Psychoacoustic evaluation of tonal components in view of sound quality design for high-speed train interior noise

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1. Introduction

In high-speed trains, tonal components produced either by the motor or by corrugated rails may occur.
As it is well-known from literature ([1], [2], [3]) that environmental or artificial noise containing tonal components is more annoying than noise without tonal components, the present investigation assesses the importance of reducing such tonal components. Therefore, typical sounds were synthesized and analyzed in psychoacoustic experiments with the following intentions: how much has a tonal component to stick out to be perceived at all? How are increases or decreases in sound energy in a limited frequency band related to the psychoacoustic sensation tonalness? What influence does this tonalness have on the perceived sound quality?

2. Experiments

Fourteen normal hearing subjects participated in the experiments. Nine of the subjects belonged to the department's staff and were trained in psychoacoustic experiments. Five of the subjects had no practice in psychoacoustic experiments.

All sounds were presented diotically via an electro-dynamic headphone Beyer DT 48 with freefield equalizer [4]. The presentation level of all stimuli was 89 dB(lin) or 62 dB(A). Each stimulus had a duration of 4 seconds.

As basic stimulus a noise was synthesized which is simulating a typical interior noise inside high-speed trains (fig. 1). This kind of third-octave band spectrum is nowadays used as design rule in specifications of high-speed trains. Deviations may occur during the development process or in real operation.

The motor or corrugated rails can produce deviations from the spectrum of the basic stimulus. Therefore as test stimuli sounds with the following deviations from the basic stimulus were realized: in filtering the basic stimulus with a 1/3 - octave filter bank with slopes of 24 dB / oct. the 1/3 - octave bands at 630 Hz or at 1250 Hz have been increased by 2, 4, 6, 8, 10, 15 or 20 dB and decreased by 2, 4, 6, 8, 10 or 20 dB, respectively.

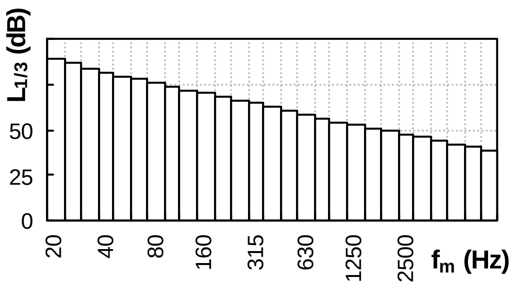

Fig. 1: Third-octave band spectrum of the basic stimulus, simulating a typical spectrum inside high-speed trains.

To measure the discrimination threshold the method "Paired Comparisons" was used. Pairs of stimuli were presented with the first being always the basic stimulus and the second one of the test stimuli. In the remaining 2 seconds the subjects had to answer to the question "Is there any difference between the two stimuli audible?" with "yes" or "no". It was also possible to add "yes, there is a big difference". Each stimulus pair was estimated four times by each subject.
For the experiments concerning tonalness, the method "Free Magnitude Estimation" [5, 6] was used. According to Hellbrück [6], thereby only the first stimulus has to be judged absolutely, the following stimuli have to be judged with the preceding stimulus as standard. All stimuli were presented four times in a different random order. To reduce context effects in this way for each of the four presentations of one stimulus in the experiment, the stimulus had a "new" precursor and respectively a "new" successor. (The in this kind arranged experiment was presented to all subjects in the same order.)

In a third kind of experiment, the sound quality of a selection of the stimuli was assessed. Therefore, again the method "Paired Comparisons" was used with the first sound of the pair being always the basic stimulus. The subjects were instructed to imagine they were sitting in a train and they want to read a book. With this background information they had the task to classify the sound pairs due to their differences in sound quality by symbols. They had the choice between: "the sound quality of B is much better (+ + +), better (+ +), slightly better (+), the same (O), slightly worse (-), worse (- -), much worse (- - -) compared to that of A". All subjects estimated in this regard each stimulus pair 4 times.

3. Results and discussion

3.1 Discrimination threshold

The upper inset of figure 2 shows the results for the stimuli with the modifications in the third-octave band at 630 Hz, the lower inset those for the stimuli with the modifications at 1250 Hz. 100 % discrimination means the answer given was 56 times "yes, there was a difference". The hatched columns show how often a big difference was reported. Since the results for the subjects with psychoacoustic experience and those without didn't differ significantly, they were combined in figure 2.

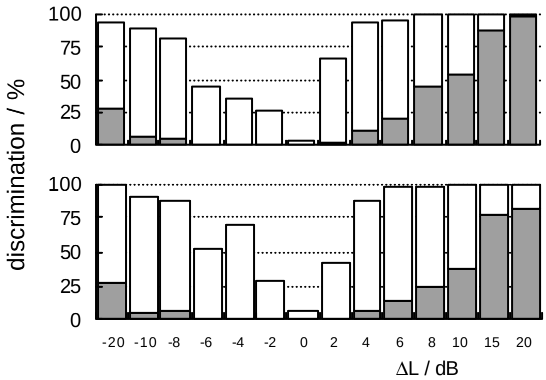

Fig. 2: The discrimination in % shown over the level difference between basic and test stimulus in the third-octave band at 630 Hz (upper inset) and at 1250 Hz (lower inset). Hatched columns indicate the percentage of big differences perceived.

Overall, increases are much more noticeable than decreases. An increase of 2 dB is needed for the third-octave band at 630 Hz whereas a 6 dB decrease is needed to attain 50 % discrimination. Similarly, for the 1250 Hz band, a 2 dB increase and a 5 dB decrease are needed. 100 % discrimination are reached for the stimuli with the modifications in the third-octave band at 630 Hz for 8 dB increase, but for 20 dB decrease only 95 % of the subjects could detect a difference. For the stimuli with the modifications in the third-octave band at 1250 Hz for 100 % discrimination 10 dB increase or 20 dB decrease are necessary.

The results of the detection of "big differences" show even a more asymmetric behaviour than those of the discrimination threshold: the same percentage for "big differences" is reached about for an increase of 8 dB and a decrease of 20 dB. Overall, the enhancements at 630 Hz seem to produce clearer differences, thus for an increase of 20 dB at 630 Hz nearly 100 % of the subjects mentioned "big differences", but at 1250 Hz only 80 %.

According to Zwicker [4], the threshold is determined at that stimulus magnitude for which the corresponding sensation is audible with 50 % probability. Thus we get on the average for all test stimuli for increases a threshold of 2 dB and for decreases a threshold of 6 dB. The threshold for increases is much lower than that for decreases. This can be explained in comparing the spectral masking patterns of stimuli with an increased or a decreased third-octave band, where the area of the spectral masking pattern is not changing for the respective same amount for a decrease as for an increase.

In the literature [4] a relatively simple model for just-noticeable slow sound variations is reported: the threshold of variation is reached when the excitation level produced by the sound changes somewhere along the critical band-rate scale by more than 1 dB. Since this model was developed for modulation threshold, whereas in our experiments a comparison threshold was measured, the measured value of 2 dB is in the right order of magnitude.

3.2 Tonalness

Each data point displayed in figure 3 is the median of 56 estimations with its interquartile ranges. The data were scaled individually for each subject so that the stimulus which produced the maximum tonalness received the value 100 %. Even though the untrained subjects produced larger intraindividual differences than the trained subjects, the median's tendency is the same and therefore the data are merged in figure 3.

The basic stimulus produces practically no tonalness. If the third-octave band is increased, the tonalness is increasing intensively and also a decrease of sound energy produces a faint tonal sensation. Thus an increase of 2 dB produces for the stimuli with the modifications in the third-octave band at 630 Hz the same tonalness as a decrease of 8 dB. For the stimuli with the modifications in the third-octave band at 1250 Hz an increase of 2 dB produces the same tonalness as a decrease of 4 or 6 dB. If we want to halve the maximum tonalness, the increase of the respective third-octave band has to be halved.

If the criterion for significance is defined at 5% (signed Wilcoxn test), the increase in tonalness is at third-octave band increases for both frequencies from 2 dB on significant, at third-octave band decreases it is for 630 Hz for -6, -8 and -10 dB significant, for 1250 Hz for -8, -10 and-20 dB.

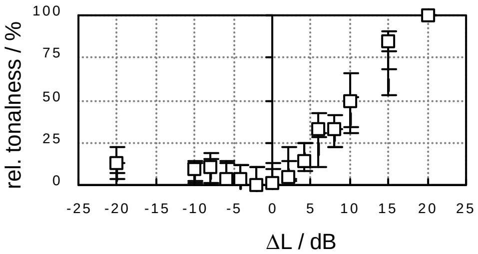

Fig. 3: The relative tonalness in dependence of the level difference between basic and test stimulus in the third-octave band at 630 Hz (rhombs) and at 1250 Hz (squares).

The tonalness produced by decreasing a third-octave band can be explained by recalling results of experiments for the pitch strength of low-pass noise [7]. There a faint pitch strength occurred at the edge of the low-pass noise which is about in the order of magnitude of the tonalness measured in our experiments for the decreased third-octave bands.

That tonalness originated by a spectral gap shows some similarity to the results of Duifhuis' experiments [8]. He describes that harmonics above a certain number in a harmonic complex tone are audible when spectrally absent. Even though, in our case a full third-octave band is decreased, the results seem to be comparable. While in Duifhuis' experiments the audible pitch is related to a spectral gap produced by the addition of a pure tone out of case with a component of the complex tone, in our case a frequency band of third-octave band width in a broad band noise was reduced by up to 20 dB.

The results of the experiments for the increased third-octave bands can be compared with data from basic psychoacoustic experiments by Hesse [9] as done in figure 4. He measured with the method "Magnitude Estimation with Anchor Sound" the relative pitch strength of pure test tones at 3.3 kHz masked by uniform masking noise in dependence of the test tone level above the masked threshold.

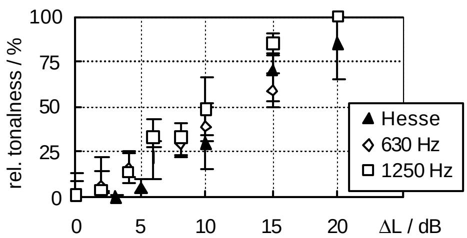

Fig. 4: Comparison of our data with data from Hesse. Modifications in the third-octave band at 630 Hz (rhombs), at 1250 Hz (squares) and the data from Hesse (triangles).

The results seem to be quite similar in spite of the different test and masking sound and also in spite of the different tasks: in one case the pitch strength, in the other case the tonalness was estimated.

If the results for the relative tonalness (fig. 3) are compared with the percentage of the big differences (fig. 2), the data seem to suggest that the subjects made their decision for "a big difference" on the basis of the differences in tonalness.

To reveal the frequency dependency of the observed tonalness, for each subject the ratio of the maximum medians of the absolute estimations was calculated:

$$\frac{\text{abs. tonalness}_{max}\ (630\text{ Hz})}{\text{abs. tonalness}_{max}\ (1250\text{ Hz})}$$

The median over all those ratios of the 14 subjects results in 1,36. This means that in the mean the maximum tonalness for an increase in the third-octave band at 630 Hz is judged 36 % higher than for an increase at 1250 Hz. Those higher maximum absolute values for tonalness at the lower frequency apparently seem to be at variance with data from literature (see e.g. [4], [10]). However, in our case with increasing frequency also the bandwidth increases which leads to a decrease in pitch strength (see e.g. [7]).

3.3 Sound Quality

The columns in figure 5 show the median with its interquartile ranges of 56 estimations. The results for the modifications in the two different third-octave bands are quite similar. For 0 dB level difference the subjects are not able to notice any difference in sound quality, a result which shows the reliability of the subjects. The sound quality of the stimuli with increases of 6 dB or decreases of 20 dB is judged as "slightly worse" than that of the basic stimulus, the sound quality of the stimuli with increases of 15 dB as "worse".

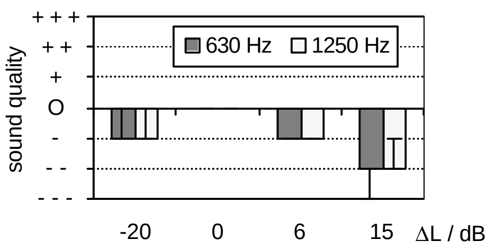

Fig. 5: Sound quality in categories in dependence of the level difference in the respective third-octave band.

In figure 6, the results of the experiments for the tonalness are combined with those for the sound quality: with increasing tonalness, sound quality is judged worse by the subjects.

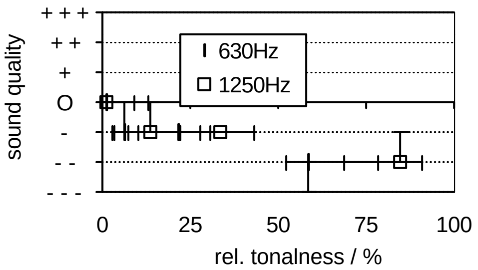

Fig. 6: Correlation between the change in sound quality and the change in tonalness.

4. Conclusion

Manipulations (increases or decreases) in a third-octave band were realized by nearly all subjects from +4, respective -10 dB on. The perception of "big differences" seems to be caused by the existence of tonalness. Both sensations show a strong asymmetric behavior regarding <u>in</u>crease or <u>de</u>crease. Thus compared to the maximum tonalness for an increase of 20 dB, a decrease of the same amount achieves just 10 to 20 % of the maximum tonalness. With ascending tonalness however - no matter whether caused by an increase or by a decrease - the perceived sound quality is deteriorating.

Those data provide hints how future specifications of high-speed trains should be described.

Thus, due to the fact that deviations from the basic spectrum always decrease sound quality, specifications should hold tolerable deviations. From the given results a span of +5 / -10 dB in a single band around the basic spectrum can be recommended.

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