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COMPARISON BETWEEN SUBJECTIVE EVALUATION AND PSYCHOACOUSTIC PARAMETERS FOR CAR STEERING WHEEL RATTLE NOISE ASSESSMENT

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Abstract
Rattle noise is one of the main concerns of automotive manufacturers regarding final product quality. With the engine noise reduction obtained in electric cars rattle noise becomes even more significant. Steering wheels are one of the car components prone to produce rattle noise. Current methods used in the industry for sound quality assessment are based mainly on subjective evaluation. This evaluation is subject to variability, particularly for non-trained technical staff, due both to differences occurring among evaluators, as well as variations for one single evaluator when rating the same noise in different periods of time. Hence, an assessment based on objective parameters would be desirable to provide more consistent results. In this work, noise measurements have been carried out in the Centro Tecnológico de Automoción de Galicia (CTAG) semi-anechoic chamber using different steering wheels exposed to random vibration profiles approximating the real car conditions. The subjective evaluation carried out from a trained subject is compared with the psychoacoustic parameters (statistical loudness, statistical sharpness and roughness) computed from sound pressure measurements. The results show that only the statistical loudness provides a good correlation with the subjective tests but limitations in its application are found that suggest that further research must be done in order to obtain a robust objective evaluation method for rattle noise.

Keywords: automotive, rattle, noise, steering wheel, vibration.

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1 Introduction

During the last years the noise and vibration produced by machines have been extensively studied as they have direct impact on the health of people exposed to them. Noise is also related to the product quality perceived by a user. Unwanted noises may decrease the customer satisfaction after buying a commercial product (electrical appliance, cars, etc) and damage the brand image. Particularly in the automotive industry some surveys have shown that the appearance of unwanted noise during the first three months after the car purchase is the third main factor considered by the customers to assess the product quality [1]. The main noise sources in a car are the rolling noise produced by the tyre-road interaction, engine noise and wind noise, this being significant for car speeds above around 120 km/h. The vibration generated by these mechanisms is transmitted to elements placed inside the car cabin such as seats, steering wheel, and dashboard, among others, producing a relative displacement between their different components. Squeak and Rattle noise (S&R) can be generated when an intermittent contact between two adjacent components occurs. S&R noise is one of the main reasons for the customer complains related to unwanted noise and it is directly related to a decrease of the product quality perception. Some factors such as a high input vibration (i.e. bumps or low-quality roads), looseness due to vehicle aging, etc. can increase the level of S&R noise or trigger noises that were not perceived in normal conditions. Also a reduction of noises of other type inside the cabin, such as the airborne noise from the car engine, can make noticeable S&R noises that before were masked. For this reason, with the reduction of engine noise achieved in electric cars the significance of car interior S&R noise is prone to increase.

S&R noise is a well-known problem in the automotive industry. Most of the car manufacturers have developed internal methodologies and procedures to assess it. These can be divided into two groups: those based in subjective evaluation, and those based on noise measurements. The subjective evaluation is normally performed by one or more specialists that classify the different noises detected according to an assessment scale. Even though these internal procedures have their own acceptance criteria and particularities most of them are based on the standard SAE J1060 [2]. This method has the advantage of being performed “in situ” by trained subjects that are able to detect, localise, separate and evaluate different noises that appear simultaneously. Some drawbacks of subjective evaluation are: 1) it shows variability, as it depends on a subject assessment, which reference level must be revised periodically in order to keep it constant in time. 2) Variability on the assessment can be also found when the subjective evaluation if performed by different evaluators, mainly when these are no trained. 3) Difficulty about describing detected noises to other people involved in the product development.

The methods based on noise measurements normally use parameters such as A-weighted sound pressure level (AOSPL) or loudness, which tries to account for some of the subjective features of the human hearing. The measured values are compared with reference levels that allow establishing an acceptance/rejection criterion. This provides an objective criterion for the noise assessment. However, by using this method a global value for the noise assessment can be obtained but the different noises cannot be either separated or localized. In large components made of several pieces, some of the noises can be partially masked so they cannot be detected by means of noise measurements using a single microphone even though they are noticeable for a subject. Additionally, parameters such as AOSPL and loudness do not account for all the subjective features that can play a role in the noise perception.

Some examples are found in the literature about the development of models for the detection and evaluation of unwanted noise inside a car. Tran et al. [3] developed a method for the detection and separation of different noise sources but they did not consider the psychoacoustic features of the human hearing. Brines et al. [4] used the loudness percentiles for the evaluation of noises recorded in vehicle while driving in test tracks and in laboratory by using an electrodynamic shaker to apply a vibration profile. However, they did not separate the different noise sources present during the tests. It was also found that the use of loudness for noise evaluation presents some limitations for low signal-to-noise ratio. Recently, Chandrika and Kim [5] developed a method for noise detection and evaluation. The results obtained using this method show good agreement with those from jury tests.

However, this method does not include noise separation as it was applied for only one noise source. A sound database was used which was not representative of the real noises present inside a car cabin.

Binaural microphones installed in headsets or dummy heads are typically used for subjective evaluation as these measurements include information about the time delay of the signal recorded by the two microphones and the filter effect of the human head and torso [6]. This makes feasible to localize and separate different sound sources that appear simultaneously. Other techniques for noise source localization, particularly used for noise map generation, are those based on microphone arrays such as beamforming techniques and acoustic holography.

Once the different noise sources have been localised using any of the techniques mentioned above, to evaluate and classify them it is necessary to apply psychoacoustic models approximating the features of the human perception. Some examples are the models developed by Zwicker and Fastl [7] and Moore and Glasberg [8]. These are based on different parameters (e.g. loudness) using psychoacoustic principles for their calculation.

The authors of the present study aim to develop a method for the objective evaluation of S&R noise originating in car components, such as a steering wheel, so that it allows for noise source detection, separation and evaluation. As a first step for the model development, the presented study shows the comparison between the results obtained by subjective evaluation and by the measurement of established psychoacoustic parameters (loudness, sharpness and roughness) to assess the S&R noise from steering wheels exposed to random vibrations. The experiments have been carried out in the Centro Tecnológico de Automoción de Galicia (CTAG) semi-anechoic chamber using an electrodynamic shaker for the vibration excitation and a jig to approximate the real mounting conditions in a car.

Section 2 describes the experimental set-up used and the methodology followed to measure and analyse the S&R noise from the steering wheels, Section 3 includes an analysis of the measured noise from the steering wheels. A comparison between the subjective evaluation. The psychoacoustic parameters loudness, sharpness and roughness is given in Section 4. Conclusions are presented in Section 5.

2 Experimental set-up and methodology

The test presented in this work was carried out according to the General Motor (GM) General Specification GMW 14096 [9]. The noise measurements and subjective evaluation were performed in the Centro Tecnólogico de Automoción de Galicia (CTAG) semi-anechoic chamber in order to minimise the sound reflections from the chamber walls. An electrodynamic shaker was used to apply the vibration profiles to the test samples. This was installed inside an acoustic enclosure designed to isolate the chamber interior from the noise radiated by the shaker, this allowing the reduction of the background noise during the tests. Figure 1 shows the facility and the electrodynamic shaker used during the tests.

Figure 1 – Facility used during the test: An electrodynamic shaker was used for the vibration excitation. This was installed inside an acoustic enclosure to reduce the noise from the shaker inside the chamber. The measurements were carried out inside the CTAG anechoic chamber.

The test samples were ten driver steering wheels, each of them equipped with an airbag module. The floating configuration of the modules make them prone to generate S&R noise when subjected to vibration. Since the aged components are more likely to generate S&R noise, the samples were subjected to a vibration ageing prior to the analysis. The steering wheel was attached to the shaker by means of a jig that represents the real position of the steering wheel in a car. For simplicity, the steering column is not used in the test. An accelerometer was placed at the jig base in order to control the applied vibration signal. A free-field omnidirectional microphone was placed at 15 cm from the centre of the steering wheel, as shown in Figure 2.

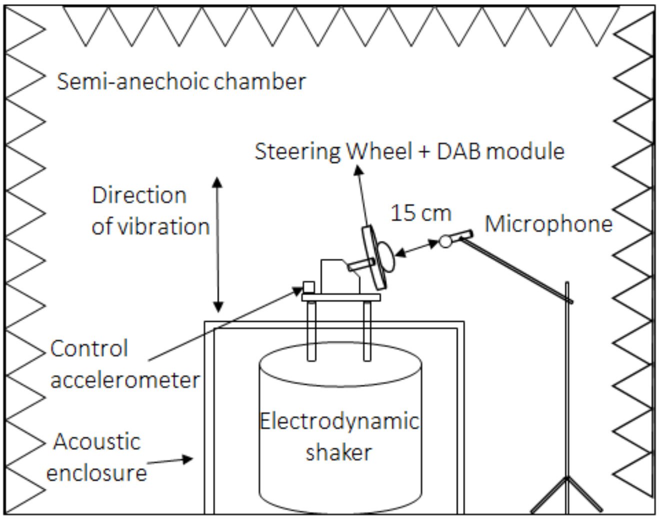

Figure 2 – Test set-up used for the application of the vibration profile in the Z direction.

Each set of steering wheel (SW) plus driver airbag (DAB) module was excited in three directions (vertical, longitudinal and lateral) using random noise. A vertical shaker was used and the samples were rotated for each direction of excitation. The vibration profiles used for the three directions of excitation are shown in Figure 3.

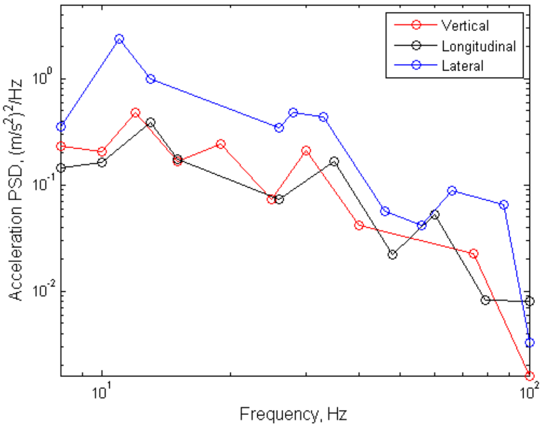

Figure 3 – Random vibration profiles used for exciting the steering wheels during the noise evaluation. Profiles according to the General Specification GMW 14096 [9].

The noise from the steering wheel was recorded during ten seconds with a sampling frequency of 44100 kHz. The subjective parameters were calculated in accordance to the standard ISO 532 [10], with a frequency range up to 20 kHz using a 4th order high-pass Butterworth filter with cut-off frequency of 300 Hz.

The psychoacoustic parameters statistical loudness, statistical sharpness and roughness were calculated according to the methods given in [7]. For the statistical loudness and sharpness the 10% percentile is used. These results are compared with the subjective evaluation, which was carried out by a trained subject at the same time as the noise was recorded. A first correlation analysis is done based on the calculation of the correlation coefficient and the corresponding p-value, so that the statistical significance of the result is accounted for. This analysis allows the evaluation of the linear relationship between the subjective rating and the computed parameter. When the correlation coefficient is above 0.75, a linear polynomial curve fitting using a linear function is applied to the results.

The subjective noise evaluation was carried out by a trained subject according to the scale shown in Table 1. The evaluation was made at a distance from the steering wheel equivalent to that from the steering wheel and the driver head when driving a car.

Table 1 – Scale used for the subjective evaluation.

	Scale				
	L0	**L1**	**L2**	**L3**	**L4**
Noise level	No noise	Slight	Medium	High	Very high
Noise impact	*	Noticeable by a trained subject	Noticeable by any customer. Some of them will claim	Noticeable by any customer. Most of them will claim	Noticeable by any customer. Immediate claim

3 Analysis of the noise radiated by the steering wheels

Most of the test samples were found to radiate noise. In all cases this was described as rattle noise by the trained subject who carried out the subjective evaluation. The perceived rattle noise was mainly produced by the intermittent contact between the module and the case at the horn area. In some of the test samples rattle noise was also detected at the button pad. Table 2 shows a summary of the results of the subjective evaluation carried out with ten steering wheel (SW) plus driver airbag module (DAB) assemblies for three different directions of vibration.

Table 2 – Results from the subjective evaluation using ten steering wheel plus DAB module assemblies excited in three different directions.

	Scale				
	L0	L1	L2	L3	L4
Rated samples	8	7	11	4	0

Figure 4 shows the time history of the A-weighted sound pressure level (SPL) produced by three different samples with different subjective evaluation. The background noise is also included, this being the noise measured when the steering wheel was removed but the rest of the components of the experimental set-up were maintained. It can be seen that SPL varies with time for all the samples showing that the rattle noise is non-stationary. For the test sample rated as L3 the difference between the maximum and minimum measured level is of around 15 dB(A). This difference is of around 10 dB(A) for the test sample rated as L2 and of around 7 dB(A) for the test sample rated as L1. In terms of the amplitude of the overall sound pressure level (OASPL) the sample rated as L3 is significantly louder than the other two samples with OASPL = 69.2 dB(A), while the sample rated as L2 (OASPL = 57.2 dB(A)) is slightly louder than that rated as L1 (OASPL = 53.7 dB(A)). The background noise was nearly constant with time.

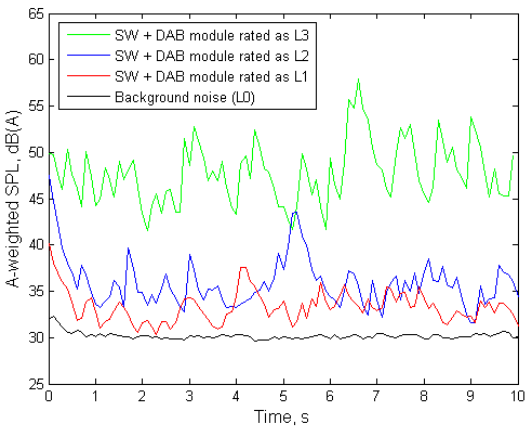

Figure 4 – A-weighted sound pressure level versus time measured for three different steering wheel plus DAB module assemblies producing rattle noise evaluated with different ratios.

Figure 5 shows the spectrogram obtained for one of the sample rated as L3 included also in Figure 4. The horizontal lines in pink colour show the time instants when the rattle noise was produced. These appear repeatedly along the time. These lines cover the whole frequency range showing that the measured rattle noise is broadband. No tonality is found in the results shown in Figure 5.

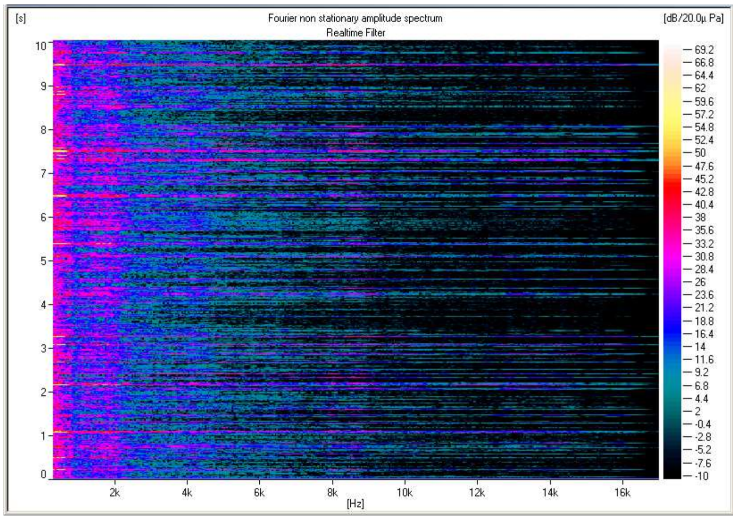

Figure 5 – Spectrogram measured for one of the steering wheel plus DAB module assembly that generated rattle noise rated as L3.

4 Comparison between subjective evaluation and psychoacoustic parameters

The results from the computed psychoacoustic parameters are compared with the subjective evaluation performed by a trained subject. The correlation coefficient is calculated to evaluate if these results are linearly correlated. If so (correlation coefficient higher than 0.75), a polynomial curve fitting is applied to the data to approximate this linear relationship.

4.1 Statistical loudness (N10)

Figure 6 shows the values of the 10% percentile of the statistical loudness (N10) computed for the different tests samples. The results are compared to the subjective evaluation given by a trained evaluator so the computed loudness for each sample can be related to one of the categories of the scale used for the subjective evaluation.

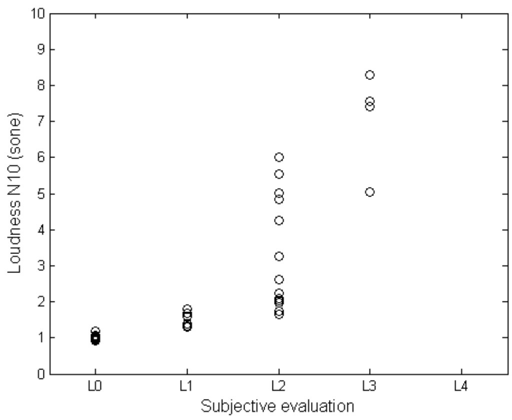

Figure 6 – Comparison between the measured statistical loudness (N10) and the subjective evaluation for the different tests samples.

Loudness between 1.29 and 1.80 were measured for the test samples rated as L1, for tests samples rated as L2 the values of loudness are in the range between 1.65 and 5.51 while for the ratio L3 the loudness is between 5.00 and 8.12. None of the samples was rated as L4. For the samples that were rated as L0 (no noisy) values of Loudness between 0.91 and 1.18 were measured. Different ranges of loudness can be defined for the classification of the test samples in the different subjective evaluation categories. However, both samples rated as L2 and L3 lay in the range between 1.65 and 1.80, making not possible to classify them accurately. This also occurs for one of the samples rated as L3 with a loudness of 5, which is within the loudness range of the samples rated as L2.

The calculation of the correlation coefficient provides a result of 0.79, with a p-value under 0.01, which confirms the existence of a correlation between the indicated subjective rating scale and the N10 loudness. A further analysis is performed by applying a polynomial curve fitting using a linear function. For such purpose, numerical values are given to the different scales so that L1 = 1, L2 = 2 and L3 = 3.
The averaged values of the statistical loudness, N10, were considered, resulting in equation 1.

$$N10 = 2.75 \times L_i - 4.31 \tag{1}$$

Figure 7 shows the results of the curve fitting obtained by using the equation 1.

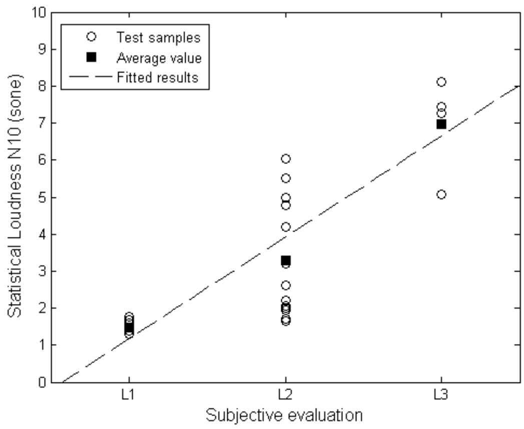

Figure 7 – Average N10 vs. subjective evaluation fitted using a linear function.

4.2 Statistical sharpness (N10)

The 10% percentile of the statistical sharpness (N10) is compared with the subjective evaluation obtained from a trained subject, as shown in Figure 8.

From the results it can be seen that the sharpness measured for the samples rated as L0 and L1 are in the same range. The sharpness measured for the samples rated as L2 are higher than that measured for samples rated as L0 and L1, with values between 1 and 3. Sharpness from 2 and 3 were measured for the samples rated as L3.

High-frequency noises produced a sensation dominated by sharpness [7]. Figure 5 shows that the measured rattle noise is broadband and the energy at high frequencies is not significant. From these results it can be inferred that the sharpness is not suitable for assessing the steering wheel rattle noise.

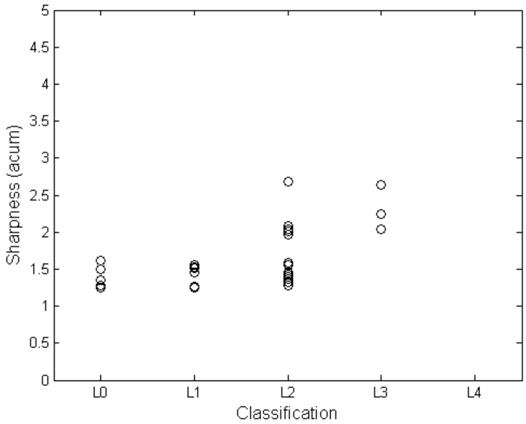

Figure 8 – Comparison between the measured statistical sharpness (N10) and the subjective evaluation for the different tests samples.

In this case the correlation coefficient of 0.66 is obtained, with a p-value under 0.01. A fair correlation between the subjective rating scale and the N10 sharpness but this is lower than the defined threshold (0.75).

4.3 Roughness

The results from the subjective evaluation are compared in Figure 9 with the measured roughness. This subjective parameter is related with the modulation of the noise both in amplitude and frequency [7].

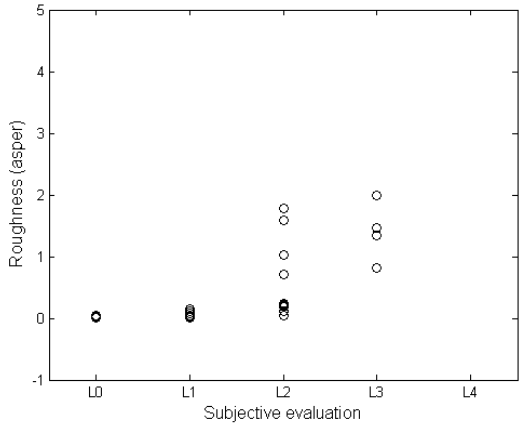

Figure 9 – Comparison between the subjective ration and the measured roughness.

The results in Figure 9 show that the measured roughness does not allow defining a range of values to classify the test samples in different categories. The range of values obtained for samples rated as L0 and L1 are similar. The variability of the roughness for samples rated as L2 is high and the values of roughness for the some of the test samples rated as L2 are similar to those rated as L3. A correlation coefficient of 0.68 was obtained in this case.

5 Conclusions

The noise radiated by steering wheels when they are subject to a random vibration was measured in a semi-anechoic chamber using and electrodynamic shaker and a subjective evaluation was performed by a trained subject. In all cases the noise was described as rattle. This was found to be non-stationary and broadband, repeated over the time and with short duration. The psychoacoustic parameters roughness, 10% percentile of the statistical loudness and sharpness computed from the noise measurements were compared with the results from the subjective evaluation. The roughness and statistical sharpness provided poor results in terms of usage as indicators for subjective evaluation. The statistical roughness provides better results and it makes possible to distinguish different range of values for each category of subjective evaluation. The correlation coefficient obtained between the statistical loudness and the subjective evaluation shows a linear relationship between them. However, some of the samples rated as L1 and L2 have similar values of loudness, this also occurring for some samples rated as L2 and L3. This shows a limitation on the use of this parameter at the boundaries between two different categories.

Future work would be to perform subjective evaluation using a large number of samples and evaluators to obtain more representative results and on assessing the variability on the subjective evaluation carried out by different trained and untrained. Further research is also planned on finding the attributes that better defines the rattle noise from steering wheels by studying frequency and time domain parameters and accounting for the influence of the background noise.

References

[1] Nolan, S.A.; Sammut J.P. Automotive squeak and rattle prevention, *Proc. of the Eighth Int. Conf. on Vehicle Structural Mechanics and CAE*, Traverse City, MI, USA, April 1992, pp 355–363.

[2] SAE J1060: Subjective rating scale for evaluation of noise and ride comfort characteristics related to motor vehicle tires. 2000.

[3] Tran, V.; Lei, S. F. ; Hsueh, K. Application of adaptive impulsive noise separation to automotive squeak and rattle detection/quantification, *The Journal of the Acoustical Society of America*, Vol 106, 1999, p 2249.

[4] Brines, R. S.; Weiss, L. G.; Peterson, E. L. The application of direct body excitation toward developing a full vehicle objective squeak and rattle metric, *SAE Transactions*, Vol 110, 2001, pp 1944–1948.

[5] Chandrika, U. K.; Kim J. H. Development of an algorithm for automatic detection and rating of squeak and rattle events, *Journal of Sound and Vibration* Vol 329, 2010, pp 4567–4577.

[6] Blauert, J. *Spatial hearing: the psychophysics of human sound localization.* MIT Press, Cambridge, Massachusetts, 1983.

[7] Zwicker, E.; Fastl, H. *Psychoacoustics: Facts and Models.* Springer-Verlag, NewYorkInc, 2007.

[8] Moore, B. C. J., Glasberg, B. R. A model of loudness perception applied to cochlear hearing loss. *Auditory Neurosci.* Vol 3, 1997, pp 289-311.

[9] (GM) General Specification GMW 14096: *Steering Wheel Assembly - Verification Requirements section 3.2.1.2.7 Noise Test: Subsystem-Level Validation.* 2012.

[10] ISO 532:1975: Acoustics – *Method for calculating loudness level.* 1975.