By Jim Williams and Todd Owen, Linear Technology Corp

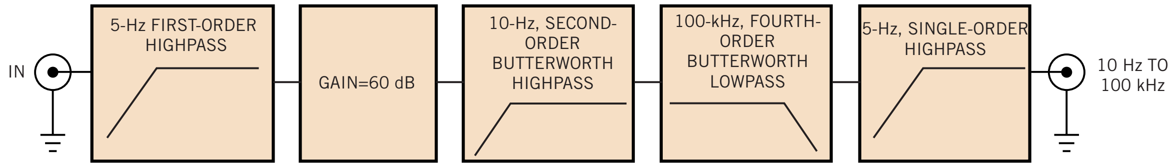
ALTHOUGH VERIFYING THAT A LOW-DROPOUT REGULATOR MEETS ITS DROPOUT SPECIFICATION IS STRAIGHTFORWARD, VERIFYING ITS NOISE PERFORMANCE PROVES MORE DIFFICULT. YOU HAVE TO PAY CAREFUL ATTENTION TO THE TEST SETUP, INCLUDING THE VOLTMETER YOU USE.

Exacting noise test ensures low-noise performance of low-dropout regulators

TELECOMMUNICATIONS, NETWORKING, audio, and instrumentation applications increasingly require low-noise power supplies. Low-noise, low-dropout linear regulators interest designers who work in these application areas. These components may exclusively power noise-sensitive circuitry, circuitry that contains only some noise-sensitive elements, or both. Additionally, to conserve power, particularly in battery-driven apparatus, such as cellular telephones, the regulators must operate with low input-to-output voltages. New devices meet the concurrent requirements for low noise, low dropout, and small quiescent current. For example, the LT1761 has noise of 20 μV_{RMS}, a dropout of 300 mV at 100 mA, and a quiescent current of 20 µA. Clearly, all designs have different low-noise and low-dropout needs. For some help in selecting the right device, see **sidebar** "Selecting a low-noise, low-dropout regulator." For some more background on low-dropout-regulator architecture, see **sidebar** "The architecture of a low-noise low-dropout regulator."

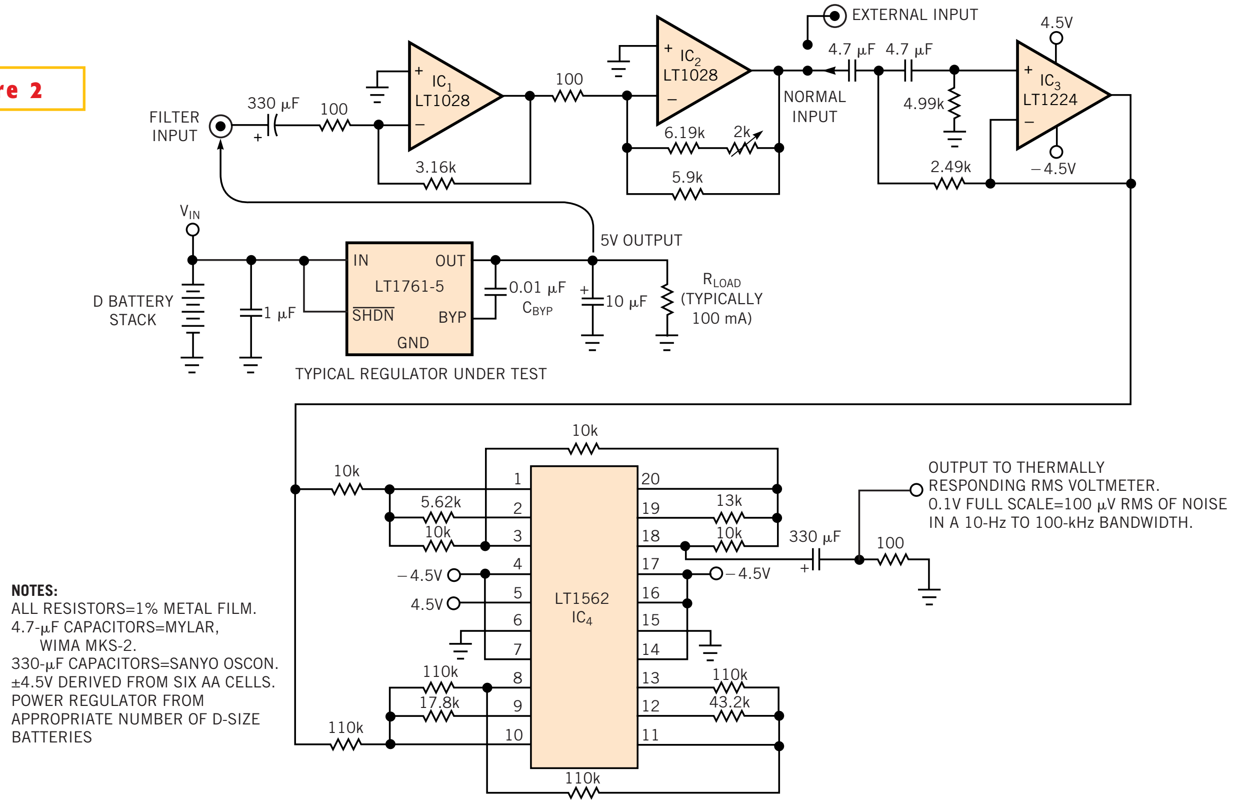
Testing such low-noise devices takes great care. Fortunately, establishing and specifying low-dropout performance is easy. Verifying that a regulator meets dropout specification is similarly straightforward. However, accomplishing the same missions for noise and noise testing involves more effort. The manufacturer or whoever is performing the testing must clearly call out the noise bandwidth of interest along with the operating conditions. Operating conditions can include regulator input and

Figure 1



In this filter structure for noise testing of low-dropout regulators, Butterworth-filter sections provide the steep slopes and flat passband in the desired frequency range of 10 Hz to 100 kHz.

Figure 2



NOTES:
ALL RESISTORS=1% METAL FILM.
4.7-µF CAPACITORS=MYLAR, WIMA MKS-2.
330-µF CAPACITORS=SANYO OSCON.
±4.5V DERIVED FROM SIX AA CELLS.
POWER REGULATOR FROM APPROPRIATE NUMBER OF D-SIZE BATTERIES

Low-noise amplifiers IC_1 and IC_2 provide gain and initial highpass shaping. IC_4's filter IC implements a fourth-order-Butterworth lowpass characteristic.

output voltage, load, and the characteristics of assorted discrete components. Numerous subtleties can affect low-noise performance, and changes in operating conditions can cause unwelcome surprises. Thus, manufacturers must quote low-dropout- regulator noise performance under specified operating and bandwidth conditions for the specification to be meaningful. Misleading data and erroneous conclusions result when you fail to observe this precaution.

DETERMINE THE NOISE BANDWIDTH FOR TEST

Before testing, you have to determine the noise bandwidth of interest. For most systems, the range of 10 Hz to 100 kHz is the information-signal-processing area of concern. Additionally, linear regulators produce little noise energy outside this region. Switching regulators are a different proposition and require a broadband noise measurement (**Reference 1**). These considerations suggest a measurement bandpass of 10 Hz to 100 kHz with steep slopes at the bandlimits. **Figure 1**

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SELECTING A LOW-NOISE, LOW-DROPOUT REGULATOR

Any design has requirements for a low-noise, low-dropout regulator, and you should carefully examine each situation for specific needs. However, some general guidelines apply in selecting a low-noise, low-dropout regulator. Consider the following significant issues:

Current capacity: Ensure that the regulator has adequate output-current capacity for the application, including worst-case transient loads.

Power dissipation: The device must be able to dissipate whatever power is necessary, which affects package choice. Usually, the $V_{IN}-V_{OUT}$ differential is low in low-dropout-regulator applications, obviating this issue. Prudence dictates checking to be sure.

Package size: Package size is important in limited-space applications. Current capacity and power-dissipation constraints dictate the package size.

Noise bandwidth: Ensure that the low-dropout regulator meets the system's noise requirement over the entire bandwidth of interest; 10 Hz to 100 kHz is realistic, because information usually occupies this range.

Input-noise rejection: Ensure that the regulator can reject input-related disturbances originating from clocks, switching regulators, and other power-bus users. If the regulator's power-supply rejection is poor, its low-noise characteristics are useless.

Load profile: Know the load characteristics. Steady-state drain is important, but you must also evaluate transient loads. The regulator must maintain stability and low-noise characteristics under all such transient loads.

Discrete components: The choice of discrete components, particularly capacitors, is important. The wrong capacitor dielectric can adversely affect stability, noise performance, or both.

ARCHITECTURE OF A LOW-NOISE, LOW-DROPOUT REGULATOR

Figure A shows a design scheme for a low-noise, low-dropout regulator that the LT176X through LT196X family of regulators uses. This scheme minimizes noise transmission within the loop and minimizes noise from an unregulated input. The bypass capacitor, C_{BYP}, filters the internal voltage reference's noise. Additionally, the scheme shapes the error amplifier's frequency response to minimize noise contribution while preserving transient response and power-supply rejection ratio. Regulators that do not shape this response have poor noise rejection and transient performance.

Achieving an extremely low dropout voltage requires careful design of the pass element. The pass element's on-impedance limits set dropout limitations. The ideal pass element has zero impedance between the input and the output and consumes no drive energy.

A number of design and technology options offer various trade-offs and advantages. **Figure B** shows some pass-element candidates. Followers (**Figure Ba**) offer current gain, ease of loop compensation because the voltage gain is below unity, and drive current that ends up going to the load. Unfortunately, saturating a voltage follower requires overdriving the input, at the base or gate, for example. Generating the overdrive is difficult because the regulator usually derives the drive directly from V_{IN}. Practical circuits must either generate the overdrive or obtain it elsewhere. Without voltage overdrive, the V_{BE} sets the saturation loss in the bipolar case, and channel on-resistance sets the saturation loss for MOS. MOS-channel on-resistance varies under these conditions; you can more easily predict bipolar losses. Voltage losses in driver stages, such as Darlington stages, add directly to the dropout voltage. The follower output of conventional three-terminal IC regulators combines with drive-stage losses to set dropout at 3V.

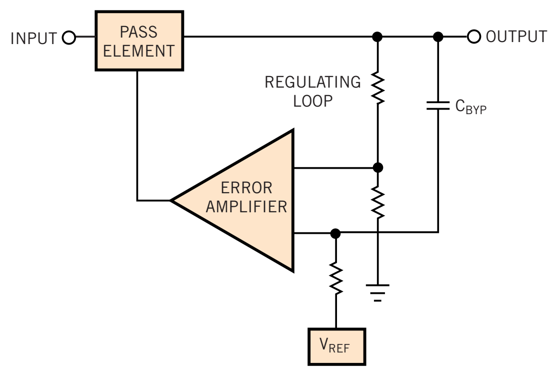
The common emitter/source is another pass-element option (**Figure Bb**). This configuration removes the V_{BE} loss in the bipolar case. The pnp version is easy to fully saturate, even in IC form. The trade-off is that the base current never arrives at the load, which wastes power. At higher currents, base drive losses can negate a common emitter's saturation advantage. As in the follower example, Darlington connections exacerbate the problem. Achieving low dropout in a monolithic pnp regulator requires a pnp structure that attains low dropout while minimizing base drive loss. This requirement becomes the case at higher pass currents. Designers of the LT176X through LT196X regulators expended considerable effort in this area.

Common-source-connected p-channel MOSFETs are also candidates (**Figure Bb**). They do not suffer the drive losses of bipolar devices but typically require volts of gate-channel bias to fully saturate. In low-voltage applications, this bias may require generating negative potentials. Additionally, p-channel devices have poorer saturation than equivalent-size n-channel devices.

The voltage gain of common-emitter and -source configurations is a loop-stability concern but is manageable.

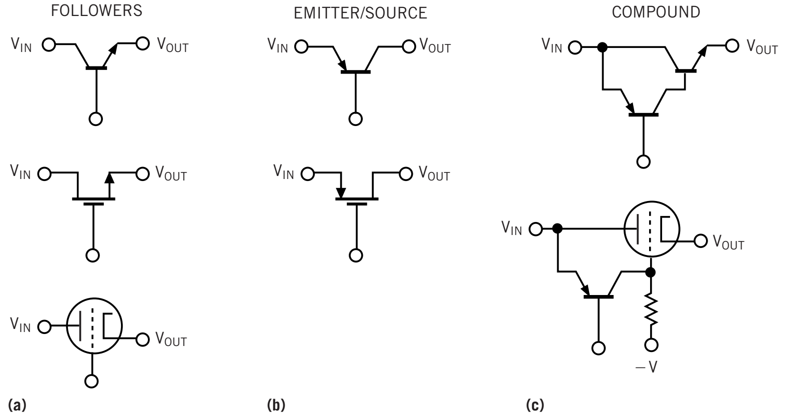
Compound connections using a pnp-driven npn (**Figure Bc**) are a reasonable compromise, particularly for high power—beyond 250 mA—IC construction. The trade-off between the pnp V_{CE} saturation term and reduced drive losses over a conventional pnp structure is favorable. Also, the major current flow is through a power npn, which is easy to realize in monolithic form. The connection has voltage gain, necessitating attention to loop-frequency compensation. Regulators that use this pass scheme, such as the LT1083 through LT1086, can supply as much as 7.5A with dropouts below 1.5V.

Figure A



A low-dropout-regulator design scheme minimizes noise within the loop and minimizes noise from an unregulated input.

Figure B



Pass-element candidates include followers (a), common-emitter/source types (b), and compound types (c).

shows a conceptual filter for low-dropout-regulator-noise testing. Steep slopes and flatness in the passband require the Butterworth-filter sections. The small input level requires 60 dB of low-noise gain to provide an adequate signal for the Butterworth filters.

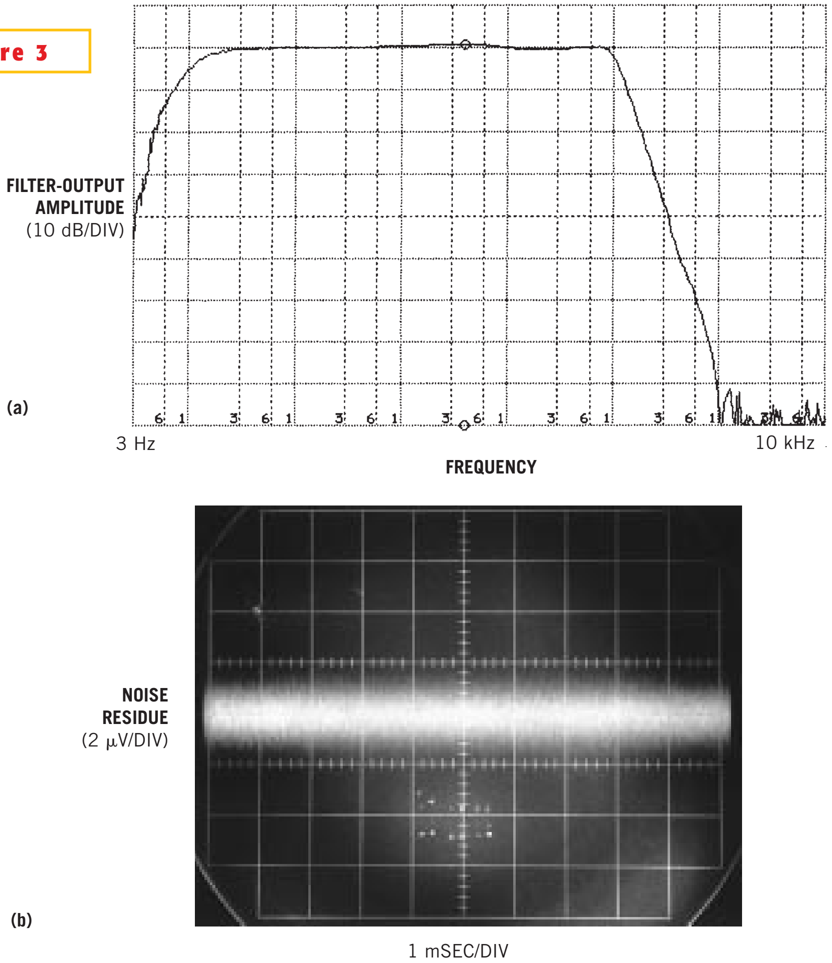
Figure 2 details the filter scheme for the LT1761-5 regulator under test. IC_1 to IC_3 make up a 60-dB-gain highpass section. IC_1 and IC_2, which are extremely low-noise amplifiers (<1 nV/$\sqrt{\text{Hz}}$), comprise a 60-dB gain stage with a 5-Hz highpass input. IC_3 provides a 10-Hz, second-order-Butterworth, highpass characteristic. The design configures IC_4's filter IC as a fourth-order-Butterworth, lowpass filter. The circuit delivers the output of this filter to the output via the 330-μF/100Ω highpass network. The circuit's output drives a thermally responding rms voltmeter. Obtaining meaningful measurements depends greatly on your choice of an rms voltmeter (see "Understanding and selecting rms voltmeters" on page 54.) Batteries furnish all power to the circuit, which precludes ground loops from corrupting the measurement.

VERIFY INSTRUMENTATION PERFORMANCE

Good measurement technique dictates verifying the noise test instrumentation's performance. **Figure 3a**'s spectral plot of the filter section shows an essentially flat response in the 10-Hz to 100-kHz passband with abrupt slopes at the band extremes. Some flatness deviation exists, but the response stays well within 1 dB throughout nearly the entire passband. Grounding the filter's input determines the tester's noise floor. **Figure 3b** shows noise of less than 4 μV p-p , corresponding to a 0.5-μV-rms voltmeter reading. This noise level is only about 0.5% of full scale, contributing negligible error. These results give you the confidence to proceed with regulator-noise measurement.

Regulator-noise measurement begins with attention to test-setup details. The extremely low signal levels require attention to shielding, cable management, layout, and component choice. **Figure 4** shows the bench arrangement; to obtain faithful noise measurements you need a completely shielded environment. The

Figure 3

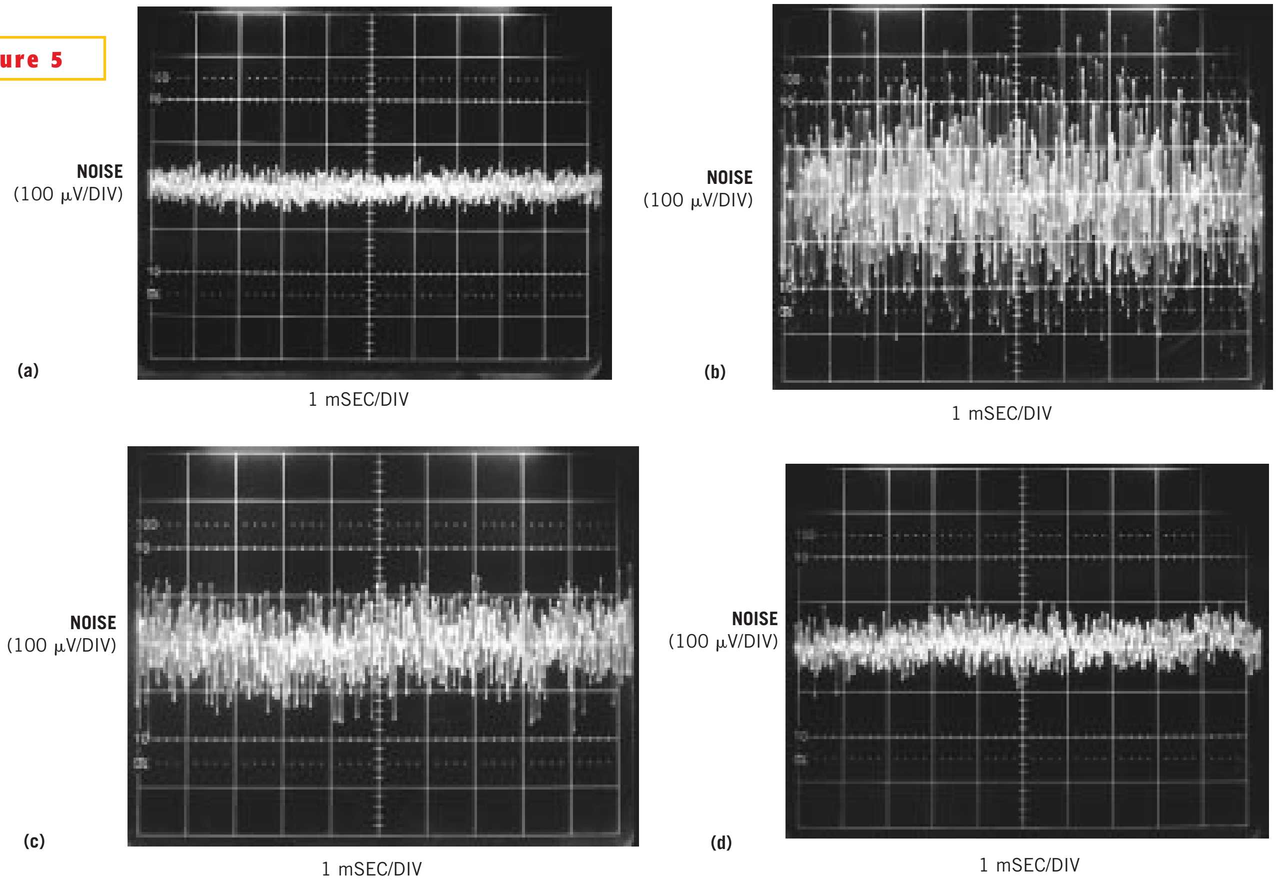


A spectrum analyzer plot (HP-4195A) of the test circuit's filter characteristics (a) verify a nearly flat response over the desired 10-Hz to 100-kHz frequency range with a steep roll-off outside the band-pass region. The test setup's noise residue of less than 4 mV p-p corresponds to approximately a 0.5 μV-rms measurement-noise floor (b).

Figure 4

A shielded can contains the regulator, and the noise filter circuitry occupies the small black box. The oscilloscope and rms voltmeter never connect to the test set simultaneously, precluding a ground loop from corrupting the measurement.

Figure 5



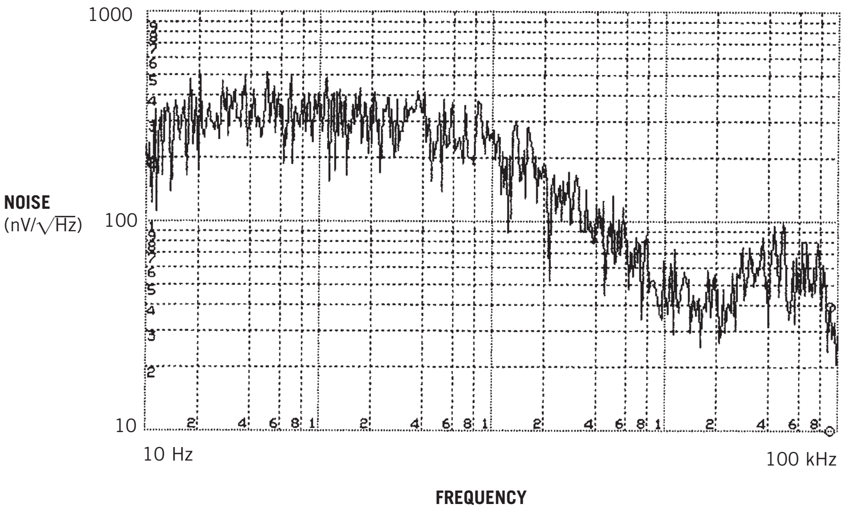
The regulator's output noise (a) corresponds to an rms voltmeter reader of 20 µV rms. Three other regulators (b, c, and d) are supposedly low-noise types, but the photos do not indicate low-noise performance. Ambiguity in test methods or specifications may cause the contradiction.

metal can encloses the regulator under test and an internal battery power supply. A BNC fitting connects the regulator's output to the noise-filter test circuit in the black box. This fitting eliminates triboelectric disturbances—extremely low-level disturbances that result when adjacent conductors move and charge "rubs" off—that a cable might contribute (**Reference 2**). The monitoring oscilloscope and voltmeter never connect to the output at the same time, precluding ground loops that would corrupt the measurement.

COMPARE NOISE RESULTS

Figure 5a shows an LT1761 regulator's noise measured at the filter output of **Figure 2**. Monitoring this point with the rms voltmeter shows a 20-µV-rms reading. **Figure 6**'s spectral plot of this noise indicates diminished power above 1 kHz in accordance with expected regulator noise density. This plot also verifies that

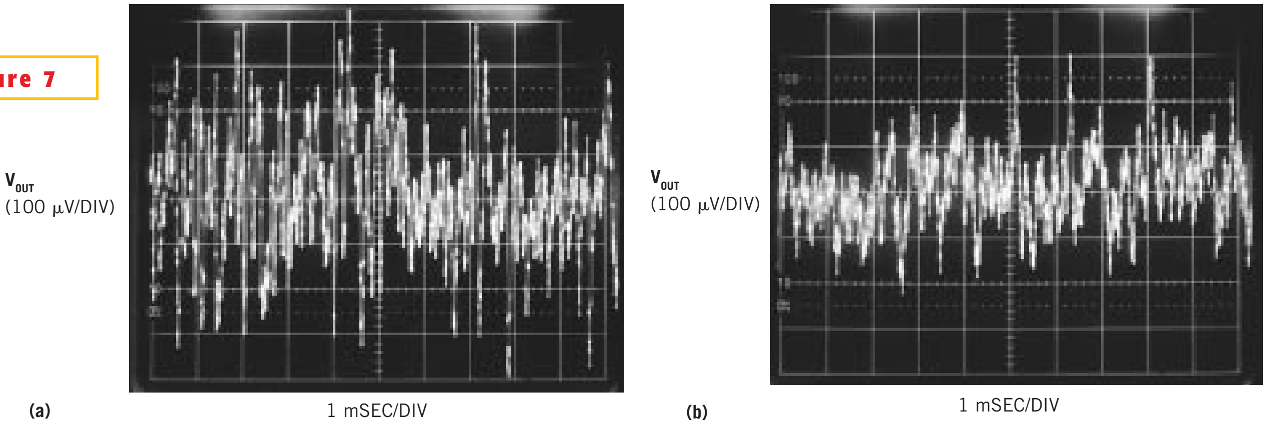
Figure 6



NOTE: C_{BYP}=1000 pF.

A spectral plot of Figure 2's output indicates diminished power above 1 kHz, which is in agreement with the expected regulator-noise density.

Figure 7



NOTES: C_{OUT}=10 µF, C_{BYP}=0, I_{LOAD}=100 mA.

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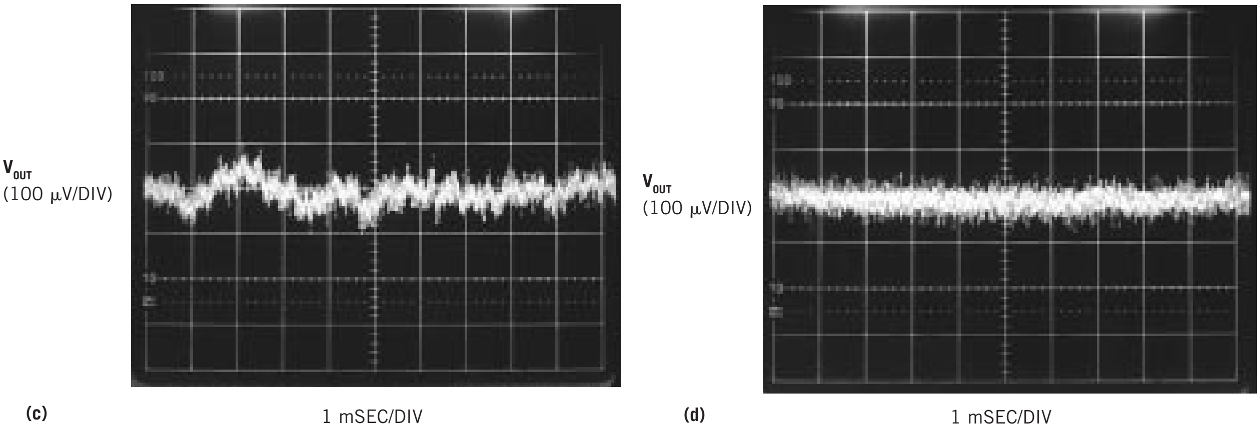


NOTES: C_{OUT}=10 µF, C_{BYP}=1000 pF, I_{LOAD}=100 mA.

NOTES: C_{OUT}=10 µF, C_{BYP}=0.01 µF, I_{LOAD}=100 mA.

Bypass-capacitor values have a great impact on the measured noise level. Noise is very high when C_{BYP}=0 (a), nine times lower when C_{BYP}=0.01 µF (d), and at intermediate levels when equal to 100 and 1000 pF (b and c).

a 10-Hz to 100-kHz bandwidth is appropriate for the measurement.

Figure 5 also shows the output noise of three other regulators. The manufacturers specify these devices for low-noise performance, but the photos do not indicate low noise. Ambiguity in testing methods or specifications results in the seeming contradiction. For example, an inappropriate choice of test equipment or measurement bandwidth can easily cause as great as five times the errors. This uncertainty mandates noise testing to ensure realistic conclusions.

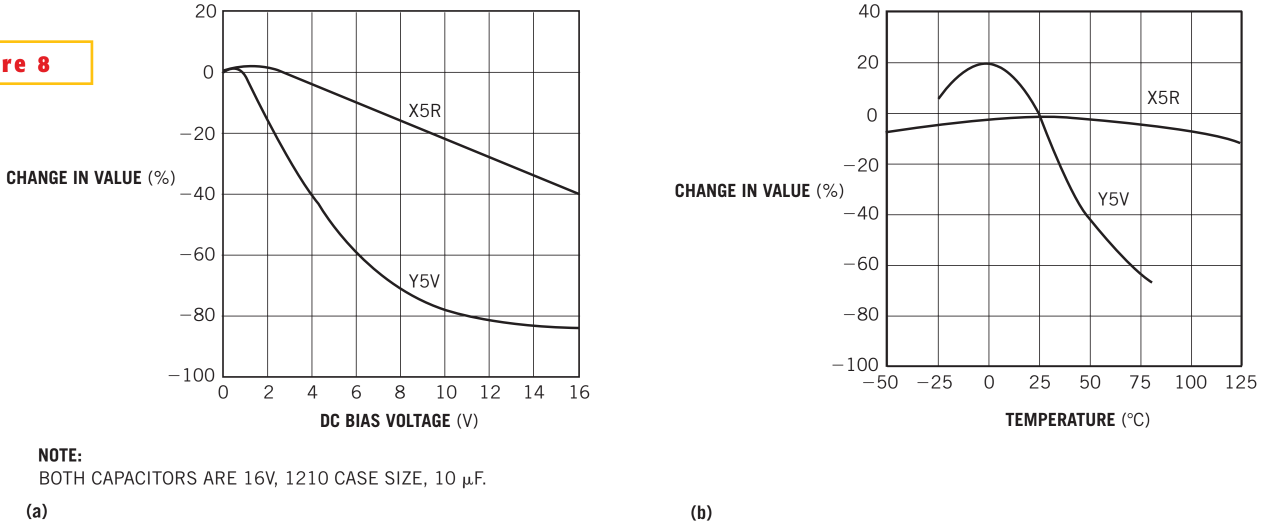
The noise that **Figure 5a** depicts results when the bypass capacitor, C_{BYP}, has a value of 0.01 µF. The regulator's internal voltage reference contributes most of the device's noise. The bypass capacitor filters reference noise by adding a low-frequency noise pole and precludes the noise from appearing in amplified form at the output. Thus, adding a capacitor from the regulators V_{OUT} to BYP pin lowers output noise. **Figure 7** shows regulator noise versus various values of C_{BYP}. **Figure 7a** shows substantial noise for C_{BYP}=0 µF, and **Figure 7d** displays nearly nine-times improvement with C_{BYP}=0.01 µF. Intermediate values of 100 and 1000 pF (**figures 7b** and **c**) produce commensurate results.

Your best choice for C_{BYP} is a good-quality low-leakage capacitor. Using a bypass capacitor also improves transient response. With no bypassing and a 10-µF output capacitor, a 10- to 500-mA load step settles to within 1% of final value in less than 100 µsec. With a 0.01-µF bypass capacitor, the output settles to within 1% for the same load step in less than 10 µsec, and total output deviation is within 2.5%. Regulator start-up time is inversely proportional to bypass-capacitor size, slowing to 15 msec with a 0.01-µF bypass capacitor and 10-µF capacitance at the output. Also, prudent selection of C_{BYP} reduces transient peak-to-peak amplitude by more than a factor of five.

CHOOSE CAPACITORS WITH CARE

The regulator in **Figure 2** is stable with a range of output capacitors. Output-capacitor ESR affects stability, most notably with small capacitors. A minimum output value of 3.3 µF with an ESR of 3Ω or less prevents oscillation. Transient response is a function of output capacitance. Larger values of output capacitance decrease peak deviations, providing improved transient response for large-load current changes. Bypass capacitors, which you use to decouple individual components powered by the regulator, increase the effective output-capacitor

Figure 8

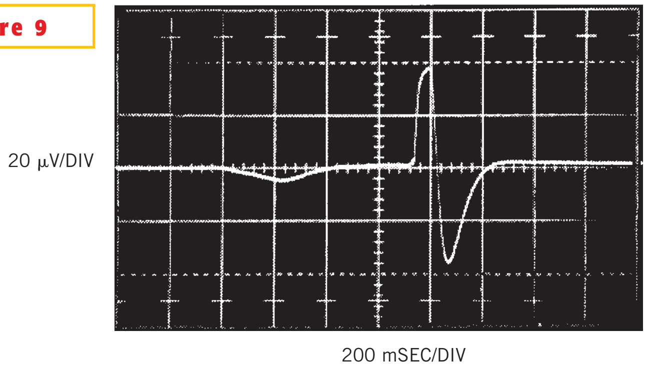


NOTE:
BOTH CAPACITORS ARE 16V, 1210 CASE SIZE, 10 µF.

Ceramic capacitors exhibit strong voltage (a) and temperature (b) coefficients.

value. Larger values of bypass capacitance dictate larger output capacitors. For a 100-pF bypass capacitor, the recommended output-capacitor value is 4.7 µF. With 1000 pF of bypass capacitor or larger, a 6.8-µF output capacitor is necessary.

Figure 9



The vibration that results from simply tapping a ceramic capacitor with a pencil can cause appreciative amounts of noise.

Ceramic capacitors require extra consideration. Manufacturers use a variety of dielectrics, each with different behavior across temperature and applied voltage to construct these capacitors. The most common dielectrics are Z5U, Y5V, X5R, and X7R. The Z5U and Y5V dielectrics provide high capacitance in a small package but exhibit strong voltage and temperature coefficients (**Figure 8**). With a 5V regulator, a 10-µF Y5V capacitor shows values as low as 1 to 2 µF over the operating-temperature range. The X5R and X7R dielectrics have more stable characteristics and better suit output-capacitor use. The X7R type has better stability over temperature; the X5R costs less and comes in higher values.

Voltage and temperature coefficients are only two sources of problems. Some ceramic capacitors have a piezoelectric response. A piezoelectric device generates voltage across its terminals due to mechanical stress, similar to the way a piezoelectric accelerometer or microphone works. For a ceramic capacitor, vibrations in the system or thermal transients can induce the stress. The resulting voltages can cause appreciable amounts of noise, especially when you use a ceramic capacitor for noise bypassing. A ceramic capacitor produced the trace that **Figure 9** depicts is a response to light tapping of a pencil. Similar vibration-induced behavior can masquerade as increased output-voltage noise.□

REFERENCES

1. Williams, J, "A monolithic switching regulator with 100 µV output noise," Linear Technology Corp, Application Note 70, October 1997.

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AUTHORS' BIOGRAPHIES

Jim Williams, a staff scientist at Linear Technology Corp (Milpitas, CA, www.lineartech.com), specializes in analog-circuit and instrumentation design. He has served in similar capacities at National Semiconductor, Arthur D Little, and the Instrumentation Laboratory at the Massachusetts Institute of Technology (Cambridge, MA). A former student at Wayne State University (Detroit), Williams enjoys art, collecting antique scientific instruments, and restoring old Tektronix oscilloscopes.

Todd Owen works as a design engineer for Linear Technology, where he has worked for six years. He designs low-dropout linear regulators and received his BSEE from California Polytechnic State University (San Luis Obispo, CA). He enjoys skydiving with his wife.