Vol 57 No 2—May 2023

ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™
AnalogDialogue

StudentZone—ADALM2000 Activity: Heartbeat Measurement Circuit

Doug Mercer, Consulting Fellow, and
Antoniu Miclaus, System Applications Engineer

Objective

The objective of this lab activity is to learn how to use a chain of amplifiers for gain and filtering, in a practical example that aims to recover heartbeat information. The result of the system provides a relevant output that is displayed using the Scopy software tool.

Going through this lab activity, the students will learn how to drive an IR LED and a phototransistor, design and understand the behavior of a low-pass filter, and explore functionalities provided by the operational amplifiers (op amps) in different configurations.

Combining the previously mentioned electronic devices, the result of the activity will demonstrate how a real-world application can be implemented with minimum software and hardware equipment.

Background

A type of heartbeat measurement device consists of an electronic circuit that monitors heartbeat by clipping onto a fingertip. It does this by shining light through your finger and measuring how much light is absorbed. This goes up and down as blood is pumped through your finger. For the operation of an optical heartbeat detector, an IR LED and a phototransistor are used. The LED emits light through the finger and is detected by the phototransistor, which acts like a variable resistor conducting different amounts of current depending on the light received.

The voltage variations change with the heartbeat and are acquired from the collector of the phototransistor. The small signal obtained is used as input for the circuit, obtaining the behavior of a heartbeat detector.

To have a relevant output, the input signal is passed through multiple circuits:

- Preamplifier: the output signal from the heartbeat measurement setup is decoupled through the series capacitor and amplified using a negative feedback resistor (R4)
- Low-pass filter: RC filter that cuts the high frequencies (noise)
- Voltage follower: buffers the output of the low-pass filter and reproduces its voltage with a low impedance output
- Inverting amplifier with low-pass filter: amplifies the voltage signal and cuts the high frequencies (noise).

Materials

- ADALM2000 Active Learning Module
- Solderless breadboard
- Jumper wires
- One OP484 precision rail-to-rail I/O op amp
- One 100 Ω resistor
- One 470 Ω resistor
- One 1 kΩ resistor
- One 10 kΩ resistor
- Two 47 kΩ resistors
- Two 1 µF capacitors
- One 47 µF capacitor
- One infrared LED (QED-123)
- One infrared transistor (QSD-123)

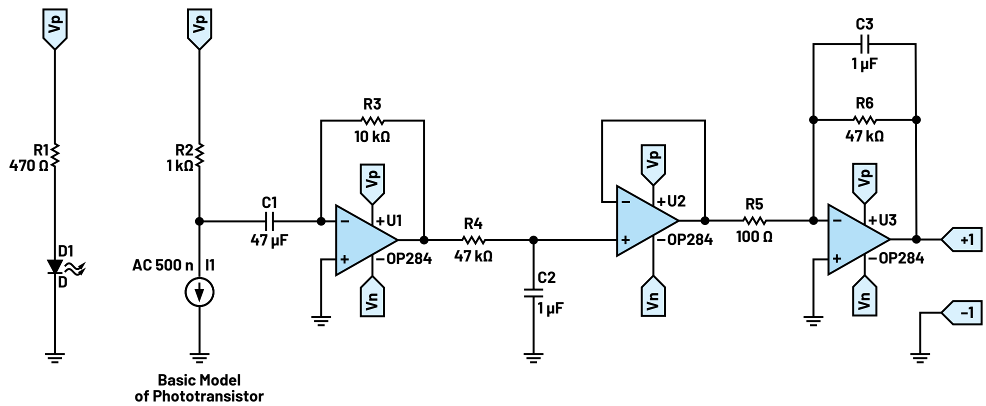


Figure 1. A heartbeat measurement circuit.

Directions

On your solderless breadboard, construct the heartbeat measurement circuit (designed in LTspice®) as shown in Figure 1.

The LTspice simulation uses OP284s, which is included in the standard set of LTspice models. The actual circuit is constructed with the quad OP484FPZ from the ADALP2000 Analog Parts Kit and powered by ±5 V from the ADALM2000 module (a total supply voltage of 10 V).

IR LED

To have a proper current that will not damage the IR LED, a resistor needs to be added in series to limit the current. Varying the value in between the operating range will change the intensity of the emitted signal of the IR LED. The following formula expresses the value of the forward current (I_F) through the LED, based on the positive voltage supply 5 V (V_P), series resistance (R1), and forward voltage drop on the LED (V_F):

$$I_F = \frac{V_P - V_F}{R1} \quad (1)$$

Phototransistor

To acquire information from the phototransistor (Q1) when it is in contact with the IR light, a common-emitter amplifier circuit is designed. This circuit generates an output that transitions from a high state to a low state when the light in the infrared range is detected by the phototransistor. The output is created by connecting a resistor (R2), whose value was determined experimentally, between the voltage supply and the collector pin of the component.

Preamplifier

The input signal from the heartbeat measurement setup is fed into a differentiator amplifier circuit (C1, A1, R3). The capacitor blocks any DC content, C1, and R3 behaving as a high-pass filter with the cut-off frequency F_{C1} being determined by the following formula:

$$F_{cl} = \frac{1}{2\ \pi\ R3C1} \quad (2)$$

Besides filtering, this stage serves also as an amplifier taking as input the current (I_{A1}), and generating at the output an inverted voltage (V_{A1}) based on the negative feedback resistance (R3):

$$V_{AI} = -I_{AI} \times R3 \quad (3)$$

Active Low-Pass Filter

Active filters contain active components such as operational amplifiers, within their circuit design. They draw their power from an external power source and use it to boost or amplify the output signal. The active low-pass filter principle of operation and frequency response is the same as that of a simple RC low-pass filter, the only difference being that it uses an op amp for amplification and gain control.

This first-order low-pass active filter (A2, R4, C2) consists simply of a passive RC filter stage providing a low frequency path to the input of a noninverting operational amplifier.

The filter aims to cut the high frequencies that correspond to the noise signal. Taking into account that the heart rate does not exceed a value of 180 beats per minute (bpm) and the dependency between the bpm and the frequency is:

$$bpm = frequency\ (\mathrm{Hz}) \times 60 \quad (4)$$

The result is that frequencies higher than 3 Hz should get cut. The RC low-pass filter is designed for the mentioned frequency value using the formula:

$$F_{c2} = \frac{1}{2\ \pi\ R4C2} \quad (5)$$

The amplifier is configured as a voltage-follower (buffer), giving it a DC gain of one, $A_V = 1$.

The advantage of this configuration is that the op amps' high input impedance prevents excessive loading on the filters' output while its low output impedance prevents the filters' cut-off frequency point from being affected by changes in the impedance of the load. While this configuration provides good stability to the filter, its main disadvantage is that it has no voltage gain above one, $A_V = 1$. However, the power gain is very high as the filter stage output impedance is much lower than its input impedance.

Final Amplifier with Low-Pass Filter

The configuration of the final stage represents an AC op amp integrator with DC gain control. In simpler words, the circuit has the aim to low-pass filter (R4, C2) the signal from the remaining unnecessary frequencies that are higher than the maximum frequency of the heartbeat and amplify through the inverting amplifier the useful signal with a gain (A_V) determined by the ratio between R6 and R5:

$$A_V = -\frac{R6}{R5} \tag{6}$$

$$F_{C3} = \frac{1}{2\pi R6C3}$$

Simulation

Considering the circuit designed in LTspice, two types of simulation are made:

- Transient: Connect at the input of the circuit a waveform generation source. Configure the source to generate a sine with an amplitude of 500 µV, frequency of 2 Hz, and 500 mV offset. Observe the output signal amplitude to determine graphically the total gain of the circuit (Figure 2).

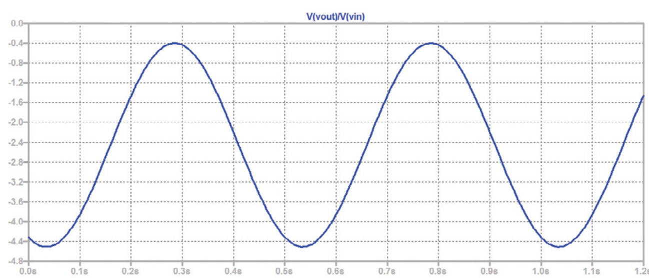


Figure 2. Output voltage–transient analysis.

- AC sweep: Connect at the input of the circuit an AC source. Configure the source to have a magnitude of 500 µV. Observe the output signal in a chosen frequency domain (100 mHz to 1 kHz) to determine graphically in which frequency range the output signal has the biggest amplification (Figure 3).

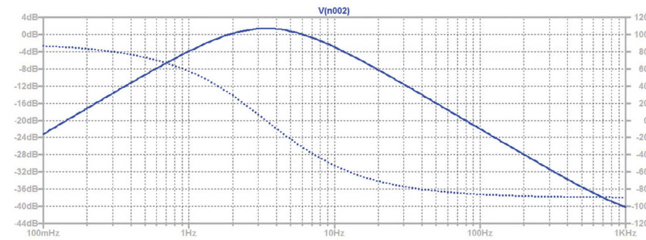


Figure 3. Output voltage–AC sweep.

Hardware Setup

Use the variable positive and negative power supply from the ADALM2000 module set to 5 V to power your circuit. Use Scope Channel 1 to monitor the voltage at the collector node of V_{OUT}.

The circuit implemented on the breadboard should look similar to the one in Figure 4. The blue LED represents the IR LED, and the gray one represents the phototransistor.

Procedure

Put the top of your finger between the IR LED (D1) and the phototransistor (Q1). The emitter and the receiver should be aligned and pointing one to another.

Observe the voltage waveform seen at the output of the third stage op amp (A3). An example of the output waveform is presented in Figure 5.

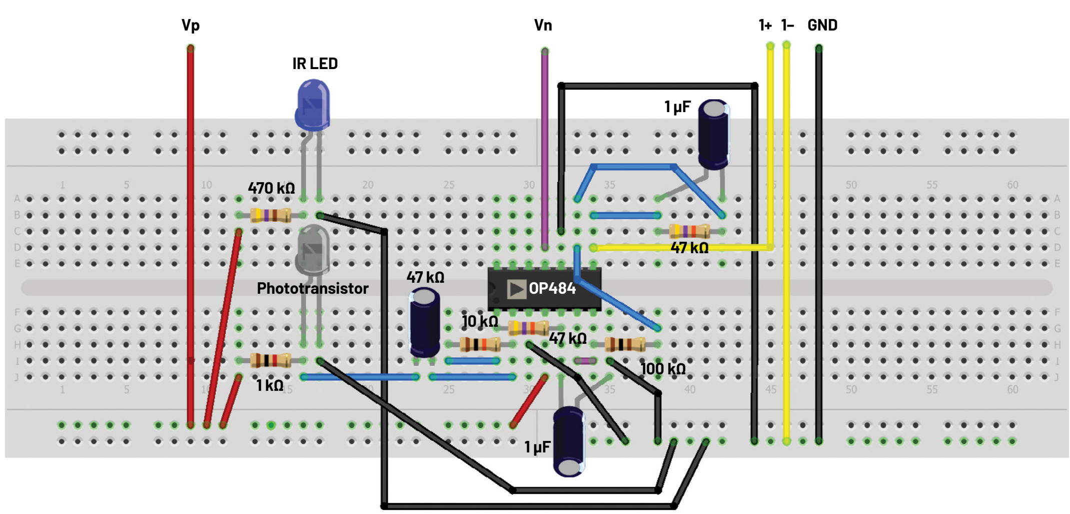


Figure 4. A breadboard heartbeat measurement circuit.

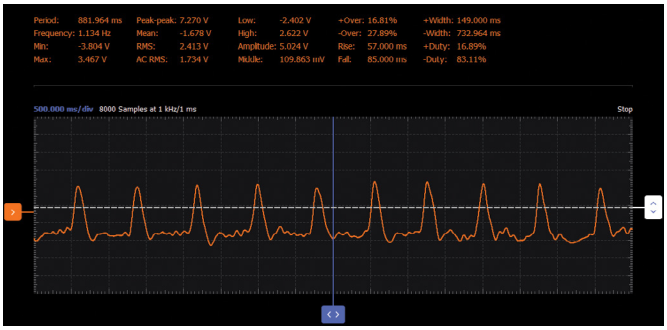


Figure 5. A heartbeat output waveform.

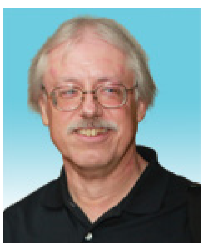
In the oscilloscope feature of the Scopy tool, activate the measure feature to read the frequency of the obtained signal. To convert the frequency into bpm, use the formula from the laboratory directions.

Questions:

1. Using the values and formulas provided in the laboratory directions compute the following parameters:

- Forward current through the IR LED (use the data sheet of the QED-123)
  - Cut-off frequency of the high-pass filter
  - Cut-off frequency of the second stage low-pass filter
  - Cut-off frequency of the third stage low-pass filter
  - Gain of the third stage amplifier
- What parameters change if R5 is modified?
- What parameters change if R6 is modified?

You can find the answers at the StudentZone blog.



About the Author

Doug Mercer received his B.S.E.E. degree from Rensselaer Polytechnic Institute (RPI) in 1977. Since joining Analog Devices in 1977, he has contributed directly or indirectly to more than 30 data converter products and holds 13 patents. He was appointed to the position of ADI Fellow in 1995. In 2009, he transitioned from full-time work and has continued consulting at ADI as a fellow emeritus contributing to the Active Learning Program. In 2016, he was named engineer in residence within the ECSE department at RPI.

About the Author

Antoniu Miclaus is a system applications engineer at Analog Devices, where he works on ADI academic programs, as well as embedded software for Circuits from the Lab®, QA automation, and process management. He started working at ADI in February 2017 in Cluj-Napoca, Romania. He is currently an M.Sc. student in the software engineering master's program at Babes-Bolyai University and he has a B.Eng. in electronics and telecommunications from the Technical University of Cluj-Napoca.