Roughness calculation utilizing envelope waveforms

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ABSTRACT

Psychoacoustical roughness refers to the tactile percept of rough surfaces related to an acoustical sensation. The presence of roughness influences many sound-quality aspects such as for example annoyance, comfort or the sportive character in a vehicle interior sound. A reliable calculation method for roughness predictions would be a very powerful tool in processes like sound design or sound analysis. Roughness perception depends on many acoustical parameters like modulation depth, sound level, audio frequency, modulation frequency or the shape of the modulating envelope waveform, which has not been taken into account in previous calculation methods. Also the temporal regularity of occurring modulations strongly affects the amount of perceived roughness. A new algorithm for roughness calculations based on a generalized hearing model will be presented taking into account all these dependencies for synthetic signals as well as several sound properties occurring in natural sounds. During development, the focus was set on vehicle interior noises as roughness can be seen as a sound feature governing attributes like “dynamic”, “sportive” or “comfortable”.

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1. INTRODUCTION

Perceived roughness depends on various basic signal parameters in case of synthetic signals, but will also differ for natural sounds. This results in a large variety of reference signals that need to be predicted by a roughness calculation algorithm. Processing different classes of signals such as for example synthetic AM-signals with and without variations in the envelope waveform or vehicle interior and exterior noises with a simple, hearing-model based approach does not reproduce subjective roughness ratings accurately enough. Therefore a more complex model was developed which explicitly accounts for the envelope waveform and other specific signal properties such as the temporal regularity of the modulation based on observations from subjective ratings.

2. ENVELOPE-SHAPE DEPENDENT ROUGHNESS

Previous studies about roughness perception show dependencies on modulation frequency, center frequency, level and modulation depth for pure tones modulated with a sinusoidal waveform [1]. Recent investigations also show changes in subjective roughness ratings for pure tones modulated with triangular waveforms with altering ratio between the rising and falling part [2].

2.1 Subjective Ratings

As a basis for a roughness detection algorithm utilizing envelope waveforms a listening experiment with 25 participants was carried out. A sinusoidal carrier signal with a frequency of 25 Hz was modulated with different waveforms. These waveforms consisted of 7 triangular waveforms with different portions of rising and falling flank ranging from 5% (damped) to 95% (ramped) rising flank.

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Additionally, waveforms which exchange the linear flanks of the triangular waveforms were exchanged with cosine-shaped flanks to create continuously differentiable waveforms. In an adaptive 2-alternative forced-choice procedure listeners were asked to choose the signal with higher roughness. One signal contained the test signal with one of the modulating waveforms described above, the other signal contained the reference signal modulated with the triangular waveform with 5% rising flank (damped). In the adaptive procedure the modulation depth of the reference signal was varied depending on the ratings such that it reached the same roughness as the test signal. Measuring thresholds for each different triangular envelope condition resulted in 13 pairs of signals with subjectively equal roughness. All single comparisons were presented in a randomized, interleaved order respectively to the test conditions.

Observing the mean results across all listeners, more asymmetric waveforms were matched to higher degrees of modulations of the reference signal, i.e. had a higher roughness than more symmetric waveforms. Also, the signals modulated with the cosine-shaped waveforms had a lower roughness than their pendants with triangular waveforms.

2.2 Envelope-Shape Dependent Model

Predictions from existing roughness models did not reproduce the results of this listening experiment, as well as the results from previously made studies[2]. This is the motivation for developing a new roughness calculation algorithm being able to cover these principle findings. As natural signals such as sounds from combustion engines also contain non-sinusoidally shaped periodic waveforms this approach may also provide improvements for general roughness predictions.

2.2.1 Detecting Differences in Envelope Shape

The basis for the calculation algorithm is formed by a simple hearing model consisting of a gammatone filterbank, half-wave rectification and lowpass filtering. The magnitude spectrum of the Hilbert envelope is then analyzed by summing up the components at the fundamental frequency and its overtones. This procedure leads to higher predicted roughness for modulated waveforms containing more dominant overtones which corresponds to the results from the listening experiment.

In Figure 1 calculated roughness values for the 13 pairs of subjectively equal roughness described in section 2.1 are shown. Considering that the predicted results are very close to the subjective ratings the detection algorithm seems well-suited to predict the effects of different envelope shapes.

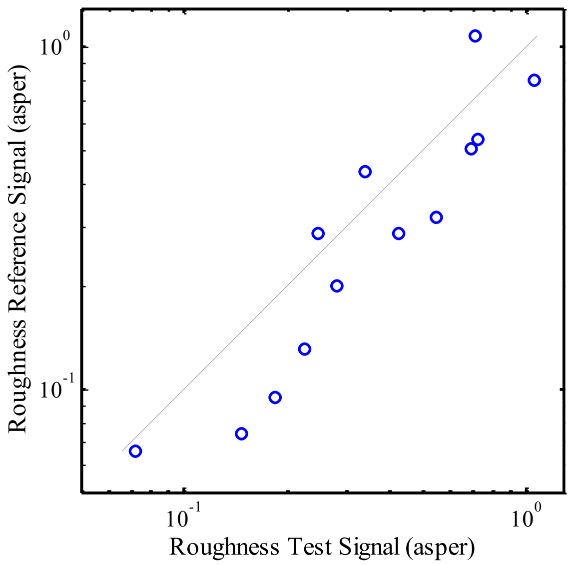

Figure 1: Calculated roughness for 13 signal pairs of subjectively equal roughness. The reference signals (y-axis) was varied in modulation depth, the test signals (x-axis) had varying envelope shape. The dashed line indicates equal roughness.

2.2.2 Other Basic Signal Classes

From literature, other dependencies of perceived roughness on several basic signal parameters are known[1]. By tuning the algorithm to these parameters a more general applicability of the calculation method is realized. This included tuning to the correct behavior for altering signal levels as shown in Figure 2. For the dependency on the modulation depth an exponent was introduced which ensures correct behavior for this signal class. Adding filters in the envelope domain and weighting factors depending on the center frequency of the auditory channel provides predictions being in line with subjective ratings for altering center- and modulation frequencies for AM-sinusoids (Figure 3). It showed that no further tuning for ratings of FM-sinusoids was needed as the algorithm already showed correct behavior for these signals.

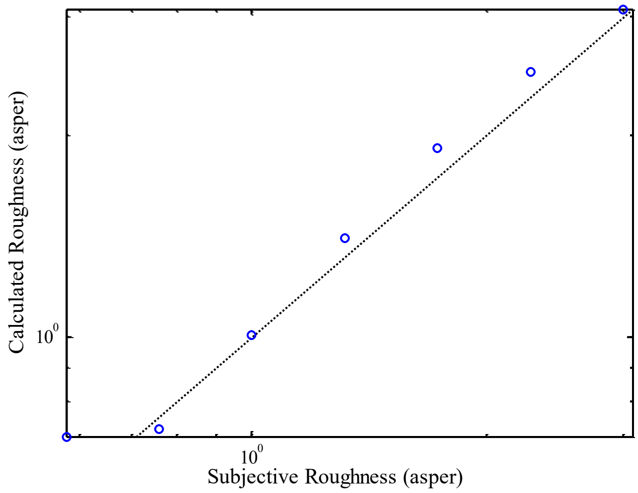

Figure 2: Roughness calculations (y-axis) and generalized subjective ratings (x-axis) for amplitude modulated 1 kHz pure tones with a modulation frequency of 70 Hz varied in sound level from 40 to 100 dB SPL in steps of 10 dB

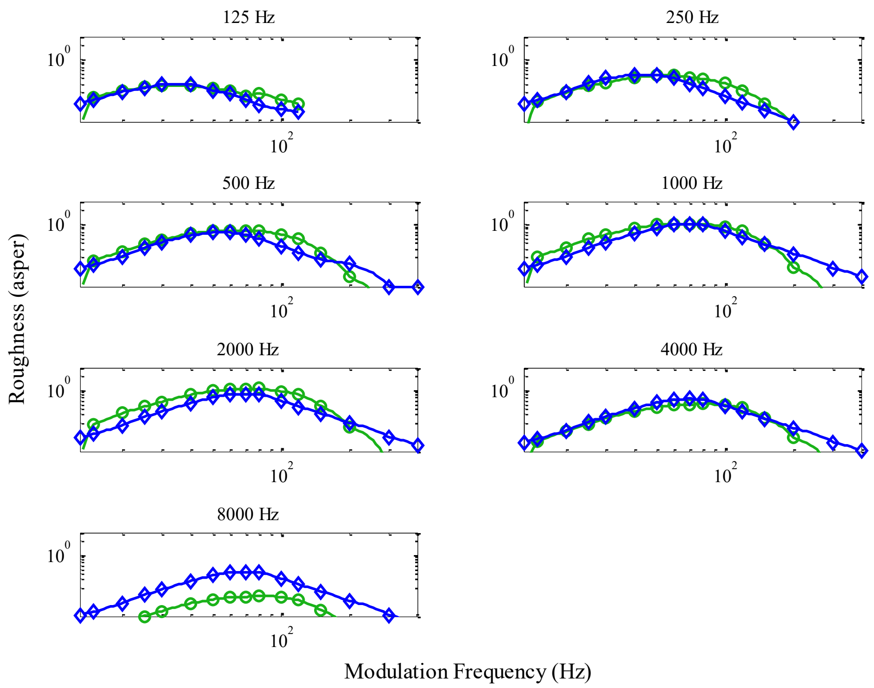

Figure 3: Generalized subjective ratings[1] (blue) and calculated roughness (green) for AM-sinusoids with different center frequencies (different panels) and modulation frequencies (x-axis)

3. ROUGNESS FOR VEHICLE SOUNDS

Artificial sounds provide the possibility of systematically tuning the behavior of an algorithm with respect to several basic signal parameters. The main application of a roughness calculation algorithm however lies in the analysis of more complex natural or machinery sounds for quality rating and sound design processes.

A set of 30 stationary vehicle sounds was rated in roughness on a scale from 1 to 11 by an expert collective of 20 listeners. The set consisted of 10 signals from each of the 3 different operating conditions engine idle recorded outside the vehicle, engine idle recorded inside the vehicle and driving at a constant speed of 60 km/h recorded inside the vehicle.

The calculated results showed good correlations with the subjective ratings for the engine idle conditions but came out too high for the driving at a constant speed condition which had basically low roughness ratings. A close inspection of these signals showed that, in contrast to other signals, the dominant modulation frequencies detected in the consecutive 0.3 s time steps of the roughness analysis were fluctuating over time. As wind noises in these signals provided randomly distributed modulations which are not perceived as rough due to their irregular character a statistical approach came out to be well-suited for this problem.

Over a period of 1.5 s the distribution of dominant modulation frequencies in each overlapping time window is calculated. From this statistics, the Shannon entropy[3] can be seen as a measure of regularity. Using this measure as a weighting factor provides a good possibility to take the random character of modulations occurring in many natural signals into account. Figure 4 shows the result of this weighting providing calculations being in line with subjective ratings for three classes of machinery sounds.

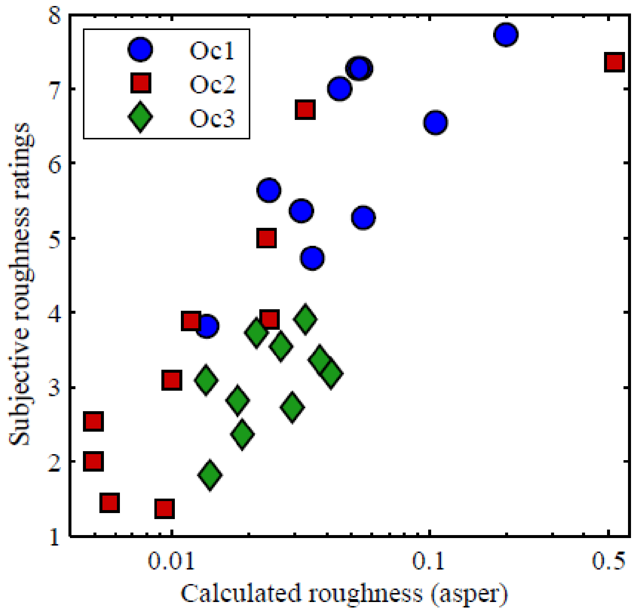

Figure 4: Roughness calculations (X-axis) and categorical subjective ratings (Y-axis) for vehicle sounds in three different operating conditions: engine idling recorded outside (Oc1, blue circles) and inside (Oc2, red squares) the vehicles and driving at a constant speed of 60 km/h (Oc3, green diamonds). The correlation coefficient of the calculations and the ratings is 0.79.

4. CONCLUSION

The newly developed roughness calculation algorithm utilizing modulating waveforms provides good results for a large variety of signal classes containing synthetic and natural sounds as all calculations shown in Figures 1-4 were made with one single set of parameters. Specific elements that contributed to the predictive power of the model are the auditory motivated pre-processing, the evaluation of the envelope spectrum which included modulation spectral weighting, and the use of an entropy measure to include the effect of stochastic variations in the envelope spectrum.

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