LINEAR INTEGRATED CIRCUITS

APPLICATIONS AND EXPERIMENTS

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PREFACE

LINEAR INTEGRATED CIRCUITS: APPLICATIONS AND EXPERIMENTS is a comprehensive survey of modern linear integrated circuits and the practical systems in which they are used. Each of the 12 experiments in the book is accompanied by discussion material that summarizes the important characteristics of a particular type of integrated circuit and covers the theory related to a number of specific applications. The book could be used as a stand-alone text for a predominantly laboratory-oriented course, or as a companion to a textbook in a lecture-laboratory sequence.

All experiments have been successfully performed by students whose background included the traditional two-semester sequence of courses in DC and AC circuit analysis and one course in basic semiconductor device theory. In recognition of the importance of the operational amplifier in so many linear circuit applications, the first two experiments deal exclusively with the characteristics and limitations of these versatile devices. The inexpensive and widely available 741 operational amplifier is used in many of the experiments. Other integrated circuits used in the experiments were similarly selected on the basis of low cost and wide availability. Complete manufacturers' specifications and data sheets are provided in Appendix B for all of the integrated circuits used. No special trainers or unusual equipment is required for any of the experiments, all of which can be constructed and performed in any reasonably equipped electronics laboratory.

Many of the experiments will be found to be too long for a typical scheduled laboratory session. The experimental procedures were intentionally made long to provide an instructor with flexibility in the choice of topic coverage and/or scheduling of successive meetings. The Questions section following each experiment generally requires the student to compare experimental results with values predicted by the theory outlined in the Discussion section. These too may be pruned at the instructor's discretion. Following each Discussion section is a set of Exercises, many of which are similar to the Questions in that they require the student to perform theoretical calculations on the experimental circuits. These have been included because many instructors prefer that students perform theoretical calculations before constructing circuits in the laboratory.

A number of Design Projects are provided at selected intervals after certain of the experiments have been completed. The purpose of these projects is to enable students to gain experience designing linear circuits of the types they have studied and to interface and combine circuit types into larger systems.

Appendix A, Writing Lab Reports, summarizes standard practices for presenting and interpreting experimental results. It emphasizes the importance of quantitative references to the data, the correct method for graphing experimental data, and the expression of concise error analyses and conclusions. Included is a sample lab report that illustrates the major points of good technical writing and the special considerations applicable to linear integrated circuit experiments.

I wish to thank Mr. Bruce Elliot, my laboratory assistant at the University of Southern Mississippi, for his help in constructing and checking all of the experimental circuits in this book and for suggestions that improved the instructional value in many of the procedures. I am also grateful to Dr. C. Howard Heiden for departmental support and encouragement during the preparation of this material.

THEODORE F. BOGART JR.

CONTENTS

1 Introduction to Operational Amplifiers

OBJECTIVES

1. To learn how to construct operational amplifier circuits that perform inverted and non-inverted voltage scaling.

2. To verify experimentally the theoretical closed-loop voltage gain of inverting and non-inverting operational amplifier circuits.

3. To learn how to construct and to verify experimentally the voltage follower circuit using an operational amplifier.

4. To verify experimentally the virtual ground of an operational amplifier with feedback.

5. To verify experimentally the input impedance presented to a signal source by an operational amplifier with feedback.

6. To learn how an operational amplifier can be operated with a single power supply voltage.

EQUIPMENT AND MATERIALS REQUIRED

1. Dual trace oscilloscope.

2. Sinewave signal generator, 0-10 V peak, 100 Hz - 1 kHz.

3. ± 15 V DC power supplies.

4. 741 operational amplifier.

5. 10K potentiometer.

6. Resistors: 1K, 4.7K, 10K (2), 22K, 33K, 100K (2).

7. 0.1 μF capacitor.

DISCUSSION

An operational amplifier is a high gain, high input impedance voltage amplifier with two inputs and a single output. One input(labeled + on the amplifier symbol) is called the non-inverting input, and the other (labeled -) is called the inverting input. When the non-inverting input is grounded and a signal is connected to the inverting input, the output is 180° out of phase with the input. If the input connections are reversed (signal applied to non-inverting input) the output is in phase with the input. If signals are applied to both inputs, the output is proportional to the difference of the inputs.

The amplifier is called operational because in many applications it is used to perform mathematical operations (summation, integration, etc.) on voltages connected to its input (s). In one such application, a resistor is connected between the output and the input to provide voltage feedback. See Figure 1.1.

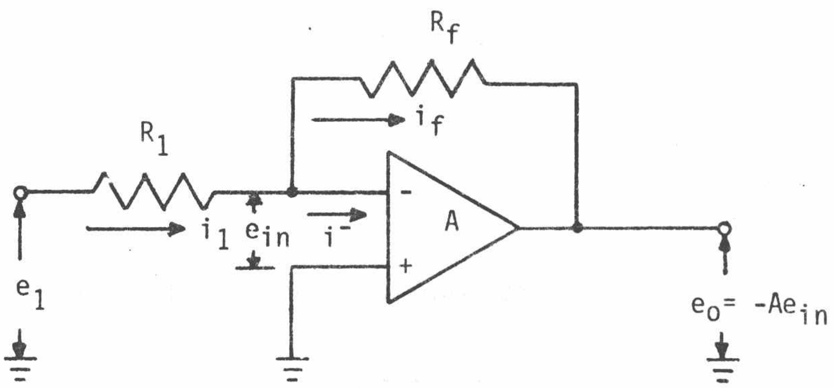

Figure 1.1 An operational amplifier connected to perform voltage scaling. $e_o/e_1 = -R_f/R_1$, where the minus sign denotes phase inversion.

Applying Kirchhoff's current law at the - input, we have

$$i_1 = i_f + i^- \tag{1}$$

Since the input impedance of the operational amplifier is very large (typically several megohms or greater), i^- is negligibly small and equation (1) becomes

$$i_1 = i_f \tag{2}$$

But $i_1 = \dfrac{e_1 - e_{in}}{R_1}$ and $i_f = \dfrac{e_{in} - e_o}{R_f}$.

$$\text{Hence, } \frac{e_1 - e_{in}}{R_1} = \frac{e_{in} - e_o}{R_f}. \tag{3}$$

Since $e_o = -Ae_{in}$, where A is the open loop gain of the amplifier (the gain when the feedback resistor is removed), we have $e_{in} = -e_o/A$, which when substituted in (3) yields

$$\frac{e_1}{R_1} + \frac{e_o}{AR_1} = \frac{-e_o}{AR_f} - \frac{e_o}{R_f} \tag{4}$$

Solving (4) for e_o/e_1 we find

$$\frac{e_o}{e_1} = \frac{-R_f}{R_r}\left(\frac{A}{A + 1/\beta}\right) \tag{5}$$

where $\beta = R_1/(R_1 + R_f)$ = the feedback ratio and the minus sign denotes the 180° phase inversion. In the above derivation we used the fact that $e_{in} = -e_o/A$. Since A is very large, we see that e_{in} is very small. It is in fact so close to zero in most cases that the - terminal is essentially at ground potential and is called virtual ground. For this reason, $i_1 \approx e_1/R_1$ and we see that the impedance seen by the signal source is effectively R_1.

Since an operational amplifier has a very large value of open loop gain A, typically 10,000 to 1,000,000, we have $A + 1/\beta \approx A$, and equation (5) may therefore be written

$$\frac{e_o}{e_1} = -\frac{R_f}{R_1} \tag{6}$$

The significance of this result is that the closed-loop gain, R_f/R_1, of the circuit depends only on the ratio of the resistors and not on precise values of the amplifier characteristics. This operation is called scaling, since the output equals the input multiplied by the scale factor R_f/R_1 (and, of course, inverted.)

Figure 1.2 shows how the operational amplifier may be connected for non-inverted scaling.

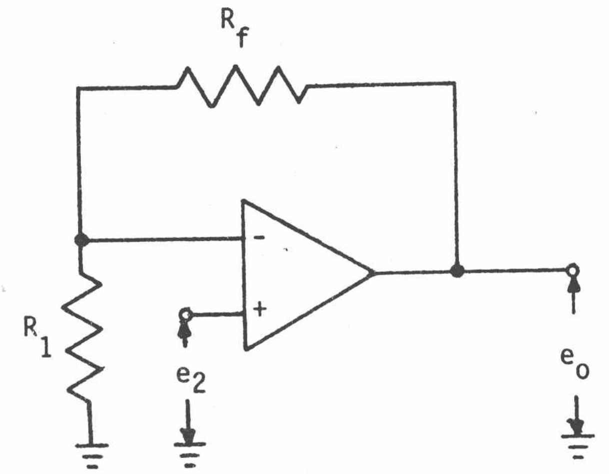

Figure 1.2 An operational amplifier connected to perform non-inverted voltage scaling. $e_o/e_2 = (R_f + R_1)/R_1$.

For the configuration of Figure 1.2 it can be shown that

$$\frac{e_o}{e_2} = \frac{1}{\beta}\left(\frac{-A}{1/\beta + A}\right) \tag{7}$$

where A and β are the same as previously defined. Again, since $A >> 1/\beta$, equation (7) reduces to

$$\frac{e_o}{e_2} = \frac{1}{\beta} = \frac{R_f + R_1}{R_1} \tag{8}$$

Another frequently used operational amplifier configuration is the voltage follower, shown in Figure 1.3.

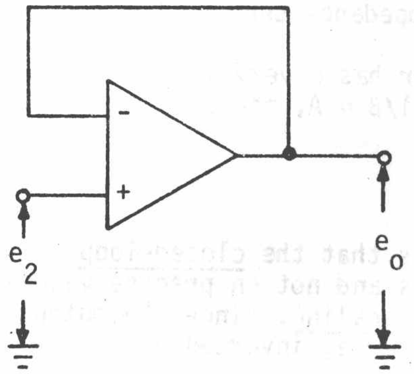

Figure 1.3 A voltage follower.
$e_o/e_2 = 1$.

In Figure 1.3 $R_f = 0$, so from equation (8), $e_o/e_2 = 1$. Thus the output voltage is the same (in magnitude and phase) as the input, i.e., the output follows the input. The voltage follower has a very high input impedance and a low output impedance, and is therefore used as a buffer in applications requiring isolation of a signal source from a load.

In many applications the operational amplifier is direct-coupled to the signal source that provides its input. Direct-coupling is necessary when the input signal is a dc voltage or has very low frequency variations. In these direct-coupled situations, the output voltage must go both positive and negative when the input goes positive and negative. Therefore, the amplifier requires both positive and negative power supply voltages.

In applications where the amplifier is used strictly for ac signals and dc levels are not important, it may be operated with a single dc power supply voltage. We will investigate a typical application of this type in more detail in Experiment 4, "Audio Amplifiers." When a single power supply voltage is used a dc (bias) level must be added to the output of the amplifier. The ac signal variations then cause the output to vary above and below this dc bias level. Figure 1.4 shows the input and output waveforms of a unity-gain amplifier whose input is a 2 volt peak sine wave and whose output has a 5 volt dc level.

Figure 1.5 shows an operational amplifier circuit in which a dc level is added to the output by connecting a dc voltage to the non-inverting input. The potentiometer is used to adjust the magnitude of the dc output level. Note that the (ac) input signal connected to the inverting input must be capacitor-coupled. The ratio of the ac signals e_o/e_1 is still given by: $e_o/e_1 = -R_f/R_1$.

When the operational amplifier is used with a single (positive) power supply, as shown in Figure 1.5, the terminal used for the negative supply is grounded. Note that the dc level in the output will influence the maximum peak-to-peak ac voltage that can appear at the output without distortion. For example, if the positive supply voltage is 10 V DC and the dc output level is 7 V DC, then the output is limited to 3 V peak (6 V pk-pk), since the output can only rise 3 V (from 7 V to 10 V). Similarly, if the output dc level is 4 V, then it can only decrease 4 V (from 4 V to 0 V), so the maximum output would be 8 V peak-to-peak. For optimum operation, that is, to permit the maximum peak-to-peak output signal variation, the dc level in the output should be set to one-half the positive supply voltage.

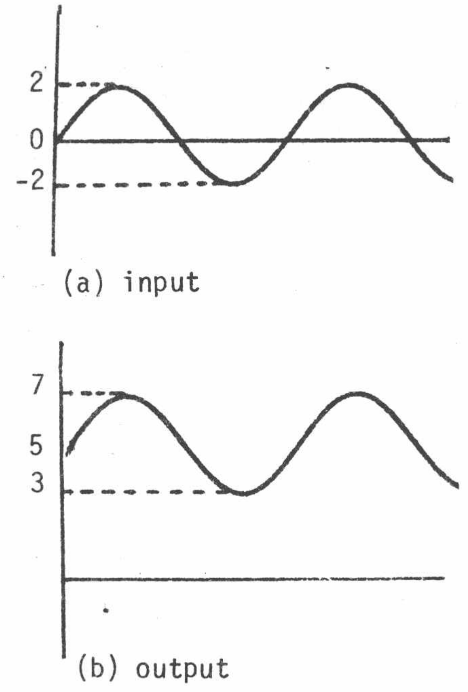

Figure 1.4 A 4 V pk-pk input producing a 4 V pk-pk output having a 5 V DC (offset) level.

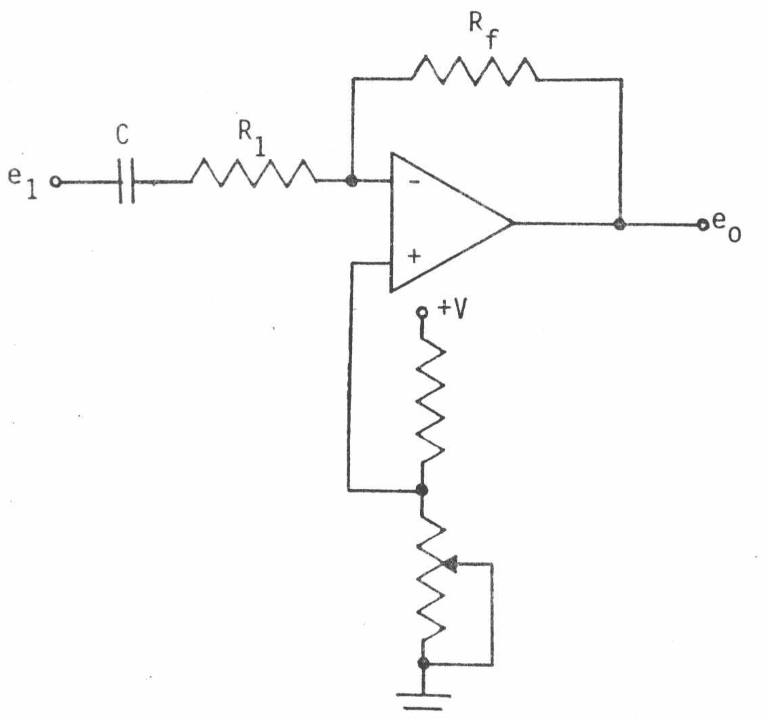

Figure 1.5 A dc level is added to the output using the non-inverting input. The amplifier is operated with a single positive power supply.

EXERCISES

1. An operational amplifier connected as shown in Figure 1.1 has R_f = 33K and R_1 = 10K. If the input e_1 is a 2.5 volt peak sine wave, what is the output? Repeat, if the values of R_f and R_1 are interchanged. (Assume the amplifier's open-loop gain A is extremely large.)

2. An operational amplifier connected as shown in Figure 1.1 has $R_f = R_1$ = 10K. If these resistors have 10% tolerances, what are the theoretical minimum and maximum values of closed-loop amplifier gain that could be expected? (Assume the amplifier's open-loop gain A is extremely large.)

3. An operational amplifier connected as shown in Figure 1.1 has an open-loop gain of $A = 2 \times 10^5$. The output is a 5 volt peak sine wave. What is the peak value of the voltage e_{in} at the inverting input to the amplifier?

4. An operational amplifier connected as shown in Figure 1.1 has an open-loop gain of $A = 2 \times 10^5$. If R_f = 47K and R_1 = 10K, what is the theoretical (exact) closed-loop gain of the amplifier (taking into account the open-loop gain and the feedback ratio β)? Compare this result with the approximate closed-loop gain when it is assumed that $A + 1/\beta = A$. Repeat for $A = 2 \times 10^3$. What is your conclusion, as regards the validity of calculating the closed-loop gain by the ratio R_f/R_1?

5. An operational amplifier connected as shown in Figure 1.2 has R_f = 100K. The input e_2 is a 0.5 volt peak sine wave. Assuming the open-loop gain A is extremely large, what should be the value of R_1 in order that the output be a 5.5 volt peak sine wave?

6. Using the values calculated in exercise 5, what is the exact theoretical peak value of the output if the open-loop gain is $A = 10^4$?

7. An operational amplifier is connected for use with a single positive power supply voltage as shown in Figure 1.5. If V_{CC} = + 15 V, and R = 22K, what resistance should the potentiometer be set to in order to obtain a + 5 V DC level in the output of the amplifier? What maximum peak-to-peak ac output voltage could then be obtained at the output without distortion?

8. An operational amplifier is connected as shown in Figure 1.5. If V_{CC} = + 15 V, R = 10K, R_1 = 4.7K, R_f = 10K, and the potentiometer is set for 10K, what is the peak value of the maximum sine wave <u>input</u> voltage e_1 that can be used without distorting the output?

9. Derive a general equation that can be used to determine the peak value of the maximum sine wave input voltage e_1 that can be used without distorting the output in Figure 1.5. Your equation should be written in terms of R_1, R_f, R, and the potentiometer resistance R_1 in Figure 1.5.

PROCEDURE

1. Connect the operational amplifier circuit shown in Figure 1.6.

2. Connect a dual trace oscilloscope for simultaneous viewing of e_0 and e_1. Adjust the signal generator to produce a 1 V peak sine wave at 100 Hz. Then measure and record the peak value of e_0 for each of the following values of R_f: 1K, 4.7K, 10K, 33K, and 100K. Note the phase of e_0 with respect to e_1.

3. With R_f = 100K and e_1 = 1 V peak as in step 2, measure the voltage at pin 2. (Recall that this point is at virtual ground.)

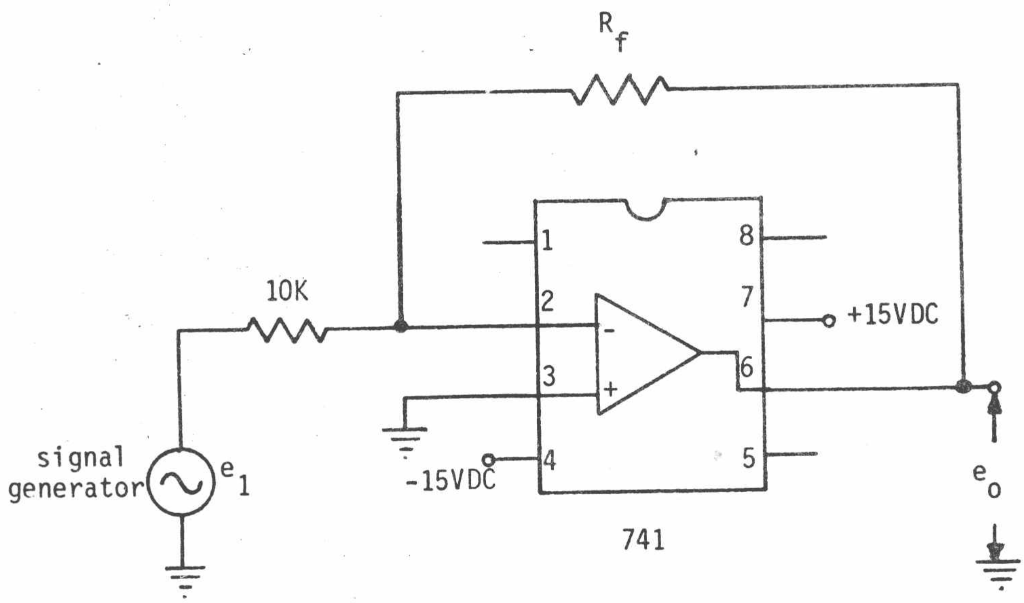

Figure 1.6

4. Now connect the circuit shown in Figure 1.7. (Pin numbers are shown for the 741 amplifier output and inputs; all other pin connections are the same as in Figure 1.4.)

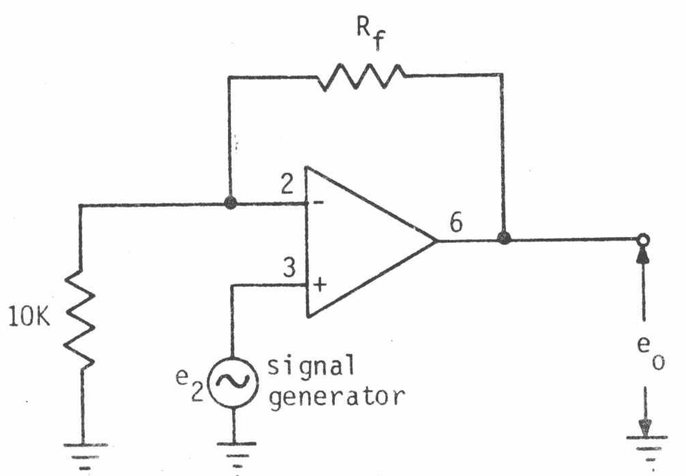

Figure 1.7

5. Set e_2 to 1 V peak at 100 Hz and measure and record the peak value of e_o for R_f = 1K, 4.7K, 10K, 33K, and 100 K. Note the phase of e_o with respect to e_2.

6. Connect the circuit shown in Figure 1.8.

7. Using a dual trace oscilloscope, measure and record the peak value of e_o for each of the following signal generator settings: 1 V peak at 100 Hz, 5 V peak at 500 Hz, 10 V peak at 1 kHz. Note the phase of e_o with respect to e_2 in each case.

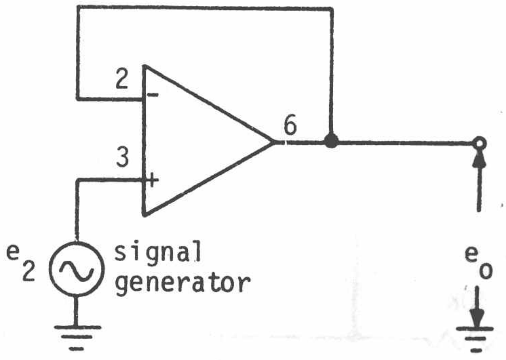

Figure 1.8

8. The circuit shown in Figure 1.9 will be used to determine the input impedance seen by the signal generator looking into the amplifier stage. The current drawn from the signal generator is $i_1 = (e_1-e_2)/10K$. Therefore, the input impedance seen by the signal generator is $e_1/i_1 = (e_1 \times 10^4)/(e_1-e_2)$. Connect the circuit.

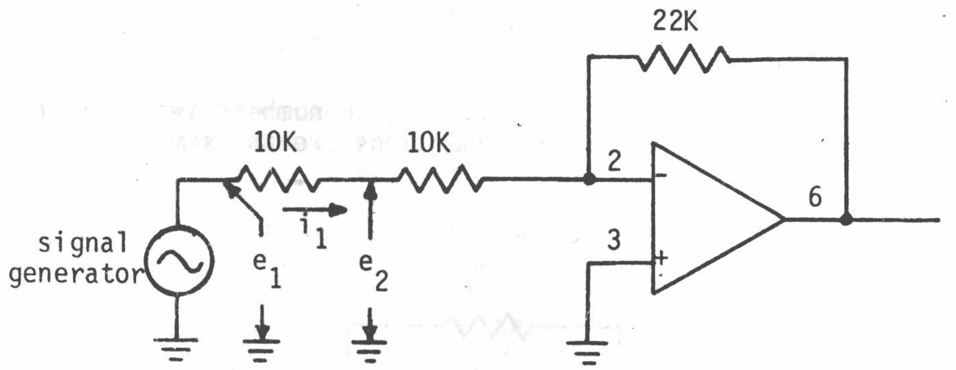

Figure 1.9

9. Set e_1 to 10 V peak at 100 Hz and use an oscilloscope to measure and record the peak values of e_1 and e_2.

10. To verify that the amplifier can be operated with a single power supply voltage, connect the circuit shown in Figure 1.10.

11. With the input e_1 grounded and the amplifier output direct-coupled to the oscilloscope (i.e., with the oscilloscope input selector set to "dc"), adjust the 10K potentiometer until the dc output of the amplifeir is 7.5 V.

12. Now connect the input e_1 to a signal generator adjusted to produce a 2 V pk sine wave at 1 kHz. Record the waveform observed on the oscilloscope, which should still be direct-coupled to the amplifier output. Note in particular the minimum and maximum values of the output waveform.

13. Increase the input signal level to 10 V pk and repeat your measurements. Sketch the waveform observed on the oscilloscope.

14. Remove the signal generator and again ground the input e_1. Adjust the potentiometer to achieve the lowest possible dc level in the amplifier output. Measure and record this level.

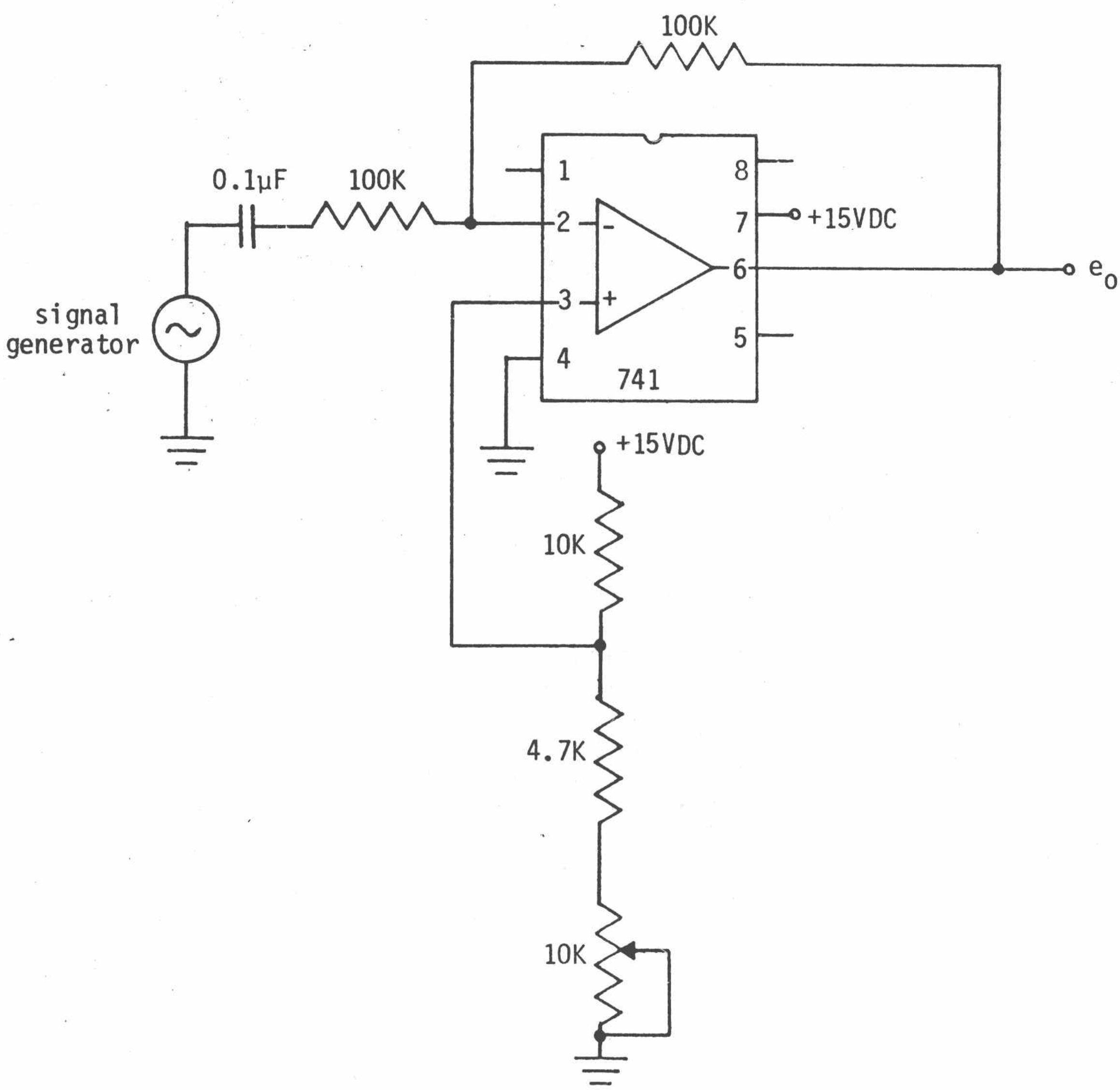

Figure 1.10

15. Reconnect the signal generator and adjust its amplitude to achieve the maximum possible (ac) output from the amplifier that is displayed without distortion by the oscilloscope. Measure and record the peak value of the ac input signal when the maximum undistorted output is achieved.

QUESTIONS

1. Calculate the theoretical closed-loop voltage gain of the circuit in Figure 1.6 for each of the values of R_f used in step 2 of the Procedure. Compare these with the voltage gains determined from the experimental data recorded in step 2. Report your results in a data table that shows all measured values, results of theoretical calculations, and percent differences between theoretical and experimental results. Account for any significant differences between theoretical and experimental results. What do your phase angle observations confirm about this circuit?

2. What does your measurement in step 3 of the Procedure tell you about the voltage at the input to an operational amplifier that has feedback?

3. Repeat question 1 for the data recorded in step 5 of the Procedure.

4. Repeat question 1 for each of the inputs e_2 used in step 7 of the Procedure.

5. Using the data recorded in step 9 of the Procedure, calculate the input impedance presented by the circuit of Figure 1.9 to the signal generator. Compare this with the theoretical value. What do you conclude is the effect of feedback on the impedance presented to a signal source by an inverting amplifier, as compared to the impedance looking into the inverting input without feedback?

6. What minimum and maximum voltage levels were observed when the amplifier was operated with a single supply voltage in step 12 of the Procedure? What is the ac gain of the amplifier in this case? Compare with theoretical values. What is the maximum ac peak input voltage that could be connected to the input of this single-supply amplifier?

7. Sketch the waveform observed in step 13 of the Procedure. Explain its appearance.

8. What minumum dc output level was achieved in step 14 of the Procedure? Assuming the potentiometer can be adjusted to zero ohms, what is the theoretical minimum voltage that can be applied to the non-inverting terminal in Figure 1.10? Is this the same as the minimum dc output voltage you measured? Should it be?

9. With the minimum dc output level that you set in step 14 of the Procedure, what is the theoretical maximum ac peak input voltage that can be applied to the amplifier without having a distorted output? Compare this value to that determined in step 15 of the Procedure.

2 Op-Amp Limitations: Bandwidth, Slew Rate, Offsets

OBJECTIVES

1. To learn through experimental observation how the bandwidth of an operational amplifier decreases when its closed-loop gain is increased.

2. To verify experimentally that the gain-bandwidth product of an operational amplifier is constant.

3. To learn how to measure the slew rate of an operational amplifier and to observe the effect of driving the amplifier with a signal that causes the slew rate to be exceeded.

4. To learn how to measure and interpret input offset voltage and input offset currents.

5. To verify experimentally the theoretical output offset voltage due to input offsets.

6. To learn circuit techniques for reducing or eliminating offset.

7. To learn how to measure open-loop gain and how to calculate common mode gain given the common mode rejection ratio (CMRR).

EQUIPMENT AND MATERIALS REQUIRED

1. Dual-trace oscilloscope

2. Sine/square wave signal generator, adjustable to 1 MHz, 15 V peak.

3. dc millivoltmeter.

4. $\pm$ 15 V DC power supplies.

5. 741 operational amplifier.

6. Resistors: 1K (2), 10K (2), 33K, 100K (2), 220K, 330K, 470K, 1M (2).

7. 10K potentiometer.

8. 0.1 μF capacitors (3).

DISCUSSION

The practical operational amplifier has certain limitations that adversely affect its performance in some applications. The user or designer of operational amplifier circuits must be aware of these limitations so that he or she can select an amplifier whose specifications meet the requirements of the application, or, in some cases, so that he or she can provide circuitry necessary to compensate for the limitations. Failure to do so may result in errors, in the sense that the output voltage may not conform to that which is predicted by the theory. Broadly speaking, amplifier limitations that may give rise to erroneous outputs can be classified as being due to either the dc or ac characteristics of the amplifier.

An important ac limitation of an operational amplifier is its frequency response. Since operational amplifiers are used down to zero frequency (dc), the bandwidth (BW) of the amplifier is equal to the cutoff frequency f_c, where the output level is 3 dB down from (or .707 times) its dc value. It is an important fact, expressed by equation (1), that the gain-bandwidth product of an operational amplifier is constant:

$$G \times BW = \text{constant} \tag{1}$$

The actual constant depends upon the particular amplifier. If the amplifier is used in its open-loop configuration ($R_f = \infty$, a relatively rare case), its gain is exceptionally high and its bandwidth is therefore quite small. In closed-loop applications where R_f is large compared to R_1, that is, in applications requiring high values of gain $G = R_f/R_1$, we must be aware of the reduced frequency range that equation (1) implies as a consequence.

Another ac limitation of the operational amplifier is its specified slew rate. This refers to the maximum rate at which the output voltage can change in large signal applications, and is given in V/sec (or V/μsec). If the amplitude and frequency of a signal are both large, the rate at which the voltage must change may exceed the specified slew rate, even though the frequency of the signal may be within the bandwidth of the amplifier. The maximum frequency of a sinusoidal signal with peak value E_p that an amplifier can accommodate, due to the limitation of its slew rate S, is given by inequality (2):

$$f \leq \frac{S}{s\pi E_p} \tag{2}$$

For accurate operation, the output of an operational amplifier should be zero volts when both inputs are at zero volts. The dc, or bias, characteristics of a typical amplifier are such that this is rarely the case. Unless the amplifier is used strictly for its ac characteristics, some provision must be made to compensate for, i.e., eliminate or reduce, the output voltage, called the output offset voltage, that exists when the inputs are zero.

There are two causes of output offset. One of these is the fact that the internal voltage drops at the inverting and non-inverting inputs are not identical, due to slight differences (mismatches) in the input devices. This gives rise to a different voltage, called the input offset voltage, V_{io}, that is amplified and therefore contributes to output offset. Consider the configuration shown in Figure 2.1. Resistor R_2 in this figure is used to compensate for offset and will be discussed subsequently. In Figure 2.1, it can be shown that the output offset voltage V_{os} due to input offset V_{io} is

$$V_{os} = \frac{V_{io}}{\beta} \tag{3}$$

where $\beta = R_1/(R_f + R_1)$, as before. Input offset V_{io} is usually given in manufacturers' specifications and is typically in the range from 1 to several millivolts.

The other source of output offset is the fact that both inputs must draw bias currents (I^+ and I^- in Figure 2.1). These currents may be slightly different and flow through different values of external impedance, again giving rise to a difference voltage. Manufacturers generally specify an input bias current I_B which is the average of I^+ and I^-:

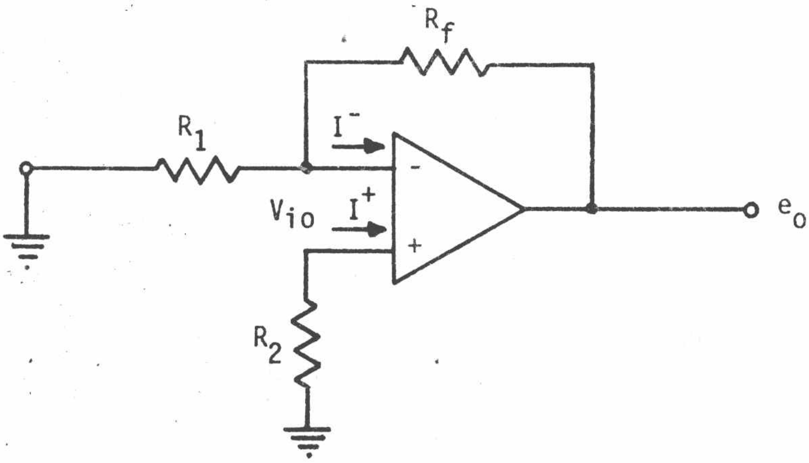

Figure 2.1 An operational amplifier circuit showing the input offset voltage V_{io} between the + and - inputs and the input bias currents I^+ and I^-.

$$I_B = \frac{I^+ + I^-}{2} \tag{4}$$

Since I^+ and I^- are approximately equal, we usually have

$$I_B \simeq I^+ \simeq I^- \tag{5}$$

I_B is typically in the nanoamp or picoamp range. It can be shown that the component of output offset due to I^+ and I^- is

$$V_{os} = I^-R_f - I^+R_2/\beta \tag{6}$$

One way to reduce this component of offset is to set R_2 in Figure 2.1 equal to the parallel equivalent of R_1 and R_f:

$$R_2 = \frac{R_1R_f}{R_1 + R_f} \tag{7}$$

When this is done, equation (6) becomes:

$$V_{os} = I_{io}R_f$$

where I_{io} is the input offset current, and is equal to the difference between I^+ and I^-. Clearly I_{io} is much less than I^+ or I^- and manufacturers typically specify it as a few nanoamps or picoamps.

The total output offset voltage is the sum of its components due to input offset voltage and input offset current:

$$V_{os} = -\frac{V_{io}}{\beta} + I^-R_f - \frac{I^+R_2}{\beta} \tag{8}$$