ON THE MECHANISM HOW THE MISSING FUNDAMENTAL IS PRODUCED

Takahide Matsuoka
Utsunomiya University

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 F1 (the first formant) were used in the 1980's. F1, F2, and F3 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 apears) 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 autocorreleogram 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). The
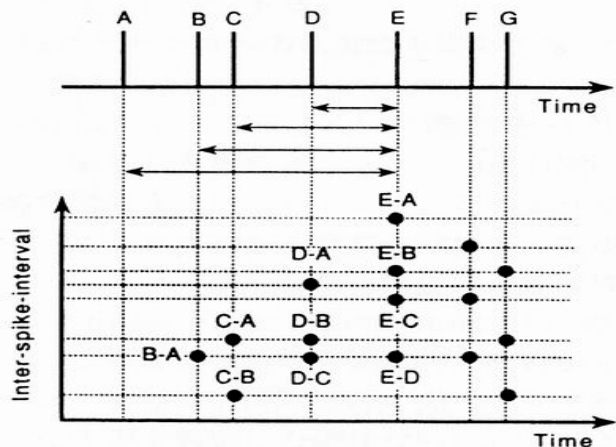

Fig.1 How to make autocorrelogram

interspike-interval histogram of the autocorreleogram of the output pulse train contains peaks of every 1/500ms. The interspike-interval histogram of the autocorreleogram 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 autocorreleogram by overlapping two autocorreleograms 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.
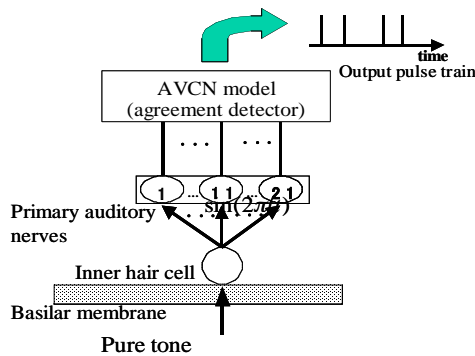

Fig.2 Cochlear model - Anteroventral Cochlear Nucleus model (AVCN model)
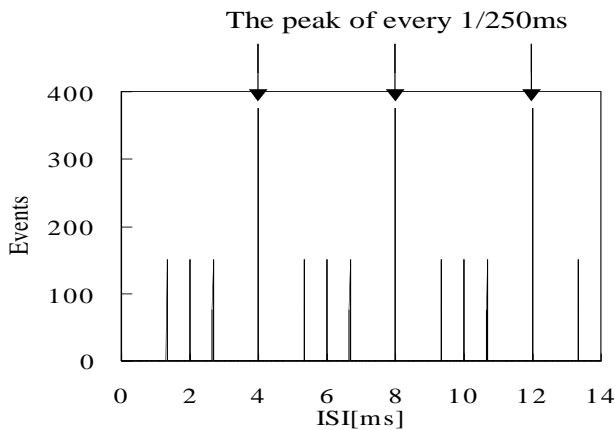 A cochlear model consists of Basilar Membrane, Inner hair cells and Primary Auditory nerves.

Fig.3 The interspike-interval (ISI) histogram of the aggregated autocorreleogram
(f_1=500Hz,f_2=750Hz, a_1=a_2, θ_1=θ_2=0).

   In the case that the influence of spontaneous discharge of primary auditory nerves can be ignored [3], each of 21 pathways in Figure 2 has the same pulse train. In actual fact, the influence of spontaneous

discharge of primary auditory nerves cannot be ignored. Each pulse train in 21 pathways in Figure 2 is different.

THE MODEL OF ANTEROVENTORAL 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 synchronized pulse train is 1 for 1 phase-locked pulse train to the input pure tone.

THE MODEL OF SPERIOR OLIVARY COMPLEX (INTEGRATE-AND-FIRE UNIT WITH REFRACTORY PERIOD)

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

autocorrelogram of a pulse train and its interspike interval histogram) in the auditory center. But, the function making aggregated autocorelogram (overlapping two autocorrelogram) is not obvious. The experiment by Integrate-and-Fire unit with refractory period (τ) is shown in Fig.4. The input signals are a pulse train $\{f_1\}$ and a pulse train $\{f_2\}$. Each pulse train is '1 for 1 synchronized to f_1 Hz and to f_2 Hz respectively' pulse train. '1 for 1 synchronized to f_1 Hz' pulse train means that 1 phase-locked pulse per 1 period of the input signal (f_1 Hz) is generated. A pulse train $\{f_{out}\}$ is output pulse train. The autocorrelograms of the pulse train $\{f_1\}$, the pulse train $\{f_2\}$ and the pulse train $\{f_{out}\}$ are made. The aggregated autocorrelogram of 'the autocorrelogram of the pulse train $\{f_1\}$ and the autocorrelogram of the pulse train $\{f_2\}$' is made by overlapping the two autocorrelograms. The aggregated autocorrelogram is compared with the autocorrelogram of the pulse train $\{f_{out}\}$, when the frequencies of f_1 and f_2, and the length τ of absolute refractory period of Integrate-and-Fire unit change. It has been made clear that the autocorrelogram of the pulse train $\{f_{out}\}$ has the information of the aggregated autocorrelogram when $1/f_1 < \tau < 1/f_0$ (where $f_1 < f_2$).

The afferent nerves from right Cochlear Nucleus and left Cochlear Nucleus is aggregated at Superior Olivary Complex. I suppose that Superior Olivary Complex has the function of the above mentioned Integrate-and-Fire unit refractory period.
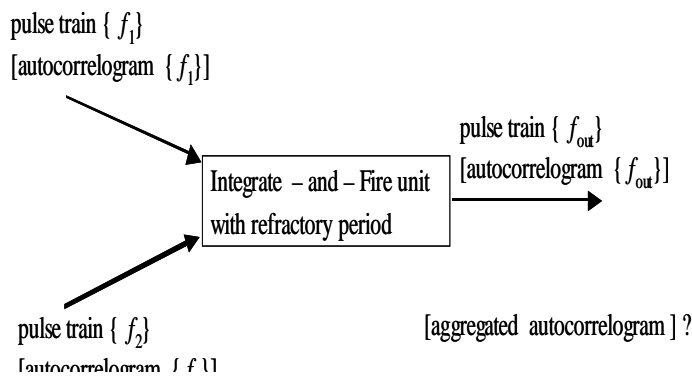
pulse train $\{ f_1 \}$

[autocorrelogram $\{ f_1 \}$]

pulse train $\{ f_{out} \}$

[autocorrelogram $\{ f_{out} \}$]

Integrate – and – Fire unit with refractory period

pulse train $\{ f_2 \}$

[autocorrelogram { f }]

[aggregated autocorrelogram] ?

Fig.4   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.

ACKNOWLEDGEMENTS

REFERENCES

[1]   S. Greenberg, W.S. Rhode. In: W.A. Yost, C.S. Watson, editors, "Auditory Processing of Complex Sound", Lawrence Erblaum Associates, pp.225-236 ,1987

[2]   T. Matsuoka and H. Morita, "The occurrence of synchronous pulse train of 1 pulse output per n periods of the input signal by IPFM with absolute refractory period", IEICE Trans. Information and Systems, Vol.J72-D-II, No.6, pp.974-977 (In Japanese) , 1986

[3]   T. Matsuoka, and K. Ito,"Perception of Missing Fundamental and Consideration on its Characteristics", Proc. 25th Annual Int. Conf. IEEE in MBS, pp.2059-2062, 2003

[4]   P.X. Joris, L.H. Smith, T.C. Yin,"Enhancement of Neural Synchronization in the Anteroventral Cochlear Nucleus. I. Responses to Tones at the Characteristic Frequency", J. Neurophysiology, 3, pp.1038-1051, 1994