Consumer's Demand for Better Sound and Vibration Quality

Eric Frank, **B. Engels**, **B. Naimipour** and **G. Rinaldi**, Sound Answers (part of Brüel & Kjær), Canton Michigan

As original equipment manufacturers (OEMs) continue to improve the sound quality of their products, the expectation of consumers has changed over time. Companies that traditionally only addressed noise or vibration issues when they were problematic are now using sound quality as a fundamental selling feature. OEM's and suppliers in many different industries have endeavored to capture the acoustic preference of their customers and subsequently use it to drive their testing and design practices. This article describes how, in the experience of the authors, SQ targets have evolved over the years and how companies that have been early adopters of SQ targets have addressed this challenge. We also review some of the limitations of the traditional SQ development process and describe the approaches and tools that have been developed to address these limitations.

Sound quality became prevalent in the late 1980s, and by the early 1990s 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 may not work for the other.[1]

Assessing sound quality is different than measuring the level of sound pressure or sound power. The sound pressure level is typically correlated to perceived amplitude of a sound, but the human hearing recognizes and responds to many more attributes of a sound other than just amplitude; such as tonality (the presence of strong tones, often very annoying), roughness (such as that due to a rough running engine), the lower frequency modulation (such as due to beating between two fans), or high-frequency noise such as that due to cutting blades or fans.

Assessing the sound quality at an operator's ears means to measure not just the amplitude of the sound but also the amount of these other perceivable features of the sound. To assess the degree of sound quality, it is necessary to measure both frequency and temporal characteristics of the signal at the operator's ears. This is accomplished by computing sound-quality-specific metrics that can be used in conjunction with subjective assessments to quantify the perception of the operator – such as annoyance, discomfort or, more simply, dissatisfaction.

Connection To Marketing

As with many attributes related to the perceived quality of a product, sound and vibration quality has become a selling feature that consumers have come to expect, even though the customer expectation may be difficult to gauge at times. This phenomenon was first introduced by Professor Noriaki Kano as is described in the Kano Model[7] and is graphically described in Figure 1. This explains that consumer satisfaction is related to desired product features that can be classified into three main categories:

- Delightful features that are innovative, unexpected by consumers, and yield satisfaction.
- One-dimensional features that describe the more-is-better concept (for example, too little memory in a computer is a negative quality, while more than normal is highly desirable)
- Must-have features that are the bare-minimum features. Without these, consumers are unlikely to even consider buying the product.

As with many product attributes, sound quality is subject to this model. When it first became a design-driven feature, it was innovative and highly desirable. In the 1980s, for example, luxury vehicles began marketing their quiet and refined interior cabins,

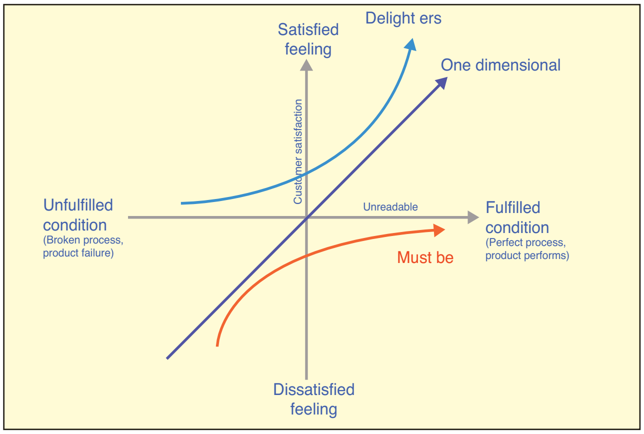

Figure 1. Graphical depiction of the Kano Model.[8]

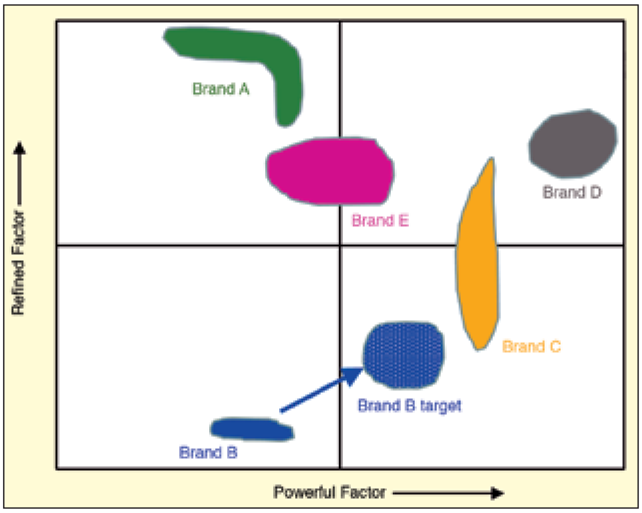

Figure 2. Example of vehicle brand sound development matrix.

which was considered a delightful feature. Over time, quiet cars became the standard and a common selling feature, falling into the one-dimensional category. In this stage, sound quality is a known attribute; the more quiet and refined the vehicle, the more desirable. Although in recent years, sound quality has evolved into a must-have feature. Consumers have specific expectations for engine sound quality, for road and wind noise and for the noise of accessories such as powered seats, windows, sunroofs, etc. The acoustic signature of each of these subsystems has to match the vehicle image in the customer's mind.

The increasing demand for sound and vibration quality has driven many OEMs in various industries to continuously improve their products and develop engineering targets that are also driven by sound and vibration quality. More and more companies over the last 25 years have adopted a data-driven approach to the sound and vibration quality of their products that are derived from the voice of the customer (VOC). The following sections describe tools that are commonly used in the industry to achieve this goal and examples of their application as a continuous process.

SVQ Development and Analysis Tools

Sound and vibration quality targets are not cast in stone, since they are connected to customer expectations and to evolving technology. The standard SVQ target development process has

Based on a paper presented at Inter-Noise 2015, 44th International Congress on Noise Control Engineering, San Francisco, CA, August, 2015.

to be modified and updated to adapt to the different needs of the market. As an example, it is acknowledged that different sensory cues (visual, audio and tactile) interact, and multi-modal simulators have been developed to study the effect of this interaction that is not accounted for in off-line, one-modal, SQ listening studies. Sound quality concepts have also been extended to investigate the expectation and need for the acoustic signature of electric vehicles and to assess the detectability of military vehicles and the impact of their noise on mission survivability.

In most industries sound/vibration quality is a fundamental aspect of the brand design process. In the automotive industry, for example, the sound quality of an engine is linked to its performance feel. The powerful/refined plane has been used for years for designing the SQ that matches the vehicle brand image (see Figure 2).

In a sporty vehicle, consumers want to hear the firing orders that give an impression of power, as opposed to a luxury vehicle, where consumers want it to be much more refined. This bi-modal approach (matching acoustic space to physical space) has been implemented by the authors into a software tool and has been used for listening studies of a wide range of products, not just vehicles. In which case the powerful and refined semantics are replaced by ones that best fit the application. Once all the sounds are located on the plane, they can be grouped manually or automatically and further inspected.

SVQ Brand Design Tool. To help facilitate SQ brand design process, we have developed a software tool called the Sound Listening Interactive Cluster Environment (SLICE), as shown in Figure 3, for free-form listening of sounds, displaying metrics, and subsequently performing statistical analyses.

Free-form listening is an important step in the sound quality process, where subjects listen to sounds and give qualitative assessments using their own words. The results of these pilot studies are then used to design a more structured and controlled jury evaluation. Acoustically accurate listening studies can be conducted within SLICE by importing binaural recordings and using a pre-loaded correction filter for playback headphones. A user may then create custom scatter plots for a series of given metrics and assign rankings for a set of jurors. Once a dataset has been defined, SLICE can then perform clustering analysis to help identify trends.

NVH Vehicle Simulator. Another way of performing subjective evaluation is by using an NVH vehicle simulator (see Figure 4), where the interior noise of a vehicle is reproduced for any combination of road or engine speed, throttle opening and selected gear. The simulator provides context and interactivity and it is critical for designing passenger vehicle sounds. This allows engineers to compare multiple vehicles in real time on the same roads for benchmarking and target-setting, and to assess the noise characteristics of a vehicle at various stages of its NVH development. By evaluating reactions in the simulator, the whole decision-making process is captured in a realistic driving environment.

Off-Line Jury Testing. If the product is not a vehicle (vacuum cleaner, lawnmower, etc.) or if the driver's experience is less dynamic and interactive, such as in a tractor, off-line SQ jury evaluations provide a robust understanding of the customer preference. To characterize the perception or quality of any sound, it is important to understand the subjective assessment of what people think or to gain an understanding of their opinions.

A common and multi-industry accepted method of accurately quantifying people's subjective feedback is through the use of jury testing/evaluation. The objectives of jury test can be summarized in four categories. One category involves the target of sound/vibration signature development. For example, automotive companies around the world have invested considerable resources to understand what role sound and vibration play in a customer's perceptions and establish realistic targets to ensure commercial appeal.

Another category is detecting studies, with an emphasis on detecting subtle cues, where the sound quality focus is shifted by the customer expectation and using a particular product. For example, appliances (washing machines, dishwashers, refrigerators, etc.) perform a function while consumers are focused on other tasks. Here, sound quality may involve sounds (like chimes) produced to alert the consumer of a cycle starting/stopping/moving forward.

Figure 3. SLICE application used for visualizing metrics; plot shows subjective rankings of sportiness vs refinement.

Figure 4. Brüel & Kjær's NVH vehicle simulator.

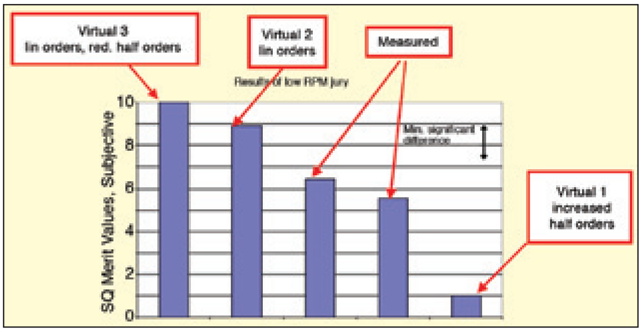

Figure 5. Jury testing application used to identify a problem (root cause).

A third category is to help identify a sound/vibration quality problem, such as understanding the root cause of a sound quality concern. During the acoustic image evaluation of a vehicle, the results of a jury test indicated that the perception of growl during wide open throttle events was drastically reduced by improving order linearity and not by reducing (assumed) half-orders. This is shown in Figure 5.

The last category involves value proposition assessment of sound/vibration quality through the use of decomposition and synthesis techniques. An example of this is 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 or test-based prediction tools.

Jury Design. One of the key advantages of using jury testing is the ease (in most cases) in which to derive a linear scale of preference or preference ranking. A formal and controlled jury test is recommended whenever a statistically representative SQ model is desired, because this allows screening of jurors for data quality (consistency and repeatability) prior to attempting to build the model. This is especially relevant when engineering targets need to be derived from the sound quality.

There are many types of jury tests, some examples include ranking (or rank order), scaling (or rating scales), magnitude estimation, paired comparison, and semantic differential. Ranking is described

Descriptor A	very A	slightly A	neither	slightly B	very B	Descriptor B
	1	2	3	4	5	
Quiet						Loud
Smooth						Rough
Soft						Hard
Luxury						Cheap
Powerful						Weak
Sporty						Flat
Sharp						Dull
Variable pitch						Steady
Wowing						Constant
Like						Dislike
Pleasant						Annoying

•Red: Evaluative Blue: Potency Green: Activity

Figure 6. Example of a semantic differential test with three scales (evaluative, potency, and activity).

as when subjects rank stimuli, from 1 to N (where N = number of stimuli) based on criteria like overall preference, loudness, annoyance, harshness, etc.

Scaling describes the subjects judging stimuli in reference to a scale, but here the scale is in reference to numbers or words to express intensity of a certain attribute. Similarly, magnitude estimation is where subjects assign a number to some attribute of the stimuli. Here the scale is "internal" (unbounded). In paired comparison tests, subjects are asked to choose a stimulus from a pair of stimuli-based criteria like overall preference, loudness, annoyance, harshness, etc.

Semantic differential uses subjects to evaluate stimuli on a number of descriptive response scales utilizing bipolar adjective pairs. An example of a semantic differential scale is shown in Figure 6, where this semantic differential uses three groups of scales. The first scale is evaluative, which describes good/bad, pleasant/annoying, strong/weak, etc. The second scale is potency, describing quiet/loud, smooth/rough, harsh/dull, etc. The third scale is activity, which describes steady/variable, changing/constant, slow/fast, etc. For this semantic differential test, the concepts to be measured are loudness, roughness/sportiness/powerfulness, modulation/fluctuation, and sharpness.

The most common jury tests used in the industry for SVQ target development are paired-comparison and semantic-differential tests; however, certain companies and research institutions may have other methods that are better established. The selection of the jury test depends on the objective/output desired. If the desired output is preference ranking, then a paired-comparison test is usually best. Generally, this is because the paired-comparison test is the easiest test (well suited for untrained subjects/listeners). However, if the output desired is to assess which features affect the SQ of a particular product (and there is little *a priori* knowledge of that product), then a paired-comparison test along with a semantic-differential test is more appropriate.

One critical step in the design of any SVQ jury is the synthesis of virtual sound or vibration to test hypotheses of preference. The jury designer does not need to be constrained by the measured signals,.Rather he should evaluate the different hypotheses based on experience and the results of the free-form pilot listening studies, attenuate and/or enhance individual features of the signal and play back the modified signals to the jurors. Having synthesized stimuli is essential for a good design of the jury experiment. These synthesized stimuli can be used to validate testing hypotheses, control the range of individual features in the stimuli and identify strategic directions for product development.

Sound/Vibration Quality Preference Equation. In most cases the linear scale (ranking) produced from jury testing output can be used in conjunction with objective parameters extracted from the sounds/vibration to produce a preference equation (functional relationship) that estimates the subjective perception from one or more objective parameters. Two approaches, as shown in Figure 7, can be used to identify which objective parameters (metrics) best describe each dimension as it relates to sound/vibration quality.

The first approach relies on regression, single or multiple, linear

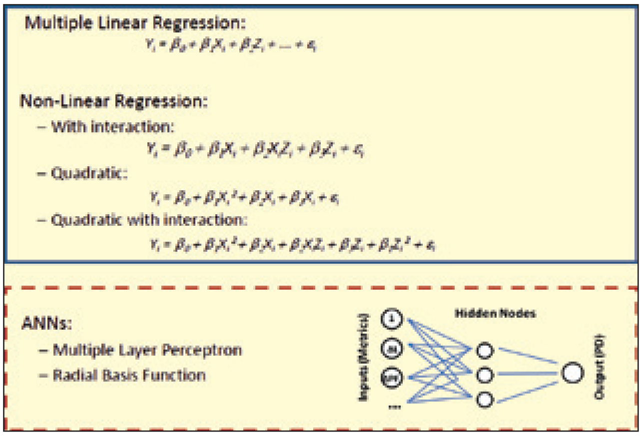

Figure 7. Two correlation approaches to relate sound/vibration quality objective parameters to subjective preference – regression and artificial neural network.

or nonlinear. The second is artificial neural network (ANN) and genetic algorithms. The advantage of the regression approach is that it's simple but does require much knowledge of the measured signals and their mathematical representation. The advantage of the ANN approach is that it does not require *a priori* knowledge of the signals and it facilitates the exploration of nonlinear behavior.

Jury testing and the preference equation (SQ model) provides a design tool for addressing SQ concerns experienced by the customer by being able to objectively measure and compare units in terms of sound quality. It also provides the root cause controlling mechanisms of specific SQ issues by utilizing the diagnostic power of SQ metrics and helps to identify the most efficient noise and vibration approach for designing low-noise products.

Sound and Vibration Quality Applications

The sound and vibration quality process has been applied by many companies that design for SVQ in many different industries. Below are some examples of how this process was applied and the justification for it based on increasing sound and vibration quality demands of consumers.

A company that makes small engines for lawn-care equipment was interested in developing a preference equation for engineering development purposes. Sound quality has traditionally not been considered as a primary product feature in this industry, and it was their objective to set such a standard. They used actual consumers as jurors and took the opportunity to interview them after the test to get a first-hand understanding of market expectations. This experiment was repeated in global markets and was able to form both specific and generalized results.

A manufacturer of car tires identified the need for sound quality since it has become a selling feature for many tire retailers. This company had traditionally installed its parts on a test vehicle and subjectively rated them for noise under normal driving conditions. They identified the need to remove this subjectivity and draw correlation between objective data and juror preference. They used a jury study to derive a preference equation and subsequently cascaded the preference equation to component tests. Today, they test individual tires and use a customized software code to predict how the tire would sound in a vehicle and how a juror would rate it.

A company that manufacturers luxury home refrigeration appliances identified the need to establish sound quality targets to meet their customers' expectations for superior acoustic performance. They used a jury study to create a preference equation and began using it in their engineering design process. Their engineers quickly adopted this practice and began designing for sound quality and using the preference merit as a prominent design target.

Limitations of Typical SQ/Jury Processes

The sound quality and jury processes discussed here should be used with consideration for their limitations. For example, upon completing a jury study and deriving a preference equation, it is critical to understand its applicability. Many engineering departments assume that one preference equation can be used for many different sounds or even operating conditions. It is important to realize that its validity is based on the sounds that were used in the jury test to create it – hence the importance of a robust jury design.

A sound that is fundamentally different from those evaluated during the test may produce an unrealistic merit when calculated through the preference equation. The correct answer lies in the metrics that are ultimately regressed against the jurors' preference ranking. This should be considered when deciding which metric or metrics are ultimately used in the linear regression. Between two metrics that produce similar r^2 values, it may be wise to choose the one that is universally more applicable so that the equation is more robust in future applications.

Another consideration is the sample population of jurors to be tested. It has been our experience that jurors from greatly differing demographics may have different preferences or even no experience with the sounds presented. Focusing on a single mode, such as sound, carries the assumption that the jurors have an expectation of acceptability based on their own experience. For example, it is of little use to ask for opinions on sounds of agricultural equipment from people who have never visited a farm. This may be resolved by screening potential jurors before admitting them to the test.

Both of these limitations illustrate the importance of clearly designing the jury test so that it is as beneficial as possible when commissioned. However, even the most stringent planning cannot account for the possibility of a changing market. For example, an OEM might invest significant time and resources to determine ways to optimize the sounds of their product. But if a competitor develops and releases a similar product that has a vastly different and universally preferred sound quality, the first OEM may need to reconsider the validity of its historic results and future design plans. In a hypothetical example, one company that offers entry-level sedans suddenly introduces a new vehicle in that class that sounds like a Formula One race car. If it is well received by consumers and changes market expectations, the rest of their competitors will need to respond more quickly to regain market share.

Conclusions

The sound and vibration quality process has been applied by many companies that design for SVQ in many different industries. Assessing the sound quality of a product means to capture not just the amplitude of the sound but also the amount of other perceivable features of the sound when inserting sound quality targets into the design and development process of a product.

Acknowledgements

The work presented in this paper is the result of a joint collaboration between Sound Answers Inc., Brüel & Kjær, and numerous customers. It would not have been possible without the key contribution of all the partners. The authors would also like to express our gratitude and special thanks to Dr. Gabriella Cerrato for her guidance and supervision.

References

1. Cerrato Jay, G., "Sound/Vibration Quality Engineering," *Sound & Vibration*, pp. 16-23, April 2007.
2. David, H. A., *The Method of Paired Comparisons*, 2nd Edition, Charles Griffin & Co. Ltd., London, 1988.
3. Davidson, R. R., and Farquhar, P. H., "A Bibliography on the Method of Paired Comparisons," *Biometrics 32*, pp. 241-52.
4. Osgood, E. C., Suci, G. J., Tannenbaum, P. H., *The Measurement of Meaning*, University of Illinois Press, Urbana, Illinois,1957.
5. Snider, J., Osgood, C., *Semantic Differential Techniques: a Source Book*, Aldine, 1969.
6. Otto, N., Amman, S., Eaton, C., Lake, S., "Guidelines for Jury Evaluations of Automotive Sounds," SAE Paper 1999-01-1822, SAE NVH Conference, Traverse City, May 1999
7. Kano, Noriaki; Seraku, Nobuhiku; Takahashi, Fumio; Tsuji, Shinichi, "Attractive Quality and Must-Be Quality," *Journal of the Japanese Society for Quality Control* (in Japanese) Vol. 14, No. 2, pp. 39–48. ISSN 0386-8230, April 1984.
8. Kano, Noriaki, "The Kano Model," *Konstantin Kumynsky*. WordPress, n.d. Web. May 2015.
9. Mueller, Max. "Sounds Good," *Automotive Testing Technology International*, pp. 30-36 Web, March 2013.

SV

The author may be contacted at: eric.frank@bksv.com.