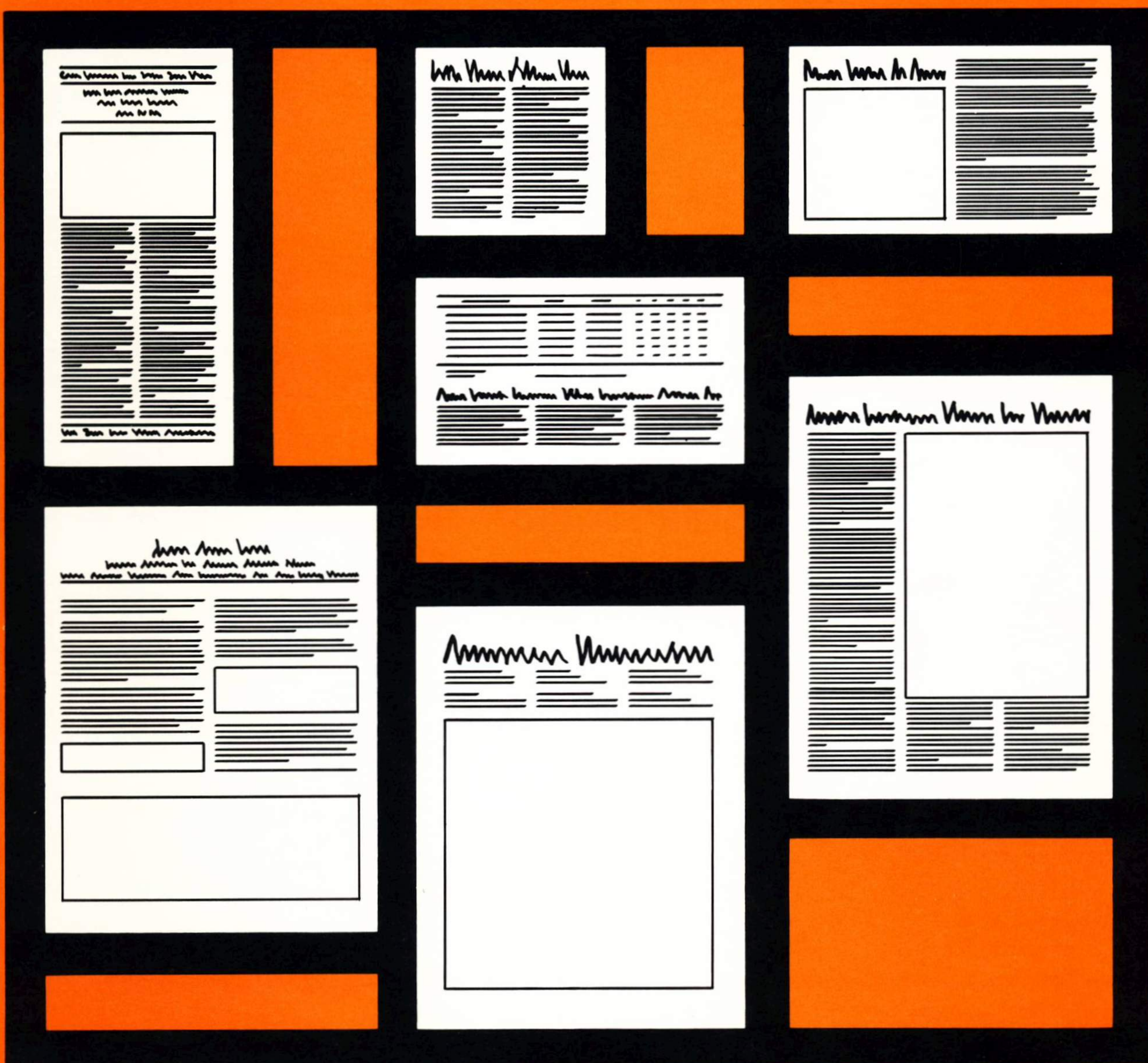
EDITORIAL COVERAGE OF

OP-27/37

ULTRA-LOW NOISE, PRECISION OP AMPS



Precision Monolithics Incorporated

Reprinted from *Electronic Design*, Dec. 20, 1980, p.3

BehindTheCover

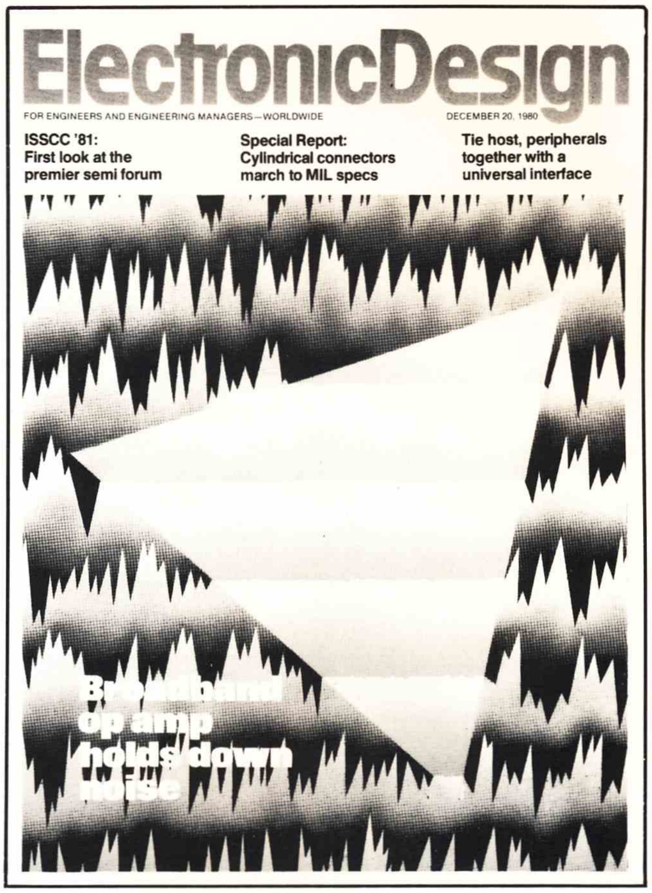
Bringing down the voltage noise of a precision op amp without sacrificing gain or bandwidth is a tough challenge—even for a veteran designer like George Erdi, Precision Monolithics' staff vice president of engineering. Over the course of a year, he isolated, examined, and eliminated all sources of noise, one by one. His starting point, the industry-standard OP-07, already ranks as one of the quietest bipolar op amps; at 10 $nV/\sqrt{Hz}$, its voltage noise is below the measuring capacity of many instruments.

As Erdi describes the process, he carefully examined the OP-07 circuit and layout to determine how each element of the circuit contributed to the total noise. The results were surprising and frequently difficult to improve upon: Erdi found, for example, that the second stage of the op amp circuit sometimes contributed as much noise as the input stage. Since the input resistors to the second stage act as load resistors for the first stage, Erdi solved the problem by inserting buffers between the first and second stages.

The bias-cancellation circuit of the OP-07 also proved to be responsible for some of the voltage noise. As a counterattack, Erdi redesigned the bias-cancellation circuit to put it outside the signal path and thereby end its contribution to the total noise.

Still more noise came from the high-value source resistors at the input stage. Although they were supposed to protect the OP-07 from overload, these resistors had to be removed entirely, to eliminate them as a source of noise.

The result of George Erdi's one-year development effort—the OP-27—comes in at $3nV/\sqrt{Hz}$ and a remarkably low 1/f corner. PMI marketing engineer Tom Schwartz describes the day he saw first wafers on the part as a highlight in his career. With broad experience in telecommunications, audio, and linear IC manufacturing companies, Schwartz regards the OP-27/37 as the culmination of a long-term dream to develop and market the best amplifier in the business.



Cover of Dec. 20, 1980 issue of *Electronic Design*. Artwork depicts low noise performance of OP-27.

Op amp authority and consultant Walter Jung is equally enthusiastic about the part. Having designed all the audio circuitry for our cover story (PMI engineer Scott Bernardi contributed other application circuits), Jung confirms that the OP-27 pushes down noise barriers without any of the typical trade-offs. Jung, who is a Fellow in the Audio Engineering Society and author of eight books (including *The Op Amp Cookbook*), claims that the OP-27 will let designers get low-voltage noise and low current noise from the same amplifier, for the first time ever.

(Article is reproduced in this booklet beginning on p. 5)

Table of OP-27/37 Editorial Coverage

Reprinted from *EDN*, Jan. 21, 1981, p. 155

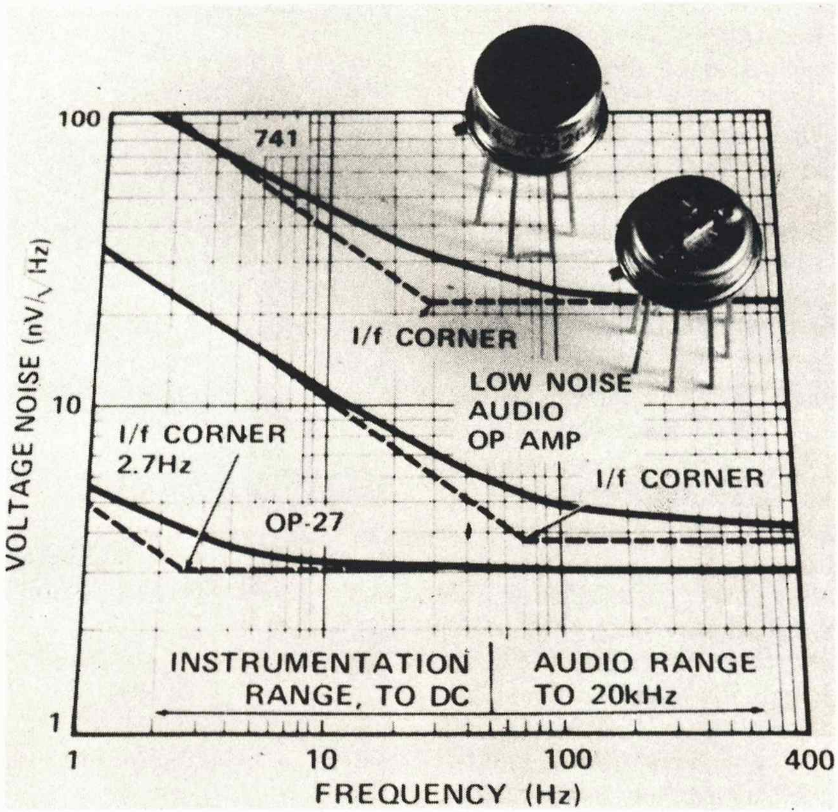
Feature Products

Monolithic op amp specs lowest noise, maintains high speed and precision

Coupling the OP-07's dc performance with a 75% reduction in voltage noise, the OP-27 combines precision, speed and low noise in one package.

With 3.8-nV/$\sqrt{\text{Hz}}$ max input noise-voltage density, this device sports the lowest noise of any op amp on the market. But its speed also stands out: Slew rate equals 1.7V/μsec min and 2.8V/μsec typ. And precision is also noteworthy: 25-μV input offset voltage, 35-nA input offset current and long-term V_{OS} drift of 1 μV/month max.

Although such specs are available separately in other devices, this part is the first to successfully combine them in a monolithic chip. Other impressive specs include average input-offset drift of 0.6 μV/°C max, typical large-signal voltage gain of 1 million, 5-MHz min gain-bandwidth product and input noise voltage of 0.18 μV p-p max over 0.1 to 10 Hz.



In one monolithic device, *the OP-27 combines the lowest noise of any op amp with noteworthy precision and speed specs.*

DC specs not compromised

While offering some performance improvements over the OP-07, the OP-27 retains its predecessor's dc performance. For instance, common-mode rejection ratio is typically 126 dB, and power-supply rejection is 120 dB.

Bias current specs at ±40 nA, a low figure attributable to a bias-current compensation network at the inputs. With this scheme, the direction of bias-current flow varies with the magnitude of the current fed to the base of the device's npn input transistors by its pnp current sources.

This characteristic could make the device unsuitable for some applications, such as rectification or precision ac-voltage conversion, where you must know the current direction. However, the part suits applications in which source impedance is very low, such as strain gauges, 3-op-amp instrumentation amps and precision integrators or differentiators. And it also suits production environments where use of a trimming pot is undesirable or too expensive.

Power consumption is 140 mW, slightly higher than that of the OP-07 because of the higher input-stage currents required for noise reduction. Additionally, the OP-27 has diode-protected inputs but no protection resistors, so large common-mode voltages (greater than approximately 12V) could damage the input section.

The OP-27 comes in the same package types as the OP-07 and with the same pinouts. $5.50 to $50 (100), depending on grade and temperature range.

Precision Monolithics Inc, 1500 Space Park Dr., Santa Clara, CA 95050. Phone (408) 727-9222.

Reprinted from *E.E. Times*, March 16, 1981, p. 47

Device	Manufacturer	e_n 10Hz (nV/$\sqrt{Hz}$)	V_{OS} 25°C (μV)	TCV_{OS} (μV/°C)	I_{OS} T_a LIMIT (nA)	I_{OS} 25°C (nA)	I_b T_a LIMIT (nA)	Gain 2-Kilohm load (V/mA)	GBW (MHz)	Slew Rate (V/μs)
OP-27AJ	PMI	5.5	25.0	0.6	50.0	35.0	±60.0	1000.0	5.0	1.7
OP-07AJ	PMI, Micro Power Systems	18.0	25.0	0.6	4.0	4.0	±4.0	300.0	0.4	0.1
BB35105M	Burr-Brown	14.0‡	120.0	1.0	40.0	15.0	±65.0	1000.0	0.4‡	0.2‡
AD517	Analog Devices	35.0‡	75.0	1.8	1.5	1.0	8.0	250.0	0.25‡	0.1‡
ICL7650*	Intersil	600.0‡	5.0	0.05	0.5‡	0.005‡	11.0	250.0‡	2.0‡	2.5‡
NE5534A	Signetics, Exar, TI	10.0‡	2000.0	10.0	500.0	200.0	1500.0	50.0	10.0‡	6.0‡
μA741	PMI, Fairchild, Nat'l Semi.	100.0‡	5000.0	10.0	500.0	200.0	1500.0	50.0	0.5‡	0.5‡

Note: All specifications are limits unless otherwise noted. All devices are compensated for unity gain. V_s is ±15V unless otherwise noted. ‡ = typical; * = V_s = ±5V

The OP-27 is a standout performer, offering a combination of both low noise and low offset voltage.

PMI'S Op Amp Is A High-Performance Leader

SANTA CLARA, CA — A high-performance op amp from Precision Monolithics offers a new low in noise—only 5.5nV;Hz and typically just 3nHz in audio-frequency applications. (The previous low-noise leader was the NE5534A, at 10nV$\sqrt{Hz}$.) And while that spec is extraordinary by itself, the OP-27 combines it with an ultralow offset of just 25μV max at 25°C. (That compares to 2000μV for the 5534A.)

"This amp is the next step in the evolution of the monolithic operational amplifier," enthuses Ron Gadway, vice president of marketing at PMI. "It's the first of the next generation."

According to Gadway, the key to the new design was the segregation of the noise bands into separate design problems. "That means 1/f noise and white noise received individualized attention regarding circuit design and geometric layout of components," Gadway explains.

Modeled after the OP-07, the OP-27 offers one-third the noise voltage of that earlier model—that makes it the highest-precision, lowest-noise monolithic op amp currently in the commercial market.

Other key specifications of the OP-27 include an 8-MHz bandwidth, unity-gain compensation, slew rate of 3.2V/μs, and a long-term drift of 0.2V per month. Typical power dissipation is 90 to 100mW. The OP-27 is to be joined shortly by the OP-37, a similar device compensated for gains of five or more.

Delivery is from stock. Prices range from $5.50 to $50 (100s).

Precision Monolithics, Santa Clara, CA 95050. (408) 727-9222.

Reprinted from *Electronic Design*, March 19, 1981, p. 288.

OP-07 spawns low-noise and dual op amps

A low-noise gain-compensated amplifier and a dual op amp, both from Precision Monolithics, capitalize on the company's industry-standard OP-07. The OP-37, a high-gain compensated version of the OP-27 (ELECTRIC DESIGN, Jan. 8, 1981, p. 302) was developed from the original OP-07 design; and the OP-207 puts two exceptionally well-matched OP-07s on the same chip. The OP-07 is noted for its ultra-low offset voltage (10 μV), for its low offset-voltage drift (0.2 μV/°C), and for its low noise (10 nV/$\sqrt{Hz}$).

The OP-37 offers an unusually high gain-bandwidth product (63 MHz), in addition to exceptionally low voltage noise (3 nV/$\sqrt{Hz}$ typical at 1 kHz). It brings precision performance to applications requiring gains higher than five. The slew rate of the OP-37 is better than 17 V/μs, and its typical voltage gain is 1.8-million. A low 1/f corner (2.7 Hz) establishes low noise figures for low-frequency instruments. The noise is within 80 nV peak-to-peak in the instrumentation region from 0.1 Hz to 10 Hz (typical: 3.5 nV/$\sqrt{Hz}$ at 10 Hz).

More closely related to the OP-07 parent, the OP-207 contains two well-matched OP-07s. The input offset voltages of the two amps are matched to within 30 μV typical, and tracking is within 1.0 μV/°C. Input bias currents are matched to within 3.5 nA. In spite of this tight matching, channel separation between the two devices is still better than 126 dB.

For the OP-37, hundred-piece pricing will range from $50 for the very highest grades down to $5.50 for the very lowest. The OP-207 has a price spread of $42 to $17 in hundred quantities. Delivery on both types is from stock to several weeks.

Reprinted from *Electronic Products*, March 1981, p. 75

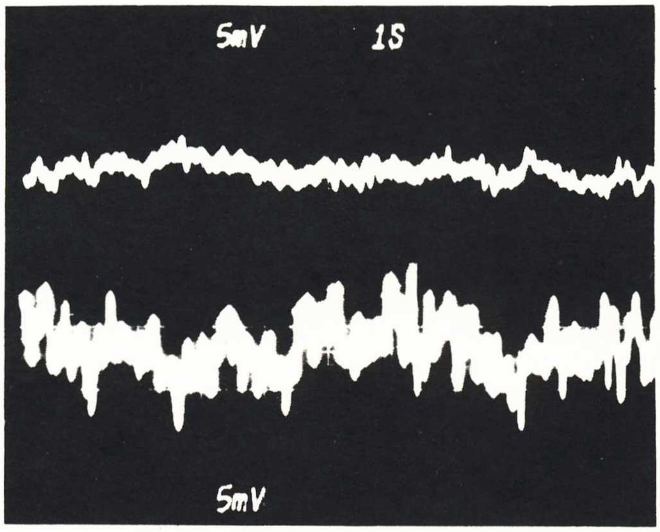
product HIGHLIGHTS

High-speed op amp gives low-noise operation

LOW FREQUENCY NOISE

OP–27

OP-07



0.1 Hz to 10 Hz PEAK-TO-PEAK NOISE
40 nV/DIVISION REFERRED TO INPUT
(CLOSED-LOOP GAIN = 50,000)

Low-frequency instrumentation and audio frequency amplifier designs requiring high accuracy and speed coupled with low noise can benefit from using Type OP-27 Operational Amplifiers. Optimized for precision, the OP-27 exhibits only 80 nV pk-to-pk noise levels (typical) from 0.1 to 10 Hz. Noise in af stage use (1 kHz) is speced at 3 $nV/\sqrt{Hz}$. These figures are about 75% better than those for industry-standard OP-07 types, after which this device is modelled.

Offset voltage of only 10 μV is enhanced by excellent stability. Typical drift over temperature is only 0.2 μV/°C with 0.6 μV/°C max. Long term drift specs also reveal great stability, coming in at 1 μV per month, max, with typical values of only 0.2 μV/month.

Speed has not been sacrificed. Type OP-27 offers designers a slew rate of 3.2 V/μs. Gain bandwidth product is 8 MHz. Decompensated versions (OP-37) will be available later this year extending the GBW to 40 MHz with 17 V/μs slew rates.

Packaged in either 8-pin mini-DIPs or as TO-99 cans, Type OP-27 ICs dissipate about 100 mW. Devices are available in two temperature ranges of −55 to 125°C and 0 to 70°C, with three grades of electrical specifications with a maximum input offset voltage of 25 μV (A and E suffix types). All devices, regardless of accuracy/temperature specs, will provide ±10V minimum voltage swings into 600Ω loads (±11.5 typical). ($5.50 to $50 ea/100, depending on accuracy — stock.)

Precision Monolithics
Tom Schwartz 408-727-9222

eem file 1100

CIRCLE 168

Reprinted from *Electronics*, Feb. 24, 1981, p. 202

Monolithic Op Amp Has High Speed And Low Noise

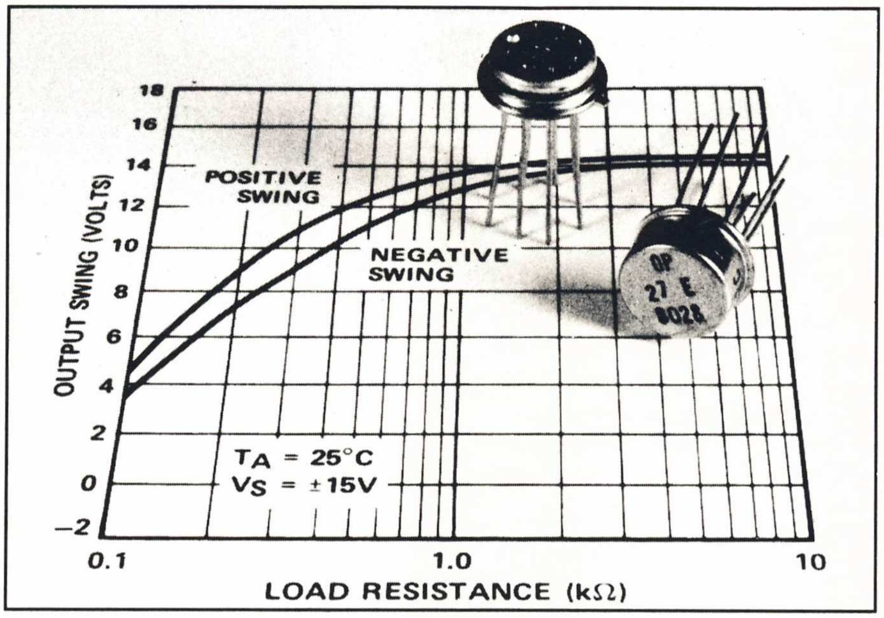
An integrated circuit operational amplifier offers a peak-to-peak noise of only 80 nV in low-frequency instrumentation applications and 3 $nV/Hz^{1/2}$ in audio-frequency stages, an offset voltage of 10 μV, a slew rate of 3.2 V/μs, a bandwidth of 8 MHz, and a long-term drift of 0.2 V per month. These characteristics combine to make this device unique in the industry, says the manufacturer. At 10 Hz the OP-27/37 exhibits a typical input noise density of 3.6 $nV/Hz^{1/2}$ which drops off to 3.1 at 30 Hz and 3 at 1 kHz. It has a typical power consumption of 90 to 100 mW, and input noise current density of 1.7 $pA/Hz^{1/2}$ typically, and 4 $pA/Hz^{1/2}$ maximum at 10 Hz and 0.4 $pA/Hz^{1/2}$ (typical) and (maximum) 0.6 $pA/Hz^{1/2}$ at 1 kHz.

Available in eight-lead, dual in-line packages and eight-pin TO-99 cans, the OP-27/37 has a −55° to +125°C or 0° to 70°C temperature range. In quantities of 100 and up, the op. amps range in prices from $5.00 to $50.

Precision Monolithics Inc., 1500 Space Park Dr., Santa Clara, Calif. 95050. Phone (408) 727-9222 (344)

Reprinted from *Electronic Design*, Jan. 8, 1981, p.302

Wideband op amp keeps noise down to 3 nV/√Hz



The most common conflict within op amps—between wide bandwidth and high gain on the one hand and low noise on the other—moves to a new arena with Precision Monolithics' latest device, the OP-27. The operational amplifier combines a noise density of 3 nV/$\sqrt{Hz}$ (at 1 kHz) with an 8-MHz gain bandwidth product (ELECTRONIC DESIGN, Dec. 20, 1980, p. 65).

A descendent of the industry-standard OP-07, the OP-27 offers a low 1/f corner, so that voltage noise never becomes more than 80 nV peak-to-peak in the critical instrumentation range of 0.1 to 10 Hz. Typical noise-voltage density at 10 Hz is 3.5 nV/$\sqrt{Hz}$ (5.5 nV max); it drops to 3.1 typical (4.5 nV max) at 30 Hz and to 3.0 nV (3.8 max.) at 1 kHz.

The large-signal voltage gain remains as high as 1.8-million typical, with a 2.8-V/μs slew rate. As if these specifications were not enough, the PMI OP-27 also offers low drift: less than 0.2 μV/°C from a 10-μV typical offset. Over time, the drift is less than 0.2 μV/month. Even the common-mode rejection ratio comes in nicely at 126 dB.

For the record, very few op amps can offer an equivalent package. The voltage noise can be cut, but only with sacrifices in gain and bandwidth.

The excellent characteristics of the OP-27 make it useful for instrumentation applications, for professional audio preamp circuits, or as the output amplifier of high-resolution current-output digital-to-analog converters.

As one might guess, the OP-27 is not a cheap part. Prices start at $5.50 in hundred quantities for the very lowest grades, and go up to $50 for the very highest grades. In 8-pin miniDIP packages and TO-99 cans, the devices are available from stock.

Precision Monolithics Inc., 1500 Space Park Dr., Santa Clara, CA 95050. Tom Schwartz (408) 727-9222. **CIRCLE 314**

Stephan Ohr, Components Editor

Reprinted from *Electronic Design*,
Dec. 20, 1980, pp. 65-71

Design

For accurate low-noise and high-speed instrumentation applications, the OP-27/37 operational amplifiers offer an unmatchable combination of specs, including a 17-V/μs slew and gain of 2-million.

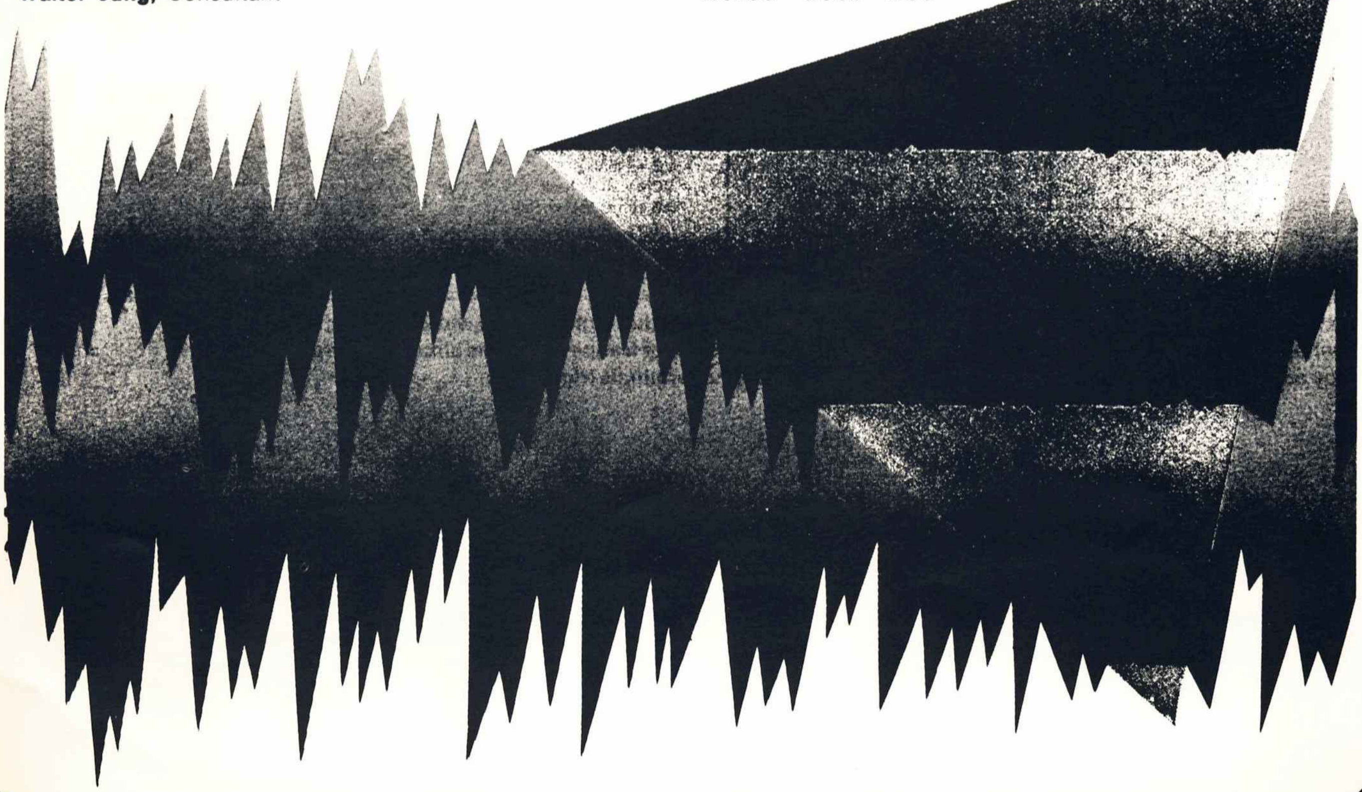
Op amps tackle noise—and for once, noise loses

Constant improvements to monolithic analog circuits have curbed nearly all the possible sources of error—except noise. Now, even that seemingly intractable error-source must give way. The OP-27/37 operational amplifiers combine excellent precision and high-speed performance with a peak-to-peak noise that is just 80 nV in the low-frequency instrumentation range and just 3 $nV/\sqrt{Hz}$ in the audio-frequency range. The OP-27 is unity-gain stable, and the OP-37 is compensated for gains of five or more (see "Holding Down the Noise"). They demonstrate their powers impressively in difference amplifiers, instrumentation amplifiers, data-converter circuits, and phono preamplifier circuits, among other applications.

George Erdi, Staff Vice-President, Design
Tom Schwartz, Staff Product Marketing Engineer
Scott Bernardi, Senior Design Engineer
Precision Monolithics Inc.
1500 Space Park Dr., Santa Clara, CA 95050
Walter Jung, Consultant

A few simple examples illustrate some of the excellent design advantages of the OP-27/OP-37. The difference amplifier in Fig. 1 (top) has a gain of 1000 (R_f/R_{in} = 100 kΩ/100 Ω), a bandwidth of 63 kHz, and a common-mode rejection of better than 100 dB at 10 kHz.

However, the source resistors in this and other configurations tend to shift the input-noise ceiling. Even low-value, 100-Ω resistors increase the input-noise density to 3.5 $nV/\sqrt{Hz}$ at 1 kHz (up from 3.0 $nV/\sqrt{Hz}$ with the input shorted). Two 1-kΩ source resistors will shift input noise up to 5.8 $nV/\sqrt{Hz}$. The exact relations of input-noise voltage density, resistor noise, and source-resistor values are shown in Fig. 1 (bottom). To ensure that resistor noise does not

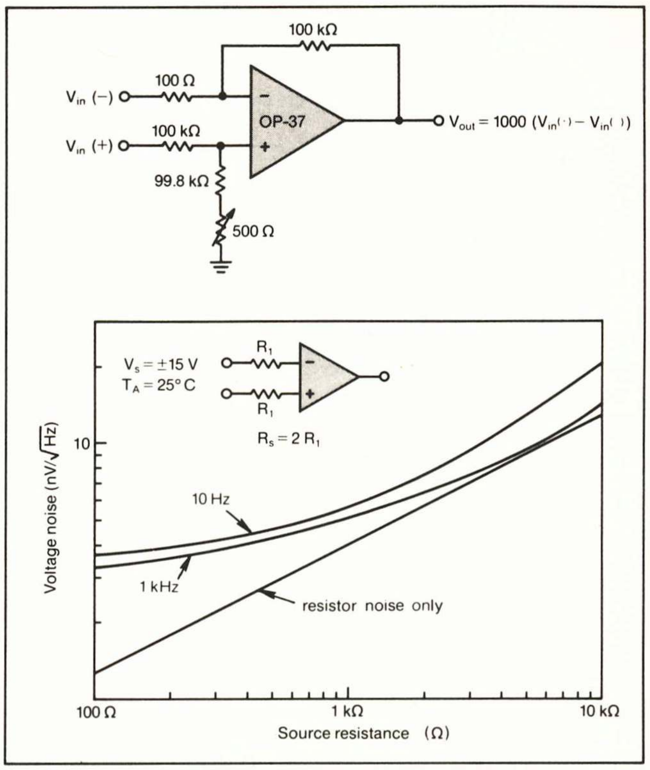


dominate, source resistances have to be kept below 500 Ω.

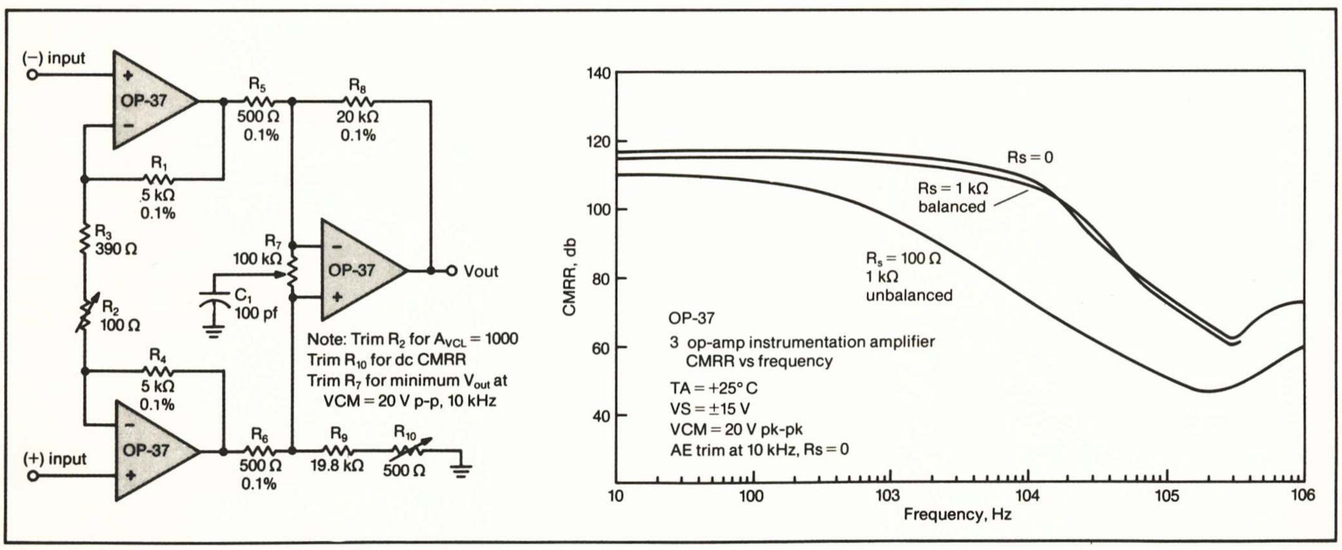
The more conventional three op-amp configuration in Fig. 2 (left) is slightly noisier than the difference amplifier in Fig. 1, but its bandwidth is much greater, with the same gain and excellent linearity. The input noise of this configuration is 4.9 $nV/\sqrt{Hz}$, which is $\sqrt{2}$-times larger because two input amplifiers are involved instead of one. (The third amplifier's contribution to the noise is negligible). In the circuit shown, the gain of the input stage is set at 25, and the gain of the second stage is 40. The overall gain of the circuit, then, is 1000.

The bandwidth of this amplifier is 800 kHz—extraordinarily wide for a precision instrumentation amp. When the gain of 1000 is factored in, the gain-bandwidth product is 800 MHz. The full-power bandwidth of the circuit, for a 20-V pk-pk output, is 180 kHz.

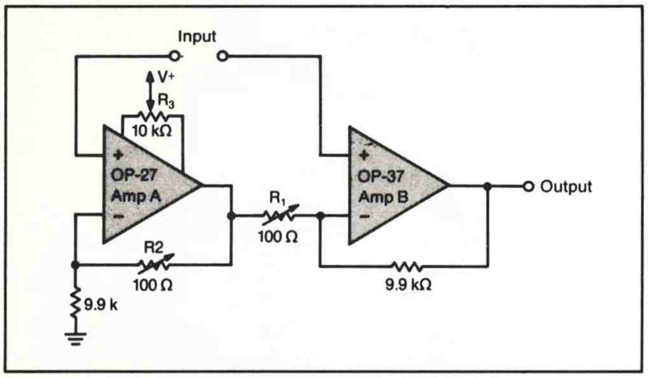
Resistor R_7 in the circuit is trimmed to optimize the instrumentation amplifier's common-mode rejection throughout its operating frequencies. As shown by Fig. 2 (right), a source imbalance can degrade the CMRR. For example, given 100-Ω source resistors with a 1-kΩ source imbalance (lower trace on curve), the CMRR drops to 80 dB at 5 kHz. Better than 100-dB CMRR can be maintained out



1. A single OP-37 can make a difference amplifier that has a gain of 1000 (top). Input noise can be kept to a minimum by using a low source resistance (bottom). Even 100-Ω source resistors will raise noise density.



2. A traditional instrumentation amplifier with three op amps provides high gain and wide bandwidth (left) when it incorporates OP-37 parts. The common-mode rejection over frequency in this circuit is improved by adjusting the resistance across the output amplifier's input terminals (right).



3. A two-op-amp instrumentation circuit offers high input impedances, a 17-V/μs slew rate, and a 450-kHz bandwidth.

beyond 20 kHz with either a low-resistance input (R_s = 0) or a completely balanced 1-kΩ source resistance on each side of the instrumentation amplifier's input.

Though the three op-amp circuit performs exceptionally well in most applications, it is subject to problems in very noisy environments or when the sensor is remote from the amplifier. In these situations, the shield on the differential input could acquire a potential relative to the sensor. This problem can be overcome by adding a BUF-03 and a few passive components. Because the BUF-03 is an open-loop buffer, with excellent capacitive-load-driving capability, it has no trouble driving the complex distributed impedances that are found in a long shielded line.

A two-op-amp configuration, with an input impedance of 3 GΩ, overcomes the very low input-impedance limitations of the one op-amp difference amplifier yet involves only one more active element. With two op amps, input noise increases by a $\sqrt{2}$ factor and referred noise becomes 4.6 nV/$\sqrt{\text{Hz}}$ at 10 Hz. In a 0.1 to 10-Hz bandwidth, the noise is just 120 nV pk-pk.

In the circuit in Fig. 3, one amplifier at the input stage is operated in a closed-loop gain of 1.0101. An OP-27 is necessary to satisfy stability requirements. The second amplifier is configured with an inverting gain of 99 (a noninverting gain of 100), to give a differential gain of 100 for the entire circuit.

The entire circuit consumes 180 mW at ±15 V and can easily swing ±10 V into a 600-Ω load. It also exhibits a 17-V/μs slew rate and a 450-kHz bandwidth.

The circuit has a gain error of only 6 ppm. However, because the bandwidth of the OP-27 is limited, the gain error increases at frequencies beyond the open-loop corner (7 Hz) of the device. The entire circuit has a 45-MHz gain-bandwidth product.

Resistor R_2 can trim the CMRR of the circuit, and specifications in excess of 114 dB are easily obtainable; R_1 can trim the gain of the circuit. But because the configuration is so simple, R_2 (CMRR trim) will have to be readjusted whenever the gain is changed to achieve maximum performance.

The offset can be easily nulled, if necessary, with a 10-kΩ potentiometer (R_3). The 10-kΩ value gives the best performance over temperature and keeps the temperature coefficient of the potentiometer out of any T_cV_{os} calculations. Attention to this kind of detail has its reward in a T_cV_{os} of 0.3 μV/°C. In a more dramatic fashion, when the circuit is nulled at 25°C, the typical output drift is only 3 mV over the full military temperature range.

Cutting noise in data-converter circuits

Another application for which the OP-27/37 is well suited is as an output amplifier for a high-resolution, current-output, digital-to-analog converter (Fig. 4, top). In many high-resolution data-conversion systems, the least-significant bit is so small that it is obscured in the current noise of the output amplifier. The ultra-low noise of OP-27/37, however, should improve the performance of 12 and 16-bit systems.

The OP-27/37, for example, can be placed in a 12-bit data-conversion system with a 1-V full-scale output. The resulting ½-LSB is only 122 μV, which is beyond the capacity of many op amps to resolve from their own noise floors. The OP-27/37 will not only resolve 122 μV well above its input-noise voltage, but also paves the way for new 12-bit d-a systems that can be operated on dual ±5-V supplies.

For a 1-V full-scale output, the slewing time of the OP-27 is only 350 ns. Settling time to ½ LSB, as a consequence, can be within a couple of microseconds—depending on the d-a converter used. The settling time can be minimized by adjusting the feedback capacitor, C_f, and the stabilizing resistor, R_a (R_a must be several orders of magnitude greater than feedback resistor, R_f) to cancel the effect of the output capacitance of the d-a converter.

In a d-a converter system processing 16 bits, with a 5-V full-scale output, the noise contributed by the OP-27 is more than 111 dB below the full-scale output. Here, 1 LSB is 76 μV. Over a passband from 0.1 Hz to 100 kHz, the OP-27 contributes only 0.95 μV rms of noise, and the 1.25-kΩ feedback resistor contributes 1.46 μV, for a total of 1.74 μV rms (Fig. 4, bottom). Converting this rms figure to peak-to-peak noise (multiplying rms by a statistical average of 7.8) provides an amplifier-noise voltage of 13.9 μV peak-to-peak (with 99.99% assurance)—less than 20% of the least-significant bit. The signal-to-noise ratio (20 log 5 V/13.9 μV) is better than 111 dB.

Even one of the best precision and low-noise op amps, the OP-07 has a noise voltage three times higher than that of the OP-27. In the same application, it could contribute as much as 26-μV noise, pk-

pk or better than 65% of the ½-LSB error budget.

Figure 5 (left) is an example of a phono preamplifier circuit using the OP-27 for A_1; R_1-R_2-C_1-C_2 form a very accurate RIAA network with standard component values. The popular method to accomplish RIAA phono equalization is to employ frequency-dependent feedback around a high-quality gain block. Properly chosen, an RC network can provide the three necessary time constants of 3180, 318 and 75 μs.[1]

For initial equalization accuracy and stability, precision metal-film resistors and film capacitors of polystyrene or polypropylene are recommended, since they have low voltage coefficients, dissipation factors, and dielectric absorption.[4] (High-K ceramic capacitors should be avoided here, though low-K ceramics—such as NPO types, which have excellent dissipation factors, and somewhat lower dielectric absorption—can be considered for small values or where space is at a premium.)

Noise and gain considerations

The OP-27 brings a 3-nV/$\sqrt{Hz}$ voltage noise and 0.4-pA/$\sqrt{Hz}$ current noise to this circuit. To minimize noise from other sources, R_3 is set to a value of 100-Ω, which generates a voltage noise of 1.3 nV/$\sqrt{Hz}$. The noise increases the 3-nV/$\sqrt{Hz}$ of the amplifier by only 0.7 dB. With a 1-kΩ source, the circuit noise measures 63 dB below a 1-mV reference level, unweighted, in a 20-kHz noise bandwidth.

Gain (G) of the circuit at 1-kHz can be calculated by the expression

$$G = 0.101\ (1 + \frac{R_1}{R_3}).$$

For the values shown, the gain is just under 100 (or 40 dB). Lower gains can be accommodated by increasing R_3, but gains higher than 40 dB will show more equalization errors, because of the 8-MHz gain-bandwidth of the OP-27.

This circuit is capable of very low distortion over its entire range, generally below 0.01% at levels up to 7 V rms. At 3-V output levels, it will produce less than 0.03% total harmonic distortion at frequencies up to 20 kHz.

Capacitor C_3 and resistor R_4 form a simple −6-dB-per-octave rumble filter, with a corner at 22 Hz. As an option, the switch-selected shunt capacitor C_4, a nonpolarized electrolytic, bypasses the low-frequency rolloff. Placing the rumble filter's high-pass action after the preamp has the desirable result of discriminating against the RIAA-amplified low-frequency noise components and pickup-produced low-frequency disturbances.

A preamplifier for NAB tape playback is similar to an RIAA phono preamp, though more gain is

Holding down the noise

Within an amplifier circuit, offset voltage can be trimmed, the operating temperature can be kept constant to erase temperature-drift effects, and source resistances can be kept low to minimize bias-current errors. Noise, however, cannot be eliminated.

The noise spectrum of a typical op amp is shown in Fig. A (top line). Two distinct regions can be defined: the flat or white noise band, and the low-frequency 1/f range where:

$$\text{voltage noise } \alpha\ f^{-1/2}$$

The white-noise region is important in audio applications, and low noise (below 50-Hz) is important in precision instrumentation, such as chart recorders. Achieving low noise in each noise band involves separate, and somewhat independent, design considerations. Many low-noise audio amplifiers have high noise at low frequencies simply because their 1/f corner occurs at a relatively high frequency (Fig. A, middle line).

The OP-27/37 optimizes both regions with only 3-nV/$\sqrt{Hz}$ white noise, and a very low 1/f corner at 2.7 Hz (Fig. A, bottom line), which results in a 0.1 to 10-Hz noise of just 80 nV peak-to-peak (Fig. B).

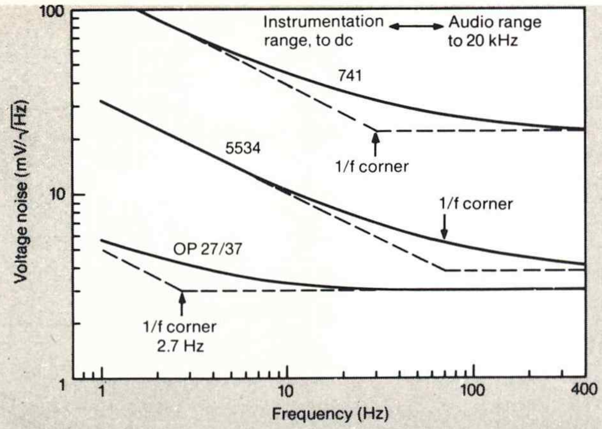
The simplified schematic of Fig. D illustrates the design principles. The resistively loaded input stage ensures that input noise is a function of the input transistors Q_1 and Q_2 only. The input transistors are operated at a relatively high current level (120 μA), since voltage noise is inversely proportional to the square root of the collector current. The resultant high-input bias current is reduced to low levels by a bias-current cancellation scheme (not shown). The device geometry of the quad-connected input transistors is such that the noise-causing base-spreading resistance is minimized. Input-bias current is 10 nA typical and input-offset current is 7 nA typical.

High-speed performance is helped by the high operating current of the input stage; a gain of 100 can be achieved with high bandwidth. Because of the excess gain in the first stage, the slow lateral-pnp second stage can be broadbanded with degenerating resistors R_{23} and R_{24} and a low controlled gain of 20. Feed-forward capacitor C_3 can bypass the second stage at significantly higher frequencies than were possible with previous three-stage precision op amp designs.

Resistors R_9, R_{11}, and R_{12} let the frequency response be shaped with appropriately placed ZEROs. Therefore, a bandwidth of 8 MHz is achieved with 70° phase margin (OP-27). A decompensated version of the circuit, which is stable in gains of five or more (OP-37), slews at 17 V/μs. The gain-bandwidth product is 63 MHz.

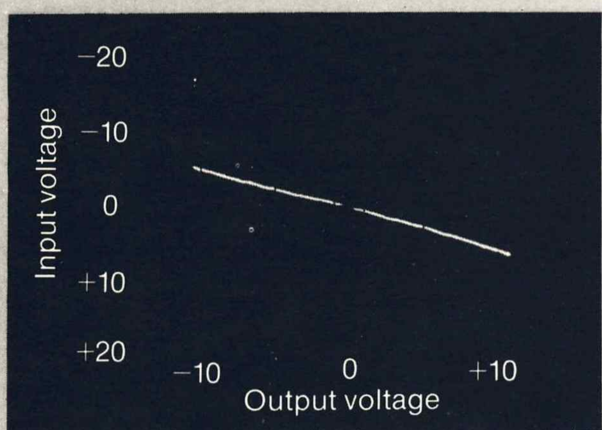
The open-loop gain of the OP-37 is still 6300 at 10 kHz, which is important in audio applications. The

(a)

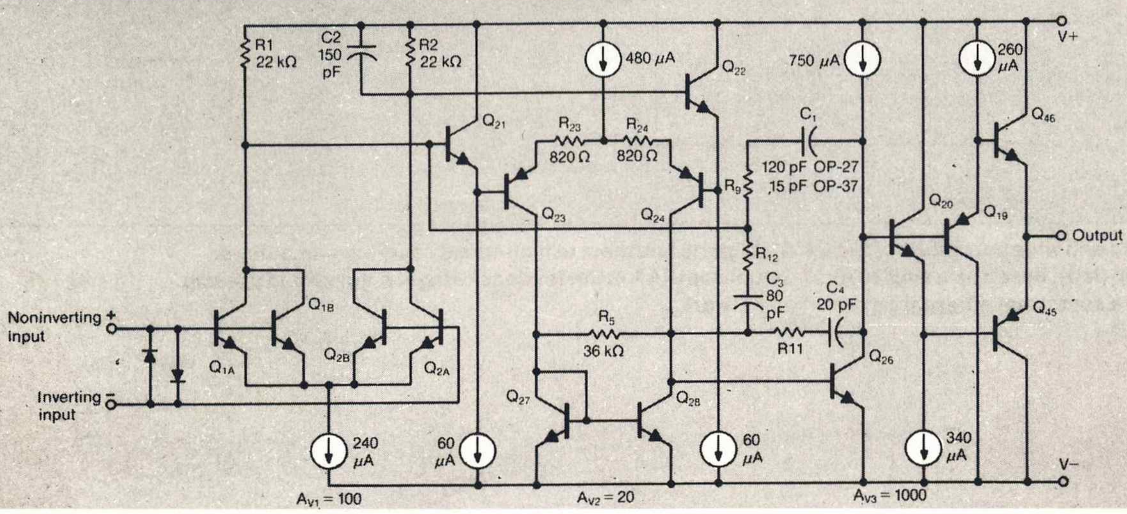


(b)

(c)



(d)



excellent dc and low-frequency specifications of the device eliminate the need for expensive ac coupling in many audio systems.

Precision performance requirements often complement the demands of a low-noise design. The simple, resistively loaded, input stage has been demonstrated in the past to be the best for low offset voltage and drift with time and temperature. The load resistors are excellent for on-wafer zener-zap adjustment of offset voltage to a few microvolts. Quad-connecting the input transistors (Q_{1A}, Q_{1B} and Q_{2A}, Q_{2B}) has the well-known benefit of canceling thermal gradients and variations in the epi layer and diffusions.

To take advantage of the device's low noise performance, all other error-producing parameters must have excellent specifications. On the OP-27/37, offset voltage (V_{OS}) is typically 10 μV. V_{OS} drift with time and temperature is 0.2 μV/month and 0.2 μV/°C. Voltage gain is 2 million, bias current is 10 nA, and common-mode and power-supply rejection are both 126 dB.

In addition to their low noise, high gain, and wide bandwidth, the OP-27/37 op amps are extremely linear under a variety of gains and load conditions. As shown in Fig. C, the output, measured with a Tektronix 577-178 linear tester, is extremely linear through its −10-V to +10-V swing, even as it delivers 10 mA into the load. The straightness of this line translates into a gain error or nonlinearity of about 2 ppm.

In most application areas, the gain linearity of the amplifier will be limited by the stability and temperature coefficients of source and feedback resistors. To take advantage of the precision specifications of the OP-27/37, therefore, only precision parts (such as metal-film or Bulk Metal resistors) should be used.

typically demanded, along with equalization requiring a heavy low-frequency boost. The circuit in Fig. 5 (left) can be readily modified for tape use, as shown by Fig. 5 (right).

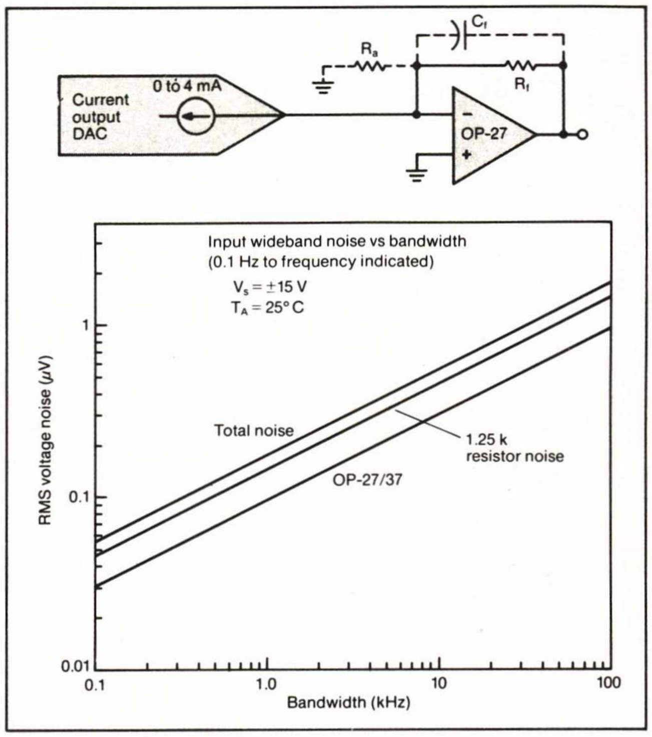
While the tape-equalization requirement has a flat high-frequency gain above 3 kHz (T_2=50 μs), the amplifier need not be stabilized for unity gain. The decompensated OP-37 provides a greater bandwidth and slew rate. For many applications, the idealized time constants shown may require trimming of R_1 and R_2 to optimize frequency response for nonideal tape-head performance and other factors.[5]

The network values of the configuration yield a 50-dB gain at 1 kHz, and the dc gain is greater than 70 dB. Thus, the worst-case output offset is just over 300 mV. A single 0.47-μF output capacitor can block this level, without affecting the dynamic range.

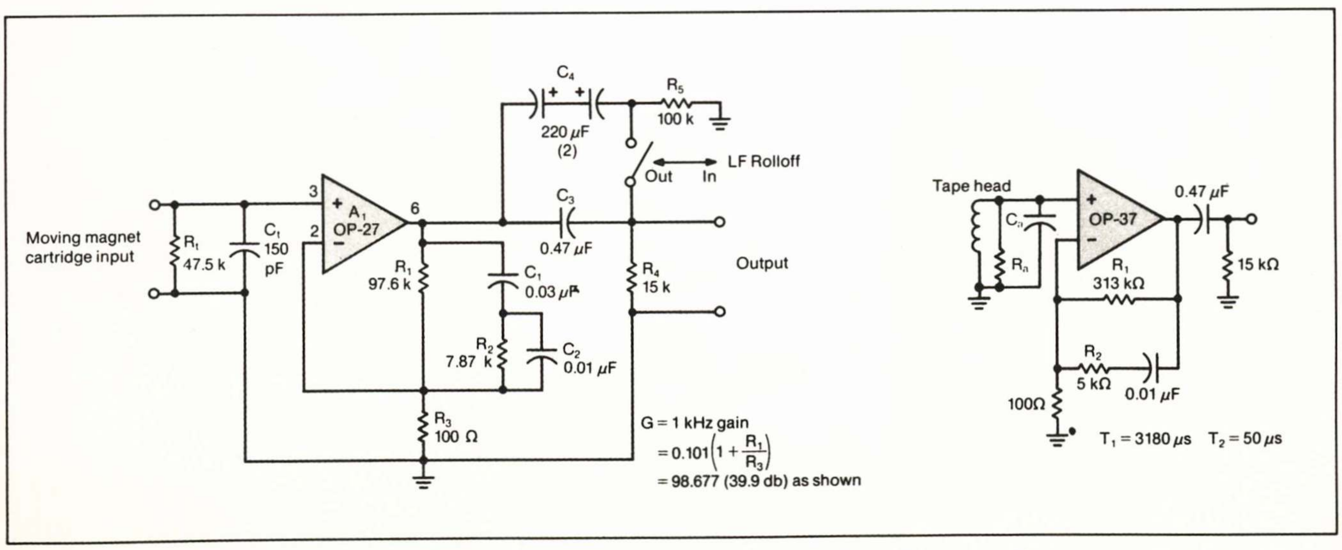
The tape head can be coupled directly to the amplifier input, since the worst-case bias current of 80 nA with a 400-mH, 100-μin. head (such as the PRB2H7K) will not be troublesome.

One potential tape-head problem is presented by amplifier bias-current transients which can magnetize a head. The OP-27 and OP-37 are free of bias-current transients, upon power up or power down. However, it is always advantageous to control the speed of power-supply rise and fall, to eliminate transients.[7]

In addition, the dc resistance of the head should be carefully controlled, and preferably below 1-kΩ.



4. At the output of a current-supplying d-a converter (top), a single OP-27 offers several options for resolution and gain, depending on the choice of feedback resistor (R_f). A 12-bit, 1-V system, for example, can be built with R_f = 250 Ω; 1 LSB equals 1 V/2^{12} or 244 μV. A 16-bit, 5-V system uses a 1.25-kΩ feedback resistor. In this case, 1 LSB equals 5 V/2^{16} or 76 μV. Since the feedback resistor contributes to the overall noise of the system (bottom), only precision low-noise components should be used.



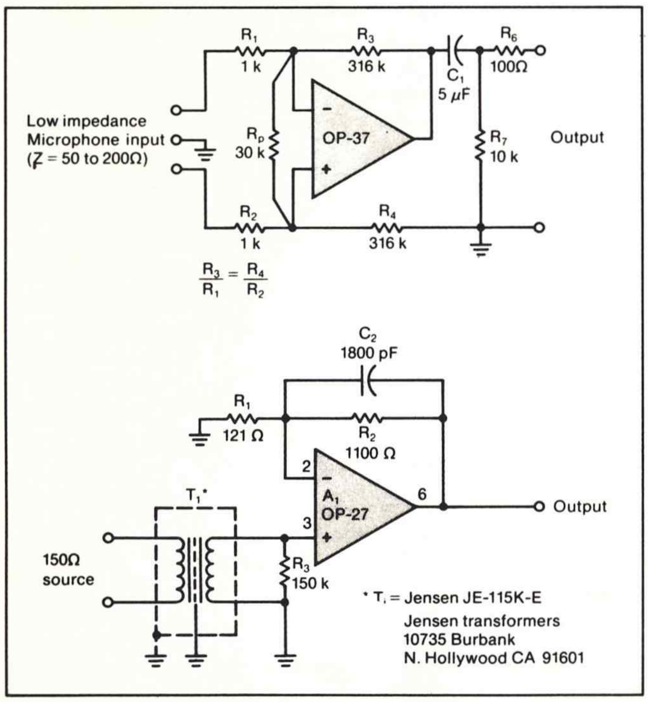
5. The low noise and wide bandwidth of the OP-27/37 parts suit them to high-quality audio preamplifiers. A phono preamp (left), based on a single OP-27, equalizes RIAA in the feedback stage. A tape-head preamp (right) employs a somewhat different equalization network.

For this configuration, the bias-current-induced offset voltage can be greater than the 100-μV maximum offset, if the head resistance is not sufficiently controlled.

A simple but effective fixed-gain transformerless microphone preamp (Fig. 6, top) amplifies differential signals from low-impedance microphones by 50 dB, and has an input impedance of 2 kΩ. Because of the high working gain of the circuit, an OP-37 helps to preserve bandwidth, which will be 110 kHz. As the OP-37 is a decompensated device (minimum stable gain of 5), a dummy resistor, R_p, may be necessary, if the microphone is to be unplugged. Otherwise the 100% feedback from the open input may cause the amplifier to oscillate.

Common-mode input-noise rejection will depend upon the match of the bridge-resistor ratios. Either close-tolerance (0.1%) types should be used, or R_4 should be trimmed for best CMRR. All resistors should be metal-film types, for best stability and low noise.

Noise performance of this circuit is limited more by the input resistors R_1 and R_2 than by the op amp, as R_1 and R_2 each generate a 4-nV/$\sqrt{\text{Hz}}$ noise, while the op amp generates a 3-nV/$\sqrt{\text{Hz}}$ noise. The rms sum of these predominant noises sources will be about 6 nV/$\sqrt{\text{Hz}}$, equivalent to 0.9 μV in a 20-kHz noise bandwidth, or nearly 61 dB below a 1-mV input signal. Measurements confirm this predicted performance.



6. For a simple microphone preamp, the OP-37 can work without a transformer (top). However, a Jensen transformer (bottom) establishes low noise with low-impedance microphones.

For applications demanding appreciably lower noise, a high-quality microphone-transformer-coupled preamp (Fig. 6, bottom), incorporates the internally compensated OP-27. T_1 is a JE-115K-E 150/15-kΩ transformer which provides an optimum source resistance for the OP-27 device. The circuit has an overall gain of 40 dB, the product of the transformer's voltage setup and the op amp's voltage gain.

Gain may be trimmed to other levels if desired, by adjusting R_2 or R_1. Because of the low offset voltage of the OP-27, the output offset of this circuit will be very low, 1 mV or less, for a 40-dB gain. The typical output blocking capacitor can be eliminated in such cases, but is desirable for higher gains to eliminate switching transients.

Capacitor C_2 and resistor R_2 form a 2-μs time constant in this circuit, as recommended for optimum transient response by the transformer manufacturer. With C_2 in use, A_1 must have unity-gain stability. For situations where the 2-μs time constant is not necessary, C_2 can be deleted, allowing the faster OP-37 to be employed.

Some comment on noise is appropriate to understand the capability of this circuit. A 150-Ω resistor and R_1 and R_2 gain resistors connected to a noiseless amplifier will generate 295 nV of noise in a 20-kHz bandwidth, or 70.6 dB below a 1-mV reference level. Any practical amplifier can only approach this noise level; it can never exceed it. With the OP-27 and T_1 specified, the additional noise degradation will be close to 4.9 dB (or −65.7 referenced to 1 mV).□

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