The intent of the standard was to provide guidance to equipment manufacturers toward designing alarm sounds that, in addition to alerting the operator, offer aid in source identification and convey priority and urgency of action. As an example: a high-priority alarm is one that requires immediate operator action; a medium-priority alarm requires prompt operator action; and a low-priority alarm requires operator awareness. The standard specifies different beat rhythms for different urgency of the alarm with different repetition rate. There is no requirement for a specific pitch, but the fundamental frequency needs to be in a specified frequency range. And the signal should contain at least four harmonics of the fundamental.

As an example, a time history and FFT spectrogram of the IEC 60601-1-8 medium- and high-alarm melodies for drug delivery equipment are shown in Figure 10. In this example, the difference between the medium- and high-priority alarms is the repetition rate, so the action required is the same but the urgency of the action has changed.

Despite this new standard, several issues and concerns have continued to be raised by clinical and nursing staff in several hospitals. Among these:

- The loudness of the alarms, especially if continuous. A louder alarm is more likely to be detected therefore medical equipment often leaves the factory with high output sound level set as default.
- Confusion between alarms. Different equipment from different manufacturers may have similar alarms, with only minor differences in frequency, level and or repetition rate. In an environment with multiple patients, equipment, clinical and nursing personnel, an alarm that could be clearly identified when tested in the manufacturer's lab can become indistinguishable from others.
- False alarms. Several references in literature report complaints by nurses of cases where the perceived severity of the alarm is not consistent with the state of the patient. An example of occurrence of a false alarm is when the alarm is perceived as conveying a "severe situation that needs to be addressed immediately" but the patient situation is not at risk. This is dangerous, as nurses have reported to have become annoyed and have either stopped paying attention to the false alarm ("cry wolf" scenario) or they have turned it off altogether. Either scenario obviously can have very serious consequences.
- An adverse effect of noise due to alarms on patients' health and recovery. Several surveys have been conducted in many hospitals around the world to assess the likelihood of sleep disruption in patients due to the proliferation of equipment and alarms in typical hospital settings. Interrupted sleep is known to have a negative impact on recovery of patients.

For these reasons, medical equipment manufacturers are currently investigating alternate alarm sound strategies, such as making the alarm multimodal; that is, by adding visual display, lights, etc., and playing with different harmonies and tempos, outside of the design envelope provided by the IEC standard. A wealth of information on the subject can be found on the website of the Association for the Advancement of Medical Instrumentation (AAMI) (http://www.aami.org/), which held a Medical Device Alarms Summit in October 2011 aimed at bringing together cross-disciplinary and cross-functional experts and leaders (nurses, doctors, clinical engineers, regulators, equipment manufacturers) to devise innovative strategies to improve the effectiveness of alarm sounds.[21,22]

Alarm optimization and standardization is a very active area of research and must go beyond the assessment of sound quality in terms of detectability and annoyance and must consider identification and learnability in complex soundscapes.

Acoustic Feedback and Privacy

A second concept unique to the medical industry and specifically to wearable devices, such as insulin pumps and ostomy pouches, is the requirement for privacy (or discretion) in action events. In the case of an actuated device such as an insulin pump or a wound therapy pump, the person wearing it would typically desire to experience some noise or vibration when the pump is running as reassurance that "everything is working," described as an action event earlier. At the same time, the same noise should be discrete enough to go unnoticed by someone who is in the vicinity of the person wearing the device. In this way, the challenge is to design the SVQ so that the action sounds are detectable, not annoying, and indicate good performance to the user of the device but are undetectable to people nearby.

From an SVQ standpoint, the main concerns are identical to any other (consumer products or automotive) device, with the caveat that identification should be minimized for nonusers:

- Pump startup/shutdown noise. Transient and discontinuous events such as start-ups and shutdowns tend to be noticed more that steady-state events. Therefore, during these transitions, the change of noise level and characteristics should be minimized by either reducing the running noise or by ramping the RPM of the pump up/down gradually.
- Running noise level or loudness should be as low as possible. It should also be as smooth and constant as possible, with no modulation, changes of speed, rattles, etc., since any of these transient noises may be perceived as symptomatic of abnormal function, which would be very unnerving for the wearer, and will be more easily detected by nonusers.

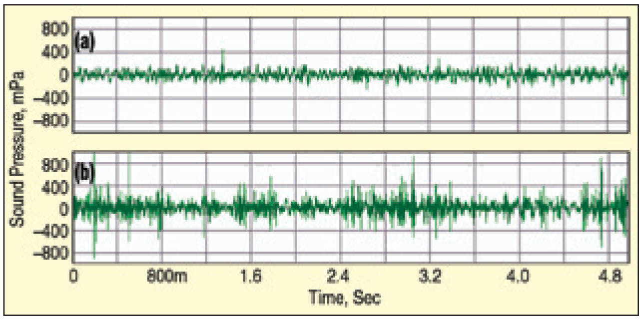

Figure 11. Sound pressure time history of quiet film (top) and loud film (bottom).

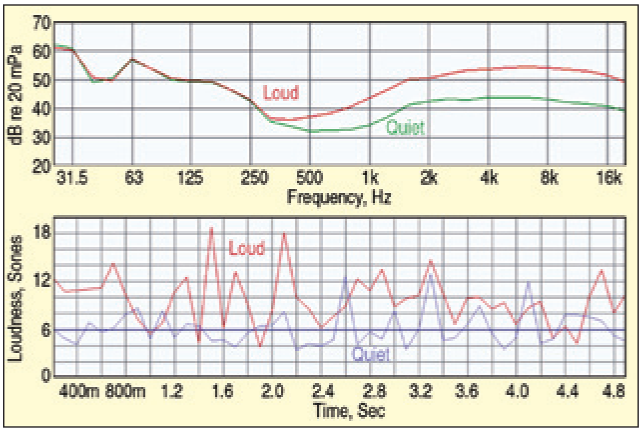

Figure 12. One-third octave spectra (top) and loudness versus time (bottom) for quiet and loud films.

An example of noise recorded when two plastic wrappers are being crumpled is shown in Figures 11 and 12. In Figure 11, the time histories of the recorded sound pressure of the quiet (top) and loud sample (bottom) are shown; while in Figure 12, the corresponding one-third octave average spectra and loudness function vs. time are shown. In this case, there is a large difference between quiet and loud samples across all domains. In most cases, however, the difference will be more subtle and, while subjectively perceived, it may not show from average quantities such as average one-third octave spectra, and time domain parameters/functions should be interrogated instead.

Sleep Disturbance

The World Health Organization issued in 2009 "Night Noise Guidelines for Europe,"[23] a document with health-based guidelines that uses indirect evidence to establish a connection between night noise and health: the effects of noise on sleep and the relationship between sleep and health. The document defines threshold outside sound pressure levels for night, and from these, assuming a certain noise reduction offered by windows, a threshold for interior sound pressure is derived that will minimize the likelihood of awakenings. Surveys conducted in several European countries show that at night exterior levels of 30 dB(A) or less, no or very few complaints for sleep disturbance are reported, while effects on sleep (body movement, awakening, self-reported sleep disturbance, arousals) are reported for levels between 30 and 40 dB.

Considering these values as reference, when evaluating the sound quality and sleep disturbance of a device, an ideal target for the maximum SPL at the ears of the receiver should be around 40 dB, at least as a starting point, with the understanding that it may change based on the soundscape. Most importantly, to avoid sleep disturbance, the delta level between OFF and ON of the device (or between cycles/states), should be less than 10 dB.[23]

In a study performed by the authors on automated air freshener dispensers, both the sound quality and the likelihood of awakening

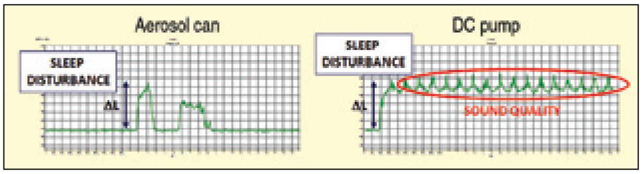

Figure 13. Loudness vs. time function for two types of air freshener dispensers.

were evaluated for different samples and the overall preference derived based on these two separate factors. In terms of sound quality, loudness was the dominant factor as indicated by a typical jury test, while the sleep disturbance criteria was understood to be the loudness difference between background noise and noise during dispensing.[24] As an example, Figure 13 shows the loudness vs. time functions for two different types of automated air freshener dispensers: aerosol can at left, and DC-motored pump at right.

The pump style freshener generates a noise typical of DC-motor-powered mechanisms, with modulated whining (also called "wow-wow"). The aerosol release mechanism is a transient, spring loading-unloading type of noise. The wow-wow component of the pump-style freshener is very annoying, so from a pure SQ standpoint, the aerosol can with its broadband hiss that lasts just a few seconds is considered less annoying. From the standpoint of sleep disturbance, the aerosol can exhibits a lower level increase than the DC pump and a shorter duration of the event, so it is less likely to awaken or be noticeable after awakening.

It is important to consider annoyance and sleep disturbance separately from sound quality based on the understanding that a main driver for sleep disturbance is the relation of the events relative to the background events (the event does not "stand out" from the soundscape). In contrast, in terms of SVQ the event, or product sound/vibration, is generally designed to meet the consumers expectation, as opposed to being undetected.

Based on the products evaluated by the authors and taking into account published sleep disturbance information,[23] the following is recommended as a means to set level difference targets for sleep disturbance:

- *Transient Sounds* – N_{10}-/N_{90} < 3 or $L_{10} - L_{90}$ < 10 dB where N_x is the loudness exceeded by X% of the data points in the recording. Therefore N_{10} is a close (but conservative) approximation of the maximum loudness and N_{90} of background noise. $L_{10} - L_{90}$ (dB) is the difference between an A-weighted SPL of event and background. Note: Statistical descriptors depend on the total number of data points, or require a "normalized" time window around the event.
- *Constant Sounds* – Difference between average loudness, or dB(A), during the event and average background noise before event started. Maximum level increase (above background) < 10 dB.

Off-Highway and Industrial

Off-highway vehicles such as agricultural, construction and moving equipment typically have to comply with two regulations:

- Maximum SPL at driver's ears to limit noise exposure during the work day at or below the threshold imposed by federal requirements (OSHA in the U.S.,[3] EEC directive in the EU,[5] etc.)
- Maximum pass-by or exterior noise level to limit the noise introduced into the community.

As already noted, neither specification is concerned with either the sound quality perceived by the driver or the noise-induced annoyance in the community. When one considers that for the operator, the off-highway vehicle is his/her work equipment and environment for the duration of the work day, it is easy to understand why the main concern for this application is the reduction of noise level and therefore of noise-induced fatigue due to continuous exposure. An additional difference lies in operator expectation. Operators of off-highway vehicles generally maneuver the equipment to perform tasks typically requiring high power output from the engine; therefore, they require a "powerful" engine, as indicated by the noise generated and are less concerned with refinement and comfort.

Having said that, in recent years sound quality has somewhat caught up as a product differentiator (even if not a main one) in the off-highway industry. This has been driven to some extent by the comparison of U.S. products to their European counterparts, which are quieter (in both interior and exterior noise) due to stricter EU noise limits. U.S. companies often have European divisions, and there has been a growing need to share platforms and subsystems in general, which has led to vehicles and equipment with some EU content being sold in the U.S. with very positive feedback about their noise and vibration performance.

For those manufacturers of off-highway equipment who are pursuing an improved image of their product by implementing NV level and quality engineering practices in their development cycle, the sound and vibration quality concerns are similar to those of the automotive industry and described in previous articles of this series.

For stationary industrial products, such as power generation systems (electric, hydro, wind, etc.), chemical treatment plants, and large industrial infrastructures, the main issues tend to be community noise level and annoyance in general (sleep disturbance at night, annoyance and fatigue during the day). In most countries, industrial plant developers have to submit detailed environmental noise impact assessments to demonstrate that a new or modified structure will not cause an increase of noise in the community. To this end, manufacturers of any equipment installed on the roof or the perimeter of the industrial premise, such as air-handling/HVAC units, transformers, etc., have to verify that the sound power of their product (frequency spectrum in one-third octave and overall level) is below a given threshold. We have already discussed how a sound power requirement does not necessarily guarantee minimum annoyance and/or sleep disturbance.

From an annoyance standpoint, narrow band components, such as pure tones, either steady or intermittent or modulated, are very annoying. Because of the frequency-dependent absorption of sound by air and terrain, the noise reaching the community at large is heavily weighted toward lower frequencies and tonal components from rotating devices such as large fans or windmills becoming very dominant in the soundscape. For this reason, the level of lower harmonics should be reduced to limit noise-induced annoyance in the community.

For sleep disturbance, the same criteria of maximum running sound and most importantly of reduced delta between ON-OFF events that were described in the medical equipment section apply to industrial equipment.

Conclusions

The sound quality concepts of consumer and medical products and of off-highway and industrial equipment have been reviewed by the authors. This article points out that the main sound quality differences between automotive and other products lie in the perception of the user, which in turn is the result of different human-machine interfaces and interactivity. The perception of the sound and vibration of consumer products has been described in terms of different operating conditions/states of the machines and their interaction with the user:

- Passive events
- Running sound
- Action sounds
- Signal and/or alarm sounds

Sound quality issues of medical devices have also been reviewed with particular focus on alarm sounds of medical equipment, which present additional challenges. They simultaneously need to be clearly audible and identifiable by the clinical staff and convey very specific information, often with a heightened sense of emergency or urgency of intervention, but should not disturb the patient(s) and interfere with their sleep.

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