INTRODUCTION

It is considered that the missing fundamental $f_0$ is produced in the auditory center, when we listen to a complex tone of $f_1=nf_0$ and $f_2=(n+k)f_0$. $f_0$ is known as the missing fundamental. For cochlear implant speech processors, $f_0$ (the fundamental) and $F_1$ (the first formant) were used in the 1980’s. $F_1$, $F_2$, and $F_3$ are recently used. In this case, it is supposed that $f_0$ (the fundamental) is made in the auditory center. It is known that some people of hearing disability can get the ability of speech perception, if they are operated on for cochlear implant speech processors at the infancy (i.e., before the neural networks in brain for speech perception will be formed).

The missing fundamental phenomenon was made clear by psycho-acoustic experiments. But it has no evidence data of electrophysiology. By making physiological models I am trying to make clear the mechanism how the missing fundamental is produced. I showed how the information of the missing fundamental $f_0$ explicitly appeared on the aggregated autocorrelogram of the output pulse train for input signal $f_1$ to one cochlear model and the output pulse train for input signal $f_2$ to another cochlear model.

In this report, I mention the following models of three neurons that play an important role in producing the information of the missing fundamental i.e., (a) the model of Primary Auditory Nerve (Integrate-and-Fire unit with spontaneous discharge), (b) the model of Anteroventral Cochlear Nucleus (agreement detector) and (c) the model of Superior Olivary Complex (Integrate-and-Fire unit with refractory period).

THE MODEL OF PRIMARY AUDITORY NERVE (INTEGRATE-AND-FIRE UNIT WITH SPONTANEOUS DISCHARGE)

S. Greenberg suggested on the basis of experimental results that the auditory center has the function seeing how the fire pattern of a neuron repeats and detecting its pitch [1]. I consider how we perceive the missing fundamental by using two cochlea models. One of two models is shown in Fig. 2. When $f_1$ is fed, an inner hair cell (which is located at the place of the basilar membrane where the envelope peak of the progressive wave of $f_1$ appears) detects the displacement velocity of the basilar membrane. (There are about 3500 inner hair cells in each ear). Primary auditory nerves transform the information of the displacement velocity into the information of pulse trains. A primary auditory nerve is an integrate-and-fire unit with refractory period. For the consideration of the characteristics of the missing fundamental, 1 for n phase-lock phenomenon (the phenomenon generating the periodic pulse train of one pulse for n periods of a periodic input signal) [2] by the integrate-and-fire unit with refractory period is used.

An experimental result by the cochlea model is shown in Fig. 3. Fig. 3 is the interspike-interval histogram of the aggregated autocorrellogram of output pulse trains from two cochlea models. One output pulse train from one cochlea model, to which a pure tone 500Hz is fed, is 1 for 1 phase-locked (to 500Hz) pulse train (the periodic pulse train of one pulse for one period of a periodic input signal).
interspike-interval histogram of the autocorrelogram of the output pulse train contains peaks of every 1/500ms. The interspike-interval histogram of the autocorrelogram of another output pulse train from another cochlea model, to which a 750Hz pure tone is fed, contains peaks of every 1/750ms. The interspike-interval histogram of the aggregated autocorrelogram by overlapping two autocorrelograms of two output pulse trains from two cochlea models contains peaks of every 1/250ms (250 is the maximum common divisor of 500 and 750). The 1/250ms(250Hz) is the missing fundamental $f_0$.

THE MODEL OF ANTEROVENTRAL COCHLEAR NUCLEUS (AGREEMENT DETECTOR)

It is suggested that an Anteroventral Cochlear Nucleus has the function of an agreement detector [4]. So, I try to make An Anteroventral Cochlear Nucleus (AVCN) model work as an agreement detector of output pulse trains and try to make one generates a pulse train for 21 input pulse trains.

The values of parameters of AVCN model are determined such that the synchronization index and the entrainment index of the pulse train from the model agree with those indexes of the pulse trains (physiological data) from Anteroventral Cochlear Nucleuses [4]. The synchronization index is the followings. When output pulses are generated at the particular phase in every cycle of the input signal, the value of the index is 1. When output pulses are generated at the random phase in the input signal, the value of the index is 0. The entrainment index is the followings. When output pulses are generated in every cycle of the input signal, the value of the index is 1. When output pulses are not generated in any cycles of the input signal, the value of the index is 0. The values of both indexes are between 0 and 1. In the case of Integrate-and-Fire unit (the unit having the parameter values determined by the above-mentioned method) with spontaneous discharge (the model of Primary Auditory Nerve), I have been able to get a synchronized pulse train to an input pure tone in Fig.2.

THE MODEL OF SPHERIOR OLIVARY COMPLEX (INTegrate-AND-FIRE UNIT WITH REFRACTORY PERIOD)

Fig.1 shows how to make autocorrellogram. A pulse train is in the upper half. An pulse E is on focus. The distance from a pulse E to a pulse D is plotted at dot E-D in the autocorrellogram in the lower half. Each distance between a pulse and previous 4 pulses is plotted respectively. The abscissa shows the occurrence time of pulses. The ordinate shows the interspike interval. The interspike interval histogram is the projection of dots to the ordinate in Fig.1.

It is suggested by S. Greenberg [1] that there is the function getting autocorrelation (the function making
Integrate-and-Fire unit with refractory period and pulse train \{f_1\} [autocorrelogram \{f_1\}]

pulse train \{f_1\}
[autocorrelogram \{f_1\}]

Integrate-and-Fire unit with refractory period

pulse train \{f_2\}
[autocorrelogram \{f_2\}]

pulse train \{f_{out}\}
[autocorrelogram \{f_{out}\}]

[pulse train \{f_{out}\}]
[aggregated autocorrelogram ?]

The block diagram of experiments about autocorrelogram

CONCLUSIONS

I already showed how the information of the missing fundamental \(f_0\) explicitly appeared on the aggregated autocorrelogram of the output pulse train for input signal \(f_1\) to one cochlear model and the output pulse train for input signal \(f_2\) to another cochlear model. I am trying by making models to make clear the mechanism how the missing fundamental is produced.

I have mentioned the following models of three neurons that play an important role in producing the information of the missing fundamental i.e., (a) the model of Primary Auditory Nerve (Integrate-and-Fire unit with spontaneous discharge), (b) the model of Anteroventral Cochlear Nucleus (agreement detector) and (c) the model of Superior Olivary Complex (Integrate-and-Fire unit with refractory period).

I have made clear that three models has the following characteristics.

(a) The model of Primary Auditory Nerve has the characteristic of spontaneous discharge. So, it generates the pulse train (the quasi periodic pulse train) adding spontaneous discharge to periodic pulses for input periodic signal.

(b) The model of Anteroventral Cochlear Nucleus works as agreement detector of pulses of the input pulse trains (above-mentioned quasi periodic pulse trains) and generates a periodic pulse train which synchronizes an periodic signal to an ear.

(c) The model of Superior Olivary Complex (Integrate-and-Fire unit with refractory period) can generates the output pulse train having the information of aggregated autocorrelogram.

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REFERENCES
