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Practical experience with psychoacoustics in automotive engineering

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ABSTRACT

Over the last few decades the noise emission of passenger cars has been reduced considerably. Today the optimization of interior and exterior noise for a new car is more focused on the complex interaction of several sound components than on the sound pressure level. As a first important tool jury testing methods have been used to evaluate the auditive perception of recorded car sounds in the laboratory.

Subsequently the application of psychoacoustics received more attention. Some of the most common sensory measures will be presented by means of a few samples of noise studies on passenger cars. By using suitable measures psychoacoustics can help to identify and rate annoying noise components and can assist in setting targets for the final vehicle sound.

Once the basic psychoacoustic measures were elaborated it became possible to develop a "sound metric" which provides a holistic noise evaluation. Like a real car driver it considers a selected set of driving conditions and a corresponding set of acoustic and psychoacoustic measures. In a multi-step evaluation process all results are normalized, weighted and summed up to form a "sound index".

Keywords: Product Sound, Psychoacoustics, Sound Metric

1. INTRODUCTION

When talking about "vehicle acoustics" the acronym "NVH" (noise, vibration and harshness) is very common. All aspects of sound and vibration sources, structural dynamics and transfer paths are considered. - In this paper, however, we will focus on the acoustical viewpoints ("product sound").

Looking back in history all NVH-related work began with the reduction of the overall sound pressure level (SPL). In a step forward "disturbing noises" had to be identified and countermeasures had to be engineered. Lacking sophisticated sound rating measures it became customary to use binaural sound recording and playback equipment for jury testing (see chapter 2).

It took several years until the methods of computational psychoacoustics became more important for applications in the development and evaluation of product sounds (see chapter 3).

The most recent approach is to create a specific sound character for the product. This combines reducing unwanted noise components ("sound cleaning") and shaping spectral and temporal patterns for a desired sound character ("sound design"). To establish a sustainable process, a holistic sound metric has been setup which is intended to forecast the "overall sound quality" of a product as evaluated by a representative customer (see chapter 4).

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2. JURY TESTING

2.1 Preliminary Remarks

With the availability of digital audio in the early 1980s, it became feasible to perform auditive evaluations of binaural sound recordings to rate the effectiveness of NVH measures in the development process of a new car. So-called “jury testings” in sound labs have been introduced for many applications of optimizing product sound. Because of the high audio quality of today’s binaural recording and playback equipment, even the smallest differences between several modifications of a car can be made perceptible in a sound lab. - For an introduction to binaural sound recordings and related technologies, see Genuit and Sottek (1).

At the facility of the first author a sound lab is located in an acoustically insulated environment. The playback system consists of a “master” computer which controls the sound evaluation procedure at twelve connected “client terminals”. For details on such systems see Fiebig and Genuit (2). - In the following sections only a few of the possible testing modes are presented.

2.2 Semantic Differentials

To get a deeper insight into the perceptual properties of several products the method of the “Semantic Differential” (SD) is commonly used. By properly selecting items for the SD a lot of aspects of the product sound may be covered (see for an example at Maiberger et al. (3)):

- Items should preferably be real antonyms (e.g. “quiet <> loud”).
- Items should fit the properties of the selected sounds and the actual specific task.
- The items in their entity should span a multidimensional room as widely as possible.

Figure 1 shows an example of evaluating a specific stationary sound in the interior of a car. Averaging the results of all participants will give an average semantic profile.

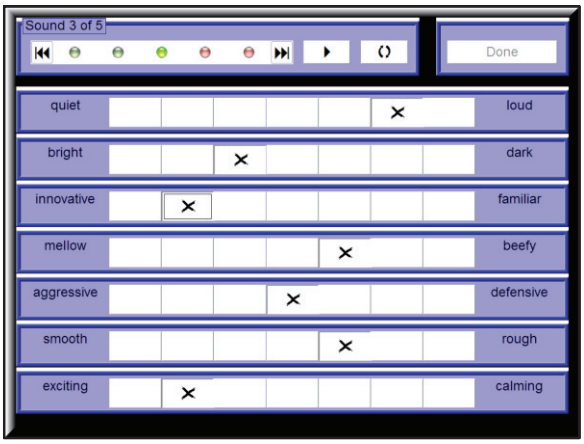

Figure 1 – Screenshot of a filled in semantic differential (individual test person)

2.3 Other Jury Testing Methods

For the comparison of several stimuli with respect to the perceived strength of just one certain sound aspect, a ranking test can be performed by one of the following methods:

- Conventional complete A-to-B comparison
- Ranking by sorting the sounds on a graphical panel

The result of such a ranking test gives a sorted order of the stimuli on an ordinal scale.

To evaluate the acoustical impact of a certain modification at a prototype car in a simple manner (even for non-experts), a so called “free listening test” has been introduced. It provides comparisons of two or more stimuli without any formal rating. This test can be run by the test persons individually or as a group listening test. The application of interactive digital filters can be advantageous for identifying the frequency range and the strength of striking noise components.

3. BASIC SENSORY MEASURES

3.1 Overview

Along with the decrease of overall SPL it became necessary to get more insight into the acoustic perception of the car driver. In addition to SPL measurements, it was necessary to determine which basic psychoacoustic measures best describe the acoustic perception for NVH purposes.

For application in car acoustics, it has been found that the most appropriate sensory measures in predicting driver perception are loudness, acoustic sharpness, tonality, acoustic roughness and acoustic impulsiveness in a suitable combination.

3.2 Loudness and Sharpness

To consider the level-dependent frequency response of the human ear it became common for SPL measurements to introduce corresponding frequency weighting curves, indicated for example as "dB(A)". The letters "A" to "D" indicate the level range of applicability. To overcome this imponderability it is recommended to use the so-called "loudness" as described by Fastl and Zwicker (4) which has been standardized in the German standard DIN 45631 and in ISO 532-A.

According to DIN 45692 the acoustic sharpness is correlated to the center of gravity on the frequency scale of the spectrum. As the sharpness of a sound increases, its sensation gets more aggressive and annoying. The normative part of DIN 45692 provides an implementation independent of the loudness. However, in product sound evaluation it may be more favorable to include the loudness dependency as described in the informative section of the DIN-standard.

Both loudness and sharpness use the same basic steps for their calculation: first of all the specific loudness (in "critical bands", i.e., aurally adequate frequency bands) is computed. At this point the loudness algorithm considers the level dependent frequency response inherently. Furthermore, the loudness calculation takes spectral and temporal masking effects into account.

3.3 Tonality

One of the most prominent "faulty" sounds in car acoustics is the presence of narrowband overshoots in the spectral domain, often named "whining", "howling" or "whistling". Usually, such spectral content can be very annoying to the car driver.

Most of the known calculation methods for tonality use the level difference between the frequency of the apparent tone and the surrounding spectral environment (i.e., critical band).

Some special features of the algorithm which was developed by the authors (e.g., Oetjen (5)) are:

- Smoothing of the toneless background spectra
- Detection of tonal components according to DIN 45681
- Spectral masking
- Tracking of "tonal components" (in the time-frequency domain)

The example given in Figure 2 is very typical: a compact class passenger car driven in a mid-speed range at a moderate acceleration on a smooth road surface. In a certain speed range some narrowband "whining noise" with a frequency proportional to the speed of the car can be perceived.

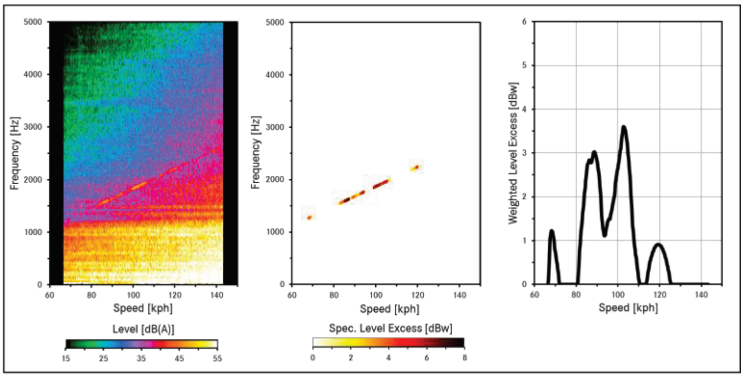

Figure 2 – Tonality of gearbox "whining" during a moderate acceleration (driver's right ear);
left: 3D-FFT-spectrum / middle: tonal components / right: overall tonality

3.4 Roughness

Especially in vehicles with combustion engines, a measure called “acoustic roughness” became important. It deals with fast periodic fluctuations of the engine noise. Typical roughness phenomena in car acoustics can be identified by a modulation of the time signal in certain frequency bands. The fundamental background is extensively covered by Fastl and Zwicker (4).

For modulation frequencies lower than appr. 20 Hz, the sensation “roughness” changes with an overlap to “fluctuation strength” with a maximum around 4 Hz. Even though in car acoustics minimum modulation frequencies may go down to appr. 10 Hz it could be of advantage not to change between those two measures for practical reasons, e.g., for analyzing a complete engine run-up.

The roughness can contribute negatively (decreases comfort) or positively (increases sportiness) to the sound quality. Thus the consideration and treatment of roughness is of major importance.

Oetjen et al. (6, 7) have developed an algorithm with these additional key features:

- Involving an approach to incorporate “missing fundamentals” of the signal envelopes.
- Including modulation harmonics to take care of non-sinusoidal modulations.
- Evaluation of the coherence between the envelopes in neighbored carrier frequency bands.
- Implying statistics for entropy weighting of engine related roughness components.

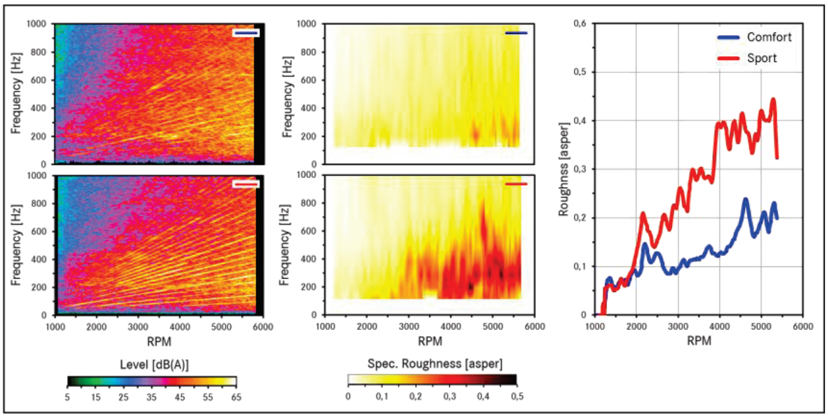

Figure 3 – Roughness of interior noise (engine run-up), two different exhaust mufflers; left: 3D-FFT-spectra / middle: specific roughness / right: overall roughness

The example in Figure 3 shows a comparison of interior car sounds recorded at one car with two different exhaust systems. From the 3D-spectrograms it can already be seen that the content of multiples of the “half engine order” for the “sport type muffler” will result in a higher degree of modulation causing the main difference in the perceived roughness.

Recent studies as in Oetjen and van de Par (8) have shown that the loudness contrast appears as a moderating factor which can amplify roughness sensation more than expected as for synthetically generated test sounds.

The standardization of roughness is currently going on at DIN-NALS.

3.5 Impulsiveness

From Diesel-engine driven cars it is well known that particularly in the low RPM range the sound may contain “spikes” with high frequency contents, known as “Diesel-knocking”.

This specific property in the time signal can be detected by a specialized version of the roughness. The main features of an impulsiveness algorithm developed by Oetjen et al. (9) are

- The modulation frequency range (the “repetition rate”) is very low (5 to 20 Hz).
- The main carrier frequencies are found in the range of 1000 to 8000 Hz.

As an example the idling noise of a Diesel car is shown in Fig. 4. The first condition refers to the original sound recording whereas the second condition has been generated from the first one by simply replacing the original phase by a random phase. - Several applications (by the authors) have shown that this algorithm is able to model the sensation of impulsiveness quite well for idling noises (exterior and interior) and to a certain extent for run-ups in an engine speed range of up to appr. 2000 rpm.

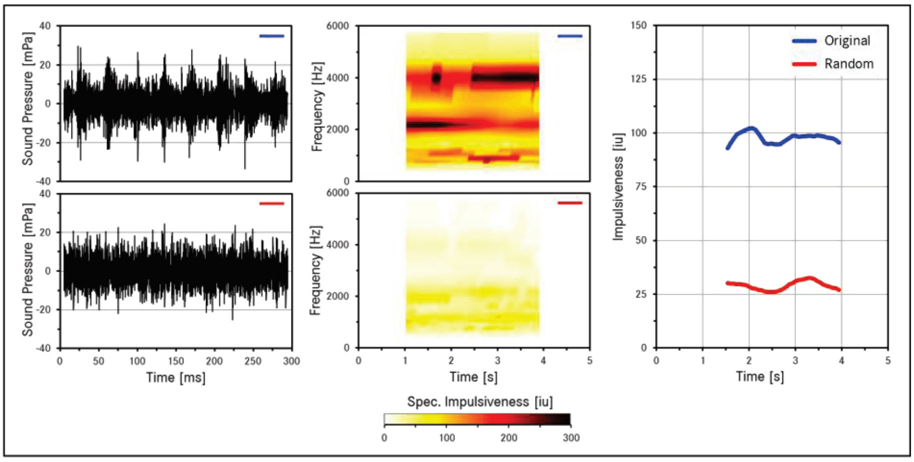

Figure 4 – Impulsiveness of exterior car noise at idle for two different conditions;
left: bandpass-filtered time signals / middle: specific impulsiveness / right: overall impulsiveness

4. DEVELOPMENT OF A HOLISTIC SOUND METRIC

4.1 Some Basic Considerations

In a model for product sound quality Blauert and Jekosch (10) suggested that the interaction between the product and the user has to be regarded. Furthermore, sound quality is related to the "suitability of the sound". Bisping (11) and Västfjäll (12) introduced "pleasantness" and "powerfulness" as important factors influencing the perceived sound quality.

In accordance with the aforementioned studies, the following dimensions have to be incorporated for a holistic approach of sound evaluation by a "sound metric":

- The noise comfort defined as the absence of disturbing noise components.
- The emotionality caused by the sound denoted as "powerfulness" or "sportiness".
- The conformity which refers to how good the noise fits the customer's expectation.

Figure 5 shows a sketch of such a metric with different layers: the physical layer, the sensory layer and a layer representing the "holistic perception" where context variables control the overall weighting process. Based on this proposal Maiberger et al. (14) developed an implementation of this model. Fiebig and Kamp (15) gave some insight into the necessary statistical background work.

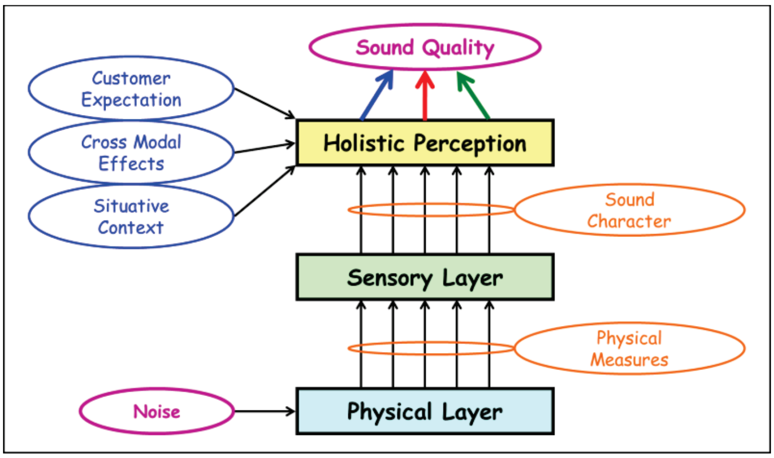

Figure 5 – The Setup of a Sound Metric (adapted from Letens (13))
(blue / red / green: comfort / emotionality / conformity)

4.2 A Proposal of a Metric for Noise Comfort

To capture the acoustic perception of the driver completely, all important noise properties must be taken into account. The metric outlined in this paper takes only engine noise, road-tire noise and wind noise into consideration. Additionally, the selection of relevant driving conditions has to be adapted to the powertrain of the car (combustion engine vs. electrical engine). The following driving conditions have been selected to give a representative overview of the acoustical behavior of the car:

- Engine at idle (interior and exterior noise)
- Accelerating with partial load (interior noise)
- Accelerating with full load (interior noise)
- Constant speeds (on smooth and rough road surfaces) (interior noise)

The main steps of setting up the sound metric for the dimension "sound comfort" are as follows:

- The sound recordings have to be analyzed using a specific set of measures.
- The output of the analysis stages is normalized to point scales (1 = bad … 10 = good).
- All normalized measures of one driving condition result in a weighted sum (1 … 10 points).
- Results of several driving conditions are merged together as a weighted sum as well.
- In the end all noise components will be summed up to an "overall sound comfort index".

The process of summing up weighted measures is similar to a prediction using a multiple linear regression model. The weighting factors here are a result of a series of listening tests and expert discussions to find the best fit for all the factors.

Acoustic Measure	Car 1	Car 2	Car 3	Car 4
Loudness / 2000 rpm	5,5	7,8	6,8	5,3
Loudness / 4500 rpm	4,7	8,2	6,9	5,3
Loudness / max.Overshoot	7,0	8,1	8,1	5,5
Low Frequency Content	7,7	8,6	6,7	1,5
Engine Order Content	7,5	8,4	6,6	1,6
Roughness / Mean	6,4	6,6	6,4	6,6
Roughness / Max	5,5	5,9	6,0	5,7
Tonalness / Mean	4,5	6,1	5,0	4,3
Tonalness / Max	3,5	7,8	5,0	4,5
Sharpness / 2000 rpm	5,9	6,9	6,6	6,3
Sharpness / 4500 rpm	5,4	6,5	5,6	5,0
Full Throttle Acceleration / overall	5,4	7,4	6,3	5,0

Figure 6 – Typical metric results for noise comfort: powertrain noise at full throttle acceleration, the cells of the tables are colored according to the cell's value (bad=1…good=10).

The final results of the metric (overall and intermediate layers) serve as a guideline for setting up NVH targets for a new car. The informative value can even be increased if the metric results for the predecessor car and some of the core competitors are compared as in Figure 6. Here an example of four cars is given, showing the metric evaluation of a full throttle engine run-up.

4.3 Extension of the metric by "Sportiness"

So far only the first dimension of the sound evaluation has been included in the metric: noise comfort. Zeitler and Zeller (16) have shown, that a properly tuned NVH behavior may improve the "perceived sportiness" of a car. To extend the metric by an evaluation of the acoustically suggested "sportiness" (as part of the "emotionality") a subset of dynamic driving conditions which can contribute to the sportiness has been selected as in Maiberger et al. (17):

- Partial-to-full-load transition (interior noise)
- Accelerated pass by (exterior noise)
- Engine start (exterior noise)

Some analysis measures have been adapted to show good correlation with the perception of sportiness. In particular, dynamic properties have been found to play an important role.

As a basis for setting the weighting factors of the sportiness metric, listening tests have been performed. Using the ranking of 16 cars with respect to their "sportiness" in all of the listed driving conditions, the weighting factors have been determined by a special variant of regression analysis.

The sportiness metric as presented here is preliminary: additional driving conditions have to be considered and probably will have to be added to the metric.

4.4 Completion of the Metric by "Conformity"

Until now the dimensions "noise comfort" and "sportiness" have been regarded without any reference to the type and the make of the car. Hence the following aspects have to be considered:

- How well does the sound fit the type of the car (sedan/saloon, sports car, SUV, etc.)? → "type conformity"
- How well does the sound correspond to the holistic requirements of the make of the car? → "make conformity"

Maiberger et al. (14) have suggested a model which extends the metric by introducing "type conformity" as a kind of "achievement level" with regard to the product specification sheet. The "type conformity" is implemented as a weighted sum of comfort and sportiness with car-depending weighting factors (e.g., for a sedan car comfort has higher priority than for a sporty car).

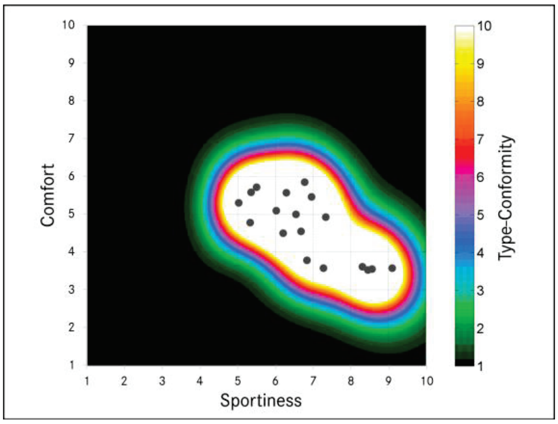

Figure 7 – Example of a type conformity evaluation of sporty cars
(each point represents one car with a conformity set to 10)

Figure 7 shows a typical example of a mapping for a certain cluster of cars. For a selection of 18 "sporty cars" (roadsters and convertibles) the evaluation for comfort and sportiness is plotted on a 2-dimensional plane. The type-conformity for these cars has been set to 10 points on a 1 to 10 point scale (by an expert panel) and raises the 3rd dimension of the figure. Apart from the resulting cluster of these given "reference cars" the value of type-conformity flattens out with some transition.

Once the comfort and sportiness of a car of known "type" is rated it can immediately be seen how well the car fits into the corresponding reference cluster for type conformity.

However, the "make conformity" has not yet been implemented, because the driving experiments reported by Maiberger et al. (18) did not include different car makes.

5. SUMMARY AND CONCLUDING REMARKS

This paper presents applications of three fundamental methodologies for the evaluation of the acoustical properties of products, particularly cars:

- Jury testing based on binaural sound recordings.
- Psychoacoustic measures to reveal perceptible disturbing noise components.
- A Noise Metric for a holistic approach for the evaluation of the overall noise quality.

The use of binaural techniques has become standard in product development. As a supplementing tool with a convenient handling, it ensures not to ignore NVH phenomena which might appear unexpectedly. Nevertheless, it is and will be necessary to finalize an NVH evaluation of a new car by driving it on the road as customers will do.

With regard to the psychoacoustic algorithms further investigation needs to be made to improve the robustness with respect to uncorrelated noise components, e.g., clicks, bumps, low frequency noise.

After an introductory phase for the noise metric (as presented here), a multiple regression with a final set of analysis parameters and an adequate number of cars must be thoroughly conducted.

Once the metric has been finalized by an implementation of the make conformity, it is likely that an answer can be found to this still pending question:

"Which acoustic properties constitute the corporate sound of a specific make?"

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