Prevent Cardiovascular Disease to Detection Health Status by Design and Measurement of an Electrocardiogram Circuit

Zheyu Wu

Collage of Electric and Computer Engineering, Virginia Tech, VA, US

zheyu@vt.edu

Abstract. Cardiovascular disease, especially myocardial infarction, is a disease that has gained increasing concern in today's more health-conscious society. Usually, these disorders cause abnormal heart beats. The collection or monitoring of heartbeat behavior is good way to judge people's current heart‘s health status. For getting this kind signal, the application of ECG is extremely important. The manufacture of ECG relies on electronic engineering. The electrical signal produced by the heart is very small. Acquiring tiny signals is always difficult. The reason of difficult is that there is error in the actual collection, and when the input signal is small, the error is relatively large. So the function that the ECG needs to have is to be able to accurately measure and optimize the signal, and in the final obtain a clear and obvious electrocardiogram by optimizing the collected signals. The principle of used on making an ECG is to complete a circuit that can correctly process the input signal. This includes using amplifiers and filters to transfer the signal to the output signal as a waveform. Based on such a combination of the circuit and some components, a fully functional ECG is successfully fabricated. By recording and analyzing the collected ECG, it is possible to discover and treat these kinds of diseases in the human body.

Keywords: Make one ECG, Stabilization Signal, Instrumentation Amplifier, Active Filter, Notch Filter.

1. Introduction

Today, health issues have become an important problem that people pay more attention on "Be Health" and "Regular Physical Examination", and not just the attention from elderly. Most people have begun to focus on their own health, including middle-aged and young people. Regular physical examinations and more equipment to monitor their body’s physical condition will reduce the possibility of known diseases becoming worse in human’s body, and will avoid the probability of unexplained diseases developing until taking life with medically unknown. During the period of 2020-2022, due to the huge diffusion range and speed of COVID-19, much more people's awareness of notice their own health has been deepened.

With the official discovery and determination of myocardial infarction, more people pay attention to this disease because of its high prevalence. As 2015, there were 15.9 million myocardial infarction patients worldwide [1]. Because myocardial infarction patients do not need to be hospitalized for observation after diagnosis and their onset frequency, time are not fixed, once the onset occurs, they must use defibrillator or take aspirin [2], which is difficult for the public timely take correct and effective treatment measures for a suddenly myocardial infarction patient in a public environment. As this hard to prevent disease with high prevalence and possibility of onset, doctors' examination of patients and potential patients' monitoring of their own bodies have become a goal which is extremely important.

The heart is constantly contracting by following the commands issued by the brain which is pumping blood including oxygen to the whole body. The heart of patients with myocardial infarction cannot beat normally like others due to the heart surrounding fat and myocardium. It leads to the abnormal delivery of the blood with oxygen which is needed by the whole body. And it will result body in physical abnormalities, even lead to death [3]. Heat beating can be regarded as an electrical signal, and abnormal beatings will produce different electrical signals [4]. So that means that if one device is used to collect and compare this kind signal with the database, myocardial infarction patients can be identified and treated. During these years’ attempts and research, Electrocardiogram, also referred to as ECG, has been recognized as one effective and accurate device for detecting and determining myocardial infarction patients [5]. Building ECG has become important work for myocardial infarction patients to keep save. ECG is to obtain the electrical signal of heart beating to determine each one's health status. For easy reading ECG's result waveform, P, Q, R, S and T are always used to divide this result and marked the focal points which need to be mentioned. Most kinds of myocardial infarction with different inducements will cause ST-segment elevation [6]. Likewise, ECG is not only used to diagnose myocardial infarction. Other cardiovascular diseases which may cause heart problems can also be detected by ECG. As they always will cause abnormal electrical activity in the heart, even though some of them are not fatal. At the same time, these diseases are also accompanied by ECG abnormalities with fixed features, such as ST segment abnormalities often corresponding to myocardial infarction [7].

To be able to prevent more heart-related diseases, mastering the building process of ECG has become an important task of processing electrical signals. Naturally, this has become an important job for electronic engineers. That task is designing and building one kind circuit which can read the electro cardio signal of the human body. Also, it needs to display the result for observation and judgment.

2. Building ECG

Most known ECGs mainly include the following parts: electrode pads, alcohol, razor, adhesive, ECG paper and ECG machine [8]. In fact, it is easy to understand that the electrode sheet is to obtain the electro cardio signal of the human body. The electrocardiograph is used to process the electro cardio signal collected by the electrode pads. ECG paper can display the result. For alcohol, razors, and adhesives, it is to keep the electro cardio signal of the human body obtained by the electrode pads without interference. Because the hair of human body is not conductive, and the sweat contains a lot of salt which will affect the electrical signal. To get the most accurate electro cardio signal, it is necessary to clean the area up where the data needs to be collected.

To make an ECG, it is necessary to understand its working principle. Due to process tiny electrical signals in the human body, amplifiers are the suitable element for the circuit which can amplify the signal. According to the size of the original signal and the desired output signal, designing a circuit with a suitable amplification factor is the most important part. This will become the prototype of the ECG machine. Next is work for the electrodes. It needs to take the human body signal. There are many kinds of electrode pads on the market, and choosing a suitable electrode pad that can normally collect the electro cardio signal is enough to complete all the work. Finally, for ECG paper, since it will display the waveform of the output signal, using oscilloscope has the same functionality. While razor, alcohol, and adhesives can be omitted, it is only necessary to sufficiently clean the selected skin area before collecting data.

2.1. Circuit Analysis

To taking these three main parts together which are electrode pads, ECG paper, and ECG machine to form a complete ECG, connections between them and details of the main electrocardiograph's circuit need to be considered.

The first point is the connections. Since the required output signals need to be directly transmitted from the electrode pads to ECG machine and then display on the ECG paper after processing, these three parts just need to be connected in series according to the electrode pads, ECG paper and ECG machine.

The most important thing is the details of the circuit in the ECG machine. First, a simple analysis of the electro cardio signal which is collected is necessary. Electro cardio signal has low frequency and high frequency parts. Just like ST segment, a similar stage, RR-interval is likely to be affected by disease at low frequencies (0.04-0.15Hz) and high frequencies (0.15-0.4Hz) [9]. That means for electro cardio signal need to be divided into low frequency and high frequency. Among one period of electro cardio signal, it will have LF and HF. With previously mentioned P, Q, R, S, T, these also represent some specific points in LF and HF parts [10]. Also, for recording electro cardio signals, it exists many problems. The first is that the initial signal is small. And DC offset may be much larger than signal. Also, among LF and HF, 60Hz induced on signals may be much larger than signal and broadband noise will swamp signal. The solutions for these problems are: First, the amplifier circuit needs to ensure that the gain is about *1000 to amplify our initial signal into an effective output signal. Next, add high pass filter to block too low frequency and low pass filter to eliminate noise past signal bandwidth. Last but not the least, this circuit also needs to add common mode rejection plus notch filter.

To summarize these considerations, ECG machine's circuit will be divided into four main parts. The first part is the Instrumentation Amplifier. This part needs to be connected in series with the electrode sheet to obtain the electro cardio signal as the input signal. The second and third parts are respectively High Pass Filter and Low Pass Filter. These two parts will filter invalid signals. Both could be collectively called Active Filter. The last part is Notch Filter. This will connect to the scope which display the output signal and control the electro cardio signal within the proper showing range.

Until now the whole system of ECG has the basic design and Fig. 1 shows the block diagram.

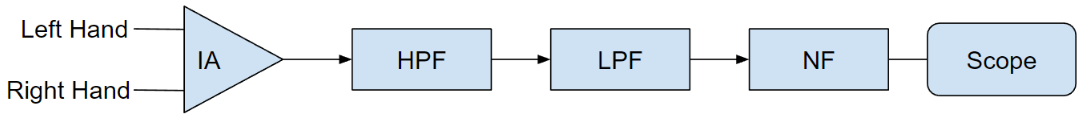

Figure 1. Block diagram of an ECG system

Since it is an amplifier circuit, it is necessary to select a suitable amplifier. LF356 is chosen as the general amplifier in the whole circuit. Resistors are selected from the 13RK7305 resistor kit box. And capacitors are directly used from RSR Electronics, Inc.

2.1.1 Instrumentation amplifier (IA)

For the human body, when collect electro cardio signal, the extremely high resistance contained in the human body will still be a part which is unignore. To solve such a problem and obtain the correct voltage value, the circuit should have high input impedance. An example of standard high impedance circuit is shown in Fig. 2. According to the characteristics of the series circuit, the voltage collected by our circuit will be at the same magnitude level as the original heart voltage in the human body. Also, it should be in common mode and differential mode. And it could be simplified as when differential mode, connect V- to ground.

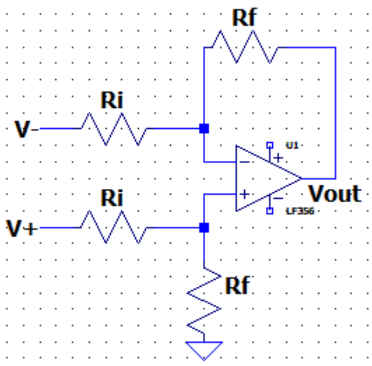

Figure 2. Standard high impedance circuit

As this standard differential amplifier does not work properly. It is necessary to adjust the circuit. The updated circuit shows on Fig. 3 with unknown value of each resistor. All value need be calculated. Based on the standard circuit, $V_{CM} = \frac{V-+V+}{2}$ and $V_{DM} = V + -V -$ can be defined.

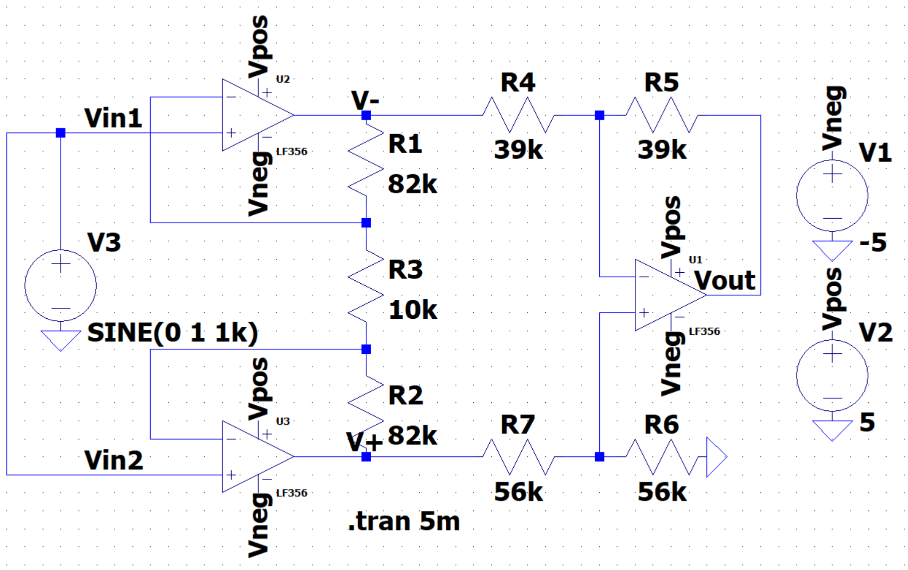

Figure 3. IA part's circuit

For the input voltage, Vin1 and Vin2 are defined for common mode and differential mode. At the same position of V- and V+, the formula of them can be expressed as $V_{-} = Vin1 - \frac{Vin2-Vin1}{R_3}R_1$ and $V_{+} = Vin2 + \frac{Vin2-Vin1}{R_3}R_2$. By superposition analysis, $Vout$ can be represented in $Vout = A_{CM}V_{CM} + A_{DM}V_{DM}$ which ACM and ADM is the gain for common mode and differential mode. And VCM and VDM have their own formulas are $V_{DM} = (Vin2 - Vin1)\left(1 + \frac{R1+R2}{R_3}\right)$ and $V_{CM} = \frac{Vin1+Vin2}{2} + \frac{R2-R1}{R_3}(Vin2 - Vin1)$. The ideal value for ACM and ADM should be 0 and 16, but 0 cannot be talked when calculate and one similar value which is 0.01 can replace. Also, ACM is equal to 0 and $Vout = A_{DM}V_{DM}$ which can simply be $A_{DM} = 1 + \frac{R1+R2}{R_3} = 16$. For Vout, CM, the equation after circuit analysis is $V_{out,CM} = V_{CM}\left(-\frac{R_5}{R_4} + \frac{R_6}{R_7+R_6}\left(1 + \frac{R_5}{R_4}\right)\right) = V_{CM}\frac{R_6}{R_7+R_6}\left(1 - \frac{R_7}{R_6}\frac{R_5}{R_4}\right)$ and $A_{CM} = \frac{R_6}{R_7+R_6}\left(1 - \frac{R_7}{R_6}\frac{R_5}{R_4}\right)$. As resistor's value could not be 0, $1 - \frac{R_7}{R_6}\frac{R_5}{R_4} = 0$. So, all resistors value should follow $\frac{R1+R2}{R_3} = 15$ and $\frac{R_7}{R_6} = \frac{R_4}{R_5}$. Among the resistor's kit, R1=R2=82kΩ and R3=10kΩ are picked first. At the same time, R4=R5=39kΩ and R6=R7=56kΩ.

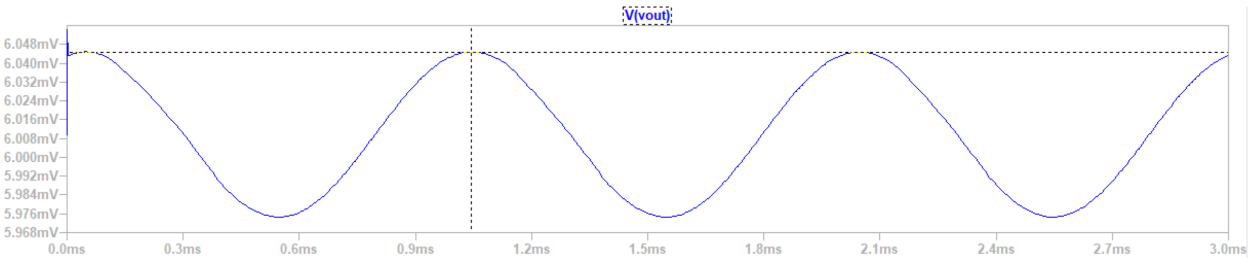

Figure 4. Common mode's time domain waveform of IA

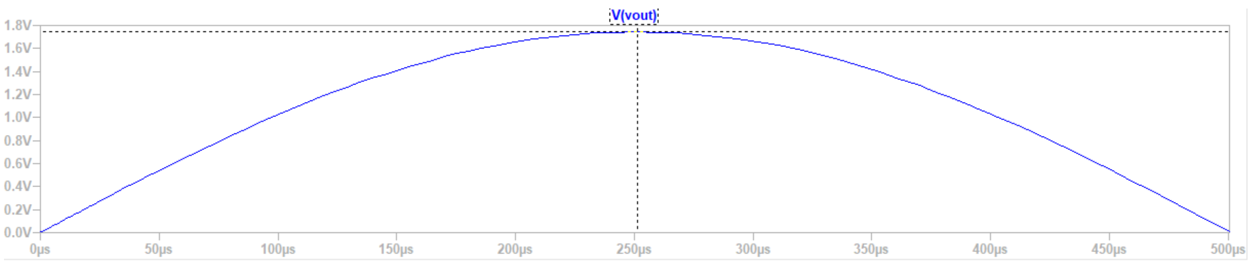

Figure 5. Differential mode's time domain waveform of IA

Follow different connected on Vin1 point, this analog circuit is run in LTspice. $A = \frac{Vout}{Vin}$ is the formula to test if it has one correct gain. Fig. 4 and Fig. 5 are the waveforms of common mode and differential mode separately. Form these waveforms, $A_{CM} = \frac{6.044m}{1} = 0.006$ and $A_{DM} = \frac{1.7436}{0.1} = 17.44$. Both ACM and ADM' value are similar with 0.01 and 16. This part's circuit is completed.

2.1.2 Active filter (HPF and LPF)

For this part, the goal is to filter out useless signals. The first step is continuing to expand the magnitude of gain. Now the amplification factor in differential mode is only about 17 or higher, but fewer than 20. For the first part, IA's Vout should be used as the input of this part, and connected in the circuit that amplifies the voltage.

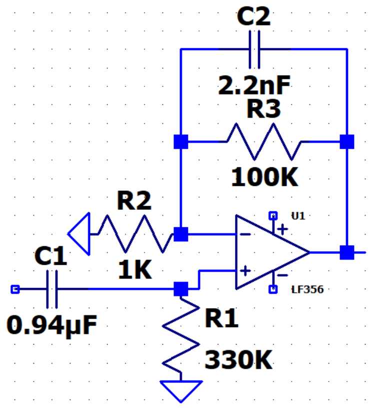

Figure 6. Amplifier's circuit of AF

This one amplifier which shown in Fig. 6 can boost the voltage by a factor of 100. This output signal is large enough to be read and analyzed normally. The remaining steps are to add a second-order, Butterworth, lowpass, active filter which is the circuit in Fig.7. This is the filter of choice for low power, low frequency which is lower than 1MHz applications because they do not involve inductors and it is simple to construct higher order filters.

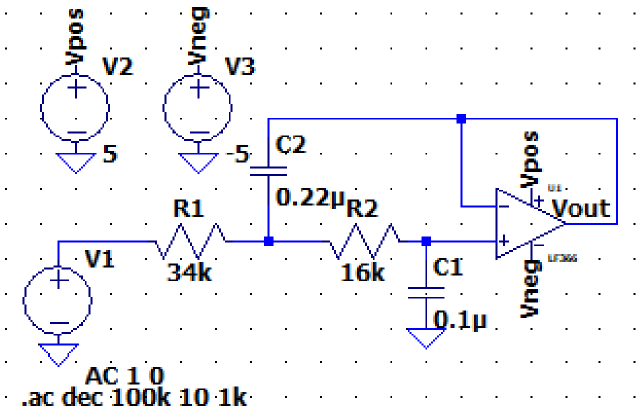

Figure 7. LPF's circuit of AF

For this second order lowpass filter, the standard transfer function is $TF = \frac{1}{1+C_1(R_1+R_2)s+R_1R_2C_1C_2s^2}$ with 2 coefficients $a_1 = \omega_c C_1(R_1 + R_2)$, $b_1 = \omega_c^2 R_1R_2C_1C_2$ which wc is the cutoff frequency. Based on these equations, R1 and R2 can be formulated by $R_{1,2} = \frac{a_1 \pm \sqrt{a_1{}^2 - 4b_1\frac{C_1}{C_2}}}{2\omega_c C_1}$. Also, C1 and C2 should follow $C_1 < \frac{a_1^2}{4b_1}C_2$. Cutoff frequency is set as 45Hz and a1=1.4142, b1=1 followed by the property of second order active filter. Chosen C1 is 0.1uF and C2>0.2uF which chosen 0.22uF. After the calculation, R1=34.15kΩ and R2=15.87kΩ. After getting all elements' value, testing of this circuit if it has the same cutoff frequency with the setting value is the reason to do the frequency response shown in Fig. 8.

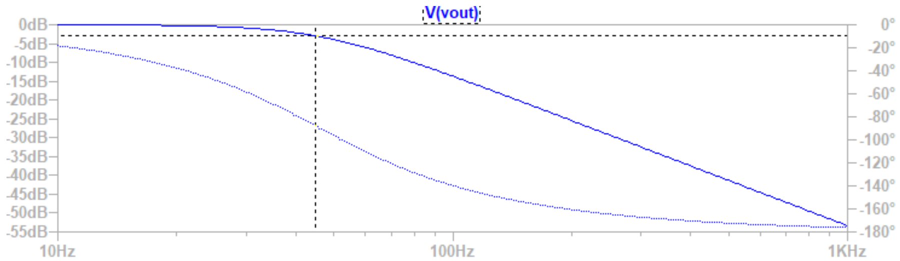

Figure 8. Frequency response of LPF

After running the circuit among LTspice, the cutoff frequency marked on the waveform is about 45Hz. That proves this second lowpass filter is work.

2.1.3 Notch filter (NF)

In fact, after completing these two parts, the circuit can already be used as a working ECG for testing. But the signal still has a lot of shocks. That means if only use the current circuit for testing, the results of the electrocardiogram will also have large fluctuations. To avoid this situation, a Passive Twin-T Notch Filter shown in Fig. 9 needs to be added at the end of this circuit to fix the waveform.

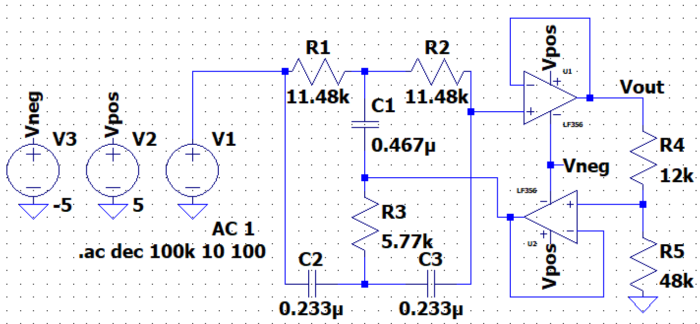

Figure 9. NF's circuit

With notch filter's property, $\frac{V_{out}}{V_{in}} = \frac{s^2+\omega_0^2}{s^2+\frac{s\omega_0}{Q}+\omega_0^2} = \frac{s^2+\left(\frac{1}{RC}\right)^2}{s^2+s\left(\frac{1}{RC}\right)4+\left(\frac{1}{RC}\right)^2}$ and $\omega_o = \frac{1}{RC}$. By combine it and fact circuit together, $\frac{V_{out}}{V_{in}} = \frac{s^2+\left(\frac{1}{RC}\right)^2}{s^2+s\left(\frac{1}{RC}\right)\left(\frac{4}{1+\frac{R5}{R4}}\right)+\left(\frac{1}{RC}\right)^2}$ with $Q = \frac{1+\frac{R5}{R4}}{4}$. The value of Q and null frequency, w0 are chosen as 1.25 and 60Hz. For each elements' values, R1=R2=2R3=R and C1=2C2=2C3=2C. Then the relations can be defined as $\omega_o = \frac{1}{RC} = 60 * 2\pi$ and $4R4 = R5$. And the value of each resistor is R=12kΩ, C=0.22uF and R4=12kΩ, R5=48kΩ.

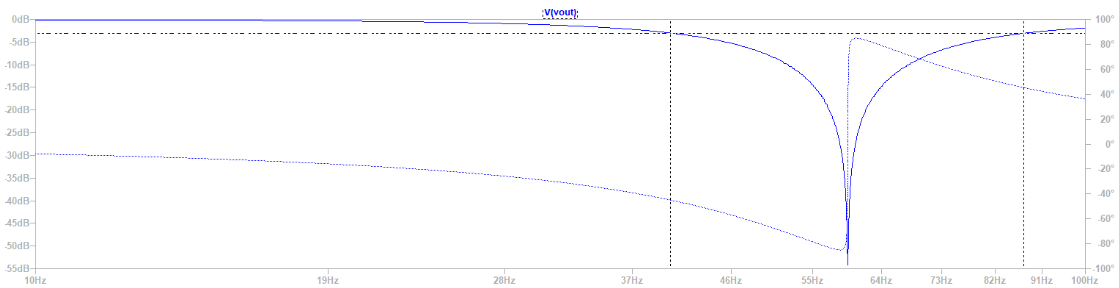

Figure 10. Frequency response of NF

Finally, running this part's frequency response among LTspice which is Fig. 10, the null frequency is about 60Hz and low, high cutoff frequency is 40.25Hz and 87.37Hz.

Until now, the whole circuit of ECG machine has finished, and its circuit drawing is in Fig. 11. Then electrode pads will connected between human and the input voltage. ECG paper connect to the Vout3 to show the electrocardiogram.

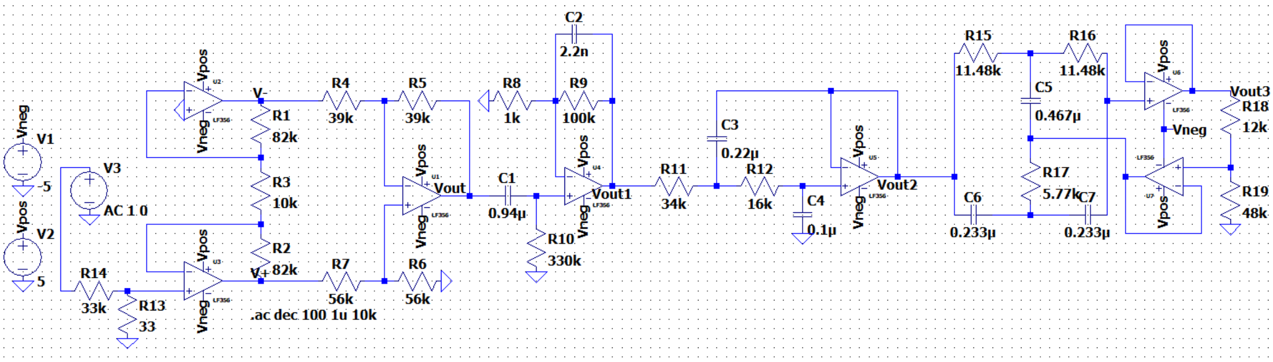

Figure 11. Whole circuit of ECG machine

2.2. Mearsurement

Based on the whole circuit drawing, the circuit will be visualized on the breadboard. At the same time, because each part has detailed requirements for each component. So, evaluating them separately is also a key step.

First one is Instrumentation Amplifiers, IA's part. Among this part, all used element is resistor, but each resistors value should follow $\frac{R1+R2}{R_3} = 15$ and $\frac{R_7}{R_6} = \frac{R_4}{R_5}$. Every fact one must have errors. For the last build one resistor, using series or parallel way to fix its value is necessary. All resistor's fact values are R1=R2=81.5kΩ, R3=9.98kΩ, R4=39.3kΩ, R5=38.7kΩ and R7=55.9kΩ. Following the equation, $R6 = \frac{R5}{R4} * R7 = 56.77k\Omega$ which is series one 56.5kΩresistor and one combined resistor with 389Ωone and 12Ω. Separated in differential and common mode, the waveforms are showing its $A_{CM} = \frac{Vout,peakToPeak}{Vin,peakToPeak} = \frac{6.07}{61.70} = 0.098 = 0.00098 * 100$ in Fig. 12 and $A_{DM} = \frac{Vout,peakToPeak}{Vin,peakToPeak} = \frac{1.06}{0.061} = 17.54$ in Fig. 13. Among these 2 waveforms, both exist a large oscillation either input or output. This is also a testimony of the necessary to use NF.

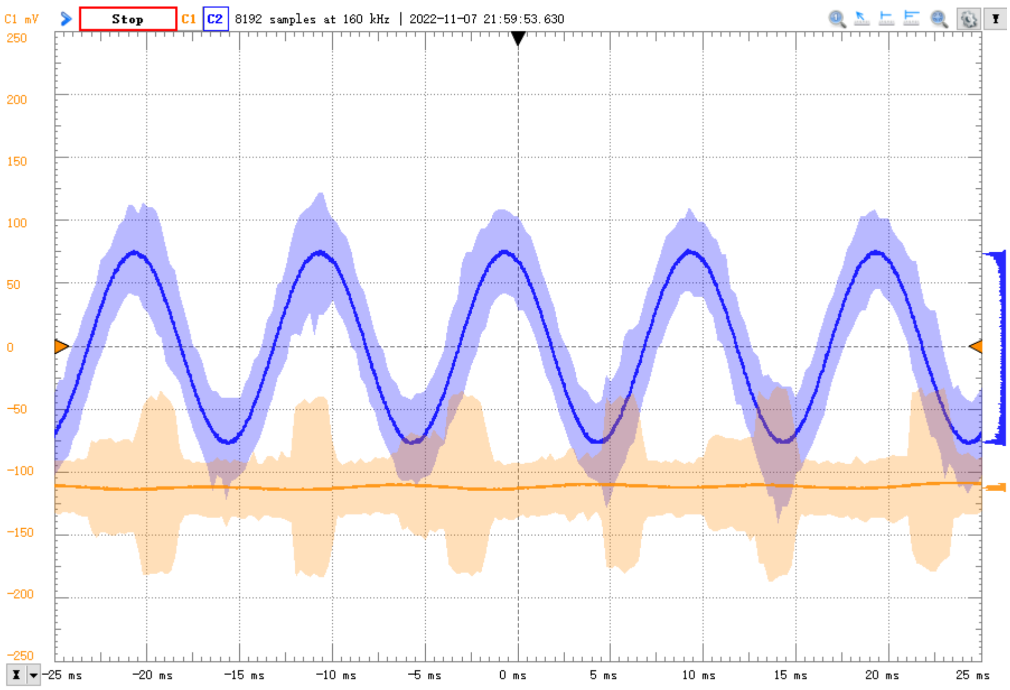

Figure 12. Measurement common mode's time domain waveform of IA

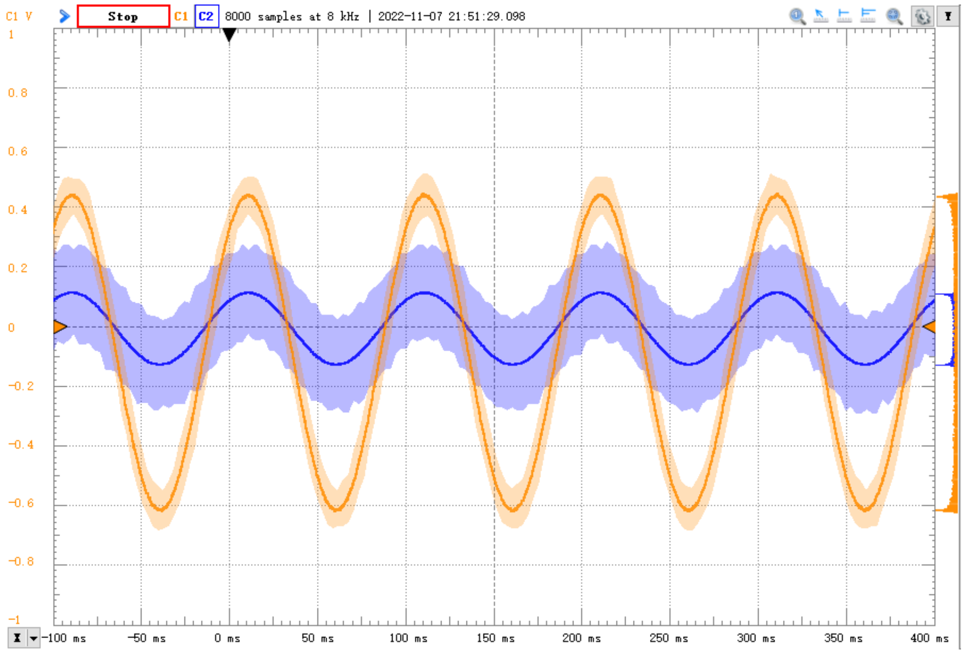

Figure 13. Measurement differential mode's time domain waveform of IA

For the next part, Active Filter, tiny fix is no more necessary for each resistor and capacitor. After its build, the test of this part should be single and connect in the whole circuit after ensuring its correct. By running the frequency response which is shown in Fig. 14, the cutoff frequency is about 45Hz which is same with setting value.

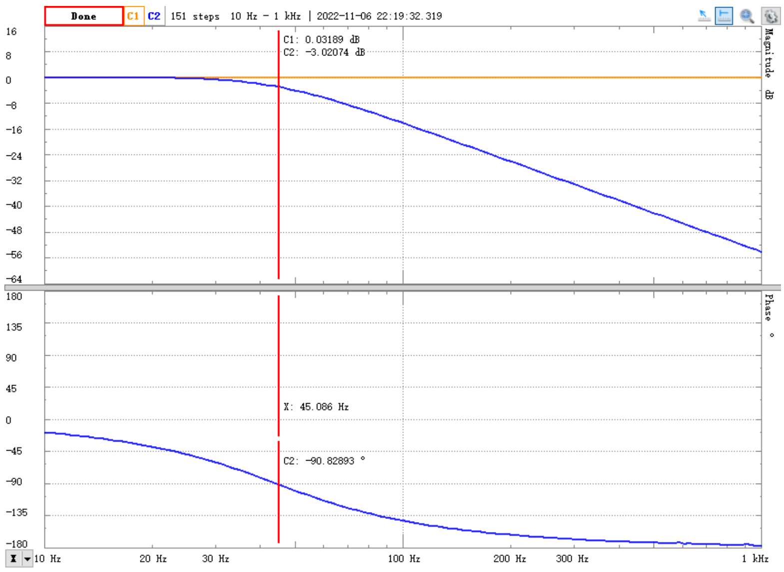

Figure 14. Measurement frequency response of LPF

Final is for Notch Filter. It is same with active filter that no tiny fixed for each element. The separate tests (Fig. 15) have shown the null frequency is 60.1Hz and the cutoff frequencies are 41.3Hz and 85.8Hz which are similar with the analysis value.

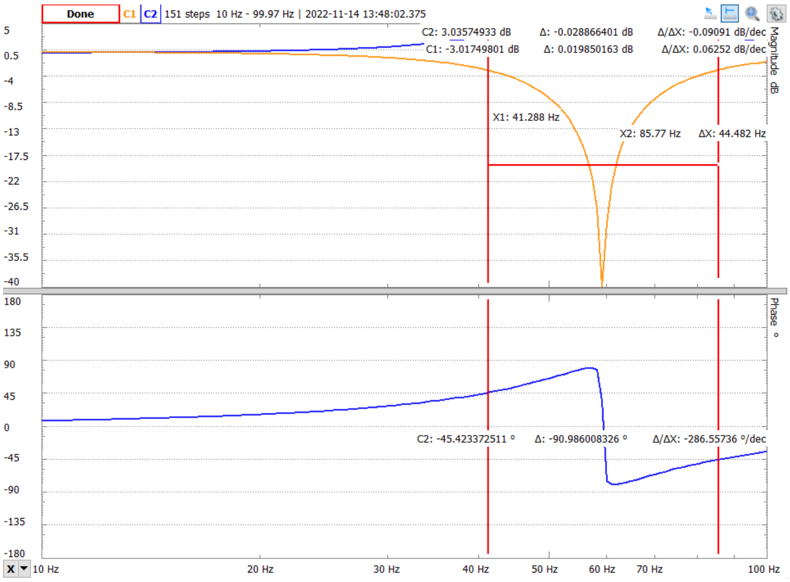

Figure 15. Measurement frequency response of NF

2.2.1 Simulation

After fact testing of each part, these 3 main parts are connected to be one whole circuit on the bread board shown on Fig. 16. As the calculation form before, the differential mode gain is about 17.44*100 = 1744. It will amplify the output be one large voltage which will produce one large error for result. One simple 1000:1 voltage divider which is 2 resistors that 100Ω resistor series between generator and whole circuit and 100kΩ resistor parallel with the whole circuit is added in the input parts.

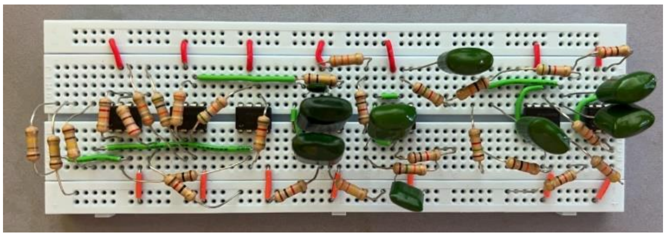

Figure 16. Actual circuit

For the whole circuit, the time domain waveforms on the scope are Fig. 17 and Fig. 18. They show the $ACM = \frac{169.56mV}{2.0012V} = 0.085 < 0.1$ and $ADM = \frac{3.5083V}{2.0005V} = 1.754 > 1.6 = \frac{1600}{1000}$. Compare with Fig. 12 and 13, the waves have become folded.

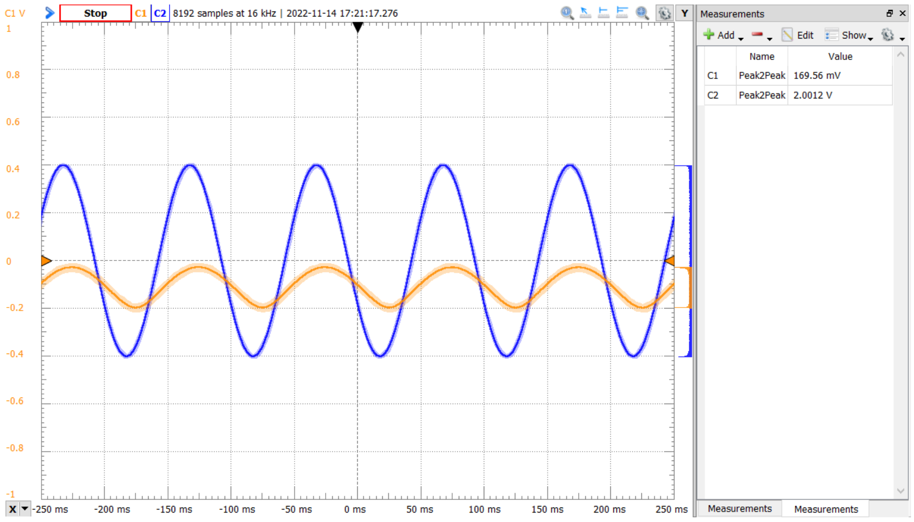

Figure 17. Measurement common mode's time domain waveform of whole

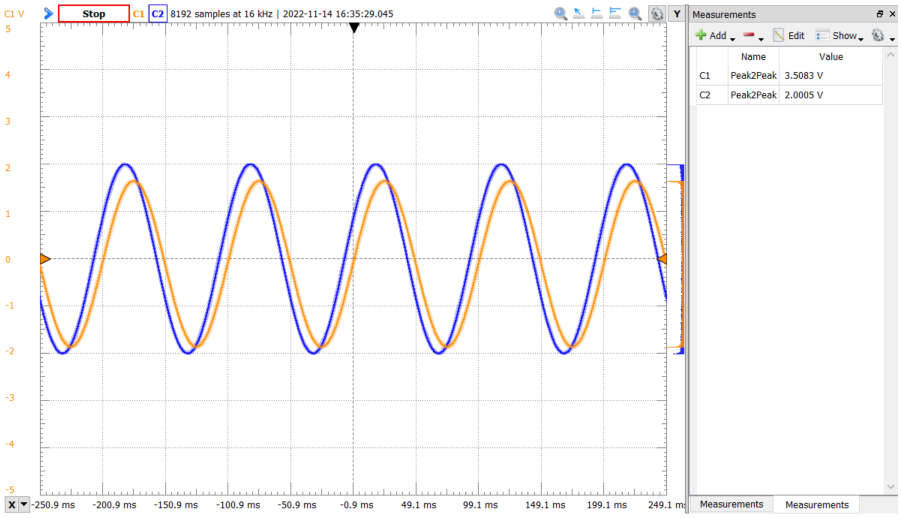

Figure 18. Measurement differential mode's time domain waveform of whole

2.2.2 Protector for high voltage

In terms of economic efficiency, most of the electrodes on the market have similar functions. The main difference is that the adhesive's stickiness will be affected to fade after repeated use. To collect the most effective data, Bio Protech ECG electrodes become the best choice. The 55mm, Round, Cloth, and Solid Hydrogel electrode sheets of the model T815 is fit for all the required functions [11].

But for the LF356 amplifier, its two ends should be based on a voltage of 5v and -5v respectively. It creates a voltage difference of 10v. This voltage also travels across the body when measurements are taken. The safe voltage of the human body is 24v and this voltage is too high. So, it is important to design a protective device. After replaced the generator and 1000:1 divider, three 180k resistors series between the electrode's connected wire and the circuit are installed in the same position.

2.3. Results

With connected the output point to the scope and attached electrodes to the skin, the electrocardiogram is recorded on the scope in time domain waveform which is shown in Fig. 19. From this picture, the ups and downs of the ECG signal is recorded, and it repeats in the same cycle.

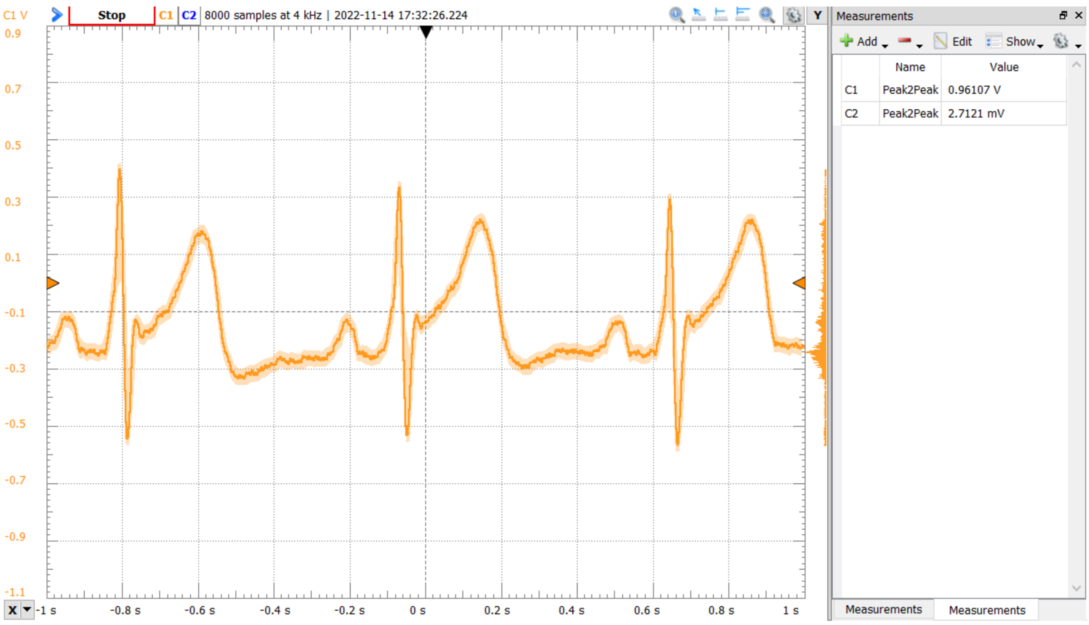

Figure 19. Measurement electrocardiogram

3. ECG Signal with Different People

In the measured electrocardiogram, the Q point is smooth, and the difference with the S point will be large. There will be a unique electrocardiogram for each person. Some properties of electrocardiograms for people who have the same traits will be similar. According to the change of age, characteristics is different, and peers are similar. For example, all for the same healthy people, elders have positive axis shift in the direction of QRS and T segment, while younger people have smaller amplitudes at this part [12]. Not only age, the difference in body shape also causes special characteristics of the electrocardiogram. Fat around the heart contributes to cardiovascular disease and fat accumulation is the mark of obesity. The heart beats differently than others because of the fat squeeze heart. Like the elders, Obese people's QRS segment also shift to the left, and their QRS point voltage will be lower than normal. This is also the features for them more prone to sudden death [13].

4. Conclusion

An ECG prototype has been successfully built, serving as the basic module for further development. Medical experts and electronics engineers can collaborate to design more advanced ECGs that read more information and collect more accurate data. By monitoring cardiovascular diseases through this ECG prototype, it is possible to prevent these diseases from occurring. Sufficient data collected from this prototype can be used to build a database, which can reveal more disease causes and susceptible populations, thus improving the health of the entire society and reducing the number of people suffering from cardiovascular diseases, including fatalities.

Additionally, the ECG prototype offers a method to analyze small signals. The circuit must consider input impedance to collect the signal, while useless signals must be filtered and shielded. Stabilizing small signals that are prone to oscillation makes them easier to observe. These methods can be applied to future circuit designs to collect and analyze micro-signals more accurately.

References

[1] GBD 2015 Disease and Injury Incidence and Prevalence Collaborators. Global, regional, and national incidence, prevalence, and years lived with disability for 310 diseases and injuries, 1990-2015: a systematic analysis for the Global Burden of Disease Study 2015. Lancet. October 8, 2016.

[2] Philip Aylward, Director of Cardiology, Flinders Medical Centre, Adelaide. Australian Prescriber, April 1, 1996, 19:52-4.

[3] U.S. Department of Health & Human Services, National Institutes of Health. What Are the Signs and Symptoms of Coronary Heart Disease? September 29, 2014.

[4] A. L. Goldberger and E. Goldberger. Clinical Electrocardiography, MO, St. Louis: Mosby. 1977.

[5] Nabil El-Sherif, Pablo Denes, Richard Katz, Robert Capone, L. Brent Mitchell, Mark Carlson, Robin Reynolds-Haertle. Definition of the best prediction criteria of the time domain signal-averaged electrocardiogram for serious arryhthmic events in the postinfarction period. Journal of the American College of Cardiology, 1995, 25(4): 908-914.

[6] Peter J. Zimetbaum, M.D., Mark E. Josephson, M.D. Use of the Electrocardiogram in Acute Myocardial Infarction. The New England Journal of Medicine. March 6, 2003.

[7] Roshan Joy Martis, U. Rajendra Acharya, Hojjat Adeli. Current methods in electrocardiogram characterization. Computers in Biology and Medicine, 2014, 48: 133-149.

[8] Sattar Y, Chhabra L. Electrocardiogram. StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing. January 2022.

[9] M. Malik and A. J. Camm, Heart Rate Variability. Clinical Cardiology, 1990, 13(8): 570-576.

[10] P. E. McSharry, G. D. Clifford, L. Tarassenko and L. A. Smith. A dynamical model for generating synthetic electrocardiogram signals. IEEE Transactions on Biomedical Engineering, 2003, 50(3): 289-294.

[11] Bio ProTech, T815 Electrode ECG Electrodes. https://www.tigermedical.com/Products/Telectrode-ECG-Electrodes--PE-Foam__BPTT715-50-.aspx.

[12] Ernst Simonson. The effect of age on the electrocardiogram. The American Journal of Cardiology, Volume 29, 1972, 1: 64-73.

[13] M. A. Fraley, J. A. Birchem, N. Senkottaiyan, M. A. Alpert. Obesity and the electrocardiogram. Obesity Reviews, 2005, 6(4): 275-281.