IC UPDATE

Understanding the OP AMP

This article presents the basic rules and explains how to properly design around the operational amplifier.

by DON LANCASTER

BY NOW. EVERYONE SHOULD BE MORE OR less familiar with the "741," a low cost, internally compensated operational amplifier that has an incredible variety of DC and audio uses. But, very often, the 741 won't seem to work at all in the circuit, or perhaps not as well as you expected. This often happens when some *use* rule of the 741 is broken, or you make some basic assumption about the device that either isn't true or, at best, isn't very true.

For instance, what is the *upper* —3 dB cutoff frequency of a 741? Would you believe 3 *hertz?* Is the 741 as good as a plain old transistor as an amplifier at, say, 80 kHz? No, it isn't—but some op-amps are. Why do we have two inputs on an op-amp with apparently identical input circuitry, one marked + and one marked —, and yet the — one acts like a dead short and the + one acts like a very high input impedance? Because the feedback you are supposed to use creates a virtual ground. And why, sometimes, does the output of the op-amp sit at the positive or negative supply, and apparently refuse to budge no matter what you do? Probably because you forgot to use feedback or forgot to properly DC bias the inputs.

Yet, if you follow the simple rules, the 741 and its improved offspring are extremely well behaved, low cost, easy-to-use devices, good for a wide variety of DC and AC amplification problems, integrators, ramp generators, electronic music circuits, active filters, and very much more. So, let's take a rather basic look at the operational amplifier, and build up a set of rules of the game, particularly seeing what the 741 can and can't do. From there, we'll look at some devices and manufacturers, and then we'll end up with some applications.

What is an operational amplifier?

The name *operational amplifier* came from the theory of feedback amplifiers. If you build a DC coupled amplifier with very much more gain than you could possibly want, and then use very heavy negative feedback around the amplifier, the performance of your circuit will depend almost entirely on what is doing the feeding back and what is doing the feeding in. Use resistors, and you have a simple and stable gain DC amplifier. The gain is determined by the resistor ratio only and is independent of the amplifier gain and power supply variations, *provided* that the op-amp has very much more gain than you need compared to the resistor ratio. For instance, with a 100K feedback resistor and a 10K input resistor, you can build a gain-of-ten amplifier, and if the frequency of operation gives you an op-amp gain of at least 1000, the most gain error you can get from the amplifier or power supply is only around 1%, and progressively less with higher gains.

If you use a capacitor for feedback, the capacitor has to charge and discharge in response to input currents. This gives you an *integrator*, or a ramp generator. You can use it for waveform generation, triangles, sawtooth, etc., or to mathematically find the area-under-a-curve of a time waveform. It's also a low-pass filter. Add more rseistors and capacitors to your feedback and input networks, and you can build other high performance *active* filters —highpass. bandpass, band reject, equalizers, etc.

So, if we have enough excess gain in our op-amp, we end up performing an *operation* based on the *ratio* of feedback to input impedance. If the op-amp has enough extra gain at the frequency of operation, the *operation* you are trying to do depends *only* on stable resistors and capacitors. So, we start our rules:

1. An operational amplifier is almost always used with heavy feedback. If the feedback is negative, the ratio of the feedback impedance to the input impedance decides what the circuit is to do.

and . . .

2. If an operational amplifier is going to work properly, it has to have much more open loop gain at the frequencies of interest than the circuit calls for.

We'll take a closer look at the 741 and its improved offspring in just a bit, but for now, the DC gain of a 741 is around 200,000. Now this is a bunch of gain. But the frequency response starts falling off immediately. For instance, you are already three decibels down from your DC value (the - 3 dB "cutoff frequency") at 3 hertz. Still, a gain of 140,000 or so is rather respectable, so we can use the beast at higher frequencies. Gain drops by 6 dB per octave (20 dB per decade) of frequency, so by 10 kHz you only have a gain of 100 left over, and by 100 kHz, only a gain of ten. So the 741 will be hard pressed to provide the excess gain we need for proper operation in the upper audio range. We'll find out about a much better (and somewhat more expensive) beast called the LM318 later on, that easily handles any audio problem. The point is that *any* operational amplifier falls off with frequency and you have a limit beyond which you can't get enough excess gain to keep the circuit working properly. The *minimum* excess gain you should ever work with is ten times the circuit needs at the maximum frequency of interest:

3. For non-precision applications, at least ten times the circuit gain must be available from the op-amp at the highest frequency of interest. Circuit gain limits for the 741 in a non-precision circuit is ten at 10 kHz and one at 100 kHz.

By "non-precision," we mean that a five or ten percent performance error won't hurt anything. For one percent precision, use one hundred times the gain, and so on. As long as you are *lower* in frequency than these limits, you get lots of *extra* gain and proportionately more precision.

An inside look

Figure 1 shows us how we can look at the operational amplifier as three distinct gain blocks, a *differential input* stage, a high gain *intermediate* stage, and a relatively high power, low impedance *output* stage. The differential input stage accepts input signals at very high impedances and with light loading. It also provides a way to take the difference between two input signals. This is the most critical stage of the op-amp. The intermediate stage only has to provide lots of gain. The output stage has to provide drive power for the outside world, very important if circuit loading isn't going to change what gets fed back.

There are two inputs to the differential input stage. One is called the *inverting* input and is normally shown as a (–). One is called the *non-inverting* input and is nor-

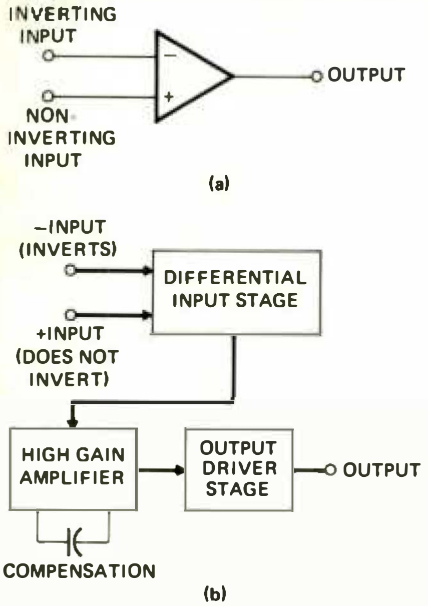


FIG. 1—SCHEMATIC SYMBOL of the operational amplifier is shown in a. The three stages of the OP-AMP is shown in b.

mally shown as a (+). Note that this + and – has nothing to do with the supply lines. The positive supply is usually called V+; V– is the normal pin callout for the negative supply. There is no ground connection for the op-amp, and the circuit works best with split supplies of equal value, ranging from +5, –5 to +20, –20, with +15, –15 being the most common. Input signals must be limited to something halfway between the two supply levels, a specification called the *common mode range*. Thus a grounded signal reference is in the middle of the common mode range for a split supply amplifier. Another rule:

4. Operational amplifiers often work with a split power supply. With a split supply, input signals should be restricted to a range that is significantly less than the positive supply and significantly more than the negative supply. The common mode range for a 741 with ±15-volt supplies is ±12 volts maximum. Thus, you cannot normally ground the negative supply and apply a grounded input.

Back to those inputs. If we apply a very small positive voltage step to the + input, it drives the output *positive*, since it is *not* (or non) *inverting* the step. If we apply the same small positive step to the – input, the output gets driven in the *negative* direction since this is the *inverting* input.

Remember that there is no ground connection on the op-amp. Ground for the circuit is simply "a stake driven in the ground" that tells us where halfway between the two supply limits happens to be, and the point where we get the most common mode swing in either direction. Our circuit always amplifies the *difference* between the two inputs and ignores any *common* signal that both inputs identically share, provided, of course, that that common signal is within the proper common-mode operating range of the amplifier.

If we use both inputs, we are operating in a *differential mode*. If we ground one input, or tie it to some other reference within the allowable limits, we are working in the *single-ended* mode. Thus, the inputs are referenced only *to each other*, unless you "stake one down" to some reference voltage such as ground.

Feedback

We apparently have a choice of where we put our feedback. Usually, we apply feedback to only the (–) or inverting input. Rarely, we can apply positive feedback to the (+) or non-inverting input, but you essentially never do both at once in simple circuits.

If the feedback network goes from the output to the + input, a small positive input gets amplified, turns around and drives the input *further* positive, and builds up avalanche style. This would be *positive feedback* and is inherently unstable. You normally can use positive feedback only where a *snap-action* or speedup is desired. With positive feedback, the output usually sits as close as it can get to either the positive or the negative supply. The output is then essentially two-valued or digital.

Normally, we are more interested in having the amplifier behave linearly instead of flipping from stop to stop, digital-logic style. To do this, we use *negative feedback* from the output to the (–) input. Negative feedback always tries to *correct* any changes forced on the amplifier by the input signals. *Negative feedback always tries to force the difference between the two inputs to zero.*

If we make the + input ground for single-ended operation, the negative feedback will always force the input to *ground* continuously. For if it *wasn't* at ground, the high gain of the amplifier would immediately amplify the error signal and feed it back for correction.

If the (–) input is never allowed to go away from ground by anything but a tiny amount, we can think of it as being the *same* as ground as far as the feedback networks are concerned. The name for this is a *virtual ground*. and in a properly connected and fedback operational amplifier, the (–) input behaves as a *dead short to ground*, as far as the rest of the circuit can tell. Since there is no feedback taking place at the (+) input, it remains as a very high impedance. So, with negative feedback, the (–) input looks like a short and the (+) input looks like an open, despite apparently identical internal circuitry. Some more rules:

5. If the feedback on an operational amplifier goes from the output to the + input, you will get a snap-action and a digital-logic style output. This is useful only for comparators and other snap-action circuits.

6. If the feedback on an operational amplifier goes from the output to the – input, you will get a linear operation useful for amplifiers, integrators and filters. The output will exactly follow the ratio of the input to output impedances, provided there is enough excess gain at the operating frequency.

7. When negative feedback is used, the input impedance on the + input is normally very high. The input impedance on the – input is normally extremely low and is called a virtual ground.

Now, this virtual ground thing is extremely useful. It means you can *sum* input signals without crosstalk or interaction. It means that the input and feedback networks don't interact with signal levels or each other. And it vastly simplifies the math behind whatever you are trying to do.

Offsets

Figure 2 shows a typical differential amplifier stage from the input circuit of

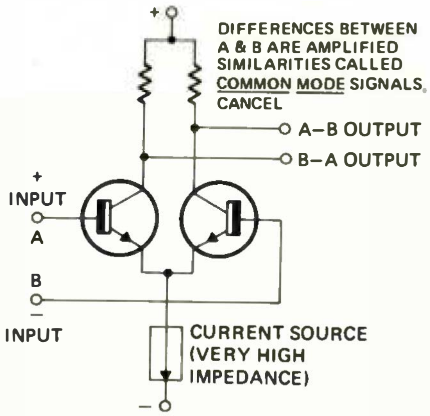


FIG. 2—THE DIFFERENTIAL INPUT STAGE provides an output signal proportional to the difference between the two input signals.

an operational amplifier. The + input goes through the first transistor as an emitter follower and through the second transistor as a grounded base stage to arrive at the A–B output. Neither stage inverts and the amplified signal stays the same polarity as it went in. On the other hand, the – input goes to the A–B output as a common emitter stage, which inverts the sense of the signal, so that at the output, *identical polarity signals on both inputs are cancelled, while differential polarity signals on both inputs are amplified.* We've already seen that these identical polarity signals are *common-mode* signals. If the op-amp is good enough, common-mode signals are essentially totally eliminated. Since power supply hum and voltage variations are one form of common-mode signal, this is extremely handy.

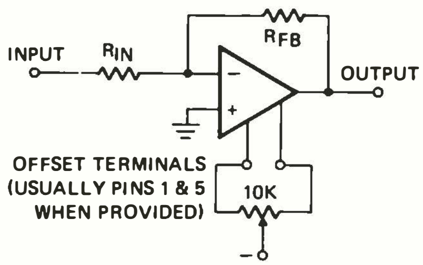
If you look at the mirror image of the inputs, you'll find that the — input ends up uninverted and amplified on the left output and the + input gets inverted by a common emitter stage. The pair of outputs will be an amplified version of only the *difference* between the two inputs, and common-mode signals will be ignored as they exactly cancel.

Now the inputs go to the bases of two NPN transistors. Where does this base current come from to run them? Well, ah, er . . ., You better have a good answer to this or your circuit won't work. The base current can come from your input circuit through a low-impedance DC path, from a resistor to ground, from a special current source, or from the output via a feedback resistor, but it MUST be provided. The most important rule and the cause of most op-amp problems:

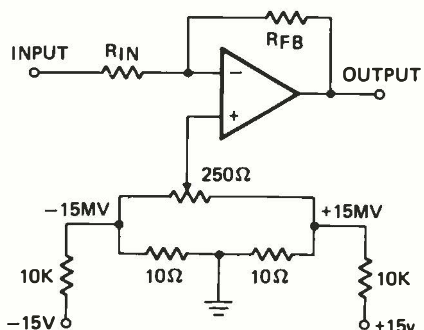
8. DC base bias current MUST be provided for both the + and — input to an operational amplifier. This is usually done as resistors or coils to ground, back through the input, from the output, or from another reference voltage. In a 741 style amplifier, around 100 nA of current must be provided for both + and — inputs.

The input transistors are very nearly identical, being integrated and all on the same chip at essentially the same temperature. They also track very well with temperature. However; even with the best of matching, there will be a slight voltage difference (a millivolt or two) between the inputs. This is called the *input offset voltage*. The rest of the amplifier has no way of telling the difference between this offset and a legitimate input signal.

Figure 3 shows some tricks we can pull



(a)



(b)

FIG. 3—INPUT OFFSET VOLTAGE results from a mismatch in the differential input stage. Two methods for reducing the voltage is shown.

to reduce the input offset. A pot can be added if pins are available for this (usually omitted on dual and quad devices), or input currents can be balanced by unbalancing impedances, or special bias sources can be added. Correction of offset will only be perfect at one temperature, but a 10:1 reduction in input offset is usually easy to do over a reasonable temperature range.

The importance of the offset depends on what you are trying to do with the operational amplifier. If you set your amplifier to a gain of 100 with feedback resistors, a 2-mV input offset becomes a 0.2-volt output offset. AC couple your output and there is no problem at all. But for DC outputs and high gain, the amplifier input offset must be allowed for. Another rule:

9. An operational amplifier such as the 741 has an input offset of one or more millivolts. This offset voltage is amplified and treated as a legitimate input signal. Input offset can be externally bucked out at one temperature if it is a problem. The remaining offset defines the minimum acceptable value for the DC input signals.

and . . .

10. The output offset in DC volts will equal the input offset times the in-circuit gain of the operational amplifier.

So we have to provide a source of base current for both the + and — inputs, and we get a DC offset voltage "free" that we have to minimize somehow.

Besides the voltage offset, we have another problem to worry about — *current offset*. Whatever resistance is doing the biasing for our inputs will produce a voltage drop across it caused by the biasing current. This biasing current is typically 100 nA, but a *difference* of as much as 20 nA typically might be exhibited by both inputs under identical conditions.

A current of 100 nA is the same as 0.1 μA. A 0.1-μA current through a 10K resistor gives you a 1-mV drop, not really very much. But a 100K resistor gives you a 10-mV drop which can get important, and a 1-megohm one gives you a full tenth of a volt, which is hard to ignore, particularly in high-gain applications. For instance. Ground the + input and use a 1-megohm input resistor and a 20-megohm feedback resistor to try to get high input impedance in an inverting gain-of-20 amplifier. The output offset will be a very hard-to-ignore 2 volts!

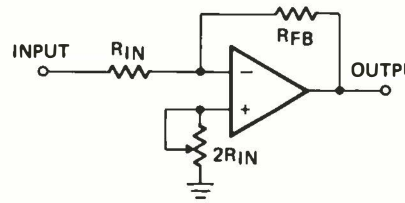
How do we get rid of it? Simply provide a 1-megohm resistor in the + lead as well. Now, the input bias currents provide the same drop on both sides and everything cancels out. Everything that is, but the differential offset current, and you can get a one temperature cancellation of this by making the two source impedances slightly different. Figure 4 shows how we can go about cancelling offset currents. Another rule:

11. The impedances doing the DC biasing of the op-amp inputs should be approximately the same value particularly at high gains or at high impedance levels. Input offset current can be adjusted by trimming one impedance level with respect to the other. Impedance levels above 100K on a 741 will introduce major offset problems.

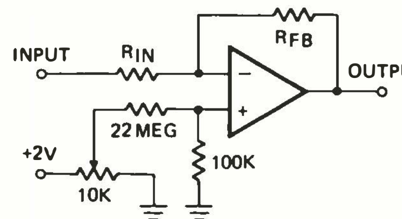
TABLE OF OP-AMP MANUFACTURERS

ADVANCED MICRO DEVICES **901 Thompson Place** **Sunnyvale, California 94086**	**RCA SOLID STATE** **Box 3200** **Somerville, New Jersey 08876**
FAIRCHILD SEMICONDUCTOR **313 Fairchild Drive** **Mountain View, California 94040**	**RAYTHEON SEMICONDUCTOR** **350 Ellis Street** **Mountain View, California 94040**
MOTOROLA SEMICONDUCTOR **Box 20912** **Phoenix, Arizona 85036**	**SIGNETICS** **811 E. Arques Avenue** **Sunnyvale, California 94086**
NATIONAL SEMICONDUCTOR **2900 Semiconductor Drive** **Santa Clara, California 95015**	**SILICON GENERAL** **7382 Bolsa Avenue** **Westminster, California 92683**

See Radio-Electronics back-of-the-book ads for surplus availability and prices.



(a)



(b)

FIG. 4—INPUT OFFSET CURRENT results from a mismatch in the input stage. Two methods for reducing the current is shown.

At very low impedance levels, say 1K or so, you usually can ignore the input currents and input offset currents. As the impedance level goes up, the offset currents become more important. So, at low impedance levels, only worry about the offset voltages. At higher levels, consider both the offset voltages and currents.

Compensation

At some very high frequency of operation, the internal capacitance, delays, and storage times of any amplifier will begin adding delay or phase shift to the signal being amplified. If we ever reach a frequency that shifts the phase by 180° and still have gain, a negative feedback connection will give us *two* 180° inversions, or it will put us back *in* phase with the input. If the loop gain is high enough, we end up with an oscillator rather than an amplifier, because the added phase shift converts what is supposed to be negative feedback into positive feedback, reinforcing its own input.

This is true of any feedback amplifier. Depending on the design, the circuit can be stable, conditionally stable, or inherently unstable. One of the surprising things that turns up is that the *lower* the in-circuit gain of the amplifier, the *more* likely it is to oscillate! This is caused by a greater percentage of the input being fed back in lower gain situations. Unity gain of a feedback amplifier is much more likely to oscillate than say a gain of 100 or some other high value.

The process of stabilizing an amplifier is called *compensation*. The basic rule of compensation says that for any gain (open loop) above one, your amplitude versus frequency slope must always be less than −12 dB-per-octave. Hit −12 dB-per-octave, and if you do it at a frequency where the open loop gain equals one or more, you've got yourself an oscillator, not an amplifier. One obvious way to compensate is to hang a very large capacitor in the middle of the circuit. So large that it completely dominates the amplitude versus frequency response, giving you a simple and safe 6-dB-per-octave slope. This is called a *dominant pole*, and while it certainly stabilizes the amplifier, it also drastically reduces the frequency response.

The dominant pole capacitor is used in the 741. This gives you an unconditionally stable amplifier (unless you go out of your way to try to make an oscillator out of it on purpose), and results in simple and easy circuits. The price paid is the frequency response. The dominant pole breaks at 3 hertz, dropping at 6 decibels per octave eventually to reach unity gain at 1 megahertz.

Another rule:

12. Frequency compensation must be provided for any operational amplifier using negative feedback. The 741 is internally compensated at the price of a relatively poor frequency response. The LM318 offers either internal or external compensation.

Slew rate

When we are done with our compensation, we end up with another problem, called the *slew rate* problem. At small signal levels and small output swings, our normal frequency versus amplitude response curves apply. But, if we try to swing the output through larger amplitudes, the output goes into a *current-limited ramp mode* and, as Fig. 5 shows us, considerable distortion.

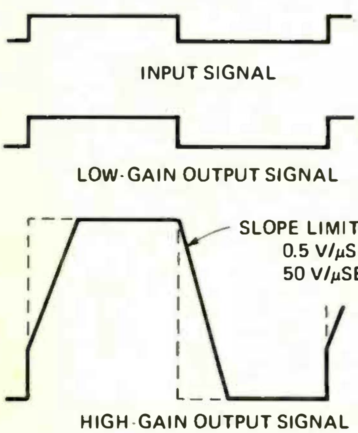


FIG. 5—THE SLEW RATE of an operational amplifier limits large output, high-frequency signals.

What this means is that you can't have high-frequency operation and large output swings at the same time. The fastest you normally can change the output of a 741 is 0.5 volt/μs. You can estimate how bad the slew-rate problem is by substituting a triangle wave of *one and one half* times the normal amplitude of your highest frequency sinewave and see what happens.

For instance, suppose you have a 4-volt peak-to-peak, 10-kHz sinewave. Approximate it with a 6-volt peak-to-peak triangle wave. The period of the waveform will be 100 μs. The half period will be 50 μs. We have to change 6 volts in 50 μs, or around an eighth of a volt per microsecond. Since the 741 can only handle 0.5 volt μs maximum, you're pretty near the reasonable limit of operation.

Note that slew rate is determined both by frequency and amplitude. Eight volts peak-to-peak at 5 kHz will have about the same needed slew rate as 2 volts peak-to-peak at 20 kHz, and so on.

If you need larger signal swings in the upper audio region, the 741 simply won't do the job. Consider the more expensive LM318 that has a 50-volt μs slew rate, or one hundred times as much for these applications. For our next rule:

13. The slew rate limits the large signal output swing to a maximum slope ramp at higher frequency. The slew rate is 0.5 V/μs for the 741 and 50 V/μs for the LM 318.

Besides these slew rate limits, there are obviously drive limits at the output stage that apply to any operataing frequency. If possible, you should keep your external output and feedback loads above 1000 ohms, although you can reduce this to several hundred ohms with lower output swings. The maximum output current you can possibly get in a limiting (clipping) mode is around 25 mA. This is beyond the normal range of linear operation.

Noise

A final limit to an operational amplifier is the input noise level which gets amplified along with the signal. All amplifiers produce some noise, and the worst of it is usually involved with the first stage. The 741 is not particularly a low-noise device, but it is useful for many small-signal amplification problems. Typical noise for a 741 referred to the input is 10 μV. Thus if you have a gain of ten, you get 100 μV of noise out. At a gain of 100, you get 1 mV out, assuming you are using the full bandwidth of the device.

If you reduce your bandwidth, the noise goes down, but only very slowly, for noise is proportional to the square root of the bandwidth. So, to get only 1 μV of noise, you have to cut your bandwidth by 100, from a nominal 100 kHz to only 1000 Hz. Regardless of your application, the final noise sets your overall signal-to-noise ratio. For instance, with a gain-of-ten circuit, you can amplify a 10-μV signal with unity signal-to-noise ratio (essentially worthless), a 100-μV one with 20 dB signal-to-noise (possibly useful) or a 1-mV one with a 40-dB signal-to-noise ratio (pretty good.)

The LM318 generally has better noise performance than the 741, although at high impedances and wide bandwidths (remember it has 100 times the bandwidth), the noise can get up to 200 μV at the input. With a 1000-ohm source on the inputs, the equivalent noise to the 741 is around 3 μV, 12 dB better than the 741, provided that you limit the bandwidth suitably. A final rule:

14. The first stage noise level of any operational amplifier sets the minimum possible signal level for a given signal-to-noise ratio. Referred to the input at a 100-kHz bandwidth, this noise is 10 μV for the 741 and 3 μV for the LM318. Noise is normally proportional to the square root of bandwidth.

(to be continued)

Virginia electronic technicians take strong stand on warranties

The Board of Directors of the Virginia Electronics Association adopted the following resolution unanimously at its meeting in Chester, VA.

"WHEREAS: The Virginia Electronics Association recognizes that warranties extended beyond a period of 90 days

1. have no bearing on the quality, serviceability or anticipated life of a product;
2. are frequently used to mask inferior product quality and/or performance;
3. are a deceptive sales tool used by some manufacturers and retailers to create a captive repair market with the customer's own money, and
4. actually hamper consumer satisfaction by frequently foisting inadequate compensation upon the servicer or less than quality service on the buyer, and

WHEREAS: the Virginia Electronics Association feels that the manufacturer, the servicer and the customer are best served by devoting more time and money to improving product performance and safety and less of the consumer's purchasing dollar on extended warranty/insurance schemes, and

WHEREAS: one major manufacturer, in the face of rising consumerist pressures, has decided to reduce its labor warranties to a more realistic 90-day period, therefore:

BE IT RESOLVED: that the Virginia Electronics Association hereby commends GTE-Sylvania for its wise and courageous decision in taking the lead to restore sanity to the field of consumer-electronics product warranties, and

BE IT FURTHER RESOLVED: that the Virginia Electronics Association implores all such manufacturers to review their present costly, deceptive frustrating and self-defeating extended warranty programs and take similar steps to redesign and reduce those warranties to better serve the consumer and the electronics service industry."

Copies of the resolution were mailed to nearly 500 manufacturers and importers, 50 association, trade and technical publications, three national electronics associations, and to all persons who might be concerned.

IC UPDATE

Understanding the OP AMP

The operational amplifier is an important building block to the design engineer and experimenter. This article presents some practical circuit applications.

by DON LANCASTER

THE FIRST ARTICAL IN THIS SERIES AMAY 1975 issue) described the operational amplifier and presented 14 basic rules needed to design around them.

This concluding article describes a few practical devices and presents and presents some circuit applications.

Some devices

So, we now have most of the use rules for negative-feedback op-amps, particularly the 741. Let's take a close look at some actual devices, and then we'll go on to some actual circuits you might like to try or use for design.

The four easiest to use op-amps are the 741 itself, available from just about anybody (see the table). The 5558, a dual 741 in an 8-pin can and a plastic mini DIP is from *Signetics* and in a can and 8- and 14-pin DIP's from *Motorola* as a MC1458; a quad 741 in a 14-pin package called the 4136 is made by *Raytheon*; finally a greatly improved 741 called the LM318 is available from *Advanced Micro Devices* and *National*. Condensed data for these four devices appear in Figs. 1 through 4. Only the 741 and the LM318 have pins brought out for balancing offsets—you have to use external offsets for the rest of the circuits. Costs vary widely, but around 80¢ per 741-style amplifier new and half that for surplus are typical, with the LM318 priced under $5. The LM318 is thus very much a premium device, but anytime you need the slew rate or the higher frequency response, it is a very good choice. There are other moderately improved 741-style devices, including the *Motorola* MC1741S, and several devices by *Silicon General*. These are intermediate in price and performance and generally offer around 5 V/µs slew-rate and better noise performance. And, of course, there are many premium devices offering considerably better performance.

Finally, there are some other quad amplifiers often called *Norton amplifiers* or *automotive op-amps*. These are not true operational amplifiers and cannot be used in the circuits that follow. Further, there are very serious use restrictions for these devices. For the vast majority of your applications, you'll find the devices of Figs. 6 through 9 the best overall choice to use.

Some applications

Let's turn to some applications. We'll assume you have a good split power sup-

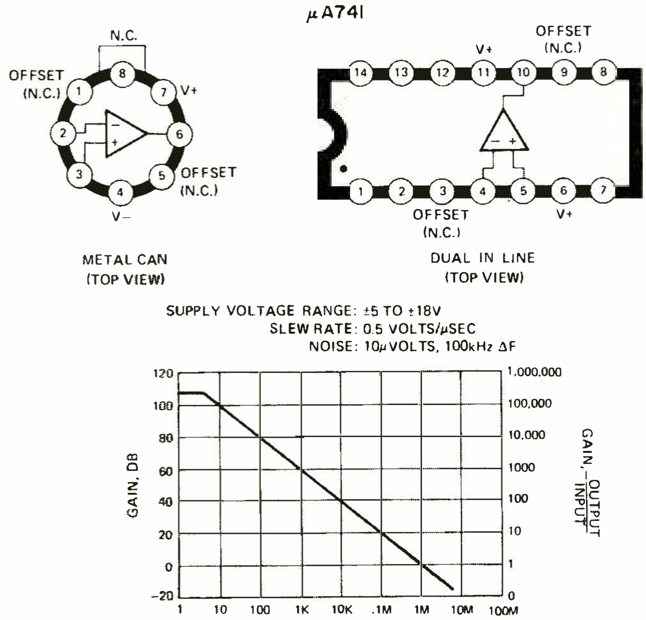


FIG. 1 (above)—THE VOLTAGE VERSUS FREQUENCY characteristics of the µA41 op-amp.

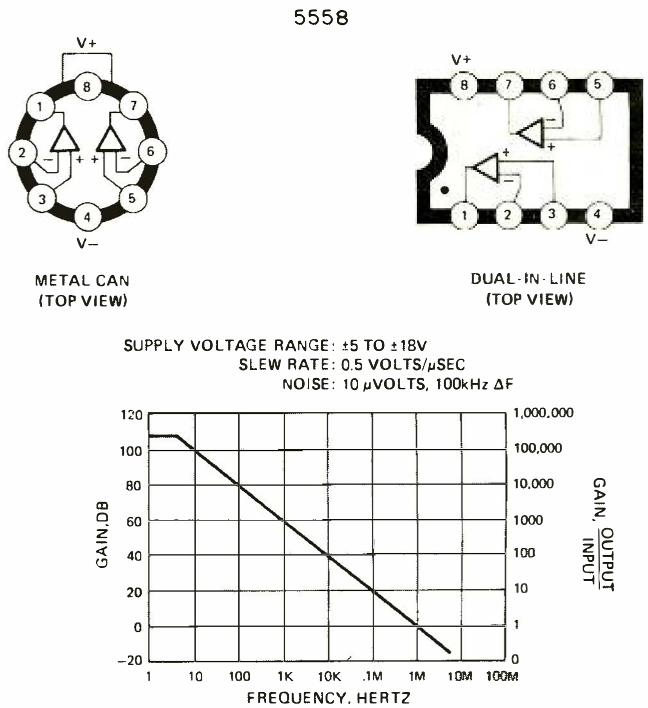
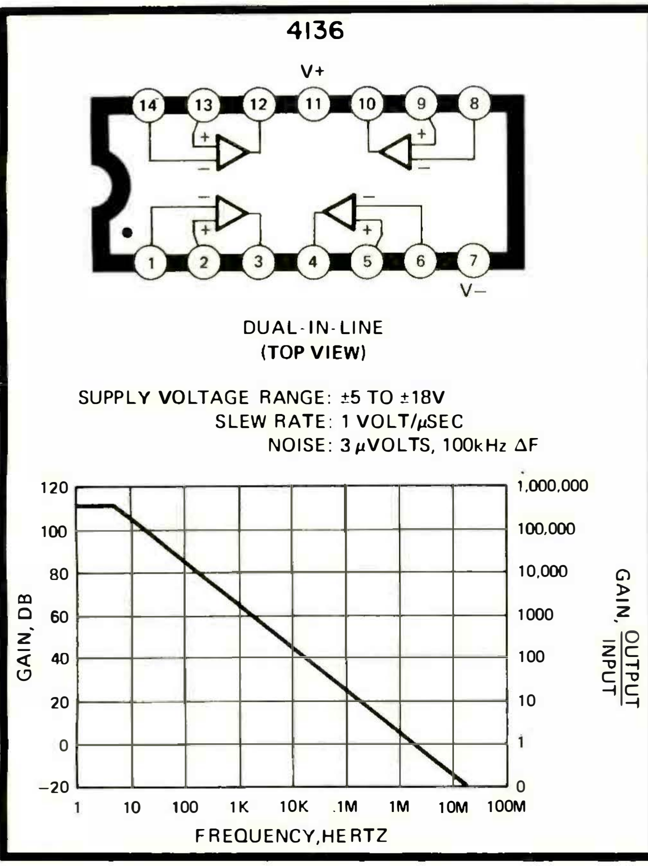
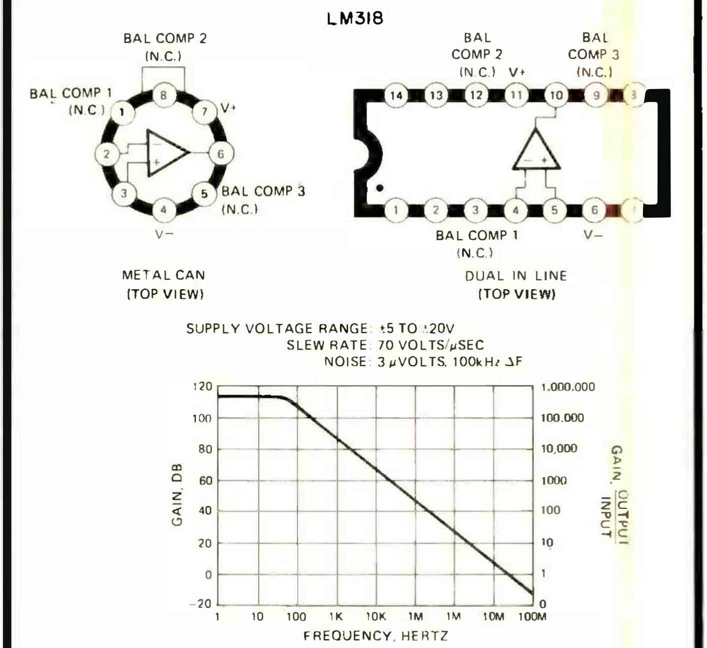


FIG. 2 (right)—THE VOLTAGE VERSUS FREQUENCY characteristics of the 5558 op-amp.





FIGS. 3 AND 4—THE VOLTAGE VERSUS FREQUENCY characteristics of the 4136 (left) and the LM318 (above) operational amplifiers. The 4136 integrated circuit contains four operational amplifiers. The LM318 is a premium device that has additional bandwidth. The basing diagrams for both integrated circuits are shown for the dual-in-line and metal-can packages.

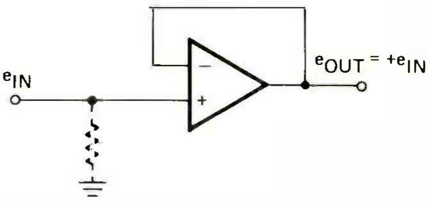


FIG. 5—THE UNITY-GAIN CONFIGURATION of an operational amplifier. The circuit has a voltage gain of exactly one.

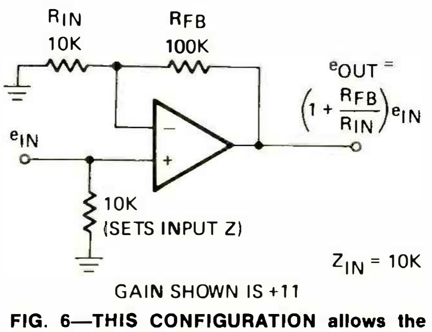


FIG. 6—THIS CONFIGURATION allows the gain to be adjusted by the ratio of feedback to input resistance.

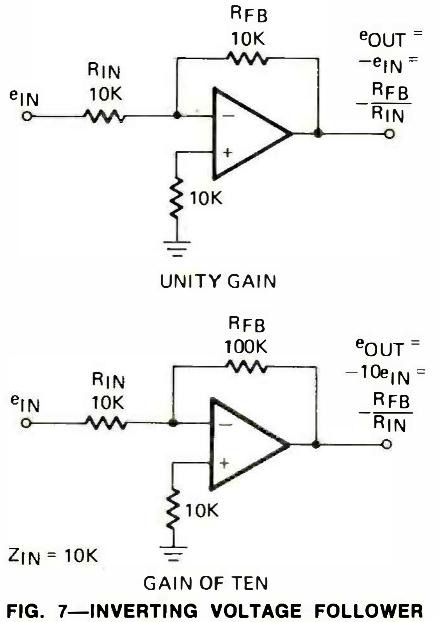


FIG. 7—INVERTING VOLTAGE FOLLOWER circuit. The gain is determined by the ratio of feedback and input resistance.

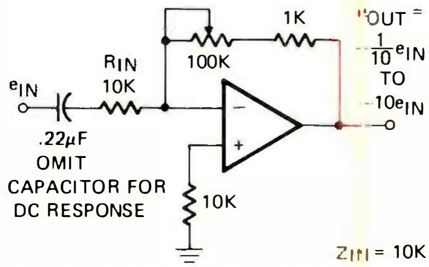


FIG. 8—INVERTING VOLTAGE FOLLOWER circuit. This configuration allows adjustment of the gain via a potentiometer.

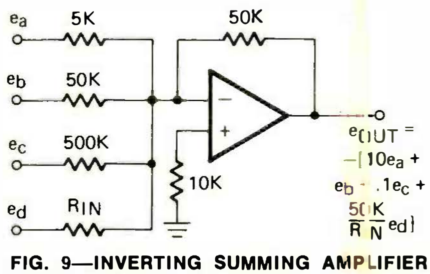


FIG. 9—INVERTING SUMMING AMPLIFIER circuit. The gain of each input is independently determined by the resistance ratio.

ply, ranging from ±5 to ±20 volts, with ±15 being the best, or its battery equivalent.

Suppose we use 100% voltage feedback from the output to the negative input. The output voltage always must equal the input voltage and the gain of the amplifier will always force the difference between output and the + input to zero. The output will follow the + input with unity gain, giving us a *voltage follower*. The input impedance is very high since we are going into the + input and the frequency response (although not necessarily the slew rate) is very good since we don't need much loop gain. The output impedance is very low and you can think of the circuit as a super emitter follower.

The circuit is shown in Fig. 5. Its advantages over a single transistor include a gain of *exactly* one, no temperature dependent 0.6-volt offset between input and output, a higher input impedance, and a lower output impedance. Note that you must provide base current bias through your source for the + input.

Figure 6 gives us a voltage follower with gain. Here instead of 100% feedback, we feed back only a fraction, voltage-divider style, and we end up with a non-inverting voltage amplifier with gain. The gain is anything you want from one upward to anything less than ten times the open-loop gain. Reasonable limits for a gain of ten are 10 kHz and 100 kHz for unity gain. With the LM318, you can run respectively at 200 kHz and 2 megahertz for the same gains.

Note that the gain is NOT the ratio of the two resistors but is *one plus the ratio*. Thus, the *minimum* gain is unity. Note also that you must provide base bias current for the + input through the source of your signal.

The standard inverting gain-of-one am-

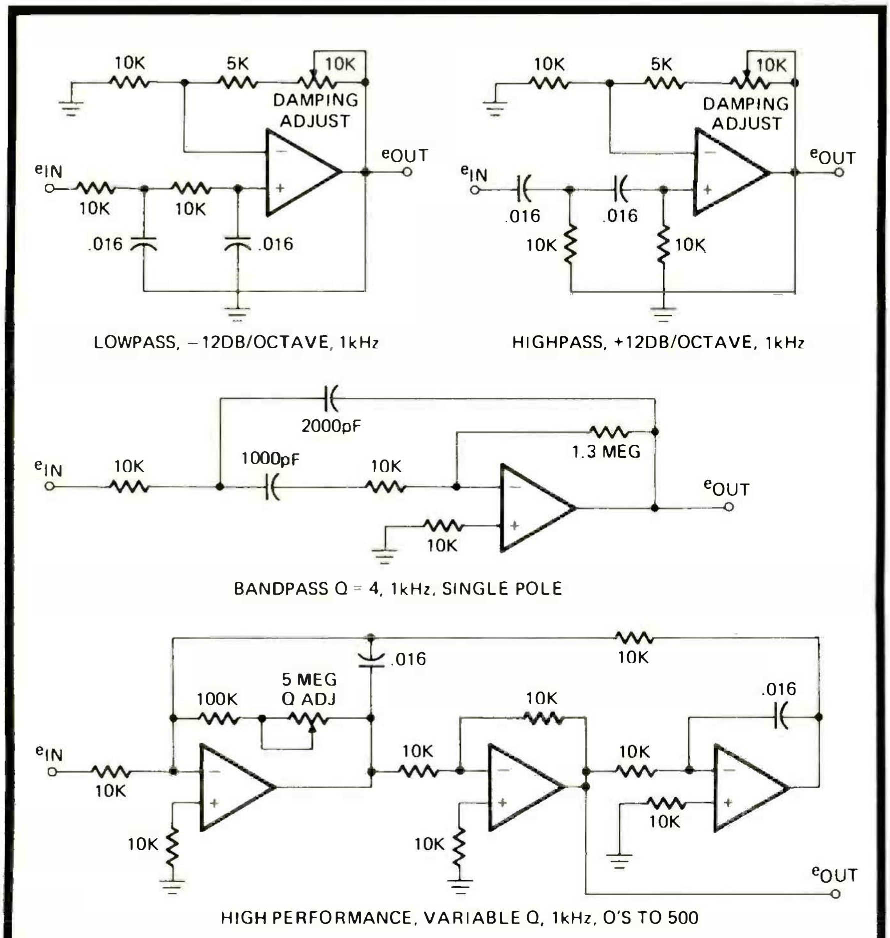


FIG. 10—ACTIVE FILTER circuits. Highpass, lowpass, and two bandpass filter circuits are shown. The values of the capacitors are changed to change the frequencies.

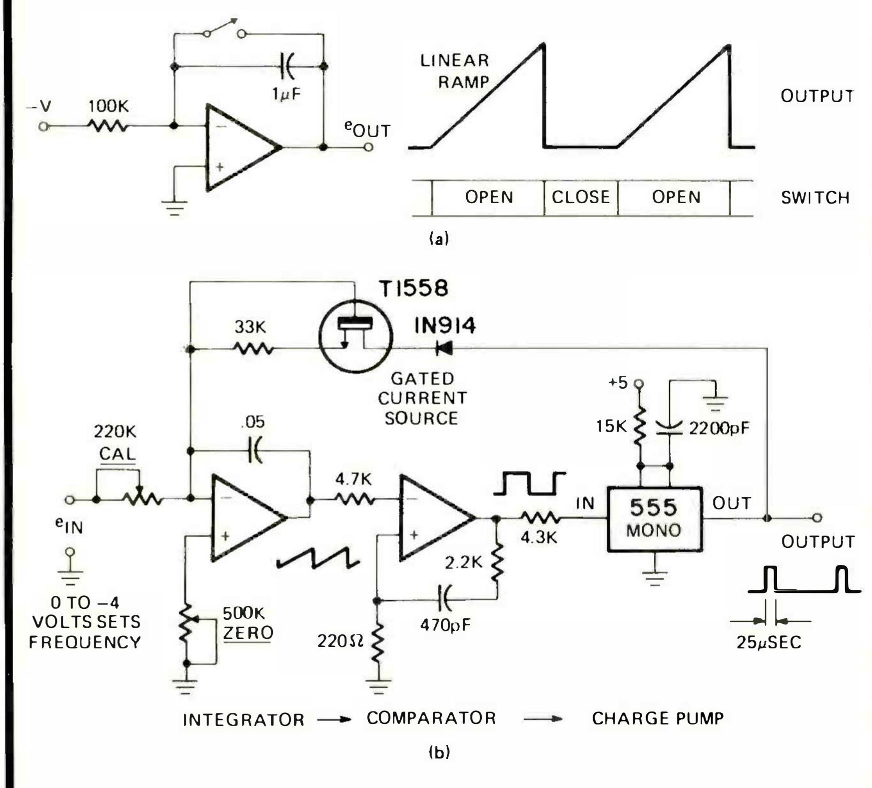


FIG. 11—ACTIVE INTEGRATOR is shown in a. The slope of the linear ramp output is determined by theR-C time constant. The switch reaurns the output to zero. A voltage-controlled oscillator using an integrator is shown in b.

plifier is shown in Fig. 7. Here the gain is set by the ratio of the output resistor to the input resistor. With a 10K resistor on the input and a 100K resistor on the output, the gain will be 10, and so on. DC bias need not be provided by the source, and you can capacitor-couple the input for AC only applications. With identical resistors, the gain will be –1. Since we are going into the – input and since the – input is a virtual ground, the input impedance equals the input resistor, or 10K if a 10K resistor is being used. We can vary the gain as shown in Fig. 8. In Fig. 9, we have a mixer or summer circuit. As many inputs as needed can be used, and the gain of each will be independently set by the ratio of its input resistor and the feedback resistor. Since there is a virtual ground on the – input, there is no interaction between inputs and you get a linear summation of the inputs. Input impedance and gain is set for each input by its resistor. Note that the circuit inverts, so the low-frequency output will be 180° out-of-phase with the input.

Figure 10 shows us some active filter circuits, including second-order low-pass and high-pass filters, and two different types of bandpass poles. The frequencies shown are 1 kHz. Change capacitors to change frequency. The damping control sets the peakedness or droop of the response at the cutoff frequency. The three-amplifier band-pass filter needs only a gain of 3Q or so per amplifier at the center frequency and independently adjusts Q, gain, and frequency. Q's of several hundred to a thousand are possible.

A ramp generator is built using the circuit of Fig. 16. It is also called an integrator and the slope rate of charge buildup is given by the formula:

$$i_{in} = C \frac{\Delta v}{\Delta t}$$

i = current in milliamperes
C = capacitance in µF
Δv = voltage change in volts
Δt = time interval in milliseconds

Note that you MUST enter via the – input for an integrator of this type and you must provide base current bias through the source.

A voltage-controlled oscillator or VCO can be built using the combined integrator-comparator circuit of Fig. 11. The negative input continuously charges the capacitor in the positive direction. When it reaches zero, the snap-action comparator (note *positive* feedback) trips a monostable and current source (both these have to be precision) and charges the capacitor rapidly negative. The capacitor jumps back negative and the time to charge is set by the input current. Output frequency is precisely related to the input voltage. It is called a charge subtractor VCO and can be made very stable. Maximum frequency using 741's is around 10 kHz, with best performance below 5 kHz.

We'll end our applications survey with a quick look at some non-linear techniques. If we use an op-amp and two ordinary silicon diodes, we can build the half-wave rectifier with a choice of polarity shown in Fig. 17. The normal 0.6-volt drop across the silicon diode is taken out completely by the op-amp, and you

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nals with reasonable fidelity, the bandwidth of this amplifier is generally not great. Bandwidths in the order of 1 to 3-MHz are quite common. Normally this is no serious limitation, as most external horizontal signals are of the sweep nature themselves.

One should also remember that when specifying a limit of horizontal bandwidth such as −3-dB at 3-MHz, the manufacturer is also specifying a phase shift. In certain measurements (especially phase measurement), phase shift in the horizontal amplifier relative to that in the vertical amplifier can cause measurement errors.

The input impedance of a horizontal amplifier may vary from oscilloscope to oscilloscope. However, most oscilloscopes are specified with either 100K or 1 megohm with some shunt capacitance. On more elaborate oscilloscopes, the horizontal sensitivity specification may also include specifications for a horizontal attenuator and a variable gain control. The most limited of oscilloscopes has only a fixed amplitude specified for horizontal sensitivity. External horizontal input connectors will normally be the same as those of the vertical input. However, the 5-way binding post is occasionally used when the vertical input connector is of the BNC type. **R-E**

OP-AMPS

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get a linear rectifier that crosses over essentially at zero. You can add a second stage to invert one side to make this into a full-wave rectifier.

There are, of course, many more things we can do with low-cost operational amplifiers, particularly the 741, its improved offspring, and the LM318. The only trick

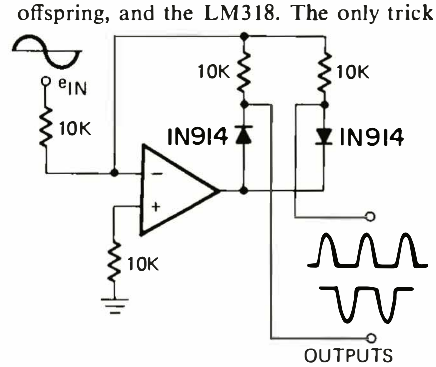

FIG. 17—PRECISION RECTIFIER eliminates diode offset and non-linearity.

is to be sure you obey the simple use rules associated with them. Remember, always use feedback (usually to −). Always provide a source for input base current bias on both the + and − inputs. And never try to run at an operating frequency unless you have at least ten times the open loop gain your circuit calls for. **R-E**