Research and simulation of membrane potential integrate-and-fire strategy cochlear implants

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Abstract. Hearing loss (HL) is now disturbing the life of more than 1.5 billion people worldwide. Cochlear Implant (CI) System is at present the only practical method to endow a person who is suffering from hearing loss with sound cognition. In this article the audio coding function, which is the crucial part of Cochlear implant, is estimated and improved based on membrane potential integrate-and-fire (MPIF) strategy. MPIF strategy is applied for the conversion of sound signals to electronic signals. It resembles the accumulation and releasement of membrane potential and considers the influence of audio intensity on the generation time of action potential and the time feature of not only hair cells but also auditory nerve synapses. Hence stimulation signals is generated variably according to the intensity and the volume of the sound received, which is more resemble to healthy auditory system. Cochlear implants with MPIF strategy provides its users more realistic sense of sound than other cochlear implants at present.

Keywords: Cochlear Implant, signal conversion, MPIF strategy, membrane potential.

1. Introduction

The 2021 World Hearing Report reveals that hearing loss (HL) disturbs the life of more than 1.5 billion people worldwide. Cochlear Implant (CI) System is now the only practical method to offer a person who is suffering from hearing loss with auditory perception [1]. In Chapter 2, basic acoustics, hearing threshold, and the structure of the human ear is introduced. At the same time, the development of hearing impairment and cochlear implants is presented. Speech procession is the core component of cochlear implants. After long-term development, the current speech processing strategies are roughly divided into two categories: coarse feature strategy and fine feature strategy. In chapter 3 the structure of the membrane potential integrate—and—fire (MPIF) strategy and its benefits are described. The design of this strategy is based on the excitement transmission function of synapses, which better simulates the time effect of synapses [2]. Cochlear implants using this program can give users a closer to the actual auditory experience, which is better than other current cochlear implants. In Chapter 4, the simulation and result analysis of the MPIF scheme will be performed. The simulation shows the filtering function of the cochlear implant, the time envelope function, the integration and discharge process and the generation of pulses. Because the parameters set for different users of cochlear implants are different, the parameter values used during the simulation are not the actual values. The entire study is summarized in Chapter 5.

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2. Hearing loss and treatment

2.1. Acoustics

2.1.1. Sound. Sound, a mechanical wave, is generated by vibration of object. Frequency (Hz) and amplitude are the two basic physical parameters of sound wave. The frequency of sound wave human can sense range from 20 ~ 20000 Hz. Moreover human are particularly sensitive to the sound wave between 1000 ~ 4000 Hz.

2.1.2. Sound intensity and sound pressure. Sound intensity (I), which is also called acoustic intensity, is defined as the energy carried by sound waves per unit area in a direction perpendicular to the area. The unit of sound intensity is defined as the watt per square meter (W/m^2).

Sound pressure (P) is also named as acoustic pressure. Its definition is the local pressure deviation from the ambient (average or equilibrium) atmospheric pressure, which is the result of a sound wave. The unit of sound pressure is defined as the pascal (Pa). 1 Pa=1 N/m^2

The relationship between sound intensity and sound pressure is obtained through equation $I = \frac{P^2}{\rho c}$. ρ refers to medium density while c refers to sound wave velocity passing through the medium.

2.1.3. Hearing threshold. Sound is only perceptible to human with enough intensity. The lowest intensity to activate hearing which is hearing threshold and the highest intensity without rendering pain to ears is pain threshold. Represented in figure 1, human's hearing threshold varies from different frequencies [3]. The x label is frequency and y label is sound intensity. The upper curve is pain threshold while the curve below is hearing threshold. Hearing threshold indicates the sensibility of the receptor. Low threshold means the receptor is able to react to sound higher than low intensity meanwhile high threshold means only sound lower then high intensity could trigger the receptor without causing pain.

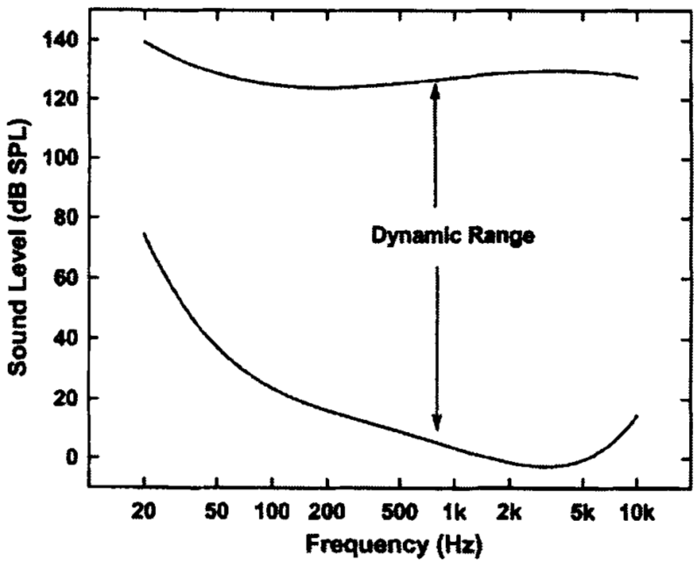

Figure 1. The hearing threshold and pain threshold of human eats reacting to sound of different frequency.

2.1.4. Physiological structure of human's ear. Human senses sound through auditory system. The auditory system consists of two major parts which are ear part and center part. Ear part includes outer

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ear, middle ear, inner ear and auditory nerves [4]. Center part includes all the conduction pathway and central nucleus. Figure 2 represents the ear part anatomy.

Outer ear is constructed by pinna and auditory canal. Pinna identifies the position where sound is generated and gathers acoustic signals. After sound wave meets pinna, it is reflected to the auditory canal and during this reflection the sound wave transmitted into the canal is amplified. Auditory canal is the major path for sound wave to reach inner ear.

Middle ear consists of malleus, incus, stapes and eustachain tube. After the sound wave reaches from outer ear to inner ear, which is filled with flued, mass of energy is depleted because the impedances of two parts are not matching. Middle ear has the ability of lowering depletion to the extreme.

Inner ear includes semicircular canals and cochlea. The cochlea is a spiraled conical chamber of bone. The transmission of sound waves starts at its base, which is close to the middle ear, to apex, which is the top or center of the spiral).

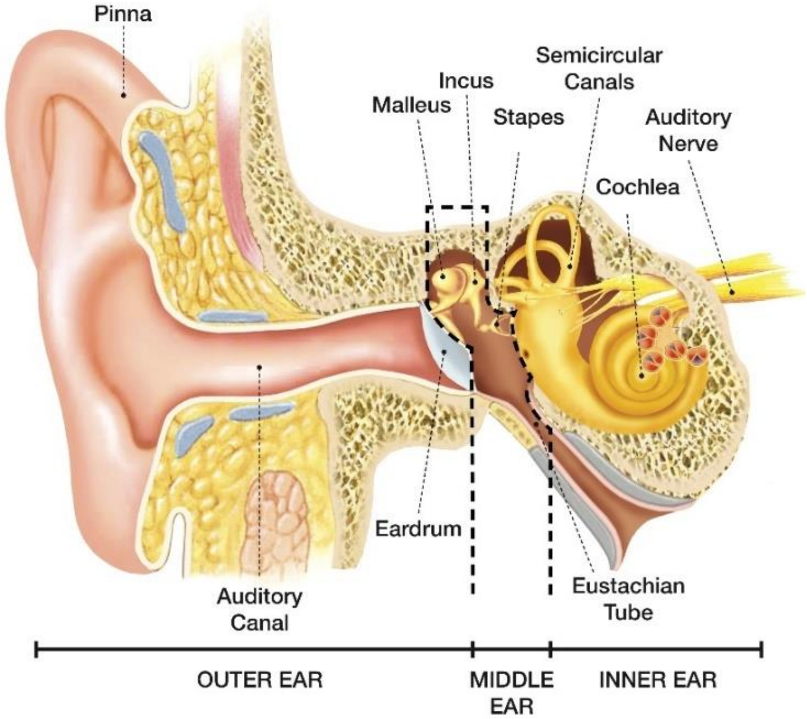

Figure 2. Ear part anatomy.

2.2. Treatment for hearing loss—cochlear implant

2.2.1. Worldwide hearing loss and treatment. According to World Report on Hearing 2021 from World Health Organization (WHO), 1.5 billions worldwide are under the tolerance of hearing loss to different extents among which 430 millions are at disability level. By 2050, 2.5 billion people worldwide will be suffering from some degree of hearing loss in daily life, among which 700 millions will require rehabilitation services.

Cochlear implant is now the major treatment for patients who are unable to hear or severely hard-of-hearing. According to a investigation conducted by the U.S. Food and Drug Administration (FDA) in December 2019, the number of implanted registered devices worldwide has reached 736,900. Approximately 118,100 adults and 65,000 children have implanted devices in the U.S. only.

2.2.2. Signal converting. After sound wave passes through auditory canal, it causes vibration on eardrum. Then the vibration is transmitted through a bone chain to the oval window membrane where the vibration result in variation of fluid and membrane pressure in the cochlea. As the fluid being pushed toward the oval window, starting from the base of cochlea, a vibration happens on the basilar membrane and propagates to its apex [5], as figure 3 demonstrates [6].

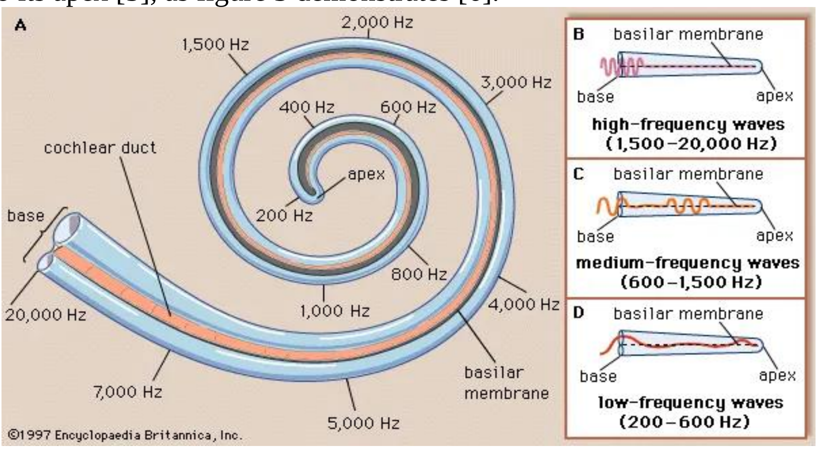

Figure 3. Schematic diagram of basement membrane traveling wave theory.

The function of cochlea resemble a spatial Foriour converter. As the vibration caused by a wave with particular frequency propagates from the base to the apex, the vibration amplitude of basilar membrane increases and after reaching the peak at a specific position, depletes rapidly. As for basilar membrane, the part close to its base can produce resonance with the waves of high frequency. Its middle part produces resonance with medium-frequency waves while the part close to its apex produces resonance with low-frequency waves. Hence basilar membrane acts like a wide band mechanical filter, which can separate sound wave composites into different frequency bands. The resolution ability of human ears can reach 0.3% when processing sound wave between 50~4000 Hz. This is impossible for the basilar membrane with resonant feature itself, hence hair cell and central nucleus are both involved in the resolution process.

2.2.3. The past and present of cochlear implant. Speech procession is the core component of cochlear implants. It extracts the features of the signal and encode it, converting sound wave into electronic pulses.

From the first single-electrode cochlear implant 3M-House to multi-electrode cochlear implants in the 1980's not only the material and the number of electrodes have changed, more importantly the speech processing strategies has largely improved. At present all speech processing strategies can be divided into two major categories which are coarse feature and fine feature, as figure 4 represents [7].

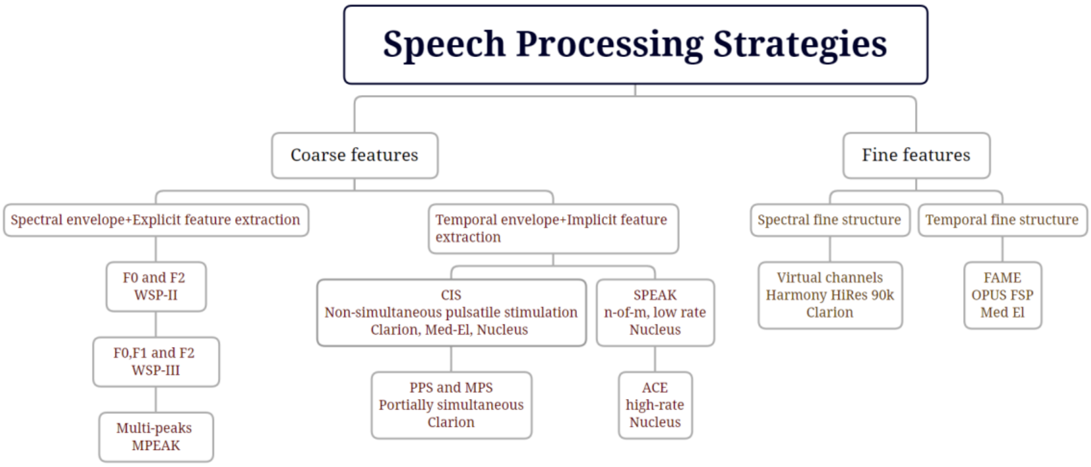

Figure 4. Speech processing strategies.

Coarse feature strategy includes spectral envelope explicit feature extraction and temporal envelope implicit feature extraction.

Spectral envelope explicit feature extraction has the strategy of extracting the parameters for example the fundamental frequency and the resonance of the acoustical signal. The next step is to synthesize the corresponding stimulation pulse so that action potential is obtained on the auditory nerves. This strategy includes F0/F2, F0/F1/F2 and MPEAK.

Temporal envelope implicit feature extraction is designed according to the band-pass filter group of the auditory model. The acoustical signal, which is first processed first by multiple band-pass filters, then a series of processing. Hence each electrode is able to obtain the stimulation pulse sequence. This strategy includes CA, CIS, SPEAK and ACE.

Fine feature strategy includes spectral fine structure and temporal fine structure. This strategy includes Virtual Channels and FAME.

2.2.4. F0/F2 strategy. Australian company Cochlear developed the F0/F2 strategy in the early 1980s and the company used it in its WSP II voice processor. F0 is the fundamental frequency of the voice signal, which contains the tone information of the voice signal. The tone information is extracted by a 70Hz low-pass filter and a zero-crossing detector. F2 is the second formant of the speech signal, which is extracted by a 1000~4000Hz band-pass filter and a zero-crossing detector. F0 determines the electrode’s stimulation frequency, and the F2’s frequency determines which electrode is specifically stimulated, that is, the higher the frequency of F2, the electrode close to the bottom of the cochlea is selected for stimulation; instead, choose an electrode close to the top of the cochlea. Before F0/F2 strategy, no others had the function to enable patients to acquire a certain degree of open speech recognition ability [8].

2.2.5. CA strategy. The CA (Compressed Analog) strategy is a speech coding scheme for cochlear implants proposed in the 80s. This solution was first used in the Ineraid cochlear implant system of Symbion in the United States. At first a self-gain control is constructed to compress the speech signal and then the signal is band-passed filtered by four band-pass filters which center at 0.5kHz, 1kHz, 2kHz, and 3.4kHz. The signals of these four frequency bands are then send to corresponding implanted electrodes after adjustable gain control to generate pulses. The electrodes are 4mm apart, and the

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stimulation pulse is unipolar. The CA strategy has achieved good results when applied to cochlear implant systems, allowing many deaf patients to recognize speech signals in an open environment [9].

2.2.6. FAME strategy. FAME (Frequency Amplitude Modulation Encoding) strategy mainly extracts the amplitude and frequency components of the voice signal. The basic process starts with the preprocession of the sampled voice signal. In the next step the signal passes through a plurality of narrowband pass filters, and the narrowband signal of each channel is Hilbert transformed while the frequency and amplitude information is extracted at the same time. The instantaneous phase or zero crossing point obtained by the center frequency of the electrode is frequency modulated, rectified and low-pass filtered. The amplitude information obtained by previous procession is used to determine the amplitude of the stimulation in different frequency bands. Finally, the modulated pulse signal is sent to the electrode. This makes it possible to take advantage of the power of narrowband analysis to provide wideband voice information. FAME can improve the recognition of music, speech intonation and overcome the effects of the "cocktail party effect" [10-11].

3. MPIF strategy for cochlear implant

3.1. MPIF strategy

The processed speech signal (pre-emphasis to compensate for the high-frequency components of the signal) and passes through N channels of the combination of band-pass filters, rectification and low-pass filtering so that it is enveloped. Then nonlinear compression is carried out to obtain the membrane potential, after which the membrane potential is temporally integrated to reach the threshold to generate the action potential, and the sequence of the action potential is used to stimulate the corresponding electrode. This process is demonstrated in figure 5.

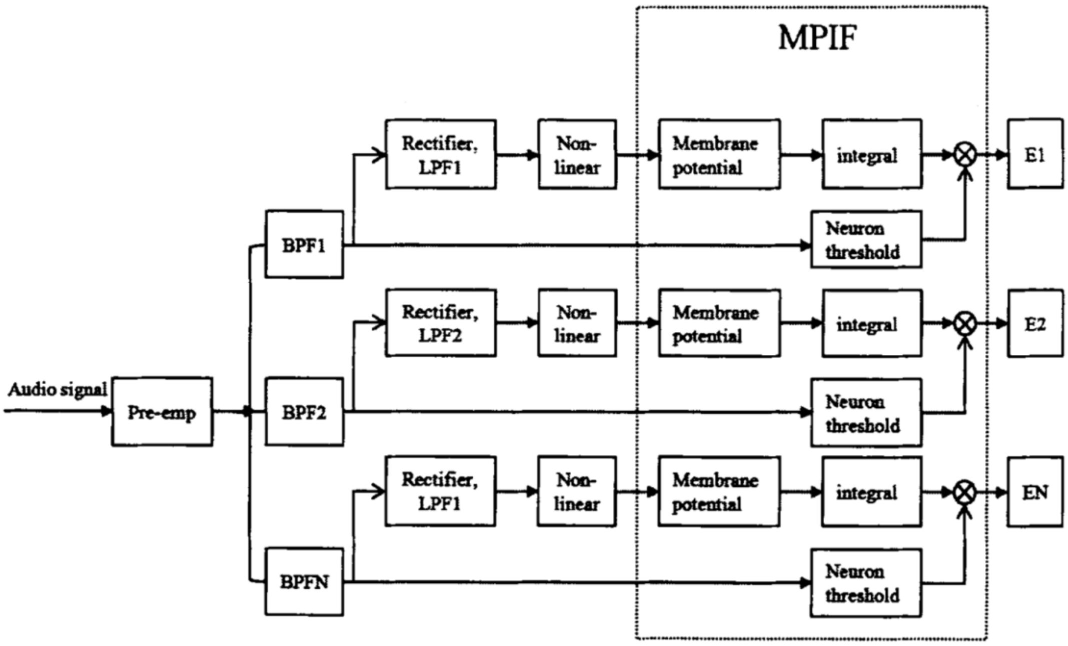

Figure 5. Block diagram of the MPIF program.

Hair cells in the cochlea is connected to auditory nerves by synapses. The presynaptic membrane of this synapse is a partially specialized hair cell membrane in the cochlea, and the postsynaptic membrane is a specialized afferent nerve membrane at the end of the nerve cell dendrites. They transmit excitement through neurotransmitters. The presynaptic membrane of the inner hair cells releases the neurotransmitter (glutamic acid) through the synaptic gap to the dendrite membrane of the auditory afferent nerve. The neurotransmitter binds to the neurotransmitter receptor on the postsynaptic membrane, and the receptor activated by the neurotransmitter triggers the opening of the sodium ion channel. Driven by an electrochemical gradient, the high concentration of sodium ions outside the cell passes through the membrane, so that the membrane potential gradually rises from the resting potential to the threshold potential, which leads to the generation of action potential. Now it completes synaptic transmission, while the neurotransmitter is rapidly removed, waiting for the start of the next same process(figure 6) [12]. The MPIF strategy is to simulate the process's physiological factors such as this synaptic property and its time-switching function (figure 7). In natural acoustic stimulation, the stronger the sound intensity, the earlier the action potential is generated. This phenomenon is manifested by the delay time.

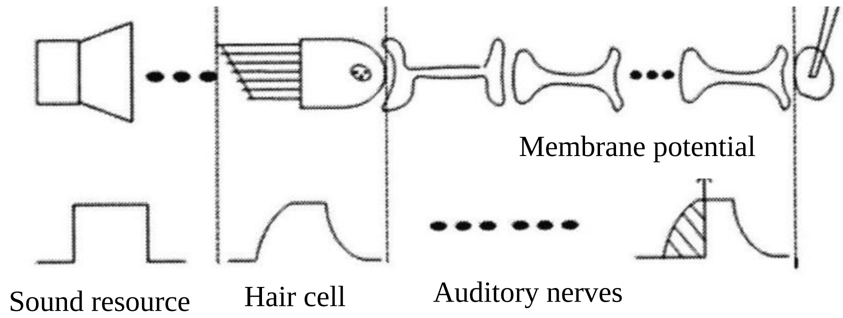

Figure 6. LIEFTS model.

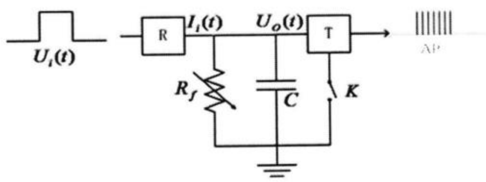

Figure 7. MPIF model.

$$T_0 + A\left(1 - e^{-\frac{\tau}{\alpha}}\right) = \int_0^t U_i(\tau) \times \frac{1}{RC} \times e^{-\frac{t-\tau}{R_f C}} d\tau \tag{1}$$

Equation (1) is the mathematical model of MPIF. T_0 is initial threshold. A is the degree of change in the additional threshold. α is the velocity of change in the additional threshold. U_i is the input signal. C, R, R_f are the parameters of the membrane. The left part indicates the threshold potential of nerve cell, consist of initial threshold T_0 and input added threshold $A(1 - e^{-\frac{\tau}{\alpha}})$. The right part indicates the membrane potential. Input U_i is first converted to $I_i(t)$ through resister R, then is integrated temporally by R_fC circuit. When the membrane potential adds up to threshold a action potential is generated and membrane potential decreases rapidly to resting potential. The integral-discharge process is repeated in this way so that the neuron can convert the input signal into action potentials generated at different times at a relatively stable threshold.

3.2. MPIF strategy estimation

It should be noted at first that the practical application of cochlear implants is to stimulate the auditory nerves with electrodes to produce hearing, so the actual sound effect felt by hearing loss people is not be able to obtain and test at this stage.

The number of stimulation pulse per time of the stimulation pulse sequence obtained by the MPIF coding scheme increases with the passband envelope amplitude. The larger the envelope amplitude, the more stimulation pulses per unit time, which resembles physiological characteristics.

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The stimulation pulse generated by MPIF strategy contains the temporal coding effect of synapses, and as the strength of the speech signal increases, the time interval of the stimulation decreases, which better reflects the characteristics of auditory premasking and post-masking.

Therefore, the MPIF strategy is closer to the processing mechanism of auditory physiology. Hence this strategy has better future prospects.

4. Cochlear implant simulation

4.1. Cochlear implant model

The cochlear implant model use MPIF strategy in simulation. When adjusting cochlear implants for people with hearing loss, each individual has his or her own parameter values. Therefore, in order to demonstrate the model, the parameter used in the simulation are qualitative values instead of quantitative values. They are not the actual value in practical operation. The parameters are shown in table 1.The simulation runs on Matlab 2022a.

Table 1. Parameters for cochlear implant (MPIF).

Parameter	Value	Unit
R	1	Ω
R_f	5	Ω
C	1	F
T_0	0.1	$\mathcal{V}$
A	0.5	
α	1.5	

4.2. Simulation results

Analogue sound waves are set to a mixture of sine waves of different frequencies and amplitudes to simulate the complex sounds heard by the human ear in real life. To demonstrate the filtering function of the cochlea, a filter is built to filter out sound waves of a specific frequency. The sound wave is represented by a red line in the figure. The specific sound waves obtained by filtering are then time enveloped. This shows that when exposed to excitation sound waves, the presynaptic membrane of the hair cells in the cochlea continuously releases neurotransmitters, which are transmitted to the the dendrites of the auditory afferent nerves, causing it to accumulate electric potential. The envelope result is represented by a green line. The result of this procession is demonstrated in figure 8.

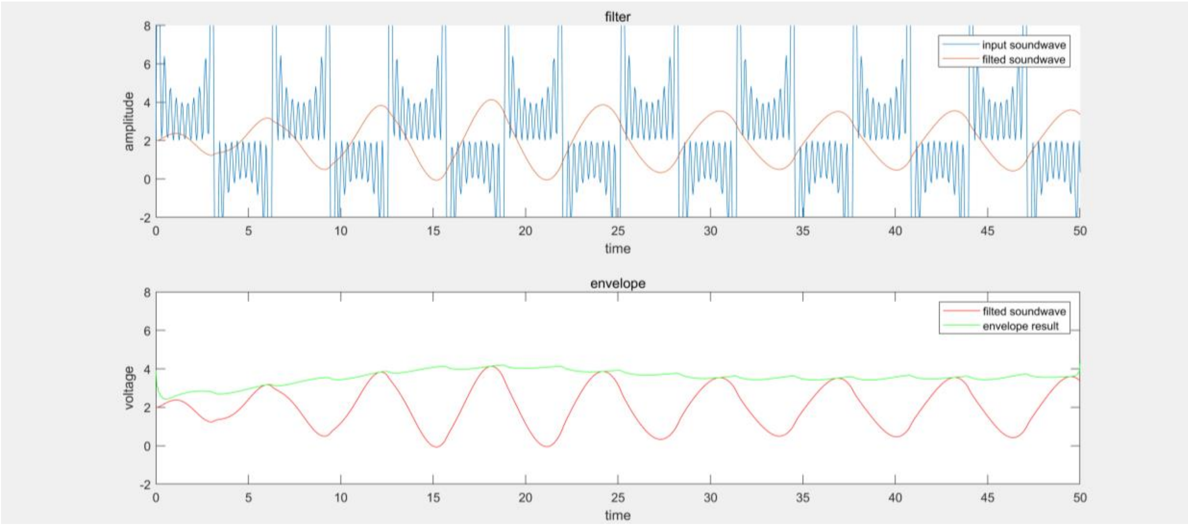

Figure 8. Sound filter and envelope.

A square wave is set up to demonstrate the hair cells' reaction when exposed to discontinuous excitation sounds. When the square wave is located at a high amplitude, the hair cells receive sound waves with a specific frequency, and the dendrites of the auditory afferent nerve continues to accumulate electric potential. When the square wave is located at a low amplitude, the hair cells are not exposed to sound at a specific frequency. The auditory afferent nerves recover and remains at resting state. When potential accumulation reaches action threshold, the auditory afferent nerve emits a pulse. As can be seen from the figure, even if the hair cells receive a specific frequency of sound, as long as the accumulation is not enough, the auditory afferent nerve will not pulse. This better simulates the physiological characteristics of the human ear that do not respond to small amounts of subtle sounds. The result of this procession is demonstrated in figure 9.

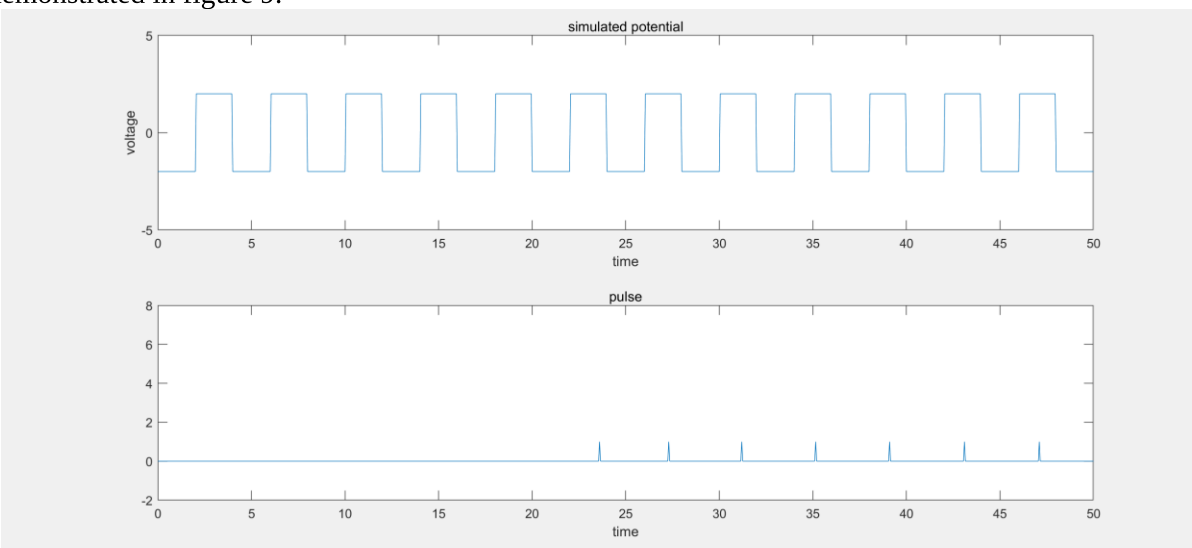

Figure 9. Analogue square wave and output pulses.

5. Conclusion

Cochlear implants are an important tool that can make people with hearing loss feel the world of sound again. Speech procession is the core component of cochlear implants. Most of the speech processing strategies used in cochlear implants only consider the acoustic-electrical conversion function and ignore the time effect of synapses. MPIF cochlear implant strategy adds the temporal

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features of hair cells and auditory afferent synapses. Under the premise of the original speech signal band-through rectification to extract the envelope, the membrane potential integral discharge is used to generate a stimulus pulse sequence, which means the action potential is used as the stimulation pulse to stimulate the nerve, which improves the quality of sound perception for cochlear implant users from a new perspective and obtains the improvement of auditory effect.

References

[1] Chadha, S., Kamenov, K., & Cieza, A. (2021b). The world report on hearing, 2021. Bulletin of the World Health Organization, 99(4), 242-242A.

[2] Yiwei, Y., Yuejin, X., & Jichang, M. (2012). Digital signal processing of a novel neuron discharge model stimulation strategy for cochlear implants. Journal of Southern Medical University, 32(10), 1435-1439.

[3] Bacon, S. P., Fay, R. R., & Popper, A. N. (Eds.). (2004). Compression: From Cochlea to Cochlear Implants. Springer Handbook of Auditory Research.

[4] Heine, PA. (2004). Anatomy of the ear. Vet Clin North Am Small Anim Pract, 34(2), 379-95.

[5] Fettiplace, R. (2017). Hair Cell Transduction, Tuning, and Synaptic Transmission in the Mammalian Cochlea. Compr Physiol,7(4),1197-1227.

[6] human ear | Structure, Function, & Parts. (2022). Encyclopedia Britannica. From https://www.britannica.com/science/ear/Transmission-of-sound-within-the-inner-ear

[7] Zeng, F.G., Rebscher, S., Harrison, W., Sun, X., & Feng, H. (2008) Cochlear implants: system design, integration, and evaluation. IEEE Rev Biomed Eng, 1, 115-42.

[8] Dowell, R.C., Mecklenburg, D.J., & Clark, G.M. (1986). Speech recognition for 40 patients receiving multichannel cochlear implants. Arch Otolaryngol Head Neck Surg, 112(10), 1054-9.

[9] Loizou, P.C., Dorman, M., Poroy, O., & Spahr, T. (2000). Speech recognition by normal-hearing and cochlear implant listeners as a function of intensity resolution. J Acoust Soc Am, 108(5 Pt 1), 2377-87.

[10] Haykin, S., Chen, Z. (2005). The cocktail party problem. Neural Comput, 17(9), 1875-902.

[11] Moore, B.C., & Skrodzka, E. (2002) Detection of frequency modulation by hearing-impaired listeners: effects of carrier frequency, modulation rate, and added amplitude modulation. J Acoust Soc Am, 111(1 Pt 1), 327-35.

[12] Petersen, C.C.H. (2017) Whole-Cell Recording of Neuronal Membrane Potential during Behavior. Neuron, 95(6),1266-1281.