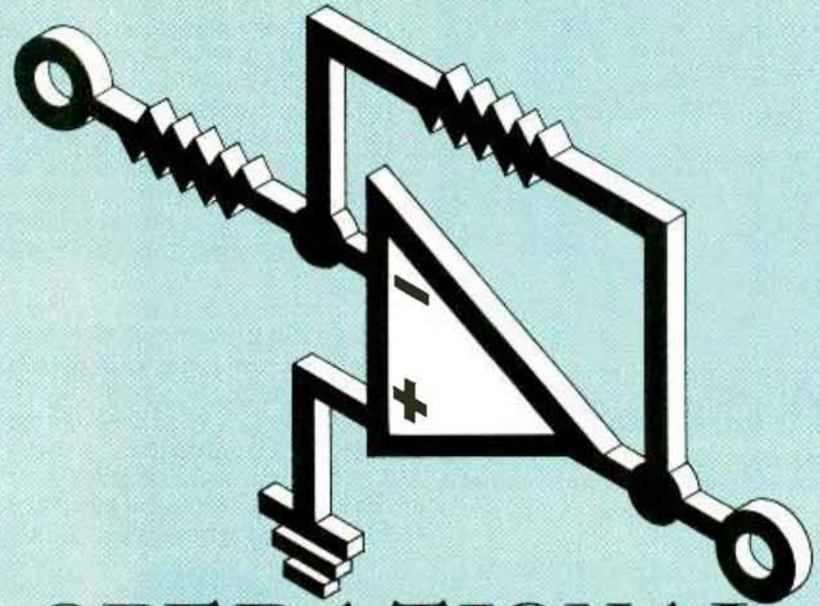

OPERATIONAL AMPLIFIERS

Learn how to design with operational amplifiers and put them to work in various analog and audio circuits

RAY MARSTON

THE OPERATIONAL AMPLIFIER (OP-amp) is a high-gain, DC-coupled amplifier with a differential input (two input leads) and a single-ended output (one output lead). It is one of the most versatile circuits ever invented because it closely approximates the ideal amplifier.

The versatility of the op-amp has made it a key functional building block in linear or analog circuitry because it eliminates the need for bulky transformers in many low-frequency and audio circuits. This article will focus on the role of the op-amp in performing audio signal processing.

The op-amp was developed more than 40 years ago to perform mathematical operations such as addition, subtraction, integration, and differentiation in analog computers. Originally a vacuum-tube, DC-amplifier circuit, it evolved into a discrete transistor circuit before being made as a monolithic integrated circuit.

The availability of mass-produced, low-cost, monolithic op-amps has had a significant impact on all linear circuitry. Op-amps are included in both discrete and monolithic circuits for signal conditioning, power regulation, active filtering, function generation, digital-to-analog conversion, and many other applications.

Ideal amplifier

An op-amp has many of the characteristics of an ideal amplifier. It will be instructive to review the characteristics of an ideal amplifier and then compare them with the performance characteristics of existing monolithic IC op-amps. The characteristics of the ideal amplifier are:

Gain. An ideal amplifier would have infinite gain. However, this is not desirable in a practical amplifier because the smallest input signal would cause maximum output. Thus, high but controllable gain is acceptable.

Input impedance. An ideal amplifier would have infinite input impedance or resistance so its input source would not be incorrectly loaded.

Output impedance. An ideal amplifier would have zero output impedance or resistance so that it could be connected to a load with any resistance value without affecting its output voltage.

Bandwidth. An ideal amplifier would have infinite bandwidth so that it could amplify any frequency from zero hertz (DC) to the upper limits of the radio-frequency spectrum.

Common-mode rejection ratio. An ideal amplifier would have an infinite common-mode rejection ratio or CMMR. This means that if the amplifier has two input terminals (one positive and the other negative), there will be no output if both inputs (common mode) receive the same signal simultaneously. The output of an amplifier that exhibits high CMMR is essentially a zero output if the same signal is applied simultaneously to both of its inputs.

Supply voltage. An ideal amplifier would be unaffected by reasonable variations in power supply voltage.

Practical monolithic op-amps

The 741 is a mature, popular, general-purpose monolithic IC operational amplifier. A bipolar device, it was developed more than 25 years ago by Fairchild Semiconductor Corp. (acquired by National Semiconductor Corp.) as the μA741, an improved version of its μA709. It has retained its popularity and become an industry standard. The μA741 had internal frequency compensation and full overload protection on both its inputs and output.

Many different manufacturers make their own brands of the μA741 and some have improved the performance of the original. Nevertheless, all have similar electrical characteristics. Among the alternate-sourced 741s are four versions from Analog Devices, four from

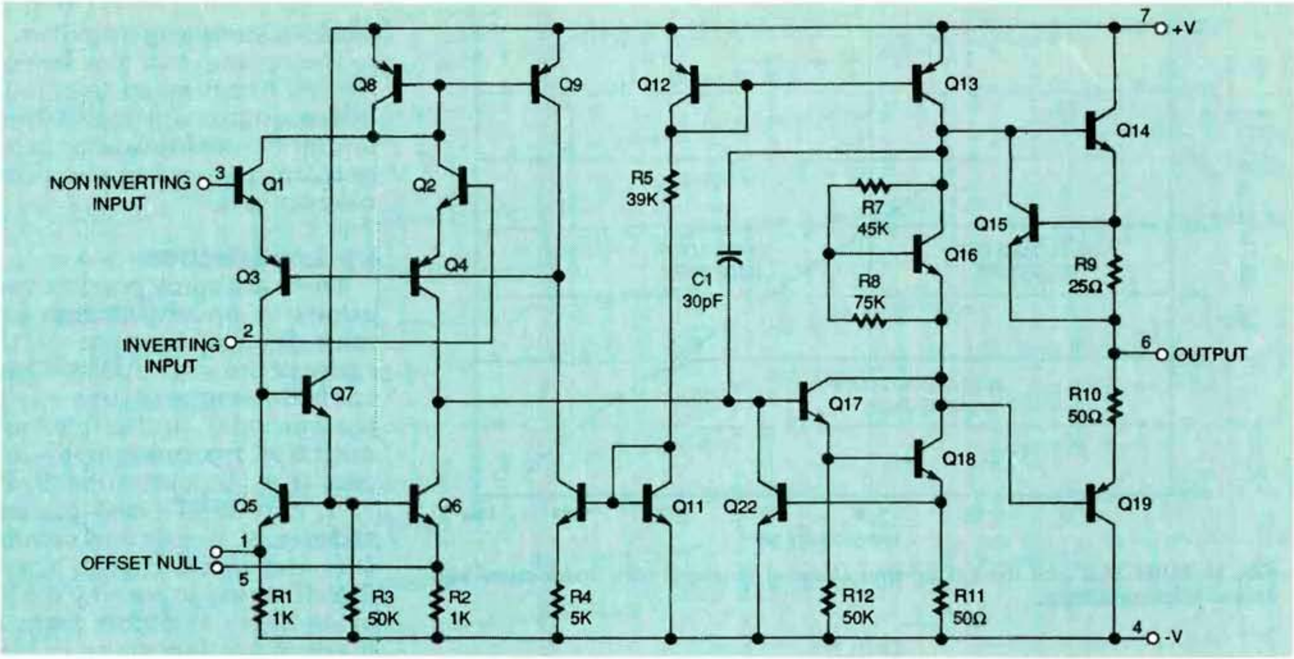

FIG. 1—SCHEMATIC AND CONNECTION DIAGRAM for the industry-standard 741 operational amplifier.

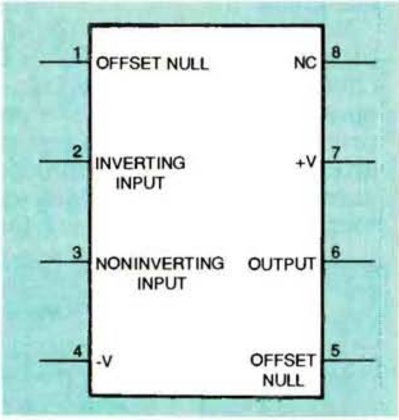

FIG. 2—PINOUT DIAGRAM for a 741 operation amplifier in an eight 8-pin plastic DIP package.

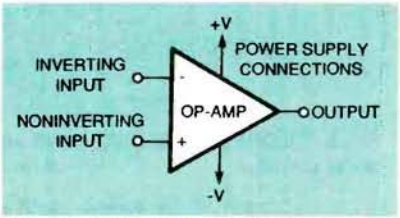

FIG. 3—SCHEMATIC SYMBOL for a 741 op-amp.

Harris, nine from Maxim, eight from National Semiconductor, three from Philips, and nine from SGS-Thomson.

Because op-amps from all of these suppliers have essentially the same characteristics, the μA741 will be referred to by the generic designation "741" for the remainder of this article. Far from being a leading-edge device, the 741 is, nevertheless, well suited for experiments and prototyping because of its low price and ready availability.

A "commodity" 741 can be purchased from electronic distributors for less than 50 cents, and that unit price falls significantly in large purchases of hundreds.

Some of the typical electrical characteristics of the 741 are given in the first column of Table 1. Many op-amps now in production have characteristics that surpass those of the 741, but they generally cost more. The performance of the two other op-amps included in the table will be discussed later in this article.

Figure 1 is the schematic for the 741 illustrating its complexity. (This contains 19 transistors, but in other versions diodes have replaced two transistors.) Figure 2 is the pinout diagram for the commodity 741 in an eight-pin plastic DIP case. Figure 3 is the standard schematic symbol for all op-amps, but power supply connections are not always shown.

Many op-amps are powered from split power supplies as shown in Fig. 3. The +V, −V and ground (zero volt) rails permit the op-amp's output to swing on either side of zero volts and be set at zero volts when the differential input voltage is zero. However, some op-amps can be powered from single-ended supplies.

Figure 4 is the frequency response curve or *Bode plot* of a 741 op-amp. The 741 offers low-frequency (below 10 Hz) voltage gain that is greater than 100 dB. However, that gain rolls off at 6 dB per octave (20 dB per decade) at frequencies above 10 Hz. It eventually falls to unity gain (0 dB) at its (f_T) *unity gain transition* or cutoff frequency of 1 MHz.

The Bode plot of Fig. 4 can also represent the latest op-amps, but those devices will tipically have different values of low-frequency gain and cutoff frequency.

Closed-loop amplifiers

The op-amp usually serves as the active device in a feedback circuit. Gain is precisely determined by the negative feedback applied from output to input though the components in the external feedback loop. The values of those components set the gain value. However, the feedback loop effectively cancels the op-amp's open-loop electrical characteristics

Figure 5 shows an op-amp configured as a fixed-gain inverting amplifier. The output is fed back to the input, and voltage

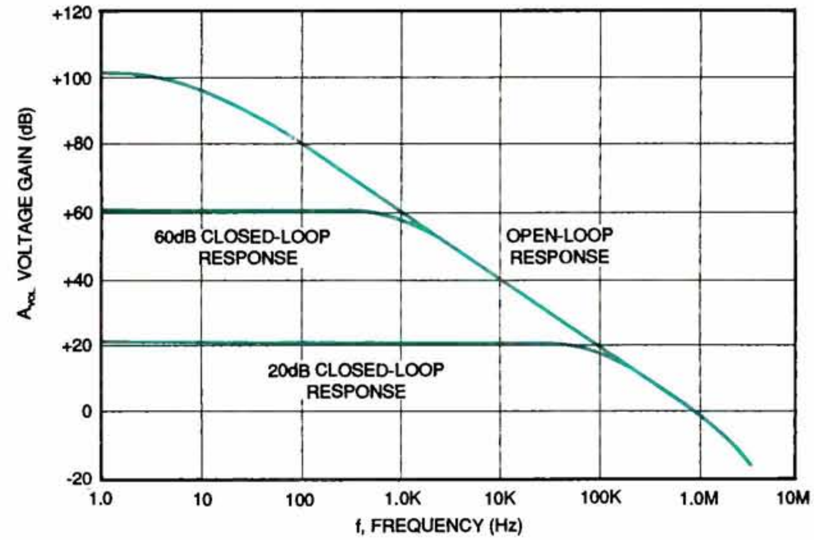

FIG. 4—BODE PLOT for the 741 op-amp showing values of gain under open- and closed-loop conditions.

TABLE 1
TYPICAL ELECTRICAL CHARACTERISTICS OF THREE OP-AMPS

		741	CA3140	LF411	
PARAMETER	**SYMBOL**				**UNITS**
Input offset voltage	V_{IO}	2	5	0.8	mV
Input offset current	I_{IO}	20 (1)	0.1	25	pA
Input bias current	I_{IB}	80 (1)	2	50	pA
Input resistance	R_{IN}	2×10^6	10×10^{12}	1×10^{12}	Ω
Large-signal voltage gain	A_{VOL}	200	[100K (2)	200	V/mV
Output voltage swing	V_O	±14	----	±13.5	V
Common-mode rejection ratio	CMRR	90	90	100	dB
Supply current	I_S	1.7	1.6	1.8	mA
Slew rate	SR	0.5	7	15	V/us
Gain-bandwidth product	GBW	——	3.7	4	MHz
Supply voltage	±18		±15	±18	V
Power dissipation	50		8		mW
(1) nanoamperes	**(2) volts per volt**				

gain A is determined by the ratio of R1 to R2, and equals −R1/R2. This ratio also equals the output voltage divided by the input voltage. This circuit's input impedance equals the value of R1. The circuit can easily be modified to give any desired gain and input impedance values by changing component values.

Current induced at the junction of R2 and R1 is A times greater than that caused by the input signal alone. Therefore, the input acts as if it has an impedance of R2/A connected between the terminal and ground, so it acts like a low-impedance "virtual ground."

Figure 6 shows an op-amp configured as a fixed-gain noninverting AC amplifier. Here the closed-loop voltage gain equals (R1 + R2)/R2 or the output voltage divided by the input voltage. The input impedance approaches infinity.

An op-amp can be made to function as a differential input amplifier by combining the inverting and noninverting connections. If that differential amplifier is modified so that two or more input signals can be added algebraically, the op-amp becomes a *summing amplifier*.

The op-amp can also be configured to act as an integrator, differentiator, and logarithmic amplifier, useful functions for performing analog computer calculations.

Op-amp selection

There are many possible variations in op-amp design and manufacture because of the range of desired options. These include temperature range (commercial, industrial and military), manufacturing process (e.g., bipolar, BiMOS, Bi-FET, and JFET), and package styles (e.g., plastic and ceramic DIP, and metal cases). Therefore, it is easy to see why the list of op-amps available from so many manufacturers is long and bewildering— even for experienced professional circuit designers.

Where required in the application, the designer can choose from a wide selection of op-amps today. Some are proprietary designs and others are alternate-sourced-versions of standard products. Many op-amps are optimized to obtain

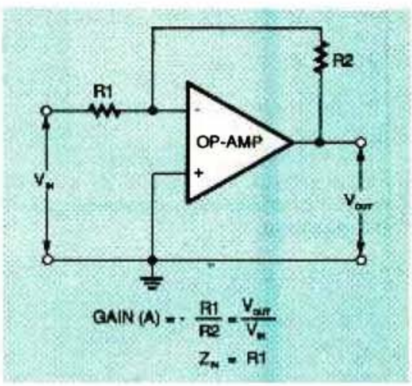

FIG. 5—CLOSED-LOOP INVERTING amplifier circuit.

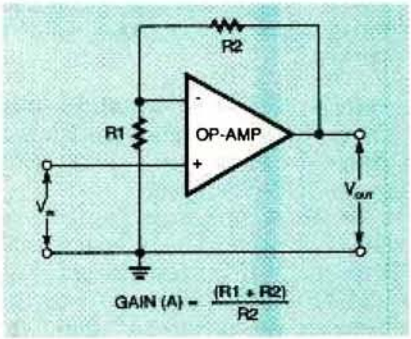

FIG. 6—CLOSED-LOOP NONINVERTING amplifier circuit.

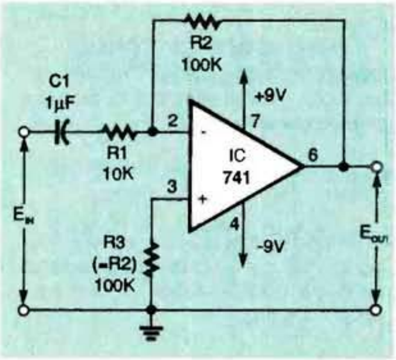

FIG. 7—INVERTING AC AMPLIFIER with a gain of 10.

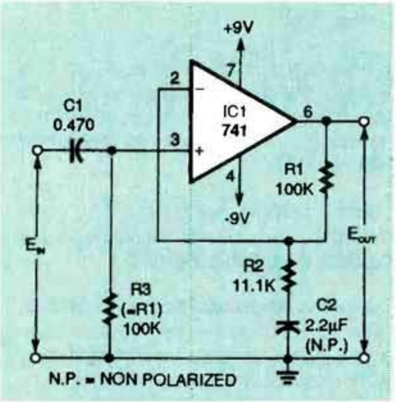

FIG. 8—NONINVERTING AC AMPLIFIER with a gain of 10.

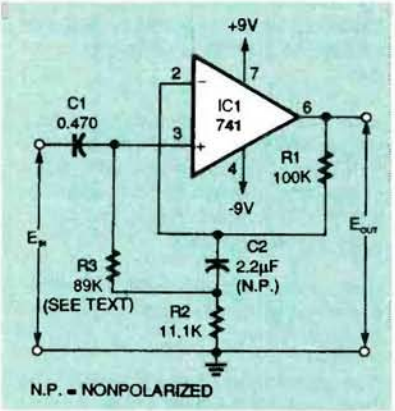

FIG. 9—NONINVERTING AC AMPLIFIER with a gain of 10 and 50-megohm input impedance.

features of special importance in certain applications, such as low noise, high slew rate, wide bandwidth, or various combinations of these.

Op-amp manufacturers specialize in either the high-volume, low-priced commodity or general purpose op-amps ("jelly beans") or more specialized, premium-priced (and often proprietary) devices for instrumentation, signal processing, and communications.

The Harris CA3140 is an example of a high-volume BiMOS op-amp that offers very high input impedance (1.0×10^{12} ohms) that can operate from either single or dual power supplies. The CA3140 combines the advantages of high-voltage PMOS transistors with high-voltage bipolar transistors on a single chip.

The CA3140 has a bipolar output stage, is internally compensated, and has the versatility of 741 op-amps. Column 2 of Table 1 lists some of its typical electrical characteristics.

National Semiconductor's LF411 is a low-cost, high-speed JFET input op-amp that is also made in volume. It offers low input offset voltage and low voltage drift. A large gain-bandwidth product and fast slew rate are maintained with low supply current. High-voltage input JFETs give the LF411 its low input bias and offset current. It is both pin-compatible and interchangeable with the 741. Column 3 of Table 1 lists some of its typical characteristics.

Linear amplifiers

There are many ways to configure op-amps as linear amplifier circuits. Although the 741 series op-amps is specified in the schematics discussed in the remainder of this article, all of the op-amps discussed here will work in these circuits.

Figure 7 shows an op-amp organized as an inverting AC amplifier with an overall voltage gain of 10. Noninverting input pin 3 is grounded through resistor R3. It has the same value as R2 to preserve the op-amp's DC balance. Input impedence Z_{IN} equals the value of resistor R1.

Figure 8 also shows the 741 configured as a noninverting AC amplifier with an overall voltage gain of 10. However, in this circuit modification, resistors R1 and R2 are isolated from ground by nonpolarized capacitor C2.

At normal operating frequencies, C2 has a low AC impedance, so voltage gain is still set by the ratios of R1 and R2. However, inverting input pin 2 receives all of the DC negative feedback through R1, giving the circuit excellent DC stability.

Again, for optimum biasing, resistor R3 should have the same value as R1. The op-amp's input impedance Z_{IN} at noninverting pin 3 is several hundred megohms, but it is shunted by resistor R3, which reduces the circuit's overall input impedance to approximately a 100-kilohms value.

Figure 9 shows how the circuit in Fig. 8 has been modified to give the op-amp a 50-megohm input impedance (Z_{IN}). The location of capacitor C2 has been changed, and the lower end of resistor R3 is connected to the junction of R2 and C2 rather than directly to ground.

The AC feedback signal that appears on the R2-C2 junction is nearly identical to the input signal at pin 3. As a result, nearly identical signal voltages appear on both ends of resistor

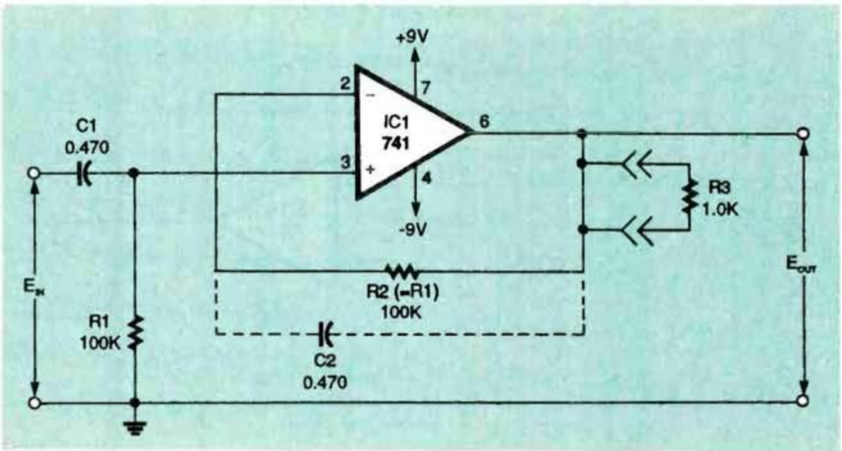

FIG.10—AC VOLTAGE FOLLOWER with 100-kilohm input impedance.

R3. Thus it passes negligible signal current.

Theoretically, the apparent impedance of R3 is raised to thousands of megohms by this "bootstrap"-feedback action, but in practical circuits the input impedance is limited to about 50 megohms by external leakage paths in the op-amp's mounting socket and/or the circuit board.

For optimum biasing of the circuit in Fig. 9, the sum of the values of resistors R2 and R3 should equal R1. However, in practical circuits the value of R3 can differ from this ideal by as much as 30%. Thus, a 100-kilohm resistor will work for R3.

Voltage followers

An op-amp can function as a voltage follower if the inverting and noninverting connections are combined for unity voltage gain. Ideally the differential amplifier's output responds only to the difference in voltage between the two inputs and does not respond to a voltage common to the two inputs (common-mode voltage).

Figure 10 illustrates some of the design options for a voltage follower with all of its negative feedback applied from output to inverting input pin 2 through resistor R2.

Ideally, resistor R1 (which determines the circuit's input impedance) and R2 should have equal values. Again, in practical circuits, the value of R2 can be any value up to 100 kilohms without significantly affecting circuit accuracy.

If the circuit's op-amp has a low-frequency cutoff value like that of the 741, R2 can usually have a value of zero. However, op-amps with high cutoff frequency values tend to be unstable when operated in the unity-gain mode.

Stability can be assured by installing an R2 of 100 kilohms, or by adding 1-kilohm plug-in resistor R3 in series. The 0.470µF capacitor C2 across R2 reduces the op-amp's AC impedance.

A very high input impedance can be obtained from an AC voltage follower by configuring the circuit as shown in Fig. 11. Resistor R1 is "bootstrapped" from the op-amp output through capacitor C2. Thus, the impedance of R1 is increased to the multimegohm range.

A 741 op-amp circuit will typically have an input impedance

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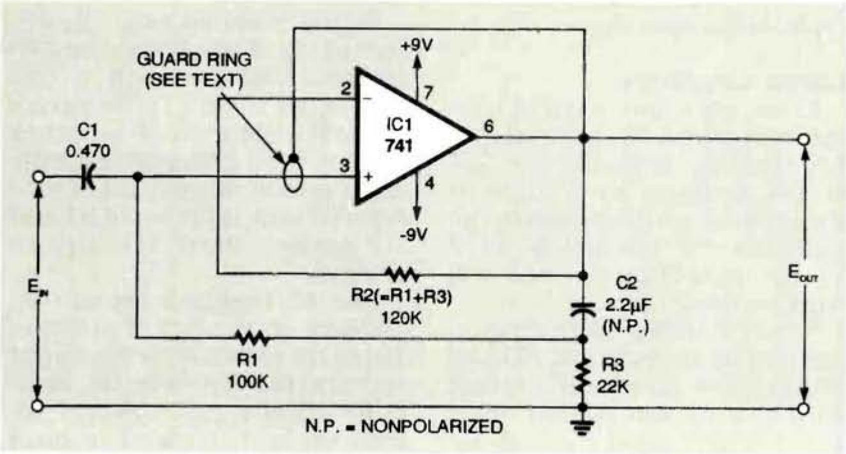

FIG. 11—AC VOLTAGE FOLLOWER with a 50-megohm input impedance.

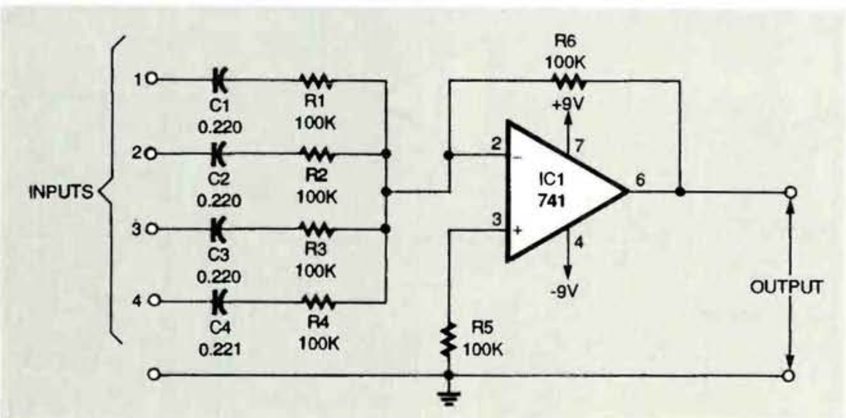

FIG. 12—SUMMING AMPLIFIER as a four-input audio mixer.

GLOSSARY OF TERMS

Input-offset voltage (V_{IO}). The differential input voltage required to produce zero output voltage.

Input offset current (I_{IO}). The difference between the two input currents.

Input bias current (I_B). The current flowing into (or out of) either input terminal while the output voltage is near zero volts.

Input resistance (R_{IN}). The ratio of a small change in the differential input voltage to a resulting change in the input current, with the output remaining in its linear region.

Large-signal voltage gain (A_{VO}). The ratio of the change in output voltage to the change in differential input voltage causing it. Also known as *open-loop voltage gain.*

Output voltage swing (V_O). The maximum output voltage available under specified loading conditions.

Common-mode rejection ratio (CMRR). The ratio of the change in the input common-mode voltage to the resulting change in input offset voltage created by it, usually expressed in decibels.

Supply current (I_S). The quiescent supply current required by the amplifier, measured when the output is zero volts so that no current is delivered to the load.

Slew rate (SR). The ratio of the output-voltage swing, measured from the 10 to 90% point of the leading or trailing edge, to the time required for the output to traverse this level, measured under large-signal conditions.

Unity gain bandwidth (BW). The frequency at which the open- loop gain is zero dB.

Gain-bandwidth product (GBW). The product of the available open-loop gain at a specified frequency times that frequency.

agram (Fig. 1) and begin the wiring by connecting the hot side of the line cord (black wire) to one side of the fuse holder. Next solder a wire from the other side of the fuse holder to one terminal of the main power switch, S1.

Connect the other terminal of S1 to the other side of the fan and to one terminal of S2. Connect power indicator NE1 across the fan terminals so it will indicate when power is applied to the fan and to S2.

Standby switch S2 allows power to the transformer to be shut off while still allowing the fan to work. Wire indicator NE2 across S2 so that it illuminates when S2 is open, or when the unit is in the standby mode. Next, connect S2 to the other side of the transformer. Connect the neutral (white) wire from the line cord to one side of the fan and also connect it to one terminal on the input side of the transformer.

Connect both output leads of the transformer to the AC receptacle SO1. Next connect the output-power indicator NE3 across the receptacle. As a last important step, run a ground connection from the line cord (the green wire) to the base of the transformer and to the fan. If the transformer has not been grounded to the chassis, be sure to do so now with a separate wire.

Testing

Before closing up the case, plug an appliance such as a coffee maker, a lamp, or another appliance that draws about 500 watts into the isolation transformer outlet and turn on the power. Run the transformer with the load turned on for approximately 30 minutes while checking it every five minutes or so for excess heat.

The prototype was tested with an 800-watt coffee maker, and the transformer ran warm—but not hot—to the touch. Do not use the isolation transformer to power anything with that high a power rating for extended periods of time. Most modern TVs, even those with large screens, consume 350 watts or less. Ω

SINEWAVE GENERATOR

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Construction

A circuit board with a ground plane is required for building this project because of the high frequencies involved. You can make your own board or buy one from the source given in the Parts List. Figure 3 is the parts-placement diagram. The NCO and DAC ICs are expensive and can be damaged if they must be removed, so it is recommended that you install them in low-profile, machined-contact sockets.

Do not mount the input/output connectors on the PC board. BNC connectors are recommended for the FSK input and sinewave output. Attach a grounding lug to the BNC connectors, and then solder it to the ground plane of the board to provide mechanical support for the connectors. Wire the power source directly to the board or wire a suitable power jack to the board.

Cut a four-foot length of five-conductor cable for the PC cable. Solder one end of the cable leads to a male DB-25 connector, as shown in Fig. 3, and the other end directly to the PC board. Figure 4 shows the complete board.

After carefully inspecting the board for incorrectly installed components and poorly soldered joints and making any necessary repairs, the generator is functional. Now you can generate any sinewave you need up to 10 megahertz on the fly. Ω

Go ahead. . .it's an old schematic.

OP-AMPS

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of about 50 megohms. As stated earlier, this limit is set by the leakage impedance caused by the mounting socket and/or circuit board. A conductive trace "guard ring" on the circuit board surrounding noninverting input pin 3 and tied to output pin 6 will improve input impedance. However, if significantly higher impedance is required, substitute an FET-input op-amp such as the LF411.

Audio mixer circuit

It was stated earlier that the voltage gain of the basic inverting amplifier circuit equals −R1/R2. Consequently, signal currents flowing in R1 and R2 are always equal but opposite in phase, regardless of their individual values.

The inverting amplifier circuit shown in Fig. 5 can be modified as shown in Fig. 12 to become a *summing amplifier*. It has four identical resistor-capacitor input networks in parallel, all connected to inverting input pin 2.

The signal current flowing in feedback resistor R6 will equal the sum of the input signal currents flowing in resistors R1 through R4. The circuit's output signal voltage then becomes proportional to the sum of the signal voltages.

If the input and feedback resistors have equal values (100 kilohms in this circuit), the summing amplifier will provide unity voltage gain between each input pin and the output pin. The circuit's output is equal to the sum of the four input signal voltages.

This simple circuit can become a practical audio mixer by feeding each input signal to its input network channel with a 10-kilohm, volume-control potentiometer. If desired, the circuit can provide voltage gain greater than unity by increasing the value of feedback resistor R6. The number of input channels can also be increased by adding additional RC networks for each new channel desired. Ω