inter.noise 2000
The 29th International Congress and Exhibition on Noise Control Engineering
27-30 August 2000, Nice, FRANCE

I-INCE Classification: 0.0

INSTRUMENTAL DESCRIPTION WITHIN THE SOUND QUALITY ENGINEERING PROCESS

R. Heinrichs

Ford Werke AG, Acoustic Centre Cologne, Spessartstr., D-50725, Cologne, Germany

Tel.: +49 221 903 4859 / Fax: +49 221 903 5145 / Email: rheinri1@ford.com

Keywords:
SOUND QUALITY, GEAR RATTLE, METRIC, POWERTRAIN

ABSTRACT
The application of an instrumental description for sound quality is becoming more and more important for the automotive industry. Generally one distinguishes between annoying noise contributions which should be avoided and specific sound characters that convey particular personalities by means of designed sounds. Hence having reliable instrumental descriptions is mandatory for a variety of very different sound sensations. Since the sound quality engineering process is rather complicated to deal with, this paper is aiming to outline its most important aspects. In that respect the very specific human perception which differs from case to case for the various sound sensations has to be taken in to account appropriately. Furthermore a suitable signal theoretical metric also needs to reflect the most important perception aspects. On two examples this paper is going to show the complexity of reliable sound quality metrics.

1 - INTRODUCTION
Meanwhile people of modern industrial society are used to a huge variety of different elements of comfort. Within the automotive industry elements of comfort such as navigation systems, hands free phones, various electrical assistance systems, as well as non-operative elements such as the vibration comfort and acoustics, are implemented in a mandatory fashion. Fig. 1 shows a first step to sort the acoustical events of a vehicle.

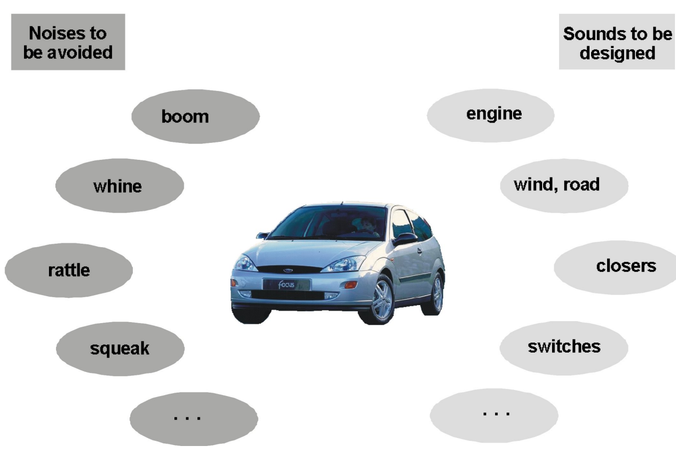

Figure 1: Auditory events of a vehicle sorted according to wanted and unwanted sounds / noises.

In this scenario the wanted sounds are to be designed in a specific manner in order to enhance the perceived vehicle sound quality aiming to improve the overall impression. Moreover specific sound designs may set a particular acoustic image that needs to fit in the specific brand image perfectly. Therefore the sound design must convey the right acoustical information. Talking about unwanted noises one has to sort out the most important ones first. These noises can either become annoying over time or they deteriorate the sound quality impression of the vehicle. As a result of this the overall impression of the vehicle is affected negatively as well. In this respect the question how to describe the perceived sound quality with objective parameters becomes essential. Simply applying the well known psycho-acoustical parameters such as loudness, sharpness, roughness, etc. often does not satisfy very much. These parameters, which were developed on a basis of rather artificial sounds, namely sinusoidal noise, white noise, etc. still have problems describing rather complex sounds of the real world. Besides this, the link to the physics is rather bad due to its non-linear character. Furthermore these parameters does not take non-sensorial aspects such as image, trend, fashion, aesthetics, degree of attention, socio-demographic parameters and so on into account. At the time being one must state that general sound quality metrics do not seem to exist. Based on many examples it can be shown that each auditory event has to be considered very specifically if a reliable sound quality metric is to be developed.

2 - SOUND QUALITY METRIC DEVELOPMENT

It is not the intention of this paper to show the general sound quality engineering process in very much detail. However, Fig. 2 shows the most important aspects very roughly.

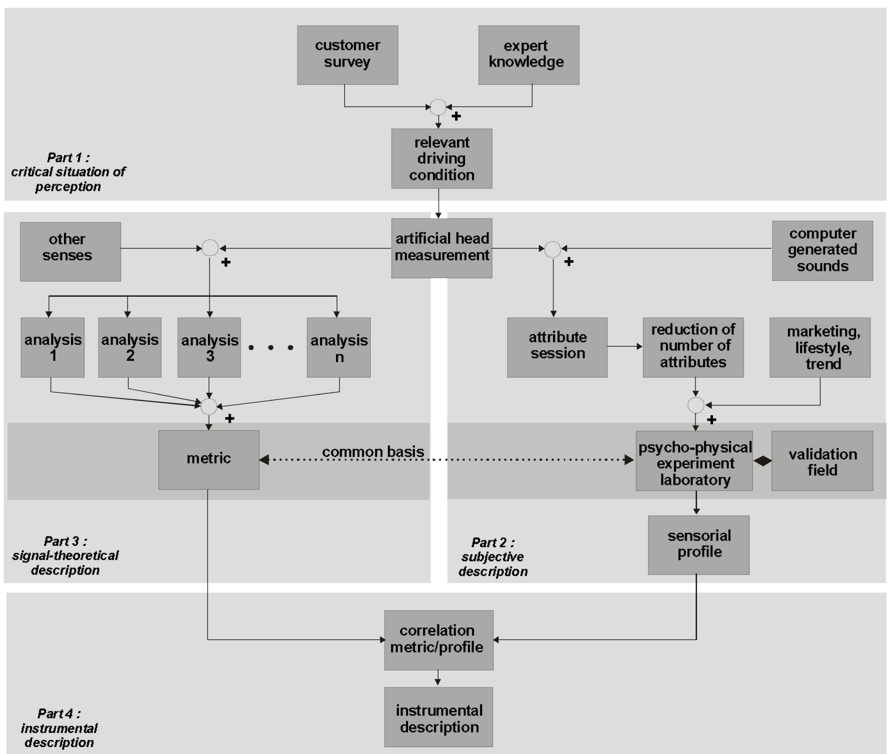

Figure 2: Sound quality engineering process and its most important elements.

First of all the process kicks off with a customer survey and gathering expert knowledge which determines the driving situation to be considered. Next, various measurements, e.g. artificial head and acceleration measurements take place in order to cover all necessary sensorial parameters. On the other side, the sound data basis is completed by adding computer synthesised sounds aiming to perform suitable psycho-physical experiments. Important parameters for these experiments are appropriate verbal descriptors (adjectives), instructions such as information about the situation of perception, marketing and lifestyle intentions as well as information about the subjects involved in the experiment. Finally, the customer wants need to be translated into objective metrics which enable the engineer to design the acoustics exactly according to the wanted profile.

3 - SOUND QUALITY APPLICATION FOR GEAR RATTLE

3.1 - Sound quality engineering process: part 1 (critical driving situation)

According to customer complains, the Stop-and-Go driving situation of a traffic jam is the most annoying situation regarding gear rattle. In this scenario the vehicle is being accelerated just by means of applying and releasing the clutch pedal in order to follow the other vehicles of the traffic jam. With applying the clutch pedal in segment 2 the perceived sound changes significantly. Whereas the engine sound character and all other sounds such as road, wind and environmental noises stay constant the rattle contribution of the transmission changes dramatically if the transmission is a rattle sensitive one. This ties in nicely with the expert experience that this situation can be seen as a representative situation for describing the gear rattle sensitivity of a vehicle. Thus this situation was chosen to derive a metric which allows the engineer to define a customer acceptance threshold. In Fig. 3 the Stop-and-Go situation is shown with its measured parameters "Sound Pressure Level" (SPL) $p_1(k)$ and $p_2(k)$ on co-drivers ears.

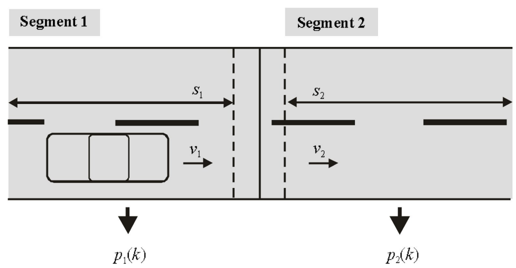

Figure 3: Critical stop-and-go driving situation.

3.2 - Sound quality engineering process: part 2 (subjective description)

The stimuli to be evaluated in the experiment consists of two parts, each about 3 seconds long. Within the first part of the stimuli the sound measured in segment 1 is going to be presented. The second part of the stimuli is the sound measured in segment 2. First of all an attribute session was performed. The first step of the attribute session with 10 experts led to 90 appropriate adjectives intending to set up a verbal description of the gear rattle noise character for different diesel vehicles. Within the second step of the attribute session all adjectives were grouped according to their similarity. In the end 12 different subgroups have been defined. A psycho-acoustical experiment using Semantic Differential method was conducted with 10 different diesel vehicles and 15 subjects based on a 7-point bipolar scale. The sensorial profiles for the 10 diesel vehicles are depicted in Fig. 4. The profiles orientated around the horizontal axis indicates diesel vehicles with very good gear rattle behaviours whereas profiles around the vertical axis indicates gear rattle sensitive ones. A principal component analysis for the mean average values of a psycho-acoustical experiment led to just one significant factor with an eigenvalue > 10. All other factors had eigenvalues < 1. The variance of the different factors are shown in Fig. 5. Interesting to see is that just one factor alone counts for about 88 % of the variance. This dominant factor can be interpreted as 'quality of the gear rattle behaviour' (good − bad) from the considered diesel vehicles. This result is rather surprising since various papers outline the general importance of the attribute 'timbre' (bright − dark).

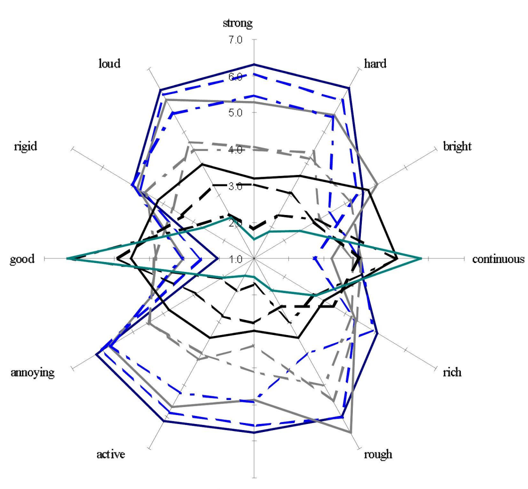

Figure 4: Sensorial profile for gear rattle.

Obviously gear rattle is such a robust and negative noise that the attribute 'timbre' does not affect the gear rattle impression of a diesel vehicle. The fact that only one factor describes the gear rattle perception

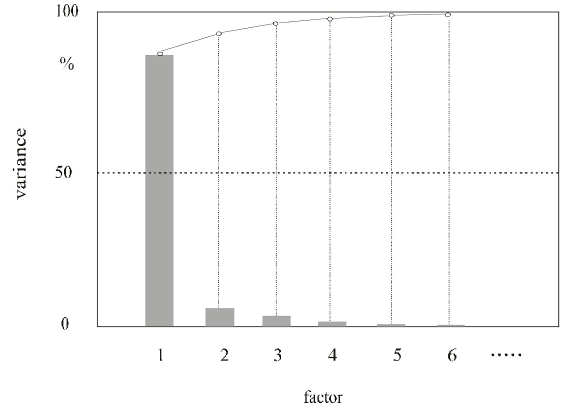

Figure 5: Variance of different factors.

is very beneficial for the instrumental description, since just one attribute needs to be correlated with the metric to be developed. In order to reflect the whole market situation regarding gear rattle the amount of diesel vehicles was next expanded to 18. Fig. 6 shows the mean average and standard deviation for the attribute 'quality of the gear rattle behaviour' (7 for very good and 1 for very bad) from a psycho-acoustical experiment conducted with the 18 vehicles.

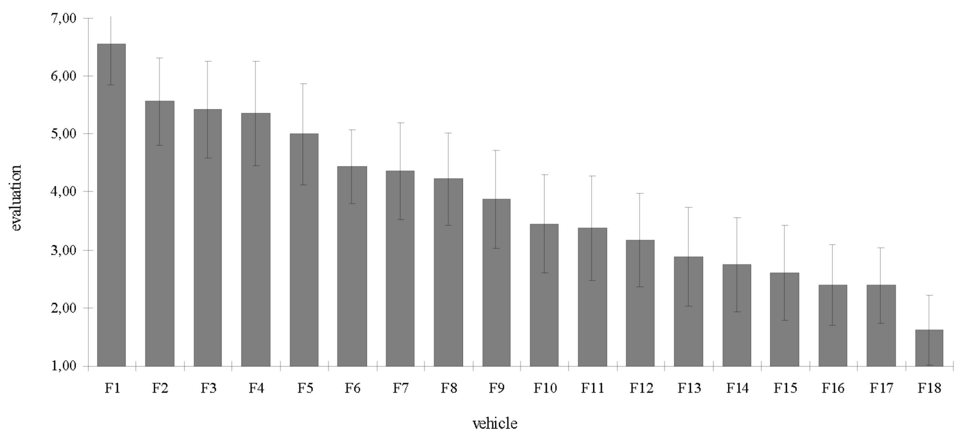

Figure 6: Mean average and standard deviation for 18 different diesel vehicles.

3.3 - Sound quality engineering process: part 3 (signal-theoretical description)

For the gear rattle perception the auditory sense is the most important one. Thus a simple artificial head measurements covers all sensorial aspects for the metric development. In order to reflect the human perception within the metric the measured sounds of segment 1 and 2 need to be taken for the metric development. Since the acoustical difference of the nearly stationary sounds measured in segment 1 and 2 determines the gear rattle perception first of all the Spectrogram according to Equation 1 was calculated by means of the Discrete-Fourier-Transform (DFT) for both signals.

$$P_{1,2}\left(n,l\right)\Big|_{l=0}^{L} = \sum_{k=lN(1-O)}^{lN(1-O)+(N-1)} p_{1,2}\left(k\right) \cdot w\left(\left(k - lN\left(1-O\right) \cdot e^{-j\frac{2\pi kn}{N}}\right|_{l=0}^{L} \qquad (1)$$

In Equation 1 a moving Hann-Window $w(k)$ with an Overlap of about $O = 0{,}5$ was applied. The mean square magnitude spectrum (Periodogram) of segment 1 and 2 signal was calculated by averaging over all spectral lines n of the subsequent spectra. Next both Periodograms were subtracted from each other frequency line for frequency line and named Diff.-Log.-Magnitude Spectrum (DLS). Simply averaging over all frequency lines of $DLS(n)$ in the gear rattle relevant frequency range led to a reliable metric based on pure spectral data. This way the Average-Difference-Level (ADL) [2] is given by Equation 2.

$$ADL = \frac{1}{n_0 - n_u} \sum_{n_u}^{n_0} DLS(n) = \frac{1}{n_0 - n_u} \sum_{n_u}^{n_0} \left[10\lg \frac{\sum_{l=0}^{L} |P_1(n,l)|^2}{\sum_{l=0}^{L} |P_2(n,l)|^2} \right] \text{ dB} \quad (2)$$

In order to take the time structure of the signals $p_1(k)$ and $p_2(k)$ into account a narrow band modulation frequency analysis was additionally conducted. Since the spectrogram according to Equation 1 was calculated of subsequent spectra, each frequency line n of the different time series also represents the behaviour of the envelope for the corresponding carrier frequency. The modulation spectrum [1] can be calculated by means of applying a DFT to the time series of the magnitude $|P_{1,2}(n,l)|$ for each frequency line n according to Equation 3.

$$P_{m1,2}(n,m)\big|_{n=0}^{N} = \sum_{l=0}^{M-1} |P_{1,2}(n,l)| \cdot w(l) \cdot e^{-j\frac{2\pi lm}{M}} \Bigg|_{n=0}^{N} \quad (3)$$

Referred to the value at $P_{m1,2}(n{,}0)$ the modulation index was defined as $P_{mi1,2}(n{,}m)$. Similar to the spectral metric now the average modulation index $P_{mi1,2}(m)$ was calculated within a limited frequency range n_u to n_0. It can be shown that just for the half engine orders and their multiples (Index *mo*) significant modulations occur. Because just these modulations need to be taken into account the difference modulation index is given by Equation 4

$$\Delta \overline{P}_{mi}^{mo}(m_{mo}) = \overline{P}_{mi,1}^{mo}(m_{mo}) - \overline{P}_{mi,2}^{mo}(m_{mo}) \quad (4)$$

Finally the Diesel-Rattle-Modulation-Index (*DRMI*) was defined as

$$DRMI = \Delta \bar{P}_{mi}^{mo}(m_2) - \sum_{mo=0,5;mo\neq 2}^{mo=4} \Delta \bar{P}_{mi}^{mo}(m_{mo}) \quad (5)$$

With *ADL* and *DRMI* now two signal-theoretical parameter capable of describing the diesel vehicle gear rattle behaviour are available for the instrumental description.

3.4 - Sound quality engineering process: part 4 (instrumental description)

Aiming to develop a robust instrumental description both sets of data need to be correlated in an suitable manner. For the gear rattle noise a polynomial fit according to Equation 6

$$V_X = a_X \cdot X^2 + b_X \cdot X + c_X \quad (6)$$

turned out to be appropriate for a spectral instrumental description as well as for an instrumental description based on time history data. Equation 6 predicts the gear rattle behaviour of the considered vehicle based on a 7-point scale where X is a substitute either for *ADL* or for *DRMI*. In the end a combination of V_{ADL} and V_{DRMI} according to Equation 7 leads to a robust signal-theoretical description that also reflects the most important evaluation aspects of the critical Stop-and-Go driving situation.

$$V_{combi} = 10 \cdot \lg \left[\frac{10^{V_{ADL}/10} + 10^{V_{DRMI}/10}}{2} \right] \quad (7)$$

A correlation of about $c_{\text{corr}} = 0{,}94$ could be achieved between the real evaluations of the 18 diesel vehicles (see Fig. 6) and the predicted evaluation V_{combi}. With that specific metric the engineer is now able to describe the gear rattle noise with an easily understandable parameter which also allows him understanding the physical background responsible for the noise.

4 - POWERTRAIN SOUND QUALITY COMPLEXITY

While gear rattle simply should be avoided completely (just one dominant factor) developing a particular sound character becomes much more complicated due to more then one dominant dimension to be considered. For a reliable description of the powertrain sound character dimensions such as 'powerfulness', 'pleasantness', 'fullness' and 'timbre' are expected to play an important role. Even more complicated the sound character also depends on the driving situation. Usually the customer prefers a quiet powertrain sound for travelling speed as opposed to acceleration with full load where the personality of the brand should be conveyed by means of the powertrain sound. This means also that the objective metric to be developed has to become much more complex. Important parameters for the objective metric are level, order balance dependent of the RPM, spectral distribution and so on. Hence applying correlation technique for the objective metric and the most important subjective dimensions is much more difficult to deal with. Lastly appropriate hardware has to be found and modified in order to realise the wanted sound character. For the small sports coupé Ford Puma for example the intake system was chosen as the most appropriate tuneable system.

5 - SUMMARY

It was stated that global sound quality metrics are often not able to describe the human perception to such an extent that reliable sound targets can be set. However, those metrics mostly can just be taken for a limited number of applications. In order to develop a more accurate metric both the psycho-acoustical experiment and the final objective metric need to reflect the actual sound situation in which the sound sensation occurs. For the gear rattle noise successful application of the sound quality engineering process was presented. For the power- train sound character development it was shown how complex this process can become.

REFERENCES

1. **Bodden, M., Heinrichs, R.**, Analysis of the time structure of gear rattle, In *Internoise 99, Fort Lauderdale Florida USA*, 1999

2. **Heinrichs, R., Bodden, M.**, Perceptual and instrumental description of the gear rattle phenomenon for diesel vehicles, In *6th International Congress on Sound and Vibration, Technical University of Denmark, Copenhagen*, 1999