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Design of a Low-cost Active Dry Electrode Module for Single Channel EEG Recording

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Abstract: This paper presents a design of 1-channel active dry electrode module for EEG from one's forehead. The IA(instrumentation amplifier) circuit inside the module is based on the configuration sown on the paper MettingVanRijn et al. We analyze the IA circuit to find out the related equation, and then compare its simulated characteristic with the result obtained from the real active dry electrode circuit. With the active dry electrode and the wet(Ag/AgCl) electrode connected to the separated analog processing module on one's forehead at the same time, their real time and FFT outputs of EEG are examined for comparison. The active dry electrode module has advantages over the wet electrode and its analog processing module : 1) The size of the analog processing circuit of the active dry electrode module is smaller than that of existing EEG analog processing module ; 2) the total cost required to make the proposed analog processing circuit is much lower than that of the existing circuit, since the designed circuit needs smaller parts; 3) the electrical characteristic is comparable to the general EEG analog processing module even if the designed module has simpler circuit configuration.

Key words: Active dry electrode, EEG, IA, FFT, Ag/AgCl

INTRODUCTION

There are many applications for scalp electrodes. As diagnostic tools, electrodes are routinely used to monitor and analyze heart conditions, brain activity, and other biological phenomena [1,2,3]. To get reliable EEG signal from one's scalp, a scalp-electrode impedance should be less than 5kΩ and the usually required procedure was to abrade the skin. Electrode materials should be those which do not interact chemically with the electrolytes of the scalp. Electrodes coated with gold, silver chloride, platinum are satisfactory.

Babak A. Taheri et al.[4] showed a design method of dry electrode for EEG. Based on the research, this paper shows a design method of making the active dry electrode and its analog processing circuit for extracting EEG from one's forehead.

Forehead is not good for EEG detection because of many artifacts like EOG, EMG, and eyeblinks. That's why hair-covered areas on the scalp are usually selected for EEG recording. However, if we consider increasing convenience from user's point of view in designing a bio-feedback system, it won't be appropriate to use hair-covered areas on the scalp. For this reason, several BCI systems like Cyberlink system of Brain Actuated Technologies Inc. and Neuro Harmony of CS Brain Technology Inc. are using foreheads for EEG detection and its analysis. The dry electrodes of those systems are assumed the form of gold plated buttons. They don't contain the analog processing circuit together with the dry electrode like the proposed module in this paper. EEG signals from one's forehead are detected with the gold plated button and delivered to the separate analog processing module through wires. But in some cases, the wires could be media of noises generated by the electromagnetic wave from test instruments or consumer electronics, the sudden movement of the wires and so on. One way of solving that kind of problem is to use shielded wires, but this would not be the perfect solution.

So a design of compact active dry electrode module including the analog processing circuit for detecting EEG from one's forehead is suggested here for the purpose of convenience for users. And with the active dry electrode designed in this paper give a chance to detect EEG without the separate analog processing module. A different type of active dry electrode, which can be used on the hair-covered areas, will also be studied further on the basis of forehead-EEG detecting research.

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METHODS

The Short Review of the General EEG Signal Processing

For EEG signal detection, the analog and digital signal processing methods are applied as shown on Fig. 1. In case of the analog processing, the raw EEG signals from the wet electrodes are applied to IA(instrumentation amplifier), which rejects the common mode signal like half-cell potential and outputs the differential mode signal. The IA is mostly used as a form of one-chip and has the voltage gain from 10 to maximally 20000. When IA is adopted as a part of the analog processing circuit as Fig. 1, the usual voltage gain is several tens. The reason why IA has not get the full range of gain is DC offset voltage happened by the variation of contact situation of two inputs. To get rid of this DC offset voltage the high-pass filter follows IA. And then the 60Hz noise is rejected by band-rejection filter(notch filter). Finally additional amplifier and filter circuits follows notch filter to increase the EEG signal level(10uV ~ 100uV) in the range from several mV to hundreds of mV and reject high frequency signal(>40Hz). Sometime some analog processing modules of Open EEG and BioPac system are added one or two additional amplifier circuits to make EEG level increased for digital signal processing. So the total voltage gain of the analog processing circuit module is around 20000.

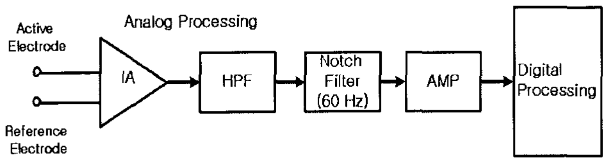


Fig. 1. Block diagram for signal processing.

The Proposed Analog Processing Circuit

Fig. 2 shows the brief description of internal configuration of the active dry electrode module. It consists of IA and notch filter circuit. The notch filter circuit is made with a well-known circuit configuration, so here we don't explain about it in detail. With the notch The IA circuit is realized with the circuit configuration proposed by MettingVanRijn et al[5]. This IA circuit has several advantages over the general analog processing circuit shown on Fig. 1. First, DC offset voltage and high frequency signal can be removed without additional high-pass filter and low-pass filter because it has band-pass filter characteristic. Second, high level of gain up to 20000 can be achieved at the first stage with no supplement of amplifiers. In other words, the proposed IA circuit can replace IA, HPF, several amplifiers, and LPF blocks shown in Fig. 1. Third, the compactness of the proposed circuit can make the existing EEG analog processing circuit much smaller, so the total cost needed for making the circuit will be decreased.filter, the attenuation of -10dB at 60Hz can be achieved.

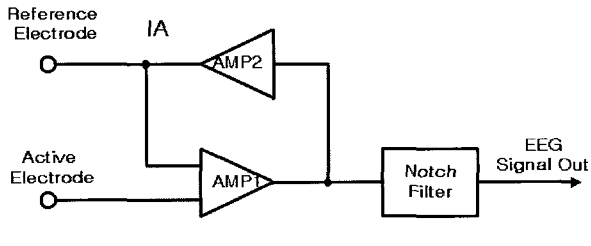


Fig. 2. Block diagram of the circuit inside the dry active electrode module.

Analysis of Non-inverting Operational Amplifier

In Fig. 3 the output voltage U_0 has the following relation with E_0.

$$U_0 = (1+\frac{R_2}{R_1})E_0 \quad (1)$$

For the analysis of non-inverting op-amp circuit, Fig. 3 can be transformed into the circuit shown on Fig. 4 with $U_0=0$.

And U_1' becomes

$$U_1' = (1+G)(\frac{sC_AR_A}{sC_AR_A+1})E_1 \quad (2)$$

where

$$G = \frac{R_4R_5+R_3R_6+R_4R_6}{R_3R_5}$$

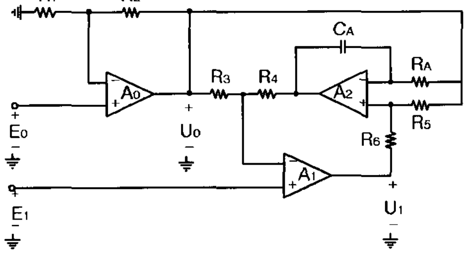


Fig. 3. Instrumentation amplifier

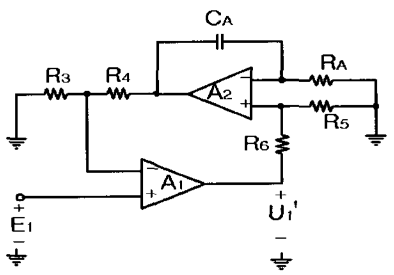


Fig. 4. Circuit for non-inverting analysis.

Analysis of Inverting Operational Amplifier

For the analysis of inverting op-amp circuit, Fig. 3 can be transformed into the circuit shown on Fig. 5 with $E_1=0$. Based on the relation of $\frac{U_0}{R_3}=-\frac{V_A}{R_4}$, we get the following equation.

$$V_A = -\frac{R_4}{R_3}U_0 \tag{4}$$

And from the relation of $sC_A(V_A-V_B)=\frac{V_B-U_0}{R_A}$, we also get the following equation.

$$V_B = \frac{sC_AR_AV_A+U_0}{sC_AR_A+1} \tag{5}$$

Finally, the combination of the equations obtained, the U_1'' becomes

$$U_1''=-\frac{R_4R_5+R_3R_6R_4R_6}{R_3R_5}\frac{sC_AR_A}{sC_AR_A+1}U_0+\frac{1}{sC_AR_A+1}U_0 \tag{6}$$

In Eq. 6, the term of $\frac{1}{sC_AR_A+1}U_0$ could be zero in the frequency range from 1Hz to 40Hz with $C_AR_A \geq 1$.

So we get the final equation as below :

$$U_1'' = -G\frac{sC_AR_A}{sC_AR_A+1}U_0 \tag{7}$$

where

$$G = \frac{R_4R_5+R_3R_6+R_4R_6}{R_3R_5}$$

And this G represents the gain by feedback loop in pass band.

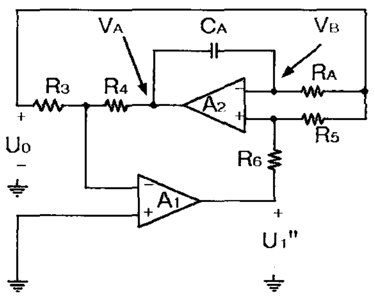


Fig. 5. Circuit for inverting analysis.

Total Output

Based on the analyses of non-inverting and inverting circuits, the total output is achieved by combining Eq. 2 and 7 :

$$U_1 = U_1'+U_1''=[(1+G)E_1-GU_0](\frac{sC_AR_A}{sC_AR_A+1}) \tag{8}$$

or

$$U_1=(\frac{R_4}{R_3}+1)(\frac{R_6}{R_5}+1)(\frac{sC_AR_A}{sC_AR_A+1})(E_1-E_0) \tag{9}$$

As we expect in Eq. 9, the proposed IA circuit has the gain component obtained with resistors (R_3, R_4, R_5 and R_6) and high pass filter characteristic generated by the combination of operational amplifier A_2, resistor(R_A) and capacitor(C_A). And a few important factors should be also considered. Those are CMRR(common mode rejection ratio) and GBP(gain bandwidth product). Based on the IA configuration[5], CMRR could be expressed as

$$CMRR = 20\log(\frac{100}{2TOL_R}) + 20\log A_{DIF} \tag{10}$$

This relation is achieved by the unique shape of circuit ; that is, if in Fig. 3 the output of operational amplifier A_0, R_5 and R_A were designed to be connected together, the gain of common-mode inputs is limited to unity. Therefore the resultant CMRR equals to the gain of differential-mode inputs(A_{DIF}), and the matching or tolerance(TOL_R) among resistors is contributed to enhance the value of CMRR.

The expression related to GBP (Gain-Bandwidth-Product) is written by

$$f_{3dB} = \frac{GBP}{A_{DIF}} \tag{11}$$

From Eq. 11, the corner frequency of low pass filter is determined, and together with the property of high-pass filter explained earlier the proposed IA circuit has the characteristic of band-pass filter. The bandwidth of band pass filter are selected to get the range from 1Hz to 40Hz and the gain is set to 20,000 which is equivalent to CMRR as 86dB. Accordingly, the GBP should be 800kHz. OPA2111 manufactured by Burr-Brown is a good candidate which satisfies the required CMRR and GBP, and other electrical properties like high imput impedance ($10^{13}\Omega$) and low input noise (11 $nV/\sqrt{Hz}$).

Simulation and Real Test

Before H/W design of the active dry electrode module, the characteristic of the designed IA was simulated and tested. We selected the EEG frequency range from 1Hz to 40Hz. The values of parts in the circuit were set to fit for the frequency range.

Fig. 6 shows the simulated result based on the Eq. 9. with R3=R5=1kΩ, R4=R6=140kΩ, RA=1MΩ,CA=1uF and E1 - E0 = 100uV The total gain is around 20000. In Fig. 6, the frequency bands below 1Hz have very small gain. On the other hand, from the start frequency of the selected pass-band(1Hz ~ 40Hz) the high level gain is accomplished. As mentioned earlier, from Eq. 11 the corner frequency of LPF is determined, and together with the property of HPF has the characteristic of BPF. This BPF characteristic is witnessed at the real test result in Fig. 7.

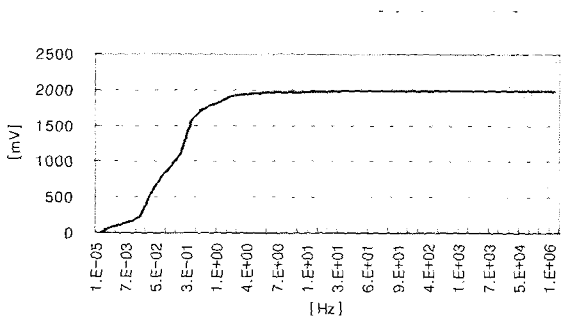


Fig. 6. Simulated result based on Eq. 9.

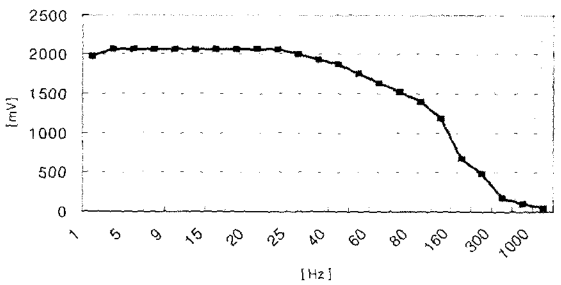
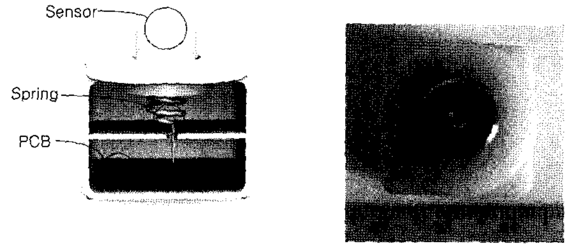


Fig. 7. Test result of the designed IA circuit.

After the circuit based on Fig. 3 is made, the real test is done with signal generator to check the frequency response of the designed IA. Values of parts are same as the simulation condition. In Fig 7, the designed IA shows the exact BPF frequency range from 1Hz to 40Hz and the high gain of 20000 through the pass-band frequency range.

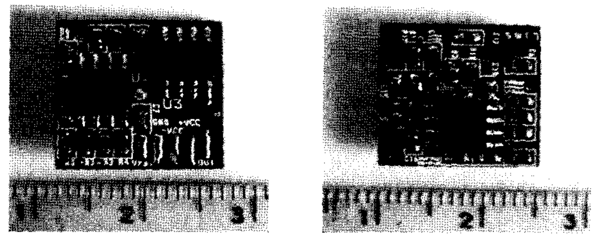
Electrode Module Construction and Test Condition

The electrode itself was made by using a plastic body plated with gold. The electrical connection between electrode and PCB board is done by spiral spring. The spring is also plated with gold and designed to have elasticity so that users feel comfortable when the electrode module is attached to their scalps. The diameter of electrode itself is 10mm and the total dimension of the module is 24mm × 24mm × 21mm (length, width, thickness). The drawing and the real design of the dry active electrode is shown in Fig. 8(a) and (b). And Fig. 9 shows the picture of designed PCB(15mm × 15mm × 1.6mm (length, width, thickness)) inside the electrode module.



(a) (b)

Fig. 8. The dry active electrode construction (a) the internal structure ; (b) the mock up.



(a) (b)

Fig. 9. PCB for analog IA circuit : (a) front-side ; (b) back-side

The placements of the active dry electrode module and the wet(Ag/AgCl) electrode are shown in Fig. 10. To compare the signal characteristics between the dry active electrode module and the conventional wet(Ag/AgCl) electrode and its analog processing module, two electrodes were mounted on the forehead scalp. For the attachments of the reference and ground electrodes of the active dry electrode test, left mastoid and right mastoid areas were used without any skin preparation or electrolyte application. And in case of general wet electrode and its analog processing module test, left and right earlobes were used as ground and reference respectively.

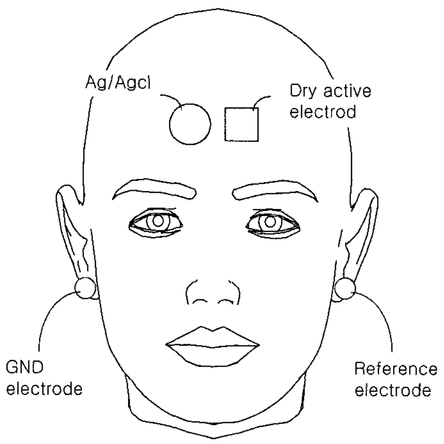


Fig. 10. Positions where electrodes are located.

RESULTS

Put both types of electrodes on foreheads of two subjects(subject A and subject B), spontaneous EEG potentials were recorded to compare the performance of the standard wet electrode and its analog processing module with that of the proposed dry active electrode module using BIOPAC MP150 bio-signal test instrument.

For the test of the general EEG detecting method, we used the disposable conductive gel electrodes and EEG100C which is specially designed for processing the EEG signal. On the other hand, to examine the ability of the designed active dry electrode module, the module was connected with UIM100C which is interface module with computer screen and is not equipped· with any other additional signal processing circuit. The pass-band frequency ranges of both test conditions were set from 1Hz to 40Hz, and their gains were also set to 20000 altogether.

To extract the subjects' EEG signals, they were ordered to have their eyes closed. And then the resultant real-time signals and FFT output were compared. Fig. 11 and Fig. 12 show the test results .

From the results, we got the general similarities in EEG signal outputs from two types of electrodes and their analog processing circuits. As we can see from Fig. 11 and Fig. 12, the real-time outputs are very similar each other and the both FFT results show the high level around 9Hz. When the subjects' eyes are closed, alpha wave(8Hz ~ 12Hz) is generated dominantly. And this result can be easily checked from FFT outputs. In the FFT result, the designed module shows higher amplitude than the general processing module. Even if there are no perfect same real-time signal and FFT outputs between two modules, that kind of difference can be negligible when considering the simplicity and compactness inside the designed module.

As a result we can conclude that the performance of the designed electrode is really comparable to the general wet electrode and its analog processing module.

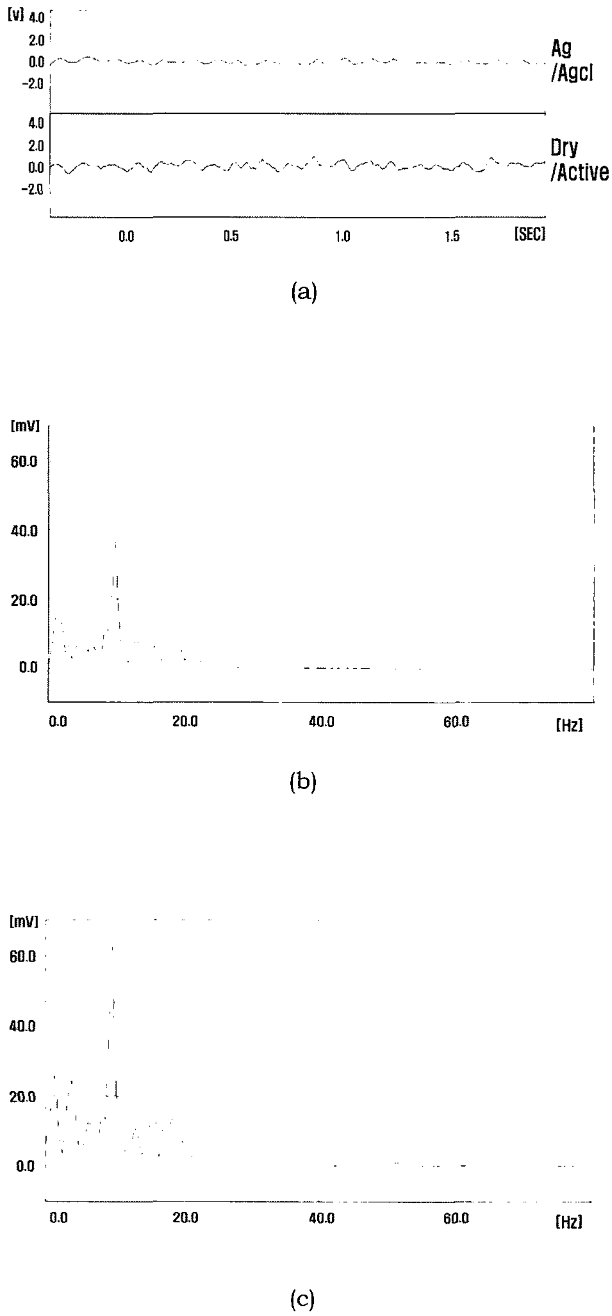


Fig. 11. Spontaneous EEG signals simultaneously recorded by a wet and a proposed electrodes when the subject A's eyes are closed ; (a) Real time signal output, (b) FFT results based on the signal from wet and (c) dry active electrodes.

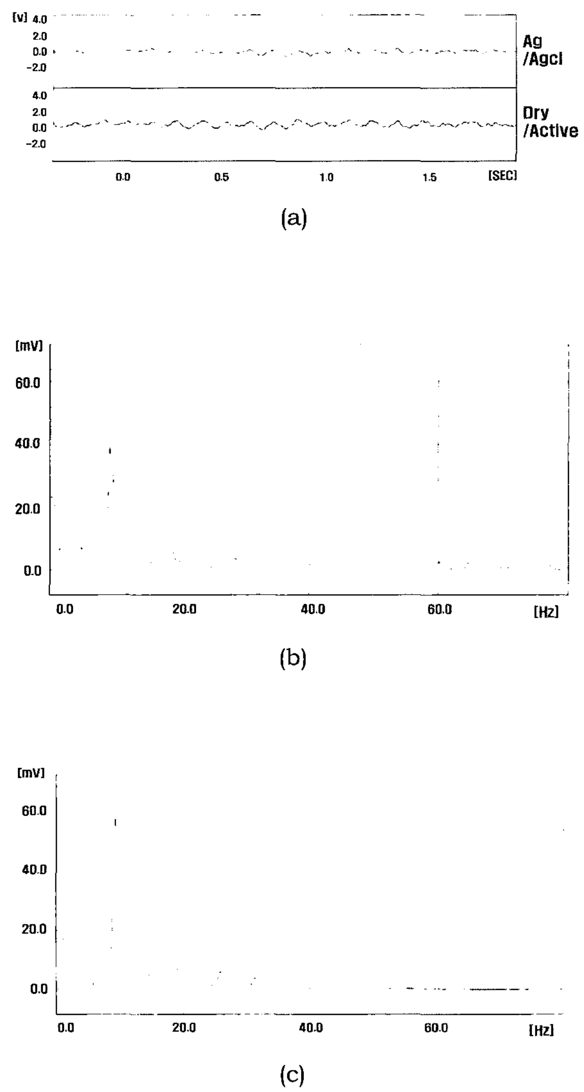


Fig. 12. Spontaneous EEG signals simultaneously recorded y a wet and a proposed electrodes when the subject B's eyes are closed ; (a) Real time signal output, (b) FFT results based on the signal from wet and (c) dry active electrodes.

DISCUSSION AND FUTURE PLAN

Conventional wet electrodes have several disadvantages for using in real fields : Over a long period they are attached one's scalp, the region of the skin in contact with the conductive paste may become irritated. Additionally, skin preparation and attachment times for wet electrodes are long. Many usual people feel unpleasant to have the wet electrodes on their scalp. And to process the raw EEG signals, the separate analog processing module which includes many operational amplifier ICs and electronic parts is essential. For the purpose of introducing a solution for the problems of the existing wet electrode, and a way of making the general EEG analog processing module small enough to be used in a user-friendly BCI system, the active dry electrode module was suggested.

The gold coated active dry electrode module with analog IA circuit is compared favorably with standard electrode and its analog processing module for EEG recordings. However, several issues remain to be addressed. The contact condition of the electrode's surface with the scalp varies due to hair and motion causing mechanical decoupling of the electrode surface from the skin. Even though the current active dry electrode module was applied only to forehead, we will further try to have focus on the research and development for the new style active dry electrode which can make good contact with the scalp over the hair enough to detect the pure EEG signal.

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