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A Generalized Psychoacoustical Model of Modulation Parameters (Roughness) for Objective Vehicle Noise Quality Evaluation

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ABSTRACT

In the assessment of vehicle noise quality, sound characteristics caused by modulation play an important role because they contribute significantly to the perceived annoyance. The sensations can be roughness, rumble or fluctuation strength depending mainly on the modulation frequency range.

The proposed generalized model for modulation parameters was developed as part of a research program with the aim of establishing an onboard analysis system for vehicle interior noise quality based on objective sound parameters. The model can be adjusted by model parameters to calculate versions of roughness, thereby accentuating different psychoacoustical assumptions. The model was successfully tested as reported in [1].

INTRODUCTION

In the procedure of improving vehicle interior noise quality, most car manufacturers evaluate their vehicles by cost intensive subjective assessments of experts. In order to reduce this time-consuming method of subjective assessment, a measurement system was developed for noise quality evaluation [2] based on objective sound parameters such as the psychoacoustical entities: loudness, sharpness, tonality, impulsiveness and roughness. The new tool establishes a noise quality map for passenger cars covering all operating conditions. Results of regression analysis show that in most of the cases, the subjectively perceived noise quality can be described by objective parameters with very high accuracy [2].

For some vehicles and operating conditions however, the expected high correlation coefficients could not be reached in our multiple regression analysis due to the fact that the available objective parameters were not appropriate. This is especially true for sensations caused by modulation such as roughness, fluctuation strength and rumble. All analytical desciptions of psychoacoustical roughness available from literature or instrumentation suppliers are based on algorithms which only partly correlate with subjectively perceived roughness. We have observed in numerous tests, concentrating on powertrain related vehicle interior roughness, that perceived roughness could be assessed by available methods only in the case of loudness differences. It seems that loudness correlates quite well with calculated roughness, which is a well known fact from psychoacoustical literature [3,4]. For noises with equal loudness however, the correlation between perceived and calculated roughness vanishes. As a typical example, figure 1 shows the missing correlation for a sample of 9 noises [1].

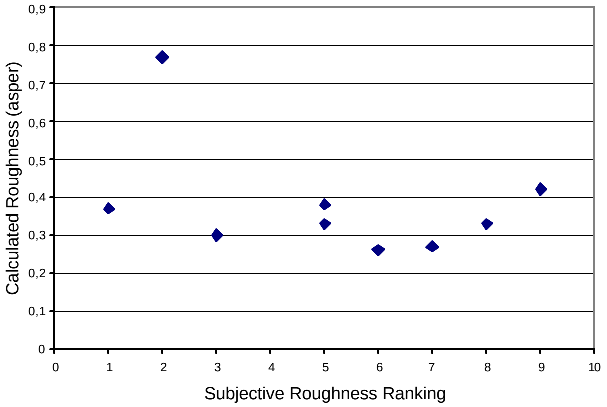

Figure 1. Correlation of subjectively perceived vehicle interior roughness with calculated results

In this paper we present a generalized psychoacoustical model of modulation parameters which is based on existing approaches in [5,6,7], but can be particularly adjusted to assess the roughness perception of vehicle interior noise. The model was successfully tested in predicting roughness assessment as reported in the companion papers [1, 2]. The model was developed as part of a research program in collaboration with AVL LIST GmbH, the Institute of Applied Systems Technology and the Institut of Applied Statistics of Joanneum Research as well as the College of Vehicle Technology in Graz.

STRUCTURE OF THE ROUGHNESS MODEL

Our roughness model is based on the excitation-time pattern of the interior car sound which is recorded using an artificial head system. The excitation-time pattern takes into account the properties of the perpherial auditory system, such as the outer-middle ear filtering, the nonlinear masking properties and absolute threshold. From the excitation-time pattern, a set of specific roughness parameters in overlapping critcal bands is obtained utilizing the effective modulation index in each band. The modulation index is determined by various weighting functions for the envelope spectrum. The specific roughness parameters in critical bands are superimposed in several ways by taking into account the envelope correlation between adjacent bands. This results in a set of modulation parameters for every 100 ms.

THE EXCITATION-TIME PATTERN

The excitation pattern is extracted from a 170ms signal frame for every 100ms. The FFT spectrum of the frame is multiplied by a transmission factor which represents the filtering due to the outer and middle ear. For frequencies above 1kHz, the filter mimicks the inverse absolute threshold. For frequencies below 1kHz, the appropriate filter contour is a matter of discussion. Some authors argue in favor of a flat filter [8] (solid line in fig.2), while newer proposals use the inverse 100 phon curve [9] (broken line in fig.2). Our model offers both possibilities. To calculate the excitation pattern for each frequency component, the spectrum is transformed to the critical band rate scale z in Bark [10]. The excitation $L_E(z)$ within a single frame is obtained using the pattern slopes:

$$S_l = -27 \frac{dB}{Bark} \qquad \text{Eq1}$$

for the lower slope and

$$S_u = [-24 - \frac{0.23\ kHz}{f} + \frac{0.2L}{dB}] \frac{dB}{Bark} \qquad \text{Eq2}$$

for the upper level dependent slope (f and L depicting component frequency and level). The excitation pattern is analysed in a filterbank containing 47 overlapping bandpass filters with bandwidths of 1 Bark. Excitations below the absolute threshold at a filter position do not contribute to the filter output. The calculation scheme of the excitation pattern is depicted in fig.2.

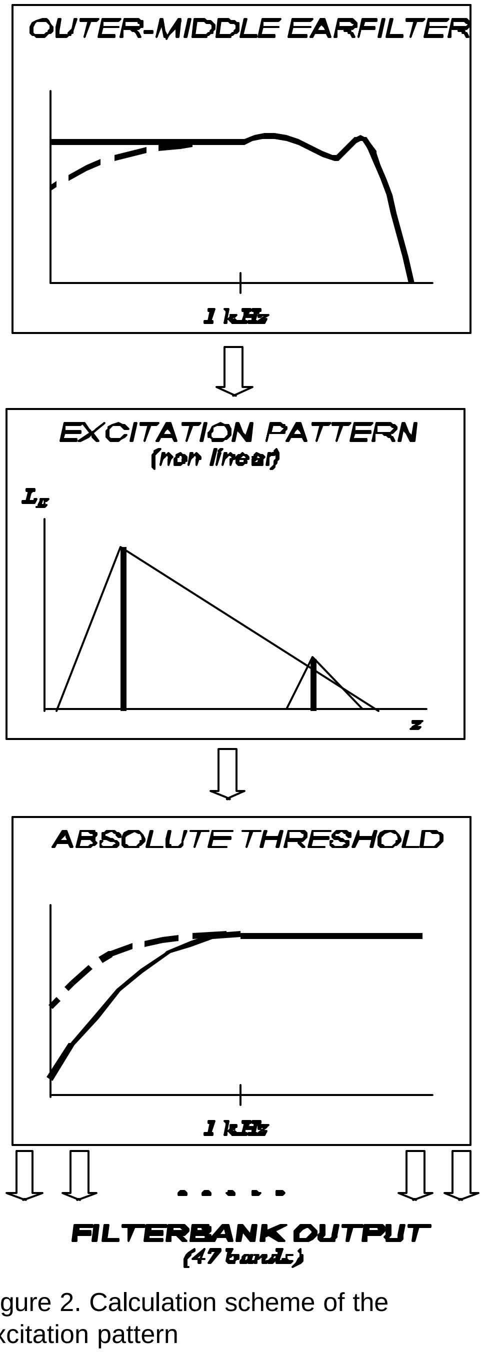

Figure 2. Calculation scheme of the excitation pattern

In the model proposed in [5,6,7] the level L of each single spectral component (FFT bin) is used to determine the inclination of the appropriate upper slope S_u and therefore the spread of excitation over frequency. This method does not take into account the property of the auditory system to integrate spectral energy over a critical band. It is known from psychoacoustical research that narrow band noise causes the same pattern of excitation as a sinusoidal tone of equal level [8]. The difference is explained by the following example. Assume an amplitude-modulated 450 Hz tone with a modulation frequency of 30 Hz and a modulation index m=1. The level of the carrier is 70 dB. The resulting spectrum contains a 64 dB-component at 420 Hz (z=4.2 Bark) , a 70 dB-component at 450 Hz (z=4.5 Bark) and another 64 dB-component at 480 Hz (z=4.8 Bark). Considering each spectral component separately, the pattern slopes S_u are -11.7, -10.5, and -11.7 dB/Bark respectively resulting in a excitation at the bandpass filter centered at z_i=8 Bark of 19.4, 33.3 and 26.6 dB (fig.3).

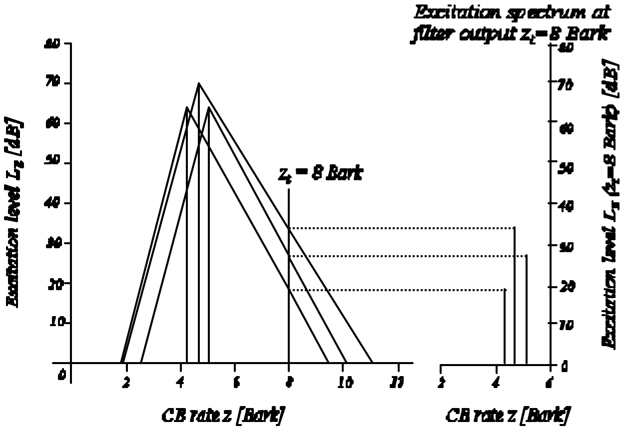

Figure 3. Excitation pattern for AM, slopes are calculated for each component separately

If we utilize the summation level of the 3 components (71.8 dB) for calculating the slope after Eq.2, we obtain approximately S_u= -10.1 dB/Bark for every component. The resulting excitation at z_i=8 is 25.3, 34.5, and 31.6 dB (fig.4).

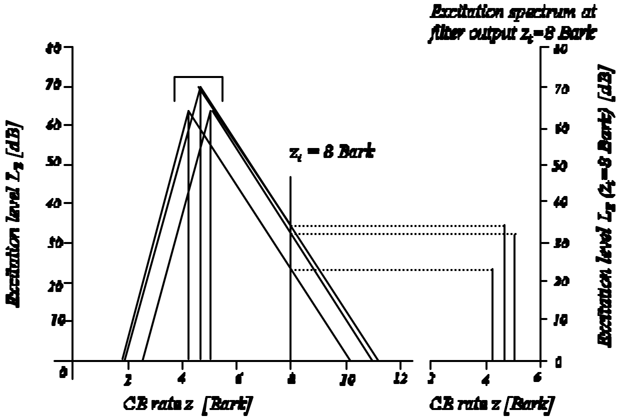

Figure 4. Excitation pattern for AM, slopes are calculated from the summation level.

In order to compare the 2 approaches, we included both excitation patterns in our generalized model.

CALCULATION OF THE MODULATION INDEX

The sensation of roughness depends strongly on the modulation frequency. To account for this fact, the envelope spectrum in each critical band has to be weighted by using appropriate filters. The effective modulation index m_i for z_i is obtained by dividing the RMS-value of the weighted envelope by the envelope´s DC-value before weighting $e_{DC}(z_i)$.

The crucial point is the choice of the weighting filters. As we found in listening tests, applying the popular filter functions proposed in [5] does not lead to the perceived roughness values. These bandpass filter shapes depend on the carrier frequency as can be seen in figure 5.Considering the particular characteristics of vehicle interior noises, we developed two weighting filters which are both independent of the carrier frequency. Adopting the proposals in [11,12], one type utilizes a low frequency weighting by accentuating modulation frequencies between 20 Hz and 40 Hz (broken line in fig.6). The broadband variant covers the modulation frequency range from 25 Hz to 90 Hz (solid line in fig.6).

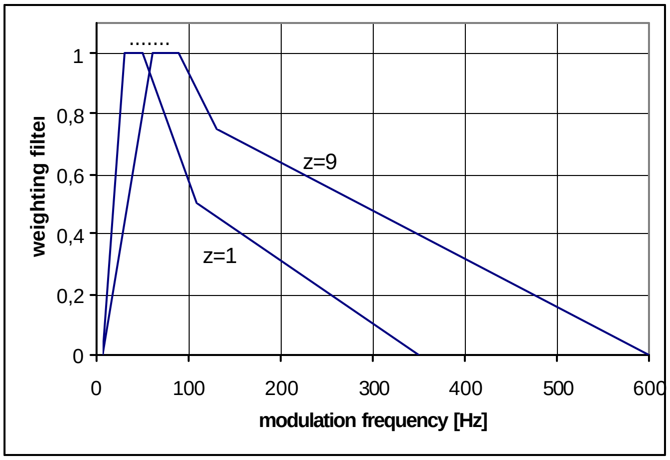

Figure 5. Bandpass weighting filters as proposed in [6]

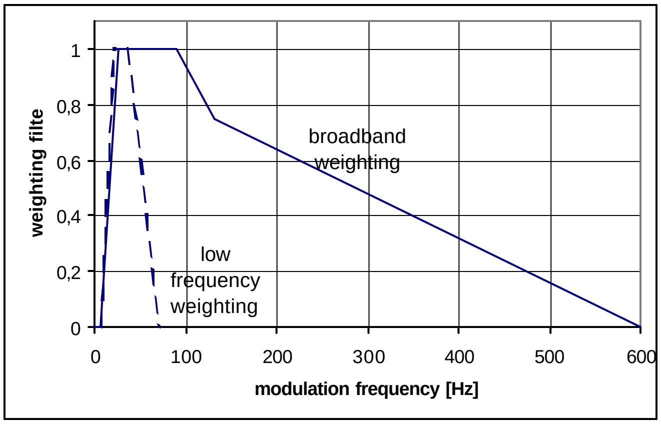

Figure 6. Frequency independent weighting filters

SUPERPOSITION OF SPECIFIC ROUGHNESS

The specific roughness in each band r_i is estimated using:

$$r_i = m_i^t \cdot g(z_i)^p \cdot e_{DC}(z_i)^q \qquad \text{Eq3}$$

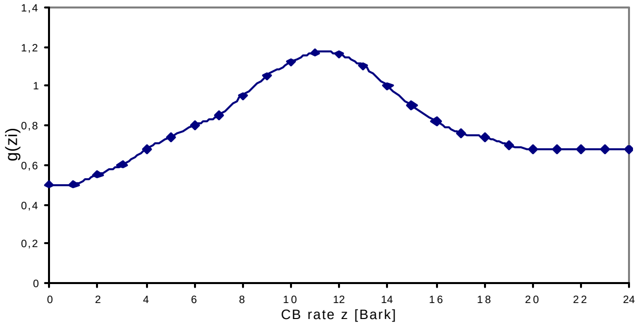

Figure 7. Weighting function $g(z_i)$ for carrier frequency according to [4]

with exponent t between 1.5 and 2 according to [3,7] and a weighting function $g(z_i)$ with exponent p between 0.5 and 2 which accounts for the dependence of roughness on the carrier frequency (see fig.7).

To improve numerical stability and fit the roughness model to hte results of ourlistening tests, we included the envelope´s DC-value $e_{DC}(z_i)$ with exponent q between 0 and 0.15 in the calculation of specific roughness. Up to this point, each band is considered independent from the neighbouring bands. A simple superposition of specific roughness would lead to an overestimation of perceived roughness especially for broadband noise. To obtain correct roughness values, one must take into account the correlation of the envelopes of adjacent critical bands. There are several proposals for the proper consideration of a critical band´s cross correlation with its lower and upper neighbours k_{i-2} and k_i [5,7]. So, we decided to use variants of monotonic transforms $T(k_i,k_{i-2})$ as a additional parameter of our model. Furthermore, we generalized the linear superposition introducing the superposition parameter s in

$$Roughness = C \cdot \sqrt[1/s]{\sum_i \left(r_i \cdot T(k_i,k_{i-2})\right)^s} \qquad \text{Eq4}$$

with calibration constant C. A parameter value s > 1 accentuates the more prominent roughness components compared to the average roughness leading to a psychoacoustically reasonable extension of our model.

CONCLUSION

In this paper we presented a generalized psychoacoustical model for modulation parameters which can be adjusted for the correct assessment of roughness present in vehicle interior noise. The model is based on two versions of the excitation-time pattern taking into account different psychoacoustical assumptions of the properties of the peripherial auditory system. To gain flexibility in the adjustment procedure, the model offers certain degrees of freedom in the calculation of the effective modulation index, the specific roughness, and the superposition. The model was successfully tested not only in predicting roughness assessment as reported in a companion paper, but it also proved to be a valid objective parameter for the noise quality map.

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