Signal Enhancement in the Presence of High Noise Levels—The Electrocardiogram

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It is always a challenge to find laboratory projects that stimulate the interest and imagination of students. At the same time, such projects should be feasible, "doable" in a limited amount of time, and not too demanding with regard to available equipment and financial resources. The project described in this paper can be completed by physics students with a basic knowledge of circuitry and an introductory knowledge of electronics. It involves the detection of an electrocardiogram (EKG) signal, picked up from two "electrodes" loosely held in each hand by the subject. This signal is extremely weak, and contaminated by large amounts of 60-Hz noise from power cords, laboratory equipment, fluorescent lights, etc. By using a differential amplifier and some simple filtering techniques, a rather "clean" EKG signal can be displayed on an oscilloscope, and this signal can be used to synchronously trigger a sound generator. Everything can be constructed on a "breadboard." No shielding is necessary and components can be easily interchanged or added. The signal can also be easily traced at various points of the circuit and provides an excellent demonstration of signal enhancement and amplification.

The Differential Amplifier

Differential amplifiers are commonly used to amplify a voltage difference between their input terminals, while rejecting a noise signal that is common to both terminals. In this case the voltage difference signal is the EKG, while the 60-Hz pickup from the environment represents the common noise signal.

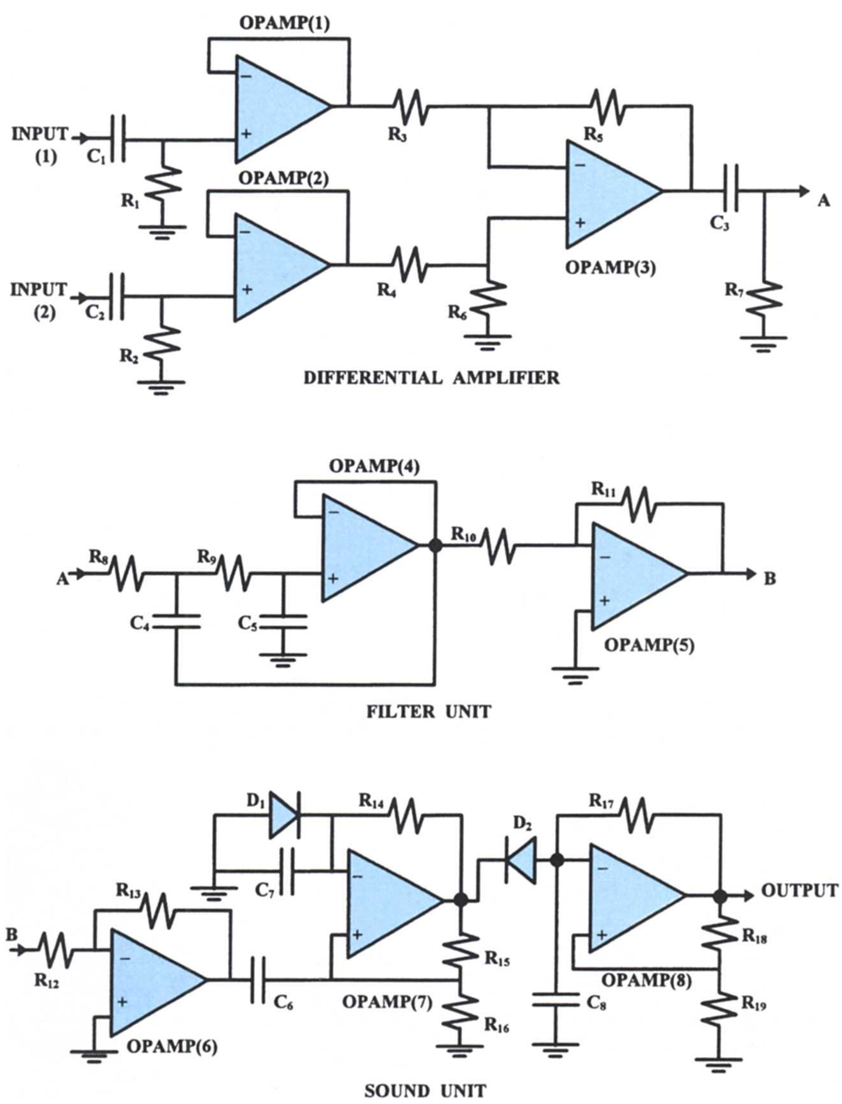

Fig. 1. Circuit diagram of EKG detection system. Inputs 1 and 2 are connected to the hands of a subject through two loosely held conductors. A 45-Ω speaker is connected between the output and ground.

In Fig. 1 connections 1 and 2 represent the input of the differential amplifier. The capacitors, C_1 and C_2, together with the resistors, R_1 and R_2, represent

Parts List for Fig. 1.

R_1, R_2, R_7 = 1MΩ
R_3, R_4, R_{10}, R_{12} = 1 kΩ
R_5, R_6, R_{14} = 470 kΩ
R_8, R_9 = 330 kΩ
R_{11}, R_{18}, R_{19} = 10 kΩ
R_{13}, R_{17} = 4.7 kΩ
R_{15}, R_{16} = 100 kΩ
C_1, C_2, C_6, C_8 = 0.1 μF
C_3, C_7 = 1 μF
C_4 = 0.01 μF
C_5 = 0.04 μF

All operational amplifiers (OPAMPS) are LM324 "four-in-one" chips. All diodes are 1N914.

a high-pass filter to block dc voltages (mainly from electrode-skin interfaces) while passing the EKG signal virtually unaltered. The resistor value of 1 MΩ has been selected to obtain a high input resistance as compared with the skin-electrode resistance, which can be as high as several hundred kΩ for loosely handheld electrodes. The two voltage followers (OpAmps 1 and 2) have a gain of 1 and a very high input resistance compared with the 1 MΩ value just mentioned. The outputs of the two voltage followers provide the input to the differential amplifier (OpAmp 3), which has an amplification of R_5/R_3 (equal to R_6/R_4), or 470x for this circuit. It is important to select R_3, R_4 and R_5, R_6 as equal pairs, to improve the performance of the differential amplifier. Capacitor C_3 acts to filter out additional offset voltage created up to this point in the differential amplifier; R_7 allows this capacitor to discharge to ground in a reasonably short time. In effect, C_3 and R_7 represent an additional high-pass filter.

The Filter Unit

The first part of the unit consists of a Sallen-Key[1] filter using OpAmp 4. The filter is a second-order low-pass filter with a cutoff frequency of $f_c = 1/(2\pi R_8\sqrt{C_4 C_5})$ and quality factor $Q = 0.5\sqrt{C_5/C_4}$. These relationships assume $R_8 = R_9$. For the EKG circuit, the cutoff frequency of this filter should be sufficiently below 60 Hz to eliminate 60-Hz noise. Q needs to be as close to 1 as possible to assure a sharp cutoff and prevent oscillations (ringing) of the filter. For the capacitor and resistor values selected, f_c = 24 Hz and Q = 1. The following OpAmp 5 is a 10x inverting amplifier (gain $= -R_{11}/R_{10}$), that simply amplifies the signal so that it can be better observed when connecting an oscilloscope to point B. If still too much noise is present, another Sallen-Key filter can be used with the same resistor and capacitor values.

The Sound Generator

The first element of the sound generator is an inverting amplifier (OpAmp 6) that multiplies the signal by –4.7 (gain $= -R_{13}/R_{12}$). In conjunction with the amplifier from the filter unit, this increases the signal enough to consistently trigger the mono-stable Schmitt trigger (OpAmp 7) when a heartbeat occurs. However, this is not a good point from which to observe the EKG, since saturation of the amplifier might occur due to the high signal levels. C_6 serves as a coupling capacitor to separate the different dc levels of the OpAmp 6 output and the OpAmp 7 input. A positive pulse will pass through C_6 and raise the positive input of OpAmp 7 sufficiently to trigger the mono-stable Schmitt trigger. This creates a positive pulse at the output of OpAmp 7, the duration of which is approximately $\tau = 0.7(R_{14} C_7)$ or 0.33 s. The positive output voltage will then change the biasing of D_2 (previously forward biased, but now reverse-biased), allowing the a-stable Schmitt trigger oscillator (OpAmp 8) to run, since C_8 can now discharge and charge. The output drives a speaker causing a tone of frequency $f = 1/(2.2\ R_{17} C_8)$ and duration τ. Both formulas for f and τ are based on the assumption that $R_{15} = R_{16}$ and $R_{18} = R_{19}$. For the diodes as shown in Fig. 1, the positive portion of the EKG will trigger the sound unit. However, by reversing *both* diodes (D_1 and D_2) the sound unit can be activated by a negative pulse.

Power Supply Requirements

The circuit has been designed for a dual power supply of ± 5 V to power the OpAmps. However, any other dual power supply of up to ± 15 V will do. Also, instead of a dual power supply, two batteries may be used (for example, two 9-V batteries) or two dc wall transformers.

Construction and Testing

The circuit can be assembled on a "breadboard." Resistor and capacitor leads do not have to be cut since their position is not critical, except that it is good practice to keep everything as symmetrical as possible with respect to inputs 1 and 2 and to prevent "signal loops" that might cause oscillations. For the same reason, one LM324 chip should be used for each unit. Also, it might be necessary to include capacitors between + and ground and – and ground, again to prevent oscillations.

Each unit can be tested separately. The output of the differential amplifier unit will show a barely visible EKG on top of a much larger 60-Hz noise signal. After the filter unit, output B will show a rather "clean" EKG. If more or less amplification is desired, R_{11} can be changed. If the noise level is too high, another filter may be added after OpAmp 5. The sound unit can be tested with connection B open. Removal of diode D_1 should give an intermittent sound. Additional removal of diode D_2 should give a continuous sound output.

Conclusion

This unit is absolutely safe to use since it employs only two loosely handheld electrodes (alligator clips in this case) that are capacitor-coupled to a low-voltage OpAmp circuit. An oscilloscope is used in all cases to display the signals. Signal levels are approximately 2 V for the EKG signal and 0.2 V for the remaining 60-Hz noise. Components shown in the circuit diagram (OpAmps, diodes, resistors, capacitors) can be purchased for less than ten dollars. This relatively inexpensive project proves educational, as well as entertaining.

Reference

1. P. Horowitz and W. Hill, *The Art of Electronics* (Cambridge University Press, Cambridge, MA, 1990), p. 267.