Sound/Vibration Quality Engineering

Part 1 – Introduction and the SVQ Engineering Process

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A series of four articles will introduce sound and vibration quality (SVQ) techniques for automotive, consumer, industrial and medical products. The series will provide a technology summary and get readers jump-started with SVQ engineering. The articles in the series are: Part 1 – The Sound and Vibration Quality Engineering Process; Part 2 – Automotive Sound and Vibration Quality; Part 3 – Sound and Vibration Quality of Consumer, Industrial and Medical Devices; Part 4 – Sound and Vibration Quality in Product Design. Parts 2-4 will appear in subsequent issues of S&V.

This first article will focus on the sound/vibration quality engineering process. This is a thorough and rigorous process that is guaranteed to give you the understanding of the sound/vibration of your product, whatever that may be. The five steps of the process are shown in Figure 1.[1]

The second article will review in-depth the sound/vibration quality concepts of automotive components and systems as classified in Figure 2. The sound quality concerns related to detectability issues are in general easier to investigate because they are one-dimensional in the sound quality space. Think of axle whine, as an example: the whine is due to one narrow-band frequency that first becomes audible, then annoying, as its level increases over the rest of the vehicle noise (also called masking). The sound quality problem, in this case, is: "What is the maximum allowable level of noise coming from the axle that will not cause a sound quality complaint, i.e. that will not be clearly perceived by the driver?" The solution depends clearly on the vehicle masking, which is vehicle and operating condition-dependent, and from the difference level between axle noise and masking. Targets for powertrain and driveline systems have been derived now for several years following this strategy of "noise-over-masking." This article will review the main findings and provide a summary of known target assessment strategies.

The acoustic image of a vehicle is multi-dimensional in that multiple components which are time and frequency dependent interact and combine to create the overall vehicle sound. Concepts of sportiness, luxury, reliability, etc. are strongly affected by sound and vibration, and automotive companies around the world have invested time and money to understand what role sound and vibration play in their customers' perceptions and to establish realistic targets to ensure commercial appeal.[2]

The third article will focus on appliances, consumer products, industrial and medical devices and customer expectation differences among different products. Similarly to the automotive sound quality concepts described in the second article, sound quality concepts for these products will be introduced and discussed. As an example, typical sound quality concepts for appliances are listed in Figure 3, from which we can clearly see how the customer expectation and usage truly define the sound quality problem. In most cases, appliances perform a function while we are focused on a different task; therefore, they are expected to be quiet while getting the job done. What if a kettle makes a sound which is like "a plane taking off"? Researchers at the University of Salford, UK, have actually applied sound quality evaluation and metric development technique to solve the "kettle sound quality" problem.[3]

Medical equipment for hospital and home use has other challenging sound quality concerns. Intensive Care Units and hospital wards in general are very noisy environments due to the presence of countless types of equipment, generally crammed in small spaces, with a wide variety of beeps and chimes to provide feedback to medical and nursing staff.[4] With the aging of the baby boomer generation and increasing in-patient hospital costs, out-patient and home therapies are increasing in demand, posing interesting challenges for the noise and vibration engineer. In the case of a home therapy device such as a dialysis machine, patients desire a quiet but audible operation, with a sound pleasant enough that allows them to fall asleep, and minimum sleep disturbance for the patient and his/her partner. In this case, the guidelines from the World Health Organization[5] offer only limited guidance since they apply to noise coming from the outside, such as from traffic and industrial premises, and do not account for pleasantness and comfort of sound.

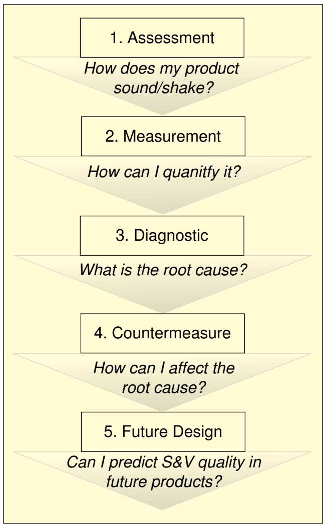

Figure 1. The sound and vibration quality engineering process.

The fourth article in the series will focus on sound and vibration quality in product design. In this age of digital signal processing, advanced decomposition, extraction and synthesis techniques are more and more available to the noise and vibration engineer. These techniques help us do a better job in:

- Understanding the root cause of a sound quality concern, by extracting signal from a noisy background, identifying the hot spots on a product, estimating the vibration of the surface that radiates noise, listening to the noise generated in one specific area, etc.
- Playing "what-if" games by using digital filters to mix-and-match sources and paths, changing characteristics of sound and vibration, reproducing sound and/or vibration with high-end simulators, etc.

In each article, a review of the most relevant literature will also be included. The techniques will be reviewed, experiences of the author will be included and main findings from published references will be provided.

Understanding Sound and Vibration Quality

This article is written as a general overview of the topic and is intended to form the basis for future, more application specific articles. From this article, the author hopes that the reader will able to develop a better understanding of the sound quality process and is provided with enough information to effectively interact with this field. For those that wish a deeper understanding, the author has provided a detailed list of references that help establish a strong foundation in sound and vibration quality.

In any troubleshooting activity triggered by a perceived lack of sound or vibration quality, the first task of the engineer is to understand the concern. Engineers often tend to try to skip this step, and assume that they fundamentally understand the issue since they have "measured it." However, data on paper, such as frequency spectra, often tell one story, but the customer may tell an entirely different one. What affects the sound level of the component may not be at all what the customer objects to in the final product. One has to note that NVH troubleshooting activities are expensive since they require dedicated resources and, due to the vast amount of data produced, may present several challenges for the engineer. It is therefore vital to understand well from the start what the problem is and make sure that the engineers involved in the activity maintain their focus.[6]

Detectability – component should not be detected in normal driving conditions
- Transmission, gear, A/C compressor, alternator, fuel pump, tires, power steering, etc.

➡ ***Tone-over-masking criteria***

Acoustic image – component expected to make audible noise, but it has to match customer expectations
- Character: engine
- Quality: accessories (door closure, seat adjuster, power window, windshield wiper)
- Comfort: road noise, wind noise

➡ ***Brand Sound***

Figure 2. Automotive sound quality concepts.

Passive sounds (SQ = image)
- Sounds produced when product is touched but not operating (doors open/close, etc.)
- Very important, because they affect purchase decision (customer in-store scenario

Running / operating sounds (SQ = comfort + reliability)
- Sounds produced by machine when running
- Not aimed at providing specific information but may funciton as such

Signal sounds (SQ = information)
- Sounds produced by machine when running

Figure 3. Appliance sound quality concepts.

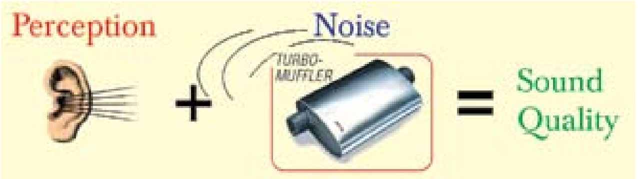

Figure 4. Sound quality ingredients.

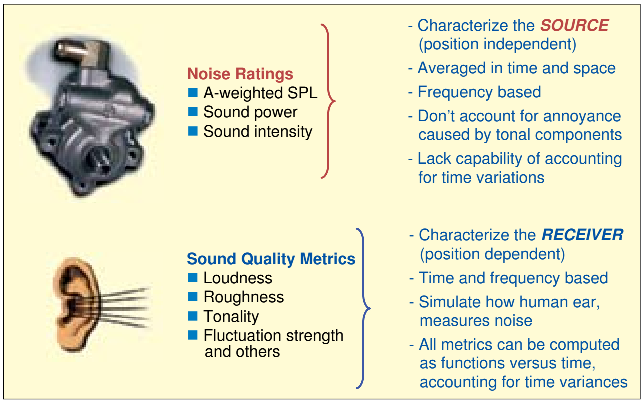

Figure 5. Noise ratings vs. SQ metrics.

To understand whether the customer is objecting to a particular tone or to a high frequency hiss or to something else is a necessary first step, even if this is not done with a formal jury test. Questions such as "How do you know that this is the problem?" are certainly difficult to ask to management and sales and marketing staff but they need to be asked to avoid the risk of starting an expensive investigation on the "wrong noise."

So, my advice to the engineers who have to investigate a sound or vibration quality issue for the first time is to make sure that they understand what the issue is for the customer. Forget preconceived notions, such as "This has a higher dBA (sound level) than the other one" and truly listen to your customer. Virtually every NVH lab now has software to record and play back sound and vibration data. Listen and dissect the signal until you are certain that you understand the customer's complaint.

Myth – sound quality is all about Metrics

I often hear that "sound quality is all about metrics." My opinion, as a practitioner of sound quality for over 15 years, is that sound quality is not at all about metrics. I often say that only 5% of sound quality is about metrics, 95% being about understanding your product inside-out, its noise and vibration characteristics, and what the customers expect of it. If and when you get to this point, you are ready to compute sound quality metrics. Not earlier. I believe it is very difficult, if not impossible, to understand sound quality if you don't have a basic understanding of the physics of the system combined with a quantitative assessment of the customer expectation. It is therefore very important to approach sound quality with a rigorous process, exactly as you would approach modal analysis, finite element modeling or any other technique that you may need to use to understand your product.

Sound/vibration quality (SVQ) is one attribute of the product that derives from our expectation. With no expectation, i.e. preconceived notions of how a product should sound/vibrate, there is no sound/vibration quality. When you go to the store to purchase a vacuum cleaner, you have an expectation of vacuum cleaner sound, which means that you do not expect the vacuum cleaner to sound like a refrigerator or a lawn mower. So, you have an expectation of vacuum cleaner sound, at this point just an acoustic picture in your mind. Then, when you are trying the different models, one or two will sound less annoying and you will prefer their sound, but maybe not their look or features. Now, your purchasing decision process is affected by one additional parameter, the sound of the vacuum cleaner. And the acoustic picture in your mind is more precise, it is that of the best sounding vacuum cleaner (see Figure 4). Whether the sound quality will affect your purchasing decision depends on other parameters such as cultural/social sensitivities of the customer and expected use of the device.

When sound/vibration quality shows up as an important factor in the decision process (from marketing polls and customer clinics), product engineers need to start worrying about SVQ. In the Detroit NVH community, to which I have had the privilege to belong for the past 13 years, it is well known that vehicle manufacturers have put a strong emphasis on understanding and designing the sounds that are first heard by a customer visiting a dealership: door closure, chimes and powered seat adjusters. These sounds have nothing to do with how the vehicle drives, handles, accelerates etc., yet they are extremely important because they are the first to affect the expected image of that vehicle in the customer mind.

Sound/Vibration Quality is Not Absolute

Noise and vibration engineers have a tough time in understanding sound/vibration quality because it is not absolute. That is, it is not the same for all products. In my opinion, engineers have been very spoiled by using the A-weighted sound pressure level or dBA, as I will refer to it for brevity in the following text. As most know, dBA was introduced by the standardization community as a temporary parameter to describe not just the noise but also the perceived loudness of a product. And it has done a very good job since it has helped the engineering community establish guidelines for test procedures and limits for industrial and environmental noise exposure. The automotive community was first to embrace sound quality (SQ) when it became apparent that dBA targets pushed out to suppliers by vehicle OEMs, even when satisfied, did not guarantee the expected sound image of the vehicle. Sound quality started to become a buzz word in the late '80s and by the early '90s had a prime spot at noise and vibration conferences and exhibitions. Engineers were faced with the challenge of quantifying not just the noise but also its perception and they were starting to realize that the parameters used for one don't work for the other.

The reason for this is illustrated in Figure 5, where the differences between noise ratings and sound quality metrics are highlighted. Noise ratings such as sound power have been derived to provide a noise label for a product by averaging out small differences and adopting data reduction techniques as octave- and third-octave band spectra. Sound power is the time-averaged acoustic power output of a source. 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 judgment of that source on the part of the receiver.[7]

In many laboratories, sound power is calculated from measurements of sound pressure (or sound intensity) 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. This is why sound power alone cannot be used to quantify sound quality, especially when the sound of the product is not constant and exhibits multiple tonal components. We hear the local and transient phenomena, not their average over time.

There is of course still a place for traditional metrics such as dBA, sound power, etc. but the engineer using these tools needs to understand their limitations. In many applications, SVQ often requires its own target which needs to be developed following an engineering process, exactly like other performance and functional attributes.

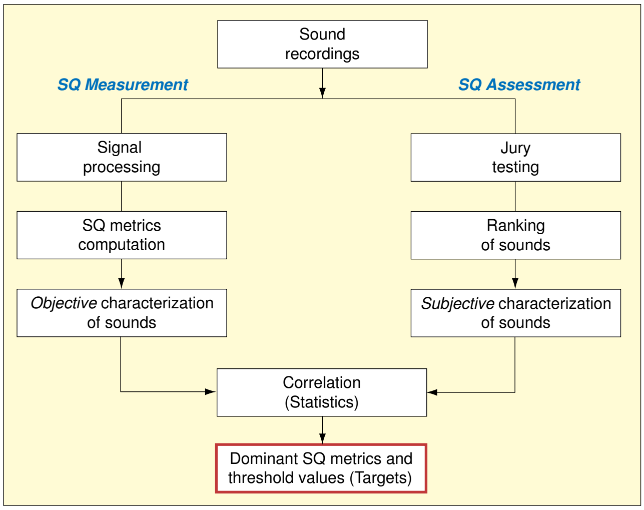

Figure 6. Sound/vibration quality target development process.

S/V Quality Target Development

Any process to address sound or vibration quality issues should always start from the voice of the customer to understand what features are objectionable and what are desirable ("1. Assessment" in Figure 1). Once the features are understood then we need to find an objective way to quantify them ("2. Measurement in Figure1). The two steps can actually be performed in parallel as shown in Figure 6.

For SVQ assessment (right-hand process), there are two main methods to measure subjective response to a noise or vibration issue – real-time and off-line. I refer to the real-time method as the "what-do-you-think" method, the engineer/customer experiences the noise/vibration by walking around the item running in a lab (or driving, in case of a vehicle) and expresses an opinion, typically in relation to a previously tested sample. This method is by far the most preferred because it is easy, it provides instant feedback, the engineer/customer has a real feel for the product and facilitates the discussion among engineers. This method may also be the only one possible in cases in which the concern cannot be reproduced by artificial devices, such as loudspeakers or shakers.

The off-line methods are those in which the sound or vibration of multiple samples have been recorded and are reproduced to either one or more people at the same time in a laboratory environment. Naturally, the precision of the recording and the fidelity of the reproduction play a major role for this type of task and require an up-front investment of equipment and facility. But it is also very important to remember that to test for sound/vibration quality means to record sound in conditions that best represent the real life sound or vibration experience, as will be discussed in the next section.

The off-line methods are preferred in a benchmarking situation, when there is a need to compare the S/V quality of competitor samples, or when a target needs to be established. Either objective requires robustness of procedure and data accuracy since they will lead to specific countermeasures to improve the product and/or achieve the target and we all know that these will be judged on the '$/dB' scale. This means that the subjective experiment has to be as controlled as possible in order to minimize the risk of biases in the result and misleading information.

In recent years, the off-line and real-time methods have been combined by several researchers trying to quantify the relative effect of different perceptual dimensions (sound, visual, temperature, vibration). Vehicle and flight NVH simulators have been developed that reproduce video, audio and tactile stimuli, providing a more complete driving experience. Especially in the automotive and aerospace industry, where noise and sound quality targets have been used throughout product development for several years, there is a growing need to understand how the different stimuli interact. As an example, how does the vibration felt at the steering wheel during parking maneuver ('shudder' in NVH automotive jargon) affect the perceived noise? Would the perception of the noise be somewhat masked by that of the vibration? The results of preliminary investigations indicate that the test environment where vibration, visual and operating instrument panel are present is more believable as well as comfortable for the juror. [8,9] The possibility of interaction between the juror and the vehicle especially during acceleration and deceleration is likely to help the juror focus on the 'powerfulness' aspect of the sound or the smoothness of the vibration.

In another recent paper,[10] French researchers have investigated the auditory and thermal cross-modal interactions involved in the perception of a HVAC system. They found a significant interaction between sound and thermal comfort, in that a specific sound significantly enhanced thermal comfort and that some noises are more suitable (that is, acceptable) to air-conditioning system than others. The conclusion being that HVAC product engineers have to account for both auditory and thermal perceptions in order to provide the most comfortable thermal condition at home or in a vehicle.

Sound Quality Measurement – Monaural or Binaural?

Using an artificial head with microphones at the ears' locations is the best possible way to capture the sound as it would be heard by a human being. The spatial cues provided by the two ears are necessary for the fidelity of reproduction. Spatial cues are especially important in environments where the sound of the object is reflected or diffracted by surfaces and therefore it can reach the ears of the subject from different directions.[11] This is the main reason for which the automotive industry has pretty much standardized on the use of binaural heads for vehicle interior noise recordings to be reproduced for subjective evaluations.

If instead the product is tested in an anechoic or hemi-anechoic space and therefore its sound reaches the person from one direction only, the difference between using a binaural head and a microphone is much smaller, and my recommendation in these cases is to simply use one or more single microphones. This is the typical scenario of a sound power test, in which the product is placed in the middle of an anechoic or hemi-anechoic space and several microphones or an intensity probe are used to measure the sound pressure or sound intensity on a surface surrounding the product. This test procedure applies to either components of larger systems (such as a compressor in a refrigerator or a power steering pump in a vehicle) or to entire systems used outdoors (lawnmowers, tractors, etc.). The main difficulty in using a sound power test procedure to test for sound quality is that, there is no fixed occupant position, so where would we put the binaural head? Component noise can be fairly directive, as it is shown in Figure 7 where the loudness values measured at several locations on a hemisphere surrounding a refrigeration compressor are plotted (the compressor, not shown, is located in the center of the circle).[12]

Sound power tests are also conducted in reverberant chambers,

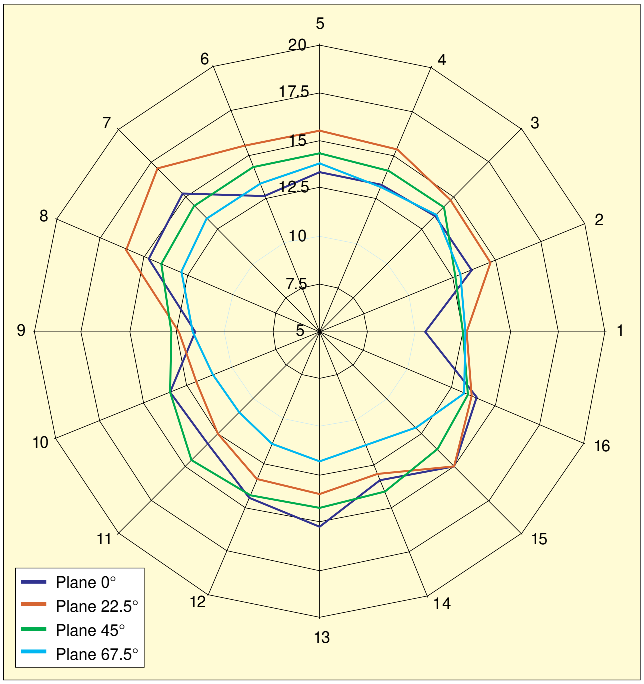

Figure 7. Sound/vibration quality engineering process.

where the sound field is diffuse and reaches the listener from all possible directions. In this case, the recorded sound is not realistic and I generally try to avoid listening to recordings made in a reverberant chamber.

So to answer the question of this paragraph, "binaural head or single microphone?" you need to understand first which is the boundary condition in which the sound will be experienced. If there is an occupant position and the environment is neither totally reflective nor absorptive, such as in a vehicle or in a kitchen, definitely use a binaural head, if you can. For example, in a refrigerator sound quality test, the binaural head would be positioned in front and at an average height and distance (i.e. 5 ft height, 3 ft in front). In addition, if you were to test the refrigerator in an anechoic or hemi-anechoic space, add at least two surfaces to represent the floor and back wall.

While it is nice to have an artificial binaural microphone available, the lack of it should not stop you from conducting a sound quality investigation. Even if the sounds that you recorded may not be played back in the most realistic way, still good information can be gathered from single microphone data.

Vibration Quality

The measurement of vibration quality presents the same challenges and constraints of a measurement of sound quality. All interfaces between the body and vibrating item have to be mapped, in realistic conditions. Like sound quality, specially designed acceleration transducers are commercially available to allow for measurement at these interfaces. Examples of vibration quality concerns (as opposed to vibration exposure) are the vibration that may be felt at the steering wheel during parking maneuvers (typically referred to as steering shudder) or the vibration of a cellular phone in manner mode or the vibration felt at the seat of a garden tractor.

Because a realistic perception of vibration is much more complicated to reproduce than sound, in most cases vibration quality is assessed in real-time, unless some type of vibration simulator is available. If the subjective evaluation is done in real time, it is recommended to have all samples available at the same time to facilitate the comparison. Also it is important to have written instructions, along with the rating sheet, and ask more focused questions to ensure that the juror is tuned in to the problem. Since a real-time test is less controlled, it is necessary to introduce as much structure to the test as possible in order to obtain consistent and reliable subjective rankings.

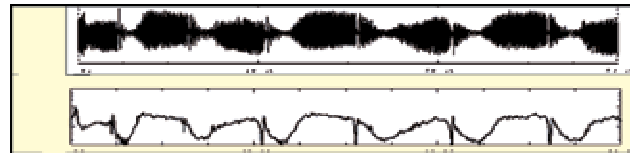

Figure 8. Steering wheel vibration time history and RMS envelope.

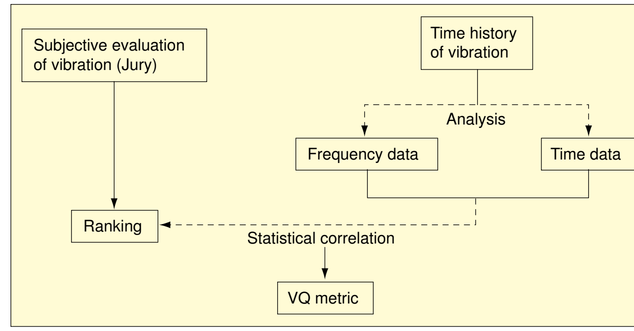

Figure 9. Vibration quality target development process.

I am aware of a few companies with a simulator for either vibration only or both noise and vibration. In this case the task of the juror is easier since the jury administrator has control of the signals reproduced and of the boundary conditions. The more sophisticated simulators reproduce both sound and vibration and allow assessing the relative influence of each. Other investigations have also focused on the effect of visual cues on the perception of sound and vibration.

There are several standards available which provide guidelines for minimizing the risk of physical damage due to exposure to high levels of vibration[13,14] but none of these really address vibration quality. These guidelines are expressed in terms of frequency sensitivity curves and duration of exposures, based on energy-equivalent level over 2, 4 and 8 hours. As is well known, there are two groups of frequency sensitivity curves – those representing the sensitivity of the whole body, standing or seated, and those representing the sensitivity of the hand-arm system. In both cases, the sensitivity curves are derived from experiments with constant vibration signals. A comprehensive treaty on all aspects of human exposure to vibration can be found in Reference 15.

Very little has been done so far to assess threshold of acceptability for comfort and quality in cases of exposure to much lower levels of vibration. Also, little is known regarding the perception of changes of vibration level. A recent EU (European Union) directive indicates that, typically, vibration assessment for comfort depends on the crest factor (peak to RMS ratio) of the vibration exceeding a threshold value. This implies that the temporal behavior of the vibration and not just its frequency spectrum has an effect on the perception. This is evident from the time history of the vibration at the steering wheel during several left-to-right parking maneuvers in Figure 8. The bottom plot is the RMS envelope of the time history in the top plot. The dynamic excursion of the signal is quite evident and suggests the use of statistical descriptors of the time function such as crest factor, kurtosis and others.

While several academic organizations are currently investigating vibration quality parameters, the author recommends approaching a vibration quality project as if it was sound quality as reiterated in Figure 9. A similar recommendation can be found in Reference 16.

Formal Subjective Evaluations

There are several methods to execute the process in Figure 6, but they all share the same objectives, which are: a) to understand what SVQ customers like or dislike; and b) why. The first objective is obtained by performing a formal jury evaluation, the second one by correlating these subjective results to objective data computed on the signals presented to the jurors. The subjective ranking of the sounds required for the target development process in Figure 6 needs to be statistically representative of the perception of a group of customers. These could be final customers, i.e. those who purchase the lawnmower or the lawnmower manufacturer if you are the manufacturer of the engine. Whoever your customer is in the product-to-market chain, it is always a good idea to include your customer in the formal jury test. A detailed discussion of methods of jury testing is outside the scope of this article. For the automotive industry, an excellent summary of jury methods is presented in Reference 17.

The simplest jury test is one in which the jurors are presented with two signals, A and B, and are asked to choose the one they prefer. You can then add complexity to the task by either asking more specific questions, i.e. "which one is rougher/louder?," or by adding different type of questions, such as rating the sounds on semantic scales, such as quiet-loud, smooth-rough and so on. Paired Comparison (Forced and Unforced), Semantic Differential, Magnitude Estimation are examples of jury test types.

My experience has been that if the customer preference is unknown, then a simple AB Paired Comparison test with at least 35-40 jurors and good data screening techniques gives you an excellent representation of preference. In order to dig deeper, so-to-speak, and understand why jurors prefer one sound to another and differences between sound quality perception, it is sometime necessary to conduct a pre-test with a few jurors to understand terminology and issues, or add a second type of jury test (i.e. Semantic Differential) to better characterize the jurors' perception or to screen and analyze the results with different statistical techniques.

The advantages of a formal jury test are that, if well designed, it provides reliable data (minimum bias) that can be used to derive a linear scale of sound quality preference, a sound quality model and a sound quality target. The disadvantages are that jury design is time consuming and the test requires a high-fidelity reproduction system and dedicated resources for scheduling and administering the tests. The best sources for understanding jury testing techniques come from sensory testing references such as Reference 18.

Sound and Vibration Quality Metrics

My definition of sound/vibration quality metrics is much broader than that of a psycho acoustician, in that I call sound or vibration quality metrics any objective parameter that correlates to the perception of sound/vibration. Therefore, sound/vibration quality parameters can be of the following types:

- Psychophysical descriptors, such as Loudness, Fluctuation Strength, Roughness, etc., which are algorithms representing our sensitivity to common, generic attributes of a sound, like Loudness, Pitch and Timbre. These are derived from fairly complex psychoacoustic jury studies conducted using elementary synthesized signals, such as sine waves and white noise, on a controlled group of subjects.
- Physical descriptors, such as overall RMS Sound Pressure, octave and third-octave band spectra and all the derived quantities, and statistical parameters describing the temporal behavior of the signal.

If the reader desires to have a deep understanding of the complex phenomena controlling our hearing and of the algorithms developed to represent them, the universal reference is the book by Professors Zwicker and Fastl.[19] I often also recommend the book by Professor Hartman in Reference 20. However, if you need to understand the concept of a metric, i.e. what it measures, and you don't need to know the details of how it is computed, I recommend that you use one of the several commercial packages available on the market today and experiment by synthesizing different sounds and computing metrics. You will be amazed by how much you can learn in a relatively short span of time! Also, you can purchase from the Acoustical Society of America a CD with good demonstrations of sound quality attributes.[21]

The most important metric of sound quality perception is that of Loudness. Louder products are judged worse than quieter ones in most cases. The Loudness dimension can be measured by the psychoacoustic metric Loudness or by other correlated descriptors, such as A-weighted Sound Pressure Level, Articulation Index, Speech-related metrics such as Speech Intelligibility, Preferred Speech Intelligibility etc.[22] In general, Loudness and dBA are

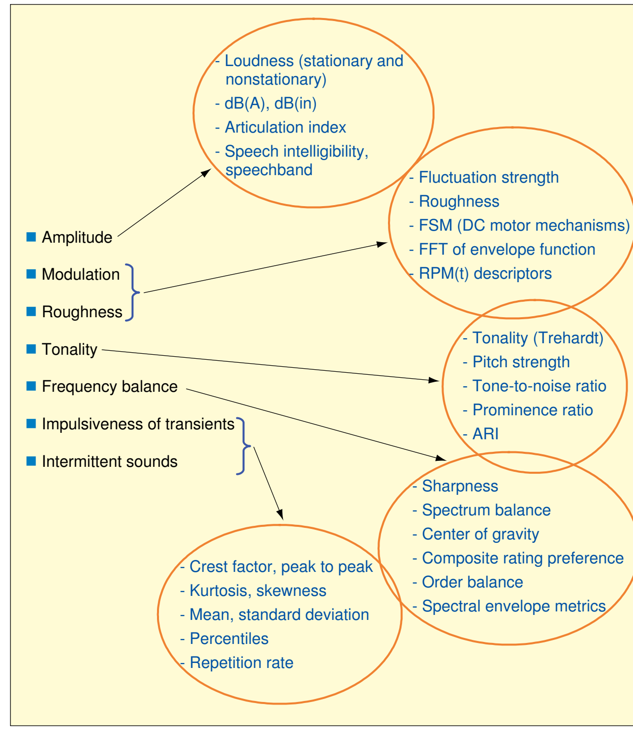

Figure 10. Sound/vibration dimensions and corresponding metrics.

	Factor1	Factor 2	Factor 3
Gentle - violent	0.89	-0.11	0.18
Soft - hard	0.87	-0.22	0.23
Quiet - loud	0.86	-0.05	0.17
Weak - strong	0.57	0.35	0.45
Variable pitch - steady	0.01	0.87	-.20
Oscillating - constant	-0.26	0.75	0.24
Dull - sharp	0.29	-0.05	0.89

Three Factors (or dimensions):
- Loudness
- Modulation
- Sharpness

	Pleasant
Quiet - loud	0.60
Gentle - violent	0.71
Variable-pitch - steady	-0.22
Hard - soft	0.70
Weak - strong	0.27
Dull - sharp	-0.33
Oscillating - constant	0.27

Loudness dimension mostly correlated to PLEASANT

Figure 11. Dominant SQ dimension extraction from jury results of power window sounds.

highly correlated. However, the reader has to be aware that the relationship between Loudness and dBA is not linear and depends vastly on the spectral envelope of the signal.[23] If available, I recommend that you use Loudness instead of dBA since it is a more accurate representation of how loud/quiet a sound is.

Loudness is the most important dimension, but not the only one. Therefore, other metrics will be required to quantify the perception of tones, oscillating sounds, rattles and so forth. In many cases, the other psychoacoustic metrics, such as Fluctuation Strength, Roughness, Pitch Strength, Tonality etc. do a very good job at characterizing these other dimensions. However, sometimes one may find that none of those really work for a particular group of sounds and in that case it may be necessary to develop a product, or product-type, specific metric, often based on physical parameters.

The reason for including the physical descriptors in the pool of candidate sound quality metrics is that real sounds are much more complex than the elementary sounds typically used in psychoacoustics experiments. If, after having computed the psychoacoustic metrics offered by several commercial packages, one realizes, even without conducting a formal correlation, that they do not correlate with the results of the jury, the conclusion is not

Figure 12. Pictorial representation of NVH source-path-receiver.

that the psychoacoustic metrics are wrong but instead that either the signals are too complex or the jurors' expectation is biased by parameters other than sound quality or a combination of both. In reality this conclusion may not be correct; the real issue can also be not having an appropriate metric to define the customer perception of that particular sound.

In Reference 24, the authors describe the process of developing a sound quality metric for DC-motor powered mechanisms based on the RPM of the motor itself. This metric was found to account better than Fluctuation Strength for the frequency modulation induced by the gear meshing. Since then, parameters based on the RPM function vs. time of DC-motors have been widely adopted as a measure of perceived quality of the mechanism.[25]

This approach requires an in-depth analysis of the recorded signal, typically done in frequency, time and order domain. Based on the data analysis, additional sounds exhibiting different degrees of one or more attributes are created and presented to jurors with the specific objective of deriving a metric for that attribute. This often involves an additional jury test, with a smaller pool of jurors.

This analysis allows the engineer to gather an exhaustive understanding of the signal attributes and to formulate hypotheses of which features most affect the perception of the jury. As a result, instead of computing all possible metrics offered by the software tool he/she uses, the engineer will compute only those metrics describing a subset of features. Figure 10 lists on the left the most common dimensions of sound/vibration, while on the right, each bubble includes a list of metrics describing a dimension (in the interest of brevity only a few have been included).

If, as an example, the sound quality engineer has sounds showing large differences of loudness and modulation, then he/she will certainly have to compute all loudness- and all modulation-related metrics. If certain sounds exhibit pure tones, then also tonality-related metrics will be computed. In other words, the metrics computation process is not blind, rather it is guided by a-priori knowledge of the signals. This approach facilitates the correlation task, since a limited pool of metrics needs to be correlated to the jury data.

A rather different approach is a "black-box" approach, in which an exorbitant number of metrics (or maybe all available ones) is computed and "thrown into the pot." No a-priori knowledge of the signal is required and the engineer can very quickly get to the correlation phase. While seemingly straightforward, this approach is in my opinion very dangerous, in that the engineer, lacking an in-depth understanding of the signals and systems, will not be able to easily assess the validity of the results of the correlation task. It is not advisable to rely so heavily on the correlation algorithms without a critical approach to the problem.

Correlating Subjective to Objective Data

The task of the sound quality engineer is to extract the 'dimensions' of the sound that are the attributes that affect the overall acoustic image of the product under investigation. An example of this process for the sound quality of a power window is shown in Figure 11.

In this example, a Semantic Differential test was run. The jurors were asked to judge each sound on a few semantic scales, such as gentle-violent, soft-hard, weak-strong, and pleasant-unpleasant, etc. The analysis of the scattering of jury results is a powerful tool that allows identifying groups or 'clusters' of features. This technique is called Factor Analysis and the matrix at the top of Figure 11 shows a summary of the three main Factors and their correlation coefficient to the semantic ratings. The physical interpretation is that three dimensions affect the ratings, and that these are likely to be Loudness (which can be associated to gentle-violent/soft-hard/quiet-loud/weak-strong), Modulation (associated to variable-pitch/oscillating-constant) and Sharpness (associated to dull-sharp). However, at this point it is not clear which of these three dimensions contribute more to the overall judgment of pleasant-unpleasant. From the correlation among the pleasant-unpleasant rating and the semantic ratings from the other attribute scales, it can be derived that Loudness is the dimension that most affects the judgment of pleasant/unpleasant. But it is also clear, from the low correlation coefficients, that it is not the only dimension affecting 'pleasant,' and the process has to be repeated for a second dimension once the contribution of Loudness is removed from the data and so forth.

Factor Analysis is just one possible technique commonly used to identify the dimensions of sound or vibration quality. Other similar techniques used with the same purpose are Principal Component Analysis (PCA) and Analysis of Variance (or ANOVA). A detailed discussion of these techniques is outside the scope of this paper, and I refer the reader to References 26 and 27.

Once the dimensions are known, then one desires to identify which metrics best describe each dimension as it relates to the sound/vibration quality. Two types of approaches can be used:

- Regression, single or multiple, linear or nonlinear.
- Analytical Neural Networks (ANN), genetic algorithms and other "black box" methods.

The advantage of the regression approach is that it is simple, but it does require quite a bit of knowledge of the measured signals and their mathematical representation. The advantage of the neural networks approach is that it does not require much a-priori knowledge of the signals and that it facilitates the exploration of nonlinear behavior. An example of the use of Artificial Neural Network (ANN) to derive rumble and booming index for a passenger car can be found in Reference 28.

In my experience, it is always recommended to start assuming the simplest possible model, that is a linear, simple or multiple, relationship between subjective and objective data. Nonlinear models may indeed be required but only if a simpler model cannot be found to represent the data with the required accuracy and precision.

SVQ Diagnostics and Troubleshooting

Once an objective descriptor of the perception is found, it can be used during diagnostics and troubleshooting for identifying root-causes and for evaluating countermeasures. Diagnostic testing is the task that allows the engineer to trace the sound/vibration quality issue to a part or mechanism of an assembly. Several techniques can be used for this. The choice of which one to use first depends on the characteristics of concern. If this is a low frequency issue, let's say as an example a 200 Hz tone, it may be due to a fundamental motion of or within the system, like a rigid body mode or an acoustic cavity mode or a standing wave. I am not saying

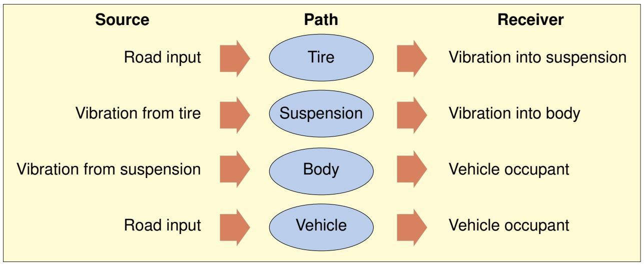

Figure 13. S-P-R applied to tire/road noise.

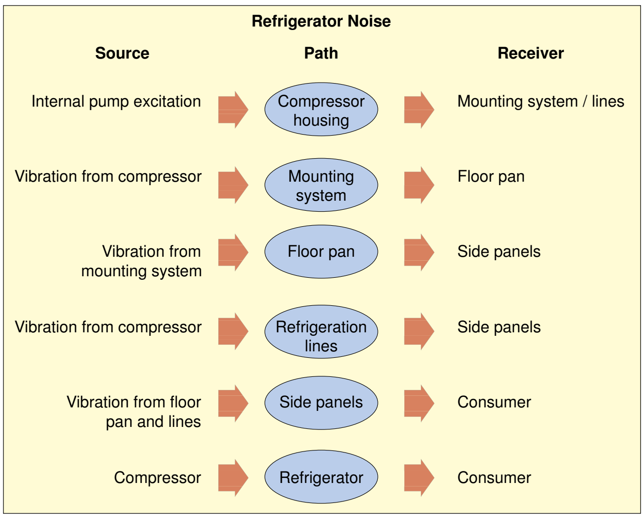

Figure 14. S-P-R applied to refrigerator compressor noise.

that this is necessarily the answer, but that this would be my first hunch. If the issue is at high frequencies, it is likely to be due to more complex phenomena, such as local motion of a panel, reflection/diffraction from an edge in a duct, etc. If the noise/vibration is of transient nature, i.e. is not constant but changes during the operation of the unit, then you should be suspicious of changes in temperature, pressure or other physical parameters associated with the operating status of the machine.

Troubleshooting for noise and vibration does not mean at all that you should use only microphones and/or accelerometers. You need to map the physics of the system and all its associated parameters. Temperature is a key clue for acoustics in any media with hot or cold fluid, since the speed of sound depends on temperature.

A systematic approach to troubleshooting, embraced by most NVH engineers, is that of Source-Path-Receiver modeling. Figure 12 shows the source as the airplane engine, the path as being the structure between the engine and the cabin and the receiver being the airplane passengers.

Any system, no matter how simple or complex, can be broken down into source(s), path(s) and receiver(s). As an example, Figures 13 and 14 display a typical S-P-R approach for two very different sounds and systems – in-vehicle tire/road noise and refrigerator compressor noise.

From this diagram it is clear that the path from road input to vehicle occupant is made up of smaller sub-systems. The importance of understanding these sub-systems is to help direct the solution towards the problem area. Comments such as "the vehicle is too sensitive" will mean different things to different people and needs further description before finding a solution. Using structure borne tire noise as an example, there are at least three large sub-systems that can contribute to vehicle sensitivity: the tires, the suspension and the body. Each sub-system must consider themselves as the path, with a defined source and receiver, before a long-term solution to the problem can be found.

Refrigerator compressor noise is a completely different phenomenon then road noise but the same basic principles apply, as shown in Figure 14. In this case the source is a pump inside the compressor housing and the receiver is the consumer standing in front of the refrigerator. As in this case, there are often several sub-system opportunities to address a noise or vibration issue. The role of the engineer is to quantify the sub-systems and determine the most appropriate solution.

A detailed discussion of troubleshooting techniques is outside the scope of this article. Some of these techniques will be described in the next couple of articles, when applications of sound quality engineering will be described.

Regardless of the techniques used, it is worth noting that once the sound/vibration quality concerns are known and can be quantified, then the task of the NVH engineer will become that of developing a standardized test to consistently capture these features and compare them to their targets (we call this the Validation phase). The execution over time of validation tests will generate a significant amount of data and knowledge of the product and this will organically lead to the capability of including SVQ in the design of the next generation product.

Conclusions

Sound quality is not all about metrics but is a deep understanding of your system. Without this understanding, incorrect conclusions can easily be reached about your system's behavior.

- SVQ is not an absolute number and requires investigation into the Customer's perception of the event. Due to the interaction between user and product, the level of SVQ is not necessarily consistent across market segments but can be characterized for each.
- SVQ target development is a necessary process that starts with the voice of the customer. This process is established, rigorous and with experience can be applied to any situation.
- There is still a place for traditional metrics such as dBA, Sound Power, etc. However, the engineer must realize that these metrics were never intended to discern between signals that have characteristics such as changes over time, impacts, modulation, sharpness, etc.
- Few standards exist for SVQ due to the complex nature of the source, environment and customer perception. New metrics are continually being developed and tailored to each product and application. This is a necessary step at this early stage in the understanding of SVQ and its role in industry.

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