Variations of the Leaky-integrator Model and Validation with Detection of Sinusoidal and Percentage Duty-cycle Modulated Noise

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Abstract: The leaky-integrator model is commonly used to describe auditory temporal processing. In the current study, the low-pass filter and decision device of the model were investigated. Maximum-to-minimum envelope magnitude, rms envelope power, envelope fourth moment, and envelope crest factor were implemented as possible decision devices (1, 2). Model predictions demonstrated interaction between the decision device and low-pass filter cutoff frequency. To validate model variations, detection thresholds of sinusoidal and percentage duty-cycle modulated broad-band noise were measured at octave frequencies 2 – 512 Hz for listeners with normal hearing. The data show low-pass filter characteristics across all modulation functions. A two-line regression fit of the data revealed that the crossover frequency, slope, and amplitude varied as a function of the duty-cycle modulation function. As the data points available to the two-line regression fit were limited, the method may not have the necessary precision to validate one model over another. Subsequently, an SSE procedure was utilized to differentiate between the model variations. The results indicated that some model variations are more accurate in predicting psychophysical thresholds and provide insight into the limitations of auditory coding of complex amplitude modulations.

INTRODUCTION

Essentially all acoustic signals contain amplitude fluctuations which can be described in terms of the carrier and modulation components. As both components are important for perception, it is valuable to understand how the auditory system processes them. This study concentrated on the auditory coding of amplitude modulations of acoustic signals. The leaky-integrator model has been proposed (1, 3) to explain the psychophysical measurements obtained from an amplitude modulated noise stimulus. The model consists of a band-pass filter, half-wave rectification, a low-pass smoothing filter, and a decision mechanism.

In the current study, a computer simulation of the leaky-integrator model was developed within the MATLAB® environment. A first-order Butterworth band-pass filter (2-8 kHz) was implemented followed by a half-wave rectifier. The low-pass smoothing filter was first-order Butterworth with cutoff frequencies evaluated at either 50, 100, 150, or 200 Hz. The decision mechanisms were either the maximum-to-minimum envelope magnitude, rms envelope power, envelope fourth moment, and envelope crest factor which were found to be successful previous model predictions of temporal fluctuations by Strickland and Viemeister (1).

The goal of the current study was to determine which of the model variations (low-pass filter and decision mechanisms) were valid for the prediction of sinusoidal and percentage duty-cycle rectangular functions. The refinement of the leaky-integrator model would further the understanding of how the auditory system processes temporal modulations and assist in the implementation of acoustic-signal processing schemes.

METHODS

The stimuli were created digitally using the continuous time relationship,

\[ y(t) = c(dB_{md}) \times [A + k \times m(t)] \times n(t) \]

where \( y(t) \) is the modulated signal, \( c(dB_{md}) \) is an average power compensation factor as a function of modulation depth (\( dB_{md} \)), \( A \) is a DC shift (\( A = 1 \)), \( k \) is the amplitude of the modulation function (0 ≤ \( k \) ≤ 1), \( m(t) \) is the modulation function, and \( n(t) \) is the carrier signal. The modulation functions consisted of sinusoidal and 10, 20, 30, 40, 50 (square), 60, 70, 80, and 90 % duty-cycle rectangular functions. Modulation frequencies were octave steps between 2 – 512 Hz. The average overall rms power was compensated to be equal to that of the

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unmodulated noise. To further ensure that subjects were responding to temporal cues, an intensity roving technique was also implemented. Detection thresholds were obtained with a three-interval forced-choice paradigm and a two-down, one-up adaptive procedure to estimate 70.7% point on the psychometric function (4). Original step size was 4 dBmd and after two reversals, it was reduced to 2 dBmd. A listening block consisted of 12 reversals and threshold was estimated by averaging the last ten reversal points. Three thresholds were obtained at each condition for each of the three individuals with normal hearing who participated in the study.

RESULTS / DISCUSSION

Thresholds were predicted by all model variations (low-pass filter and decision mechanism) for all conditions with three repetitions. The general shape was a low-pass filter when plotted as a function of detection threshold (in dBmd). The behavioral threshold measurements were also characteristic of a low-pass filter. In other words, all variations of the model support the behavioral thresholds results which indicate that the auditory system has equal sensitivity to low frequency modulations (pass-band region) and greater modulation depths are required for detection of higher modulation frequencies (transition-band region) for a given modulation function. The crossover frequency between the pass-band and transition-band regions is not constant across modulation functions as a lower crossover frequency is seen as duty cycle is decreased to 10% or increased to 90%. Further, the modulation depth required for the pass-band region was greater for shorter duty cycles and especially greater duty cycles, i.e. a less sensitive overall function.

Data from previous investigations (e.g., 1, 2) have used subjective measurements to determine the descriptive characteristics of the detection functions. In an attempt to find an objective measurement for data comparison, a two-line regression method was used and the crossover frequency, slope and amplitude of the modeled and psychophysical measurements were calculated and compared. Due to the limited number of modulation frequencies, the potential error was variable and thus, the measurements were not stable. Another analysis technique was then implemented where a sum of the squared residuals (SSE) was calculated as the difference between the modeled and psychophysical data. These values indicate that some of the model variations are better estimates of the psychophysical measurements than other model variations. The presentation will focus on the subjective differences and the objective analysis techniques that have been explored.

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REFERENCES