Quantifying tonal phenomena in interior car sounds

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When analyzing car interior sounds one often encounters tonal components. These tonal components may cause unpleasantness and contribute to poor sound quality. Here an algorithm is presented which is to quantify specific tonal aspects of sounds correctly. It is to allow to identify unwanted tonal properties at the early stages of the car design process in order to initiate possible countermeasures. Two experiments are conducted in order to provide a basis of subjective ratings to validate the algorithm developed. The stimuli used represent typical car sound phenomena "whistle" and "whining". "Booming" noise is excluded. The sounds have been binaurally recorded and they are modified systematically according to their tonal content. In all a number of 33 stimuli result based upon 5 different original car sounds. Firstly a sound quality experiment using a semantic differential is conducted (30 subjects) in order to investigate the perceptual dimensions of the sounds under scrutiny. Using the PCA a four-factor solution is obtained, which can be interpreted well. Secondly a categorical scaling experiment using only the adjective scale "tonal - not tonal" was conducted with a broader range of stimuli (32 subjects) in order to provide a basis for the validation of the algorithm. The algorithm itself is based on E DIN 45681 and modified with respect to masking, prominence region and duration.

1 Introduction

In the evaluation of car interior noise tonal components may play a major part in the overall sound quality estimation. Though evaluated often negative [1] they are in the case of sporty vehicles a positive feature and can deliberately be used in the sound design process [2].
Tonal components are often described with various onomatopoeic descriptions such as 'whining', 'whistling' or 'booming'. These descriptions can be categorized according to their frequency: 'booming' $<$ 200 Hz, 'whining' in the medium and 'whistling' in the higher frequency range. Furthermore they can be categorized into stationary phenomena with constant frequency such as 'tire-torus-resonance' or engine order dependent such as 'gear whining'.
The aim of this study is to extract a reliable threshold of prominance for the 'tonal' phenomena in car interior acoustics. Therefore an extraction algorithm combining several psychoacoustical laws is suggested to identify and evaluate the tonal components encountered providing a tool in the sound design process.
By using a representative stimuli selection of 'whining' and 'whistling' sounds in which the tonal contents has been modified systematically two hearing tests are conducted. To get an insight into the effects of tonal content variations the perceptual space is investigated using the semantic differential technique. In this way the influence of the varying tonal contents on the connotative meaning can be measured. To investigate the effect on tonality the second experiment, a categorial scaling experiment using the scale 'not tonal - very tonal', is performed using a broader stimuli set to form a basis to validate the algorithm.

2 Stimuli

The stimuli used in the experiments are car interior sounds recorded with an artificial head. These stimuli are modified via digital filtering in order to vary the tonal content systematically. Firstly, a 5s sample is extracted and tonal components not belonging to the frequency or engine order in question are reduced below threshold. After this the remaining prominent orders are reduced or amplified stepwise. With this approach six to seven stimuli are generated per car interior sound, which sums up to a total of 32. The modifications are such that the modified sounds are still perceived as car sounds.
The following frequency regions and accordingly engine orders are covered:

Car I Frequency Region: 650-450 Hz, engine order: 10

Car II Frequency Region: 700-500 Hz, engine order: 19

Car III Frequency Region: 240 Hz

Car IV Frequency Region: 1500-2000 Hz, engine order: 46 and Frequency Region: 3400-3900 Hz, engine order: 92

Car V Highly transient 10kHz-15kHz in 0.5s (turbocharger)

In this way not only the strength of the tonal components cover a broad nevertheless realistic range, but also a number of common tonal phenomena in car interior acoustics are adressed.

3 Experiment I: Perceptual Space

In order to investigate the percetual space of the stimuli a sound quality evaluation is conducted using the semantic differential method [1, 3]. The examination of the perceptual space is to answer the following questions:

- In which way is the judgement of tonal components integrated into the judgement of other aspects such as pleasantness?
- What is the relation of “tonal” to more onomatopoeic descriptions such as “whistle”, “whining” or “booming”?
- Are there other aspects of the connotative meaning varying with changing tonal contents?

3.1 Stimuli

21 out of the original 33 stimuli described in section 2 are chosen (Car I-IV) for this experiment in order to reduce the experiment to a reasonable duration.

3.2 Procedure

Every subject has to examine the sound presented using 14 bipolar, 7-step adjective scales. The scales are listed in Table 1. The stimuli are presented at original sound pressure level through headphones. Every sound is repeated four times. The stimuli and adjective scales are randomized three times, in this way every subject has to examine one of the nine setting versions. The experiment is devided in the following sections:

Orientation The subjects listen to all sounds in order to build a frame of reference.

Training The subjects have to evaluate 6 stimuli using the same condition as in the main experiment in order to accustom themselves to the scales and the task.

Main Experiment In the main experiment the subject have to evaluate the 21 stimuli. 3 stimuli are repeated for a reliability check.

The total experiment takes 40-60 minutes.

3.3 Apparatus

The stimuli are presented via electrostatic, callibrated headphones in a sound proof room at DaimlerChrysler, Sindelfingen. The subject’s response via touchscreen interface.

3.4 Subjects

30 subjects, 6 female and 24 male, with a mean age of (29 ± 9)a participate in the experiment. 12 subjects can be regarded as acoustical experts as the regularly participate in evaluation of car acoustics or work in this field. All subjects have no reported history of hearing loss.

3.5 Results

As a reliability test result 28 of 30 subjects are considered reliable ($r_{crit,0.01} = 0.36$).
On the basis of the reliable subjects a principal component analysis (PCA) is conducted followed by a varimax rotation. The KMO-criterium is 0.85, which indicates a reasonable solution (SPSS; vers.: 12). The following four factor solution is obtained (please refer also to Table 1 for more details):

(1) “evaluation” ‘harmonic - discordant’, ‘not whining - very whining’, ‘not tonal - very tonal’

(2) “powerful” ‘not booming - very booming’, ‘powerful - weak’

(3) “metallic” ‘shrill - dull’, ‘metallic - deep’

(4) “whistle” ‘not whistling - very whistling’, ‘not tonal - very tonal’

The first three factor names are according to sound quality analysis by S. Kuwano and S. Namba [4].
The adjective scale “not tonal - very tonal” loads equally strong on factor 1 and factor 4. The scale lies geometrically spoken in the plane spanned by factor 1 and 4.
In order to check what kind of changes in connotative meaning are evoked by the changes in tonal content on factors not directely connected to tonal perception ANOVAs are run. These aspects of sound quality

Table 1: The perceptual space has a four factor solution. The scale "not tonal - very tonal" loads equally on Factor 1 and 2. (Factor loadings > 0.4 are omitted for clarity reason.)

Adjective Scales	1	2	3	4
harmonic - discordant	**0.82**			
uniform - non-uniform	**0.78**			
annoying - not annoying	**-0.71**			
pleasant - unpleasant	**0.71**			
not whining - very whining	**0.62**			
not booming - very booming		**-0,81**		
rough - smooth		**0.79**		
powerful - weak		**0.75**		
hard - soft	-0.41	**0.53**		
loud - soft		**0.53**		
shrill - dull			**0.85**	
metallic - deep			**0.76**	
not whistling - very whistling				**0.91**
not tonal - very tonal	**0.46**			**0.49**
Explained Variance	**23.7 %**	**17.8 %**	**16.5 %**	**10.6 %**

gather in factor 2 and 3, the "metallic" and "powerful" factor. There is no significant main effect due to different tonal content for each seperate car ($p > 0.05$), i.e. these aspects are not influenced by the variation of the tonal content. Nevertheless a significant main effect is obtained on the factors scores ($p > 0.05$) between each group formed on the basis of the original car sound, i.e. car I - IV. In this way the factor scores of the "powerful" and "metallic" factor change only with each car.

3.6 Discussion

The first three factors can be identified as similar to those obtained by S. Kuwano and S. Namba [4]. The tonal components are associated with other evaluative aspects. They are split up into two factors: factor (1) "evaluation" and factor (2) "whistle' . The scale 'not tonal - very tonal' loads on both of them. In this way the scale 'not tonal - very tonal' can be used as a scale for the analysis of tonal components by replacing more onomatopoeic descriptions such as 'whistle' and 'whining'.
Tonal components are understood as components which are in a frequency region above 200 Hz, as these components are classified as tonal in the perceptual space by the test subjects. Tonal components lower than 200 Hz are associated with the 'booming' sensation, which is not classified as originally tonal but associated with 'powerful'. In this experiment such low frequency components are not varied, a fact that maintains the 'powerful' perception within each car group constant. The same holds for the 'metallic' factor.

4 Experiment II: Subjective rating of tonal components

The second experiment is a subjective rating on the seven step categorial scale 'not tonal - very tonal' to form a subjective basis in order to validate the algorithm for the extraction and evaluation of tonal components proposed.

4.1 Stimuli

Every stimuli introduced in section 2 are assessed during the experiment.

4.2 Apparatus

Please refer to section 3.3.

4.3 Procedure

Please refer to section 3.2 as the procedure identical to the procedure of experiment I apart from the following exception:
There are 6 re-test stimuli. The test lasts for 30-45 minutes. As 'tonal' is not a common description, in the instruction tonality is explained as follows: "Tonality is the sensation, which indicates the prominance of tonal components ('whining' or 'whistling') in a given sound". Together with the stimuli in the orientation section this explanation suffices as tonality as a sensation is very common and can be easily demonstrated by examples [5].

4.4 Subjects

32 subjects, 2 female and 30 male, with a average age of (28 ± 8)a participate in the experiment. 10 subjects can be regarded as acoustical experts, as they are regularly participating in evaluation of car acoustics or are work in this field. All subjects have no reported history of hearing loss.

4.5 Results

22 of the 32 test subjects can be considered as reliable ($r_{crit,0.01} = 0.83$). Everyone of the expert responded reliable. Furthermore the test score are distributed evenly across the categorial scale, in this way the stimuli cover the whole range in tonal perception in interior car noise. Further results are presented in section 6 with comparions of objective and subjective data.

5 Algorithm for extraction and evaluation of tonal components

In order to extract and weight tonal components in a given signal several steps are necessary. A spectrum of a sample stimulus is shown in figure 1.

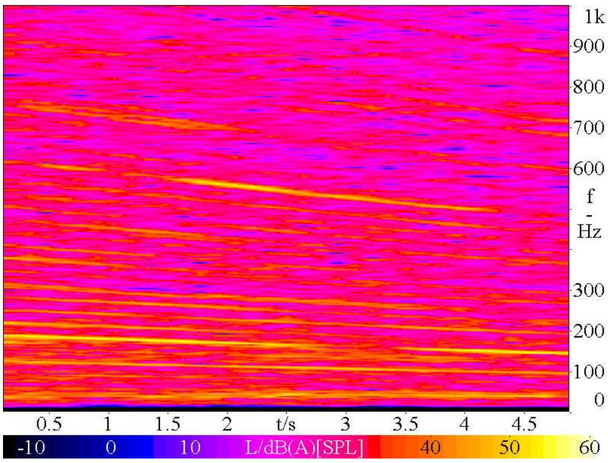

Figure 1: Spektrum of a sample car noise with dominant 10th engine order. (16k spectrum size, hanning window, a-weighted, 60% overlap).

At first the prominent orders/frequency bands have to be extracted, then an appropiate weighting has to be applied and at last a summation over time has to be done.
In order to extract the relevant order/frequency the algorithm of DIN 45681 is used [6]. The algorithm chooses 'candidates' which have to be 6dB above the mean narrow band level of its critical-band. Thereafter the tone level L_T of each 'candidate' is determined. The difference LX_μ between the tone level and the narrow band level of the critical-band around the frequency μ is corrected for masked threshold.
Additionally the masking due to the prominent tones is included, which reduces the difference LX_μ further [7].

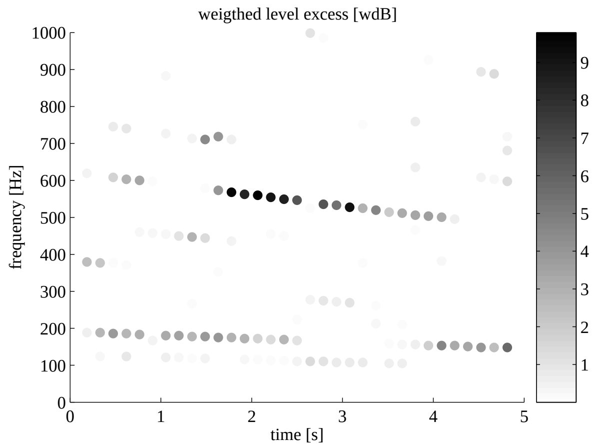

Figure 2: Extracted candidates for tonal perception with a dominant 10th engine order. Note that the 2nd engine order is below 200 Hz.

The sound pressure level excess is weigthed using weighting functions by Terhardt et al. [7]. The weigthing functions WS take effect on the frequency f_μ (Equation: 1) and the sound pressure level excess S_{spl} (Equation: 2) of each detected component μ.

$$WS_f = \left[1 + 0.07\left(\frac{f_\mu}{0.7kHz} - \frac{0.7kHz}{f_\mu}\right)^2\right]^{-\frac{1}{2}} \quad (1)$$

The frequency weigthing WS_f takes account of the spectral dominance phenomenon, i.e. that spectral components around 700 Hz contribute relatively strong to the pitch perception.

$$WS_{spl} = 1 - \exp\left(-\frac{LX_\mu}{15dB}\right) \quad (2)$$

The weighting according to the sound pressure level excess abates small excesses more as they do not contribute as much as more prominent frequency components.

6 Validation of the algorithm

To validate the algorithm the weighted level excess pattern over time has to be represented by a single value. The specific order/frequency in question is identified as shown in figure 2 and a weigthed level excess over time of the specific order/frequency is calculated. Using the

5%-percentile (the value which is excessed in 5% of the total time) of these temporal fluctuating values the single value is calculated. This procedure is used in analogy to findings of S. Namba and S. Kuwano [8] in the studies on temporal fluctuating sounds in respect to loudness evaluation. The analogy is based on the hypothesis that the strategy of giving an overall judgment of tonal prominence might be similar to the way of making an overall noisiness judgement.

The subjective and objective ratings show a high

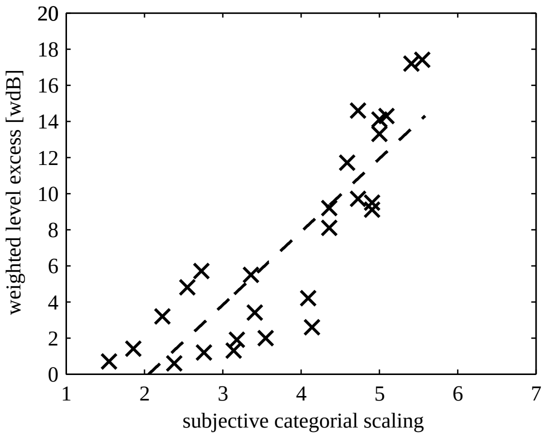

Figure 3: Comparing the objective algorithm data (ordinate) with the results of the subjective categorial scaling experiment (abscissa) a highly significant correlation coefficient: $r = 0.86$) can be found.

correlation of $r = 0.86$ (highly significant). In this way the algorithm can be used to predict the judgement on tonality. The data however do not include the stimuli of car V as the algorithm's time resolution is too low in order to detect the highly transient tonal component of the turbocharger. Furthermore 'tonal' in this context is defined as a result of experiment I as an attribute of components with a frequency higher than 200 Hz, i.e. which are not attributed as 'booming' (see section 3.6).

7 Summary

- The perceptual space of the car interior noises with tonal components has 4 dimensions, 3 coincide with other studies [4].
- The adjective 'tonal' is able to describe tonal phenomena in car acoustics barring 'booming' noises.
- The presented algorithm is based on several psychoacoustical laws. The predicted values give a good estimation of subjective 'tonal' content.

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