

## Precision Variable Gain Amplifiers (VGAs)

### INTRODUCTION

Most data acquisition systems with wide dynamic range need some method of adjusting the input signal level to the analog-to-digital-converter (ADC). Typical ADC full scale input voltage ranges lie between 1 V and 10 V. To achieve the rated precision of the converter, the maximum input signal should be fairly near its full scale voltage.

Transducers however, have a very wide range of output voltages. High gain is needed for a small sensor voltage, but with a large output, a high gain will cause the amplifier or ADC to saturate. So, some type of predictably controllable gain device is needed. Amplifiers with programmable gain have a variety of applications, and Figure 1 below lists some of them.

- ◆ Instrumentation
- ◆ Photodiode amplifier circuits
- ◆ Ultrasound preamplifiers
- ◆ Sonar preamplifiers
- ◆ Wide dynamic range sensors
- ◆ Driving ADCs (some ADCs have on-chip VGAs)
- ◆ Automatic gain control (AGC) loops
- ◆ Gain control
  - Resistor programmable
  - Pin programmable
  - Continuous analog voltage
  - Digital (5 to 8-bits typical)

### **Figure 1: Variable Gain Amplifier (VGA) Applications**

Such a device has a gain that is controlled by a dc voltage or, more commonly, a digital input. This device is known as a *variable gain amplifier (VGA)*, or *programmable gain amplifier (PGA)*.

In the case of voltage-controlled VGAs, it is common to make the gain in dB proportional to a linear control voltage.

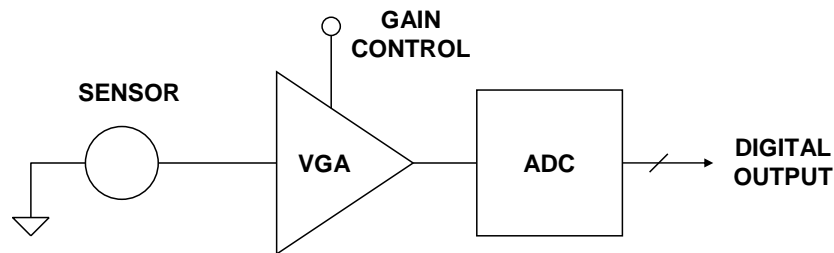
Digitally controlled VGAs may be configured either for a few selectable *decade gains* such as 10, 100, 1000, etc., or they may also be configured for *binary gains* such as 1, 2, 4, 8, etc. In many cases the gain range in dB is divided into equal steps determined by a 5 to 8-bit control word. It is a function of the end system of course, which type is the most desirable.

It should be noted that a factor common to the above application examples is that the different types of signals being handled is diverse. Some may require wide bandwidth and low distortion,

others very low noise, from either high or low impedance sources. The inputs may be either single-ended, or they may be differential.

The output from the VGA may be required to drive some defined input range of an ADC, or it may be part of a smaller sub-system, such as an AGC or gain-ranging loop. The circuits following fall into a range of categories addressing some of these requirements.

A VGA is usually located between a sensor and its ADC, as shown in Figure 2 below. Additional signal conditioning may take place before or after the VGA, depending on the application. For example, a photodiode needs a current-to-voltage converter between it and the VGA. In most other systems, it is better to place the gain first, and condition a larger signal. This reduces errors introduced by the signal conditioning circuitry.



- ◆ Used to increase the dynamic range of the system
- ◆ A VGA with a gain of 1 to 2 theoretically increases the dynamic range by 6dB.
- ◆ A gain of 1 to 4 gives a 12dB increase, etc.

**Figure 2: VGAs in Data Acquisition Systems**

To understand the benefits of variable gain, assume an ideal VGA with two settings, gains of one and two. The dynamic range of the system is increased by 6 dB. Increasing the gain to a maximum four results in a 12 dB increase in dynamic range. If the LSB of an ADC is equivalent to 10 mV of input voltage, the ADC cannot resolve smaller signals, but when the gain of the VGA is increased to two, input signals of 5 mV may be resolved. Thus, a central processor can combine VGA gain information with the digital output of the ADC to increase its resolution by one bit. Essentially, this is the same as adding additional resolution to the ADC. In fact, a number of ADCs now have on-chip VGAs for increased dynamic range (AD77xx-series, for example).

## PRECISION VGA DESIGN ISSUES

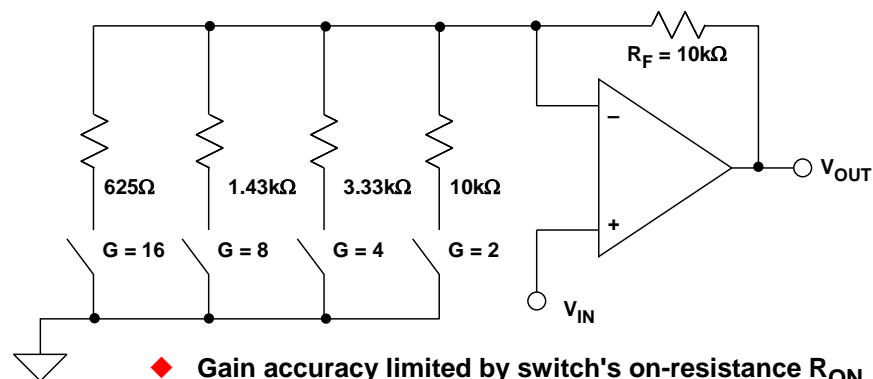
In practice, VGAs aren't ideal, and their error sources must be studied understood. A number of the various VGA design issues are summarized in Figure 3, below.

- ◆ How to switch the gain
- ◆ Effects of the switch on-resistance ( $R_{ON}$ )
- ◆ Gain accuracy
- ◆ Gain and offset drift over temperature
- ◆ Gain linearity
- ◆ Bandwidth versus gain
- ◆ DC offset
- ◆ Settling time after switching gain
- ◆ Harmonic distortion, two-tone intermodulation distortion, IP3, SFDR
- ◆ Noise
- ◆ Input / output impedance

**Figure 3: VGA Design Issues**

A fundamental VGA design problem is programming gain accurately. Electromechanical relays have minimal on-resistance ( $R_{ON}$ ), but are unsuitable for gain switching—slow, large, and expensive. CMOS switches are small, but they have voltage/temperature dependent  $R_{ON}$ , as well as stray capacitance, which may affect VGA ac parameters.

To understand  $R_{ON}$ 's effect on performance, consider Figure 4 below, a poor VGA design. A non-inverting op amp has 4 different gain-set resistors, each grounded by a switch, with an  $R_{ON}$  of  $100\ \Omega$  to  $500\ \Omega$ . Even with  $R_{ON}$  as low as  $25\ \Omega$ , the gain of 16 error would be 2.4%, worse than 8-bits!  $R_{ON}$  also changes over temperature, and switch-switch.

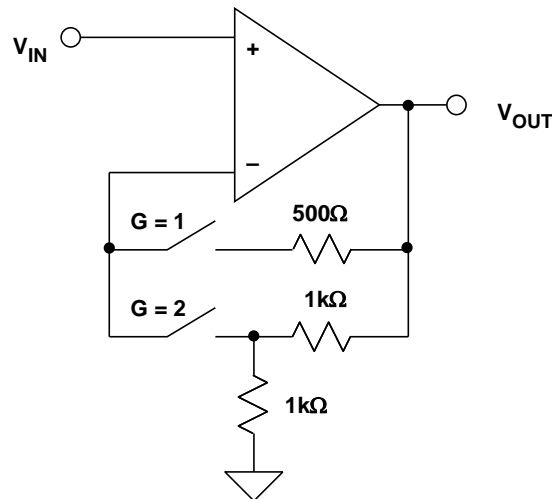


- ◆ Gain accuracy limited by switch's on-resistance  $R_{ON}$  and  $R_{ON}$  modulation
- ◆  $R_{ON}$  typically  $100 - 500\ \Omega$  for CMOS or JFET switch
- ◆ Even for  $R_{ON} = 25\ \Omega$ , there is a 2.4% gain error for  $G = 16$
- ◆  $R_{ON}$  drift over temperature limits accuracy
- ◆ Must use very low  $R_{ON}$  switches (relays)

**Figure 4: A Poorly Designed VGA**

To attempt "fixing" this design, the resistors might be increased, but noise and offset could then be a problem. The only way to accuracy with this circuit is to use relays, with virtually no  $R_{ON}$ . Only then will the few  $m\Omega$  of relay  $R_{ON}$  be a small error compared to  $625\ \Omega$ .

It is much better to use a circuit insensitive to  $R_{ON}$ ! In Figure 5 below, the switch is placed in series with the inverting input of an op amp. Since the op amp input impedance is very large, the switch  $R_{ON}$  is now irrelevant, and gain is now determined solely by the external resistors. Note— $R_{ON}$  may add a small offset error if op amp bias current is high (if this is the case, it can readily be compensated with an equivalent resistance at  $V_{IN}$ ).



- ◆  $R_{ON}$  is not in series with gain setting resistors
- ◆  $R_{ON}$  is small compared to input impedance
- ◆ Only slight offset errors occur due to bias current flowing through the switches

**Figure 5: Alternate VGA Configuration Minimizes the Effects of  $R_{ON}$**

The following sections illustrates several low frequency VGA circuits using the above and other concepts.

### AD526 SOFTWARE PROGRAMMABLE VGA

The [AD526](#) amplifier uses the just-described VGA architecture, integrating it onto a single chip, as diagrammed in Figure 6. The AD526 has 5 binary gain settings from 1 to 16, and its internal JFET switches are connected to the inverting input of the amplifier as in Figure. 5. The gain resistors are laser trimmed, providing a maximum gain error of only 0.02%, and a linearity of 0.001%. The use of the FORCE/SENSE terminals connected at the load ensures highest accuracy (it also allows the use of an optional unity-gain buffer, for low impedance loads). The AD526 is controlled by a latched digital interface.

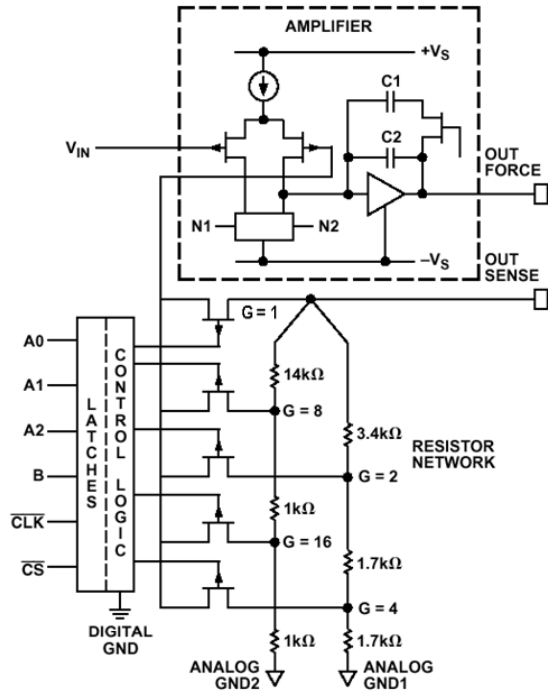


Figure 6: [AD526](#) Software Programmable VGA Simplified Schematic

### LOW NOISE VGA

This same design concepts can be used to build a low noise VGA as shown in Figure 7 below. It uses a single op amp, a quad switch, and precision resistors. The lower noise [AD797](#) replaces the JFET input op amp of the AD526, but almost any voltage feedback op amp could be used in this circuit. The [ADG412](#) was picked for its  $R_{ON}$  of  $35\ \Omega$ .

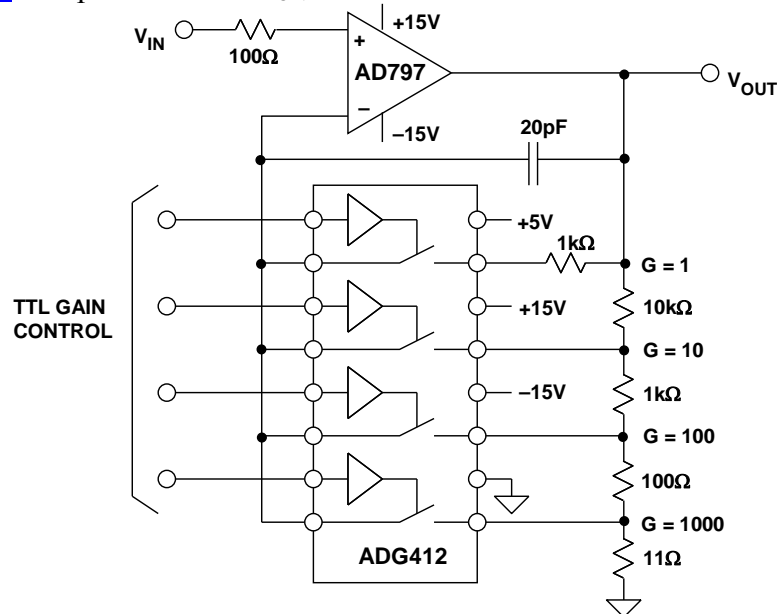


Figure 7: A Very Low Noise VGA Using the AD797 and the ADG412

The resistors were chosen to give decade gains of 1, 10, 100 and 1000, but if other gains are required, the resistor values may easily be altered. Ideally, a single trimmed resistor network should be used both for initial gain accuracy and for low drift over temperature. The 20 pF feedback capacitor ensures stability and holds the output voltage when the gain is switched. The control signal to the switches turns one switch off a few nanoseconds before the second switch turns on. During this break, the op amp is open-loop. Without the capacitor the output would start slewing. Instead, the capacitor holds the output voltage during switching. Since the time that both switches are open is very short, only 20 pF is needed. For slower switches, a larger capacitor may be necessary.

The VGA's input voltage noise spectral density at a gain of 1000 is only 1.65 nV/ $\sqrt{\text{Hz}}$  at 1 kHz, only slightly higher than the noise performance of the AD797 alone. The increase is due to the ADG412 noise, and the current noise of the AD797 flowing through  $R_{\text{ON}}$ .

The accuracy of the VGA is important in determining the overall accuracy of a system. The AD797 has a bias current of 0.9  $\mu\text{A}$ , which, flowing in a 35  $\Omega$   $R_{\text{ON}}$ , results in an additional offset error of 31.5  $\mu\text{V}$ . Combined with the AD797 offset, the total  $V_{\text{OS}}$  becomes 71.5  $\mu\text{V}$  (max). Offset temperature drift is affected by the change in bias current and  $R_{\text{ON}}$ . Calculations show that the total temperature coefficient increases from 0.6  $\mu\text{V}/^\circ\text{C}$  to 1.6  $\mu\text{V}/^\circ\text{C}$ . Note that while these errors are small (and may not matter in the end) it is still important to be aware of them.

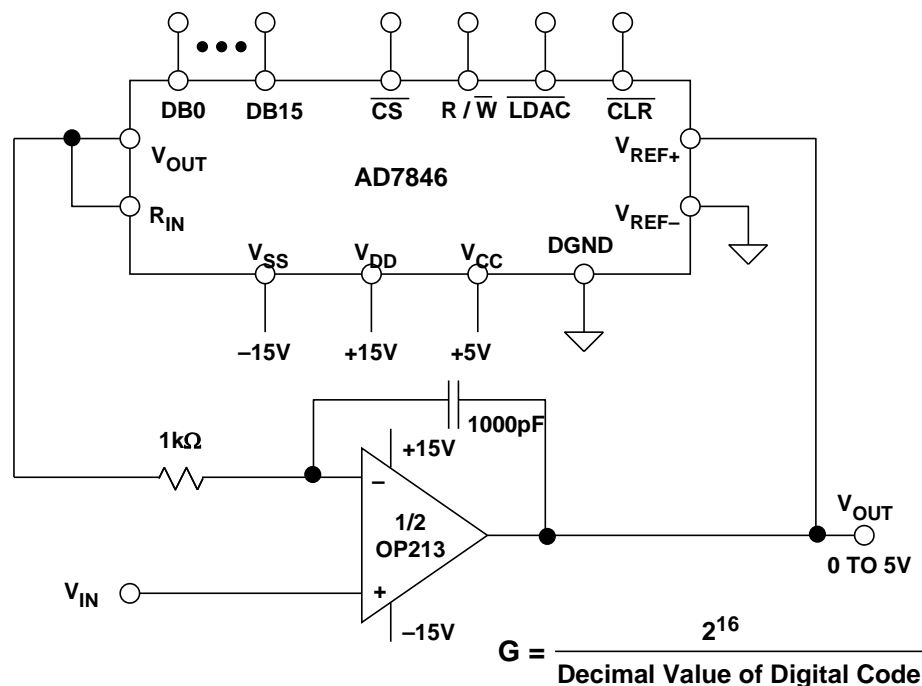
In practice, circuit accuracy and gain TC will be determined by the external resistors. Input characteristics such as common mode range and input bias current are determined solely by the AD797.

## DAC PROGRAMMED VGA

Another VGA configuration uses a DAC in the feedback loop of an op amp to adjust the gain under digital control, as shown in Figure 8 below. The digital code of the DAC controls its attenuation with respect to its reference input  $V_{\text{REF}}$ , acting functionally similar to a potentiometer. Attenuating the feedback signal increases the closed-loop gain.

A noninverting VGA of this type requires a multiplying DAC with a voltage mode output. Note that a multiplying DAC is a DAC with a wide reference voltage range, *which includes zero*. For most applications of the VGA, the reference input must be capable of handling bipolar signals. The [AD7846](#) is a 16-bit converter that meets these requirements. In this application, it is used in the standard 2-quadrant multiplying mode.

The [OP213](#) is a low drift, low noise amplifier, but the choice of the amplifier is flexible, and depends on the intended application. The input voltage range depends on the output swing of the AD7846, which is 3 V less than the positive supply, and 4 V above the negative supply. A 1000 pF capacitor is used in the feedback loop for stability.



**Figure 8: Binary Gain VGA Using a DAC in the Feedback Path of an Op Amp**

The gain of the circuit is set by adjusting the digital inputs of the DAC, according to the equation given in Fig. 8.  $D_{0-15}$  represents the decimal value of the digital code. For example, if all the bits were set high, the gain would be  $65,536/65,535 = 1.000015$ . If the 8 least significant bits are set high and the rest low, the gain would be  $65,536/255 = 257$ .

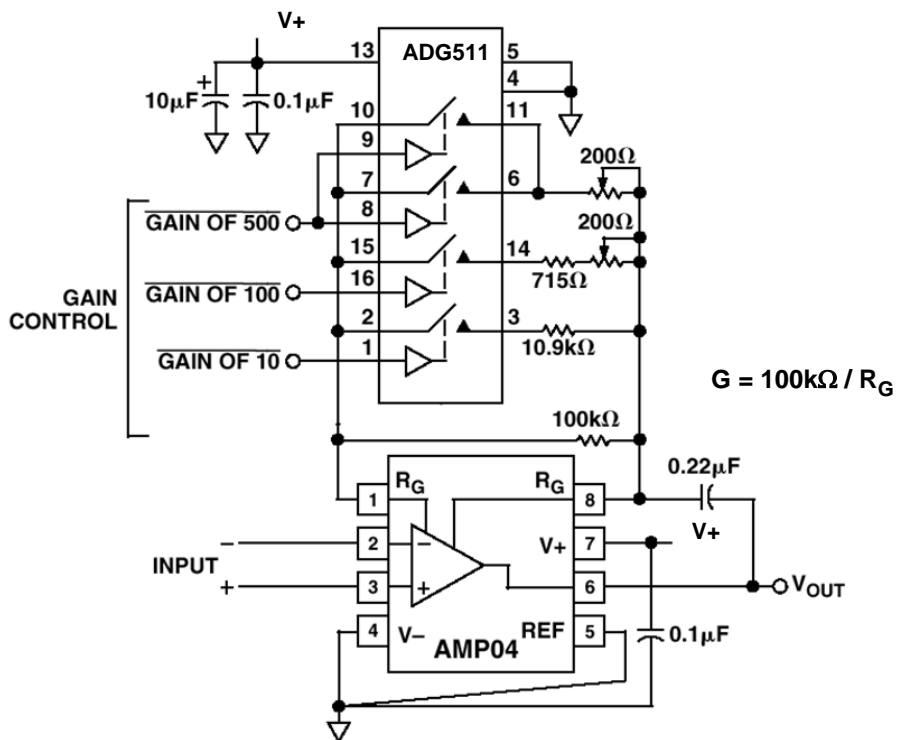
The bandwidth of the circuit is a fairly high 4 MHz for a gain of +1. However, this does reduce with gain, and for a gain of 256, the bandwidth is only 600 Hz. If the gain-bandwidth product were constant, the bandwidth in a gain of 256 should be 15.6 kHz; but the internal capacitance of the DAC reduces the bandwidth to 600 Hz.

The gain accuracy of the circuit is determined by the resolution of the DAC and the gain setting. At a gain of 1, all bits are on, and the accuracy is determined by the DNL specification of the DAC, which is  $\pm 1$  LSB maximum. Thus, the gain accuracy is equivalent to 1 LSB in a 16-bit system, or 0.003%.

However, as the gain is increased, fewer of the bits are on. For a gain of 256, only bit 8 is turned on. The gain accuracy is still dependent on the  $\pm 1$  LSB of DNL, but now that is compared to only the lowest 8 bits. Thus, the gain accuracy is reduced to 1 LSB in an 8-bit system, or 0.4%. If the gain is increased above 256, the gain accuracy is reduced further. The designer must determine an acceptable level of accuracy. In this particular circuit, the gain was limited to 256.

## A DIFFERENTIAL INPUT VGA

Non-inverting VGA circuits using an op amp are easily adaptable to single supply operation, but when differential inputs are desired, a single-supply in-amp such as the [AD623](#), [AD627](#), or the [AMP04](#) should be used. The AMP04 is used with an external [ADG511](#) CMOS switch in the single supply in-amp VGA shown in Figure 9 below.



**Figure 9: Single Supply Instrumentation VGA Using the AMP04 In-Amp and the ADG511 Switch**

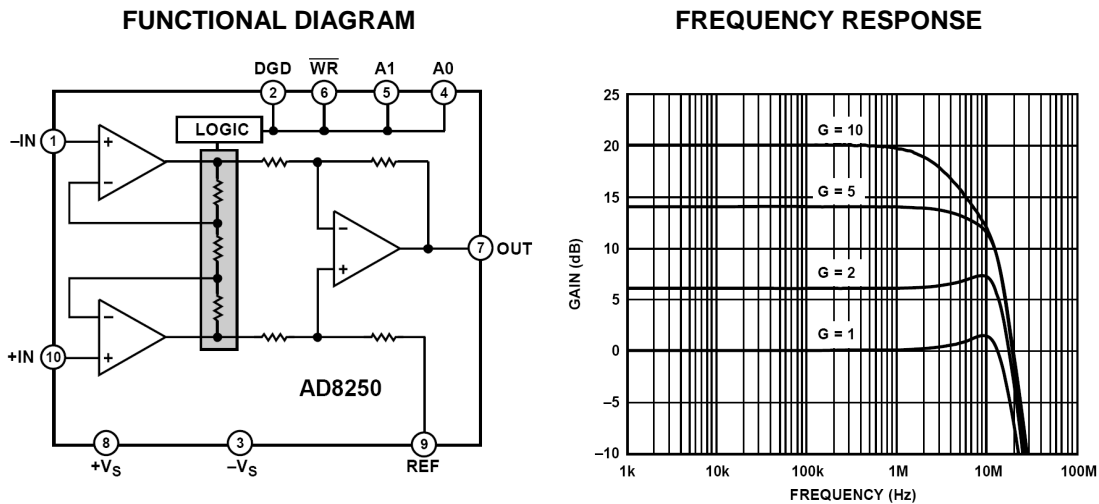
This circuit has selectable gains of 1, 10, 100, and 500, which are controlled by an ADG511. The ADG511 was chosen as a single supply switch with a low  $R_{ON}$  of  $45\ \Omega$ . A disadvantage of this circuit is that the gain of this circuit is dependent on the  $R_{ON}$  of the switches. Trimming is required at the higher gains to achieve accuracy. At a gain of 500, two switches are used in parallel, but their resistance causes a 10% gain error in the absence of adjustment.

## PROGRAMMABLE GAIN INSTRUMENTATION AMPLIFIERS

The [AD8250](#) is an *iCMOS*<sup>®</sup> instrumentation amplifier with digitally programmable gains (1, 2, 5, and 10) that has  $G\Omega$  input impedance, low output noise, and low distortion making it suitable for interfacing with sensors and driving high sample rate analog-to-digital converters (ADCs). It has high bandwidth of 10 MHz, low THD of  $-110$  dB and fast settling time of 615 ns to 0.001%. Offset drift and gain drift are guaranteed to  $1.7\ \mu V/^\circ C$  and  $10\ \text{ppm}/^\circ C$ , respectively for  $G = 10$ . In addition to its wide input common voltage range, it has a common-mode rejection of 80 dB at  $G = 1$  from dc to 50 kHz. The combination of precision dc performance coupled with high speed



capabilities make the AD8250 an excellent candidate for data acquisition. Furthermore, this monolithic solution simplifies design and manufacturing, and boosts performance of instrumentation by maintaining a tight match of internal resistors and amplifiers. The AD8250 user interface consists of a parallel port that allows users to set the gain in one of two different ways (see Figure 10 for the functional block diagram and frequency response). A 2-bit word sent via a bus can be latched using the WR input. An alternative is to use transparent gain mode where the state of logic levels at the gain port determines the gain.



**Figure 10: AD8250 iCMOS Programmable Gain Instrumentation Amplifier**

The [AD8251](#) is similar to the [AD8250](#) but has programmable gains of 1, 2, 4, and 8. The [AD8253](#) has programmable gains of 1, 10, 100, and 1000.

### ADCS WITH ONBOARD VGAS/PGAs

Certain ADCs (such as the AD77xx measurement series) have built in VGAs and other conditioning circuitry. Circuit design with these devices is much easier, because an external VGA and its control logic are not needed. Furthermore, all the errors of the VGA are included in the specifications of the ADC, making error calculations simple. The VGA gain is controlled over the common ADC serial interface, and the gain setting is factored into the conversion, saving additional calculations to determine input voltage.

This combination of ADC and VGA is very powerful and enables the realization of a highly accurate system, with a minimum of circuit design. As an example, Figure 11 below shows a simplified diagram of the [AD7730](#) sigma-delta measurement ADC which is optimized for digitizing low voltage bridge outputs directly (as low as 10 mV full scale) to greater than 16-bits noise free code resolution, without the need for external signal conditioning circuits.

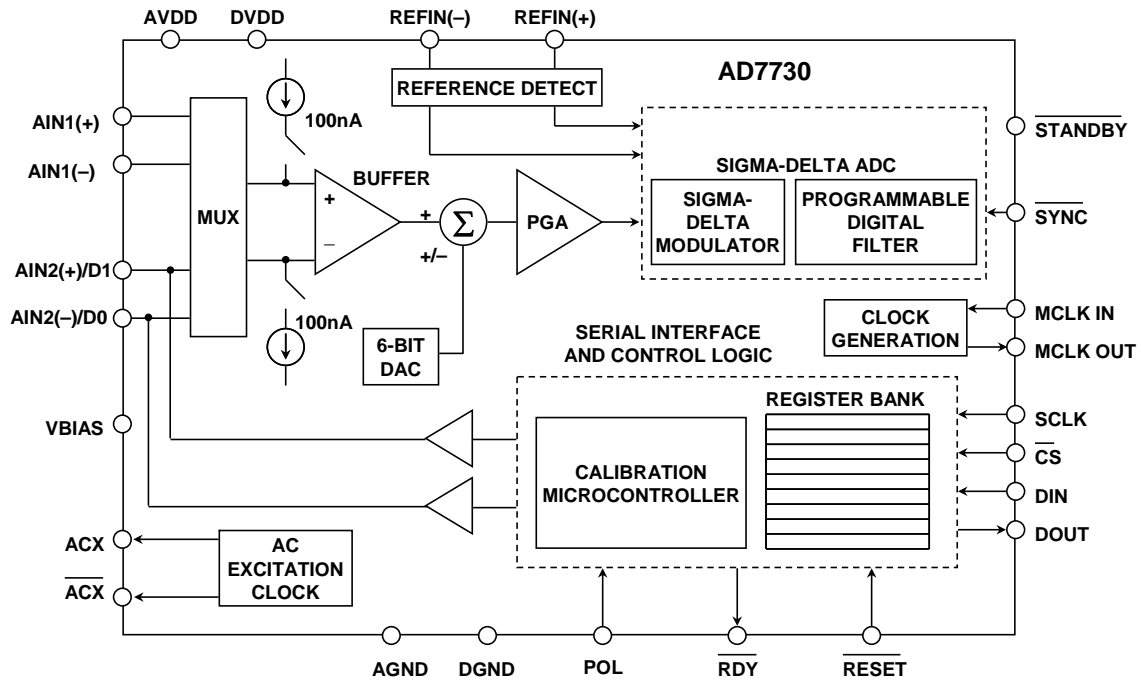


Figure 11: [AD7730](#) Sigma-Delta Measurement ADC with On-Chip VGA

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