SECTION 5

VOLTAGE REFERENCES FOR HIGH ACCURACY SYSTEMS

- A LOW-NOISE DISCRETE BANDGAP DESIGN
- AN ULTRA LOW-NOISE REFERENCE CIRCUIT
- AVOID HEAVY LOADS ON REFERENCE OUTPUTS

SECTION 5

VOLTAGE REFERENCES FOR HIGH ACCURACY SYSTEMS

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Voltage references have a major impact on the performance and accuracy of analog systems. A ±5mV tolerance on a 5V reference corresponds to ±0.1% absolute accuracy– only 10-bits. For a 12-bit system choosing a reference that has a ±1mV tolerance may be far more cost effective than performing manual calibration, while both high initial accuracy and calibration will be necessary in a system making absolute 16-bit measurements. (Many systems make *relative* measurements rather than absolute ones and in such cases the absolute accuracy of the reference is not important, although noise and short-term stability may be.)

Temperature drift or drift due to aging may be an even greater problem than absolute accuracy. The initial error can always be trimmed, but compensating for drift is difficult. Where possible references should be chosen to have a temperature coefficient and aging characteristics that preserve adequate accuracy over the operating temperature range and expected lifetime of the system.

Long-term stability is rarely specified on data sheets. Where a figure is given it is usually drift expressed in ppm/ 1000 hours. There are 8766 hours in a year and many engineers multiply the 1000 hour figure by 8.77 to find the annual drift - this is incorrect. Long term drift in precision analog circuits is a "random walk" phenomenon and increases with the *square root* of the elapsed time (this supposes that drift is due to random micro-effects in the chip and not some over-riding cause such as contamination). The 1 year figure will therefore be about $\sqrt{8.766} \approx 3$ times the 1000 hour figure and the ten year value will be roughly 9 times the 1000 hour value. In practice things are a little better even than this, as devices tend to stabilize with age.

Only three things in life are certain: death and taxes - and noise. Noise in voltage references is often overlooked, but it can be very important in system design. It is generally specified on data sheets, but system designers frequently ignore the specification and assume that voltage references do not contribute to system noise.

There are two dynamic issues that must be considered with voltage references: their behavior at start-up and their behavior with transient loads. Voltage references do not power up instantly (this is true of references inside ADCs and DACs as well as discrete designs). Many early designs took tens, or even hundreds, of milliseconds to deliver any output at all and as long again before reaching full accuracy - modern designs tend to start up more quickly (but read the data sheet) but still need time to reach thermal equilibrium. It is rarely possible to turn on an ADC and reference, whether internal or external, make a reading, and turn off again within a few microseconds, however attractive such a procedure might be in terms of energy saving. (There are also issues, which we shall not consider here, of anomalous ADC logic states on start-up. Irrespective of reference accuracy the first, and sometimes even the second, result from an ADC after powering up may be in error because of misbehavior arising from the state of its logic immediately after power is applied.)

Many reference have low power, and therefore low bandwidth, buffer amplifiers. This makes for poor behavior under fast transient loads, which may degrade the performance of fast ADCs, especially successive approximation and flash ADCs (Reference 2). Suitable decoupling can ease the problem (but some references oscillate with capacitive loads), or an additional external broadband buffer amplifier may be used to drive the node where the transients occur.

CHOOSING VOLTAGE REFERENCES FOR HIGH RESOLUTION SYSTEMS

- Tight Tolerance Improves Accuracy, Reduces Costs
- Temperature Drift Affects Accuracy
- Long-Term Stability Assures Repeatability
- Noise Limits System Resolution
- Dynamic Loading Causes Errors

Figure 5.1

There are two common types of voltage references: bandgap and buried zener. Both make good stable references, and each has particular strengths and weaknesses which are listed in Figure 5.2.

ATTRIBUTES OF REFERENCE ARCHITECTURES

BANDGAP	BURIED ZENER
■ Low Reference Voltage	■ Low Noise
■ Low Quiescent Power	■ Good Long-Term Stability

Figure 5.2

Bandgap references make use of the bandgap voltage of silicon: 1.230 V. Properly designed bandgap references compensate PTAT and CTAT ("Proportional to Absolute Temperature" and "Complimentary to Absolute Temperature") voltages to obtain a stable output near this value (Reference 3). Other voltages may be obtained by using this as the input to a precision amplifier with suitable gain.

Buried zener diodes are zener diodes fabricated beneath the surface of a chip. The surface of a chip is prone to contamination and lattice dislocations and zener diodes at the surface are more noisy and less stable than "buried" ones. Buried zener diodes may be made with a range of voltages, they all have good low noise performance (better than bandgap references) but ones which, in combination with their temperature compensating diodes, have a breakdown voltage just below 7V have the best temperature performance. Figure 5.3 shows a range of voltage references, both bandgap and buried zener, with high initial accuracy and low drift.

VOLTAGE REFERENCE CHARACTERISTICS

PART NUMBER	OUTPUT VOLTAGE	INITIAL ACCURACY	MAXIMUM TC	SUPPLY CURRENT
AD780	+2.50V	±1mV	3 ppm/°C	1mA
REF-195	+5.00V	±1mV	4 ppm/°C	40µA
AD588	+10V, +5V, ±5V, -5V, -10V	±1mV	1.5 ppm/°C	10mA
REF-43	+2.50V	±1.5mV	10 ppm/°C	450µA
AD584	+10V	±2.5mV	5 ppm/°C	1mA
AD581	+10v	±5mV	5 ppm/°C	1mA
AD680	+2.5V	±5mV	20 ppm/°C	250µA

Figure 5.3

If the output of a voltage reference must be trimmed, it is important that a single trim potentiometer be used in order to preserve the low drift of the reference. As shown in Figure 5.4, the output voltage is amplified from the reference. The gain of the amplifier is set by resistors, and gain stability depends on the matching of their temperature coefficients (TCs). If the resistors are thin film types on the reference chip the matching will be excellent, but if external resistors are used to trim gain the TCs will not match and the TC of the adjusted reference voltage will be degraded. The circuit shown in Figure 5.4 is the best way to trim the output of a voltage reference, since the TC of the external resistors has least effect on the reference TC. Of course a better, but more complex, technique would be to use a second trimmable amplifier after the output of the untrimmed voltage reference - if the TC of this amplifier can be kept low enough then the TC of the system will not be degraded.

Reference voltage drift makes maintaining 14-bit accuracy over temperature especially difficult. Figure 5.5 illustrates the accuracy that can be expected as a function of drift. Even the best available reference, at 1 ppm/°C, is only 14-bit accurate over the temperature range of +25°C to +85°C. Special techniques are required for better accuracy.

IF YOU MUST TRIM:

- Use single trim potentiometer
- Do not insert fixed resistors in the trim leg -- this causes poor tempco match

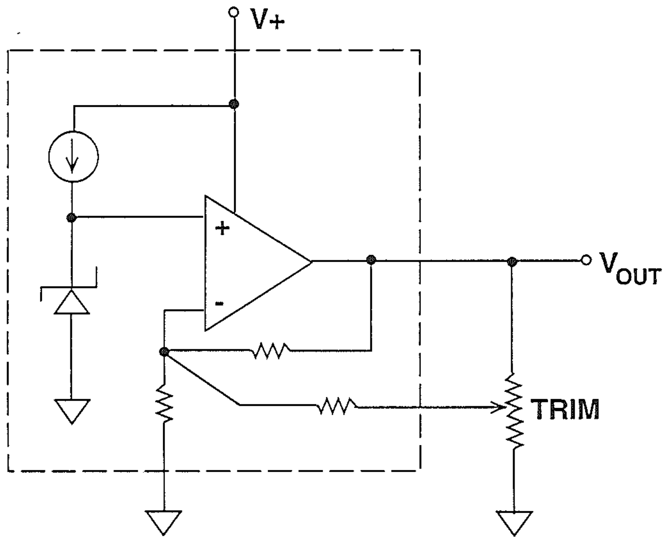


Figure 5.4

EFFECTS OF DRIFT ON SYSTEM ACCURACY

DRIFT	TOTAL CHANGE IN OUTPUT, 10V FS (25°C TO 85°C)	EQUIVALENT ACCURACY
10 ppm/°C	6mV	10 bit
5 ppm/°C	3mV	11 bit
4 ppm/°C	2.4mV	12 bit
1 ppm/°C **	0.6mV	14 bit
0.25 ppm/°C	0.15mV	16 bit

** Best Reference Available Commercially

Figure 5.5

Figure 5.6 shows the allowable reference voltage drift in ppm/°C as a function of total system temperature span. Curves are shown for 12, 14, 16, and 18-bit accuracy. The reference voltage specification becomes more demanding as resolution and temperature range increase.

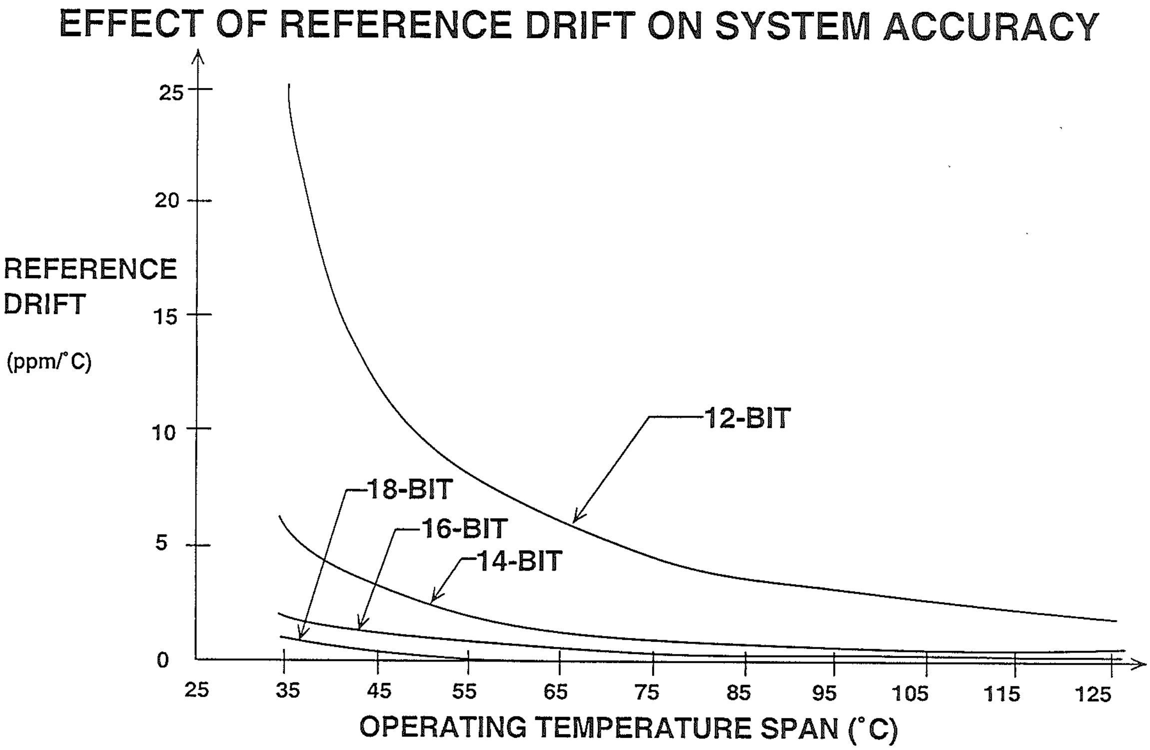


Figure 5.6

Maintaining absolute 16-bit accuracy requires reference voltage TCs of less than 1ppm/°C. The best commercially available references are only about 1ppm/°C, so continuous self-calibration must be used to maintain the required accuracy.

FOR APPLICATIONS GREATER THAN 16-BITS, IT IS DIFFICULT TO RELY ON REFERENCE DRIFT BELOW 1 ppm/°C

- Use System Calibration Technique
- Temperature Drift Compensation
- Buffer Heavy Loads to Minimize Drift Due to Self-Heating
- Reference Noise May Limit Repeatability

Figure 5.7

Heavy loads at the reference output induce self-heating of the die. Self-calibration cycles cannot always be synchronized to the self-heating time constants and consequently, thermal drift will modulate the output despite self-calibration. But buffer amplifiers will not necessarily overcome the problem, since they too will have errors due to self-heating. Careful design, self-calibration, plus heat sinking and study of thermal time constants will be necessary to meet the requirements of 16-bit systems.

Reference noise is often overlooked as a source of error. Reference voltage noise is usually specified as a peak-to-peak value in the bandwidth of 0.1Hz to 10Hz. However, many references have no provisions for limiting bandwidth, so the actual rms noise will be much larger unless steps are taken to limit the bandwidth externally. Figure 5.8 illustrates how wideband noise (100kHz bandwidth) can limit resolution.

The benefit of limiting noise bandwidth is illustrated in Figure 5.9. A terminal is provided on the AD587 for noise filtering. The capacitor C_N forms a low pass filter with the internal resistor R_B that limits the noise bandwidth at the output of the zener diode. A 1µF capacitor gives a 3dB bandwidth of 40Hz. The photo shows noise measured in a 1MHz bandwidth with and without the filter capacitor. Even lower noise can be achieved by increasing the filter capacitor at the expense of longer turn-on time. But the external filter capacitor, C_N, does not eliminate the wideband noise in the output buffer of the AD587, and this sets a limit to the possible improvement. Noise may be reduced further by placing another filter at the output terminal of the AD587.

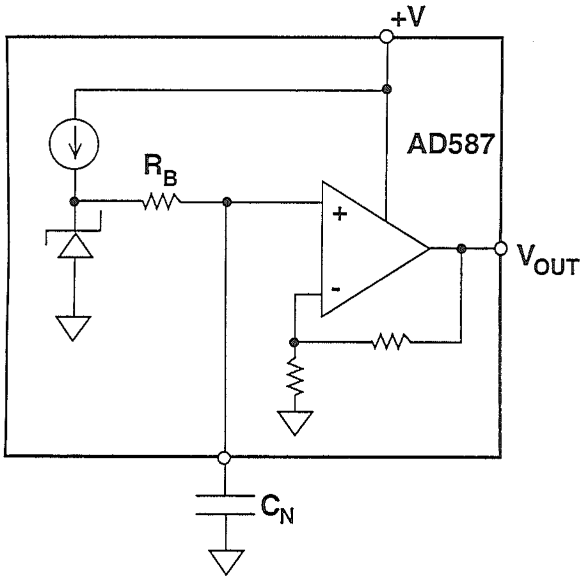
EFFECTS OF REFERENCE NOISE ON SYSTEM ACCURACY, RULE OF THUMB: KEEP NOISE < 1/4 LSB

NOISE SPECTRAL DENSITY	NOISE VOLTAGE (BW = 100kHz)	EQUIVALENT ACCURACY
322 nV/√Hz	610 μV p-p	12 bits
80 nV/√Hz	153 μV p-p	14 bits
20 nV/√Hz	38 μV p-p	16 bits
5 nV/√Hz	10 μV p-p	18 bits
1.3 nV/√Hz*	2.4 μV p-p	20 bits

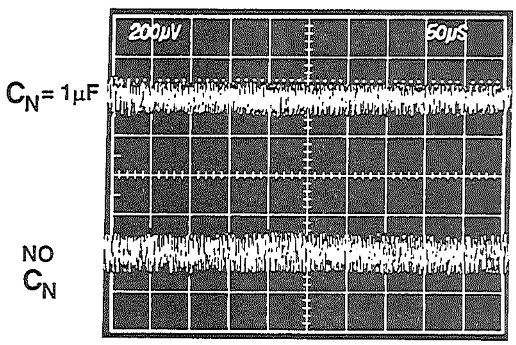
* LESS THAN JOHNSON NOISE IN A 100Ω RESISTOR

Figure 5.8

LOW REFERENCE NOISE IS CRITICAL FOR HIGH ACCURACY



Solution: Bandwidth Limiting



VERTICAL SCALE: 200μV/div.
HORIZONTAL SCALE: 50μs/div.

Figure 5.9

A LOW NOISE DISCRETE BANDGAP REFERENCE

Monolithic voltage references have better stability but can rarely achieve the noise performance of a well-designed discrete circuit. An example of a reference circuit with excellent noise performance appears in Figure 5.10. Its performance parameters is summarized in Figure 5.11. The circuit's 100kHz wideband noise is 20μV rms.

The circuit uses low noise matched transistors (MAT-04) operating at high collector currents to minimize noise. Three of the transistors are connected in parallel to reduce noise further. The fourth forms the other leg of the bandgap core. Being monolithic, the four matched transistors also maintain identical temperatures, and therefore good drift characteristics. Biasing the bandgap core with high current minimizes the noise contribution from R3.

Care must be taken to shield the entire circuit thermally to minimize drift due to ambient temperature gradients - which may produce parasitic thermoelectric voltages. The circuit layout should also be compact. All resistors should be of the same type, with matched temperature coefficients. RN55C (1%, ±50 ppm/°C) type resistors work well. R1 and R2 are particularly sensitive because any mismatch changes the current ratio in the core, and produces a higher drift. Similarly, the ratio R4:R3 amplifies ΔV by the current ratio. Mismatch due to temperature coefficient variation in R3 and R4 introduces drift by affecting the Q1 and Q2 V_{BE}. Finally, R6, R7, and R8 amplify the 1.23V bandgap voltage to 5.000V. Mismatch in them will cause additional errors.

To calibrate the circuit, adjust R5 for a bandgap voltage of 1.230V at 25°C. Then adjust R7 for a +5.000V at the output. Despite its low noise the circuit has poor temperature stability compared to the AD588 monolithic device. The designer must decide which is more important: noise or stability.

The basic bandgap reference is not self-starting. Resistors R9 and R10 plus an NPN transistor (Q3) start the circuit. When the supply is turned on, there is no current in the bandgap core, and the op amp output is at 0V. The base voltage of Q3 reaches 3.9V, and its emitter rises to 3.2V pulling up the op amp output. At this point the core starts to conduct, the op amp moves to its linear operating point, and the output stabilizes at 5V. This turns off transistor Q3, so that it no longer affects the circuit.

5

DISCRETE DESIGN PROVIDES ULTRA LOW NOISE

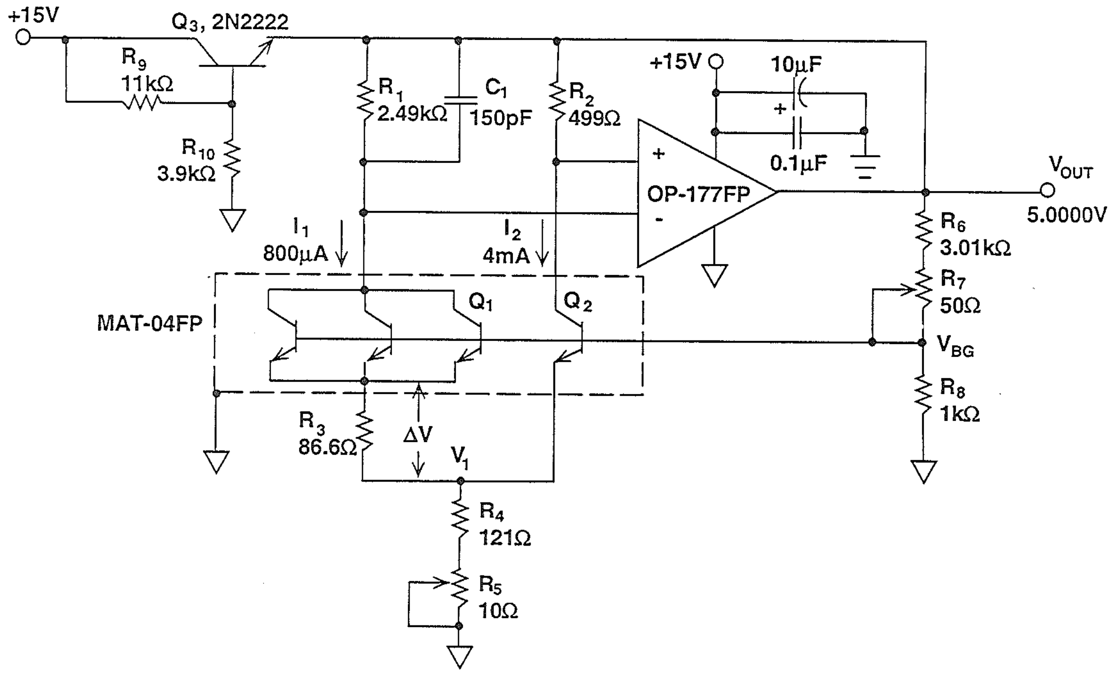


Figure 5.10

DESIGN EQUATIONS AND PERFORMANCE OF DISCRETE BANDGAP VOLTAGE REFERENCE

$$\Delta V = V_T \ln\left[\left(\frac{I_2}{I_1}\right)\left(\frac{A_1}{A_2}\right)\right] \quad ,$$

WHERE A_1 = EMITTERS IN $Q_1 = 3$

A_2 = EMITTERS IN $Q_2 = 1$

$$V_1 = \left[\left(\frac{R_4}{R_3}\right)\left(\frac{I_2}{I_1}\right)\right]\Delta V = 7.0\Delta V, \quad V_{BG} = V_1 + V_{BE}(Q2) = 1.23V \text{ @ } 25°C$$

Output Voltage:	5.000V
Output Noise Voltage (0.1 to 10Hz)	1.6μV p-p
Noise Spectral Density @ 1kHz:	63nV/√Hz
Wideband Noise (BW = 100kHz):	20μV rms
Drift ($-40°C \le T_A \le +85°C$):	14 ppm/°C
Line Regulation (6 to 40V):	2 ppm/V
Load Regulation (0 to 10mA):	6 ppm/mA
Supply Current @ 15V:	8mA

Figure 5.11

AN ULTRA LOW NOISE REFERENCE CIRCUIT (REFERENCE 4)

Another approach to achieving ultra-low noise is to use extensive external filtering. The circuit in Figure 5.12 uses an ultra-low noise amplifier, the AD797, to buffer the AD587 10V reference. It also acts as low-pass filter with a 1Hz corner frequency. The combination produces exceptionally low noise.

COMBINING LOW-NOISE AMPLIFIER WITH EXTENSIVE FILTERING YIELDS EXCEPTIONAL NOISE PERFORMANCE

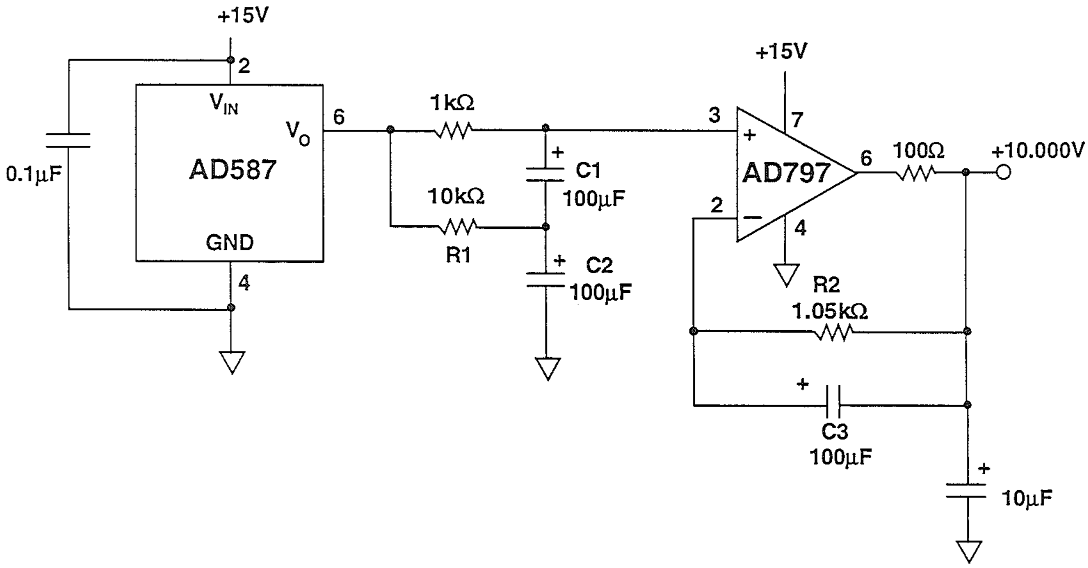


Figure 5.12

The unconventional arrangement of capacitors in the low pass filter ensure that the leakage currents of the capacitors and the bias current of the AD797, both of which are quite large, do not contribute to the DC errors in the system. C2 is biased to V_O by R1 so that the voltage on C1 is minimal, as is its leakage. R2 is a bias current compensation resistor and C3 acts as an AC bypass to it.

For frequencies less than 1Hz, the output noise of the circuit is that of the AD587. For higher frequencies, the rms output noise is that of the AD797, or approximately 1.5nV/√Hz.

HEAVY LOADING AFFECTS REFERENCE DRIFT

- Load Regulation Limitations
- Self-Heating
- Solutions: Isolate Very Heavy Loads

  Use References Designed for Driving Medium Loads

Figure 5.14

AVOID HEAVY LOADS ON REFERENCE OUTPUTS

For high precision applications, it is not advisable to put very heavy loads directly on the reference output. Increased output current will cause the reference to lose accuracy and also increases drift due to self-heating.

The simplest way to minimize reference voltage drift in the presence of very heavy loads is to buffer the reference output with an accurate current-booster amplifier.

For moderately heavy loads there are special references which have been developed to drive currents of several tens of mA without loss of accuracy. An example is the REF-195, whose key specifications appear in Figure 5.15. It will deliver at least 30mA and still offer high precision, it has very low drop-out (the voltage between input and output terminals) and can be shut down into a "sleep" mode with no output (and a graceful shutdown, and power up again afterwards) and a standby consumption of <5µA. It only draws 30µA of power (plus the load current, of course) when powered up.

THE REF-195 LOW POWER, HIGH OUTPUT, PRECISION REFERENCE

- Designed to Deliver High Current: 30 mA
- Tight Output Tolerance: ± 1mV max.
- Low Drift: 4 ppm/°C max.
- Ultra Low Power: 30 µA
- Low Drop-Out @ 10 mA Load: 0.3 V max.
- Has 5 µA Power Drain in Sleep Mode

Figure 5.15

The REF-195 makes an excellent reference / regulator for powering a 4-20mA current loop (Figure 5.16). The REF-195 provides the power to the amplifier circuit as well as the bias voltage for the strain-gauge bridge. The bridge signal is amplified by the AMP-04 single-supply instrumentation amplifier with a gain of approximately 40.

REF-195 POWERS 4-TO-20mA LOOP PLUS BRIDGE EXITATION

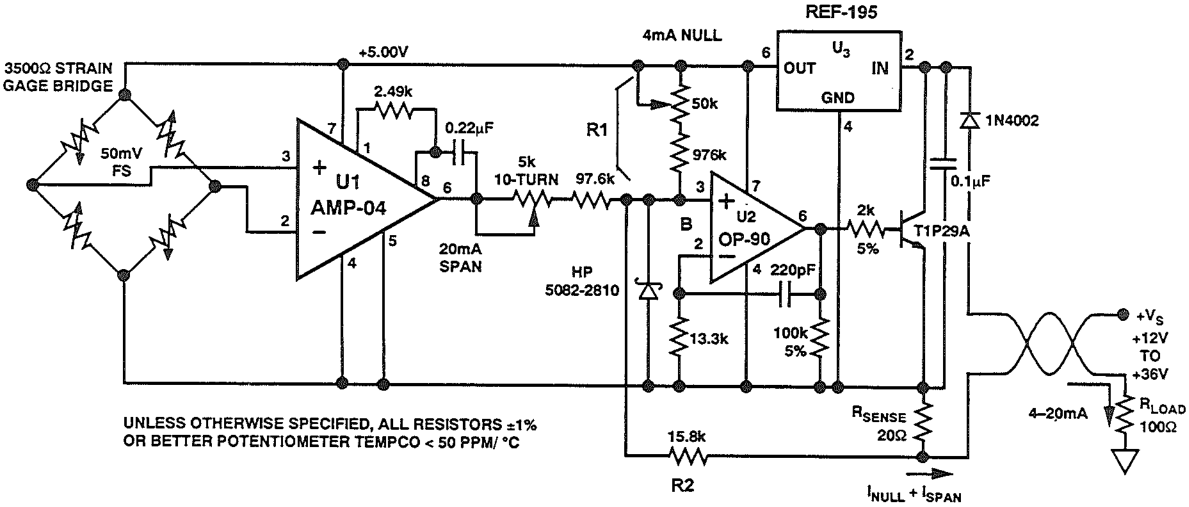


Figure 5.16

When the bridge signal output is zero, the AMP-04's output is also 0V relative to the floating reference. The 4mA output current is derived from the ratio of R1 to R2, the feedback resistor. This develops a 80mV across R_{SENSE}, the 20Ω current sense resistor (corresponding to 4mA output current). The low power consumption of the circuit allows the entire circuit to operate on the 4mA loop current so the entire circuit can be powered from a remote loop supply.

Pulse techniques to reduce power are made simple with the REF-195's shutdown ability. The circuit in Figure 5.17 is powered only during measurement. The bridge amplifier powers up and settles to better than 12-bits in under 400µs.

A PULSED STRAIN-GAUGE MEASUREMENT CIRCUIT HAS LOW POWER DRAIN AND PRECISION

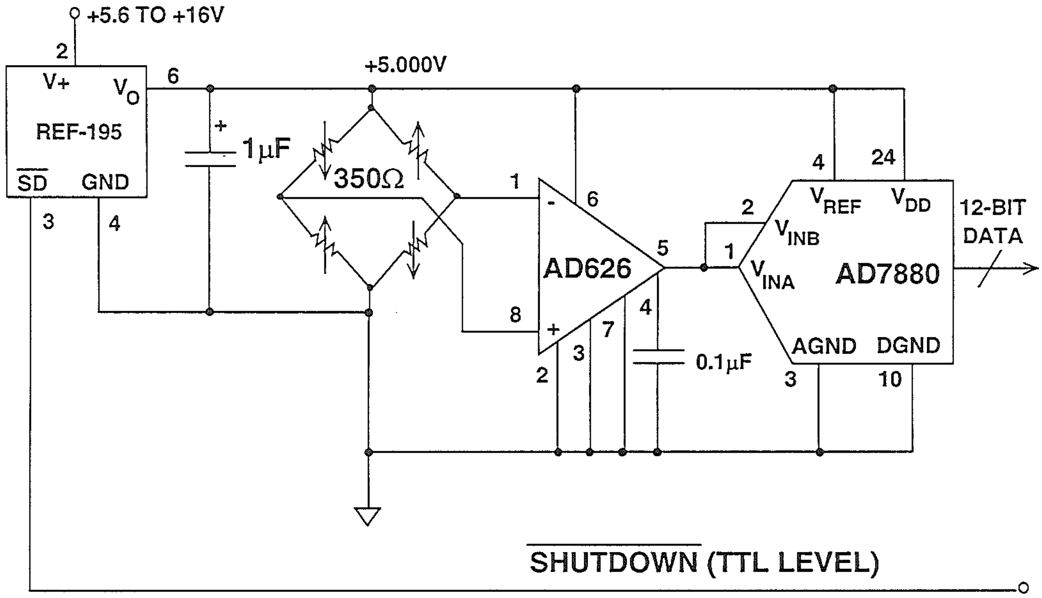


Figure 5.17

The AD680 is another reference which requires less than 250µA, and its features are shown in Figure 5.18.

THE AD680 LOW POWER, LOW COST 2.5V REFERENCE

- Low Power Drain: 250 µA max.
- Low Drift: 20 ppm/°C max.
- Laser Trimmed Accuracy: ± 5mV max.
- Low Cost

Figure 5.18

Driving the reference input of an ADC or DAC improperly can create noise which causes errors during conversion because ADC or DAC reference input impedance may change rapidly during conversion, disturbing the reference driving it. The user must evaluate the dynamic response characteristics of the reference driving such converters.

DRIVING ADC AND DAC REFERENCE INPUTS:
IS THE REFERENCE VOLTAGE STABLE ENOUGH?

EVALUATE:

- Initial Accuracy
- TC Drift
- Noise
- Dynamic Settling Characteristics

Figure 5.19

For example, the reference input to a Sigma-Delta ADC may be the switched capacitor shown in Figure 5.20. The dynamic load causes current spikes in the reference as the capacitor is charged and discharged. As a result, noise may be induced on the ADC reference circuitry.

Although sigma-delta ADCs have an internal digital filter, transients on the reference input can still cause appreciable conversion errors. An example of sampling noise on a sigma-delta ADC reference is shown in Figure 5.21. The bottom trace shows the noise that is generated if the reference source impedance is too high. The dynamic load causes the reference input to shift by more than 5mV.

DYNAMIC LOAD EFFECTS OF DRIVING SIGMA-DELTA ADCs

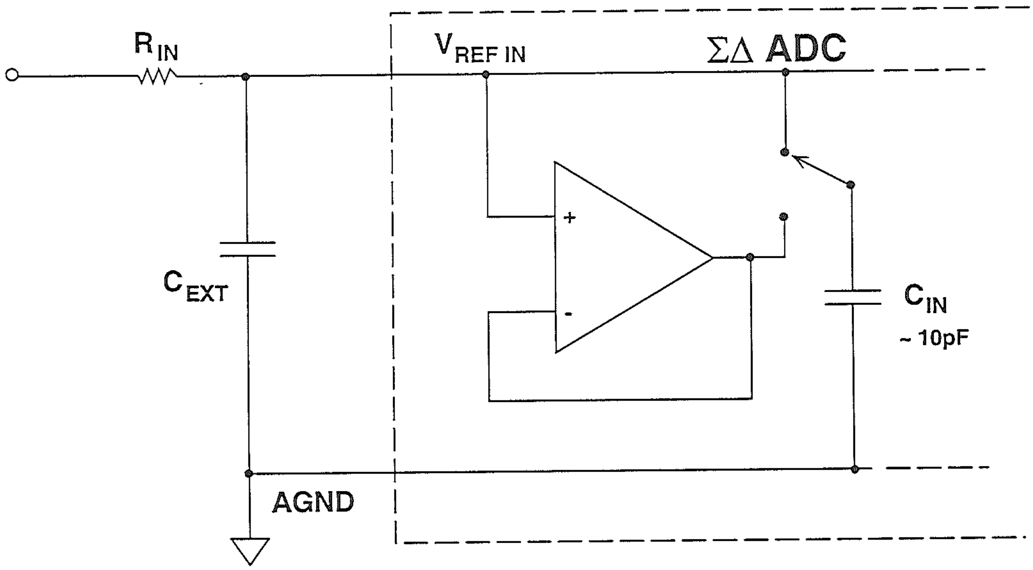
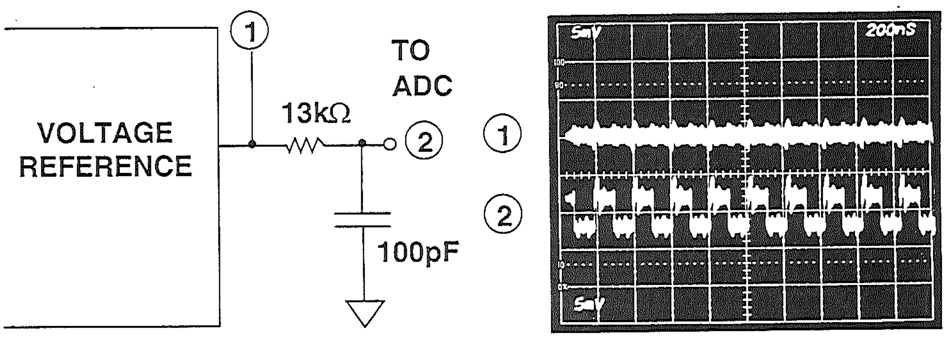


Figure 5.20

TYPICAL NOISE INDUCED AT THE REFERENCE INPUT OF A SIGMA-DELTA ADC



VERTICAL SCALE: 5mV/div.
HORIZONTAL SCALE: 200ns/div.

Figure 5.21

A bypass capacitor on the output of a reference may help it to cope with load transients, but many references are unstable with large capacitive loads, and it is important to verify that the one chosen will drive the capacitance required. (The input to all references should always be decoupled - with 0.1μF in all cases and with an additional 5-50μF if there is any LF ripple on its supply.)

BYPASSING REFERENCE OUTPUT WITH LARGE CAPACITOR HELPS TO MINIMIZE TRANSIENT LOAD DISTURBANCES

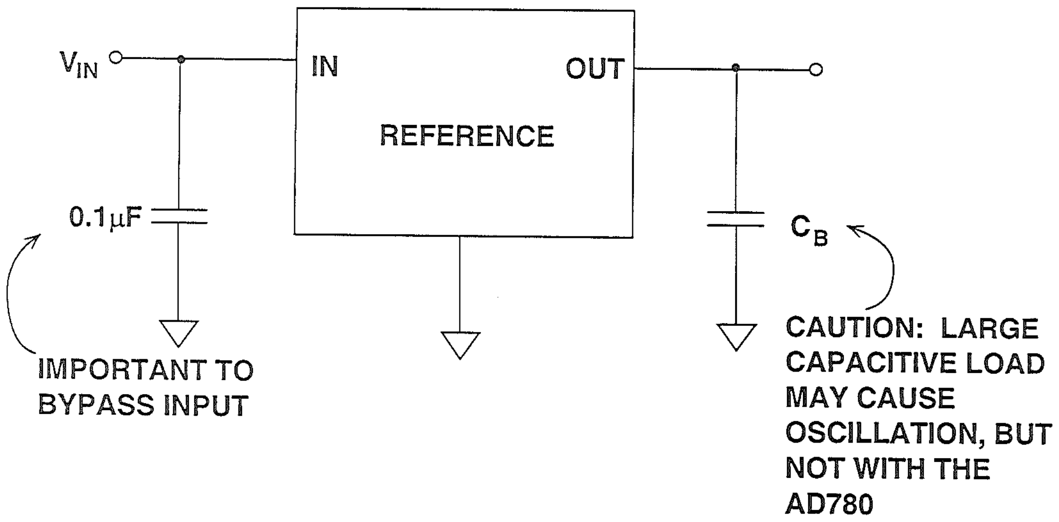
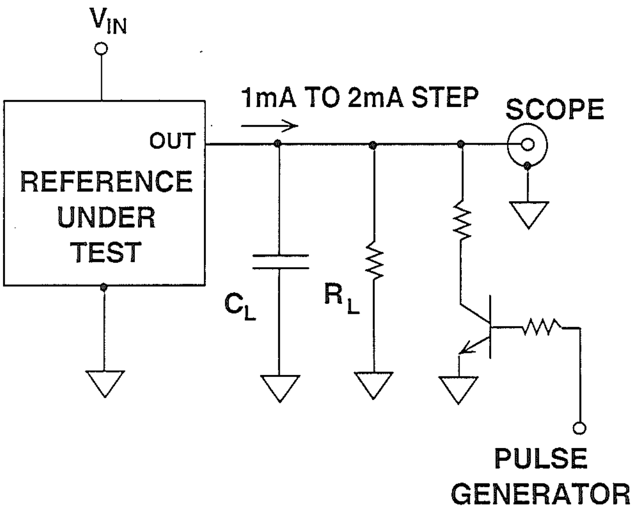


Figure 5.22

Since references do misbehave with transient loads, either by oscillating or by losing accuracy for comparatively long periods, it is advisable to test the pulse response of voltage references which may encounter transient loads. A suitable circuit is shown in Figure 5.23. In a typical voltage reference a step change of 1mA produces the transients shown. Both the duration of the transient, and the amplitude of the ringing increase when a 0.01μF capacitor is connected to the reference output.

Where possible a reference should be designed to drive large capacitive loads. The AD780 is designed to drive unlimited capacitance without oscillation. The features of the AD780 are shown in Figure 5.24. It has excellent drift and an accurate output in addition to low power consumption.

MAKE SURE REFERENCE IS STABLE WITH LARGE CAPACITIVE LOADS



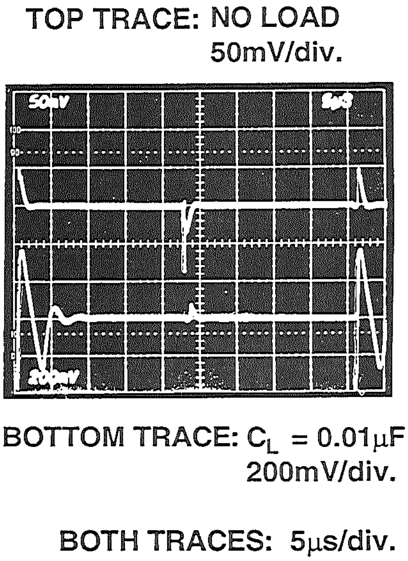


Figure 5.23

AD780 2.5V/3.0V HIGH PRECISION VOLTAGE REFERENCE DESIGNED TO DRIVE UNLIMITED CAPACITIVE LOAD

- Ultra Low Drift: 2 ppm/°C max.
- Output Accuracy: ± 1 mV max.
- Low Noise (0.1Hz to 10Hz): 4 µV p-p max.
- Low Power: 700 µA max.
- Source and Sink Capability

Figure 5.24

A reference device that can drive a large capacitive load can be used to minimize ADC reference noise. An example is shown in Figure 5.25, where the AD780 is shown driving the reference pin of a 21-bit A/D converter, the AD7710. At this resolution, even a little noise or drift can cause bad measurements. The 100µF reference bypass capacitor provides an exceptionally stable output.

THE AD780 IS IDEAL FOR DRIVING PRECISION SIGMA-DELTA ADCs

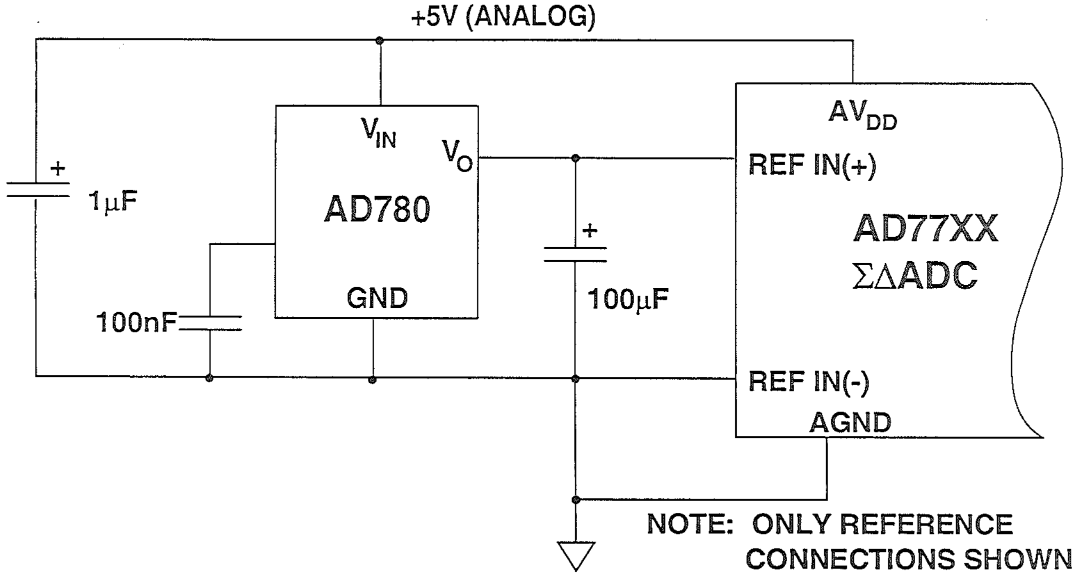


Figure 5.25

Large reference bypass capacitors are also useful when driving the reference inputs of successive-approximation ADCs. Figure 5.26 illustrates reference voltage settling behavior immediately following a "Conversion Start" command. A small capacitor (0.01µF) does not provide sufficient charge storage to keep the reference voltage stable during conversion, and errors may result. Decoupling with a >1µF capacitor maintains the reference stability during conversion.

SUCCESSIVE APPROXIMATION ADCs CAN PRESENT A DYNAMIC TRANSIENT LOAD TO THE REFERENCE

Solution: Bypass Reference Adequately

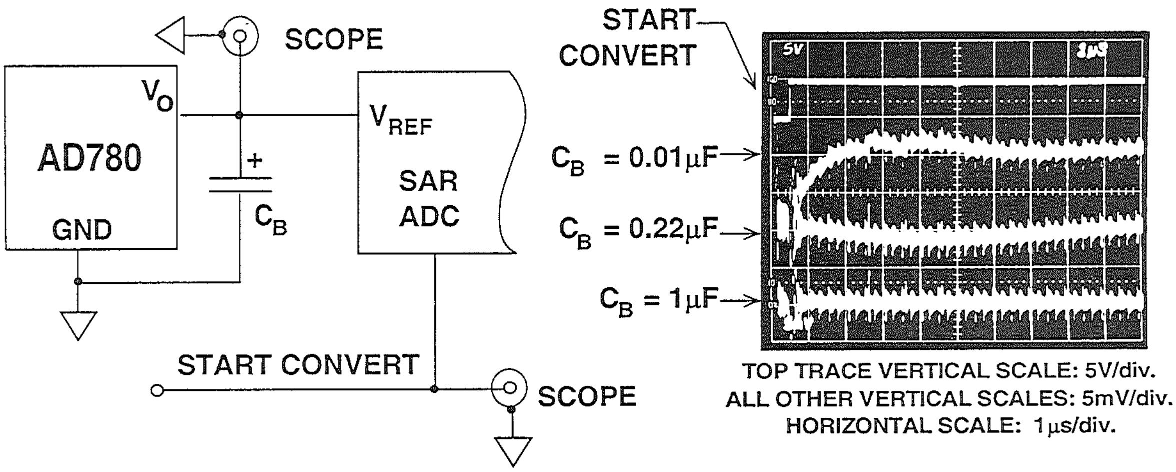


Figure 5.26

Where voltage references drive large capacitances it is important to realize that their turn-on time will be prolonged. Experiment may be needed to determine the delay before the output of the reference reaches full accuracy, but it will certainly be much longer than the time specified on the data sheet for the unloaded reference.

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3. A. Paul Brokaw, *A Simple Three-Terminal IC Bandgap Reference*, **IEEE Journal of Solid State Circuits**, Vol. SC-9, No. 6, December 1974, pp. 388-393

4. Walt Jung, *Build an Ultra-Low-Noise Voltage Reference*, **Electronic Design Analog Applications Issue**, June 24, 1993.