Experiment 386: Operational Amplifiers (ELVIS edition)

Aim

To build common operational amplifier circuits and analyse their properties, as well as to gain experience using the Elvis II from National Instruments.

References

The best reference book for this lab is the stage 2 Physics 240 text: "Linear steady state network theory" by G.E.J. Bold and J. B. Earnshaw. For more a detailed analysis of operational amplifier circuits try "Electronic circuit design" by Savant, Roden and Carpenter, or any of the many other op-amp texts available in the engineering library.

Introduction

An operational amplifier is a high-gain amplifier with typical gain values of 10^4 to 10^6 (i.e. 80 to 120dB) and has many practical applications. These amplifiers can be used to form circuits such as filters, differentiators, integrators, current and voltage regulators and more. In this experiment we will focus on building common amplifiers, where negative feedback is applied to the circuit to produce stable and predictable outputs.

Although the internal circuitry of an operational amplifier 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, in the circuit. An operational amplifier typically has at least five terminals, shown in Fig. 1.

In this lab we shall use the LF356 IC, which has the pin layout shown on the right of Fig. 1. Pin 8 has no connection and is for structural stability only, and pins 1 and 5 will not be used in this experiment.

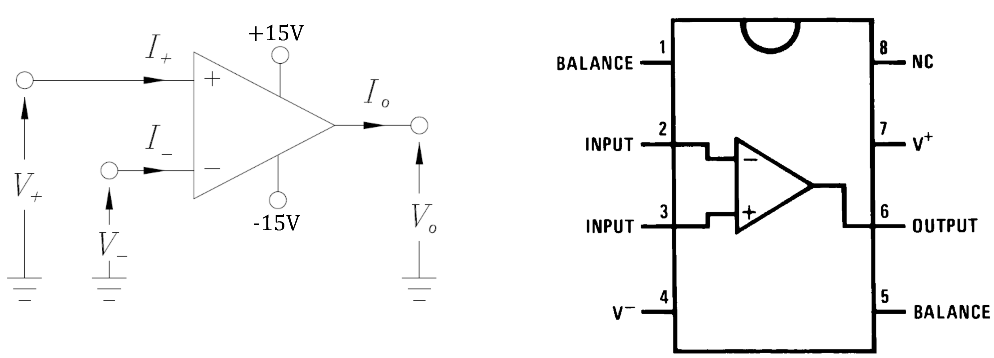

Figure 1: Operational amplifier circuit diagram (left) and integrated circuit layout (right). The pins are numbered counterclockwise from the circular identation on the chip.

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,

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

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, and to have characteristics that are independent of temperature. When considering amplifying circuits having a negative feedback arm, 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) The resistance on the inputs is infinite, meaning that the inputs draw no current.

Under certain conditions, operational amplifiers may not behave in a stable manner, and parasitic oscillations can result from feedback, especially at high frequencies. The LF356 chip used in this experiment is internally compensated to prevent these oscillations from occuring. Additionally, real circuits may not behave in an ideal fashion. We shall study some of these non-ideal characteristics that need to be taken into account when designing amplifying circuits for use in the real world.

National Instruments Elvis II

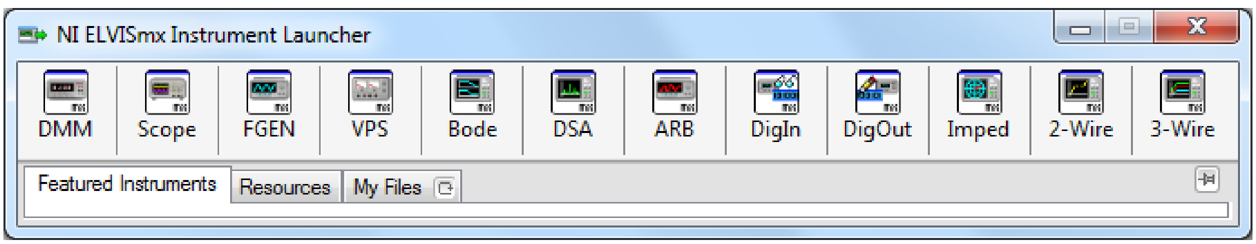

Figure 2: The instrument launcher for the NI ELVIS II, containing such useful devices as the digital multimeter (DMM), an oscilloscope (Scope), a function generator (FGEN) and a Bode analyser (Bode)

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', shown in Fig. 2. It is important to understand the layout of the NI Elvis to ensure that the circuits that you build are wired correctly. An overview is shown in Fig. 3, 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. In this experiment we shall use the DC power supplies (pins 51-54) and the function generator (FGEN, pin 33).

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 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 practise 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.

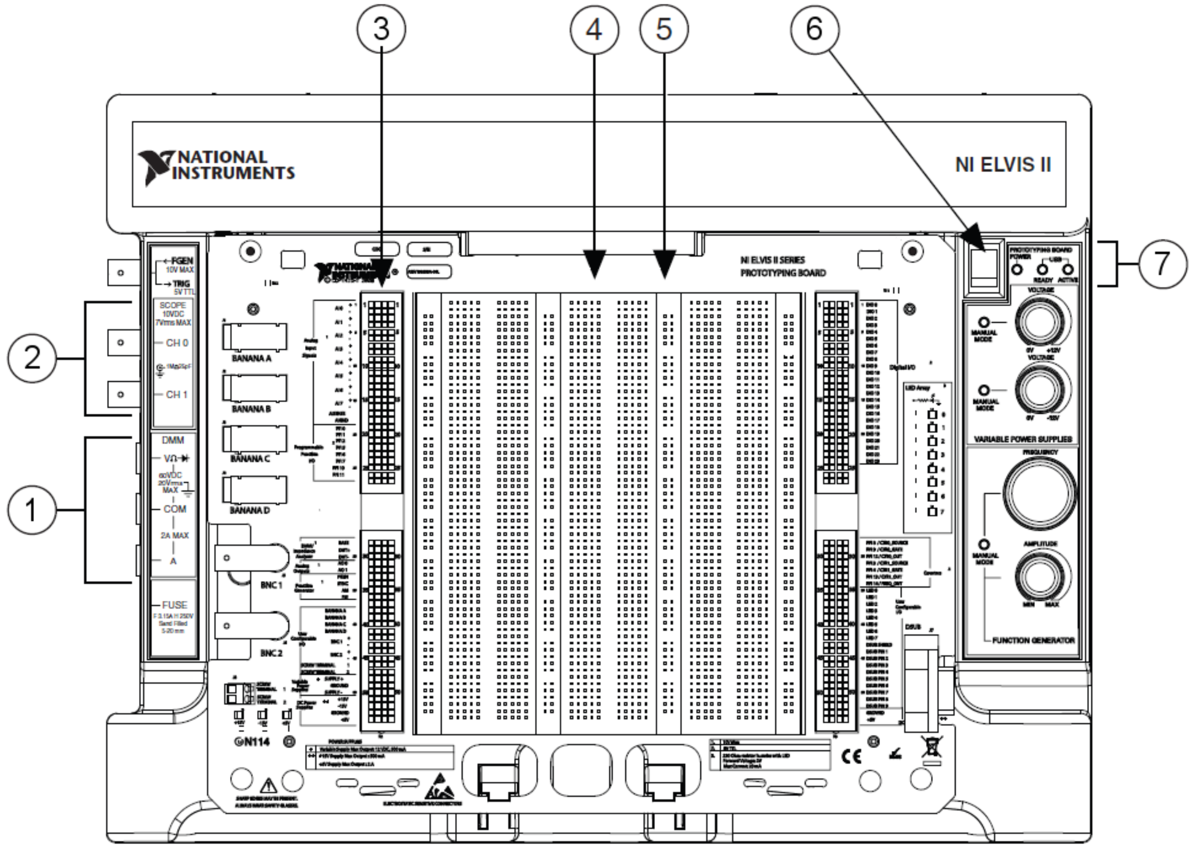

Figure 3: The Elvis II from National Instruments.

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.

Note: 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 manipulate the data, import the .txt files into Python.

1 Inverting Amplifier

The most basic type of amplifier is the inverting amplifier, shown in Fig. 4. This amplifier utilises a negative feedback arm in order to increase stability of the circuit.

(1) Using the two 'golden rules' and Kirchoff's current law, derive an equation for the output voltage V_{out} in terms of the input voltage V_{in} and the resistors used.

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

(2) Design and construct an inverting amplifier that has a gain of 10. Use the function generator to input a 1kHz triangle wave with an amplitude of 1V peak-to-peak (1V p-p). Using the scope, create a plot of the input and output signals, and verify the equation you found in (1). What is the relative phase of the input and output signals?

(3) Use the oscilloscope to observe both V_{-} and V_{out} simultaneously, with a 1kHz 2V p-p sine wave as the input. Comment on the validity of the 'virtual ground' concept.

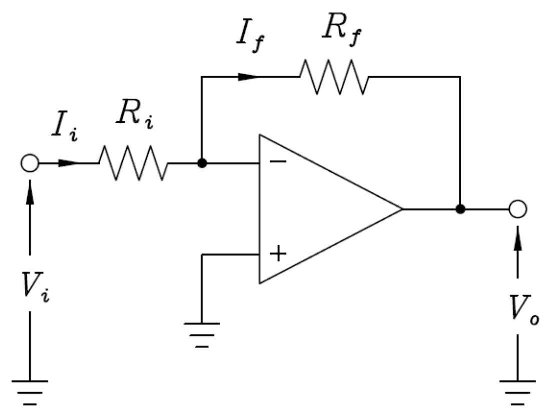

Figure 4: An inverting amplifier

1.1 Clipping

Clipping is the phenomenom that occurs when a signal is amplified beyond the capability of the amplifier. As the output cannot exceed the magnitude of the power supply's voltage, the signal is distorted when this occurs.

(4) Construct a circuit that has a gain of 100, and apply a 1kHz 1V p-p triangle wave to the input. What do you notice? Record the voltage levels at which the output is clipped (both negative and positive).

2 Non-Inverting Amplifier

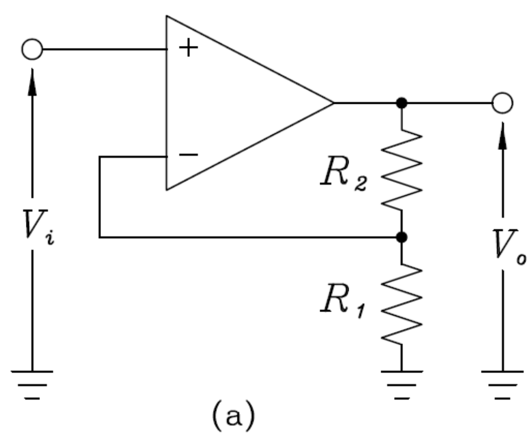

Figure 5: Non-inverting amplifier.

As noted in the previous section, the inverting amplifier inverts the output voltage with respect to the input voltage. In some applications this may be undesirable, and so we are able to build the non-inverting amplifier, shown in Fig. 5.

(5) Derive an expression for the output voltage of an ideal non-inverting amplifier using the two 'golden rules' and Kirchoff's current law.

(6) Design and construct a circuit having a gain of 2. Apply a 1kHz 1V p-p sine wave to the input and observe the output. Comment on the phase difference between V_{in} and V_{out}.

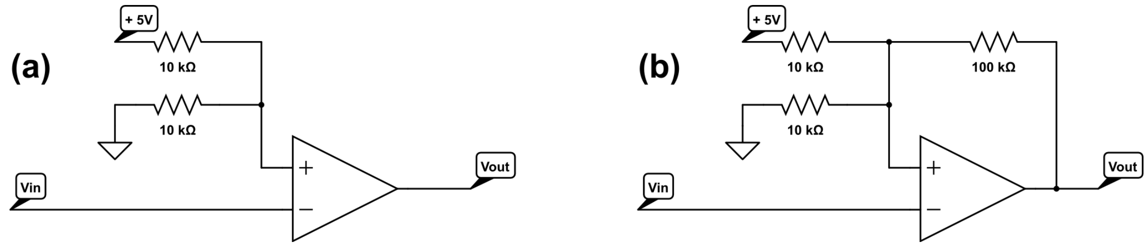

Figure 6: The comparator (left) and the Schmitt trigger (right).

2.1 Slew rate

The slew rate of an amplifier is defined as the maximum rate of change of the output signal. This parameter is especially important when designing circuits to be used in high frequency applications. Slew rate is usually quoted in units of $V/\mu s$, and is independent of the gain of the system.

(7) Apply a 1kHz 5Vp-p square wave to the input and observe the slew rate of the amplifier. State your result in $V/\mu s$. Compare your value to the manufacturers specifications.

2.2 Gain-bandwidth product

An amplifier built to work at certain frequencies may fail at other frequencies. To study the bandwidth of an amplifier requires knowledge of the gain of the amplifier at many different frequencies. Using the Bode analyser built in to the NI Elvis II, we can scan a range of frequencies and measure both the gain and phase difference between the input and output signals. A common parameter used to define the bandwidth of an operational amplifier is the gain bandwidth product, which is the product of the low-frequency gain and the frequency at which the gain drops by 3dB.

Note: When using the Bode analyser for amplifying circuits, the 'Peak Amplitude' must be chosen intelligently, as this defines the amplitude of the input signal. Any clipping of the output signal will distort your result.

(8) Construct five non-inverting amplifier circuits having gain values between 2 and 100, and measure both the low frequency gain and the frequency at which the gain has dropped by 3dB using the Bode analyser. Use these values to create a linear plot, from which the gain-bandwidth product can be extracted.

3 Schmitt Trigger

The previous sections have dealt with circuits having a negative feedback arm, producing a stable and predictable output. The use of positive feedback can also be useful in applications such as analogue-to-digital converters, where a certain level of input signal saturates the output in one direction. One example of a circuit utilising positive feedback is the Schmitt trigger, shown in Fig. 6.

(9) Construct the comparator shown on the left of Fig. 6, using a 100Hz 10V p-p sine wave as your input. Using the cursors of the oscilloscope, determine the input level that cause the output to change state.

(10) Now insert the 100kΩ resistor to form the Schmitt trigger. Note the levels at which the output changes, and observe how the properties of this circuit differ from those of the comparator.

Question 1 Demonstrate the difference between the comparator and the Schmitt trigger by plotting graphs of V_{out} against V_{in} for the two devices. Comment on how *hysteresis* relates to the properties of the Schmitt trigger.

4 Instrumentation Amplifier

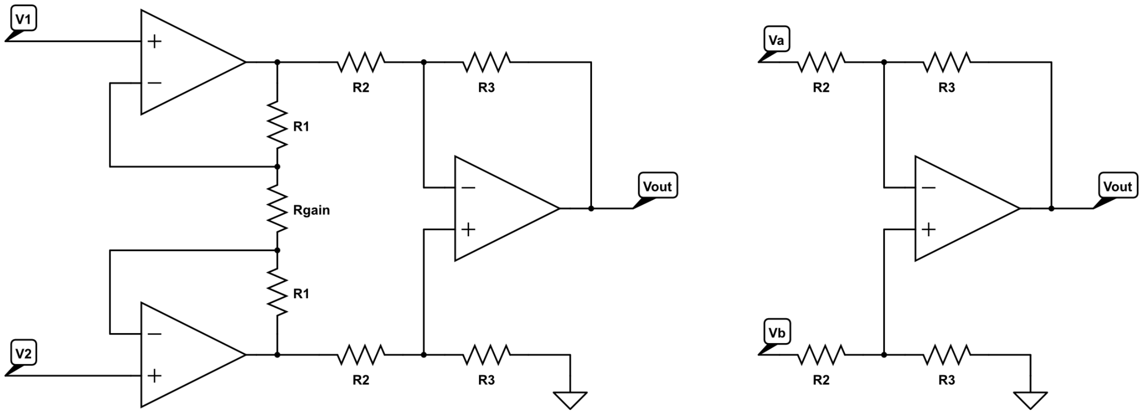

Figure 7: The instrumentation amplifier (left) is composed of a differential amplifier (right) and two input buffers.

Operational amplifier circuits can often be combined to form new, more useful circuits. An instrumentation amplifier is a type of differential amplifier, and amplifies the difference between two input voltages. It also contains two input buffers, which eliminate the need for input impedence matching, making this circuit particularly useful in measurement and test equipment. The voltage transfer function for the instrumentation amplifier is given by

$$\frac{V_{out}}{V_2 - V_1} = \left(1 + \frac{2R_1}{R_{gain}}\right)\frac{R_3}{R_2}. \tag{2}$$

(11) Consider the case where $R_1 = R_2 = R_3$. Determine the resistance that would result in $V_{out} = 1.2(V_2 - V_1)$, if $R_{gain} = 100k\Omega$.

(12) Construct the instrumentation amplifier circuit shown in Fig. 7, using the resistance values determined in (11). Using a 1kHz 5Vp-p sine wave as your input for V_1 and the +5V power supply as your input for V_2, verify equation 2.

Note: If you have access to an external signal generator, you may like to try various other inputs for V_2 to investigate the behaviour of this circuit.

Question 2 Using the 'golden rules' and Kirchoff's current law, show that the gain for the differential amplifier in Fig. 7 is given by

$$\frac{V_{out}}{V_b - V_a} = \frac{R_3}{R_2}. \tag{3}$$

Question 3 Using the result from Question 2, derive equation 2.

Revised 15/02/2013 Samuel Ruddell, SGM

Revised for Python: 24 November 2014