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Evaluation of Air-vent Rattle Noise Severity Using Sound Quality Parameters

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ABSTRACT

Air vent is a complex assembly with many child parts which leads to manufacturing and assembly variations. It has been observed that in same production lot there has been considerable assembly variations leading to issues like vane free play and shut off flap free plays. Rattle noise is main attribute parameter to judge BSR quality of final product for all automotive OEM's. However, air vent is mostly supplier driven parts for which the specification for rattle noise requirements and its mapping to assembly variations is never considered during design and development phase. This paper presents the first phase to understand the sound quality parameters required to assess the rattle intensity and subjectively relate to customer verbatim. In this study, subjective evaluation of rattle intensity is compared with the psychoacoustic parameters (statistical loudness, statistical sharpness and roughness) from physical noise measurement. Quiet shaker was used to excite the air-vent using random PSD vibration of 5-100 Hz range. Fifteen air vents were selected from three different manufacturing lot to evaluate subjective and objective measurements related to air vent rattle. Results shows a good correlation for statistical loudness and roughness with subjective evaluation. This study proposes an optimized method to test air vent at component level for squeak and rattle evaluation in product validation phase.

Keywords: Annoying Noise, BSR, SQ, SPL, CNF
I-INCE Classification of Subject Number: 15

1. INTRODUCTION

In recent years, advanced research in noise and vibration field has done at a great level that made positive impact on customer's choice to buy a new car. Today vehicle owners have high expectations for their vehicle and purchasing a smaller vehicle doesn't mean they don't want any amenities. Customer expect comfort & other features from a low budget vehicle. Hence, vehicle interiors have been growing in importance, and

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specially dashboard become prime most area of stylish look [1]. To meet customer's expectation, subsystems are designed in best approach of structural design and controlled manufacturing tolerances. To achieve this target, sometimes designer don't consider environmental factor and once actual prototype vehicle is manufactured, mating materials contacts may lead to some unwanted noise.

These kinds of unwanted noises come under category of Squeak and rattle noise, they not only annoy customer but effect their perception towards product quality hence damage brand name. Squeak noise usually observed when two incompatible material parts come in contact and rub each other while rattle noise observed when two parts or component comes in to contact intermittently. The main components inside the car cabin which are prone to squeaks and rattles are seats, doors and instrumental panel [2]. In this study, Instrumental panel's sub component air vent is used for BSR analysis because customers complaint filed regarding air vent rattle noise. Air-vent is one of component in car which is prone to squeaks and rattles due to its complex geometry. It consists many children parts like air vent bezel, Vanes, Dial Knob, Spacer, Knob, Housing, Flap, Flap control actuator etc. and even small relative displacement between them led to BSR issue. Generally, air vent connected through its housing to HVAC duct; whose function is heating, ventilating & air conditioning and supply conditioned air inside vehicle. Hence, Air vent is only device or medium to supply conditioned & ventilated air inside cabin though HVAC duct. Air vent consists of vertical & horizontal vanes to change or guide the direction of air; horizontal vane uses to change direction up & down direction while vertical changes in left & right. Air vent also include flap which is directly expose to air flow discharge and main prime function of flap is to allow or stop the air flow discharge according to customer requirement. Air vent usually consists four to five number of horizontal and same number of vertical vanes, these vanes or blades are designed in sequenced manner to change direction of air with minimal effort. But its main operation is controlled through a vent knob by passenger; rotation of knob alters the air flow direction and discharge. Air vent knob operation include a link; one end of this rotatable link connected to knob and other end is connected to flap control actuator which finally controls flap operation to allow discharge of air flow from HVAC duct. Vent knob, horizontal vane, vertical vane, link and flap are designed in such a synchronized way that; air flow direction from left to right & up to down and air discharge from minimum to maximum changes with knob rotation. Air vent's design is usually very simple, but operation is very complex mechanism as it includes many child parts in synchronize operation. To open and close air vent trough knob; there is requirement of small force effort of passenger which is designed in an optimal way that minimum force should be enough to operate function of air vent. To achieve this purpose, designer provide free play in link connection with knob and flap control actuator which finally led to Squeak and Rattle issues of air vent. Small deviation or variability in manufacturing and assembly process is enough to create relative displacements between air vent child parts leading to BSR issues like vane rattle, flap rattle or link rattle etc. This present paper talks about Squeak & rattle issues of air vent which caused due to assembly variations, manufacturing variability and complexity of air vent mechanism.

BSR analysis of any component or vehicle is mostly performed using methods of subjective and objective. We have seen recent developments of OEMs investing in squeak and rattle testing equipment. However, tier 1 and 2 suppliers are still not there. Air vent being a sub component of cockpit still must pass the criteria of noise targets set by OEMs for cockpit. Also, there is no research available on squeak and rattle evaluation of air vent as an individual component. This paper details the findings of work carried on a component validation project to write a test and evaluation procedure for a component supplier. The methodology briefs the tools and techniques required to identify the squeak and rattle issues arising due to variations in design, manufacturing and assembly using a component level test bench. It works on the generic principle, that issues of component arising at assembly level can be minimized; if they are arrested at component level. In this process, objective noise measurements were recorded, and sound quality parameters were analysed for air vent samples taken from different production lot [3]. An attempt is made to identify the suitable sound quality parameter that correlated well with subjective perception of BSR issues. Finally, a component noise factor (CNF) is derived using statistical sound quality parameters and target setting for component suppliers [4].

2. EXPERIMENTAL SET-UP AND METHODOLOGY

Squeak and Rattle are annoying, intermittent and very difficult to identify with high background noise. It is important for any squeak and rattle test bench shaker to have a low background noise during operation. Based on global best practices, it is understood that a noise value of 1.0 - 1.5 Sone is acceptable for BSR applications varying from assembly to component level tests. MB dynamics black single axis energizer is used for small components like air vents as shown in figure 1.

Figure 1. Electromagnetic shaker used in vibration test

Fixture design plays a crucial role in squeak and rattle testing. The fixture should be light in weight due to shaker pay load limitations [2]. Also, it should not create resonances under the frequency range of operation, in present case 5-100Hz. The fixture should simulate all boundary conditions of mounting and orientation. A fixture was designed to test air vent as shown in figure 2.

Figure 2. Air vent fixture used in BSR test

The test software has capabilities to replicate both time and frequency content with a deviation less than 5%. In the present work, random vibrations acquired from RWUP conditions were used. Air vent was excited only in vertical direction; the vibration data is synthesized to capture important frequencies from different road conditions and final signal is rescaled to original amplitude level to simulate realistic loads [5]. The PSD used for the test is shown in the figure 3.

Fifteen air vents were selected from three different lot to capture the variations that arise due to manufacturing and assembly. Air vent is mounted on the fixture simulating the vehicle boundary conditions as shown in figure 3. The random vibration PSD is given as vertical excitation to the fixture with a feedback control. A microphone was kept at distance of 15cm from air vent surface for noise measurement as shown in figure 3. Noise measurement of thirty seconds duration with sampling frequency 51200 Hz was recorded for each air vent sample. The noise signal was band passed for a frequency range of band pass 300-20000 Hz using butter worth 4th order filter before calculating the sound quality parameters [6]. Statistical loudness, roughness and sharpness were calculated using 90th percentile.

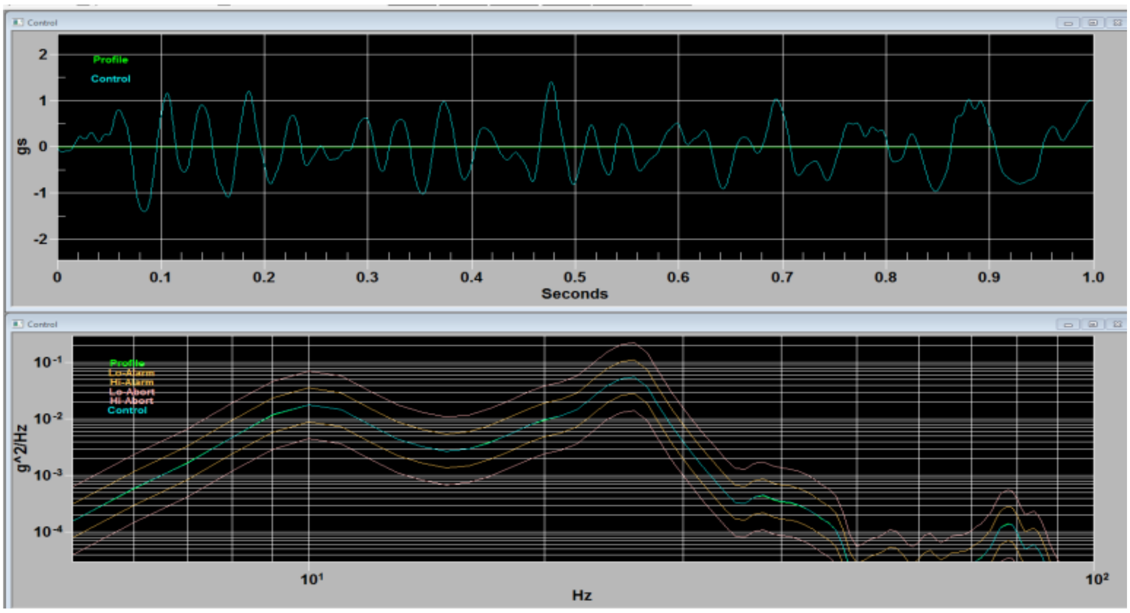

Figure 3. PSD signal used in BSR test

3. RATTLE ISSUES OF AIR VENT

When air vent is tested as per above test procedure using quiet shaker. Most air vent sample were found quiet; but some samples found faulty and were radiating noise in vibration test. Total, four major & repeatable issues were identified with varying intensities in air vents which are mentioned below.

Issue 1: Damper shut off flap rattle in open condition.
Issue Description: Free play was present at both ends for Shut off flap had with vent housing. Physical verification resulted that tolerance of Damper flap were not controlled as per prescribed GD&T limits during manufacturing & assembly process of air vent as shown in figure 4. This variation in assembly was main cause which resulted to shut off flap rattle noise in BSR test

Figure 4. Damper shut off flap free play observed in test sample

Issue 2: Air vent horizontal vanes rattle.
Issue Description: Air vent consist of horizontal & vertical vane to control air flow direction. Most number of vanes were found OK except some horizontal vane shown in figure 5; number of problematic vanes varied as per each sample. Actual tolerance limit of vane shaft with hole diameter was not within acceptable tolerance range; this led to free play of vane and resulted to vane rattle noise.

Figure 5. Horizontal vane free play locations observed in test sample

Issue 3: Control knob link free play.
Issue Description: Knob rotatable link's one end is connected to knob and other end is connected to flap control actuator though ball contact. Figure 6 shows that free play of knob link was found at flap control actuator interface which cause unnecessary movement in vibration test that resulted to loud rattle noise.

Figure 6. Knob link free play location observed in test sample

Issue 4: Air vent housing rattle.

Issue Description: Air vent is two-piece assembly which composed of vent and housing. Both parts are assembled through eight snaps as shown in figure 7 and free play was observed in snap fitting of housing with vent in physical observation. This snap free play radiates loud rattle noise during BSR test; this was also one example of uncontrolled tolerance variation in manufacturing & assembly of air vent.

Figure 7. Air vent housing free play locations observed in test sample

It is observed that free play in snaps of housing, vent vane, knob link and shut off damper are main attributes to create rattle noise. Sometimes, it happens that any loud rattle noise can mask the other minor rattle noise; alike vane rattle noise was masked by housing and link rattle noises. Hence, it is very essential to mask each noise one by one to identify other squeak and rattle noises of component in subjective evaluation. In case of air vent noise assessment, all four issues were occurred due to manufacturing and assembly variations. In physical verification of sample, some deviation was found in part's dimension like housing hole diameter, flap shaft diameter, from their standard GD &T value. These kinds of deviations in parts geometry later become causes in proto sample to creates rattle noise. Now, it is verified from this assessment that manufacturing and assembly variations are main causes for all rattle issues and this is essential to control them at each stage of product development to make component BSR issues free.

3.1 Subjective Analysis Of Air Vent Rattle Noise

Fifteen air vents noise measurements were recorded for damper flap open condition. A total of 10 noise signal for 30 seconds each were available for preprocessing. The noise level was normalized for 94dB level for a binaural playback session. Signal length was reduced to 10 seconds to avoid hearing fatigue. For subjective rating, we have used magnitude estimation method (MEM) which estimates the extent of rattle noise on a given rating scale as alpha numeric.

Table 1. Scale used for Subjective evaluation

<table>
<tr><td rowspan="3">Noise level</td><td colspan="5">Scale</td></tr>
<tr><td>L1</td><td>L2</td><td>L3</td><td>L4</td><td>L5</td></tr>
<tr><td>No noise</td><td>Minor Noise</td><td>Medium Noise</td><td>High Noise</td><td>Very High noise</td></tr>
<tr><td>Noise Impact</td><td>*</td><td>Noticeable by BSR engineer</td><td>Noticeable by few customer</td><td>Noticeable by mostly customer</td><td>Highly Noticeable</td></tr>
</table>

Subjects can listen to these test sounds repeatedly as desired and they can rate the degree of rattle on a 5 point scale. The scale from L1 to L5 is defined as per table 1. In which scale 'L1' indicates no rattle and 'L5' indicates very high rattle noise. The jury contains 20 subjects which consist of 17 males and 3 females of age group between 20 to 40 years. Subjects were composed of non- NVH background.

Noise ratings of fifteen air vents after applying statistical tools is shown in table 2. Seven air vents were rated as L1 category and two air vents are rated severe as L5.

Table 2. Subjective ranking of different test samples

Ranked Sample	Scale				
	L1	L2	L3	L4	L5
	7	2	3	1	2

3.2 Objetive Analysis Of Air-Vent Rattle Noise

It is well known that A-weighted SPL alone cannot sufficiently express the perceptual feeling of rattle. Generally, SQ metrics such as loudness, sharpness, roughness, and fluctuation strength have been employed for the SQ analysis and among these SQ metrics statistical loudness is regarded as the most important metric. It is later found that statistical roughness also correlates well to air vent rattle issues.

3.2.1 Sound Pressure Level

The stimulus of the sound pressure level needs to be interpreted as a hearing sensation and is calculated by multiplying the frequency spectrum of the acoustic pressure signal with a weighting function before calculating the RMS level. Several weighting functions have been defined, of which the A-B-C and D weightings are the most widely used. They are based on experimentally determined equal loudness contours which express the loudness sensation of single tones as a function of sound pressure level and frequency. The basic descriptor of sound signals is the sound pressure level (SPL) denoted by L_p

$$L_p = 20 \times log_{10} \frac{P}{p_0} \quad (1)$$

Where P the RMS value of the measured acoustic is pressure in Pascal (Pa) and p_0 is the RMS reference pressure, such that $p_0 = 0.00002\, Pa$. A standard model available in commercial software is used to calculate SPL for 15 sounds.
Measured sound pressure level in figure 8 is observed minimum about 26 dBA for L2 category sample and maximum about 50 dBA for L5 category samples. It was also seen in subjective evaluation that L1 category sample were most quieter and L5 category were radiating maximum noise. Other categories L2, L3 & L4 sample noise were found between both category; 28dBA for L2, 32 dBA for L3 and 45 dBA for L3. One can understand a linear relation between SPL and subjective perception for rattle, it is increasing with increment in ranking. It can be seen from figure 8 that observed rattle noise is non-stationary in nature.

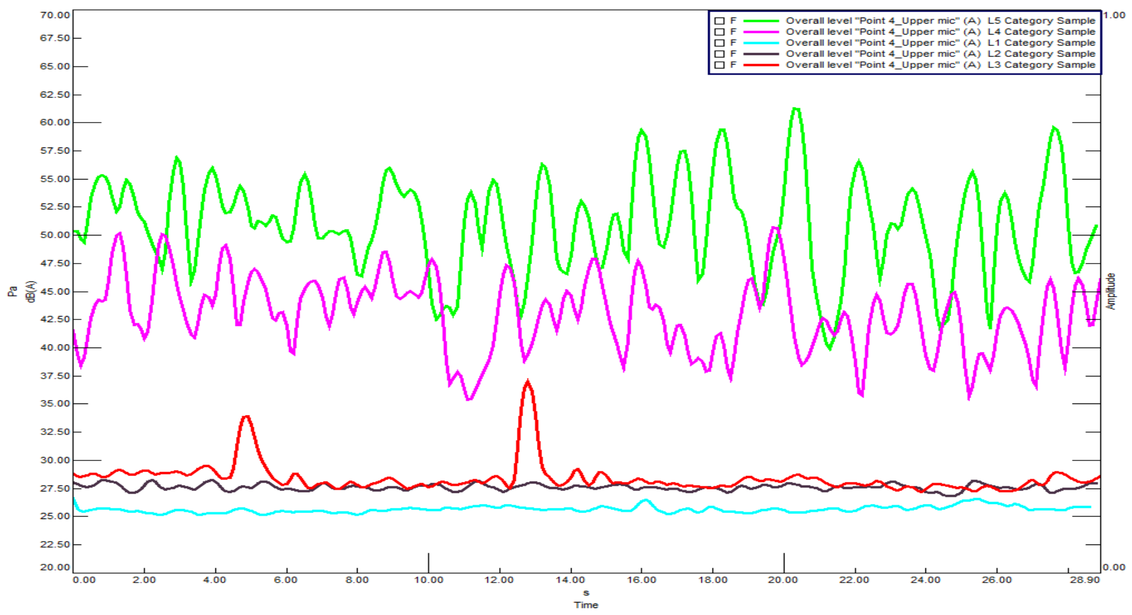

Figure 8. SPL comparison of different category sample

Figure 9 shows spectrogram of L5 category test sample; this is presenting rattle noise frequency range over a time of 30 seconds. Rattle noise intensity can be easily understanding by vertical orange color line along time; and it confirms that rattle noise is a broadband frequency noise.

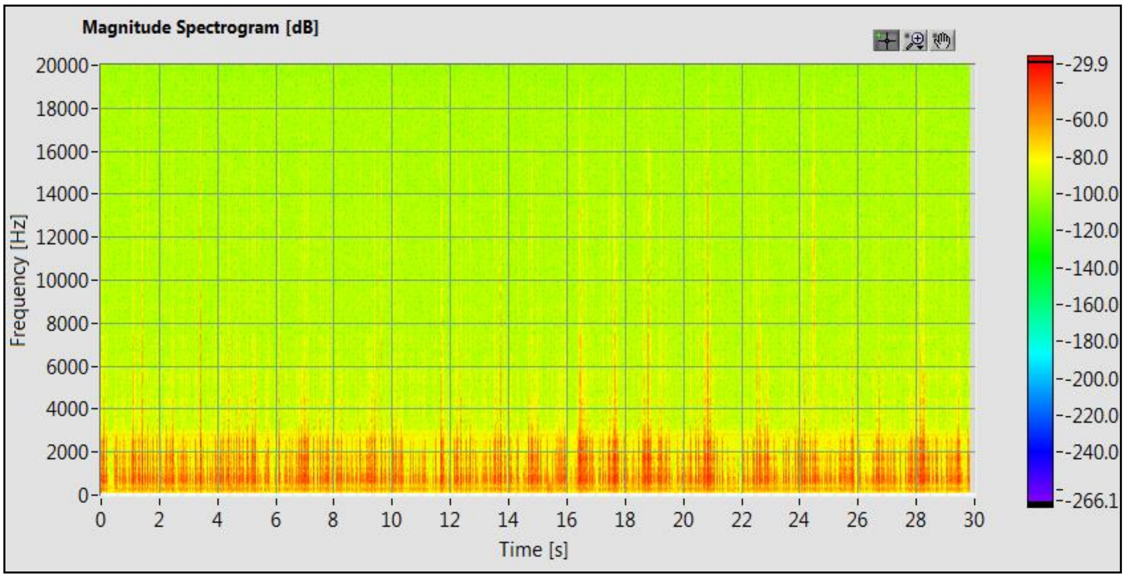

Figure 9. Spectrogram of L5 category air vent sample

4. STATISTICAL PERCENTILE CALCULATIONS

Percentile is considered the statistical parameter for evaluating the squeak and rattle of air vent. It specifies that 90% of the noise signal fall below a threshold signal level. For example, N10 percentile describes the loudness level which is exceeded in 10% of the total measurement time. The N10 loudness level is therefore a measure of the peak loudness of loudest noise peaks as it perceived by our human hearing.

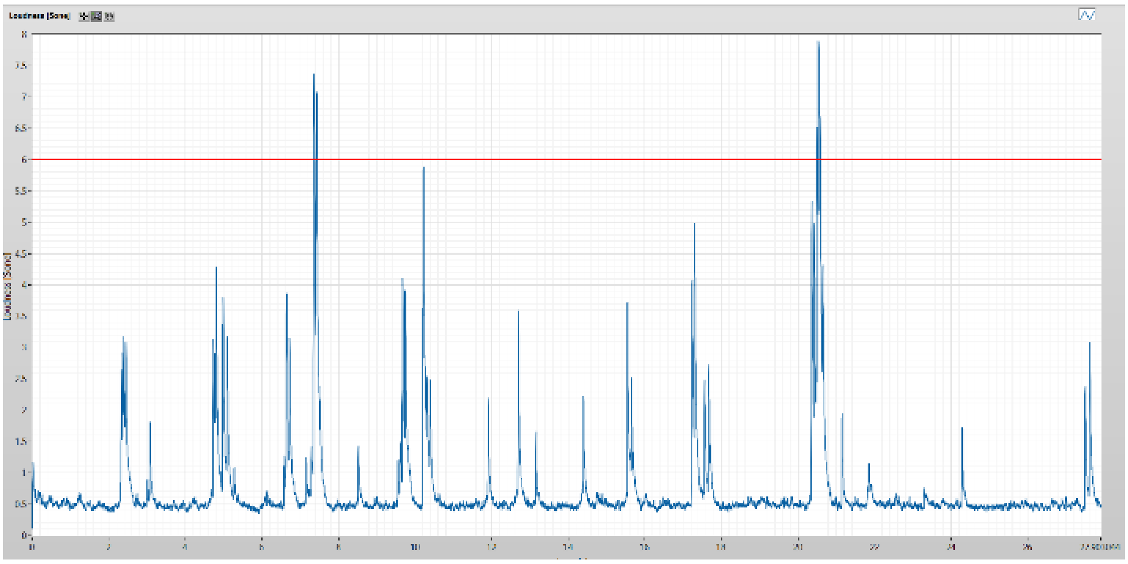

Figure 10. N10 statistical loudness

4.1 Loudness

Loudness represents the auditory perception character related to the magnitude of sounds. The loudness is measured in phones or sone; one sone is the loudness for the pure tone sound with amplitude of 40 dB at 1 kHz.

$$N = \int_0^{24\,Bark} N' dz \tag{2}$$

Where N' is the specific loudness within the critical band (Bark). According to standard DIN45631/A1 the time varying loudness can be understood as the Zwicker loudness calculated every 2ms and accounting for both spectral and temporal masking as well as other temporal effects [7].

Figure 11 shows 10% percentile of calculated statistical loudness of different test samples plotted against subjective perception of rattle. L1 category air vent loudness is less than 1 Sone, while for L5 category maximum loudness value is under ranges 8-10 Sone. Loudness value falls for L2 category in range of 1-2 Sone; for L3 category 3-5 Sone and 6-7 Sone for L4 category sample.

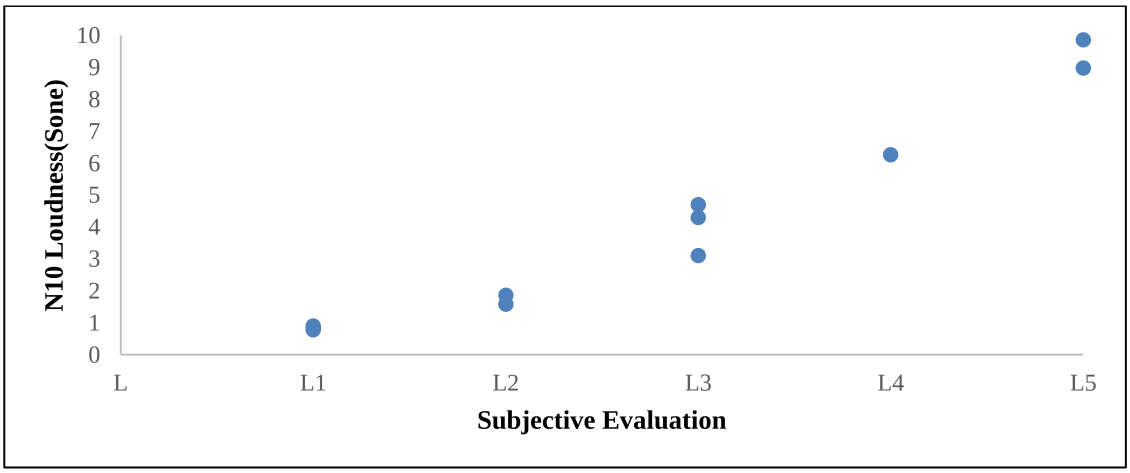

Figure 11. Comparison of statistical loudness with subjective evaluation results

Computed correlation R^2 coefficients using regression analysis was found 0.954, hence confirms accuracy for loudness correlation. Polynomial curve fitting was applied to get linear relationship between subjective and objective results using a linear function. For this analysis, numerical values are assigned to different category scales so that L1 = 1, L2 = 2, L3 = 3, L4=4 and L5=5.

Statistical loudness N10 value was calculated after deriving a linear equation.

$$N10 = (2.0336 * L_i - 1.5108) \quad (3)$$

Figure 12 shows the results of polynomial curve fitting by above equation.

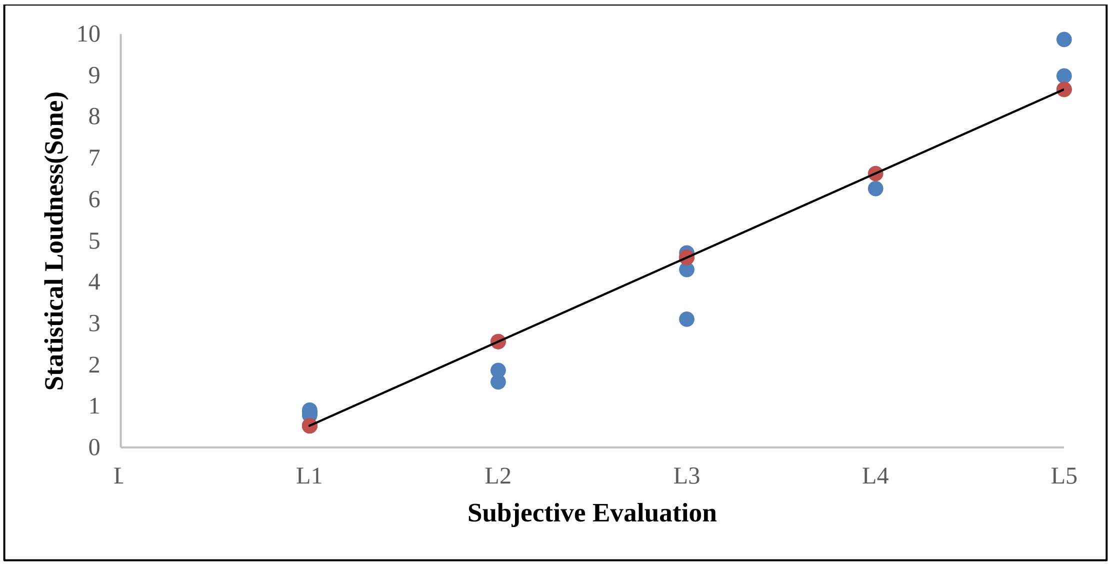

Figure 12.A linear relationship between N10 loudness with subjective evaluation results

4.2 Sharpness

Sharpness describes auditory perception related to the spectra correlation of a sound. Where N' is the specific loudness within the critical band (Bark) and $g(z)$is a critical band rate dependent weighting factor that is unity between 0 Bark and 16 Bark and then increases to four at 24 Bark. The unit of sharpness is the acum. One acum is the sharpness for a pure tone sound with amplitude of 60 dB at 1 kHz

$$S = 0.11 \times \frac{\int_0^{24} N' z g(z) dz}{N} \quad (4)$$

Figure 13 shows comparison between10% percentile of calculated statistical sharpness and subjective evaluation results. It is clear from figure 8 that sharpness for L1 & L4 category are in same range 2-3 acum while for L2 & L3 also lie between 1 to 2 acum. Maximum sharpness is observed for L5 category and minimum for L3 category. Statistical Sharpness correlation with subjective evaluation behave nonlinearly and calculated R^2 coefficients using regression analysis was found 0.067.

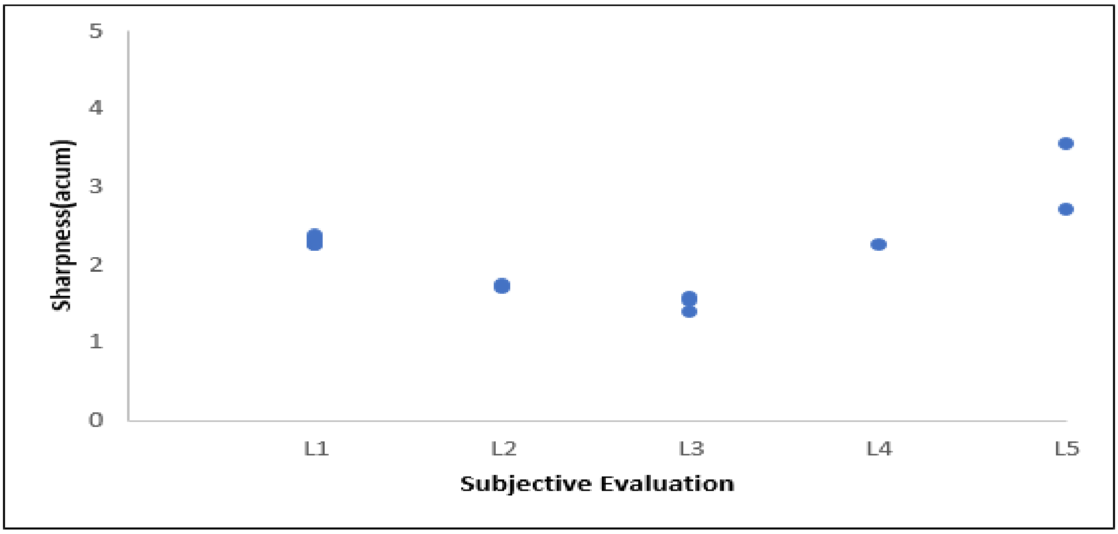

Figure 13. Comparison of sharpness with subjective evaluation results

4.3 Roughness

Roughness is a sound quality attribute which quantifies the subjective perception of rapid amplitude modulation of a sound. This give sense to customer to perceive time varying fluctuation of sound. The roughness (R) of an amplitude modulated sound can then be approximated as in which is the modulation frequency.

$$R = fmod * \Delta L \tag{5}$$

Where $fmod$ is the modulation frequency (Hz) and ΔL temporal masking depth representing the difference between maximum and minimum in the perceived time dependent loudness.

Figure 14 shows comparison between 10% percentile of calculated statistical loudness and subjective evaluation results. This correlation gives a linear relationship of roughness with subjective evaluation results and R^2 coefficients value 0.911 confirm accuracy of analysis.

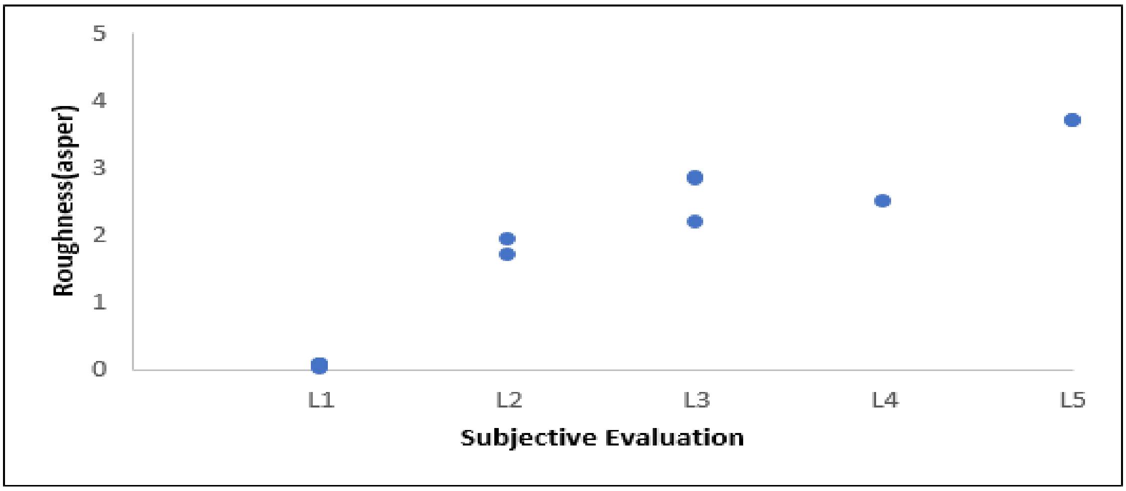

Figure 14. Comparison of roughness with subjective evaluation results

5. COMPONENT NOISE FUNCTION (CNF)

The aim of this rating criterion is to provide a scale using objective sound quality parameters to decide Component noise targets during benchmarking and prototype stage. The rating system is in the form of a star rating which allows a quick assessment of the air vent' s noise. Each sample of air vent will receive a number rating 1 to 7 based on psychoacoustic factors. The noisier sample are given in range value above 6 and the quieter sample less 1. The first step was to calculate Statistical Loudness and Statistical Roughness value from objective evaluation measurement. This step was followed for each test sample in order to correlate CNF with subjective evaluation results. Component Noise Function (CNF) is calculated by averaging sound related psychoacoustic factors.

$$\text{CNF} = \text{Average (Statistical Loudness + Statistical Roughness)} \qquad (6)$$

This CNF factor was correlated with subjective evaluation results as shown in figure15. Polynomial curve fitting was applied to get linear relationship between subjective and CNF. This correlation gives a perfect linear relationship with R^2 coefficients value of 0.994. Thus, CNF helps to decide simple target for any component test like air vent, infotainment unit etc. which is approved output of objective & subjective results. It is clear from this analysis that CNF value should always be equal or less than 1 to pass rattle noise test otherwise component is Not Ok means fail.

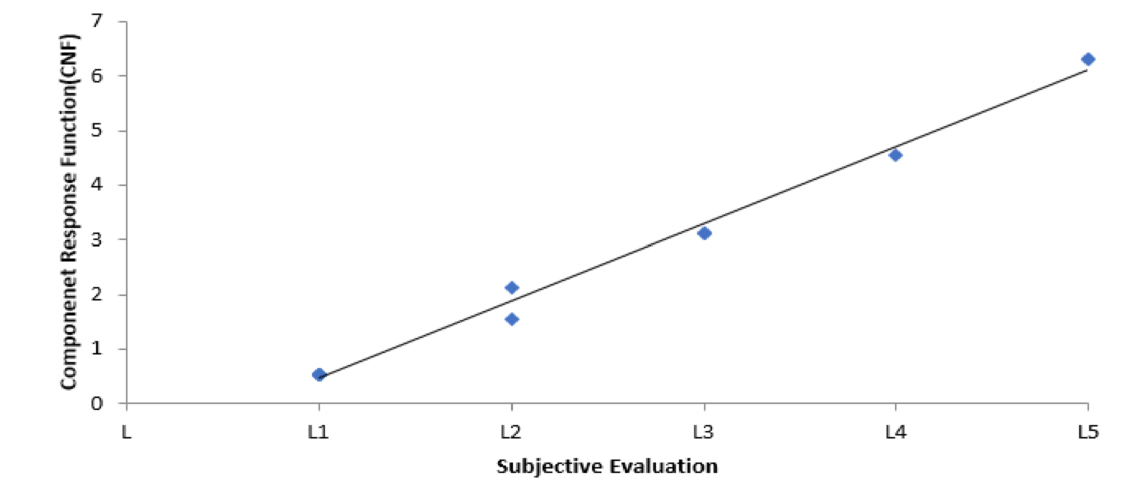

Figure 10. CNF correlation with subjective evaluation results

A new scale was also formed for subjective analysis using CNF values in table 3. This scale helps us to get one objective value which define the quality of test sample. CNF average score collected through jury in subjective evaluation can simply define the quality of test sample or component.

Table 3. New CNF Scale used for Subjective evaluation

	Scale				
	L1	L2	L3	L4	L5
Noise level	No noise	Minor Noise	Medium Noise	High Noise	Very High noise
CNF	1	2	3	4-5	6-7

6. CONCLUSIONS

Noise objective assessment of air vent rattle was performed by BSR engineer in semi-anechoic chamber using electromagnetic shaker and results were correlated with subjective results of respective jury. Four major issues like Knob link, vane, housing and flap rattle were found in air vent test samples during subjective evaluation; but no squeak was observed in any sample. These observed BSR issues were arise due to variations in design, manufacturing and assembly of air vent. All rattle noise was loud enough for easy identification except vane rattle, as it was masked by other rattle noises. The psychoacoustic parameters for these BSR issues were measured and compared with subjective evaluation results. A poor correlation was observed for statistical sharpness; but a good correlation was seen in case of N10 statistical loudness and roughness with high R^2 coefficients value. A liner relationship was found between subjective results and statistical loudness and roughness in context of air vent rattle noise. This analysis results shows that for trim parts like air vent, loudness and roughness objective results correlate perfectly with subjective results. A new factor CNF is formulated to give alternative of objective value in context to component sound quality and validated with subjective evaluation results. A good correlation with high R^2 coefficients value was observed and a new ranking scale is defined to rate any component sample. This ranking scale can be integrated in the product development cycle for any trim component noise target in future.

7. ACKNOWLEDGEMENTS

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