Psychoacoustic assessment of noise under a motorcycle helmet

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Introduction

With an onset of riding at high speeds endangering the rider's hearing ability permanently, only some research exist on quantifying the overall Sound Pressure Level (SPL) at the ear-level. A novel approach to not only quantify the SPL, but also the different psychoacoustic parameters and a corresponding correlation with the subjective impression to assess and refine the product sound quality was essential [1].

A 2018 publication quantifies the overall SPL of the noise under the motorcycle helmet to range from 90 to 100 dB(A) [2]. Additionally, the psychoacoustic sound quality metrics of the noise had to be determined to hone the perceived acoustic quality of the product.

A series of on-road trials with different *helmets*, *vehicle speeds* and *riding positions* were performed. An arbitrary magnitude digital filter to equalize the frequency-varying calibration response of the in-ear microphones was designed to linearize the frequency response for the accurate objective psychoacoustic quantification and the subjective perception of noise.

The main effects plots reveal that all the predictor variables contributes significantly to the overall SPL and other psychoacoustic metrics. An analytical association between the objective and the subjective psychoacoustic assessments using statistical regression model correlated the metrics loudness, sharpness, roughness, and articulation index at 75%, 85%, 48% and 68% respectively.

Pre-processing

Calibration correction

Measurement microphones have a constant sensitivity over the entire frequency spectrum. However, this was not the case with in-ear microphones used for the noise measurements [2]. The microphones were calibrated using a secondary calibration procedure with a reference white noise of amplitude 90 dB(A) from an omnidirectional speaker and a reference microphone. The frequency dependent calibration corrections as represented in figure 1 were performed in a reverberation room for each of the $1/3^{\text{rd}}$ octaves for the in-ear microphones.

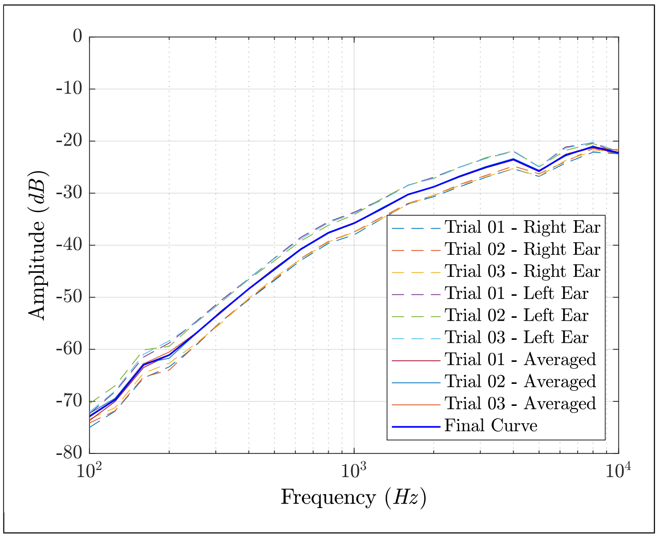

Figure 1: Calibration correction for the microphones

Filter design

Due to the frequency varying calibration response of the microphones, the recorded signals were frequency adjusted. To replay the audio files and to analyze their psychoacoustic parameters, they had to be equalized using a digital filter with a response to linearize the frequency components. A *Type I linear phase FIR even order symmetric filter* using the *least-squares error minimization* method was designed in MATLAB [3]. After the filter application it was critical to ensure the correct SPL levels for the audio files. As the filter attenuated the signal and the corresponding SPL, they were scaled by an appropriate factor to match the time signature of the original files to ensure an accurate quantification of data and audio playback for the objective and subjective psychoacoustic assessments respectively.

Data analysis

Statistical approach

Design of Experiments

For evaluating the product sound quality of motorcycle helmets, a series of on-road trials using the following input variables were performed,

- Three different *helmets* from different manufacturers belonging to different price classes anonymized as – *White*, *Grey*, *Black*.
- Three different *riding speeds* – *80*, *100*, *120 km/h*.
- Three different *rider seating positions* – *Normal*, *High*, *Low*.

Hypothesis testing

The purpose of hypothesis testing is to draw conclusions about an entire population based on a representative sample data and to determine if there exists sufficient proof in favor of a certain hypothesis. The null hypothesis (H_0) assumes that there was no difference in the overall magnitude of the objective psychoacoustic metrics and SPL by varying between the specific independent variables, i.e., the mean of *helmets* (μ_H), *vehicle speeds* (μ_S), and *riding positions* (μ_P) were comparable. An alternate hypothesis (H_A) assumes the contrary. $H_0 : \mu_H = \mu_S = \mu_P$ and $H_A : \mu_H \neq \mu_S \neq \mu_P$

p- and F-values

The statistical check as per the F-distribution, the p- and F-values obtained from MINITAB were used for analyzing the results. An F-value closer to 1.00 validates the assumed null hypothesis to be true and a probability value $\leq$ significance level, $\alpha = 0.05$ means that the data is statistically significant and that the null hypothesis must be rejected.

Objective psychoacoustic evaluation

The metrics loudness, sharpness, roughness, articulation index and overall SPL were quantified using the *Sound Diagnosis* add-in available in LMS Test.Lab. The main effects plot, p- and F-values as computed using the statistical analysis tool MINITAB are illustrated for each of the parameters.

Loudness

Magnitude estimation of sound pressure and a function level metric with a strong influence on the product sound quality, *loudness* is often confused with the associated volume. It is rather the human perception of volume. ISO 532-B norm as available in LMS Test.Lab was considered for the loudness estimation. Interpreting from the main effects plot for loudness as represented in figure 2,

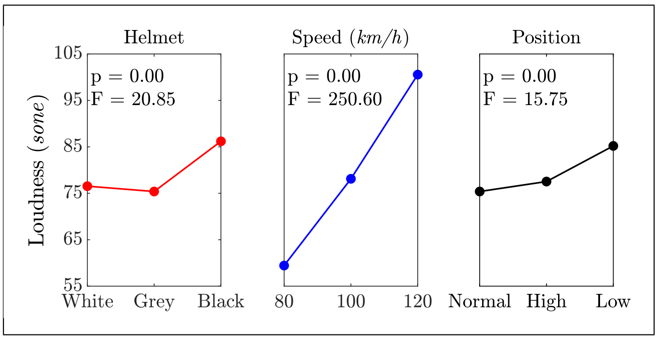

Figure 2: Main effects plot – *loudness*

- The variable *speed* has the steepest response, meaning that it was the most deciding factor in determining the overall loudness. This was in turn verified by the higher F-value corresponding to *speed*.
- Although a change in either *helmet* or *riding positions* minimally influences the overall loudness magnitude, the contribution of *speed* remains dominant as the loudness range increases sharply with nearly 20 *sone* per 20 *km/h* as a function of *speed*.

Sharpness

Sharpness, an annoyance metric caused by the high-frequency components in noise can be understood as the ratio of high-frequency spectral contents to the overall sound level [4]. The inbuilt sharpness level estimation available in LMS Test.Lab was used for computing the sharpness level. Interpreting from the main effects plot for sharpness as represented in figure 3,

- A change in the *riding position* contributes more to the total sharpness due to its high F-value. Contrarily, a p-value of $0.23 > \alpha$ for *speed* implies that it barely influences the overall sharpness magnitude.

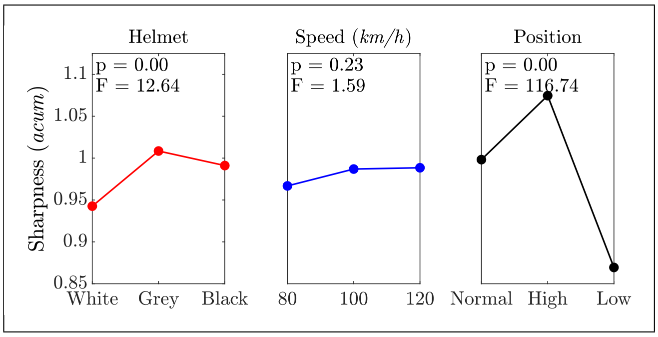

Figure 3: Main effects plot – *sharpness*

- The implication of *riding position* remains much significant than *helmet* or *riding speed* because of the influence of the motorcycle windshield.

Roughness

Roughness, a modulation metric is an elementary perception component outlined by the amplitude modulation in the perceived sound. Coarseness in the sound starts to be felt subjectively by the hearer as the difference in the frequency fluctuations Δf becomes greater than 15 Hz. Interpreting from the main effects plot for roughness as represented in figure 4,

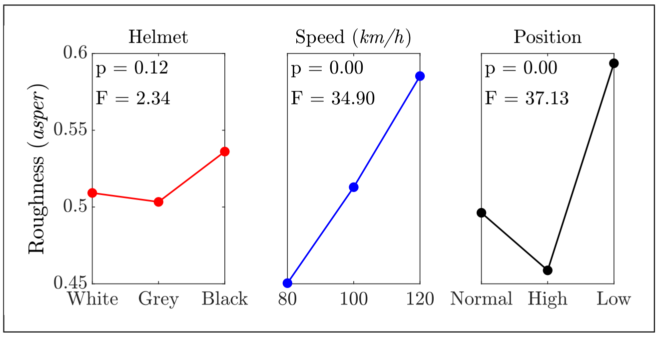

Figure 4: Main effects plot – *roughness*

- Despite the magnitude window spanning from 0.4 to 0.6 *asper*, the response of the variables *speed* and *position* are steeper than that of the *helmet*, with the extent of roughness increasing about 0.05 *asper* per 20 *km/h* gain in *speed*. The same is inferred as the variable *helmet* has a p-value of $0.12 > \alpha$.
- The riding position *"low"* contributes to much rough noise. While the contributions of *speed* and *position* remaining comparable, the F-values ranks the variable *position* above *speed* and *helmet*.

Articulation Index

A speech metric that measures the interference caused by the background noise on the intelligibility and understanding human speech, *articulation index* has a value ranging anywhere between 0%, corresponding to understanding no speech to 100%, where all the speech could be understood. Interpreting from the main effects plot for articulation index as represented in figure 5,

- At a maximum value of only 13.5% indicating an inferior noise quality inside the motorcycle helmet, articulation index is observed to deteriorate as a function of *speed* to reach the lowest value of 0.7%.

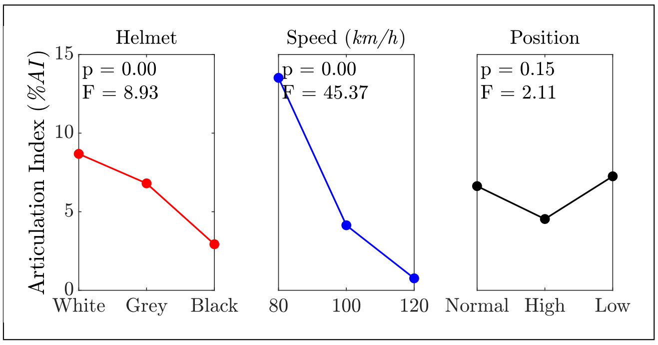

Figure 5: Main effects plot – *articulation index*

- For the variable *position*, a p-value of $0.15 > \alpha$ exhibits that it does not contribute much to the overall amplitude. As established by the F-values, the contribution of the variable *speed* is significantly higher than the other two factors.

Overall SPL

Sound pressure is the local pressure deviations from the ambient atmospheric pressure caused by a sound wave. Interpreting from the main effects plot for the overall SPL as represented in figure 6,

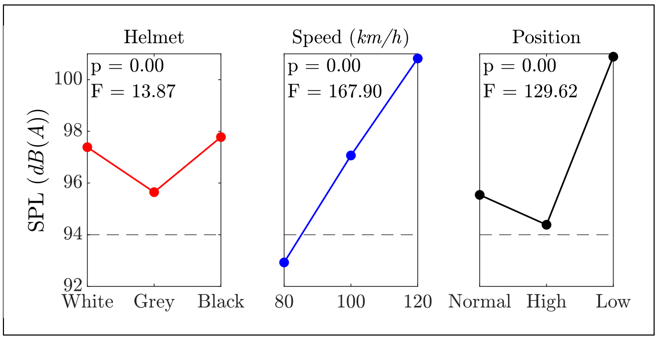

Figure 6: Main effects plot – *overall SPL*

- The variable *speed* is more dominant on the output response. The overall SPL increases by about 4 $dB(A)$ per 20 km/h increase in *speed*. The p-values corresponding to all the predictor variables being less than α signifies that all the factors significantly influences the output response.

- From the F-values, it can be analyzed that the variable *speed* is the most critical contributor to the overall noise recorded under the motorcycle helmet.

Subjective jury test

Subjective assessments were conducted as jury tests to factor in the cognition that takes place in the human mind. To gauge in the various parameters and to diversify the statistical population, 30 distinct jurors were heterogeneously chosen from across various age groups, multiple ethnic backgrounds with a mixed knowledge about riding a motorcycle and were asked to subjectively assess the audio files on different semantic differential scales namely "*Quiet ≠ Loud*", "*Soft ≠ Sharp*", and "*Smooth ≠ Rough*" to correlate them with the different computed psychoacoustic metrics.

Data correlation

Loudness

Inferring from the results of the regression analysis for the metric *loudness* as depicted in figures 7 and 8,

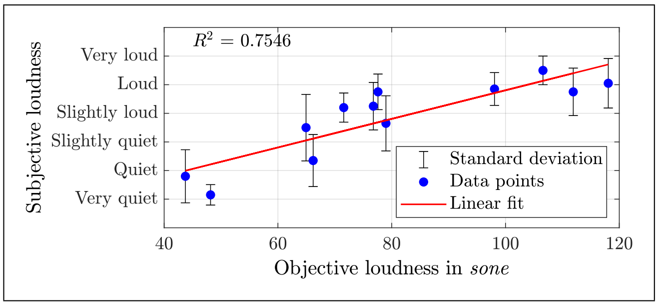

Figure 7: Objective and subjective *loudness* correlation

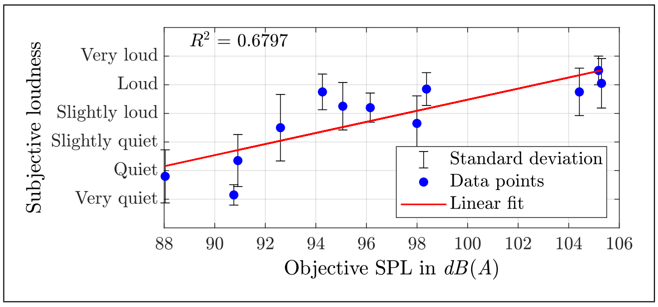

Figure 8: Objective *SPL* and subjective *loudness* correlation

- From the results of the regression analysis, there exists a good 75.46% and 67.97% correlation between the objective quantification of loudness measured in *sone*, the overall SPL measured in $dB(A)$ and the subjective perception of loudness obtained through the jury tests respectively.

- As the aspects of the overall SPL matches with loudness rather than any other psychoacoustic metric, loudness can be considered as one of the critical parameters in determining the aggregate resultant psychoacoustic perception of the given noise.

- The higher R^2 values for the correlation signifies that it is a main contributor and has an influencing factor on the subjective impression of noise than any other metric with the deviation in the subjective data be explained as the result of the sound perception by a heterogeneous population as it is difficult to obtain a less variance because of human cognizance.

Sharpness

Inferring from the results of the regression analysis for the metric *sharpness* as depicted in figure 9,

- At 85.80% there is a notable correlation between the sharpness quantified objectively and the impression of sharpness obtained from the subjective jury test.

- The higher correlation value, $R^2 = 0.8580$ was characterized by the data points being located closer to the regression line and in the appropriate perception of the audio files by the jurors in the subjective jury test.

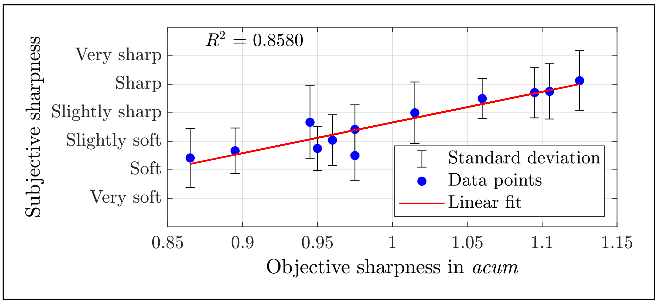

Figure 9: Objective and subjective *sharpness* correlation

Roughness

Inferring from the results of the regression analysis for the metric *roughness* as depicted in figure 10,

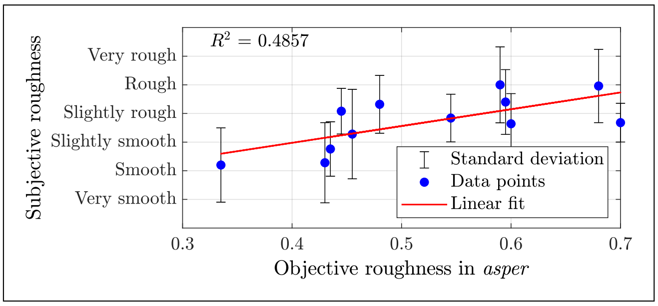

Figure 10: Objective and subjective *roughness* correlation

- A significantly lower R^2 value of 0.4857 depicts that despite a higher variance arising as a result of a mixed perception of the audio files by the statistical population, the data was still characterized by a significant linear regression line.

- The trend of the regression line indicates that the predictor variables still provided considerable information about the response variables even though the data points were located farther away from the regression line.

- The higher variances as noted in some data points corresponding to the subjective analysis signifies that human responses are often difficult to model, as the subjective evaluation was done by several respondents from a diverse background with mixed prior knowledge about riding a motorcycle.

Articulation Index

Inferring from the results of the regression analysis for *articulation index*, a measure of quietness and subjective loudness as illustrated in figure 11,

- Articulation index correlates well with the subjective impression of loudness with a correlation value, $R^2 = 0.6878$. Figure 11 indicates that louder noises are characterized by a low articulation index and quieter noises have a higher articulation index.

- The trend in the regression line emphasizes that the psychoacoustic metric articulation index is a measure of the quietness of noise. Although the direction of the regression line is opposite to those observed for the other metrics, there exists an adequate interrelationship within the variables nonetheless.

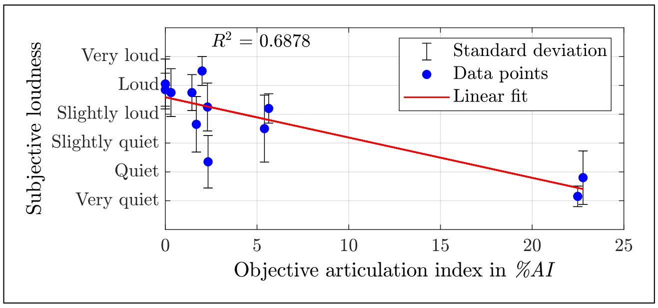

Figure 11: Objective *articulation index* and subjective *loudness* correlation

- The poorer values observed for the data points bolsters the actuality that unlike the volume of research going on to improve the interior noise quality of the passenger cars, improving the acoustic comfort for the motorcyclists remain a less researched domain.

Discussions

- Analyzing from the several available statistical tools, the contributions of the three different independent variables – *helmets*, *riding positions*, and *vehicle speeds* remain statistically significant.

- There was a considerable difference in the output by varying between the three different predictor variables. Since all the independent variables were statistically significant and contributed to the overall psychoacoustic characteristics of the noise, the assumed null hypothesis was rejected and the alternate hypothesis was adopted.

- Observing the overall SPL, from the general linear model of all the three predictor variables, the F-values of *speed* and *position* are higher than that of the *helmet*, which represents that *speed* and *position* contributes much to the overall SPL than *helmets*.

- As the characteristics of the overall SPL matches with loudness rather than with any other metric, *loudness* is a critical parameter in perceiving the overall psychoacoustic character of the given noise.

- It is interesting to note that a change in the *riding position* from *High* and *Normal* to *Low* contributes to a much louder and rougher noise with a high SPL value. As the character of the sound is influenced by the *riding position*, it can be understood as the influence of entering the slipstream and the turbulent wake region of the vehicle windshield at high speeds.

References

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