Experiment 284: Using Operational Amplifiers to Measure Your Heart Rate

Aim

To construct a device capable of measuring your heart rate from simple operational amplifier circuits.

References

The Physics 240 text: "Linear steady-state network theory", by G.E.J. Bold and J. B. Earnshaw.
"Electronic circuit design", by C.J. Savant, M.S. Roden, and G.L. Carpenter.
Any of the many other operational amplifier texts available from the engineering library.

Background

Pulse oximetry is a non-invasive technique capable of measuring the percentage of haemoglobin saturated with oxygen, as well as the pulse of a person. Haemoglobin containing oxygen (oxyhaemoglobin) absorbs light differently than haemoglobin without oxygen (deoxyhaemoglobin), and by observing the relative transmission of red and infrared light through a person's fingertip, oxygen saturation (SpO_2) can be determined.

In this experiment we will construct a similar device using common operational amplifier circuits, capable of measuring your heart rate. As your heart beats, oxyhaemoglobin is pumped to your peripheral capillaries, where it is reduced to deoxyhaemoglobin. The transmission of light from a red LED through your finger will vary with the oxygenation of haemoglobin, and by detecting this variation your pulse can be observed.

Operational Amplifiers

An operational amplifier (op-amp) is a high-gain amplifier, with typical open loop gain values of 10^4 to 10^6 (i.e. 80 to 120dB). Although the internal circuitry of an op-amp is quite complicated, its properties can be simplified and easily understood. In this way they can be treated as a sort of 'black box', where the response of the circuit will depend on the arrangement of external components, such as resistors and capacitors.

In this experiment we shall use the LF356N IC, which has the pin layout shown in Figure 1. Pin 8 has no connection and is for structural stability only, and pins 1 and 5 will not be used in this experiment.

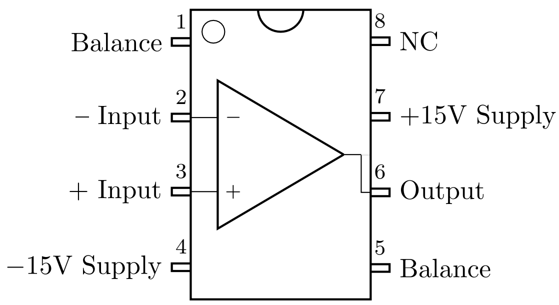

Figure 1: Integrated circuit layout for the LF356N. The pins are numbered counterclockwise from the circular indentation on the chip.

Note: This experiment utilises the ELVIS II from National Instruments. If you are not familiar with this device, please refer to Appendix A. Be sure to include oscilloscope plots and Bode plots in your report where appropriate. An image of your plots can be exported from both the oscilloscope and Bode analyser by selecting the **Print** button, and choosing to **Export to File**. If you wish to import data from the log files into python, the functions `importElvisOsc()` and `importElvisBode()` are provided in `phylab.py`.

Theory

Amplifying circuits are characterised by their gain values. The voltage gain of a circuit is defined as the ratio of the output voltage to the input voltage of the circuit,

$$\text{Gain} = \text{V}_{out}/\text{V}_{in}. \tag{1}$$

The gain of an ideal amplifier is determined purely by the arrangement of resistors in the circuit and their resistance. An ideal operational amplifier is assumed to have infinite input impedance, zero output impedance, infinite open-loop gain, and to have characteristics that are independent of temperature. When constructing an op-amp circuit with a negative feedback arm, as in many common amplifier circuits, we can obtain two 'golden rules'.

(i) The output does whatever is necessary to cause the voltage difference between the two input terminals to be zero.

(ii) As the input impedance is infinite, the inputs draw no current.

1 Input Probe

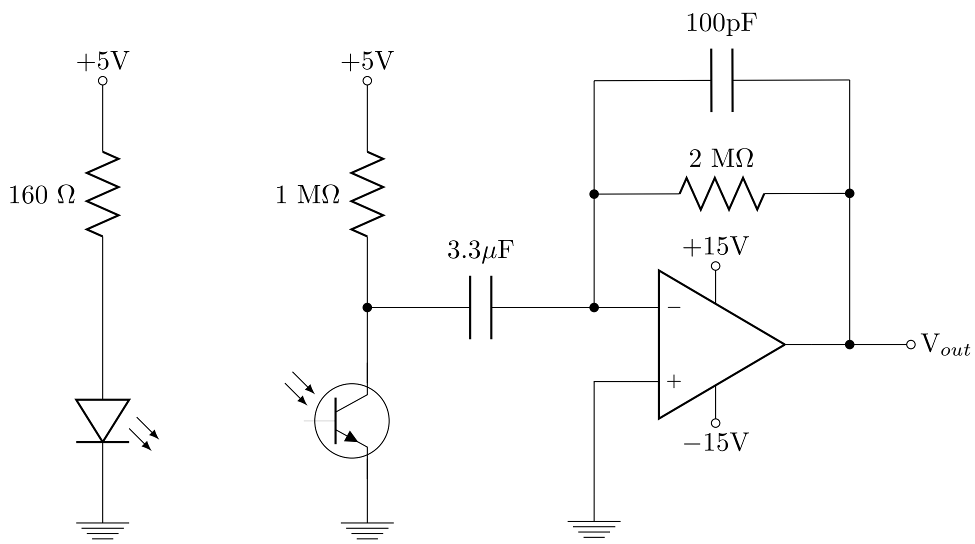

Figure 2: The internal schematics of the probe. The output signal V_{out} will form the input to your circuit.

In this section we will use the probe provided to observe a small, noisy, pulse signal. We will then build circuits to filter and amplify this signal and obtain a cleaner output. The probe's circuit diagram is shown in figure 2, and consists of a red LED (left) and a phototransistor (centre). When placing your finger between these two devices, the phototransistor will produce a signal based on the varying transmission of light from the LED. This signal is then AC coupled by a 3.3μF capacitor into a preamplifier, where it is amplified to give V_{out}.

(1) Connect the probe provided to the DC power supplies. You will need to supply ±15V, +5V and ground to this circuit. Without placing any objects between the LED and the phototransistor, use the oscilloscope function on the ElVIS II to observe the output V_{out}. Is there any particular frequency of noise present in the output signal? If yes, what is the source of this noise?

(2) Set the oscilloscope voltage scale to 100 mV per division and the time scale to 200 ms per division. Place your finger between the LED and phototransistor, and ensure that you can observe a pulsing signal related to your heart rate. Try to minimise any movement of the probe or your finger while measuring your pulse.

The signal that you obtain will have a small amplitude and also be quite noisy. Our goal is to provide a clean output from which a person's pulse rate can be clearly inferred.

2 Active Low Pass Filter

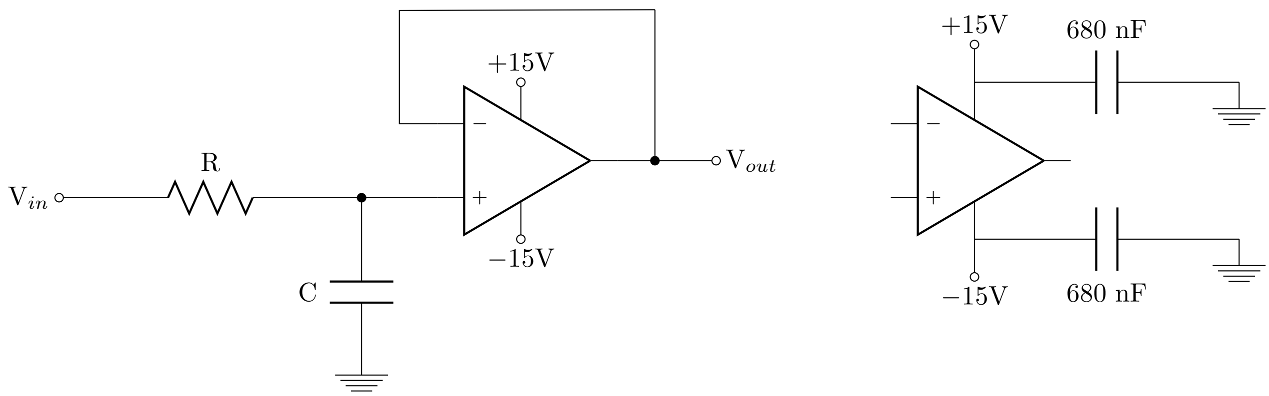

Figure 3: An active low pass filter (left) consists of a passive low pass filter and a voltage buffer. The use of bypass capacitors (right) prevents noise from the power supplies interfering with the circuit.

To remove noise from the input signal, we can use a low pass filter. Figure 3 shows an active low pass filter consisting of a passive RC filter and a voltage buffer. The voltage buffer maps the voltage at the positive input terminal to the output, in accordance with the two 'golden rules'. This is particularly useful when we don't want components from one part of a circuit interfering with the operation of another part. The input probe also contains buffering, so we do not need to worry about the components of that circuit interfering with this filter's behaviour.

For a low pass filter, the characteristic frequency is the *corner frequency.* This is defined as the frequency where the gain drops by 3dB, and is given by

$$f_0 = \frac{1}{2\pi RC}. \tag{2}$$

(3) Construct the circuit shown in Figure 3, choosing values for R and C such that the corner frequency is 500 Hz.

Note: As the probe signal is very small, we will need to use bypass capacitors on the operational amplifier's power supplies. Do this by connecting a 680 nF capacitor between the ±15V power supply pins of the op-amp and ground, as shown on the right of figure 3. Be sure to place these capacitors as close to the op-amp pins as possible. Do this for all op-amps that you use in your circuits to prevent unwanted noise.

We will now use the Bode analyser built into the ELVIS II to analyse the voltage response of our circuit to a range of input frequencies. A Bode plot is a very useful tool as it gives information on both the gain of the circuit, as well as the phase of the output relative to the input, for a range of frequencies.

(4) Using the Bode analyser, perform a frequency scan from 1 Hz to 1 kHz using a 2 V p-p signal. You will need to connect the function generator (FGEN) to the input V_{in}, and also connect both the input and the output to the appropriate oscilloscope probes. Determine the filter's corner frequency from this plot, and compare it to the theoretical value.

(5) Connect the input V$_{in}$ to the output of the pulse probe input and observe your pulse signal on the oscilloscope. What difference has the low pass filter made?

(6) Repeat (3) - (5) for filters having corner frequencies of 50 Hz and 5 Hz. Which filter gives the most suitable output for this device?

Question 1. Derive the transfer function for this circuit $\mathbf{T} = \mathbf{V_{out}}/\mathbf{V_{in}}$. Compare your experimental data with the theoretical gain curves by plotting all three experimental and theoretical curves on the same axes.

3 Inverting Amplifier

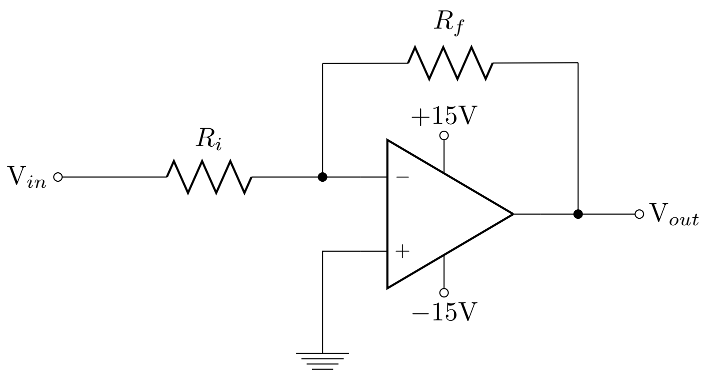

Figure 4: An inverting amplifier circuit.

Now that we have filtered the noise from our input signal, we wish to amplify it to a more useful level. One commonly used amplifier is the inverting amplifier, shown in figure 4. This amplifier utilises a negative feedback arm in order to increase stability of the circuit, and to determine the resulting gain.

Question 2. Using the two 'golden rules' and Kirchoff's current law, show that the gain for the circuit shown in figure 4 is given by:

$$\frac{V_{out}}{V_{in}} = -\frac{R_f}{R_i}. \tag{3}$$

Note: Here we introduce the concept of a 'virtual ground', where the voltage at the inverting input can be considered to be zero.

(7) Build the circuit shown in figure 4, with $R_i = 10\ k\Omega$ and $R_f = 47\ k\Omega$. Ensure that you include bypass capacitors as in the previous section. Connect your previous circuit to V$_{in}$ and simultaneously observe V$_{in}$ and V$_{out}$ on the oscilloscope. Check that the experimental gain agrees with equation (3). What is the relative phase of the input and output signals?

(8) Replace R_f with a resistor that will give an output V$_{out}$ that peaks between +2V and +10V, given the input signal of your probe. Use the oscilloscope to determine your heart rate, and give an error associated with this rate.

4 Comparator and Output

The time domain on the oscilloscope is limited to 2 seconds, which makes an accurate estimation of your heart rate difficult. Here we will build a comparator, which will output a high voltage when the signal from your circuit exceeds a certain level, and a low voltage otherwise. As there is no feedback in this circuit, the first golden rule does not apply here. We can say for an op-amp without feedback that $V_{out} = A_V(V_+ - V_-)$, where $V_+ - V_-$ is the voltage difference between the two inputs, and A_V is known as the open loop gain,

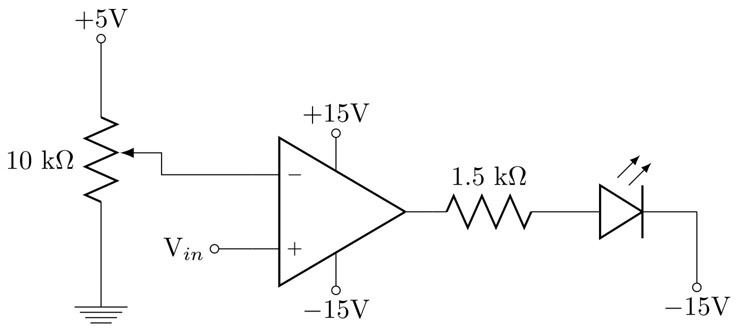

Figure 5: A comparator with a 10 kΩ potentiometer to provide an adjustable comparison voltage.

and typically has a value ranging from 10^4 to 10^6. We will use this circuit to power an LED, which will flash with your pulse.

(9) Construct the circuit shown in figure 5. Ensure that the LED is placed with the correct polarity, where the long leg is positive and the flat side of the LED casing is negative. Remember to include bypass capacitors as in previous sections.

(10) Connect the input of this circuit V_{in} to the function generator (FGEN) on the prototype board. Input a 10 Hz 10V p-p sine wave into the comparator, and simultaneously observe V_{in} and the output of the op-amp on the oscilloscope. Adjust the potentiometer and observe how the circuit works.

Question 3. How does the potentiometer allow you to choose which voltage level causes the output to change state? What is the range of voltages that you can choose for this comparison voltage?

(11) Remove the function generator from V_{in} and connect the output of your probe circuit in its place. Set the potentiometer to an appropriate level and observe your pulse. Using the flashing LED, measure your heart rate and give an associated error. Describe the technique that you use in your report.

Question 4. How does this method compare to the previous method you used to measure your heart rate? Which method is more accurate?

A National Instruments Elvis II

This experiment makes use of the ELVIS II from National Instruments. The layout of the ELVIS II allows circuits to be built without having to use solder to connect components, and also contains devices such as an oscilloscope and a function generator, all accessible via a USB connection to a PC with the appropriate software installed.

To access these components, ensure that the USB plug is connected to a PC and the Elvis II is powered on using the switch on the side of the device. The LED indicator for the USB should display 'READY'. You can now launch the 'NI ELVISmx Instrument Launcher'. It is important to understand the layout of the NI

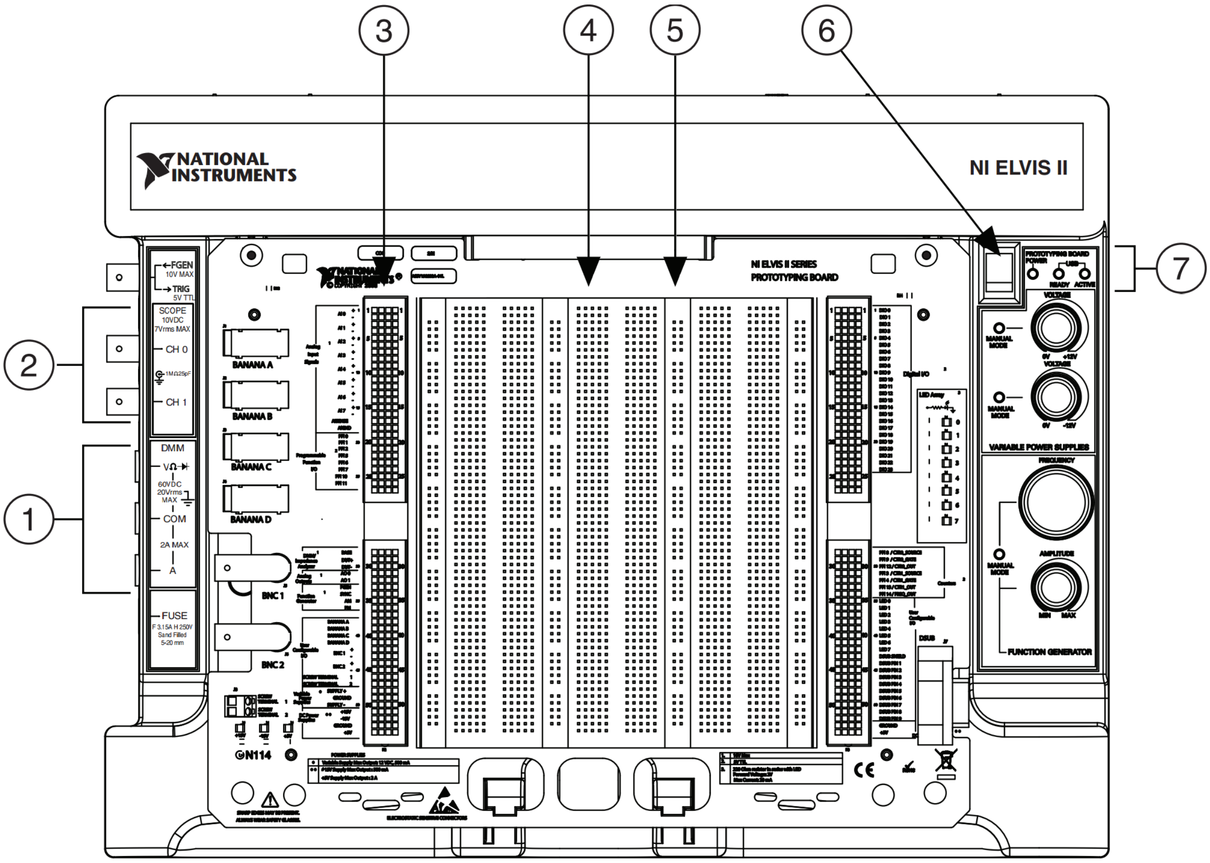

Figure 6: The Elvis II from National Instruments.

ELVIS to ensure that the circuits that you build are wired correctly. An overview is shown in figure 6, and some important features are numbered as follows:

1. Connections for the digital multimeter (DMM) leads. To use this instrument, select DMM from the instrument launcher, select the appropriate function and set it to 'Run'.

2. Connections for two oscilloscope (Scope) channels, labeled CH 0 and CH 1. The oscilloscope can be accessed from the instrument launcher.

3. Various connections that can be wired to circuits on the prototyping board. The DC power supplies (pins 51-54) and the function generator (FGEN, pin 33) are particularly useful.

4. The prototyping board, where circuits can be constructed. Ensure you understand how the pinholes are connected before you begin to wire up your circuits. An IC chip can be inserted so that its legs occupy columns E and F of the prototyping board, and wires can be taken from the four neighbouring pinholes to connect to other parts of your circuit.

5. Two columns of pinholes denoted by a red + and a blue −. It is good practice to take a wire from a power supply and connect it to the appropriate rail. Subsequent wires can then be used to power the components of your circuit.

6. Power switch for the prototyping board. This must be active for the power supplies and function generator to operate.

7. LED status indicators to show USB activity, as well as the prototyping board's power status.

24/02/15 Samuel Ruddell