Designer's guide to measuring op-amp distortion PART 1

Op-amp distortion measurement bypasses test-equipment limits

Jerald Graeme, Burr-Brown Corp

Part 1 of this 2-part series introduces the theory involved in measuring the low distortion levels of state-of-the-art op amps. It also provides simple methods for characterizing some low-distortion op amps.

Until recently, distortion performance was not important in most op-amp applications. Now, common use of the fast Fourier transform (FFT) extends the importance of op amps' distortion beyond audio applications into general signal processing. Any distortion introduced by an amplifier produces erroneous Fourier components. To predict these error components, you must first characterize your op amp's distortion. But op amps' distortion performance often surpasses that of available test equipment, defying characterization. Making the amplifier-under-test part of the test system solves this characterization problem. This solution works exclusively with feedback amplifiers, op amps included.

Feedback reduces an amplifier's distortion—at its output—to minuscule levels. Feedback also separates the amplifier's distortion from the test signal. This separated distortion is none other than the error signal fed back to the op amp's inputs. Once separated, the amplifier-distortion signal is insensitive to any distortion in the incoming test signal. Also, the separated signal has a reduced magnitude that reduces the dynamic range your test equipment has to handle.

Three distortion-measurement methods capitalize on the signal-separating action of op-amp feedback. In the first method, you measure the separated signal directly. This method circumvents test-equipment limitations. In the second method, selectively amplifying the amplifier's distortion raises this error signal above the threshold of the test equipment. Finally, the third method removes the test signal yet avoids measuring any effects of the added amplifier. This method bootstraps the op amp's power supplies on the test signal itself to remove the test signal from the measurement. Part 1 of this series covers direct measurement and selective amplification; Part 2 covers selective amplification and bootstrapping.

Each approach greatly improves distortion resolution but also has specific constraints. Signal separation adds an amplifier to the test system; selective amplification reduces the measurement bandwidth; and bootstrapping requires using a signal to drive the reference point of the op amp's power supplies.

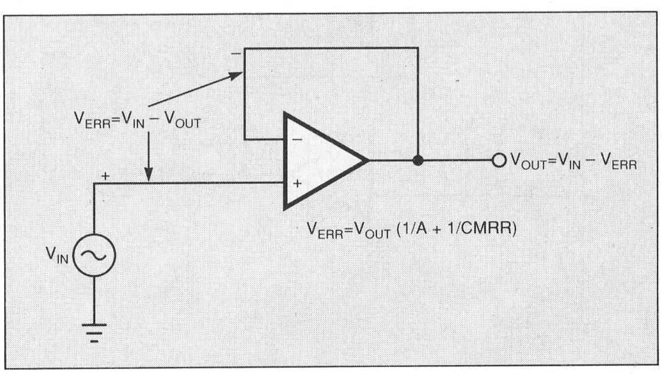

Fig 1—Feedback separates an op amp's distortion products from the test signal by developing a signal V_{ERR} equal to the difference between input and output signals.

Noise seldom limits op-amp-distortion measurement. Only in very low-distortion op amps does noise impose a limit on distortion analyzers. Amplifier noise is almost never a problem for spectrum analyzers because they are highly insensitive to noise.

Translate to ground

First consider how feedback separates the amplifier-distortion products from the test signal. This consideration is fundamental to each of the measurement circuits that follow. You can visualize the signal separation most easily with a voltage follower **(Fig 1)**. In **Fig 1**, input signal V_{IN} drives the op amp's input to produce output signal V_{OUT}, and a simple loop equation shows that

$$V_{OUT}=V_{IN}-V_{ERR},$$

where V_{ERR} is the differential-input error signal of the op amp.

As trivial as this equation seems, it holds the answer to measuring op-amp distortion with high resolution. The equation states that the output signal, V_{OUT}, is a replica of the input signal, V_{IN}, except V_{OUT} does not include the input error signal V_{ERR}. Thus, any distortion the amplifier introduces is in V_{ERR}.

Measuring V_{ERR} instead of V_{OUT} removes any effects of signal-generator distortion and reduces the dynamic range required of your test equipment. The op amp's open-loop gain and common-mode rejection attenuate whatever test signal remains in V_{ERR}.

Distortion measurement with **Fig 1**'s setup requires additional processing of the signal V_{ERR}. Signal V_{ERR} rides on the input signal V_{IN}. Consequently, any ground-referenced measurement of V_{ERR} still includes the test signal V_{IN}.

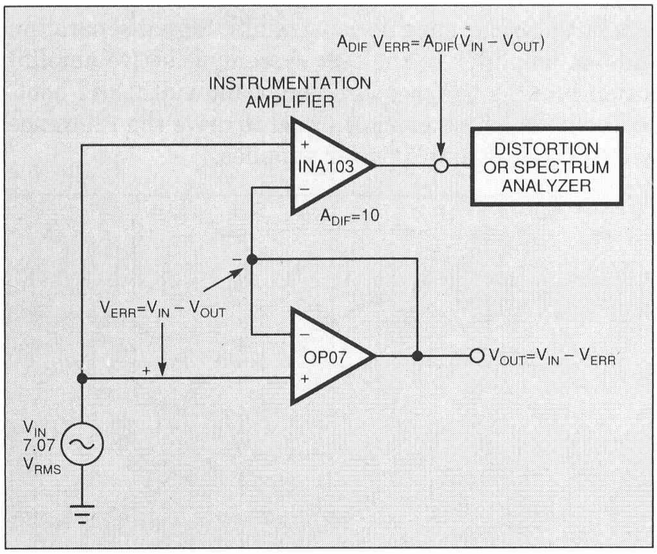

Fig 2—Directly implementing Fig 1's signal separation requires adding an instrumentation amplifier to provide a ground-referenced signal.

The instrumentation amplifier in **Fig 2** references V_{ERR} to ground and increases the signal level presented to the analyzer. Finding a low-distortion instrumentation amplifier is easier than producing a better signal generator and a better signal analyzer. This instrumentation-amplifier alternative serves the measurement of intermediate levels of distortion in feedback amplifiers.

After measuring distortion using the setup in **Fig 2**, you must adjust your results. These adjustments transform the distortion percentage measured in V_{ERR}, $THD+N_M$, to the equivalent percentage present in V_{OUT}, $THD+N_O$. ($THD+N_M$ is the measured valve and $THD+N_O$ is the corresponding output distortion and noise.)

$$THD+N_O=(V_{ERR}/V_{OUT})THD+N_M.$$

When using a spectrum analyzer, adjusting the THD result as you calculate it is the easiest way to go. Taking this tack necessitates two changes. THD expresses distortion as the ratio of the rms sum of the distortion products to the signal fundamental:

$$THD=\sqrt{(V_2^2+V_3^2+V_4^2+\ .\ .\ .\ )}\times(100\%)/V_1.$$

Here, V_1 represents the fundamental component of the signal, and V_2, V_3, V_4 and so forth represent the distortion components. For the measurement shown in **Fig 2**, the magnitude of V_{OUT} substitutes for the fundamental V_1 to correct for the smaller fundamental signal present in V_{ERR}. Also, the harmonic amplitudes measured require adjusting to account for the gain they receive from the instrumentation amplifier. For this adjustment, divide the overall THD equation by the instrumentation amplifier's differential gain, A_{DIF}.

$$THD_{OUT}=\sqrt{(V_2^2+\ V_3^2+\ V_4^2+\ .\ .\ .\ )}\times 100\%/A_{DIF}V_{OUT}.$$

For the unity-gain amplifier under test, subtraction obviously separates the op amp's distortion from the test signal. However, this condition is a coincidence unique to the voltage follower. In other op-amp configurations, the signal translation of V_{ERR} does not subtract the op amp's output from the input signal.

Fig 3 shows the generalized, noninverting, feedback configuration along with the equations relating V_{ERR} to V_{OUT}. Here, a feedback network attenuates the effect of V_{OUT} on V_{ERR}. Thus, the amplifier-distortion products reflected in V_{ERR} are smaller than those in V_{OUT}.

As before, you must separate the V_{ERR} signal from the common-mode test signal in **Fig 3**'s circuit. The first method for this separation is translation to a ground-referenced signal **(Fig 4)**. Distortion measurement with this configuration is easiest to see by considering the circuit to be an extension of **Fig 2**'s voltage follower. In **Fig 4**, the voltage-divider action of the feedback network presents a signal $V_{OUT}R_1/(R_1+R_2)$ to the amplifier's inverting input. For the voltage follower, this signal was the full V_{OUT}. Now, the feedback signal is attenuated, and a simple loop equation shows that for **Fig 4**,

$$V_{ERR}=V_{IN}-(V_{OUT}R_1/(R_1+R_2)).$$

Fig 4's circuit amplifies V_{IN} and its distortion in producing V_{OUT}. Thus, subtracting V_{OUT} from V_{IN}, as with **Fig 2**, would not remove the generator's distortion for **Fig 4**. However, subtracting an appropriately attenuated V_{OUT} from V_{IN} does remove this distortion. **Fig 4** has a gain of $(R_1+R_2)/R_1$. Then, feedback attenuates V_{OUT} by the *inverse* of this gain or $R_1/(R_1+R_2)$.

For a distortion-analyzer measurement like that shown in **Fig 4**, first compensate the result for the smaller fundamental measured through V_{ERR}. Multiply the measured $THD+N_M$ result by V_{ERR}/V_{OUT} as before. This calculation yields the input $THD+N_{IN}$ result, which you then multiply by the $1/\beta=(R_1+R_2)/R_1$ of the op amp's configuration.

$$THD+N_O=\frac{V_{ERR}\,(R_1+R_2)}{V_{OUT}\,R_1}\,THD+N_M$$

$$=\frac{R_1+R_2}{R_1}\,THD+N_{IN}.$$

You must also adjust your results for spectrum-analyzer measurements using **Fig 4**'s setup. Once again, you discard the measured fundamental because it does not represent the output signal. Then, substitute V_{OUT} for fundamental amplitude V_1 in the THD equation and divide this equation by A_{DIF} to remove the effect of the instrumentation amplifier's gain. For **Fig 4**, also make a gain adjustment for the circuit's gain of $1/\beta=(R_1+R_2)/R_1$.

$$THD_{OUT}=\frac{(R_1+R_2)\,\sqrt{(V_2^2+V_3^2+V_4^2+\dots)}}{R_1\,A_{DIF}\,V_{OUT}}\,(100\%).$$

Signal separation extends to inverting case

For the generalized inverting amplifier, distortion resolution is even greater **(Fig 5)** than for the noninverting amplifier. The most significant improvement with inverting circuits actually results from removing the instrumentation amplifier of **Fig 4**. The inverting configuration of **Fig 5** removes common-mode voltage from the op amp's input and avoids the added amplifier along with the added amplifier's distortion.

For the inverting circuit in **Fig 5**, the relationship between input and output distortion is not as obvious as with **Fig 4**'s circuit. Previously, the feedback network relayed a large signal to the amplifier's input. But inverting circuits keep this input near zero voltage, balancing V_{IN} and V_{OUT} at the amplifier's input. Both signals influence the voltage at the inverting input through the feedback network. To find the result, consider the two signals separately using superposition. This exercises the feedback network as a voltage divider driven from each end. Then, the amplifier input signal is

$$V_{ERR}=\frac{V_{IN}\,R_2}{R_1+R_2}-\frac{V_{OUT}\,R_1}{R_1+R_2}.$$

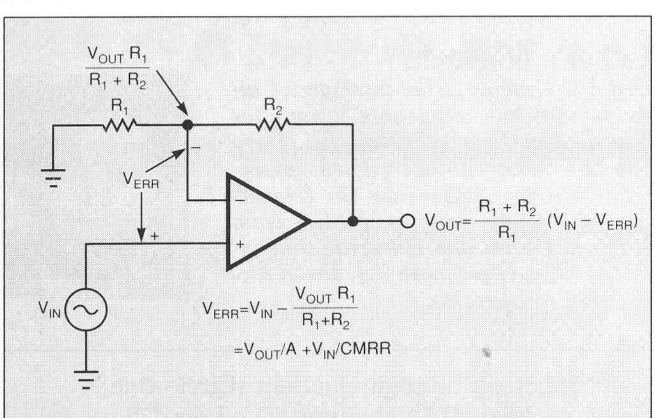

Fig 3—In the generalized feedback case, the output signal, along with its distortion, reflects to V_{ERR} through an attenuation.

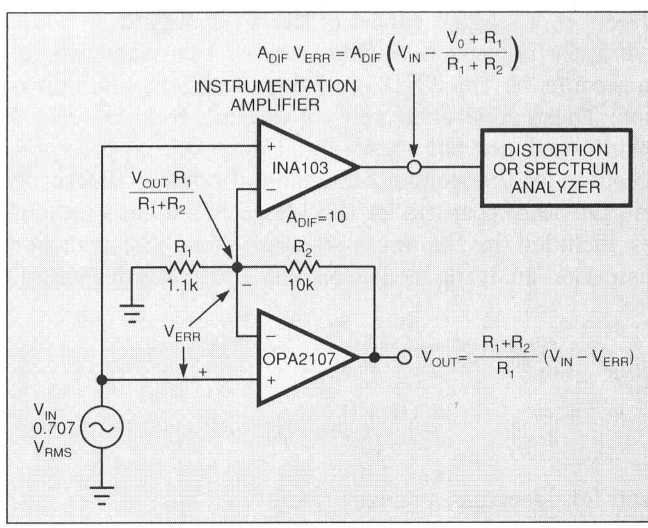

Fig 4—The amplifier's distortion products, included in V_{ERR}, remain separated from the test signal in measurements of the generalized noninverting circuit.

MEASURING OP-AMP DISTORTION

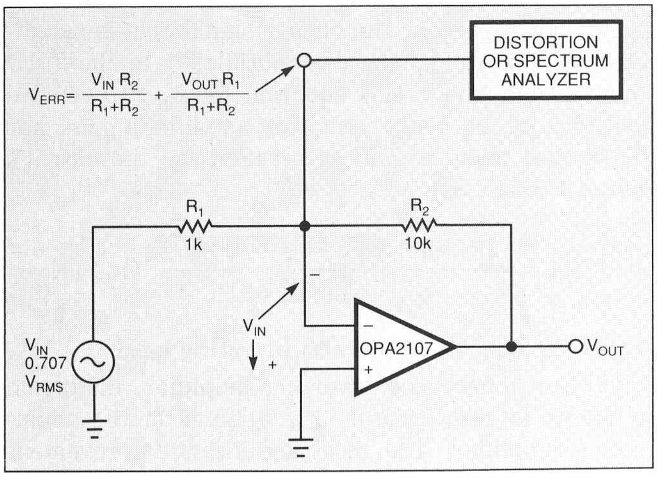

Fig 5—Inverting circuits also separate distortion and test signals. And these circuits obviate the previous measurement amplifier along with its distortion.

Although not immediately obvious, the distortion introduced by V_{IN} still cancels in this V_{ERR} signal. The above equation shows that signal V_{IN} influences V_{ERR} directly in the first term of the equation and then indirectly through feedback in the second term.

In the direct path, V_{IN} contributes to V_{ERR} through an attenuation of $-R_2/(R_1+R_2)$. Added to this contribution is the V_{IN} component transmitted through V_{OUT}. In this path, V_{IN} and its distortion products first receive a forward gain of $-R_2/R_1$ to produce V_{OUT}. Feedback then attenuates V_{OUT} by a factor of $-R_1/(R_1+R_2)$. The total gain of this path is the product of the forward gain and the feedback attenuation, or $R_2/(R_1+R_2)$. This product has the same magnitude as the attenuation of the direct path above, but these two gains have opposite polarities. Thus, the direct and feedback distortion effects of V_{IN} again cancel in the V_{ERR} signal.

Fig 5's measured results require two adjustments to account for the THD_{OUT} of the amplifier's configuration. These adjustments follow directly from the **Fig 4** results and use the same equations. One adjustment accounts for the smaller fundamental actually measured and the other corrects for the $1/\beta$ gain that the harmonics included in the measurement don't receive. For distortion-analyzer measurements using **Fig 5**'s setup,

$$THD+N_O = \frac{V_{ERR}\,(R_1+R_2)}{V_{OUT}\,R_1}\,THD+N_M$$
$$= \frac{(R_1+R_2)}{R_1}\,THD+N_{IN}.$$

And for spectrum-analyzer results,

$$THD_O = \frac{(R_1+R_2)\,\sqrt{(V_2^2+V_3^2+V_4^2+\ldots)}}{R_1\,V_{OUT}}\,(100\%).$$

With no common-mode voltage, the inverting connection of **Fig 5** provides no information about CMRR-related distortion. This result is desirable for applications having no common-mode signal, and the result proves useful even where such a signal is present. The absence of CMRR distortion in **Fig 5** permits separating the gain- and CMRR-distortion effects.

First, a distortion measurement with the inverting circuit of **Fig 5** yields the gain-related distortion, THD_A. Then, distortion measurement with the noninverting connection of **Fig 4** provides the combined gain and common-mode distortion THD_{ACM}. Subtraction of the two THD results, in rms fashion, reveals the common-mode distortion (THD_{CM}). In equation form, this distortion is

$$THD_{CM} = \sqrt{(THD_{ACM})^2 - (THD_A^2)}.$$

The signal analyzer's loading at the op amp's summing junction also influences the measurement in **Fig 5**. Connecting the analyzer's input capacitance to this junction can affect both measurement bandwidth and frequency stability. Capacitance at the input of an op amp produces response peaking.

This capacitance reduces measurement bandwidth to no more than $f_P = \sqrt{(f_C/(2\pi R_2 C_I))}$. Here, f_P is the peak frequency, f_C is the unity-gain crossover of the op amp, and C_I is the capacitance at the op amp's input. A bypass capacitor around R_2 counteracts the response peaking. For 45° phase margin, the value of this capacitor is $1/\sqrt{(2\pi R_2 f_C/C_I)}$. EDN

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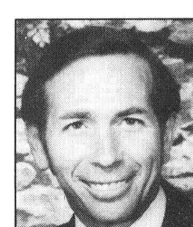
Author's biography



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Designer's guide to measuring op-amp distortion PART 2

Advanced techniques tackle advanced op amps' extremely low distortion

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The second part of this 2-part series describes how to measure the distortion of more complex amplifier circuits and how to handle the highest-performance op amps.

Selective amplification offers an alternative to the added amplifier described in Part 1 of this series. This alternative moderates, rather than negates, the limitations of signal generators and signal analyzers. In addition to separating distortion and test signals, selective amplification makes the amplifier distortion signal dominant in the measurement; however, it also reduces measurement bandwidth.

As with signal separation, the selective-amplification approach is easiest to understand starting with a voltage-follower connection. **Fig 1** shows a bootstrapped feedback network added to a voltage follower. In **Fig 1**, the common-mode rejection of the amplifier-under-test replaces the instrumentation amplifier used before. However, taking this tack moves the measurement back to the amplifier's output.

Resistors R_1 and R_2 form a feedback network that produces gain for V_{ERR} but not for V_{IN}. Signal V_{ERR}, which includes the amplifier's distortion products, appears across resistor R_1. There, this signal produces a feedback current that goes to resistor R_2. This operation develops an error-signal gain, $A_{ERR}=1+R_2/R_1$, for V_{ERR} alone.

Input signal V_{IN} does not experience this amplification because R_1 is bootstrapped rather than grounded. The resulting output signal for **Fig 1** is

$$V_{OUT}=V_{IN}-((R_1+R_2)/R_1V_{ERR}).$$

To V_{IN}, the circuit remains a voltage follower. The amplifier's output follows V_{IN} except for the difference produced by the amplified distortion signal. This difference is small as long as high loop gain keeps error signal V_{ERR} low.

Distortion above the measurement floor

Similarly, signal V_{IN} directly varies the voltage at the amplifier's noninverting input in **Fig 1**. Feedback forces the amplifier's inverting input to also follow this signal.

The selective amplification in **Fig 1** raises the relative magnitudes of the V_{ERR} distortion products for increased resolution. But the signal generator's distortion now remains in the signal measured. However, this distortion signal is not amplified and its relative

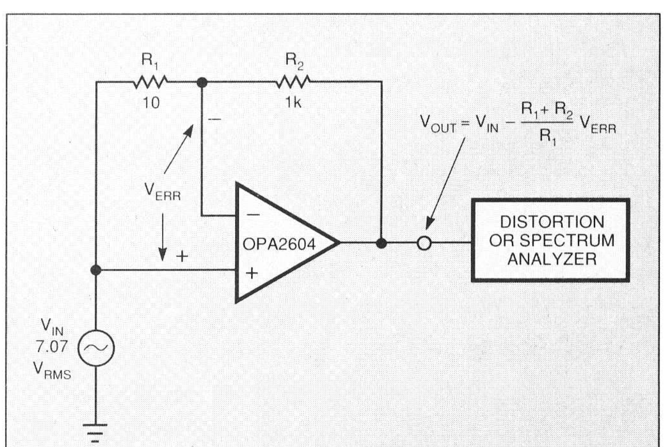


Fig 1—Selectively amplifying V_{ERR} magnifies the amplifier's distortion signal for direct measurement at the output of the amplifier tested.

significance diminishes in proportion to the gain V_{ERR} receives. Similarly, this gain moderates the dynamic range demands on the signal analyzer. Thus, selective amplification raises the amplifier-distortion signal above the measurement floor of your instruments.

Following the measurement, a THD calculation removes the effect of the selective gain. Divide the measured distortion by the distortion gain of $(R_1+R_2)/R_1$. For **Fig 1** the output-referred distortion for a voltage follower is:

$$THD+N_O=\frac{R_1}{(R_1+R_2)}\,THD+N_M=THD+N_{IN}$$

OR

$$THD_{OUT}=\frac{R_1\sqrt{(V_2^2+V_3^2+V_4^2+\ldots)}}{(R_1+R_2)\,V_1}.$$

At first blush, you'd think that maximizing the selective gain would achieve the greatest measurement accuracy. However, measurement bandwidth declines because of feedback-factor reduction as this gain increases (**Ref 1**). Because the op amp is now part of the measurement system, the amplifier's bandwidth limits resolution of higher-order distortion harmonics. Thus, you should choose the selective gain for **Fig 1's** setup to be as large as possible within your bandwidth constraints. Note that the low-value feedback resistors avoid adding noise.

Generalizing selective gain

The selective-gain approach of **Fig 1** extends to generalized noninverting and inverting op-amp configurations. The generalized noninverting version in **Fig 2** has R_3's added gain for selectively amplifying distortion products. Resistors R_1 and R_2 set the normal closed-loop gain presented to V_{IN}. As usual, this gain is simply $A_{CL}=1+(R_2/R_1)$. V_{ERR} experiences greater gain because it develops a feedback current through R_3, as well as through R_1. The resulting error-signal gain relates the parallel combination of resistors R_1 and R_3 and is $A_{ERR}=1+R_2/(R_1 \parallel R_3)$. The proper choice for R_3 makes V_{ERR}'s distortion dominant at the amplifier's output.

The distortion measurement's resolution remains unchanged between **Fig 1** and **Fig 2**. These circuits differ by the closed-loop gain, A_{CL}, supplied to V_{IN} and its distortion, but practical limits equalize the results. As A_{CL} increases, the magnitude of V_{IN} diminishes to maintain a given output-signal level. Thus, the magnitude of the input-signal distortion decreases by the same amount that its gain increases. The resulting output distortion arising from V_{IN} is, then, unchanged in magnitude from that of **Fig 1**. Adding R_3 keeps this distortion in the background by ensuring sufficient additional gain for the distortion products of V_{ERR}.

Dynamic-range constraints of the signal analyzer are also independent of A_{CL} in **Fig 2**. The relative levels of the fundamental signal and the distortion signals determine this range. For a given test condition, the output level is fixed and is essentially the level of the fundamental signal. To reduce dynamic-range requirements, raise the level of the distortion signal by amplifying V_{ERR}. This amplification results from either the intended closed-loop gain of the circuit or from this gain in conjunction with the selective gain R_3 provides. However the gain occurs, it raises the relative proportion of V_{ERR} in the output signal. As long as V_{ERR} receives sufficient gain, you can easily dis-

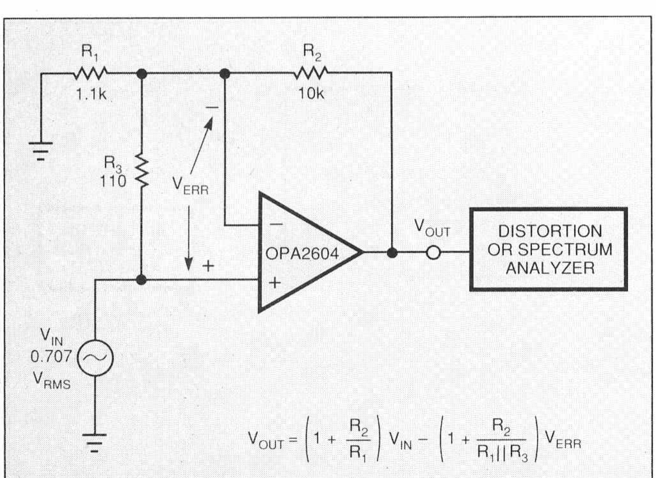


Fig 2—Adding R_3 extends selectively amplifying V_{ERR} to measuring the distortion of a generalized noninverting amplifier.

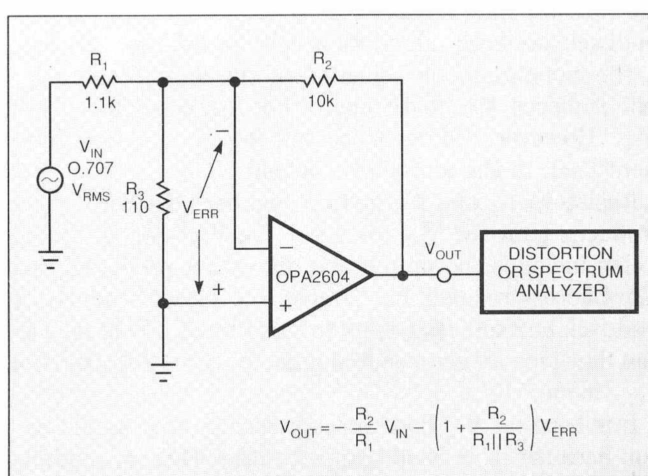


Fig 3—Selective amplification of an inverting amplifier follows directly from the noninverting case of Fig 2.

tinguish amplifier-distortion products in the output signal.

However, you must limit the gain you choose for V_{ERR}, or amplifier-response roll-off will restrict measurement of higher-frequency harmonics. The gain applied to V_{ERR}, not that applied to V_{IN}, sets the amplifier's bandwidth. To determine your measurement's bandwidth, calculate the feedback factor, considering R_3 to be grounded rather than bootstrapped. Then, for the circuit in **Fig 2**,

$$\beta = (R_1 \| R_3)/(R_1 \| R_3 + R_2).$$

This feedback factor defines a measurement-bandwidth limit of βf_C, where f_C is the unity-gain crossover frequency of the op amp. Beyond this limit, higher-order harmonics are attenuated in the measurement. Thus, again, you should consider a balance between test-equipment error suppression and higher-frequency resolution when choosing R_3.

Accounting for gain differences

However, determining the output-referred distortion still requires separating the A_{CL} and A_{ERR} effects on the circuit in **Fig 2**. Selectively amplifying the distortion signal makes its effect dominant in the measurement. You must again adjust the measured distortion to account for the difference in signal and distortion gains. To adjust the measurement result, remove the selective gain that the amplifier distortion receives. In **Fig 2**, resistors R_1 and R_2 supply a gain of $A_{CL} = 1 + (R_2/R_1)$ to both V_{IN} and V_{ERR}. R_3 supplies additional gain to V_{ERR}. This added gain $(1 + R_2/R_3)$ amplifies only the distortion signal. To compensate, divide the measured distortion result by this added gain.

$$THD+N_O = \frac{R_3}{(R_3+R_2)} THD+N_M = \frac{(R_1+R_2)}{R_1} THD+N_{IN}$$

OR

$$THD_{OUT} = \frac{R_3 \sqrt{(V_2^2+V_3^2+V_4^2+\ldots)}}{(R_3+R_2)\, V_1} (100\%)$$

The selective amplification in **Fig 2** translates directly for inverting op-amp configurations. To convert **Fig 2** to an inverting amplifier, simply switch the circuit connections to the common return and the input signal **(Fig 3)**. This switch returns the op amp's noninverting input and R_3 to ground and causes V_{IN} to drive R_1. As before, resistors R_1 and R_2 set the gain, A_{CL}, presented to V_{IN}, and resistor R_3 boosts this gain to a higher level, A_{ERR}, for V_{ERR}. This higher gain determines the feedback factor and resulting measurement's bandwidth.

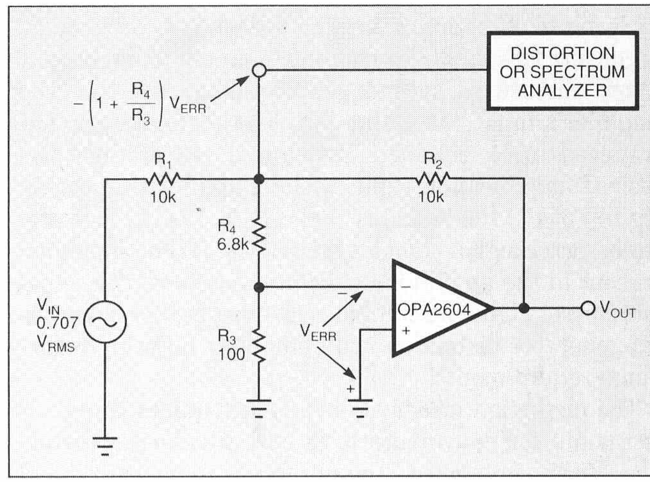


Fig 4—Adding R_4 combines selective amplification with signal separation for the inverting amplifier.

The circuit in **Fig 3** retains a measurement resolution that is independent of A_{CL}. Only gain A_{ERR} affects this resolution. Finally, convert the measured THD_M of **Fig 3** to THD_{OUT} or THD_{IN} using the equations for **Fig 2**.

The only way **Fig 3** differs from **Fig 2** is in the common-mode input signal of the amplifier. In the noninverting circuit in **Fig 2**, input signal V_{IN} is a common-mode signal to the amplifier's inputs, and it exercises nonlinearities in the amplifier's CMRR. The inverting circuit in **Fig 3** removes this common-mode signal from the amplifier's inputs. Then, only the gain nonlinearity of the amplifier influences the amplifier's distortion. This difference permits you to separate gain and CMRR distortion effects.

Combining the two methods

Selective amplification in the inverting case offers another alternative. Both selective amplification and signal separation work in inverting circuits. However, the combination places greater demands on measurement bandwidth. Selective amplification obviates the instrumentation amplifier used before. To eliminate the instrumentation amplifier, **Figs 1** and **2** move the signal measurement to the op amp's output. There, signal separation is compromised because the full test signal remains in the measurement.

This compromise is unnecessary for inverting configurations. As mentioned before, inverting configurations do not require the instrumentation amplifier for the signal-separation measurement. Thus, with inverting configurations you need not move the measurement to the amplifier's output. Instead, signal separation and selective amplification combine at the amplifier's input **(Fig 4)**. There, R_3 develops a feedback current with V_{ERR} just as before.

However, the circuit in **Fig 4** does not rely on R_2 to convert this feedback current to an amplified output error. Instead, a second resistor, R_4, added at the amplifier's input, does this job. The feedback current produced in R_3 conducts through R_4 to produce the desired amplification right at the amplifier's input. At the top of R_4, the signal is $-(1+R_4/R_3)V_{ERR}$. This amplified error signal remains free of the large test signal present in the amplifier's output. As before, this separated error signal permits measurements free from signal-generator distortion and eliminates large dynamic-range requirements.

The distortion measured in **Fig 4** requires three adjustments for converting it to output-referred distortion. First, compensate the difference in measured and actual fundamental signals as in previous signal-separation measurements. Then, make two gain adjustments. The measured signal receives a measurement gain of $(1+R_4/R_3)$ but does not receive the circuit closed-loop gain of $A_{CL}=(1+R_2/R_1)$. To compensate, divide the measured distortion by the measurement gain and multiply it by A_{CL}.

$$THD{+}N_O=\frac{R_3\,(R_1+R_2)\,V_{ERR}}{R_1\,(R_3+R_4)\,V_{OUT}}\,THD{+}N_M$$

$$=\frac{(R_1+R_2)}{R_1}\,THD{+}N_{IN}$$

OR

$$THD_{OUT}=\frac{R_3\,(R_1+R_2)\,\sqrt{(V_2^2+V_3^2+V_4^2+\ldots)}}{R_1\,(R_3+R_4)\,V_{OUT}}\,(100\%)$$

Fig 4 introduces an added attenuation to the circuit's feedback factor, restricting measurement bandwidth. In addition to the normal feedback attenuation of R_1 and R_2, a second feedback attenuation results from R_3 and R_4. R_3 and R_4 also produce a loading effect on the attenuation of R_1 and R_2. The net **Fig 4** feedback factor is

$$\beta=\frac{R_1R_3}{R_1R_2+R_1R_3+R_1R_4+R_2R_4+R_2R_3}$$

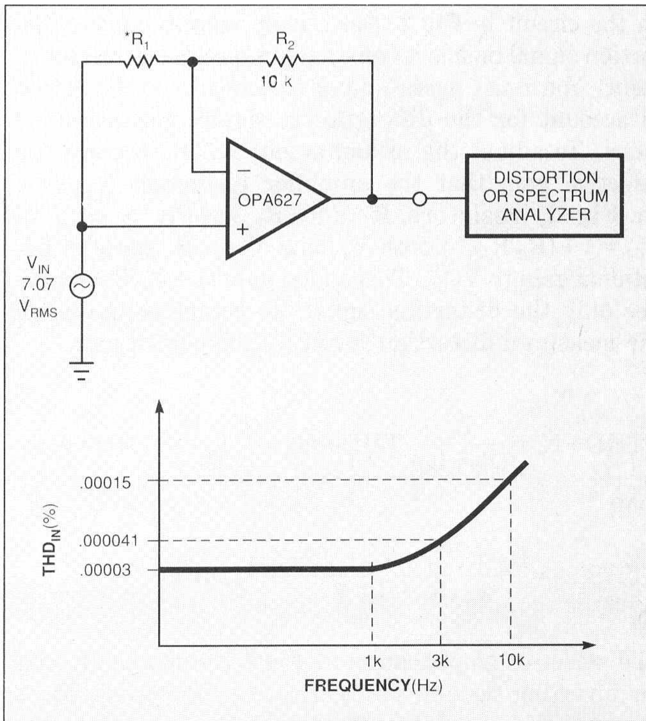
The relationship of bandwidth to gain bandwidth, $BW=\beta GBW$, then determines the bandwidth for the circuit in **Fig 4**. For the specific components of **Fig 4**, $\beta=0.0043$ and GBW=10 MHz for BW=43 kHz.

Because of the low feedback factor, this measurement's bandwidth is below the 80 kHz desired for audio applications. Other choices for R_3 and R_4 offer higher feedback factors to improve bandwidth, but such choices lower the selective gain. With less gain, the distortion signal's level is closer to the test equipment's measurement floor. Because of this compromise, you should use the circuit in **Fig 4** only where signal-generator distortion must be separated from the test signal. In other cases, the basic selective-gain configuration offers a better compromise.

The input capacitance of the signal analyzer, C_I, alters the feedback factor in **Fig 4**. This capacitance bypasses R_1 and can cause gain peaking or even oscillation. Such problems occur only if the break frequency of the bypass, $1/2\pi R_1C_I$, is within the amplifier's closed-loop bandwidth. In this case, add a compensating capacitor in parallel with R_2 to roll off the gain peaking. Choose this capacitor to break with R_2 at the same frequency that C_I breaks with $R_1 \parallel (R_3+R_4)$. Then, the feedback-divider action of the R_2 and R_1 legs remains approximately constant with frequency.

Gain variation extends resolution

Some op amps' distortion-measurement requirements exceed test equipment's capabilities even when you use the preceding methods. When your op amp



	*R_1	A	BW
20Hz TO 3 kHz	10	1001	16 kHz
4 TO 9 kHz	33	303	53 kHz
10 TO 20 kHz	100	101	160 kHz

Fig 5—For extremely low-distortion amplifiers, vary the selective gain to retain resolution and bandwidth.

has low distortion over wider bandwidths, or just extremely low distortion, you need variable test configurations to characterize fully its distortion-versus-frequency performance.

First, low distortion levels automatically rule out the basic signal-separation approach of Part 1 because that approach requires an instrumentation amplifier of even lower distortion than the op amp under test. Instead, use selective amplification, which places measurement bandwidth and measurement resolution in competition. You must maintain measurement bandwidth to around 80 kHz to resolve harmonics important to the audio range. This bandwidth limits the selective amplification to a gain of $1/\beta = GBW/80kHz$.

However, your setup need not maintain full bandwidth at every test frequency. The amplitude of distortion harmonics drops as their frequencies get further away from the fundamental's frequency. Because of this decline, a measurement bandwidth that spans only five or six harmonics is sufficient. A smaller measurement bandwidth permits the use of higher selective gains to better resolve the lower distortion levels encountered at lower frequencies. Higher test frequencies require the full bandwidth, but they also cause correspondingly higher amplifier distortion. Accordingly, higher test frequencies require less selective gain, extending measurement bandwidth. Thus, the gain/bandwidth compromise of selective amplification

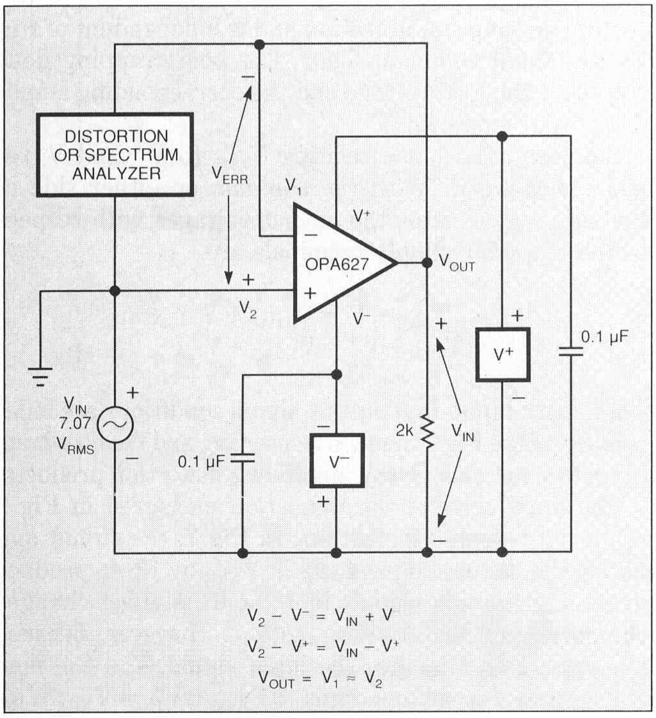


Fig 6—Power-supply bootstrapping permits directly measuring V_{ERR} and does not change an amplifier's internal voltage swings.

yields to distortion measurement with varied gains.

The OPA627, for example, requires three selective-gain steps, each step providing a different gain/bandwidth combination. **Fig 5** details this gain variation, which revolves around the THD_{IN}-vs-frequency plot. As this plot shows, op-amp distortion typically rises at higher frequencies, where measurement bandwidth is most needed.

Power-supply bootstrapping for noninverters

Signal separation is a complete solution only for inverting configurations. Using a power-supply bootstrap avoids limitations in noninverting solutions. Given care to avoid ground loops, the bootstrapping approach separates the common-mode signal, extending signal separation to the noninverting case.

To permit an optimal analyzer connection, power-supply bootstrapping moves the circuit's common from the normal circuit ground to the op amp's noninverting input **(Fig 6)**. As odd as it may seem to consider an op amp's noninverting input to be the common, the common of a circuit is a relative point that you can define to be anywhere you choose. This connection retains the common-mode swing for the amplifier but removes that swing relative to common and, thus, removes it from the analyzer's input.

Theoretical niceties aside, redefining the common introduces ground-loop errors. The effects of these errors depend on the sensitivity of the circuit to voltage drops in its connecting lines. In **Fig 6**, the element most sensitive to such voltages is the signal analyzer because it measures a small signal superimposed on a larger one. For this reason, the **figure** shows the signal analyzer returned to the circuit's new common. **Fig 6** makes the power-supply connections vulnerable to line drops, but the power-supply rejection of the op amp attenuates the resulting voltages.

For **Fig 6,** the test-equipment demands again decrease by a factor of $1/(1/A + 1/CMRR)$. However, the measurement made in **Fig 6** requires adjustment to account for the reduced fundamental measured. For this **figure**, the relevant signal swing is that across the load resistor, or V_{IN}. Therefore, multiply the measured distortion by V_{ERR}/V_{IN}.

The actual adjustment made depends on the type of signal analyzer used. Measurements made with a distortion analyzer directly produce a THD+N percentage. Simply multiply this percentage by V_{ERR}/V_{IN} and **Fig 6**'s output distortion plus noise is then

$$THD+N_O = \frac{V_{ERR}}{V_{IN}} THD+N_M = THD+N_{IN}.$$

MEASURING OP-AMP DISTORTION

You must measure the magnitude of V_{ERR} separately because distortion-analyzer outputs do not normally indicate this magnitude.

When you measure distortion with a spectrum analyzer, no separate measurement is required. Spectrum analyzers display the magnitudes of the fundamental and harmonic signals individually. You can then calculate distortion from the fundamental THD equation. Multiply this equation by V_{ERR}/V_{IN}, where V_{ERR} is equal to and therefore replaces V_1, and V_{IN} remains in the denominator. Then, the spectrum analyzer result for **Fig 6** is

$$THD_{OUT}=\frac{\sqrt{(V_2^2+V_3^2+V_4^2+...)}}{V_{IN}}\ (100\%).$$

Bootstrapping resolves noninverting cases

The convenience of **Fig 6** extends to the generalized noninverting amplifier. As **Fig 7** shows, power-supply bootstrapping again permits directly measuring V_{ERR} with a grounded signal analyzer.

Only one difference separates the measurements of the two circuits. The greater gain of **Fig 7** results in a larger load signal V_{LOAD}. This gain also amplifies V_{ERR}, making the distortion in V_{LOAD} greater than that measured in V_{ERR}. You can adjust the measured distortion later to compensate for the effect of this gain. Finally, the added gain further reduces the performance requirements of the test equipment. For a given level of V_{LOAD}, V_{IN} is smaller for **Fig 7** than for **Fig 6**. Thus, with **Fig 7**, V_{IN}'s reacting with the amplifier's CMRR produces a smaller V_{ERR} signal. The noninverting configuration reduces the signal measured by a factor of $V_{LOAD}/V_{ERR}=1/(1/A+\beta/CMRR)$.

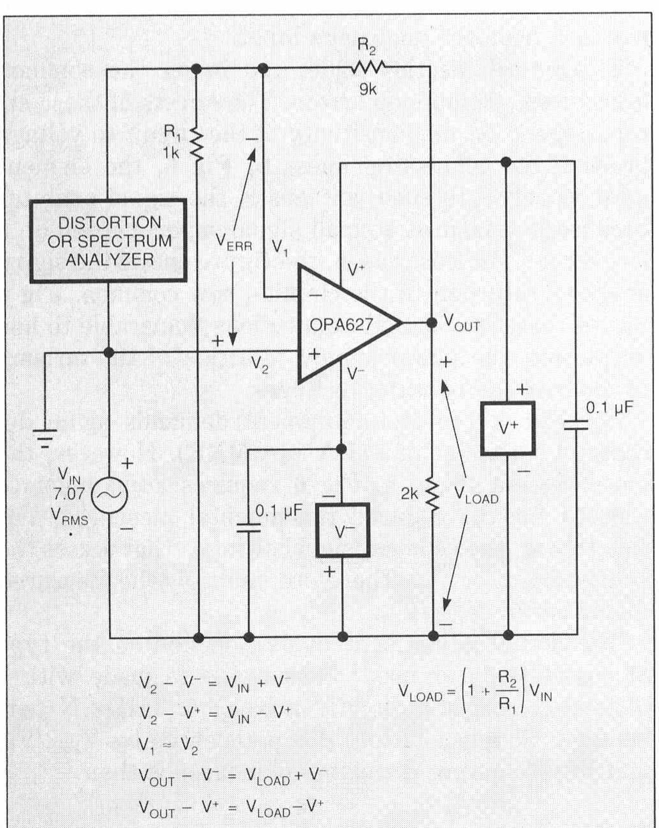


Fig 7—The bootstrapping of Fig 6's voltage follower also applies to general noninverting circuits.

Consider **Fig 7** with the common return first at the top and then at the bottom of the signal generator. This change makes no difference in the equations relating amplifier voltages to the V^+ and V^- supply terminals. For both configurations, the V_2-V^- and V_2-V^+ equations are the same as those for **Fig 6**. Amplifier feedback forces $V_1 \approx V_2$ to again extend these equations to **Fig 7**'s input. Thus, whether bootstrapped or not, the amplifier distorts the input signal.

Fig 7's greater gain produces a different output result than **Fig 6**. To define V_{OUT} relative to V^+ and V^-, first determine the load voltage, V_{LOAD}. You can find this voltage from the loop formed by the load resistor with resistors R_1 and R_2. The input signal, V_{IN}, appears across resistor R_1, producing a feedback current of V_{IN}/R_1. This current flows in R_2 to develop a voltage of $V_{IN}R_2/R_1$. Adding the voltages on R_1 and R_2 shows the voltage on the load to be $V_{LOAD}=(1+R_2/R_1)V_{IN}$. This result portrays the familiar response of a noninverting op-amp configuration and is independent of **Fig 7**'s redefined common. Thus, the bootstrapping does not affect the load voltage and the corresponding amplifier output current.

Similarly, the loops relating V_{OUT} to V^+ and V^- remain unchanged. With the common on either side of the signal generator, the output voltages with respect to the amplifier supply terminals are

$$V_{OUT}-V^-=V_{LOAD}+V^-$$
$$V_{OUT}-V^+=V_{LOAD}-V^+.$$

Thus, both input- and output-signal conditions are independent of the **Fig 7** common connection, and the bootstrapping does not change the amplifier's distortion products.

You must convert the distortion measured in **Fig 7** to output-referred distortion. In **Fig 7**, the circuit amplifies the distortion products in V_{ERR} by $1/\beta$ to produce greater distortion signals in V_{OUT}. This effect changes the correction factor to $V_{ERR}/\beta V_{IN}$. However, because the same gain amplifies the input signal, V_{IN}, the final correction factor becomes $\beta V_{ERR}/\beta V_{IN}=V_{ERR}/V_{IN}$. Thus **Fig 7**'s correction equations are the same as **Fig 6**'s.

For the voltage-follower case, combining bootstrapping and selective amplification achieves even greater distortion resolution. This way, you can test the very lowest distortion amplifiers with a distortion analyzer. This particular amplifier-and-analyzer combination is the one case where noise becomes a limit to op-amp distortion measurement. And for a spectrum analyzer, the ambient noise of the test environment requires your careful attention to avoid coupling stray noise into your circuit. With either type of analyzer, selective amplification expands distortion resolution for the bootstrapped voltage follower.

The benefits of power-supply bootstrapping and selective amplification combine in **Fig 8.** In this circuit, the only signal developed at the amplifier's output is the amplified error signal:

$$V_{OUT} = -(1 + R_2/R_1)V_{ERR}.$$

A signal analyzer measures this amplified signal referenced to ground with no interference from the test signal. In addition, the amplified distortion signal conveniently overrides the background noise of the signal analyzer and the measurement environment. This convenience does not extend to the general noninverting case because added gain there restores the test signal to the amplifier's output.

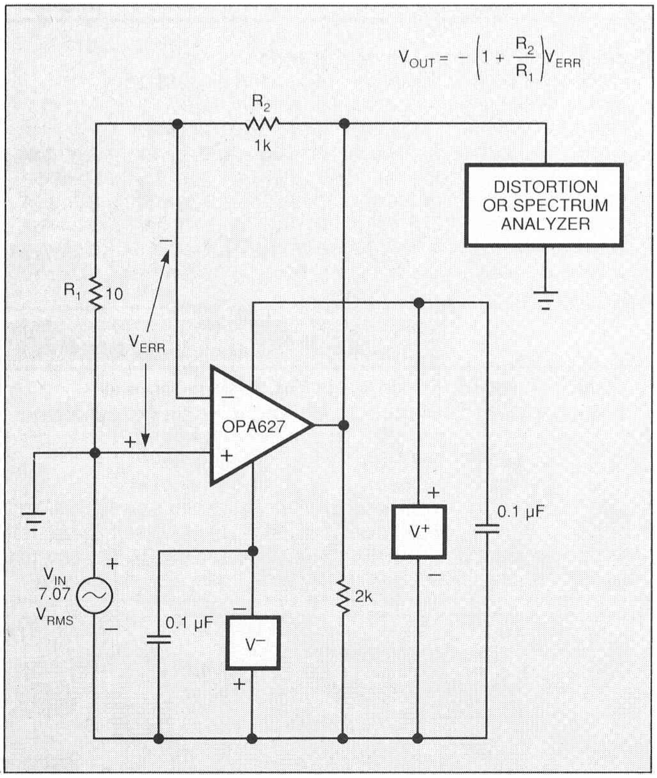


Fig 8—Combined bootstrapping and selective amplification expand distortion resolution for the voltage follower.

Other characteristics of the measurement shown in **Fig** 8 follow directly from earlier results. Selective amplification reduces the measurement bandwidth from f_C to βf_C. Here, f_C is the unity-gain bandwidth of the op amp. The feedback factor is $\beta = R_1/(R_1 + R_2)$. **Fig** 8's test-equipment requirements are the same as for the bootstrapped follower of **Fig 6.** As with that circuit, the distortion and dynamic-range requirements of the test equipment decrease by a factor of $1/(1/A + 1/CMRR)$. Because the selective amplification amplifies both the amplifier's distortion products and the background signal, V_{ERR}, it does not improve this factor. The attenuated generator distortion present in V_{ERR} gets amplified along with the amplifier distortion products. The relative significance of generator distortion is unchanged. Similarly, the selective gain amplifies both the maximum and minimum signals to be resolved by the analyzer. Thus, the dynamic range of the measurement is also unchanged.

For the same reasons, results measured with the circuit in **Fig 8** translate output-referred distortion with the same equations as those used in **Figs 6** and **7.** EDN

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Author's biography

For Jerald Graeme's biography, see Part 1 of this series on pg 133.

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