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Transcutaneous Electrical Nerve Stimulation System for Treating Tinnitus based on the Cortex-M4 Microcontroller

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Abstract

Among the methods of treating tinnitus, the transcutaneous clectrical nerve stimulation (TENS) method of treating by electrical stimulation is common. However, there is a problem that surgical operation is required to stimulate the vagus nerve (VN) main trunk near most of the bronchus. Alternatively, we found that the same effect could be achieved by electrically stimulating the vagus nerve VN branch (Arnold's nerve) distributed in the outer ear. The TENS system for stimulation of vagus nerve has been developed, but it has not been able to implement to stimulate as a parameter optimized for the patient by simultaneously playing the sound of eliminating the tinnitus frequency. Therefore, in this paper, it is important to develop a safe and practical TENS device for tinnitus treatment based on a 32-bit microprocessor that simultaneously applies non-invasive and notched sounds and to develop optimal treatment methods for treating tinnitus.

Key words: *Vagus nerve stimulation, Cortex-M4, Tinnitus, Arnold's nerve.*

1. Introduction

Recently, Tinnitus therapy focuses on nerve modulation that returns the nociceptive neural plasticity of the central nervous system to its original state. [1]. Neuromodulation techniques such as transcranial magnetic, transcranial direct current stimulation, neurofeedback, and deep brain stimulation have been developed to treat tinnitus. But, these techniques have failed to obtain the lasting effects. Recent studies suggest that tinnitus can be improved by transcutaneous vagus nerve stimulation (tVNS) with method of notched sound that removed the tinnitus frequency. Recent hypotheses that explain tinnitus are that signals in the frequency band in which cochlear injuries occur cannot be transmitted to the auditory centers of the brain. This is a so-called maladaptive neuronal plasticity in which neuronal inhibitory neurotransmission disappeared and neurons in adjacent frequency bands were reduced in lateral inhibition resulting in excessive excitation [2]. Therefore, it is ideal to hear the sound of eliminating the frequency band of the tremor because the sound of

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the tremor area excites the neuron [3] [4]. tVNS that stimulate the main trunk of the vagus nerve through cervical incision had a possibility to lead arrhythmia symptoms and the heart disease. However, stimulating the nerve branch distribution on auricle (Arnold's nerve) has similar neuromodulation reactions as direct electrical stimulation to vegus nerve by cervical incision [5] . Therefore, in this study, we developed the tVNS system to stimulate the vagus nerve of Arnold's nerve based on the 32-bit microprocessor Cortex-M4 that has efficient signal processing features applicable to digital signal control.

2. Methods

Our tVNS system consists of the microphone circuit, the power amplifying circuit, the low-pass filter circuit, the stimulator circuit, and the MP3 module. The system can receive external sound as a capacitor microphone, and can receive MP3 files through the MP3 module. At this time, DFplayer was used as an MP3 module. A noise audio amplifier with auto gain control (AGC) function was used to amplify the audio signal. We used a loss-pass filter to only receive the audio of the audible frequencies that removed the noise before receiving the audio signal from the microcontroller unit (MCU). Through the digital-analog-conversion (DAC) of the MCU, the filtered sound was amplified through a class B power amplifier.

To remove the tinnitus frequency band, the Cortex-M4 core, a 32-bit microcontroller, was used to enable fast data processing. It is suitable for fast digital signal processing (DSP) and has high performance such as the fast analog to digital conversion (ADC) as the optional floating-point unit (FPU).

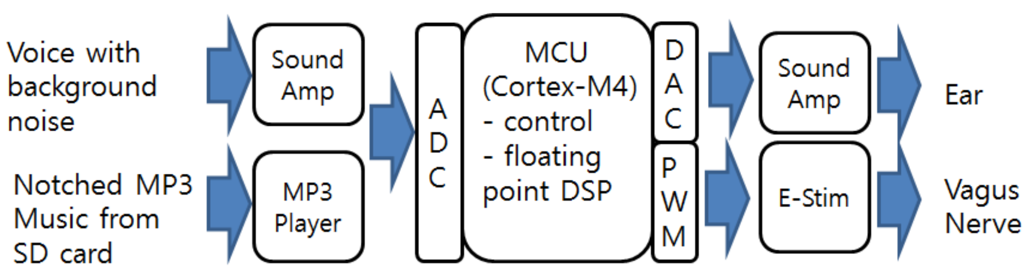

Figure 1. System block diagram of transcutaneous vagus nerve stimulation system for treating tinnitus

The stimulator circuit used a DC-boost circuit for high voltage generation. The DC-boost circuit applies a PWM waveform to the microprocessor to generate a high voltage. The magnitude of the voltage depends on the pulse width of the PWM waveform. A voltage of up to 150v can be obtained. We succeeded in reducing the size of the stimulator circuit by using a DC-boost circuit instead of a transformer. In the stimulator circuit, biphasic pulses were successfully formed using PNP and NPN BJT transistors. Because the Sensory perception threshold to biphasic pulses is lower than to monophasic pulses, the biphasic pulse is more effective and safe than the monophasic pulses [6]. The MCU generates the PWM waveforms for generating the biphasic pulse as well as forming the boosted voltage at the same time. It is also designed to set the amplitude of the biphasic pulse applied to the patient as the pulse width is varied in the PWM. Sound is delivered to the patient through the earphone and electric stimulation is performed using the ear electrode. It is necessary to develop a new model electrode because it must stimulate electricity and apply sound at the same time.

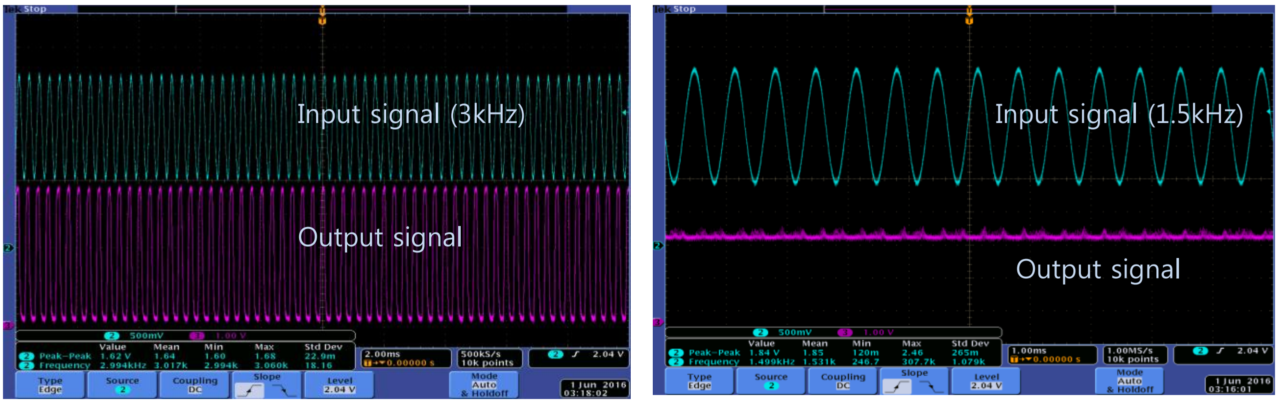

Figure 2. Comparison of filter input and output signals when the tinnitus frequency is near 1.5kHz

Our system has made four major controls possible. Switches were used to select the electrical strength and frequency of the stimulation and the frequency of the sound and the frequency to filter. Pushing the switch is designed to control the parameters though external interrupts. In addition, we used a microprocessor that receives external sound, performs DSP through an analog-digital-conversion (ADC), outputs a signal through a DAC, and outputs a PWM waveform at the same time. Our sound collector system processes the external signal through the c-MIC and removes the high frequencies through the low pass filter. We used a one pole IIR filter to remove the background noise by removing the unexpected loud noise.

We designed the band stop FIR filter which is sampling frequency is 88kHz and show the main filtering routine with timer handler below.

```
const float h[51] = {
-0.000000, -0.000166, 0.000064, -0.000147, 0.000506, 0.000902, 0.000820, 0.002553, -0.001731, 0.002235, -0.008929,
-0.000387, -0.014085, 0.000782, -0.003058, 0.009591, 0.027302, 0.010211, 0.052650, -0.030154, 0.038074, -0.124282,
-0.018908, -0.231396, -0.072776, 0.720721, -0.072776, -0.231396, -0.018908, -0.124282, 0.038074, -0.030154, 0.052650,
0.010211, 0.027302, 0.009591, -0.003058, 0.000782, -0.014085, -0.000387, -0.008929, 0.002235, -0.001731, 0.002553,
0.000820, 0.000902, 0.000506, -0.000147, 0.000064, -0.000166, -0.000000};

void TIM2_IRQHandler(void) {                      // ADC TIMER handler
   if (TIM_GetITStatus(TIM2, TIM_IT_Update) != RESET)    {
       TIM_ClearITPendingBit(TIM2, TIM_IT_Update);
                  if(ADC_GetFlagStatus(ADC3, ADC_FLAG_EOC) == RESET) {
                            Input_data = (ADC3ConvertedValue[0]*3000/0xFFF);
                  for(i=0;i<K;i++)    {
                  xn[K-i]=xn[K-1-i];    }
                  xn[0]=(float)Input_data;
                  sum=0;
                  for(i=0;i<K;i++) {
                  sum =sum + (h[i]*xn[i]); }
                            DACout =(uint16_t)sum; }         }    }
```

When collecting sounds with frequencies in the range of 20 KHz from outside, the ADC function allows a smooth processing by having a sufficiently high sampling rate. In this study, we set the sampling frequency to 44 kHz. For this purpose, The Timer period of Microcontroller is the value that is 44000 when divided the core clock. At this time, analog-digital-conversion (ADC) is performed using direct memory access (DMA).

3. Results

Our vagus nerve stimulation system can generate the sound removed from the tinnitus frequency bandwidth of patient on the basis of an algorithm implementation and control the biphasic electrical stimulation range from 20V to 150V and from 25 Hz to 120 Hz at the same time. By using the switch, it is possible to adjust the frequency and amplitude easily. VNS system generates the output waveform based on the PWM waveform generated from the MCU. There are two examples. According to figure 3, left figure is a waveform with 60V and 80Hz, and right figure is a waveform with 60V and 120Hz. The frequency was adjusted by setting the sampling frequency and the amplitude was generated by adjusting the pulse width of the PWM waveform.

Figure 3. Stimulation output voltage
(Left : Frequency : 80Hz ,Vpp : 60V , Right: Frequency : 120Hz Vpp : 60V)

4. Discussion

The purpose of this pilot study is the design of the VNS system with a sound collecting amplifier and the possibility of accurate output. The sound collecting system analyzes the volume of the sound corresponding to the tinnitus frequency and gives the patient sound or music which removal of the tinnitus frequency band. It will also be an effective treatment device because it can apply appropriate electrical stimulation to each patient according to the tinnitus frequency. Therefore, we hope that the optimal treatment of tinnitus will be developed based on the tVNS system.

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