Measuring Vibration Characteristics in Seating

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Abstract

Most methods of vibration analysis focus on measuring the level of vibration. Some methods like ISO-2631 weigh vibration level based on human sensitivity of location, direction, and frequency. Sound can be similarly measured by sound pressure level in dB. It may also be weighted to human frequency sensitivity such as dBA but sound and noise analysis has progressed to measure sound quality. The characteristic and the nature of the sound is studied; for example equal or near equal sound levels can provide different experiences to the listener. Such is the question for vibration; can vibration quality be assessed just as sound quality is assessed?

Early on in our studies, vibration sensory experts found a difference in 4 seats yet no objective measurement of vibration level could reliably confirm the sensory experience. Still these particular experiences correlated to certain verbal descriptors including smoothness/roughness. This new metric tries to capture that specific sensory experience. A larger study was done with more road profiles and non-expert occupants that further confirmed that this proposed metric correlated equally or better to sensory when compared to other industry established metrics.

Introduction

A comfortable and pleasant ride is an important factor for drivers and passengers when they decide to buy a vehicle. There are many aspects that influence riding comfort or pleasantness. For example, noise/vibration induced by vehicle components, wind and road may dramatically affect how vehicle passengers perceive the quality of ridding. Therefore, the design of a seat becomes essential since it is a way to reduce the vibration excitation to passengers as well as to compensate the negative effect of noise and vibration in vehicles by providing positive seating experience. For the efficient way of evaluating seats in terms of vibration experience, it is crucial to develop an objective algorithm, which can predict the subjective perception of seat vibration precisely, since subjective assessments often are time consuming and require more resources.

Many studies have been done to predict the subjective perception of riding vibration comfort including more recent studies [1][2]. ISO-2631 [3] is the most often used standard for this purpose. The standard suggests using the weighted RMS values for the evaluation on individual degrees of freedoms (DOFs) while it recommends taking root-sum-of-squares (r.s.s.) for the calculation of vibration total value, i.e. combining the results of individual DOFs. The relevant studies and the standards are based only on the estimation of vibration energy with a frequency weighting function applied. However, as we can see from the research on hearing [4], the human perception of vibration may be much more complicated than a simple energy summation.

For that reason, the current study made an attempt to develop a vibration metric correlating with overall subjective pleasantness by considering the findings from noise annoyance researches such as buzz, squeak and rattle (BSR) noise event detection [5] [6].

Background

Our study began during a development project with 4 seats/vehicles. Expert sensory results found small but definitive differences in the ride comfort yet we were unable definitively quantify the differences between them using internal Toyota methods or other industry techniques including ISO-2631 [3]. Could the experts be wrong or overly sensitive? Could the objective methods be lacking in precision? Could it be some combination of both?

The development project moved on but the weakness in our methodology spurned further work. A blind study of additional vibration ride comfort experts confirmed the earlier sensory results. Deeper analysis of the objective data found differences but without the sensory results as a guide the differences were too small. Despite experimental controls it could still be testing variance. None of the data showed statistical significance.

Sound Quality to Vibration Quality

It was decided to explore the characteristics of the vibration experience in a similar fashion as sound quality. Sound quality metrics measures more than just the sound level, and they quantify the feel of sound. Generally speaking objective ride comfort methods measure the level of vibration. Sound and noise analysis also measures quantity using metrics like loudness, dB, or dBA. But sound and noise analysis digs deeper using sound quality metrics like roughness, sharpness and fluctuation strength. These sound quality metrics measure more than just a level of noise they measure the characteristics.

Phenomena → Level → Weighted Level → Characteristics
Sound → dB → dBA → Sound Quality Metrics
Vibration → acceleration → ISO-2631 → Vibration Quality Metrics

Figure 1. Comparing sound quality to vibration quality

Subjective Experiment on Road

Setup and Procedure

Identifying a new objective metric began as a search for an alternative way to assess and capture the ride comfort experience of Toyota experts. Using 6 trained experts and the 4 seats/vehicles a thorough survey was created that attempted to explore the varying vibration experience from a less technical perspective and a more user descriptive perspective and similar to experiments in psychoacoustics. More details of the survey follow. (see Figure 2)

The seats are all four way manuals. Seat position (slide and recline) was standardized as were individual postures including foot, hand, and head positions. Only road noise was permitted in the vehicle. Road surface and speed was controlled. Six trained ride comfort experts were used as evaluators. Two runs down the road surface were conducted. The first was for sensory evaluation. The second was for objective data collection. Whoopi cushion style accelerometers were placed in standard seat positions - under the thigh, hip, and on the back only during the second run. Additional accelerometers were placed on the floor at the front and rear seat mounting points and at the occupant's heel point. A microphone was also collecting noise near the panelists' ear.

Figure 2. The semantic differential used for the subjective assessment of vibration attributes.

The survey of the ride comfort experts sought to identify some characteristics of the vibration. We asked participants where they felt the vibration using a picture and a list of body parts including bone, joint, lower back, knee, whole body, skin surface, and the like. We asked if they could feel the direction of the movement: vertical, fore/aft, lateral, pitch, roll, and twist. We also asked them to rate the characteristics of the vibration on the following scale. (see Figure 2)

All this data was compared to a standard Toyota sensory scale used and well known amongst all evaluators.

On-Road Results

A few of the above descriptors as well as some of the other data collected trended with overall (Toyota) sensory scores including Rough/Smooth and Intense/Slight (see Figure 3). The Toyota sensory method is at its core a simple linear subjective rating system. Intense/Slight was thought of as a descriptor or characteristic for what is traditionally measured in vibration. It was thought of as good descriptor of vibration level. Roughness and other characteristics we considered may possibly describe something different than the commonly measured vibration level as acceleration. Roughness and other sound quality metrics measure the variation and/or fluctuation of sound. Can we do something similar with vibration?

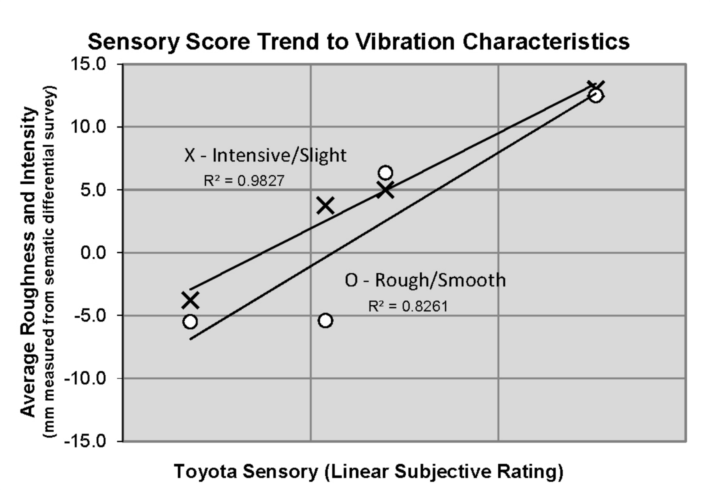


Figure 3. The correlation between the overall sensory data and the roughness and intensity data on average.

As previously mentioned we could not find any objective data that reliably correlated or trended with the sensory data. In general the objective data including those found in ISO-2631, VDV [7], and another internal Toyota method found the seats and vehicles to be performing at a level that was near equivalent. The data supported a conclusion that typical non-experts would likely not be able to discern a difference between the 4 seats/vehicles. However we wanted to be able to quantify or objectify the experts (and maybe the rare discerning non-expert customer) consensus that there were performance differences felt in the seats.

Next Step

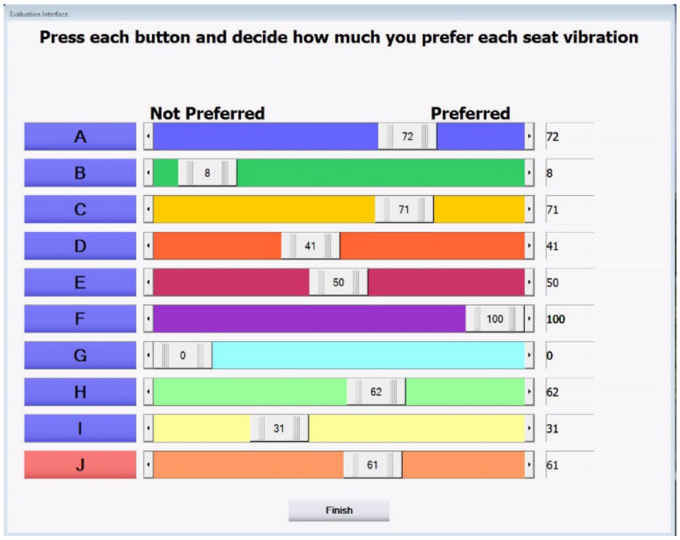
A correlation coefficient of 0.83 between Sensory Roughness and Overall Vibration/Ride Comfort Sensory was enough to move forward. The next question was can we measure or quantify Vibration Roughness or Smoothness. And can it be done precise enough that it captures the experts' consensus? Using only the data collected from the 6 expert panelists and 4 seats a variety of different metrics were explored seeking Vibration Roughness. This included existing sound quality metrics like roughness and sharpness. The results showed promise resulting in a larger and broader subjective study done on an NVH simulator.

Subjective Experiment in the NVH Simulator

Setup and Procedure

Despite the fact that the subjective experiment on road provides more precise assessment of vibration quality, the procedure takes a lot of effort and is time consuming. For more general validation of the proposed metric, more subjective data needed to be collected in a more efficient manner. For that reason, Brüel & Kjær Full Vehicle NVH Simulator Type 3644-W was utilized for the additional subjective experiment. The simulator provided the vertical and lateral excitation in the seat cushion and the fore/aft excitation in the seat back position. The excitation in each degree of freedom (DOF) is independent from the other DOF's excitations so that it is relatively easy to reproduce the measured/simulated vibration signals.

Three types of stimuli were used for the experiment. They were 10 realistic stimuli recorded on road or on a vibration plate, 24 amplitude modulated stimuli, and 18 impulsive stimuli. The carrier frequencies as well as modulation frequencies were set to similar values as the ones in the on-road stimuli. Special care was taken to ensure that the vibration level balance between the three DOFs did not become unnatural.



Press each button and decide how much you prefer each seat vibration

A	72
B	8
C	71
D	41
E	50
F	100
G	0
H	62
I	31
J	61

Figure 4. Multi-stimulus scale used for the subjective assessment of artificial and realistic vibration stimuli.

A psychophysical method similar to "MUlti Stimulus test with Hidden Reference and Anchor (MUSHRA)" [8] was applied, but the method did not use the reference (see Figure 4). The subjects were asked to rate the preference, i.e. overall sensory, of the stimuli on the provided scales assigning the rating value between 0 and 100. A visual scene from a fixed driving condition was presented during the whole experiment, and the car was driving at a speed of 50 km/h in the scene. A road noise recording from the experiment on road was played during the experiment in order to design the experiment as close as possible to the on-road experiment. The subjects were able to change the vibration stimuli by pressing the buttons displayed on the screen. In order to avoid a sharp transient excitation while changing between the stimuli, a fade-out/in function was applied to the previous stimulus and the new one respectively.

19 non-expert subjects participated in the experiment, and each subject spent approximately 2 hours for the whole experiment. They were not paid for their participation. The experiment consists of 3 sessions, i.e. for realistic, amplitude modulated, and impulsive stimuli, and the sequence of the sessions was counter-balanced across subjects. The order of the stimuli within each session was randomized using balanced Latin Square design [9].

Subjective Result

In a typical rating experiment, subjects use different ranges of the provided scale when giving their judgments. For example, one subject may distinguish the difference between stimuli within a very narrow range in the scale while another uses almost the entire range, i.e. from 0 to 100, for their assessments. In order to minimize this effect, the geometric mean across 19 subjects was calculated together with the corresponding 95 % confidence intervals. The geometric mean can be calculated by

$$\left(\prod_{i=1}^{n} X_i\right)^{1/n} \tag{1}$$

where n is the number of subjects, X_i is the individual subjective ratings and Π is the product of a sequence of numbers. Figure 5 shows the average preference ratings for the three types of stimuli, and each point in the figure represents the geometric mean of the judgments, i.e. the scale value for a button in Figure 4, from 19 subjects. Notice that the stimuli numbers in the abscissa for each curve represent different stimuli and the figure intends to compare the subjective ratings across different stimuli types. It is noticeable that the two types of artificial stimuli resulted in a similar range of preference ratings as the measured stimuli. This may mean that the results from artificial stimuli can be used for the validation of the metric proposed in the current investigation.

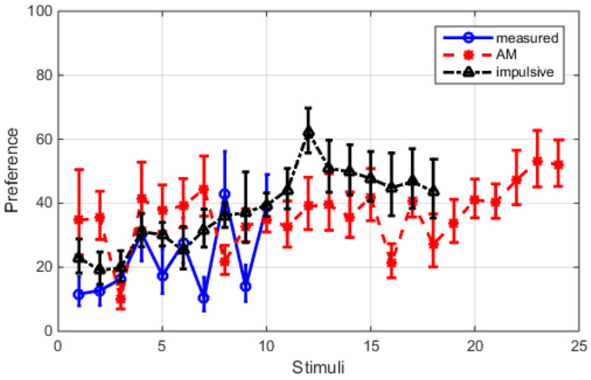


Figure 5. The average preference ratings across subjects for the 3 types of stimuli.

Objective Analysis

Investigated Metrics

Sensory profile analysis describes a product using subjective ratings based on a set of vibrational attributes and shows the relationship among individual attributes with overall sensory. The sensory profile analysis in the on-road subjective analysis illustrated that roughness sensation explains the perception of preference, i.e. overall sensory, rather well. For that reason, a new metric, i.e. Vibration Roughness (unit of vasper), was developed in this investigation based on the estimation of temporal variation in the acceleration signals. Vibration Roughness was applied for each DOF, and the overall total value was calculated by the weighted sum of the individual DOF's values. The weighting in different DOFs followed ISO-2631.

The weighted RMS value described in ISO-2631 was used as the benchmarking metric, and the sum of the weighted RMS values across different DOFs was calculated for the overall total value. The weighting function and the corresponding factors are listed in Table 1.

Table 1. The weighting function and the factor applied for different DOFs according to ISO-2631

DOF	Weighting	Factor
Seat cushion lateral	W_d	1
Seat back fore/aft	W_c	0.8
Seat cushion vertical	W_k	1

Correlation Results

In the end, the predicted values from Vibration Roughness showed excellent correlation to the 4 seats/vehicles we had earlier identified in the on-road experiment (see Figure 6). Notice that the Toyota sensory data are presented in a linear scale in the figure. A correlation coefficient higher than 0.9 was achieved.

The larger study of non-experts and differing vibration profiles found correlations for Vibration Roughness to be better than what is currently the industry benchmark (see Table 2). The correlation coefficient for Vibration Roughness does not seem to be affected by the sensor DOFs while the weighted RMS does. This ensures that the overall total value calculated by Vibration Roughness is more robust compared to the conventional weighted RMS. Additional possible metrics were developed but only this metric was found to be equivalent or better than the traditional weighted RMS from ISO-2631.

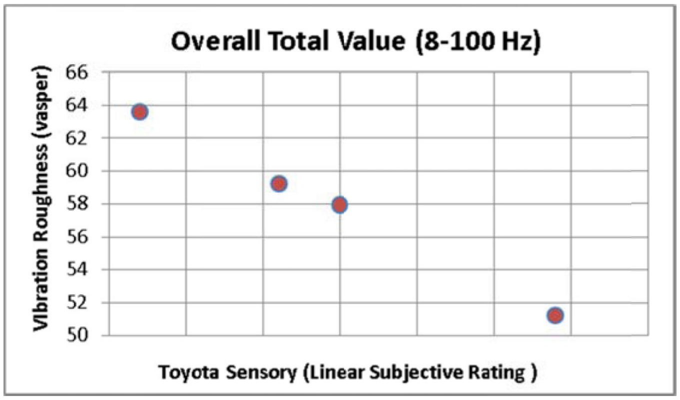


Figure 6. Comparison between the objective results of Vibration Roughness and the subjective preference judgments on road.

Table 2. The correlation analysis between the subjective ratings in the NVH simulator and the objective predictions.

	Correlation Coefficient to Sensory			
Metric	Back F/A	Cushion Vertical	Cushion Lateral	Overall Total Value
RMS ISO-2631	-0.17	-0.45	-0.65	-0.58
Vibration Roughness	-0.62	-0.66	-0.69	-0.69

It is important to note that ISO-2631 weighted RMS has significantly more history and data supporting it than this metric Vibration Roughness. The Vibration Roughness overall total value uses ISO-2631 weightings. This is an introduction to the metric and only time and more studies of the metric will truly validate its usefulness.

Summary/Conclusions

Two subjective experiments for seat vibration quality were conducted on road as well as in the NVH simulator. While the on-road subjective assessment provides more realistic ratings of seat vibration quality, it is not cost effective and does not provide the subjects a possibility of back-to-back comparisons, i.e. comparing two or more different seats one after another within the same experimental session. The range of subjective preference ratings was similar between the on-road and the simulator experiment, and this indicates the validity of the subjective assessments in the NVH simulator.

The proposed metric, i.e. Vibration Roughness, predicted the subjective data better than the traditional weighted RMS values according to ISO-2631. Especially, the correlation coefficients for Vibration Roughness do not seem to depend on the sensor DOFs while the weighted RMS correlated well only in the cushion vertical direction. This is particularly interesting since the overall total value of weighted RMS is often heavily influenced by a specific DOF having the highest amplitude of acceleration.

The proposed algorithm predicted the subjective assessments of artificial stimuli rather well and thereby demonstrated the applicability in more general seat vibrations. However, the validity of the new metric may need to be tested with more various types of seat vibration signals on road in order to generalize the conclusions in the current study.

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