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LECTURE FOUR

OPERATIONAL AMPLIFIERS

4.1INTRODUCTION TO OPERATIONAL AMPLIFIERS

Early operational amplifiers (op-amps) were used primarily to perform mathematical operations such as addition, subtraction, integration, and differentiation—thus the term *operational*. These early devices were constructed with vacuum tubes and worked with high voltages. Today's op-amps are linear integrated circuits (ICs) that use relatively low dc supply voltages and are reliable and inexpensive.

The standard **operational amplifier (op-amp)** symbol is shown in Figure 4–1(a). It has two input terminals, the inverting (–) input and the noninverting (+) input, and one output terminal. Most op-amps operate with two dc supply voltages, one positive and the other negative, as shown in Figure 4–1(b), although some have a single dc supply. Some typical op-amp IC packages are shown in Figure 4–1(c).

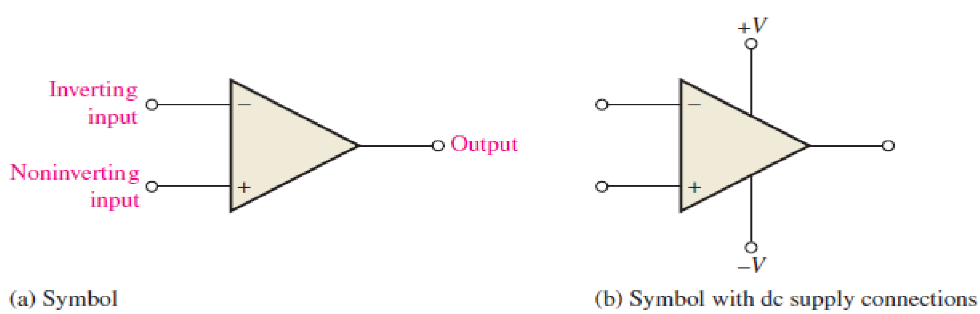


Fig 4. 1: *Op-amp symbols*

Internal Block Diagram of an Op-Amp

A typical op-amp is made up of three types of amplifier circuits: a differential amplifier, a voltage amplifier, and a push-pull amplifier, as shown in Figure 4–2. The **differential amplifier** is the input stage for the op-amp. It provides amplification of the difference voltage between the two inputs. The second stage is usually a class A amplifier that provides additional gain. Some op-amps may have more than one voltage amplifier stage. A push-pull class B amplifier is typically used for the output stage.

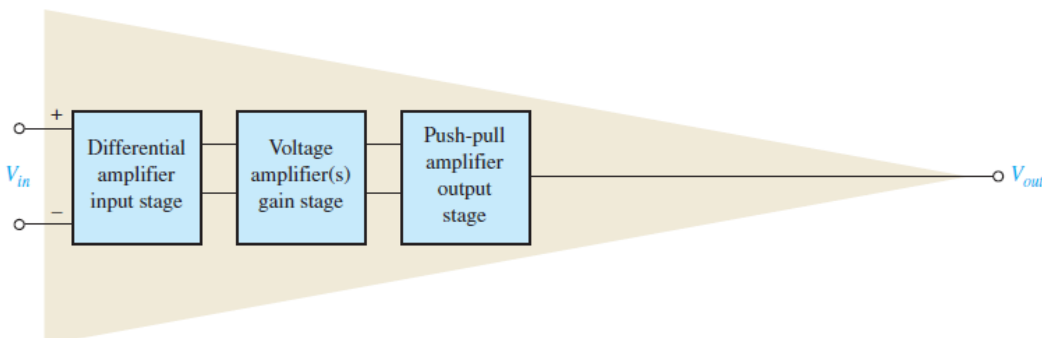


Fig 4. 2: *Basic internal arrangement of an op-amp.*

4.2 OP-AMP BASICS

An operational amplifier is a very high-gain amplifier having very high input impedance (typically a few megohms) and low output impedance (less than 100 Ω). The basic circuit is made using a difference amplifier having two inputs (plus and minus) and at least one output. Figure 4.1 shows a basic op-amp unit. The plus (+) input produces an output that is in phase with the signal applied, whereas an input to the minus (-) input results in an opposite-polarity output. The ac equivalent circuit of the op-amp is shown in Fig. 4.3 a. As shown, the input signal applied between the input terminals sees an input impedance *Ri* that is typically very high. The output voltage is shown to be the amplifier gain times the input signal taken through an output impedance *Ro*, which is typically very low. An ideal op-amp circuit, as shown in Fig. 4.3 b, would have infinite input impedance, zero output impedance, and infinite voltage gain.

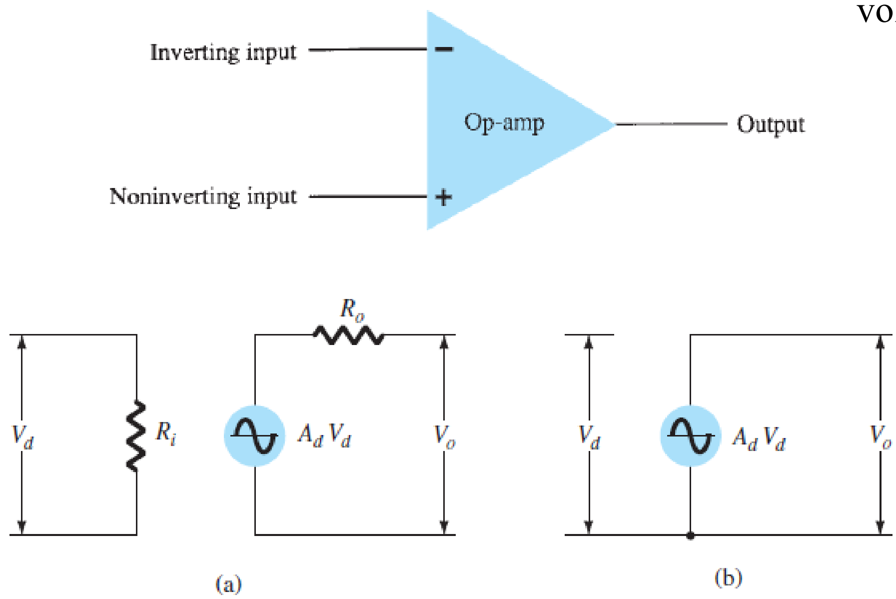


Fig. 4.3: *AC equivalent of op-amp circuit: (a) practical; (b) ideal.*

Basic Op-Amp

The basic circuit connection using an op-amp is shown in Fig. 4.4. The circuit shown provides operation as a constant-gain multiplier. An input signal *V1* is applied through resistor *R1* to the minus input. The output is then connected back to the same minus input through resistor *Rf*. The plus input is connected to ground. Since the signal *V1* is essentially applied to the minus

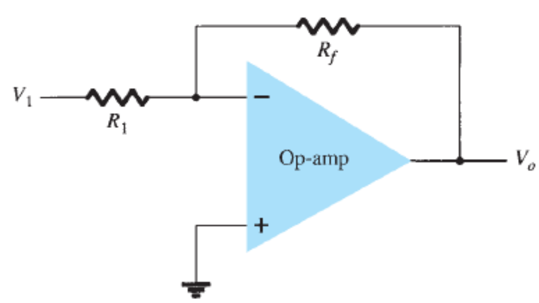
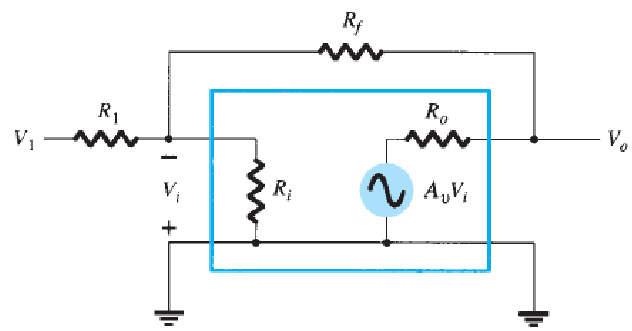


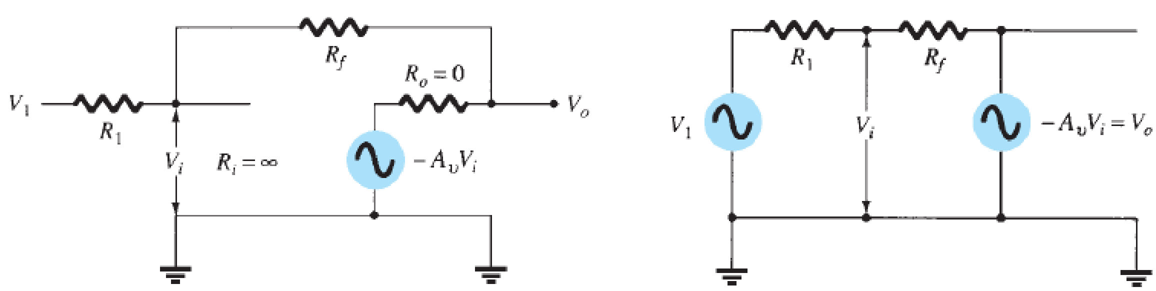
Fig. 4.4: *Basic op-amp connection.*

input, the resulting output is opposite in phase to the input signal.

Figure 4.5 a shows the op-amp replaced by its ac equivalent circuit. If we use the ideal op-amp equivalent circuit, replacing *Ri* by an infinite resistance and *Ro* by a zero resistance, the ac equivalent circuit is that shown in Fig. 4.4 b. The circuit is then redrawn, as shown in Fig. 4.4 c, from which circuit analysis is carried out.



(a)



(b) (c)

Fig. 4.5: *Operation of op-amp as constant-gain multiplier: (a) op-amp ac equivalent circuit; (b) ideal op-amp equivalent circuit; (c) redrawn equivalent circuit.*

Using superposition, we can solve for the voltage *V1* in terms of the components due to each of the sources. For source *V1* only (-*AvVi* set to zero),

$$V_{i_1} = \frac{R_f}{R_1 + R_f} V_1$$

For source -*AvVi* only (*V1* set to zero),

$$V_{i_2} = \frac{R_1}{R_1 + R_f}(-A_v V_i)$$

The total voltage Vi is then

$$V_i = V_{i_1} + V_{i_2} = \frac{R_f}{R_1 + R_f}V_1 + \frac{R_1}{R_1 + R_f}(-A_v V_i)$$

which can be solved for Vi as

$$V_i = \frac{R_f}{R_f + (1 + A_v)R_1}V_1 \qquad \text{Eq. 4.1}$$

If $Av >> 1$ and $Av\ R1 >> Rf$, as is usually true, then

$$V_i = \frac{R_f}{A_v R_1}V_1$$

Solving for Vo/Vi, we get

$$\frac{V_o}{V_i} = \frac{-A_v V_i}{V_i} = \frac{-A_v}{V_i}\frac{R_f V_1}{A_v R_1} = -\frac{R_f}{R_1}\frac{V_1}{V_i}$$

so that

$$\boxed{\frac{V_o}{V_1} = -\frac{R_f}{R_1}} \qquad \text{Eq. 4.2}$$

The result in Eq. (4.2) shows that the ratio of overall output to input voltage is dependent only on the values of resistors $R1$ and Rf—provided that $A\ v$ is very large.

Constant-Magnitude Gain

If Rf is some multiple of $R1$, the overall amplifier gain is a constant. For example, if $Rf = 10R1$, then

$$\text{Voltage gain} = -\frac{R_f}{R_1} = -10$$

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The output voltage is limited by the supply voltage of, typically, a few volts. As stated before, voltage gains are very high. If, for example, Vo = -10 V and Av = 20,000, the input voltage is

$$V_i = \frac{-V_o}{A_v} = \frac{10\ \text{V}}{20{,}000} = 0.5\ \text{mV}$$

Current goes only through resistors R 1 and $R\,f$ as shown

Using the virtual ground concept, we can write equations for the current I as follows:

$$I = \frac{V_1}{R_1} = -\frac{V_o}{R_f}$$

which can be solved for $Vo/V1$:

$$\frac{V_o}{V_1} = -\frac{R_f}{R_1}$$

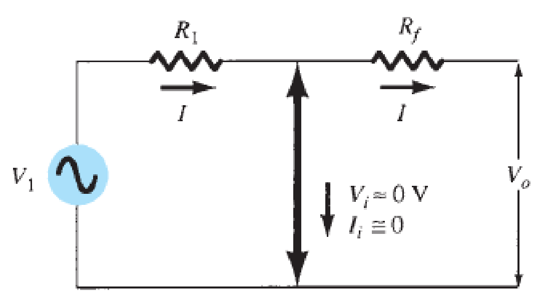

Fig. 4.6: *Virtual ground in an op-*

4.3 PRACTICAL OP-AMP CIRCUITS

The op-amp can be connected in a large number of circuits to provide various operating characteristics. In this section, we cover a few of the most common of these circuit connections.

Inverting Amplifier

The most widely used constant-gain amplifier circuit is the inverting amplifier, as shown in Fig. 4.7. The output is obtained by multiplying the input by a fixed or constant gain, set by the input resistor (*R1*) and feedback resistor (*Rf*)—this output is also inverted from the input. Using Eq. (4.2), we can write

$$V_o = -\frac{R_f}{R_1} V_1$$

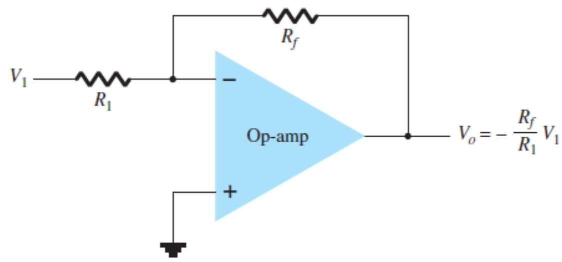

Fig. 4.7: *Inverting constant-gain multiplier*

EXAMPLE 4.1 If the circuit of Fig. 4.7 has $R1$ = 100 kΩ and Rf =500 kΩ, what output voltage results for an input of $V1$ = 2 V?

$$V_o = -\frac{R_f}{R_1} V_1 = -\frac{500\ \text{k}\Omega}{100\ \text{k}\Omega}(2\ \text{V}) = \mathbf{-10\ V}$$

EXAMPLE 4.2 Determine the output voltage for the circuit of Fig. 4.8 with a sinusoidal input of 2.5 mV.

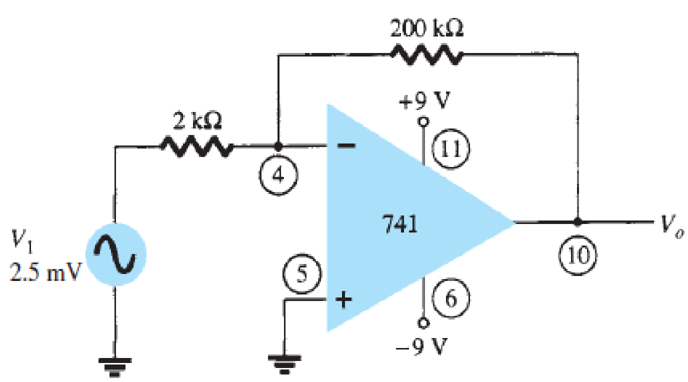

Fig. 4.8: *Circuit for Example4.2*

The circuit of Fig. 4.8 uses a 741 op-amp to provide a constant or fixed gain, calculated as:

$$A = -\frac{R_f}{R_1} = -\frac{200\,\text{k}\Omega}{2\,\text{k}\Omega} = -100$$

The output voltage is then

$$V_0 = AV_i = -100(2.5mV) = -250mV = -0.25V$$

Noninverting Amplifier

The connection of Fig. 4.9a shows an op-amp circuit that works as a noninverting amplifier or constant-gain multiplier. It should be noted that the inverting amplifier connection is more widely used because it has better frequency stability. To determine the voltage gain of the circuit, we can use the equivalent representation shown in Fig. 4.9b. Note that the voltage across $R1$ is $V1$ since $Vi = 0$ V. This must be equal to the output voltage, through a voltage divider of $R1$ and Rf, so that

$$V_1 = \frac{R_1}{R_1 + R_f} V_o$$

which results in

$$\frac{V_o}{V_1} = \frac{R_1 + R_f}{R_1} = 1 + \frac{R_f}{R_1} \qquad \text{Eq. 4.3}$$

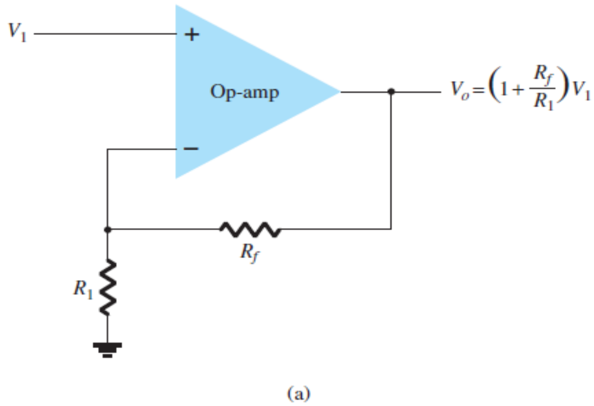

Fig. 4.9: *Noninverting constant-gain multiplier.*

EXAMPLE 4.3 Calculate the output voltage of a noninverting amplifier (as in Fig. 4.8) for values of *V1* = 2V, *Rf* = 500 kΩ, and *R*1 = 100 kΩ.

Solution:

$$V_o = \left(1 + \frac{R_f}{R_1}\right)V_1 = \left(1 + \frac{500\ \text{k}\Omega}{100\ \text{k}\Omega}\right)(2\ \text{V}) = 6(2\ \text{V}) = \mathbf{+12\ V}$$

EXAMPLE 4.4 Calculate the output voltage from the circuit of Fig. 4.10 for an input of 120 mV.

Solution:

The gain of the op-amp circuit is

$$A = 1 + \frac{R_f}{R_1} = 1 + \frac{240\ \text{k}\Omega}{2.4\ \text{k}\Omega} = 1 + 100 = 101$$

The output voltage is then

$$V_o = AV_i = 101(120\ \mu\text{V}) = \mathbf{12.12\ mV}$$

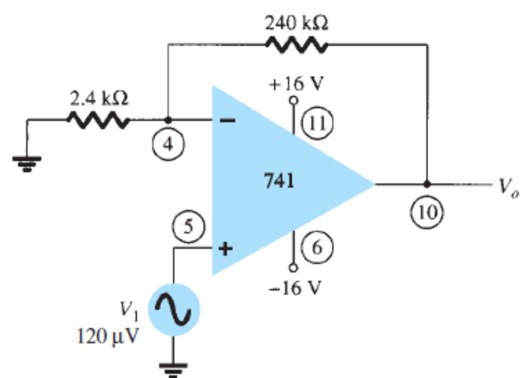

Fig. 4.10: *Circuit for Example4.4*

Multiple-Stage Gains

When a number of stages are connected in series, the overall gain is the product of the individual stage gains. Figure 4.11 shows a connection of three stages. The first stage is connected to provide noninverting gain. The next two stages provide an inverting gain. The overall circuit gain is then noninverting and is calculated by

$$A = A_1 A_2 A_3$$

where $A_1 = 1 + R_f/R_1$, $A_2 = -R_f/R_2$, and $A_3 = -R_f/R_3$.

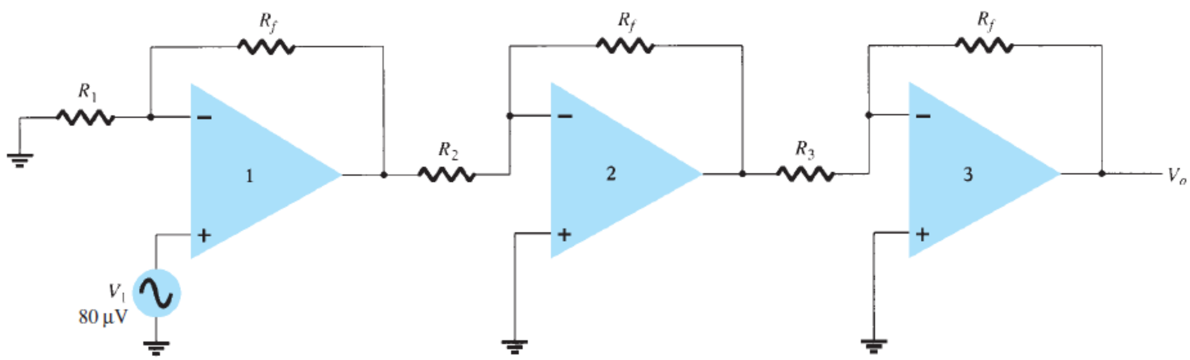

Fig. 4.11: *Constant-gain connection with multiple stages.*

EXAMPLE 4.5 Calculate the output voltage using the circuit of Fig. 4.11 for resistor components of value *Rf* = 470 kΩ, *R*1 = 4.3 kΩ, *R*2 = 33 kΩ, and *R*3 = 33 kΩ for an input of 80 µV.

Solution:

The amplifier gain is calculated to be

$$A = A_1 A_2 A_3 = \left(1 + \frac{R_f}{R_1}\right)\left(-\frac{R_f}{R_2}\right)\left(-\frac{R_f}{R_3}\right)$$

$$= \left(1 + \frac{470\text{ k}\Omega}{4.3\text{ k}\Omega}\right)\left(-\frac{470\text{ k}\Omega}{33\text{ k}\Omega}\right)\left(-\frac{470\text{ k}\Omega}{33\text{ k}\Omega}\right) = (110.3)(-14.2)(-14.2) = 22.2 \times 10^3$$

so that

$$V_o = AV_i = 22.2 \times 10^3 (80\ \mu\text{V}) = \mathbf{1.78\ V}$$

EXAMPLE 4.6 Show the connection of an LM124 quad op-amp as a three-stage amplifier. Use a 270 kΩ feedback resistor for all three circuits. What output voltage will result for an input of 150 μV?

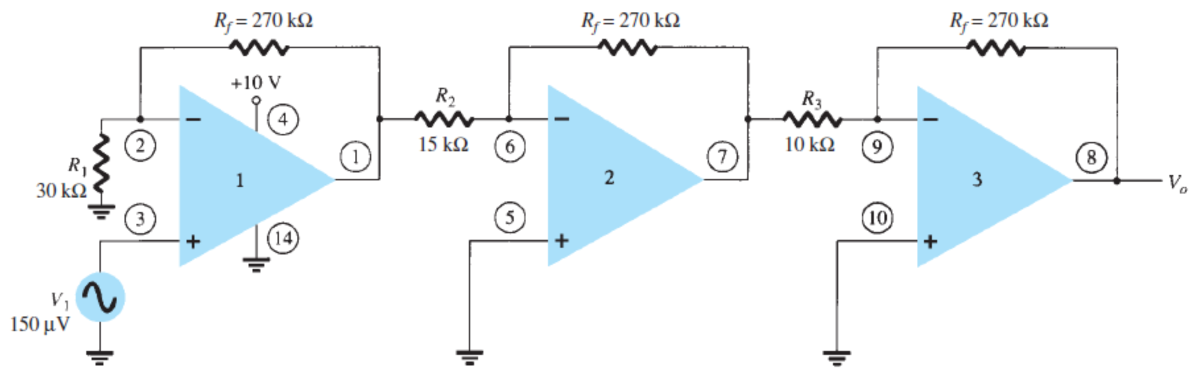

Fig. 4.12: *Circuit for Example 4.6 (using LM124).*

Solution: For A_1,

$$A_1 = 1 + \frac{R_f}{R_1} = 1 + \frac{270k\Omega}{30k\Omega} = 1 + 9 = 10$$

For A_2,

$$A_2 = -\frac{R_f}{R_2} = -\frac{270k\Omega}{15k\Omega} = -18$$

For A_3,

$$A_3 = -\frac{R_f}{R_3} = -\frac{270k\Omega}{10k\Omega} = -27$$

For an input of $V1$ = 150 μV, the output voltage is

$Vo = A_1A_2A_3V_1$ = (10)(-18)(-27)(150 μV) = 4860(150 μV)

= **0.729 V**

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A number of op-amp stages could also be used to provide separate gains, as demonstrated in the next example.

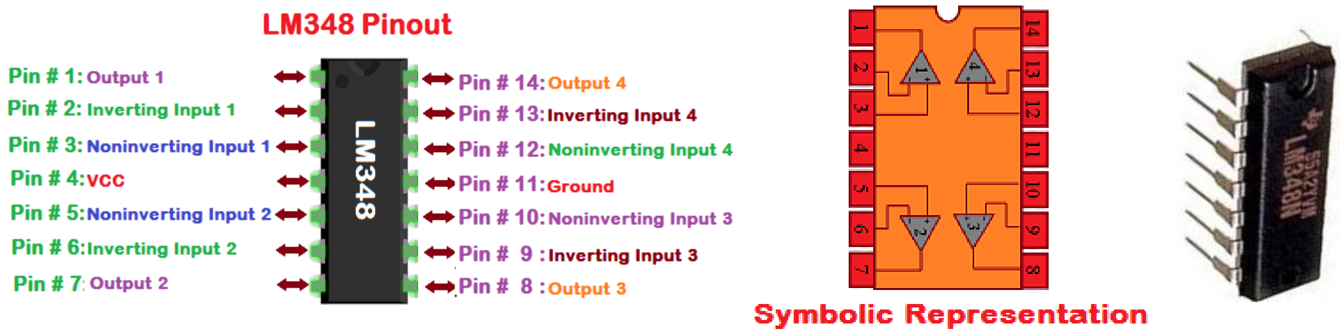

Fig. 4.13: *LM348*

EXAMPLE 4.7 Show the connection of three op-amp stages using an LM348 IC to provide outputs that are 10, 20, and 50 times larger than the input. Use a feedback resistor of Rf = 500 kΩ in all stages.

Solution:

The resistor component for each stage is calculated to be

$$R_1 = -\frac{R_f}{A_1} = -\frac{500\,\text{k}\Omega}{-10} = 50\,\text{k}\Omega$$

$$R_2 = -\frac{R_f}{A_2} = -\frac{500\,\text{k}\Omega}{-20} = 25\,\text{k}\Omega$$

$$R_3 = -\frac{R_f}{A_3} = -\frac{500\,\text{k}\Omega}{-50} = 10\,\text{k}\Omega$$

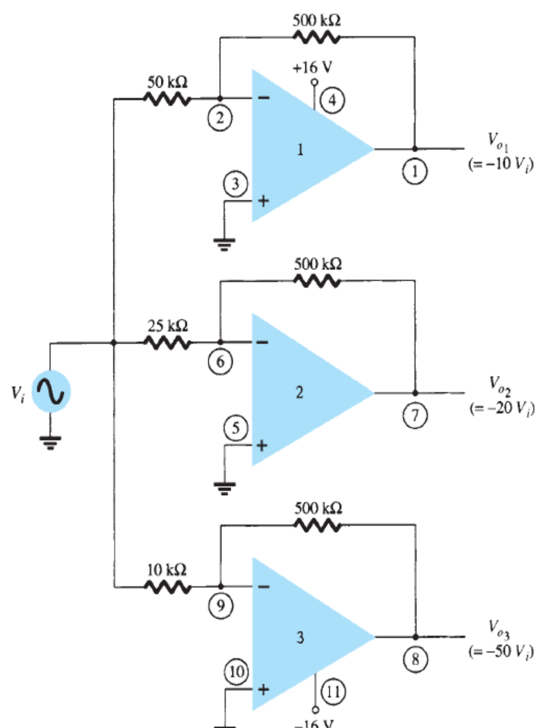

Fig. 4.14: *Example 4.7*

Summing Amplifier

Probably the most used of the op-amp circuits is the summing amplifier circuit shown in Fig. 4.15 a. The circuit shows a three-input summing amplifier circuit, which provides a means of algebraically summing (adding) three voltages, each multiplied by a constant-gain factor. Using the equivalent representation shown in Fig. 4.15 b, we can express the output voltage in terms of the inputs as

$$V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right) \qquad \text{Eq. 4.4}$$

In other words, each input adds a voltage to the output multiplied by its separate constant-gain multiplier. If more inputs are used, they each add an additional component to the output.

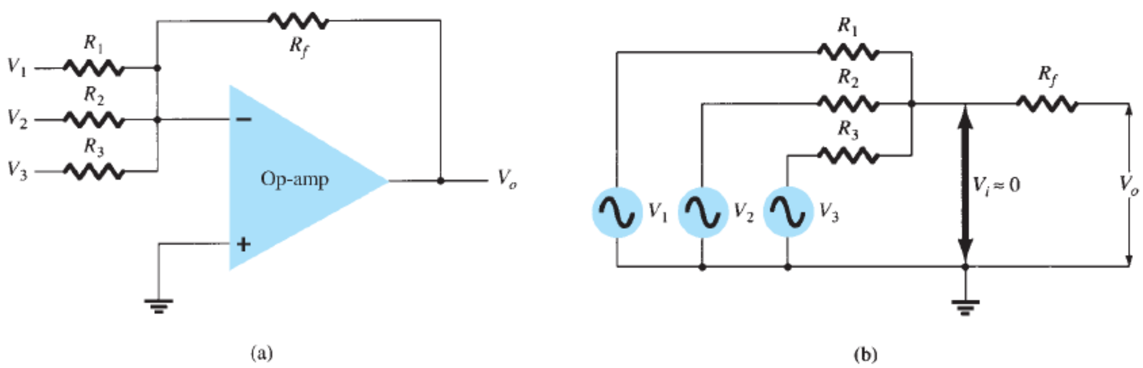

Fig. 4.15: *(a) Summing amplifier; (b) virtual-ground equivalent circuit.*

EXAMPLE 4.8 Calculate the output voltage of an op-amp summing amplifier for the following sets of voltages and resistors. Use $Rf = 1$ MΩ in all cases.

a. $V1 = +1$ V, $V2 = +2$ V, $V3 = +3$ V, $R1 = 500$ kΩ, $R2 = 1$ MΩ, $R3 = 1$ MΩ.

b. $V1 = -2$ V, $V2 = +3$ V, $V3 = +1$ V, $R1 = 200$ kΩ, $R2 = 500$ kΩ, $R3 = 1$ MΩ.

Solution:

Using Eq. (4.4), we obtain

$$\text{a. } V_o = -\left[\frac{1000\text{ k}\Omega}{500\text{ k}\Omega}(+1\text{ V}) + \frac{1000\text{ k}\Omega}{1000\text{ k}\Omega}(+2\text{ V}) + \frac{1000\text{ k}\Omega}{1000\text{ k}\Omega}(+3\text{ V})\right]$$

$$= -[2(1\text{ V}) + 1(2\text{ V}) + 1(3\text{ V})] = \mathbf{-7\text{ V}}$$

$$\text{b. } V_o = -\left[\frac{1000\text{ k}\Omega}{200\text{ k}\Omega}(-2\text{ V}) + \frac{1000\text{ k}\Omega}{500\text{ k}\Omega}(+3\text{ V}) + \frac{1000\text{ k}\Omega}{1000\text{ k}\Omega}(+1\text{ V})\right]$$

$$= -[5(-2\text{ V}) + 2(3\text{ V}) + 1(1\text{ V})] = \mathbf{+3\text{ V}}$$

EXAMPLE 4.9 Calculate the output voltage for the circuit of Fig. 4.16. The inputs are $V1 = 50$ mV sin(1000 t) and $V2 = 10$ mV sin(3000 t).

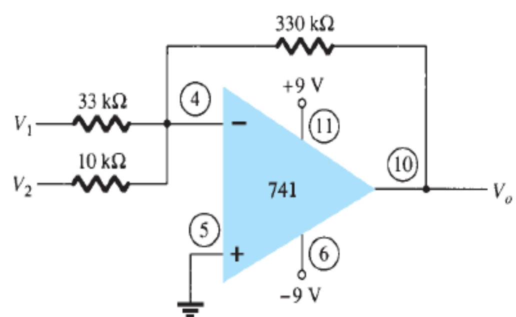

Fig. 4.16: Example 4.9

Solution:

The output voltage is

$$V_o = -\left(\frac{330\text{ k}\Omega}{33\text{ k}\Omega}V_1 + \frac{330\text{ k}\Omega}{10\text{ k}\Omega}V_2\right) = -(10\,V_1 + 33\,V_2)$$

$$= -[10(50\text{ mV})\sin(1000t) + 33(10\text{ mV})\sin(3000t)]$$

$$= \mathbf{-[0.5\sin(1000t) + 0.33\sin(3000t)]}$$

Voltage Subtraction

Two signals can be subtracted from one another in a number of ways. Figure 4.17 shows two op-amp stages used to provide the subtraction of input signals. The resulting output is given by

$$V_o = -\left[\frac{R_f}{R_3}\left(-\frac{R_f}{R_1}V_1\right) + \frac{R_f}{R_2}V_2\right]$$

$$V_o = -\left(\frac{R_f}{R_2}V_2 - \frac{R_f}{R_3}\frac{R_f}{R_1}V_1\right) \qquad \text{Eq. 4.5}$$

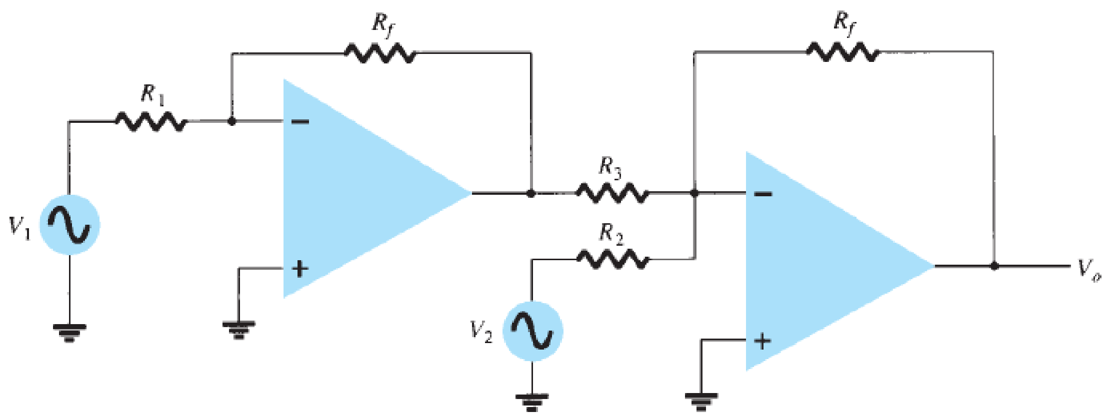

Fig. 4.17: *Circuit for subtracting two signals.*

EXAMPLE 4.10 Determine the output for the circuit of Fig. 4.17 with components *Rf* = 1 MΩ, *R*1 = 100 kΩ, *R*2 = 50 kΩ, and *R*3 = 500 kΩ.

Solution: The output voltage is calculated to be

$$V_o = -\left(\frac{1\text{ M}\Omega}{50\text{ k}\Omega}V_2 - \frac{1\text{ M}\Omega}{500\text{ k}\Omega}\frac{1\text{ M}\Omega}{100\text{ k}\Omega}V_1\right) = -(20\,V_2 - 20\,V_1) = \mathbf{-20(V_2 - V_1)}$$

The output is seen to be the difference of *V2* and *V1* multiplied by a gain factor of -20.

Another connection to provide subtraction of two signals is shown in Fig. 4.18. This connection uses only one op-amp stage to provide subtracting two input signals. Using superposition, we can show the output to be

$$V_o = \frac{R_3}{R_1 + R_3}\frac{R_2 + R_4}{R_2}V_1 - \frac{R_4}{R_2}V_2 \qquad \text{Eq. 4.6}$$

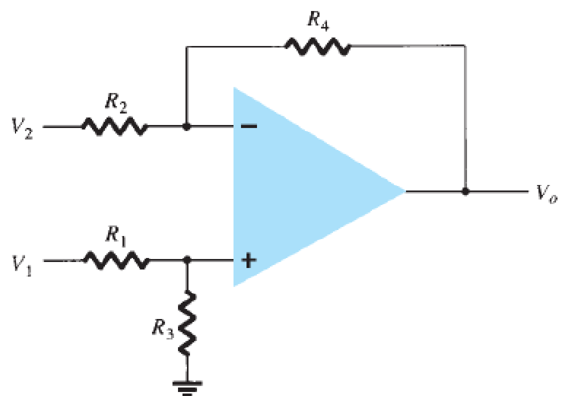

Fig. 4.18: *Subtraction circuit.*

EXAMPLE 4.11 Determine the output voltage for the circuit of Fig. 4.19.

Solution: The resulting output voltage can be expressed as

$$V_o = \left(\frac{20\text{ k}\Omega}{20\text{ k}\Omega + 20\text{ k}\Omega}\right)\left(\frac{100\text{ k}\Omega + 100\text{ k}\Omega}{100\text{ k}\Omega}\right)V_1 - \frac{100\text{ k}\Omega}{100\text{ k}\Omega}V_2$$

$= V_1 - V_2$

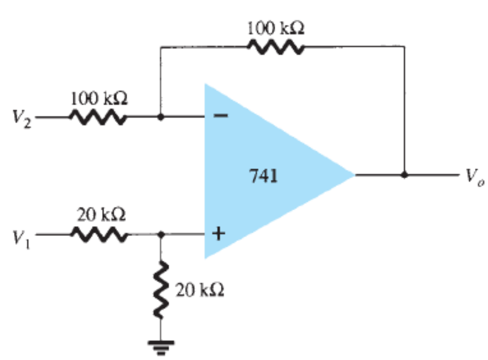

Fig. 4.19: *Circuit for Example 4.11*