EXPERIMENT 6
OPERATIONAL AMPLIFIER CIRCUIT: VOLTAGE SCALING

1) Pre-lab Assignment

- Go onto the Internet (e.g., www.national.com) and retrieve a data sheet for a 741 operational amplifier.
- Read the appendix on Voltage Scaling at the end of the handout.
- Compute $V_x$ by summing the last digit of each team member’s student ID number.

\[ V_x = 2 + \frac{2(S_1 + S_2)}{5} \]

for a two-person team. If $S_1 + S_2$ is an odd number, your team will do the design of part (a). Teams with $S_1 + S_2$ even will do the design of part (b) below.

a) Voltage scaling in same direction

Design a circuit that transforms an input voltage range from 1 to 3 V to an output voltage range between $-V_x$ and $+V_x$. In other words, a 1-V input should produce an output of $-V_x$ and a 3-V input should produce $+V_x$. The op-amp is to be powered from $+15$ V and $-15$ V power supplies. Round the computed resistances in your design to the nearest available value in the 12-pt logarithmic sequence.

b) Voltage scaling in opposite direction

Design a circuit that transforms an input voltage range from 1 to 3 V to an output voltage range between $+1.2V_x$ and $-0.8V_x$, where $V_x$ is as computed above. In other words, a 1-V input should produce an output of $+1.2V_x$ and a 3-V input should produce $-0.8V_x$. The op-amp is to be powered from $+15$ V and $-15$ V power supplies. Round the calculated resistances to the nearest available value.

<table>
<thead>
<tr>
<th>1.0K</th>
<th>1.2K</th>
<th>1.5K</th>
<th>1.8K</th>
<th>2.2K</th>
<th>2.7K</th>
<th>3.3K</th>
<th>3.9K</th>
<th>4.7K</th>
<th>5.6K</th>
<th>6.8K</th>
<th>8.2K</th>
</tr>
</thead>
<tbody>
<tr>
<td>10K</td>
<td>12K</td>
<td>15K</td>
<td>18K</td>
<td>22K</td>
<td>27K</td>
<td>33K</td>
<td>39K</td>
<td>47K</td>
<td>56K</td>
<td>68K</td>
<td>82K</td>
</tr>
<tr>
<td>100K</td>
<td>120K</td>
<td>150K</td>
<td>180K</td>
<td>220K</td>
<td>270K</td>
<td>330K</td>
<td>390K</td>
<td>470K</td>
<td>560K</td>
<td>680K</td>
<td>820K</td>
</tr>
</tbody>
</table>
II) Laboratory experiments

1) Obtain the parts needed to build the circuit designed in the pre-lab.
2) Measure the resistors using the multimeter and compute the deviation from nominal.
3) Build the circuit on a breadboard, connecting +15 and –15 V DC power supplies to pin #7 and pin #4 of the op-amp, respectively.
4) Connect a third DC power supply to the input terminals of the circuit.
5) Set the input voltage to 1 V and measure the output voltage.
6) Increase the input voltage in 0.1-V increments, measuring $V_o$ at each step, until the maximum input of 3 V is reached. Make a table of $V_o$ vs. $V_{in}$.
7) Disconnect the DC power supply from the input.
8) Connect the function generator to the input, selecting a sawtooth wave, and setting the frequency to 500 Hz.
9) Measure the input voltage with the oscilloscope using a 10X probe.
10) Adjust the amplitude of the function generator to 2 $V_{pp}$ as measured on the oscilloscope.
11) Adjust the OFFSET on the function generator so that the sawtooth voltage waveform is shifted upward and ranges from +1 to +3 V as measured on the oscilloscope.
12) Connect the other 10X oscilloscope probe to the output voltage. Measure the $V_{pp}$ and the minimum and maximum voltages of the waveform.
13) Adjust the horizontal time base on the oscilloscope so that two cycles of the waveform appear on the display.
14) Record the oscilloscope display.

III) Lab Report

The lab report should be in standard format and include at least the following specific items:

1) Purpose
2) Model numbers of all test equipment used
3) Block diagram of test setups
4) Circuit schematics
5) Test procedure
6) Table of nominal versus measured resistor values with %deviation.
7) The theoretical transfer function for a voltage scaling circuit is $V_o = GV_i + V_y$
   where $G$ and $V_y$ are the design values as defined in the appendix. Make a table of measured vs. theoretical value of $V_o$ as $V_i$ ranges from +1 to +3 V in 0.1-V steps. Compute a %error for each entry.
8) The minimum and maximum values of $V_o$ measured with the oscilloscope in step 12. Compare these values with the minimum and maximum values of $V_o$, both theoretical and measured, listed in the table produced above.
9) Image of oscilloscope display recorded above.
10) Conclusions
Appendix: Voltage Scaling

A common application of operational amplifiers is the transformation of a signal from one voltage range to another. For example, the output of a strain gauge might run from 5.0 to 5.2 V over its desired operating range and need to be translated to a range of 0 to 10 V for measurement and digitization by a computer system. This document outlines a procedure for designing a circuit to scale the voltage given the input and output ranges.

Definitions

- Let the input voltage range from $V_1$ to $V_2$.
- Let the desired output voltage range between $V_A$ when the input voltage is $V_1$ and $V_B$ when the input voltage is $V_2$.
- The **transfer function** expresses the relationship between the input and output voltages. Ideally an op-amp circuit gives a linear transfer function as shown by the straight lines in the figure.

As illustrated, a non-inverting transfer function has a positive slope, while a negative slope characterizes an inverting transfer function.

1) Determine the required slope of the transfer function:

$$G = \frac{V_B - V_A}{V_2 - V_1}$$

The slope represents an amplification factor and is generally known as **gain**.

2) Compute the $y$-intercept ($V_y$) of the transfer function, which is the value of $V_{out}$ when $V_{in} = 0$.

$$V_y = V_A - GV_1$$

3) Hence, the equation of the transformation line is

$$V_{out} = GV_{in} + (V_A - GV_1)$$

(1)
4) Select the circuit based on the direction of the slope $G$. When $G$ is positive, a non-inverting stage (circuit A) must be used. Similarly, a negative $G$ requires an inverting stage such as circuit B below

A: Non-inverting amplifier ($G > 0$)

![Non-inverting amplifier circuit](image)

It can be shown that the input-output relationship of the above op-amp circuit is

$$
V_{out} = \left[ 1 + \left( \frac{R_3}{R_1 \parallel R_2} \right) \right] V_{in} - \frac{R_3}{R_1} V_S
$$

(2)

By comparing (1) and (2),

$$
G = 1 + \frac{R_3}{R_1 \parallel R_2}
$$

and

$$
V_y = V_A - GV = -\frac{R_3}{R_1} V_S
$$

(3)

a) Ordinarily $V_s$ is taken from one of the voltages supplying the op-amp. For example, if the op-amp power supply terminals were connected to +15 and −15V, then $V_s$ would be chosen as one of those two values based on the polarity of $V_y$.

b) Given $V_s$, the value of $V_y$ sets the relationship between $R_1$ and $R_3$. In this situation, there is one equation and two unknowns; thus, the value of either $R_1$ or $R_3$ is chosen, and the other is then computed.

c) Once $R_1$ and $R_3$ are determined, $R_2$ is found from the equation for $G$ in (3).

Note: The minimum slope, $G$, that the amplifier circuit A can realize is 1. When a positive slope of less than 1 is needed, a voltage divider can be placed between $V_{in}$ and the positive terminal of the op-amp to reduce the slope.
B: Inverting amplifier \((G < 0)\)

![Inverting Amplifier Diagram](image)

It can be shown that the input-output relationship of the above op-amp circuit is

\[
V_{\text{out}} = \left[ -\frac{R_2}{R_1} \right] V_{\text{in}} + \left( \frac{R_1 + R_3}{R_1} \right) \left( \frac{R_4}{R_3 + R_4} \right) V_S
\]

(4)

By comparing (1) and (4),

\[
G = -\frac{R_2}{R_1} \quad \text{and} \quad V_y = V_A - GV_1 = \left( \frac{R_1 + R_3}{R_1} \right) \left( \frac{R_4}{R_3 + R_4} \right) V_S
\]

(5)

(a) The value of \(G\) sets the relationship between \(R_1\) and \(R_2\). In this situation, there is one equation and two unknowns; thus, the value of either \(R_1\) or \(R_2\) is chosen, and the other is then computed.

(b) Given \(V_y\) and \(R_1\) and \(R_2\) found above, the value of \(V_y\) sets the relationship between \(R_3\) and \(R_4\) using (5). In this situation, there is one equation and two unknowns; thus, the value of either \(R_3\) or \(R_4\) is chosen, and the other is then computed.

(c) Note that the power supply used for \(V_s\) is chosen based on the polarity of \(V_y\).

Circuit design

In both circuit A and circuit B the designer must determine the values of the resistors; that is, there are three degrees of freedom in the non-inverting circuit and four degrees in the inverting circuit to realize the design. However, only two parameters are fixed by the design requirements—the gain \(G\) and the \(y\)-intercept, \(V_y\). In other words, the system design is characterized by two equations with either three or four unknowns. As a result, one or two of the resistors values must be selected somewhat arbitrarily, and then the other two computed from them in accordance with relationships imposed by \(G\) and \(V_y\). In selecting resistors, choosing values that are small results in too much power consumption and possibly an overloaded op-amp. On the other extreme, excessively large resistors can add unwanted noise to the signal and make the circuit subject to higher-order errors. Hence, typical choices of resistance are in the 1K to approximately 33K range, although larger resistors are sometimes used in special circumstances.