AUDITORY PERCEPTION OF AMPLITUDE MODULATED SINUSOID USING A PURE TONE AND BAND-LIMITED NOISES AS MODULATION SIGNALS

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ABSTRACT

Frequency selectivity in amplitude modulated sound have been reported in terms of modulation threshold level for amplitude-modulation detection, where a pink or white noise carrier was modulated with a sinusoid and band-limited white noise, which showed similar band-pass type masking characteristics. Such previous studies treated limited white noise carriers; the detection level increases around 16Hz when the 1000Hz sinusoidal carrier is modulated by 16Hz pure tone and band-limited white noise, and the increase is localized around 16Hz within 1 to 1.5 octave wide.

1. INTRODUCTION

Many investigations about frequency selectivity in amplitude modulated sound have been reported. Houtgast (1989) investigated modulation threshold level for amplitude-modulation detection, where a pink noise carrier is modulated with a sinusoid and band-limited white noise. It said that the detection level increases around 8Hz when the carrier is modulated by 8Hz pure tone and band-limited white noise, which has the same center frequency as the tone. And the increase is localized around 8Hz within 1/2 - 1 octave wide. The similar results were observed for 4Hz and 16Hz modulations. Bacon and Grantham (1989) showed a similar band-pass type masking characteristics in amplitude-modulation detection, where the broadband white noise carrier is modulated two sinusoids. Dau and et al (1996,1997) proposed an idea of modulation filter bank based on their study about amplitude modulation to narrow band white noise carrier. Such previous studies treated the same band limited white noise carriers.

In this paper, an amplitude-modulation detection level is measured in the case of sinusoidal carrier. Though amplitude modulation to a pure tone with a sinusoid may cause some unexpected cues for the detection, the result in the paper shows the similar amplitude-modulation detection characteristics for sinusoidal carrier.

The sounds for stimulus are amplitude modulated sinusoids of 1000Hz. They are modulated by 16Hz sinusoid and band limited white noise that has the same center frequency as the sinusoid. While the amplitude of 16Hz sinusoid is a constant, the power density of the noises may have eight levels in the pass-band against the sinusoid. The bandwidth has nine levels from 0 to 4 octaves with 1/2 octave step. These stimuli are called B-sounds, while the stimuli without 16Hz are called A-sounds. In experiments, subjects should judge whether these sounds are same or not for the randomly presented 72 pairs of stimuli. Considering the 72 pairs as a set, each subject makes judges for four sets of stimuli, and the last three sets are analyzed. When A-sound and B-sound are perceived same, it is supposed that the 16Hz pure tone would not be perceived. The results indicated that there exists a masking characteristic of 1 - 1.5 octave wide band-pass-type. In addition, the masking characteristics do not affect beyond the above bandwidth, and the amplitude-modulation detection level remains constant. This means that frequency selectivity still exists in amplitude-modulation detection for sinusoidal carrier.

2. EXPERIMENTS

In this section, amplitude-modulation detection level is measured in the case of sinusoidal carrier. First, stimuli used in the experiments are prepared, then a protocol for listening and judgment is explained, and finally, results in the experiments are summarized.

2.1. STIMULI

The sounds for stimulus are made by amplitude modulation of 1000Hz pure tone. The modulation signal is composed of 16Hz pure tone and band limited white noise that has the same center frequency as the tone. The power density of the noises is constant in the pass-band, and each level is one of eight steps between -16 dB and -30dB from the tone. The bandwidth is prepared from 0 to 4 octaves with 1/2 octave step. These stimuli are called B-sounds, while the stimuli without 16Hz are called A-sounds. Figure 1 demonstrates the modulation frequency structure of both sounds. These sounds are represented by

\[ s(t) = (1 + m \cdot x(t)) \cos(2\pi f_c t), \]

where \( f_c = 1000 \text{Hz}, \) \( m = 0.3, \)
soundB for \( tkNA \) and Hz16 = amf. The band-pass white noise (tkN), has a bandwidth represented by index \( k \). Table 1 shows the relation between bandwidth and \( k \). The sampling frequency is 20kHz. Each stimulus has 10msec long tapers at the beginning and the ending. Two sets of the combination of A-sound and B-sound are prepared, from which each pair of sounds is selected randomly in the experiments to avoid some unexpected effects that will be caused by matching the phases of two sinusoids. In this experiment, the maximum bandwidth is 60Hz in order to avoid the interferences from the adjacent auditory filters. The critical bandwidth for 1000Hz is about 160Hz, while the bandwidth of stimulus at \( k = 8 \) is 120Hz; 60Hz in both upper side and lower side of 1000Hz, therefore bandwidths wider than 2 octaves are not used.

2.2. PROTOCOL

In experiments, A-sound and B-sound are presented for 2sec, respectively, with 2sec long rest in this order. Figure 2 indicates the protocol in this experiment. For the randomly presented 72 pairs of stimuli, subjects should judge whether these sounds are same or not. Considering the 72 pairs as a set, each subject makes judges for four sets of stimuli. Since the first set is used as training set, the last three sets are analyzed as the result of the experiments. The subjects are three males and two females, who are 22 years old. Each subject hears the sounds through a headphone (SENNHEIZER, HD265 linear) with left ear. The level is previously set every set of stimuli so that the subject can perceive both the largest and smallest band-pass white noises enough. Since some of the stimuli are close to pure tone, hearing performance of the subjects may be fatigued with such stimuli. Then subjects take a rest in three minutes at the middle of each set.

When A-sound and B-sound are perceived same, it is supposed that the 16Hz pure tone would not be perceived, and then it is considered that the combinations of bandwidth and power level that the difference of the sounds is perceived at 50% or more in the average is meaningful. In this paper, such combinations are taken account.

2.3. RESULTS

The judgments by the five subjects were summarized, and the average ratio they can perceive the difference between A-sound and B-sound was calculated for each combination of amplitude ratio and bandwidth. Table 2 shows the average ratio to

Table 1: Bandwidth corresponding to index \( k \)

<table>
<thead>
<tr>
<th>Index ( k )</th>
<th>Bandwidth [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>1</td>
<td>5.6</td>
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<tr>
<td>2</td>
<td>11</td>
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<td>3</td>
<td>17</td>
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<td>7</td>
<td>49</td>
</tr>
<tr>
<td>8</td>
<td>60</td>
</tr>
</tbody>
</table>

\[ x(t) = \begin{cases} \frac{A \cdot N(k,t)}{\cos(\pi f_{am}t)} + A \cdot N(k,t), & \text{for A-sound} \\ A \cdot N(k,t), & \text{for B-sound} \end{cases} \]

and \( f_{am} = 16 \text{Hz} \). The band-pass white noise \( N(k,t) \) has a bandwidth represented by index \( k \). Table 1 shows the relation between bandwidth and \( k \). The sampling frequency is 20kHz. Each stimulus has 10msec long tapers at the beginning and the ending. Two sets of the combination of A-sound and B-sound are prepared, from which each pair of sounds is selected randomly in the experiments to avoid some unexpected effects that will be caused by matching the phases of two sinusoids. In this experiment, the maximum bandwidth is 60Hz in order to avoid the interferences from the adjacent auditory filters. The critical bandwidth for 1000Hz is about 160Hz, while the bandwidth of stimulus at \( k = 8 \) is 120Hz; 60Hz in both upper side and lower side of 1000Hz, therefore bandwidths wider than 2 octaves are not used.
distinguish the sound with each combination. When $k = 0$,
there is no band-pass white noise, and then all subjects can
perceive the difference between A-sound and B-sound for any
amplitude level. On the other hand, when $k = 8$, there is
enough band-pass white noise, and then the score becomes
worse. As $k$ increases, the perception of the difference
becomes hard. In the case of the same bandwidth, the
perception of the difference becomes hard as the amplitude ratio
increases.

### 3. DISCUSSIONS

From Table 2, Figure 3 plots the relation between amplitude
eratio and bandwidth index $k$ as the threshold level of 50% or
more difference perception ratio. When $k = 3$ in Table 2,
there are two candidates for threshold level: one is $-18$dB and
the other is $-26$dB. In this case, $-26$dB is selected because this
is considered to be the sufficient level for us not to perceive the
difference. When $k = 8$, there is no amplitude level for the
threshold level in average. In this case, the bandwidth of the
stimuli is close to the critical bandwidth of 1000Hz, so
interferences from the adjacent auditory filters exist, which
might make the difference perception hard.

From Figure 2, the threshold of amplitude level tends to
decrease in general as the bandwidth increases. This means
that the amplitude level should be made small to perceive the
16Hz pure tone. When the bandwidth is wider than that of $k = 3$,
the threshold level is almost constant of $-28$dB. In this area,
the perception to the 16Hz pure tone does not vary with
respect to bandwidth. These characteristics indicate that
certain critical band subjects the perception of a modulation
sinusoid. In this case, the critical bandwidth is lied between
$k = 3$ and $k = 4$. Figure 4 and Figure 5 show the amplitude
thresholds of 67% and 75% difference perception ratio,
respectively. They also have similar characteristic bandwidth
in the same range. The results indicated that there exists a
masking characteristic of 1 - 1.5 octave wide band-pass-type.
In addition, the masking characteristics do not affect beyond the
above bandwidth, and the amplitude-modulation detection level
remains constant.

Studies about frequency selectivity in amplitude modulated
sound by Houtgast (1989) showed modulation threshold levels

<table>
<thead>
<tr>
<th>Index of bandwidth</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<tbody>
<tr>
<td>Amplitude [dB]</td>
<td>-16</td>
<td>100</td>
<td>33</td>
<td>27</td>
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<td>13</td>
<td>13</td>
<td>7.0</td>
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<tr>
<td></td>
<td>-18</td>
<td>100</td>
<td>80</td>
<td>60</td>
<td>53</td>
<td>13</td>
<td>7.0</td>
<td>0.0</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td>-20</td>
<td>100</td>
<td>93</td>
<td>60</td>
<td>33</td>
<td>33</td>
<td>7.0</td>
<td>33</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td>-22</td>
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<td>100</td>
<td>93</td>
<td>80</td>
<td>67</td>
<td>53</td>
</tr>
</tbody>
</table>

Figure 3: Amplitude ratio v. bandwidth index
(threshold at 50%)

Figure 4: Amplitude ratio v. bandwidth index
(threshold at 67%)

Figure 5: Amplitude ratio v. bandwidth index
(threshold at 75%)
for amplitude-modulation detection, where a pink noise carrier is modulated with a sinusoid and band-limited white noise. For each modulation pure tone of 4Hz, 8Hz and 16Hz, it said that the detection level increases locally around the frequency of each pure tone, for example the frequency range is within 1/2 - 1 octave wide for 8Hz pure tone. The similar results were observed for 4Hz and 16Hz modulations. The bandwidth obtained in this paper is almost as same as the above range or somehow wider. Bacon and Grantham (1989) showed a similar band-pass type masking characteristics in amplitude-modulation detection, where the broadband white noise carrier is modulated two sinusoids. Dau and et al (1996, 1997) proposed an idea of modulation filter bank based on their study about amplitude modulation to narrow band white noise carrier. Such previous studies treated the some band limited white noise carriers. The perception characteristics of amplitude modulated sinusoid, which was obtained in this paper, is of band-pass type as the above studies also stated.

The above mean that frequency selectivity still exists in amplitude-modulation detection for sinusoidal carrier.

4. CONCLUSIONS

In this paper, amplitude-modulation detection level was measured in the case of sinusoidal carrier of 1000Hz. Two kinds of stimulus were used; one was amplitude-modulated with band-limited white noise and the other was with band-limited white noise and 16Hz pure tone. Stimuli corresponding to some power density levels and bandwidths were prepared for the noises. Subjects judged whether these sounds are same or not, for randomly presented 72 pairs of stimulus with the same band-limited white noise. As a result, there exist particular masking characteristics of 1-1.5 octave wide band-pass type for modulation frequency of 16Hz. In addition, the masking characteristics do not affect beyond the above bandwidth, and the amplitude-modulation detection level remains constant. This means that frequency selectivity still exists in amplitude-modulation detection for sinusoidal carrier. However, the obtained shape of the characteristics is not so precise enough. It should be solved in the further researches. And experiments at another modulation frequency are also remained as further researches.

5. REFERENCES