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Op amps take the next step

OPERATIONAL AMPLIFIERS ARE THE UNIVERSAL BUILDING BLOCKS FOR SIGNAL-CONDITIONING DUTIES. AND, THANKS TO THE PROLIFERATION OF ADCs, THEY'RE NOW MORE POPULAR THAN EVER. BUT CONTEMPORARY DESIGN STRESSES LOW-VOLTAGE, LOW-POWER OPERATION THAT COMPLICATES TRADITIONAL OP-AMP CIRCUITS. FIRST, KNOW YOUR OP AMP.

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Illustration by Mike O'Leary

EVER SINCE PIONEERING device engineer Bob Widlar in 1965 designed the μA709 IC for Fairchild, operational amplifiers have been the analogue-design engineer's equivalent of glue logic. But in those early years, you had to be a competent analogue designer to apply most op amps with any real success. Early devices required careful frequency compensation and lacked any output short-circuit protection, making them vulnerable during benchtop development. Nonlinear circuit design, such as true rms-to-dc conversion, was especially tricky, requiring complex compensation networks to provide stability.

Ironically, perhaps, today's emphasis on digital systems shifts such computational duties from continuous-time to clocked-circuit operation, but systems engineers require more op amps than ever before to bridge the analogue-to-digital divide. And with fewer and fewer analogue specialists in the industry, many logic designers now face the responsibility for making these real-world connections. Partially in response to this trend, semiconductor-device designers continuously introduce new generations of parts that not only boast specifications that were unimaginable when the μA709 appeared but are also much simpler to apply.

Just one decade ago, glancing through vendors' catalogue listings might have convinced you that op-amp design had reached something of a plateau, with a device to suit every application. But, as with everything else in this industry, nothing stays the same for long. Two main factors now challenge semiconductor-device and end-user equipment designers alike: the trend toward single-supply operation and the explosive growth in mobile devices. Each of these factors adds its own requirements, but both share the ever-lower power-consumption requirements that contemporary designs demand. Although it's obvious that the ever-growing list of battery-operated electronics, such as cell phones, digital cameras, handheld games, MP3 players, notebook PCs, and PDAs, require the lowest possible power consumption, the trend doesn't stop with consumer durables. Systems engineers are now commissioning environmental-monitor-


3
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2
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ing and industrial-process-control systems that consume a quarter of the current that their counterparts required just five years ago.

SINGLE-SUPPLY OPERATION

Single-supply operation now dominates op-amp applications for several reasons. First, it's convenient; you no longer have to design and accommodate multiple power supplies. Just lowering the supply voltage from the traditional ±15V to, say, 5V helps you to conserve energy and minimise power dissipation, which in turn reduces your cooling requirements. You also minimise power losses by eliminating multiple voltage conversions. Second, if you use the same supply level that logic such as ADCs require, you can neatly match your signal-conditioning circuitry to the ADC's input level. But single-supply operation presents a number of challenges, starting with the op amp's natural desire to operate from split supplies.

Because op amps are linear devices, they operate in four quadrants that take the math form of $y=Mx+C$, where M is the circuit's gain term, and C is a constant that represents an offset value. To provide the equal positive and negative excursions that maximise a circuit's dynamic range, an op amp's input-signal level ideally centres between its supply rails. Also, the amplifier's internal circuitry invariably works best midway between the supply rails, with traditional designs becoming nonlinear as signal voltages approach the supplies. Together, these behavioural features require you to implement a virtual ground that's typically halfway between the supply rails.

This virtual ground often crucially determines overall circuit performance. A crude way to generate a midrail reference uses two resistors as a divider, with a capacitor to ground to help attenuate power-supply noise. And therein lies the first problem: Any remaining power-supply noise feeds directly into the reference input and adds to input-signal noise. In dc terms, the circuit's output impedance equals the resistor values in parallel, and ac response is poor, introducing frequency-dependent distortion.

It's also difficult to strike a balance between output impedance and power consumption. Assuming equal-value 1-kΩ resistors and a 5V supply, the output impedance is 500Ω for 2.5 mA. This value represents 12.5-mW dissipation in the resistors, and more accrues if you're using a power-supply voltage regulator. It's better to select a low-power voltage-reference IC, but for minimal output impedance and best noise rejection, ensure that this device can source and sink current. Like linear voltage regulators, almost all low-power voltage-reference ICs are designed as current sources. One exception is Linear Technology's LT1118-2.5, which achieves an output impedance of around 0.025Ω and can drive ±800 mA for an I_Q (quiescent current) of some 600 μA.

Lowering the supply voltage intrinsically reduces the op amp's output voltage swing, so the circuit's dynamic range immediately suffers. This consideration can become crucial with designs that must work down to the voltage supplied by a pair of NiCd batteries approaching deep discharge at, say, around 1.8V. Typically, all circuits must accommodate maximum input-signal levels that include transient overdriving without performance degradations, such as distortion due to nonlinear amplifier response.

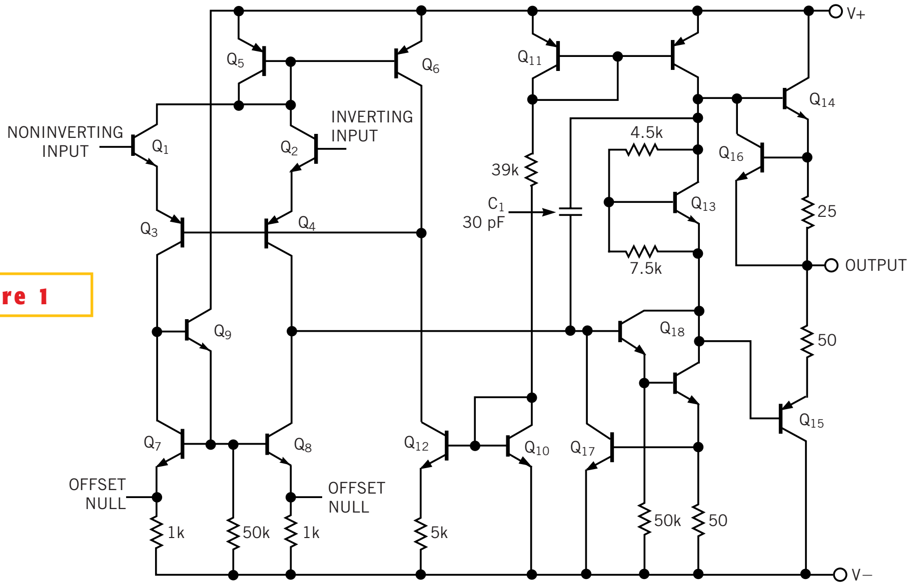
Some sensors, such as piezoresistive-bridge accelerometers, can be microphonic and generate transient overload levels far exceeding their normal output. In extreme cases, input-signal overdrive levels can cause phase reversal in some op-amp designs—the analogue-circuit equivalent of a digital device's latch-up. And, there's the SNR issue to consider: Following amplification, a few tens of microvolts of input-referred noise can become an unhealthy percentage of a low-voltage supply's headroom. For this reason, fully differential signal processing is becoming more popular; because the noise terms between two op-amp drivers are uncorrelated, you immediately improve SNR by 3 dB.

Among other attributes, an ideal op amp has infinitely high gain and bandwidth, infinitely low output impedance, and zero noise contribution. Unless you're constructing a comparator circuit, negative feedback dictates the circuit's response. First described by Bell Labs com-

AT A GLANCE

- ▷ ADCs make op amps more popular than ever before.
- ▷ Contemporary applications demand single-supply, low-current operation.
- ▷ Understanding your components is the key to application success.
- ▷ Rail-to-rail op amps preserve dynamic range but have other costs.
- ▷ You can simplify op-amp selection by focusing on prime specification parameters.

Figure 1



The 741 illustrates how an op amp works and demonstrates many shortcomings of general-purpose devices in low-voltage applications.

munications engineer Harold Black in 1934, the negative-feedback principle applies a fraction of a high-gain amplifier's output back to its input to correct a circuit's transfer-function errors. Thus, you can visualise operation within negative-feedback circuits simply by remembering that—provided that the circuit is operating within its linear region—feedback action drives the voltage between the input terminals to zero. By considering the current flow within the feedback network under given input conditions, mathphobes can escape complex-looking formulas to intuitively arrive at the correct result. But for formal analysis and a collection of single-supply circuit examples, download Texas Instruments' free "Op amps for everyone" design reference, which focuses on application-level issues (**Reference 1**).

KNOW YOUR OP AMP

Before you consider application issues, it's essential to appreciate how components work. You can see the functional blocks that comprise a typical op amp by

SIMPLIFY OP-AMP SELECTION

With multiple vendors offering thousands of devices, finding an op amp that suits your applications can be a daunting task. Simply scanning data sheets compounds this challenge, because there are routinely as many as 30 specification parameters to consider for each candidate. But you can almost always quickly eliminate options by identifying the key features that your application requires. Internet technology helps by allowing vendors to include on their Web sites selection guides that allow parametric searches, so you can soon focus on devices that can fulfill your needs.

Operational voltage range and power consumption define the first selections you'll make in the context of this article, but the first parameter that designers otherwise consider is the op amp's V_{OS} (offset-voltage) specification. Assuming unity gain in a dc closed-loop circuit, V_{OS} represents the maximum value of the voltage that appears between the input terminals. This voltage primarily dictates an op amp's dc performance; ignoring any internal correction circuitry, the matching between the op amp's differential-input transistors closely determines V_{OS}.

Assuming perfect balance, V_{OS} is zero. And under normal small-signal conditions, the stage amplifies the difference signal while rejecting common-mode voltages. But when V_{OS} is not zero, the op amp multiplies its value by the closed-loop gain to add an error voltage to the output signal. Provided that V_{OS} remains constant, you can often digitally compensate such errors. But the physics of silicon dictate that for every 1 mV of imbalance between the differential-input pair in a typical design, such as the 741, you get 3.3 μV/°C of V_{OS} drift, which is far more difficult to compensate. Such designs often include two offset-null connections that work by unbalancing the input stage, and the same physics applies when you deliberately unbalance this stage. Thus, if you have to correct V_{OS}, it's better to add an offset to the input signal.

But many contemporary op-amp designs employ matching and trimming techniques that reduce V_{OS} and drift terms to manageable proportions over both temperature and time variations. The first device to fully integrate such circuitry was the OP-07 from Precision Monolithics (now part of Analog Devices). Here, wafer-stage trimming reduces V_{OS} to less than 25 μV, and internal compensation circuitry reduces and stabilises the second major dc-performance parameter–the input-bias current that's necessary to drive the input pair.

There's also an associated input-offset current that represents the difference between the currents that the input pair takes for equal source resistances. (It's good practice to equalise source resistances by adding a resistor to the appropriate input terminal.) Bipolar-junction transistors can take enough current from high-impedance sources to create substantial errors; hence the popularity of junction-FET and CMOS-input devices. But FETs are noisier than bipolar-junction transistors, and CMOS devices are even worse. Also, junction-FET and CMOS devices present temperature variations that are more difficult to compensate, and they're more difficult to control at low supply voltages.

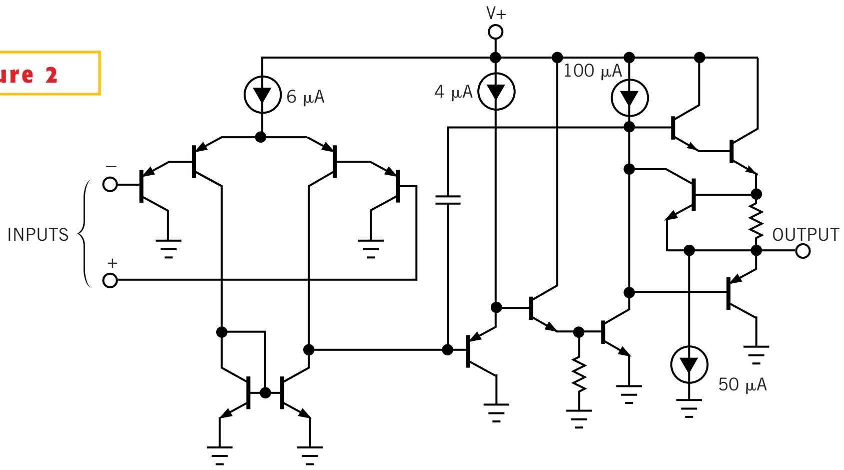
Bandwidth can be even more important than dc performance. But even for low-power dc use, you should always consider bandwidth: There is a trade-off between speed and power consumption that's due to the higher internal bias currents a fast op amp needs to maintain its output-drive capabilities at high frequencies. Data sheets quote the gain bandwidth product as the device's −3-dB point for a specific gain, so the amplifier's output swing is frequency-dependent. And gain bandwidth depends closely on closed-loop gain.

Another prime ac-performance consideration is the op amp's output slew rate, which also affects settling time. If you're working with ADCs, ensure that your circuit settles before the converter's sampling point without ringing or showing overshoot or undershoot. A common way to test this parameter is with a pulse-response test, but make sure that the circuit under test truly represents the application's resistive and capacitive loadings.

Along with signal-voltage ranges, other major specifications include CMRR (common-mode-rejection ratio) and noise performance. CMRR is a frequency-dependent term that might range from, say, 120 dB at dc to 60 dB at 100 kHz–that's a thousandfold performance degradation between the frequency extremes. Noise performance is easier to consider. Lower is always better, because overall circuit noise forms the basic limit for resolution. But engineers frequently overlook an op amp's PSRR (power-supply-rejection-ratio) specs. PSRR can contribute unexpected errors, especially when you're using a switched-mode power supply that outputs high-frequency noise components. Again, PSRR is frequency-dependent and often closely follows an op amp's CMRR characteristics.

Sometimes, all these–and more–specifications are secondary to the application's physical requirements. Many vendors now offer devices in miniature packages that make standard SOT-23 surface-mount parts look massive. But the miniaturisation that's great for your next mobile-device project can be a curse during prototyping. To simplify your life, ensure that you can source components in a range of packages that includes one you can easily handle. After all, semiconductor vendors typically start testing new devices by installing them in big, user-friendly ceramic packages!

Figure 2



The best-selling op amp ever, the LM324, was the first example to successfully fulfill single-supply rail applications.

examining the ubiquitous 741 IC (**Figure 1**). Designed in 1968 by Widlar's successor at Fairchild, Dave Fullagar, the µA741 was the first device that was genuinely easy to apply. By today's standards, the circuit is simple, but its same principles apply to all general-purpose op amps. The design also illustrates several factors that impact single-supply and low-voltage operation.

The input terminals are the bases of a pair of npn bipolar-junction transistors, Q_1 and Q_2, in an emitter-follower configuration. To provide isolation between the input signals and the stages that follow, the input pair immediately feeds two pnp transistors, Q_3 and Q_4, which form a common-base amplifier. This strategy decouples the input terminals from the following stages and prevents signal feedback at high frequencies. Transistors Q_5 and Q_6 form a current mirror that supplies constant bias current to the input stage and allows maximum headroom to the positive supply rail in the presence of large common-mode voltages. The Q_7/Q_8 pair load the stage and provide the differential-to-single-ended conversion that's necessary to drive the second gain stage.

Bias for Q_7 and Q_8 comes from Q_9, which maintains the voltage across Q_7's collector-emitter at close to two diode drops. Analogue-circuit guru John Pickering, principal of instrumentation consultancy Metron Designs, explains: "Imagine that there are no volts across the 50-kΩ resistor, and Q_7/Q_8 are off. Then, the voltage at Q_7's collector rises, due to current from Q_3. Transistor Q_9 now 'emitter-follows' it to just above $2V_{BE}$, when its emitter supplies enough current to turn Q_7 and Q_8 on—and also supply the 50-kΩ resistor." Pickering notes that Q_7's collector-base path via Q_9 is a negative-feedback loop that causes the circuit to stabilise with Q_7's collector at about 1.3V above the negative rail. Also, Q_7's collector is loaded only by Q_9's base current. According to Pickering, adding Q_9 is better than diode-connecting Q_7 as in a normal current mirror because Q_9 supplies the base current for both Q_7 and Q_8, rather than from just one side of the mirror. Thus, only Q_9's base-current requirement compromises the matching between the mirror devices.

One of the key challenges for op-amp designers is determining how to level-

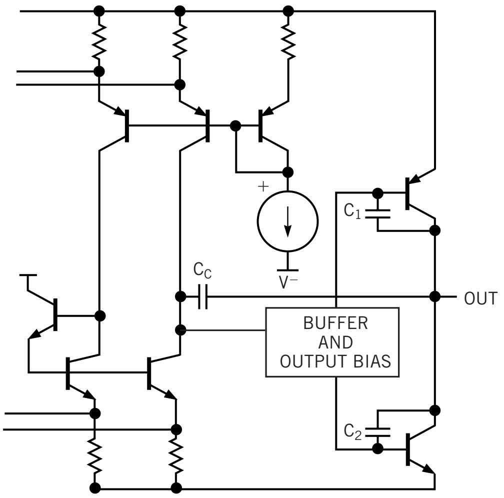


Figure 3

The LT1800 lowers the impedance of its rail-to-rail output stage using a couple of capacitors in a local negative-feedback loop.

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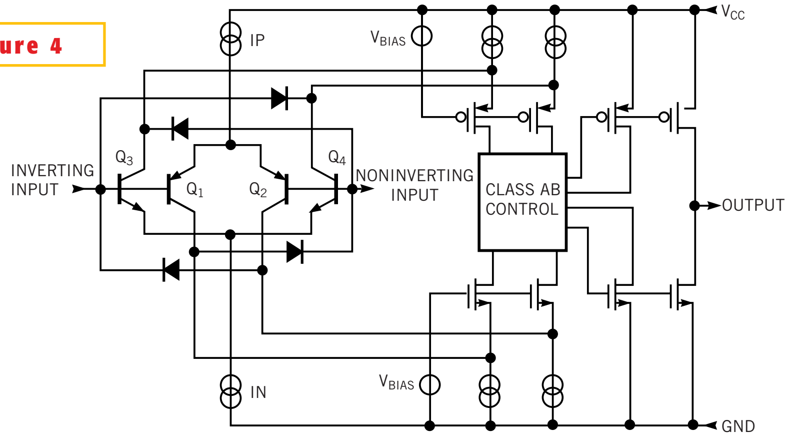
shift between successive gain stages and still maintain sufficient headroom between the supply rails. The 741 makes extensive use of Widlar's current-mirror circuits to shift and scale the biasing throughout its three stages. Pickering expands this concept, explaining that the 39-kΩ resistor together with Q_{10}, Q_{11}, and their associated mirrors, set the op amp's internal bias-current levels. This circuit defines a current in Q_{12} that pulls the bases of Q_3/Q_4 until there's sufficient current in Q_1/Q_2 to drive the mirror Q_5/Q_6 to supply the current to Q_{12}. That is, a dc bias-current-control loop maintains its operation over Q_1/Q_2's full common-mode-voltage range.

Figure 4



Rail-to-rail input op amps sacrifice V_{OS} and bias-current considerations to accommodate common-mode voltages that meet or exceed the supplies.

Working as a floating reference, Q_{13} and its base resistors form a VBE multiplier; neglecting Q_{13}'s base current, the current through the 7.5-kΩ resistor must also flow through the 4.5-kΩ resistor. Approximately 1V appears across Q_{13}'s collector-emitter, and this voltage controls the crossover point between Q_{14} and Q_{15} conducting. For output-stage protection, Q_{16} provides short-circuit current limiting for Q_{14} by diverting current from Q_{14}'s base when an overload is present. The protection for Q_{15} is subtler in that Q_{17} samples the output-stage current and then diverts Q_{18}'s drive current to the negative supply rail. Also, the integral-frequency-compensation capacitor, C_1, guarantees that the device is stable down to unity gain—a novelty at the time and a huge factor in popularising op-amp applications.

RAIL-TO-RAIL OP AMPS DRIVE ADCS

You can see that a 741-style design has problems accommodating common-mode input voltages that approach the supply rails. In either the positive or the negative directions, the Q_5 current-source and Q_7/Q_8 current sinks require ≥2V of compliance voltage to work well. The data sheet reflects this fact, stating that the input common-mode voltage range is typically ±13V for ±15V supplies. Also, the output voltage can't reach the supply rails, because each npn or pnp member of the output pair cuts off within a volt or so of the respective rail.

To improve performance in the single-supply circuits that automotive applications demand, National Semiconductor in 1974 introduced the LM324 single-supply rail op amp. With four op amps per package and able to operate from a 5V supply, the LM324 suits common logic families and is still the world's best-selling op amp. Uniquely for its time, the LM324's input common-mode range includes ground, and its output can also reach this level. Plus, the differential input-voltage range equals the supply voltage. These abilities rely on the extensive use of pnp transistors that were previously unpopular with op-amp designers because of their inferior performance and greater die area compared with npn devices (**Figure 2**). But the output level still limits at around two diode drops below the positive supply rail, intrinsically reducing output dynamic range. And for applications such as driving ADCs, output dynamic range is typically more important than an op amp's input common-mode range.

To get the maximum code-output range from a conventional ADC, you need to drive its input between ground and its supply rail. This dynamic-range consideration has led to today's generation of op amps featuring RRO (rail-to-rail-output)- level capabilities. For bipolar-junction-transistor designs, RRO op-amps reverse the 741's emitter-follower outputs to substitute a pnp device to the supply rail and its npn complement to ground. In this way, the outputs can swing within millivolts of either rail. But the device often pays a price that is not obvious in the data-sheet specs: Because the output terminal now connects to the collectors of the output-driver transistors, the device's output impedance becomes much higher than it is with a traditional emitter-follower amplifier.

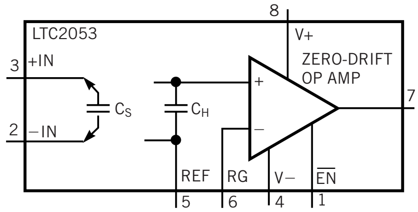


Figure 5

Switched-capacitor techniques can nullify dc errors at the expense of the op amp's becoming another system element that's subject to sampling theory.

Bill Gross, general manager at Linear Technology in Milpitas, CA, observes that customers who have been successfully designing single-supply circuits often encounter problems when they apply RRO devices for the first time: "For a given power consumption, RRO op amps have less drive and less bandwidth than conventional devices." Gross explains that Linear Technology always specifies its RRO devices as working into specific loads. He also notes that if an RRO device has an output impedance of 250Ω, and you connect a 1-kΩ load, the resulting gain of four makes it harder to close the loop and provide unconditional stability.

High-speed RRO devices, such as video amplifiers, can be prone to oscillation—sometimes even when you apply a scope probe's few picofarads of stray capacitance to the op amp's output terminal. For this reason, Linear Technology endeavours to make all its op amps capable of driving at least 50 pF. You might also consider adding a decou-

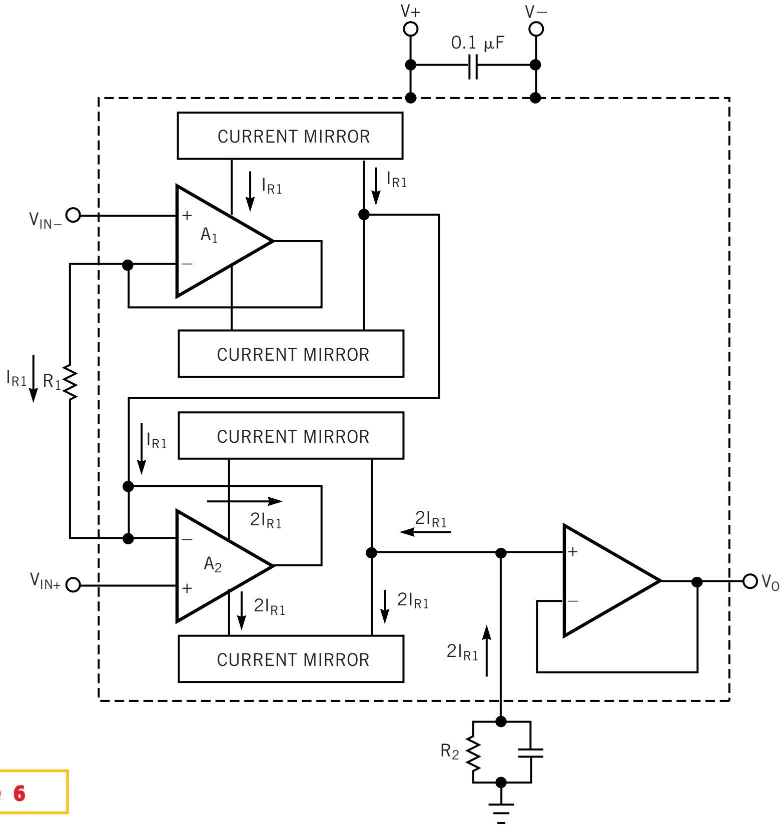


Figure 6

The INA326 converts input-signal voltages to currents to circumvent accurate resistor matching in a low-power instrumentation-amplifier design.

pling resistor between the op amp's output and a test point, but this extra load in series with a 10× scope probe introduces a proportional gain error. Interestingly, techniques that Linear Technology uses to minimise output impedance in the LT1800 IC include adding a pair of capacitors (C_1 and C_2) that provide local negative feedback to the output driver's bases (**Figure 3**). Built using bipolar process technology and specified for 3 and 5V operation, the LT1800 has a typical 80-MHz GBW (gain bandwidth) for 2 mA of I_Q; it is stable at unity gain for maximum loads of 75 pF.

Designers consider this gain-bandwidth-per-milliamp value a measure of op-amp efficiency. And, not surprisingly, the relationship between bandwidth and power consumption is a prime op-amp selection parameter (see **sidebar** "Simplify op-amp selection"). For lowest power applications, Martin Giles, amplifier-applications manager at National Semiconductor's Santa Clara, CA, facility, recognises a trend for op amps to include shutdown circuitry that minimises I_Q when the device is not in use. But, because the shutdown circuitry works by disabling various parts of the op amp's biasing circuits, a trade-off exists between shutdown current and wake-up speed. Many designers overlook this consideration. "When a vendor quotes you a shutdown current figure," Giles explains, "always ask how long the device takes to restart; the answer may surprise you." For example, National Semiconductor's LMH6647 is a 55-MHz-GBW device that suits 2.7V operation and draws approximately 650 µA; the LMV981 has a 1.4-MHz GBW and consumes about 100 µA using a 1.8V supply. Both devices feature shutdown inputs that typically reduce I_Q to 15 and 0.156 µA, respectively. But the LMV981 takes a leisurely 12.5 µsec to wake up; the LMH6647 is working within 250 nsec.

Like the LT1800, the LMH6647 and LMV981 follow the growing trend for low-voltage op amps to include RRI (rail-to-rail-input) capabilities as well as RRO capabilities; such devices earn the description "RRIO." Giles notes that National Semiconductor prefers BiCMOS technology for its low-voltage op amps because it's a truly complementary process. Bipolar processes are invariably quieter for input stages and also easier to control at low voltages, but CMOS eases driver-stage design. The main problem is in reducing the threshold voltages for the CMOS output-stage elements. Giles eagerly accepts that the ability to accommodate input voltages down to ground and below is often useful but points out that input-referred operation to the positive supply rail can be questionable, stating that in a normal application, RRI is useful only if you're building a unity-gain buffer.

There's a price to pay for the convenience of RRI operation that's a consequence of the dual-input stage that such amplifiers require (**Figure 4**). This configuration leads to three operational modes. Between ground and about 1.2V below the positive supply rail, the Q_1/Q_2 pnp pair is active. As the input voltage rises above this level, biasing arrangements start to turn off Q_1/Q_2 and turn on the npn pair, Q_3/Q_4. Thus, there's a transitional period. Eventually, the pnp transistors turn off completely, and the complementary pair provides the first stage of gain. Therefore, over the full input range, the polarity of the input bias current changes. And, because pnp and npn transistors have different gain properties, this current's magnitude also sharply changes, with a plateau during the transitional period.

Apart from introducing additional dc errors that are hard to externally or internally compensate, such stages can generate distortion during the transitions between operating modes. The message is that, for best performance, don't use RRI devices simply because you think they're convenient. Applications that can benefit from RRI inputs include high-side current-sensing applications, in which the sense resistor is at or above the op amp's supply rail. But a better option may be to use a current-sense IC, such as Texas Instruments' INA168. This op-amp based circuit accepts common-mode input voltages reaching 60V and consumes just 25 µA.

IN AMPS GO LOW POWER

You may at times consider alternatives to conventional op amps. One such example is when you're interfacing with Wheatstone-bridge circuits, such as accelerometers, thermocouple bridges, and pressure-sensor ICs. The normal connection employs an instrumentation amplifier, which you can construct from three op amps and a handful of precision resistors. For adequate common-mode rejection, you must often match these resistors to much less than 1%. But you can now get low-power, low-voltage instrumentation amps that integrate these elements and avoid component-matching difficulties. Typically, you program such amplifiers to operate at gains of 1 to 1000 with a single resistor. The micropower AD627 from Analog Devices is a classic three-amplifier design that provides RRO operation for a maximum I_Q of 85 µA. The device accommodates supplies of ±18V down to just 2V to suit power-reduction schemes in everything from process-control systems to battery-powered instruments. But with performance specified for 20- and 100-kΩ loads, you'll need a buffer to drive typical ADCs. Also notice that the minimum gain figure is five, but this restriction is unlikely to challenge most applications.

There are alternatives to the three-op-amp configuration that some vendors employ to build instrumentation amplifiers. Optimised for dc accuracy within a 400-Hz bandwidth, Linear Technology's LTC2053 boasts a maximum V_{OS} (offset voltage) of just 10 µV and an offset-drift figure of 50 nV/°C. The device consumes a maximum I_Q of 1.1 mA from supplies that can span ±5.5 to 2.7V. Features include RRIO operation that's specified for loads down to 2 kΩ. The device achieves this performance by using a switched-capacitor input architecture followed by a zero-drift op amp (**Figure 5**).

"Zero-drift op amp" is almost always a pseudonym for "chopper-stabilised," and the LTC2053 is no exception. It employs switched-capacitor techniques to synchronously modulate and demodulate the input level and nullify dc errors (**Reference 2**). The LTC2053's input circuit level-shifts the dc common-mode input voltage to its reference pin's level by sampling the input signal on capacitor C_S and transferring it to C_H. The sampling frequency is 2.5 kHz, and the capacitors are both 1 nF, so you must consider settling time. Provided that the input-source resistance is less than 10 kΩ and gain is less than 100, the switched-capacitor input's characteristics dominate, and the IC settles to n bits of accuracy within about n clock cycles.

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At high source-resistance values, a step change in input voltage allows too little time for the capacitors to charge fully within one cycle, so settling time suffers. The capacitors also require an input-charging current that ideally reaches zero for dc inputs. But parasitic capacitors disturb this charge, so the input-charging current decays exponentially during each sampling period, with a time constant that's the product of source resistance and C_S. Notice that if the input voltage across C_S settles within one clock period (400 µsec), the input architecture eliminates errors due to source resistance or source-resistance mismatches.

The INA326 from Texas Instruments demonstrates another innovative approach to achieving the high common-mode rejection that characterises instrumentation amplifiers. To avoid the resistor-matching issues that plague traditional topologies, the INA326 converts input voltages to currents (**Figure 6**). The outputs from op amps A_1 and A_2 impress the differential input voltage across R_1, which in combination with R_2 sets the amp's gain at 0.1 to 10,000. Both op amps include current mirrors in series with their supply lines, and these supply lines operate from charge pumps that lift them above the external power-supply rails. A_2's current-mirror adds the current in R_1 to its duplicate from A_1 to double the output value that flows through R_2, providing a gain equal to $(2\times R_2/R_1)$. This approach achieves 110-dB common-mode rejection, a maximum V_{OS} of 125 µV, and a V_{OS} drift of 1 µV/°C. The charge-pump arrangement permits RRI operation that extends 20 mV beyond the supplies. Other statistics include 1-kHz GBW, single-rail 2.7 to 5V operation, and drive to within 10 mV of either rail into a 10-kΩ load. The chip's I_Q is typically 2.4 mA; the similar INA327 adds a shutdown pin that reduces off-state current drain to a maximum of 5 µA.□

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1. Mancini, Ron, "Op amps for everyone," Texas Instruments, September 2001, document number SLOD006A.
2. Williams, Jim, "Application considerations and circuits for a new chopper-stabilized op amp," Linear Technology application note AN-9.