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Sound Quality Analysis of Electric Parking Brake

Bahare Naimipour[a]
Giovanni Rinaldi[b]
Valerie Schnabelrauch[c]
Application Research Center, Sound Answers Inc.
6855 Commerce Boulevard, Canton, MI 48187, USA

Andrea Cerutti[d]
Cristian Malmassari[e]
Advanced R&D Department, Brembo S.p.A.
Viale Europa 2, Stezzano (BG), 24040, Italy

As the vehicles are getting more and more refined, new parameters are being defined to study the way a sound is perceived both inside and outside of vehicles. Sound quality metrics are becoming more of an industry standard since simple frequency – sound pressure level analysis is not sufficient enough to capture the driver/passenger perception of acoustic image.

In order to understand what drives the subjective impression of the electronic parking brake (EPB) and to improve the sound quality of a reference product, a benchmarking activity of a brake supplier's current production parts along with a variety of current production competitors' products has been conducted.

Several EPB's were tested for sound quality and a combination of measured and digitally filtered sounds were played back for a formal jury. Objective parameters of the presented sounds (sound quality metrics) and subjective ratings from the jury were compiled and correlated to produce a sound quality (SQ) model. By utilizing the insight provided by the SQ model, it was possible to identify the most effective sound quality re-design strategy. Finally prototypes were designed, manufactured and tested for validation of this approach.

[a] email: bahare.naimipour@soundanswers.net
[b] email: giovanni.rinaldi@soundanswers.net
[c] email: valerie.schnabelrauch@soundanswers.net
[d] email: andrea_cerutti@brembo.it
[e] email: cristian_malmassari@brembo.it

1 INTRODUCTION

Sound quality took off in the late 80's and by the early 90's 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 doesn't work for the other[1]. Assessing sound quality is different than measuring 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), lower frequency modulation (such as due to beating between 2 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 assess the degree of comfort or discomfort experienced by the operator.

Electric Park Brakes are actuated by DC-motors and their sound quality is similar to that of other DC-motor powered mechanisms, such as electric seats, windows, sunroof, mirrors, and pedals. Noise from DC-motor powered mechanisms tends to vary with time, as the transmission of motion from the DC motor to the actuator is typically realized by means of a system of gears and either flex or solid shafts.

In this work, several EPB's were tested for sound quality. The following section will explain the general SQ technical approach. Using a combination of measured and digitally filtered sounds were played back for a formal jury. Jury design and results will be explained after the technical approach. After jury testing, objective parameters of the presented sounds (sound quality metrics) and subjective ratings from the jury testing were compiled and correlated to produce a sound quality (SQ) model. By developing the insight provided by the SQ model, it was possible to identify the most effective sound quality re-design strategy. Finally prototypes were designed, manufactured and tested for validation of this approach which will be discussed subsequently after the SQ model.

2 TECHNICAL APPROACH

Any process involving sound quality issues should always start from the voice of the customer to understand what features are objectionable and what are desirable. Once the features are understood then we need to find an objective way to quantify them[1]. Figure 1 shows at a high level, the sound quality development process implemented here.

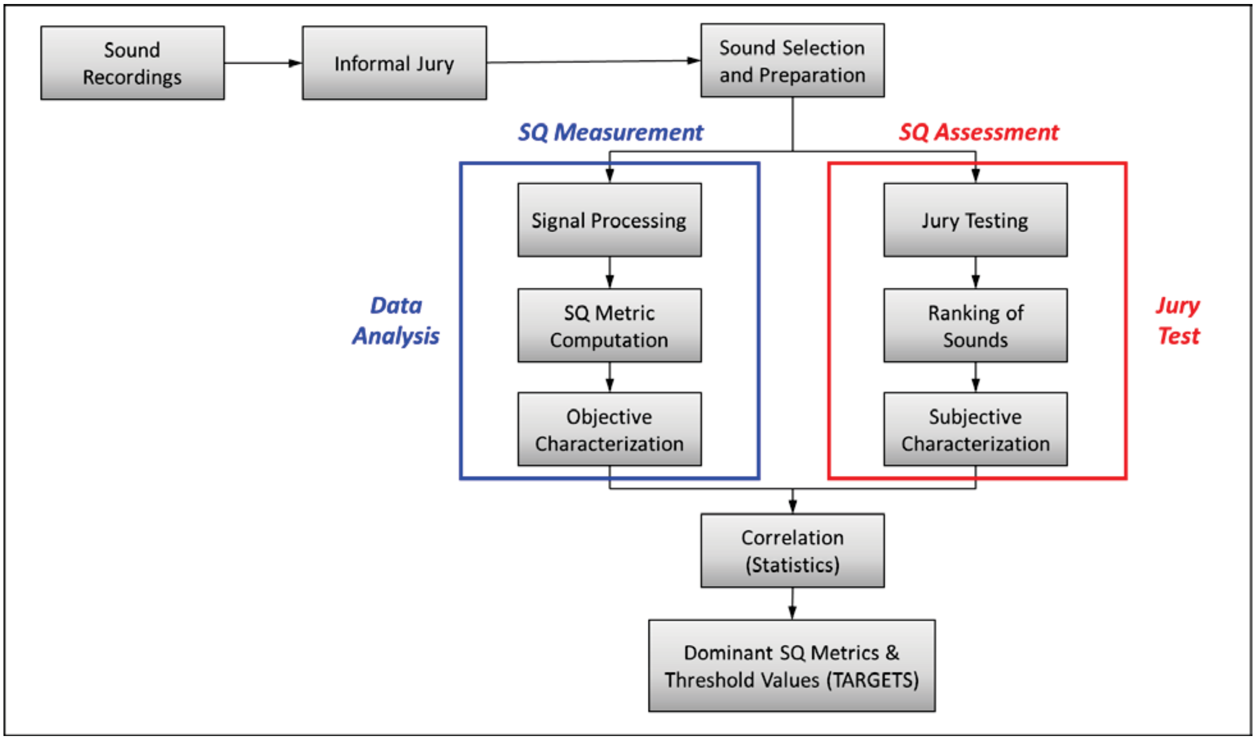


Figure 1 – Sound Quality target and preference model development process

The value of the SQ development process in this application is that it provides a platform for addressing SQ concerns experienced by the customer by being able to objectively measure and compare EPB units in terms of sound quality. It also root-causes the 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 EPB units.

It is important to capture sounds binaurally when working with sound quality related issues, due to the spatial cues provided by the two ears. The first step is to acquire the EPB sound recordings which were made binaurally, utilizing an artificial head with microphones at the ears' position.

Next, an informal jury was performed to gain a basic understanding of the features or dimensions of the EPB sound recordings. Determining the dimensions of sound present can be done in a multitude of ways. For example, if the objective is to assess what dimensions affect sound quality (with little or no a-priori knowledge), then the use of more than one formal jury (like the combination of semantic differential and paired comparison tests) may be appropriate. However, in this case based on the customer's concerns and author's experience, the EPB sounds were clustered and ranked with the use of a beta version software to be commercially released (Sound Answers SLICE). From this clustering/ranking results and the author's DC-motored sound quality experience, alongside initial SQ metric computations allowed for an optimized design combination of measured and digitally filtered sounds to be played back for a formal jury.

Finally, the development of a SQ model was achieved by performing both steps ("SQ Measurement" and "SQ Assessment") outlined in Figure 1. In order to develop a realistic SQ target, it was necessary first to understand the perceptual component (SQ Assessment), that is how people react to the product, then to identify objective parameters to quantify the perception (SQ Measurement). The knowledge of subjective feedback and objective parameters leads the investigator to the hypothesis of a functional relationship (model) that estimates perception from one or more objective parameters.

A formal and controlled jury test is recommended whenever a statistically representative SQ model is desired, as 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 ones.

3 JURY TESTING

To characterize the subjective aspect of these EPB sounds or to quantify the sound quality perception, a formal jury test was performed. The jury test included a Paired Comparison test, which is one of the simpler types of jury tests available. It was organized in a series of jury sessions, each session with 6-8 jurors. All jury tests were conducted in 1 day, with each jury session lasting less than one hour for each jury session group. In total 51 jurors participated in the testing. The jurors selected was from a diverse group that spanned different age, gender, job function, etc.

The test was administered by an engineer running a commercially available (B&K I-deas) Jury Evaluation software that controlled the playback of the sounds and collected the answers given by each juror via a keypad. The jurors wore high-quality, professional open-back headphones, which played-back sounds at the same calibrated level for all jurors simultaneously. Instructions were presented to the jurors via a monitor/screen, as shown in Figure 2. All data was automatically collected by the Jury-software and stored into a database.

Figure 2 – Typical Setup of a SQ Jury Test

3.1 Jury Design

Interrogation and data analysis of the test data was performed prior to preparing sounds for inclusion of the Jury testing. A few sample analysis methods included the following:

- FFT (and Wavelet, for any transient noise present) spectrograms to have an immediate understanding of time and frequency characteristics of each signal.
- SQ Metric functions versus time. For example, Loudness-related metrics, as well as RPM-related metrics.
- Frequency slices vs. time
- Statistics of raw time histories and of SQ metric functions versus time to extract single value parameters

Based on subjective listening and on the objective data, a number of hypotheses were formulated to simulate improvements and/or preference. These improvements or synthesized sounds were then used to provide a "virtual" sound that amplified or attenuated features that were not captured within the pool of measured sounds. The resulting pool of measured and synthesized sounds were then reduced to a final pool of jury sounds. This final pool of jury sounds was included in the Paired Comparison jury test. Each jury session was designed to last less than 45 minutes, in order to avoid or limit jury fatigue. The length of the jury test was dictated by several jury design variables such as:

- Number of sounds
- Length of sounds
- Number of repeat sounds to check jurors' repeatability
- Time between sounds and questions/training

The total number of sounds used were 15, which were comprised of a multitude of brake supplier current production parts. Of these parts there was also a mixture of both measured (original) sounds as well as virtual (synthesized) sounds. These sounds were presented in pairs, in all 157 pairs were presented to each jury session. Of the 157 pairs presented, 105 pairs represented each combination, plus 52 pairs were re-presented in reverse order at the end of the jury session.

3.2 Jury Results

The data collected from the jury sessions were analyzed and the results of the jury were also screened for data quality (consistency, repeatability, bias, etc.). Ideally it is beneficial to have a low number of jurors rejected due to either repeatability or consistency, however in this case a larger (than expected) number of jurors did not repeat while still being consistent, since the repeat pairs were presented at the end of the jury session this suggests that there were signs of fatigue. Therefore, the repeat (52 pairs) were removed from the data analysis. Because of this, a higher than normal consistency threshold (80%) was used. This means that for a juror to be considered in this analysis, the juror needed to be 80% consistent or better. Consistency here is best described in mathematics terms as the transitive property of equality/inequality, which states that if a > b, and b > c, then a > c. Of the 51 jurors that participated, 44 jurors met this consistency threshold criteria and were used to statistically represent the sound quality EPB perception.

Once the results of the jury testing were screened for data quality, the sounds were then ranked by calculating the raw scores which was relative. This result basically showed how many times sound A was preferred over sound B. These raw scores were then transformed by using linear models based on proportion of times sound A was selected over sound B. The method used to execute this transformation was the Bradley-terry model[2]. The jury sounds were then ranked from best to worst on a linear SQ merit scale. The SQ merit scale can then be used as input to the statistical analysis used to correlate the subjective characterization and objective SQ metrics.

4 DATA ANALYSIS/SOUND QUALITY METRICS

Sound Quality metrics in a broad sense can be considered any parameter that correlates to the perception of sound[1]. Sound quality parameters can be the classical psychophysical descriptors, such as Loudness, Fluctuation Strength, Roughness, Tonality, Sharpness, etc. or physical descriptors such as overall RMS sound pressure, spectral derived quantities, and statistical parameters describing temporal behaviors as well. The classical sound quality metrics use algorithms and where developed to represent 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[5, 6].

The most important metric of sound quality perception is that of Loudness. In most cases, louder products are judged worse than quieter ones. Although Loudness is the most important dimension, it is not the only one. Other metrics are needed to quantify the perception of tones, oscillating sounds, rattles and so forth. In many cases, the other psychoacoustic metrics, such as Fluctuation Strength, Roughness, Tonality, Sharpness, etc. do a very good job at characterizing these other dimensions of sound. Of the EPB's tested the most significant dimensions of sound included Loudness, Roughness, Modulation, Speed Variation, and Tonal content among a few others. However, sometimes one may find that some or none of the classical metrics 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 descriptors. Physical descriptors such as statistical parameters (mean, standard deviation, skewness, crest factor, etc.) describing temporal behaviors of the signal.

In Reference 7, 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[8]. Figure 3 lists on the left, the most common dimensions of sound, 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).

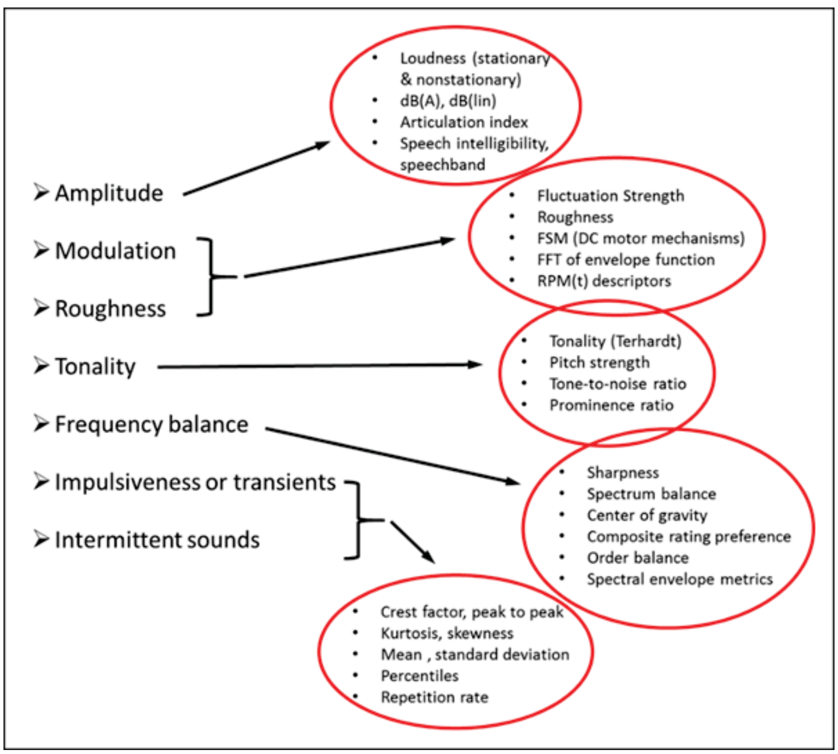


Figure 3 – Sound dimensions and sample corresponding sound quality metrics

4.1 Regression / SQ Model Results

Referring back to Figure 1, once the SQ Measurement and SQ Assessment is complete, then the next step was to correlate these two outputs statistically. Again, the SQ Measurement output refers to objective sound quality metrics and/or other parameters computed for each sound that was presented to the jury. The SQ Assessment output refers to the ranking (SQ merit) of sounds that is developed statistically from the jury results.

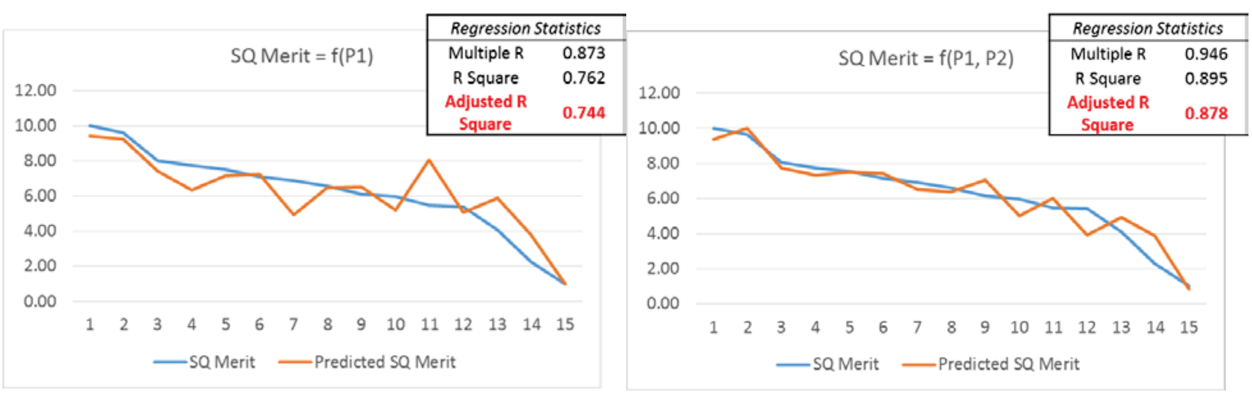
The process of linking the SQ Measurement and Assessment together is the next step. This is accomplished through statistical correlation, where a functional relationship is developed comprised of the dominant metrics that captured SQ preference. In other words, a multiple linear regression that best matched the objective metrics with the rankings of the jury.

A typical SQ preference (SQ_{pref}) model may include two to four independent sound quality variables (X_i), (as an example, loudness, speed variation, tonality, and modulation), which will look like the following:

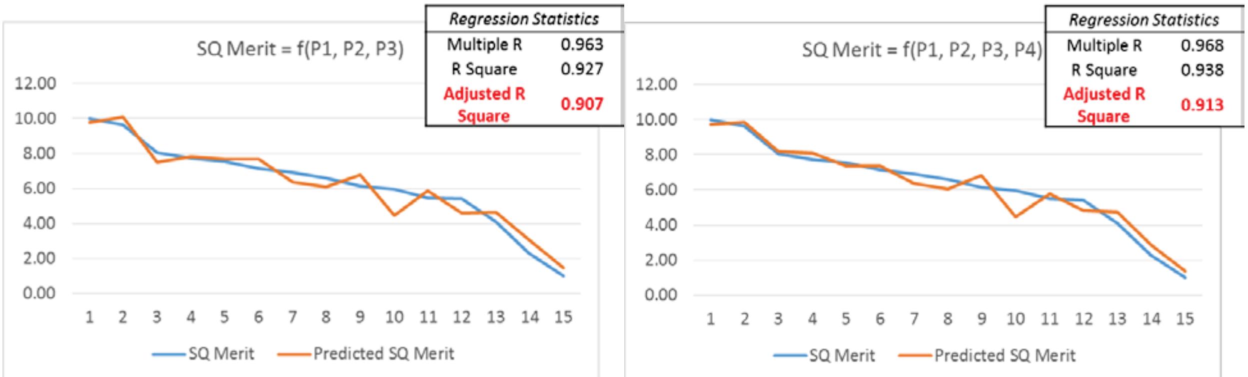
$$SQ_{pref} = \beta_0 + (\beta_1 * X_1) + (\beta_2 * X_2) + (\beta_3 * X_3) + (\beta_4 * X_4) \quad (1)$$

Where SQ_{pref} is the value of the response variable, the β_i are the constant coefficients, and the X_i are the parameters quantifying the SQ metrics (as an example) loudness, speed variation, tonality, and modulation. The number of independent SQ variables will be dependent on the size of the jury test. For example, the larger the jury test (number of sounds played to the jury), then more independent variables can be used to develop the SQ model.

An SQ model (or preference model) was developed utilizing Analysis of Variance (ANOVA) that resulted in a four term linear regression model. The first term model as shown in Figure 4 shows promising results of 0.873, 0.762, and 0.744 for the correlation coefficient (Multiple R), determination coefficient (R^2), and adjusted coefficient of determination (Adjusted R^2) respectively. It can clearly be seen that there are a number of areas where this regression model does not predict well enough to the SQ Merit (jury results). Moving to the addition of a second (term) SQ metric, we see a major improvement as shown in Figure 5, here the adjusted R^2 improved (+0.134) from 0.744 to 0.878. Likewise, with the addition of the third (term) SQ metric, we see a slight improvement in Figure 6 with the adjusted R^2 improved (+0.029) from 0.878 to 0.907. Lastly, the fourth (term) SQ metric shows the highest results of 0.968, 0.938, and 0.913 for the Multiple R, R^2, and adjusted R^2 respectively and can be seen in Figure 7. This four term linear regression model that represents with 95% confidence provided the focus for subsequent product improvement activities.



Figures 4 & 5 – Regression analysis 1-term (Fig. 4: left) and 2-term (Fig. 5: right) model



Figures 6 & 7 – Regression analysis 3-term (Fig. 6: left) and 4-term (Fig. 7: right) model

5 SQ MODEL VALIDATION

Three new EPB prototypes were designed and evaluated against the SQ model developed. Prototype 1 was a modification designed prior to the development of SQ work described in this paper. Prototype 2 was a minor modification designed to improve one of the SQ metrics developed to be compared to one of the current production (baseline) EPB's tested. Prototype 3 was a completely different design aimed at improving three of the four SQ metrics developed. The predicted SQ merit results of these three prototypes as well as the baseline EPB used prior to modifications are shown in Figure 8. It can be seen that both Prototypes 2 & 3 which were designed with the SQ metrics as the focus show improvements relative to the baseline predicted SQ merit score. As opposed to Prototype 1 which did not focus on SQ metrics design and showed poor results from an SQ standpoint. Also of note, the predicted SQ merit results of these prototype parts were also consistent with subjective impressions as well.

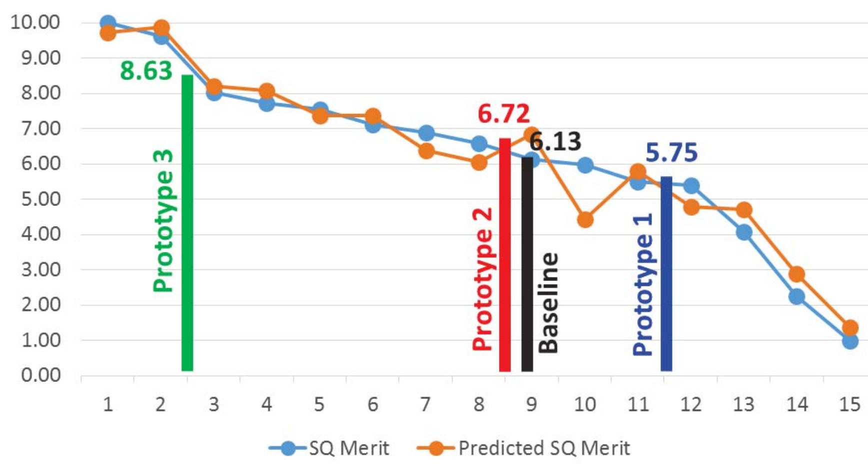


Figure 8 – Predicted SQ Merit of the three prototype EPB's developed.

6 CONCLUSIONS

In the presented paper, a novel SQ model for EPB noise characterization has been developed. A total of 15 different sounds were used and analyzed in the time and frequency domain so that an appropriate jury could be designed. This formal jury was then used to provide reliable data that was used to derive a linear scale of sound quality preference. A four term linear regression (SQ) model with 95% confidence was derived that represented the average preference of 44 jurors. The SQ model developed helped in identifying the controlling mechanism(s) of specific EPB SQ related noise. With this knowledge, the SQ model was also validated with the development of three prototype EPB units designed to improve the SQ metrics that best fit the linear regression model. Of the three prototypes developed each showed SQ merit improvements per the model and these results were also consistent with subjective impressions.

Future steps include extending the developed SQ model over a larger dataset of EPB's to test for robustness of the model. Defining a SQ threshold value from the SQ model to be used for acoustic characterization of new EPB products/designs and to cascade these thresholds down to component level parts.

7 ACKNOWLEDGEMENTS

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