

Modeling Engine Roughness

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ABSTRACT

Clearly, sound quality evaluation has become a central focus for assuring customer satisfaction. To achieve an optimized product sound at an early stage of development, subjective evaluation methods must be combined with analysis and prediction tools to provide reliable information relevant to product quality judgments. Some years ago, a "Hearing Model" was developed explaining and describing many psychoacoustic effects [1], [2], and allowing for roughness calculation in accordance with subjective listening tests [3]. Existing roughness models work well for synthetic signals such as modulated tones or noise signals, but it is challenging to predict roughness for engine sounds because of their more complex spectral and temporal noise patterns [4].

INTRODUCTION

Roughness has become a very important task for product sound design. The roughness-induced perception, varying from a sporty character to a very unpleasant impression, consistently proposes new questions and challenges in sound engineering. Additionally, there is demand for tools to predict engine roughness inside the vehicle based only on measurements of the engine on a test bench, or even based on purely simulated data. The well-known methods of **B**inaural **T**ransfer **P**ath **A**nalysis and **S**ynthesis (BTPA/BTPS), developed and refined during the past decade, can be used successfully for predicting interior sounds based on measurements of excitation source strengths (on an engine test bench or in a full vehicle) and the corresponding transfer paths to a receiver position (e.g. the driver position) [5].

This paper starts with an overview of the Hearing Model. Then a description of the roughness analysis based on the Hearing Model is given and validated, followed by first results of an ongoing study related to just-noticeable roughness differences of both synthetic signals and engine sounds.

The engine sounds were achieved and modified using BTPA and BTPS techniques. This approach offers new sound design possibilities by virtually changing the transfer paths. The effects of the modifications on the vehicle interior sound can be analyzed in the early design phase. Results of engine roughness prediction and subjective evaluations are presented.

THE HEARING MODEL

The Hearing Model was born out of a widespread interest to have one standardized psychoacoustic model. There are currently several models available, such as Zwicker Loudness, which address a single psychoacoustic phenomenon. The Hearing Model describes and explains many phenomena at once. The Hearing Model is based on the physiology of human hearing and has been validated by testing against previously-conducted psychoacoustic research results. The basic processing steps of the Hearing Model (shown in Figure 1) are described in the following.

The pre-processing consists of filtering with the outer ear-inner ear transfer function. An ear-related filter bank consisting of asymmetric bandpass filters which are implemented using equivalent lowpass filters (with a high degree of overlapping) model the frequency-dependent critical bandwidths and the frequency-to-place transform of the inner ear which mediates the firing of the auditory

hair cells as the traveling wave from an incoming sound event progresses along the basilar membrane. The increasing bandwidth versus frequency of the auditory filter bank conveys a high frequency resolution at low frequencies and a high time resolution at high frequencies. The very small product of time and frequency resolution at all frequencies empowers, for example, human hearing's recognition of short-duration low-frequency events.

Subsequent processing steps are envelope formation (using the Hilbert transform), consideration of the frequency-dependent threshold in quiet by a reduction of excitation level (approximately 20 dB/decade for frequencies below 500 Hz) and temporal integration using 3rd-order-lowpass filters. The cutoff frequency of these filters is frequency-dependent and is about 120 Hz at 1 kHz. The low-pass filtering accounts for the fact that the human ear cannot track envelope fluctuations faster than a certain rate.

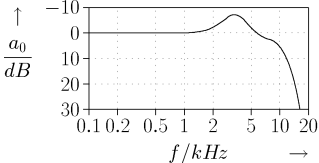
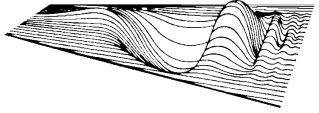
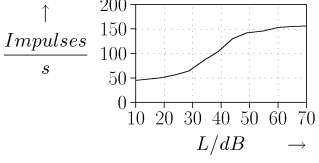
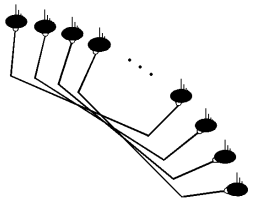
Human Physiology	Hearing Model
 Outer and middle ear	Outer and middle ear filtering (preprocess)
 Basilar membrane, traveling wave	Ear-related filter bank using band-pass filters which are implemented using equivalent low-pass filters; formation of envelope, consideration of the frequency-dependent threshold in quiet by a reduction of excitation level
 Hair cells, firing rates	The nerve cell firing rates follow the signal magnitude curve only up to a maximum frequency, modeled in a simplified manner by a 3 rd -order-low-pass filter. In an additional step, the individual bandpass signals are processed using a non-linearity as a function of the level of the exciting signal.
 Brain, neural processing	Other neural processing of the brain follows in the human hearing system, resulting in the different sensations such as loudness, roughness, impulsiveness, and pitch detection. Specific mathematical algorithms, such as spectral deconvolution in the case of pitch detection, are employed to describe these effects.

Figure 1: Steps of the human hearing process (top to bottom)

The Hearing Model spectrum vs. time (Figure 2, frequency scaling is shown in Bark (critical band number)) is accessible as an intermediate result before implementing additional nonlinear processing for calculating the basic auditory sensations such as loudness, roughness, impulsiveness, and pitch detection, making the algorithm's time/frequency capabilities available as a linear tool comparable to conventional techniques for events even at sound pressures beyond normal human hearing perception limits.

ROUGHNESS SENSATION

The roughness sensation occurs whenever a time-variant envelope exists within a critical band; for example, when tones exhibit a temporal structure due to a variation of their amplitude or frequency. With

increasing roughness, noise emissions are perceived as increasingly noticeable and usually as increasingly aggressive and annoying, even if the loudness remains unchanged. In the case of slow envelope variations (below 15 Hz), the human ear is capable of tracking the loudness changes, resulting in an impression of a fluctuation. With increasing modulation rate, other sound impressions are perceived, such as "R-roughness" (for rates around 20 Hz), which then changes into the actual roughness impression, where the ear is no longer capable of tracking the individual temporal changes. Sounds with envelope variation rates between 20 and 300 Hz are perceived as rough. Above these rates, the main spectral line and sidebands of pure amplitude-modulated tones become audible as individual tones. The roughness depends on the center frequency of the sound, the modulation rate and the modulation depth.

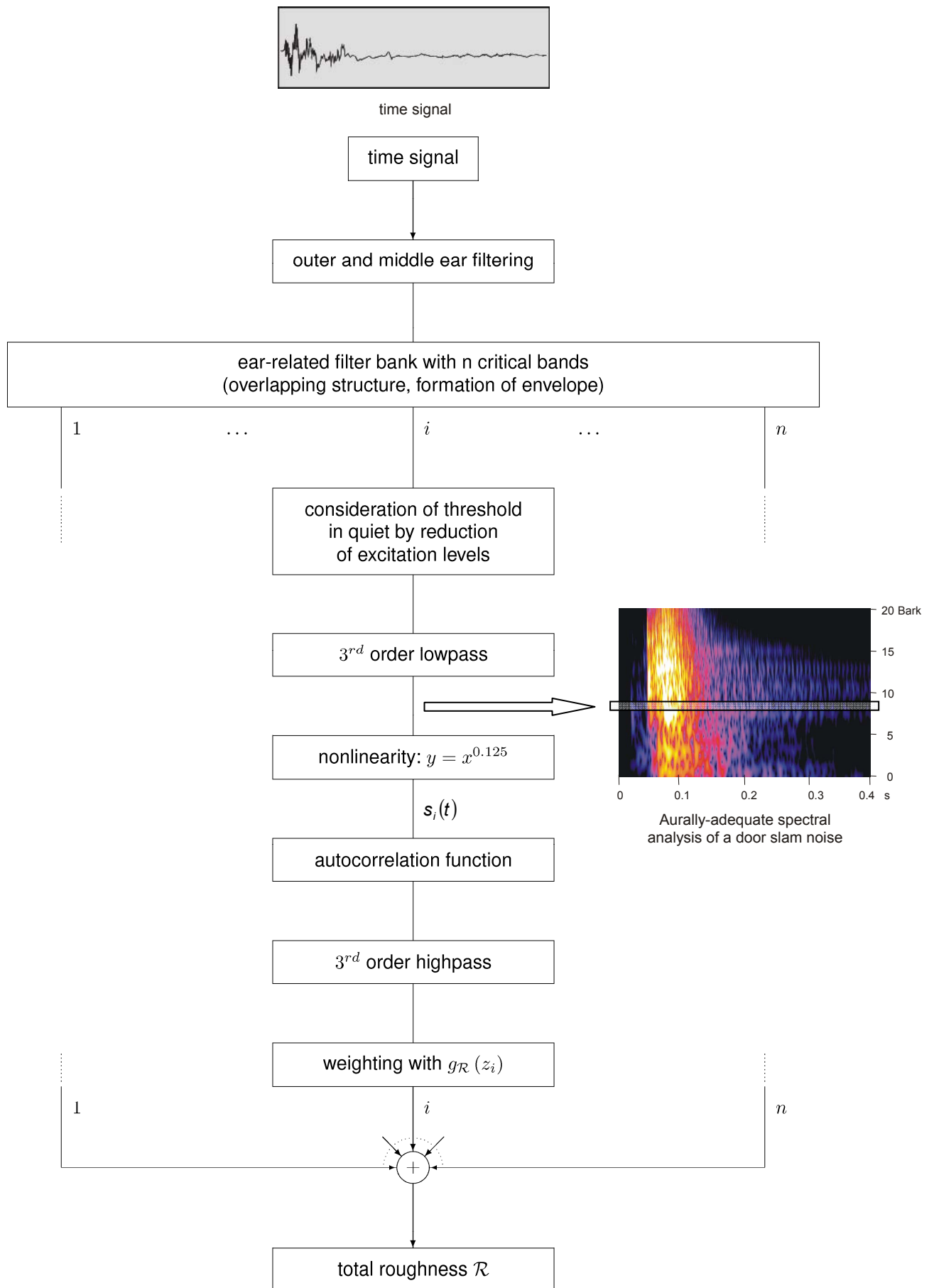


Figure 2: Functional block diagram of roughness calculation.