Pitch Perception of Time-Varying Notched Noise
- Hearing the absent frequencies -

Satoshi Oishi* and Shuji Hashimoto*

*Dept. of Applied Physics, Waseda University
ooishi@shalab.phys.waseda.ac.jp    shuji@shalab.phys.waseda.ac.jp

Abstract
People can perceive a pitch from some kinds of random noise. We focus on one of them, the notched noise. When a notch region varies temporally in frequency space, noise generates a perception of pitch shifting in accordance with the direction of the shift of the notch region to the listener. We investigated the perception characteristics with many kinds of notched noise. As a result, we learned pitch perception of time-varying notched noise is affected both by the notch width and the notch depth. The pitch recognition weakens if the notch width is narrower than 0.2 octaves or the notch depth is less than 3 dB.

1 Introduction

Noise is one of the significant factors determining the soundscape in our daily life, because noise causes psychological effects. Many studies have been done on methods to physically suppress the propagation of noise or psychologically reduce the affect of noise. Other studies on noise have investigated controlling the spectrum so that the sound makes a comfortable impression on the listener.

To control a noise is important to understand the psychological perception of sound received by the human auditory system. The perception of sound (for example, whether a particular sound is perceptible as a comfortable sound) is determined by many psychological factors and sometimes can be very subjective. However, there are physical features of noise that cause a common psychological effect.

In this study we focus on the notched noise. Although noise could be considered as sound that has no significant psychological or logical meaning, a particular filtered noise can produce a common pitch perception (Fastl, 1971; Kubovy, 1983; Small and Daniloff, 1967). Some studies revealed that the perception of notched noise corresponds significantly to the notch region in the frequency space (Zwicker, 1964; Bilsen, 1977). Our study can be distinguished from them in that most of the previous studies deal with notched noise with fixed notched regions, while we deal with notched noise in a time-varying notch region. We carried out three experiments with different varying parameters of a time-varying notch filter.

2 Time-varying notched noise

In this paper, we define “time-varying notched noise” as noise in which the notch region varies temporally in frequency space as shown in Figure 1. We used a variety of time-varying notched noise stimuli for the experiments. All stimuli were generated and recorded by programs written in Max/MSP. By using frequency variable notch filters, we obtained notched noise stimuli from the white noise signal of Max/MSP. The sampling rate was 44.1kHz. The central frequency, \( f_c \) of the notch region, and the notch width, \( N_w \), and the notch depth, \( N_d \), are defined as:

\[
\begin{align*}
\log f_c [Hz] &= \frac{1}{2} \left( \log f_L + \log f_U \right) \\
N_w [\text{octave}] &= f_U - f_L \\
N_d [\text{dB}] &= 20 \log_{10} \left( \frac{A_N}{A_B} \right)
\end{align*}
\]  

Figure 1

Figure 1. Short term fourier spectrum of a stimulus with a notch. The notch varies temporally in frequency space.
3 Experiment I

The aim of Experiment I was to examine the relation between the notch region shifting and pitch perception. As a result of this experiment, we confirmed that varying the spectral notch produces pitch perception in accordance with the direction of the shifting of the notch region.

3.1 Stimuli

In Experiment I, we used thirteen stimuli. One of them was white noise and the others were time-varying notched noise. The duration of each stimulus was three seconds. \( f_c \) was moved into ascending or descending direction over the duration of three sec. \( f_c \) of the stimuli ascended or descended linearly in one of the three ranges (from 260 to 2093, 1046 to 8372, and 2093Hz to 16744 Hz) in logarithmic scale. The velocity of the movement of \( f_c \) was 1 octave/sec. \( N_W \) of the stimulus was 1/3 or 1 octave. \( N_D \) of each stimulus was 20dB.

3.2 Procedure

In this experiment, the task of the subject was to estimate the direction of the pitch shift, whether it was up or down according to one’s subjective perception. The subject selected one of four options: the pitch shifted “up,” shifted “down,” “none,” or “undecidable,” for each stimulus.

We performed the experiment in the soundproof room in which the background sound pressure level (SPL) was less than 25 dB (A-weighted noise level, Re: 20µPa). The stimuli were presented from two speakers (BOSE MM-1) monaurally. The subject sat in front of speakers at a distance of 1 meter.

The subject could control the timing to start the sound and could listen to thirteen stimuli in any order and as many times as needed. The overall SPL of the white noise stimulus was 55dB.

In this experiment, the subjects consisted of twenty persons aged between 18 and 54 years. All subjects had normal hearing and no previous history of auditory pathology. Each subject was given referent samples and sound practice prior to the experiment.

3.3 Results

The experiment’s results are summarized in Table 1 and Table 2. All subjects recognized no pitch shift in white noise. Table 1 shows the evaluations of \( f_c \) ascending stimuli and Table 2 shows those of descending. Most of the twenty subjects evaluated the pitch shift in accordance with the moving direction of \( f_c \). The subjective perception of the pitch was weak but similar to that of a pure tone. The subjects sensed a pitched sound in the noisy background.

From this experiment, we observe that \( N_W \) is more dominant than \( f_c \) range to the pitch-shifting perception. The subjects could detect the notch in higher than 4 kHz though the pitch-shifting perception became worse, especially when \( f_c \) descended.

4 Experiment II

The aim of Experiment II was to investigate the lower limit of \( N_W \) in the pitch shifting perception. When the notch width \( N_W \) became narrower, especially less than 0.1 octaves, the clarity of pitch perception decreased.

4.1 Stimuli

In Experiment II, we used 25 stimuli including a white noise. The stimuli are three sec. in duration. \( f_c \) of a stimulus ascended or descended for two sec. (from 0.5 to 2.5sec.) in logarithmic scale as shown in Figure 2. The velocity of the movement of \( f_c \) was 1 octave/sec. \( f_c \) ascended or descended in the range of 1046 and 4092 Hz, or 4092 and 16744 Hz, as shown in Figure 2. \( N_W \) of the stimulus was 0.05, 0.1, 0.15, 0.2, 0.25, or 0.3 octaves. \( N_D \) for the respective settings was 20dB.

4.2 Procedure

In this experiment, the task of the subject was to detect the pitch shift caused by the stimuli. The subject had eight experimental sessions to evaluate the stimuli. One session consisted of 25 stimuli presented in random order. The subject evaluated stimuli with two alternatives, deciding whether the stimulus had pitch shift or not. Each stimulus

---

Table 1. Pitch recognition of stimuli whose \( f_c \) ascended.

<table>
<thead>
<tr>
<th>Range of ( f_c ) (Hz)</th>
<th>( N_W ) (octave)</th>
<th>The number of subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td>260-2093</td>
<td>1/3</td>
<td>up: 12, down: 0, none: 8, undecided: 0</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>up: 18, down: 1, none: 1, undecided: 0</td>
</tr>
<tr>
<td>1046-8372</td>
<td>1/3</td>
<td>up: 19, down: 0, none: 1, undecided: 0</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>up: 20, down: 0, none: 0, undecided: 0</td>
</tr>
<tr>
<td>2093-16744</td>
<td>1/3</td>
<td>up: 17, down: 2, none: 1, undecided: 0</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>up: 19, down: 1, none: 0, undecided: 0</td>
</tr>
</tbody>
</table>

Table 2. Pitch recognition of stimuli whose \( f_c \) descended.

<table>
<thead>
<tr>
<th>Range of ( f_c ) (Hz)</th>
<th>( N_W ) (octave)</th>
<th>The number of subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td>2093-260</td>
<td>1/3</td>
<td>up: 1, down: 15, none: 3, undecided: 1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>up: 2, down: 18, none: 0, undecided: 0</td>
</tr>
<tr>
<td>8372-1046</td>
<td>1/3</td>
<td>up: 1, down: 18, none: 2, undecided: 1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>up: 3, down: 17, none: 0, undecided: 0</td>
</tr>
<tr>
<td>16744-2093</td>
<td>1/3</td>
<td>up: 1, down: 15, none: 4, undecided: 0</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>up: 3, down: 17, none: 0, undecided: 0</td>
</tr>
</tbody>
</table>

---

Figure 2. Profile of \( f_c \) ascending.
was presented only per a session; therefore a subject listened to 200 stimuli in total.

We performed the experiment in the same soundproof room used in Experiment I. The overall level of the white noise stimulus was 55dB SPL. In this experiment, our subjects consisted of ten persons aged between 21 and 29 years with normal hearing. Each subject was given a short time to rehearse the experiment.

4.3 Results

The experimental results are summarized in Figure 3 and Figure 4. They show the mean rate of the evaluations of all subjects answering that the stimuli had pitch shift with regard to NW. The vertical axis shows the recognition rate of the pitch. The full line shows the results with the lower varying range of fC, and the dashed line shows those of the higher range.

Figure 3 shows the evaluations of the stimuli of ascending fC and white noise. The pitch shifting perception decreases rapidly in the narrower NW. The fidelity of the perception becomes 100% when NW is above 0.2 octaves.

Figure 4 gives the data for the stimuli in descending fC and white noise. Similar to Figure 3, it shows the decrease of the rate in the narrower NW. When fC descended, the pitch sensation with stimuli grew worse, especially in the higher frequency region.

The tendency of the results was similar for all subjects when NW was wider than 0.2 octaves. But when NW was 0.1 octaves, there were significant differences among individuals, especially when fC descended. Some subjects could detect the pitch shift of the narrow notch clearly while others could not.

5 Experiment III

The aim of Experiment III was to investigate the effect of the lower limit of notch depth ND in producing pitch perception. When ND became shallower, the clarity of pitch perception with notched noise became worse.

5.1 Stimuli

In Experiment III, we used seventeen stimuli including a white noise. The stimuli were three sec. in duration. fC of the notch region ascended or descended in the range of 1046 and 4092 Hz, or 4092 and 16744 Hz as in Experiment II. NW of stimuli was 0.3 octaves, and ND of the stimulus was 3, 6, 9, or 12 dB.

5.2 Procedure

The procedure was the same as for Experiment II. In this experiment, our subjects consisted of ten persons aged between 21 and 39 years with normal hearing.
5.3 Results

The experimental results are summarized in Figure 5 and Figure 6. They show the mean rate of all subjects with regard to No function. The full line shows the results of lower varying range of fc, and the dashed line shows those of the higher range.

Figure 5 shows the evaluations of the ascending fc stimuli and white noise. It also shows the decrease of the pitch recognition rate following the decrease of the depth. As in Experiment II, clarity of pitch-shifting perception was worse in the higher frequency region.

Figure 6 shows the evaluations of the descending fc stimuli and white noise. The tendency was almost the same as in Figure 5, but the evaluations of the higher range were worse than the case of Figure 5.

When No of the stimuli was 3dB, individual differences became larger. When No was deeper than 6dB, the evaluations became similar for all subjects.

6 General discussion

The first point to be discussed is the difference between the influence of the notch width and depth in the clarity of pitch sensation. The clarity of pitch with notched noise is determined by the width and depth of the notch. From Figure 3 and 5, we can observe that the decrease in both width and depth of the notch causes deterioration in the perception. But in contrast to the smooth degradation of perception as the effect of the shallower depth, the decrease of the width causes a sudden drop of perception below a certain threshold. This threshold depends on the subject, but from Figure 3 and 4 we can see that the threshold is located between 0.1 and 0.2 octaves. Therefore we suppose that the notch depth has stronger influence on pitch perception compared to width. When Nr becomes wider than 0.2 octaves, the fidelity of the perception becomes 100%. Conversely, a notch width of at least 0.1 octaves is needed to produce pitch sensation even if No is deep enough.

The second point is about the frequency of the subjective pitch. Primarily, the pitch with notched noise is very difficult to detect. Though many studies on a spectral notch have been done (Moore et al., 1989), the frequency of the subjective pitch is not clear yet. We also did an experiment to determine the pitch frequency of time-varying notched noise to compare it with bandpass noise. And we could estimate that the pitch frequencies are probably in the notch region. Another key to estimating the pitch frequency is in the results of Experiment II and III. A possible reason of why our subjects could not perceive pitch shift in higher frequencies is because the musical pitch gets lost beyond 4 or 5 kHz.

From these points of view, we consider that the pitch sensation of time-varying notched noise is related to the "enhancement effect" (Summerfield et al., 1987; Viemeister and Bacon, 1982) and the "edge effect" (von Békésy, 1961) which produce the pitch sensation with fixed notched noise.

Therefore we consider that the pitch frequency of time-varying notched noise corresponds to the central frequency fc or the cutoff frequencies of the notch region, just as in the case of the pitch perception of bandpass noise. As the two edge pitches of broadband noise merge into one pitch of narrow band noise, time-varying notched noise seems to have two pitches when the width is beyond 0.5 octaves.

7 Conclusion

In this study, we confirm the following points.

(1) Time-varying notched noise produces pitch-shifting perception similar to that of a pure tone following the notch.

(2) The pitch of time-varying notched noise depends on both the notch width, Nr, and the notch depth, No. The clarity of pitch shift decreases when Nr becomes narrower than 0.2 octaves or when No becomes shallower than 3dB.

(3) Subjective pitch corresponds to a notch region similar to that of bandpass noise. But it is not certain whether the pitch coincides with the central frequency or not.

(4) We suggest that the "enhancement effect" or the "edge effect" is the possible auditory mechanism rousing this pitch-shifting perception.

In the future, we plan to carry out more experiments to consider the question of the frequency corresponding to the subjective pitch of notched noise and the details of an auditory perceptual model and their applications in soundscape design.

We are also developing a new instrument to produce a notched noise controlled by a keyboard or sliders for music of absent frequencies.

References


