Multiple Missing Fundamental Phenomenon as a Monaural-Beat Perception

Ryota Shimokura a and Yoichi Ando b

Graduate School of Science and Technology, Kobe University
Now at: a Department of Energy, Nuclear and Environmental Control Engineering, Bologna University
ryota@ciarm.ing.unibo.it

Now at: b Department of Architecture and Civil Engineering, Kumamoto University
andoy@cameo.plala.or.jp

Abstract

It is found that a monaural beat induced by two missing fundamentals of complex tones (A and B) may be perceived, even in the condition without the envelope component of beat. This was realized by mixing the complex tone A with the missing fundamental frequency \( f_{0a} \) and the complex tone B with the missing fundamental frequency \( f_{0b} \). When we listen together, then an additional missing fundamental frequency \( \Delta f = f_{0b} - f_{0a} \) may be perceived as the beat. The \( \Delta f \) was changed to 2, 4, 8 and 16 Hz. The total tone mixed with two complex tones has the envelope fluctuation corresponding to \( \Delta f \) in the real waveform when the all components are in phase. When the components are out of phase, however, such an envelope fluctuation disappears. As experimental results, in both cases, the beats of \( \Delta f \) were perceived clearly for the stimuli until \( f_{0a} = 256 \) Hz, and the beats produced by the signals out of phase were perceived when the \( f_{0a} \) was more than 256 Hz. These results show that the beats independent of envelope fluctuations may be detected, and they can be described by the delay times of the maximum peak in the autocorrelation function (ACF) of the sound signal.

1. Introduction

The missing fundamental phenomenon referred as the phenomenon of periodicity pitch or residue pitch has played roles to explain the mechanism of pitch perception [1][2]. The fundamental frequency is absent in the spectrum, however the pitch of it can be perceived. Schouten mixed a pure tone 206 Hz on a complex tone with fundamental frequency 200 Hz and indicated that the beat corresponding to 6 Hz did not occur [2]. In this experiment, we shall examine the missing fundamental phenomenon perceived as a beat, which was caused by two fundamental frequencies. Two different fundamental frequencies (\( f_{0a} \) and \( f_{0b} \)) by two different complex tones may induce an additional fundamental frequency: \( \Delta f = f_{0a} - f_{0b} \). It is worth noting that the energies of two initial fundamental frequencies of \( f_{0a} \) and \( f_{0b} \) and the secondary fundamental frequency \( \Delta f \) are absent on the spectrum. This study refers to it as “multiple missing fundamental phenomenon”.

2. Method

2.1. Stimuli

The multiple complex tones were produced by the two complex tones using the PC with the sampling frequency of 48 kHz. Each complex tone has three components that consist of the fundamental frequency \( f_{0a} \) or \( f_{0b} \). Thus, amplitudes of three components of the two complex tones were identical. In this study, two
fundamental frequencies were mistuned by $\Delta f$ Hz maintaining a harmonic relationship. The complex tone A had the fundamental frequencies $f_{0a} = 32, 64, 128, 256$ and 512 Hz, and the additional fundamental frequencies were $\Delta f = 2, 4, 8$ and 16 Hz. The lowest component of the A was always 1024 Hz, and the components of the B had the harmonic numbers that are added by 2 to those of the A. Fig. 1 shows an example of multiple complex tones with $f_{0a} = 128$ Hz, $\Delta f = 2$ Hz. It illustrates the envelope corresponding to $\Delta f$ when the components are in-phase. When they are out of phase, such an envelope disappears as shown in Fig. 1(b).

**2.2. ACF analysis**

Fig. 2 shows the results of ACF analysis of multiple complex tones with $f_{0a} = 128$ Hz, $\Delta f = 2$ Hz.

The normalized ACF calculated by in-phase and out-of-phase signals used here forms same variation as a function of the delay time and the maximum peak shows the fluctuation corresponding to 2 Hz. The ACF scaled until 10 ms shown in Fig. 2 (b) expresses the initial fundamental frequencies (128 and 130 Hz).

**2.3. Procedures**

Three subjects A, B and C (23-24 years of age) participated in the matching tests. The beat-matching tests were conducted for multiple complex tones as test stimuli and sequential pulse tones generated by an oscillator as a reference. Subjects were seated in a listening room, and sound signals were reproduced through a headphone (SENNHEISER HE60). First, subjects listened to the multiple complex tones, so that they could be aware of a single beat in the sound signal. Second, they listened to the sequential pulse tone generated by the oscillator to adjust the same beat as perceived by the multiple complex tones. This process was repeated until subjects could match identical beat. The beat-matching tests were repeated 10 times for the single multiple complex tone.

**3. Results**

As shown in Fig. 3 and 4, all results of the beat-matching tests are shown as histograms. The frequency range is divided into the 1/3 octaves manner from 1 Hz. These figures illustrates the results of $f_{0a} = 32, 128$ and 512 Hz only.

For the condition of multiple complex tones in phase, all subjects matched the beats corresponding to the $\Delta f$ and the envelope fluctuations, as shown in Fig. 3. Above the $f_{0a}$ of 512 Hz, however, the perceived beats were not clear.

As shown in Fig. 4, the beats perceived in the multiple complex tones out of phase were equal to $\Delta f$ regardless of the absence beating frequency $\Delta f$ both in spectrum and in waveform.
Fig. 5 shows the probabilities for the beat corresponding to $\Delta f$, as a function of $f_{0a}$ and as a parameter of the beats frequency $\Delta f$. In comparison with signals in phase, the matching beat probabilities at $f_{0a} = 512$ Hz were increased for the signals out of phase. When $\Delta f = 2 - 4$ Hz, the probabilities for the frequency range of $f_{0a} = 32 - 256$ Hz were almost more than 80% for both in phase and out of phase conditions. When $\Delta f = 8 - 16$ Hz, the probabilities decreased below 65% for the both conditions.

4. Discussion

All subjects could adjust the beats of $\Delta f$ in the cases of multiple complex tones in phase and out of phase until $f_{0a}$ was 256 Hz. These results indicated the existence of a multiple missing fundamental phenomenon. The fundamental frequencies absent on spectrum can compose the additional fundamental frequency, and it is also not shown on spectrum but can be perceived as beat. This beat is independent of the envelope fluctuation shown in the waveforms, so that, in this study, it is referred as an “internal beat” to distinguish from an envelope beat. The internal beats can be estimated by an autocorrelation function (ACF) analysis. As shown in Fig. 2, the peak of ACF corresponds to the internal beat. Therefore, it is possible that the internal beat may be calculated based on the time intervals among spikes in the auditory nerve fibers.

Inoue et al. conducted pitch-matching tests using complex tones with various fundamental frequencies to examine the range acceptable the ACF model [3]. Their results shows that the listeners could identify the pitch of fundamental frequency until it is 1200 Hz and the
limit may be accounted by the maximum firing rate 1000 Hz of auditory nerves. Although the ACF analysis was possible to explain both initial and multiple missing fundamental phenomenon by the positions of their peaks, the limit of the initial fundamental frequency may not be applied to the multiple missing fundamental phenomenon. The beats from the signals in phase were attenuated extremely above the fundamental frequency 256 Hz. The signals in phase include not only the internal beat but also the envelope beat in same rate, therefore, the influence of the envelope cues for the beat detection can not be ignored. In terms of envelope detections, some studies examined the spectrum aspects of the modulation frequencies and showed examples of interactions among them, and their experiments reported that the envelope detection was attenuated when the modulation frequency increased to 256 Hz [4][5]. The beat detections from signals in phase may be influenced by the envelope beat cues.

On the other hands, the beats by the signals out of phase depend on the internal beat cues only. According to the internal beat, the attenuations of sensitivity were not shown extremely at $f_{0a} = 512$ Hz. However, when $f_{0a}$ was 512 Hz and $\Delta f$ was 2 Hz, some judgments were scattered at 8 Hz in spite of the matching of 2 Hz without difficulty as shown in Fig. 4 (c-1). The extreme errors indicate that the sensitivity at $f_{0a}$ of 512 Hz was attenuated in comparison with the sensitivity at $f_{0a}$ of 256 Hz. The attenuations at $f_{0a} = 512$ Hz can not be explained by the applicable range of ACF proposed by Inoue et al. [3]. Beside the secondary fundamental frequency, a “binaural beat” perception is the other example of beats based on the time intervals among spikes of the auditory nerve fibers. Perrott and Nelson showed that the sensitivities of binaural beat detections were high until the carrier frequency of 500 Hz, and decreased as frequency increased up to 1500 Hz [6]. Assuming that the fundamental frequency $f_{0a}$ acts as a carrier of $\Delta f$, the limit of binaural beat may explain the attenuation of the internal beats at 500 Hz. This study of the multiple missing fundamental phenomenon may play a role to advance not only the ACF model but also the binaural model at the range of low frequency.

5. Conclusions

Fundamental frequencies of complex tones may induce an additional secondary fundamental frequency, which correspond to the delay time of the maximum peak in the normalized autocorrelation function of the total signal. The beat by the secondary fundamental frequency was independent of the envelope fluctuations. This holds for the initial fundamental frequency below 512 Hz. The sensitivity to the secondary fundamental frequency is decreased for the initial fundamental frequency > 500 Hz.

6. References