

Bridge Measurement Systems

Section 5

Precision Analog Applications Seminar

Bridge Measurement Systems Outline

- ◆ Introduction to Bridge Sensors
- ◆ Circuits for Bridge Sensors
- ◆ A real design: the ADS1232REF
- ◆ The ADS1232REF Firmware

This presentation gives an overview of data acquisition for bridge sensors. We begin with a discussion of the bridge sensor, and introduce some theory. We then look at actual hookups of bridge sensors to ADCs. The ADS1232REF is introduced and discussed as an example of a real design. Finally, we briefly discuss the ADS1232REF's firmware.

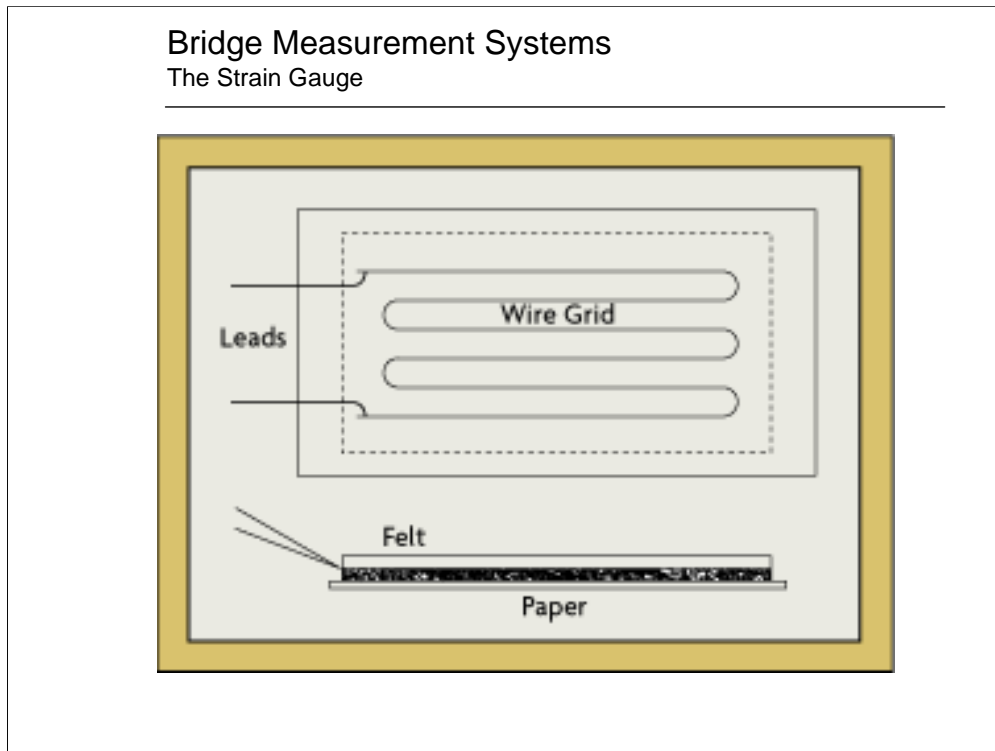
Precision Analog Applications Seminar

Bridge Measurement Systems A Common Bridge Sensor: The Load Cell



A load cell is one of the most common bridge sensor types. It can measure most kinds of force, but load cells in weigh scales almost always measure compression.

Precision Analog Applications Seminar



The strain gauge is the sensitive element in load cells.

Any common piece of wire will change resistance slightly when placed under tension. Wire arranged to maximise this effect forms a strain gauge. Strain gauges are typically etched foil patterns glued to a bar of metal or other tensionable material.

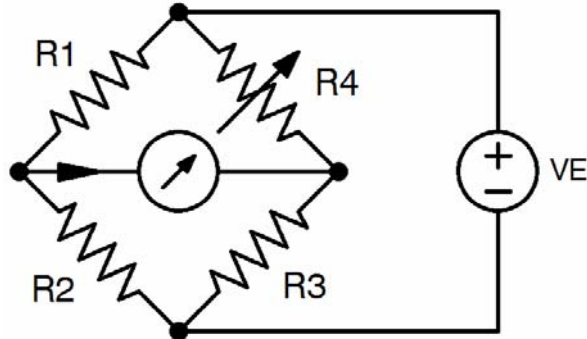
In a load cell, the strain gauge is placed so that when the cell is loaded, the gauge is strained, changing its resistance.

The resistance change per unit of strain is very small, and requires sensitive circuitry to measure it accurately.

(Image from <http://www.omega.com/literature/transactions/volume3/strain.html>)

Precision Analog Applications Seminar

Bridge Measurement Systems The Wheatstone Bridge



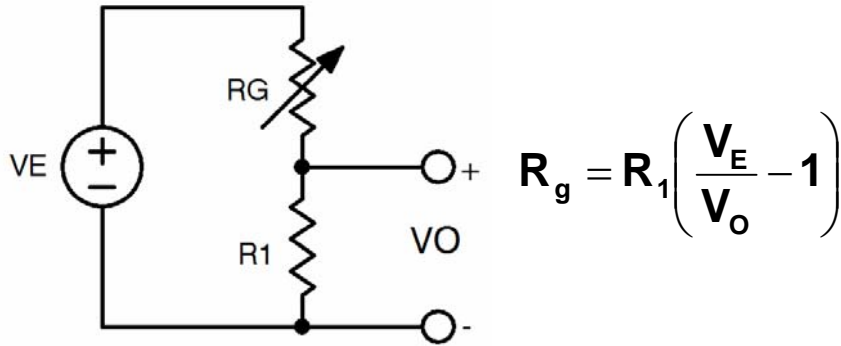
The Wheatstone bridge is a familiar circuit for measuring resistance very accurately. Invented in 1833 by Hunter Christie, the circuit was later studied by Charles Wheatstone, whose name became attached to the circuit thanks to his extensive analyses of it. Wheatstone also was the first to draw the circuit in the distinctive diamond style used ever since.

The principle of the circuit is that if three resistances are known, and the current in the cross branch is zero, the fourth resistance can be calculated. The measurement can be made very accurately since zero current can be detected with extremely high accuracy using a sufficiently sensitive galvanometer.

This circuit is actually not used in bridge sensors, despite appearances; but it is a direct ancestor of the bridge sensor. Let's now look at the circuits used for measuring sensor resistance.

Precision Analog Applications Seminar

Bridge Measurement Systems Resistance Measurement



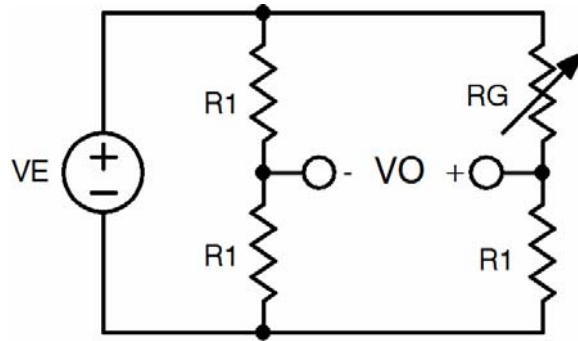
The circuit above shows how it is possible to measure resistance using a voltage divider. V_E is called the excitation voltage.

Note that the relationship between R_g and V_o is non-linear.

For a sensor like a strain gauge, this circuit will tend to produce very small changes in voltage, offset by a large amount. These are very difficult to measure if the offset is not known.

Precision Analog Applications Seminar

Bridge Measurement Systems Removing the Offset



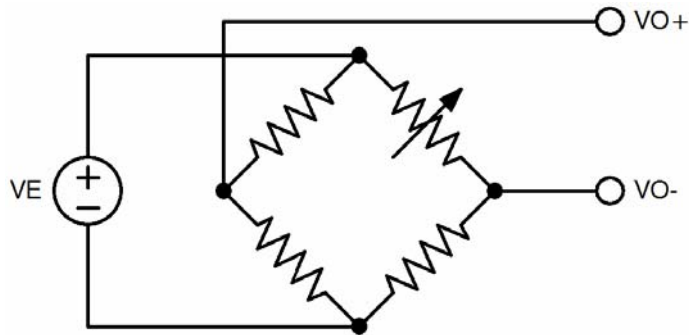
$$V_o = V_E \left[\frac{R_1}{R_1 + R_G} - \frac{1}{2} \right]$$

The large offset can be eliminated by adding a voltage divider and measuring the output differentially.

This assumes that R_G at rest is roughly equal to R_1 , and that all the R_1 s are very closely matched. Bridge sensors are nearly always built this way.

Precision Analog Applications Seminar

Bridge Measurement Systems Single-Point Bridge



$$V_O = V_E \left[\frac{R_1}{R_1 + R_G} - \frac{1}{2} \right]$$

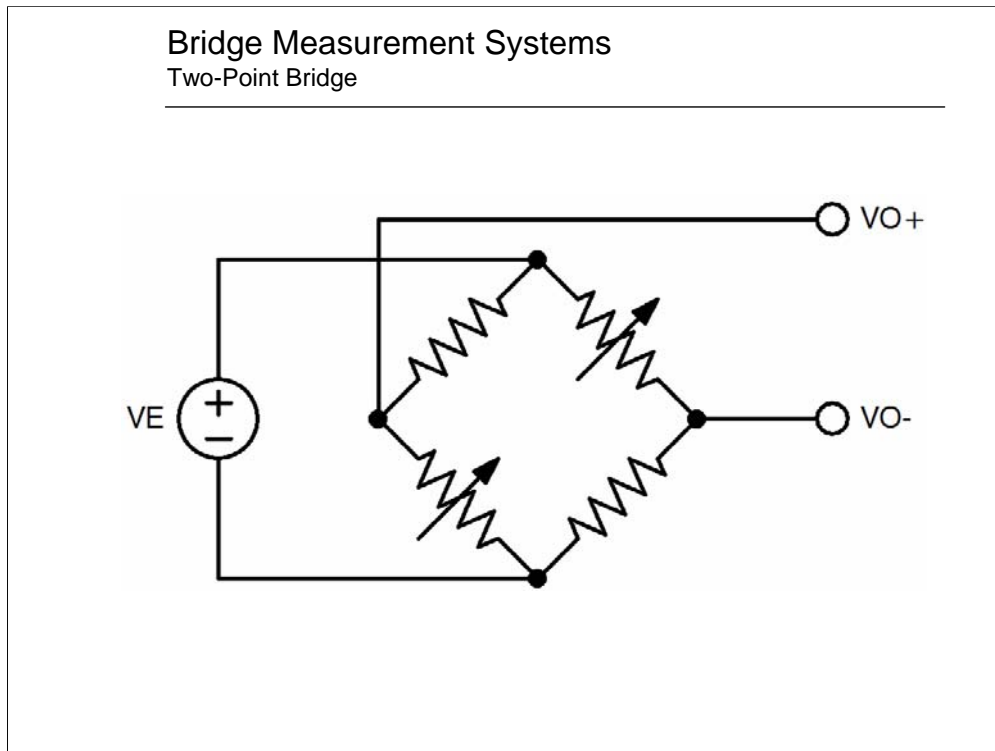
This circuit is electrically identical to the previous one. This is how bridge sensors are commonly drawn.

This configuration is called a single-point bridge sensor, since a single resistor changes, while the other three are fixed.

Again, the output voltage does not change linearly with the changing resistance.

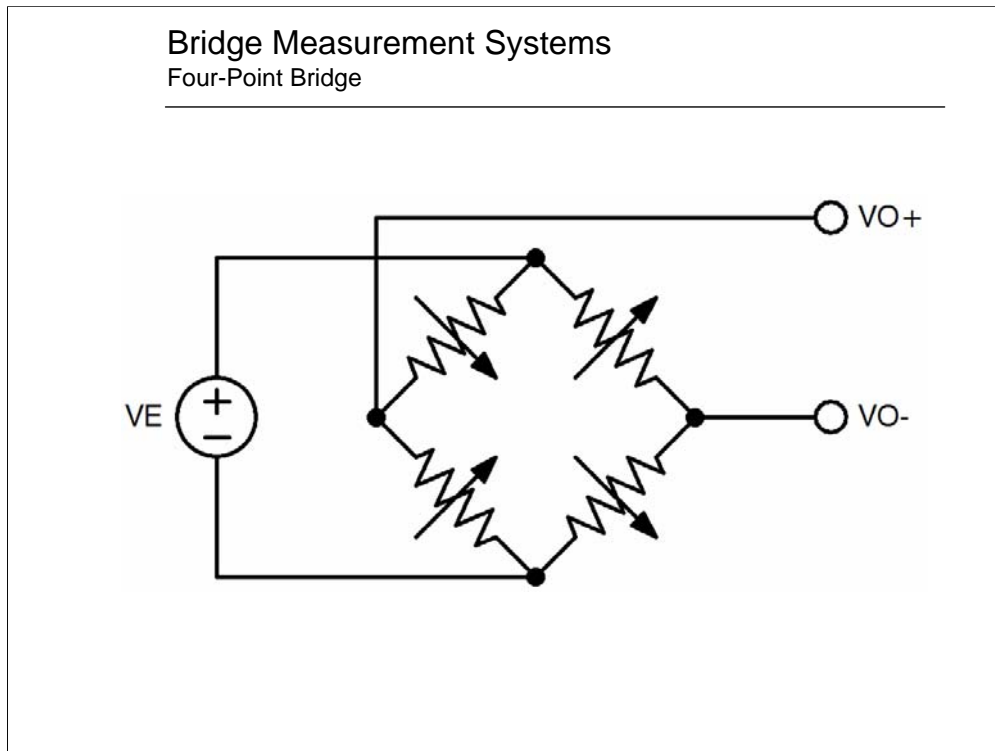
Note that this circuit is not really a Wheatstone bridge, since the legs are not connected, and voltage is measured instead of current.

Precision Analog Applications Seminar



Bridge sensors can be made with two varying points. Higher-end load cells are commonly constructed this way, with two strain gauges connected oppositely. This makes the cell twice as sensitive.

Precision Analog Applications Seminar



Bridge sensors can also be made with all four elements varying. This is done in cases where a very linear and sensitive output is needed. Matching the elements can be difficult, so this is seldom done in inexpensive sensors.

Precision Analog Applications Seminar

Bridge Measurement Systems

Bridge sensor parameters

- ◆ **Sensitivity** – measured in mV/V; voltage output when the bridge is excited with 1 volt and the sensor is at full scale; 2mV/V is common
- ◆ **Accuracy** – measured in percent; load cells are typically 0.1% - 1% accurate, due to non-linear output curve
- ◆ **Bridge resistance** – resistance of the bridge measured unloaded across the signal terminals

Three parameters are usually supplied with bridge sensors.

Sensitivity is the most important. It is nearly always expressed in mV/V. A bridge with 2mV/V sensitivity will deliver 2mV if the measurement is at full-scale and the bridge is excited with 1V. This shows that the signals to be measured are very, very small; a 10V excitation can excite a 2mV/V sensor to at most 20mV!

Accuracy is generally rated at the factory. Although the 1% and 0.1% numbers look abysmal, in practice most sensors can perform better in controlled conditions, especially after calibration and linearization.

The bridge resistance indicates the size of the resistors in the bridge when the bridge is unloaded (idle). Bridge resistances are typically less than 1k. Most bridges measure the same resistance across the excitation terminals. Note that the bridge resistance determines power consumption, which can be rather high; a 10V excitation consumes 20mA for a 500-ohm bridge.

Precision Analog Applications Seminar

Bridge Measurement Systems

Bridge sensor error terms

- ◆ **Offset error** – voltage produced when the measurement parameter is zero
- ◆ **Full-scale error** – difference between the ideal voltage and the actual voltage when the measurement parameter is at maximum
- ◆ **Drift** – change of the above as temperature varies
- ◆ **Non-linearity** – deviation of the output curve from a straight line

Bridge sensors have error terms similar to those found on other kinds of sensors.

Offset error is the voltage produced when the sensor's measurement parameter is zero. This can easily be calibrated out.

Full-scale error is the deviation in slope from the expected value. This can also be easily corrected.

Drift is very important: it is the change of the above values with temperature and time. It is much more difficult to compensate for drift – especially drift with time.

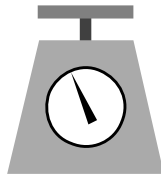
As we have seen, most bridge sensors exhibit an inherent non-linearity, in addition to the non-linearities arising from other sources. This can be corrected for to a degree, but commonly is not, as it is (with a good sensor) smaller than most other errors.

Precision Analog Applications Seminar

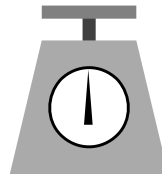
Bridge Measurement Systems Calibration

Offset calibration for a weigh scale

No weight (0kg)



Before offset
calibration



After offset
calibration

This slide and the next illustrate calibration for a weigh scale.

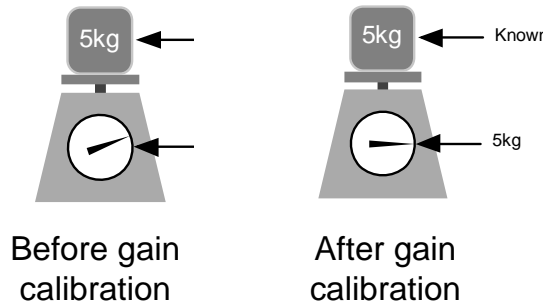
In this slide, the scale is offset calibrated. Prior to calibration, the scale displays a negative offset. After calibration, with no weight applied, the scale reads zero, as it should.

(Note that in the case of an analog scale, calibration can be performed merely by rotating the movement of the gauge.)

Precision Analog Applications Seminar

Bridge Measurement Systems Calibration

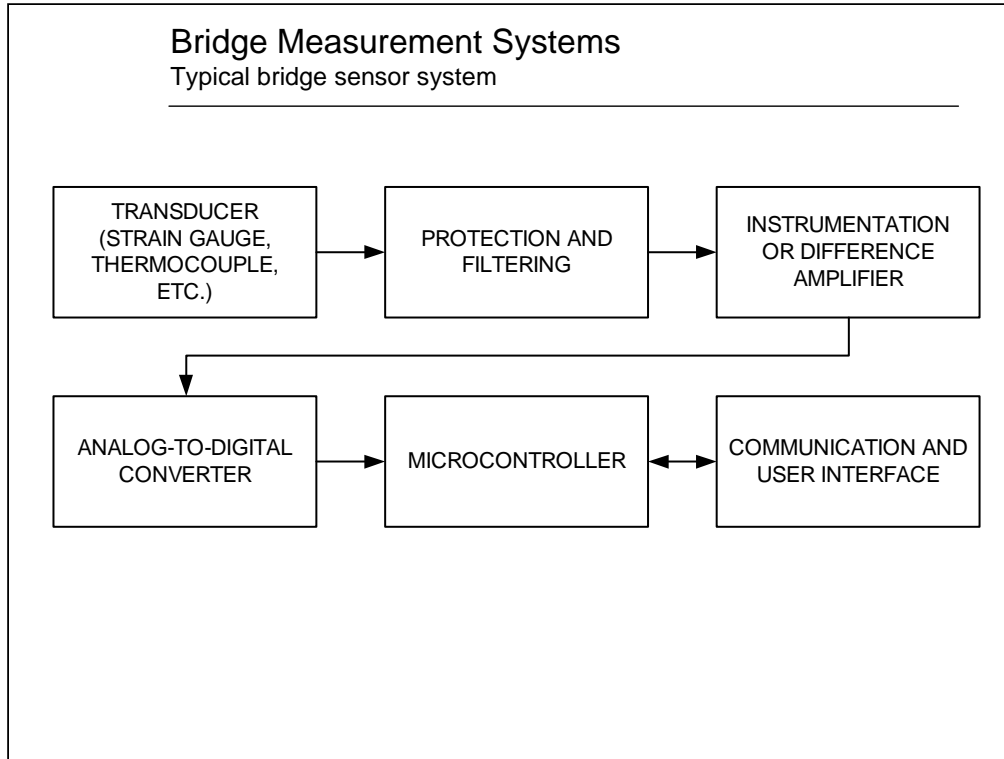
Gain calibration for a weigh scale



In this slide, the scale is shown being calibrated for gain. A known weight is obtained and placed on the scale. The scale is then adjusted until its reading is equal to the mass of the known weight.

This scale reads too low when the 5kg known weight is placed on it. Following calibration, the scale reads 5kg with a 5kg known weight on it, as it should.

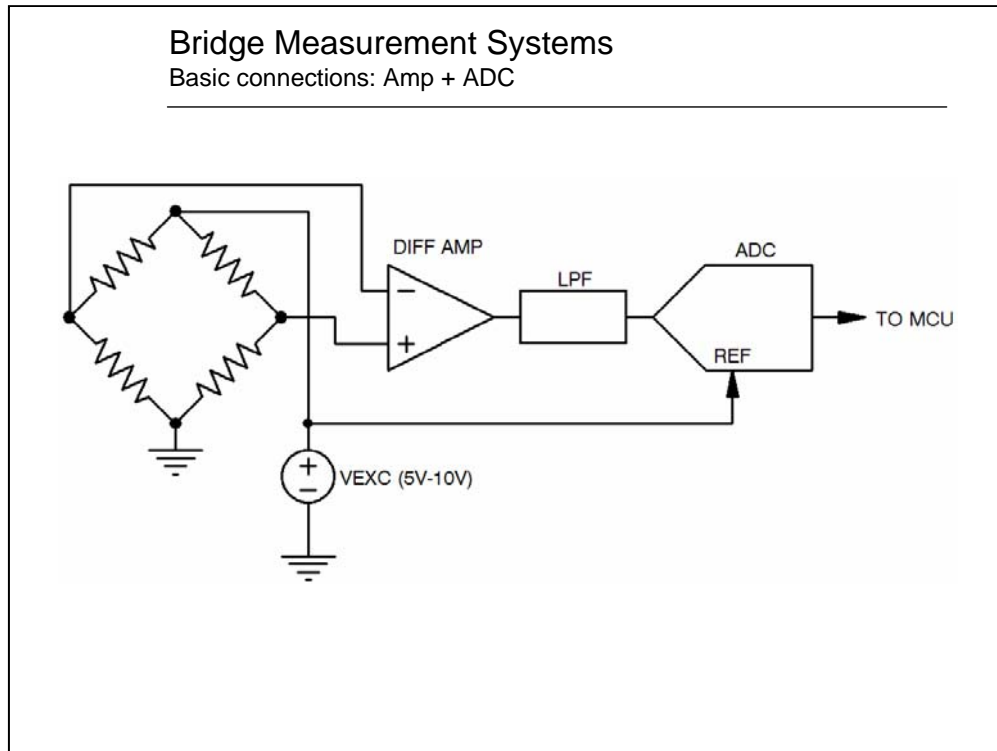
Precision Analog Applications Seminar



A typical sensor measurement system has:

- ◆ An input stage, consisting of protection circuitry and amplification. In some circuits, the amplification is incorporated into the A/D converter.
- ◆ An A/D converter.
- ◆ A microcontroller, whose task is to collect data from the converter, possibly process the data collected, convert it to a useful form, and make it available to the user.

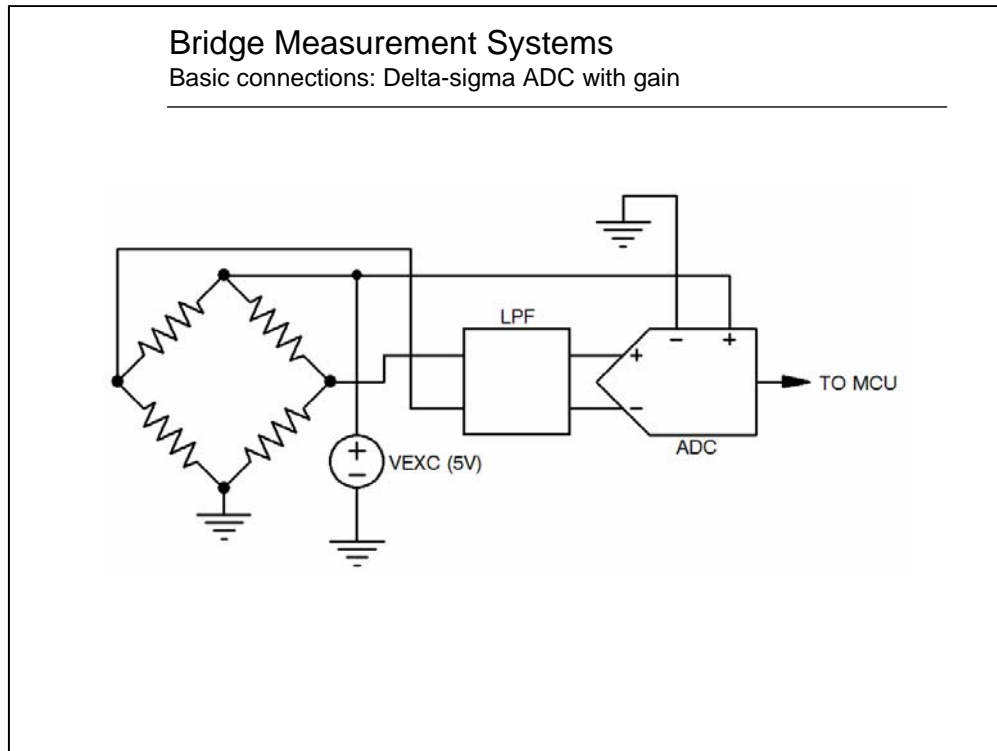
Precision Analog Applications Seminar



This is the most common circuit for bridge measurement using SAR converters. The signal is amplified using a differential amplifier of some kind, converting it from 0-20mV to the converter's input range, often 0-5V. This is then filtered.

This circuit shows a ratiometric connection. The excitation for the bridge is also used for the ADC's reference. In this connection, a four-wire load cell is used. We will see a six-wire load cell used shortly.

Precision Analog Applications Seminar

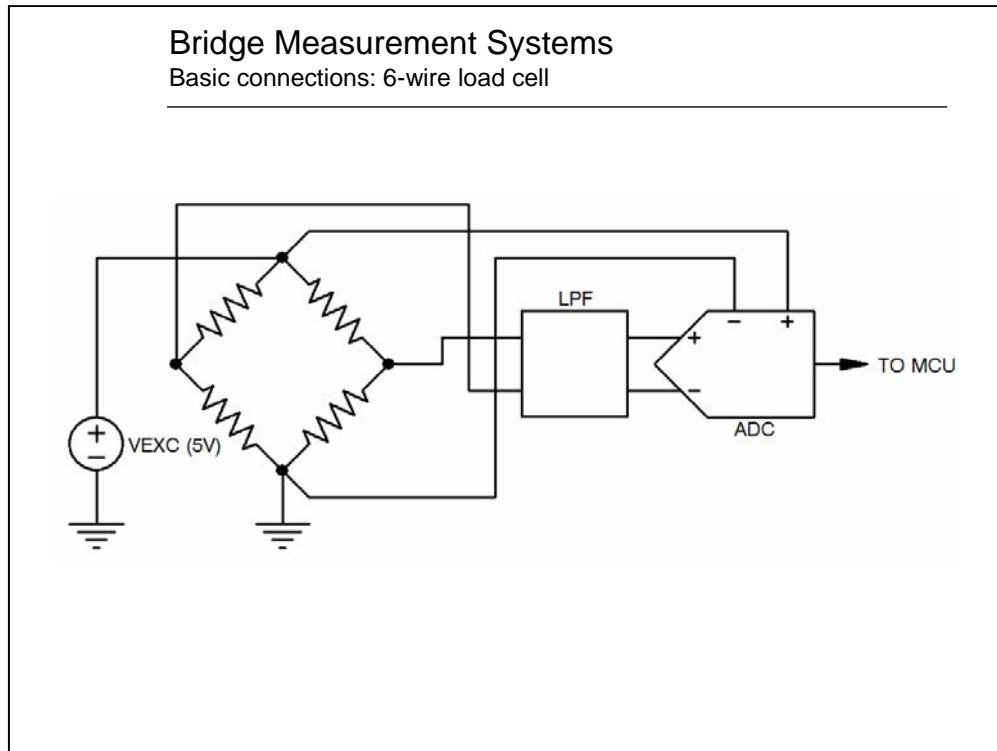


With a differential-input ADC having gain, as is the case with many industrial delta-sigma ADCs, the bridge sensor can often be connected directly. Here a differential low-pass filter is used for reduction of noise.

Again, this connection is ratiometric. Very few delta-sigma ADCs can accept larger than a 5V reference, so the excitation voltage is reduced to 5V. The reduction in gain is made up by the reduction in noise offered by a delta-sigma ADC.

Note that the gain in most delta-sigma converters is done by making adjustments to the modulator, and does not result from actual analog amplification. However, there are exceptions to this. TI's ADS1232 and ADS1234 are examples.

Precision Analog Applications Seminar

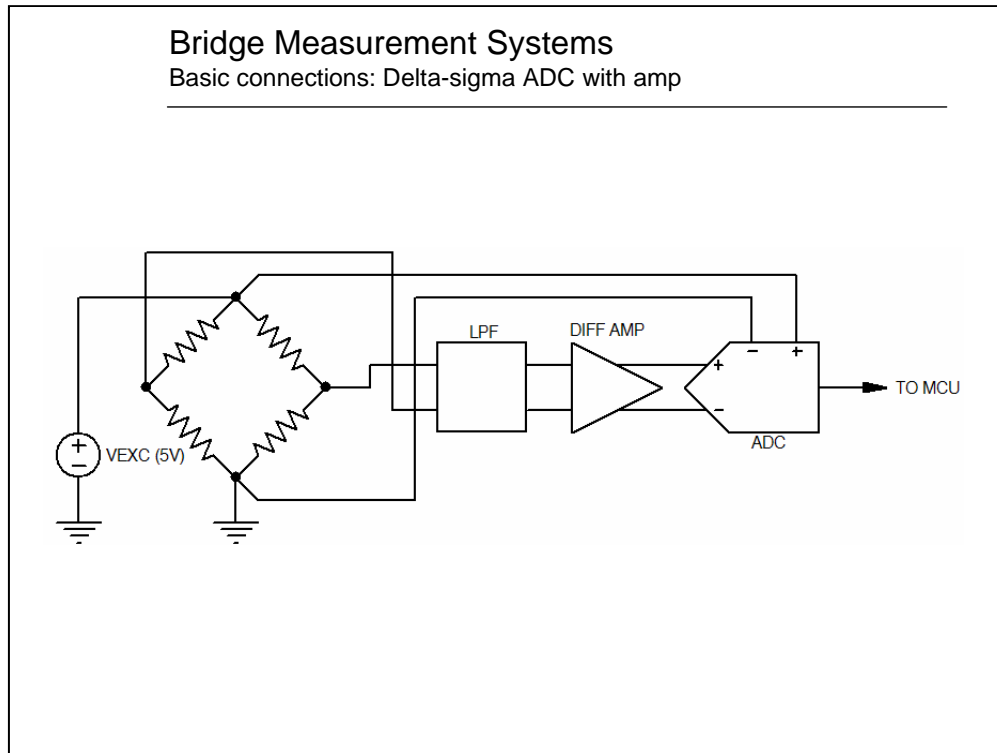


This schematic shows a 6-wire load cell connected in Kelvin fashion. For this to work, the ADC's reference input must have a very high impedance. If it does not, the reference must be buffered.

The Kelvin connection aims to reduce errors arising from voltage drops in the excitation line. The drops are caused by the relatively high current required to excite the load cell. Since the ADC's reference draws very little current, these drops do not occur in the return line, which is usually called the sense line.

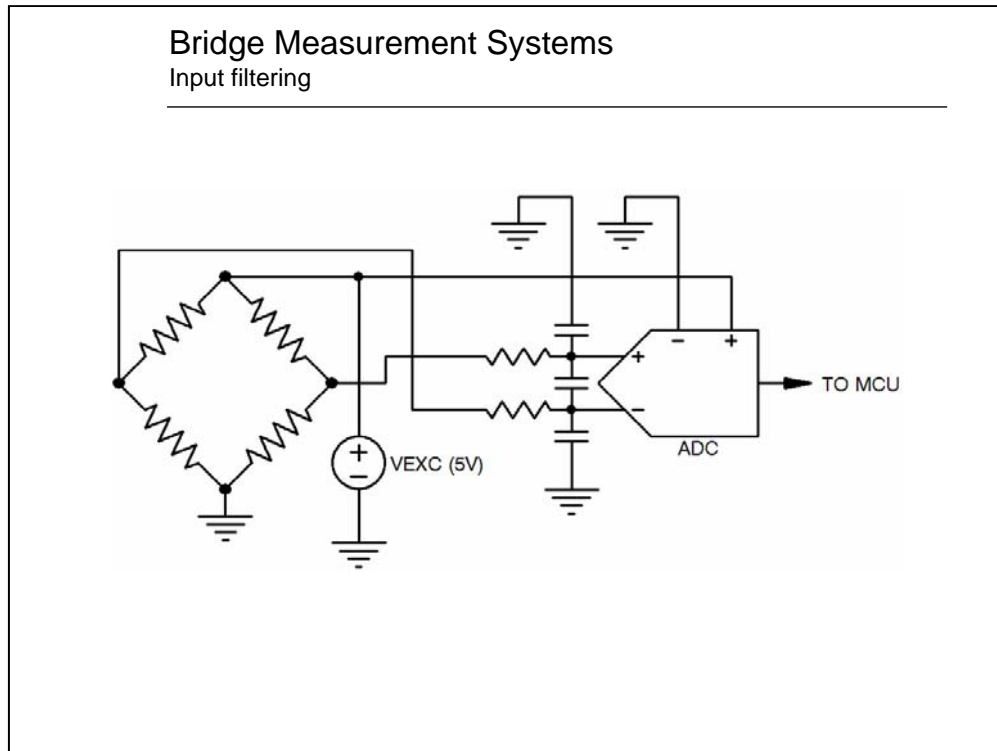
Kelvin connections are usually needed only for load cells connected through a long cable.

Precision Analog Applications Seminar



Although delta-sigma ADCs often have built-in amplification, sometimes greater performance can be obtained by adding an analog gain stage. This circuit shows this done differentially.

Precision Analog Applications Seminar



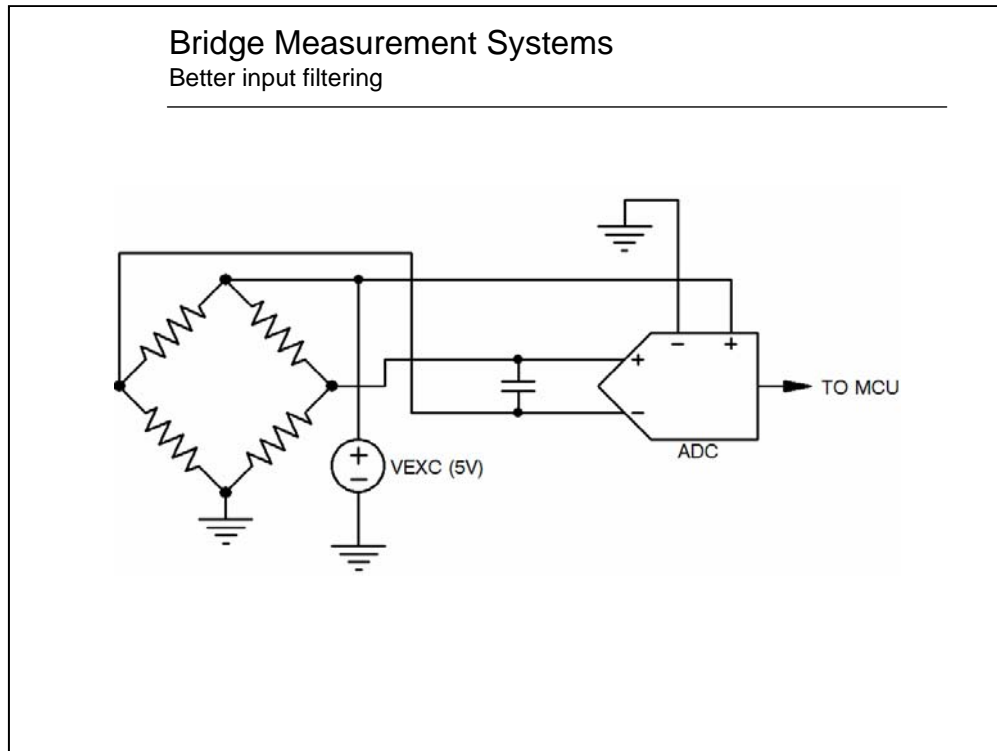
It's usually good to filter the output of a bridge sensor. This reduces wideband noise and can help reject interference.

Shown is a single-pole differential low-pass filter configuration. The differential capacitor size depends on the desired data rate and settling time. It can be anywhere from 100pF to 1 μ F and above.

The common-mode capacitors should usually be very small, for example around 100pF. They are of limited benefit, but can reduce charge dumping from the input. They should be matched, or common-mode rejection will suffer.

The resistors should likewise be very small, no more than 100-200 ohms. If they are too large, increased noise and gain errors will result. They should also be matched for good common-mode rejection.

Precision Analog Applications Seminar



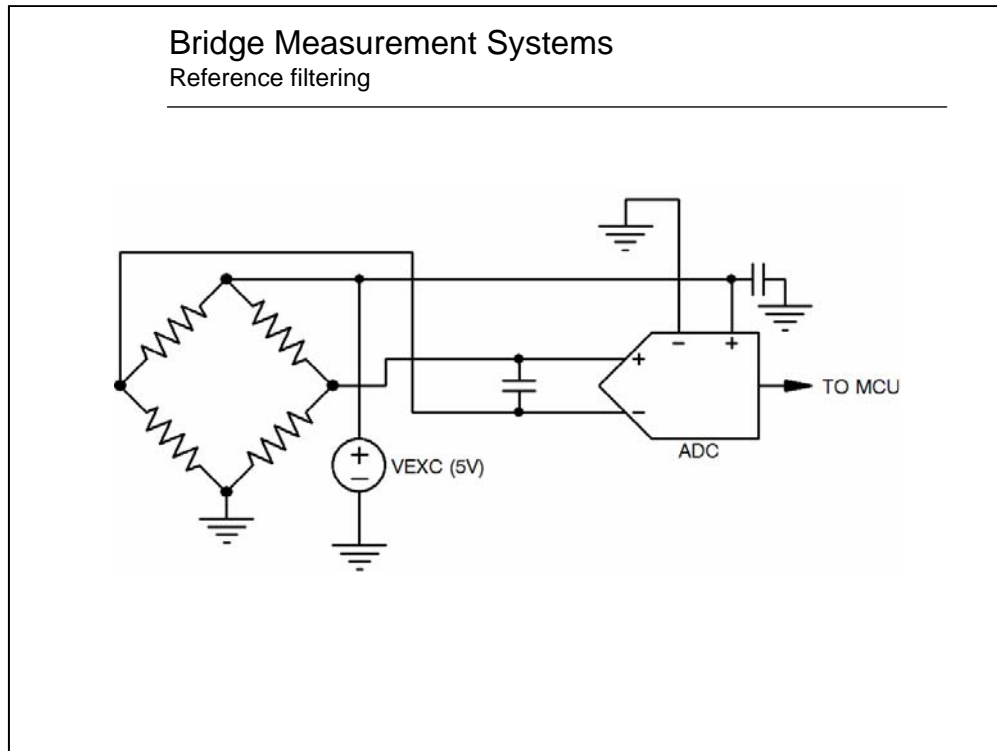
Although most people think of the previously shown circuit as a necessary input filter, the simple one shown here can actually perform better.

Since there are no components to be mismatched, common-mode rejection does not suffer. Eliminating the common-mode capacitors is of great benefit here.

Eliminating the resistors provides similar benefits. Note that there is some resistance already in the bridge itself. Also, many amplifiers and even ADCs have resistors built in to the front-end, so adding resistance usually only adds noise and gain error.

The differential capacitor is critical, and should be of very high quality. Ceramic X5Rs and worse should never be used. Even X7R-grade capacitors should be avoided. C0G or film capacitors should be used here.

Precision Analog Applications Seminar



The lowly capacitor once again forms the most effective reference filter for delta-sigma converters.

Resistance can be of benefit, but more often is not, though it can be worth trying.

There is no one perfect capacitor size to use. Capacitor size should generally be as large as possible, though this depends on the reference source and system configuration. Different values should be tested, if possible, for effectiveness.

Note that if the reference is buffered by an op-amp, the op-amp's rated capacitive load typically does not apply, since the reference signal is essentially DC. It is possible to use 100 μ F and larger values without instability on nearly any op-amp.

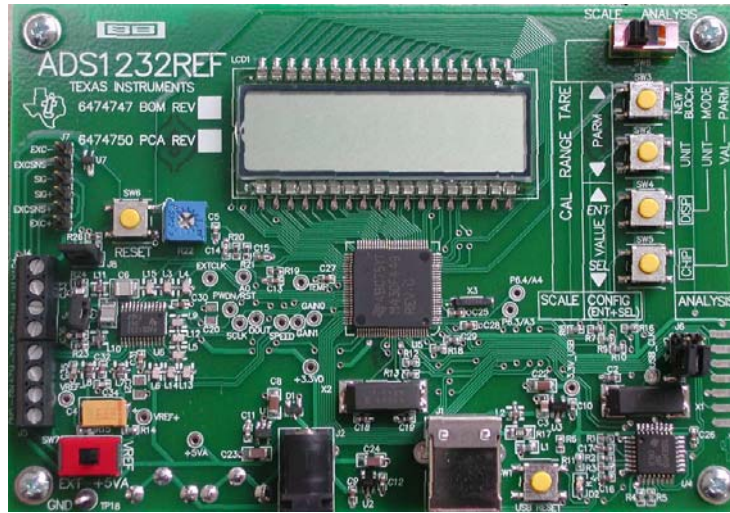
Overly large capacitor values can cause differences between the voltage at the bridge excitation terminals and the reference voltage. It is wise to try different values.

A small capacitor should always be placed as close to the IC's reference pin as possible, for interference rejection.

The capacitor type is not as critical here. Tantalum and ceramic capacitors can be safely used. However, very low-quality capacitors should still be avoided, and if drift is a concern, higher-quality capacitors should be considered, as capacitors can cause reference drift.

Precision Analog Applications Seminar

Bridge Measurement Systems The ADS1232REF

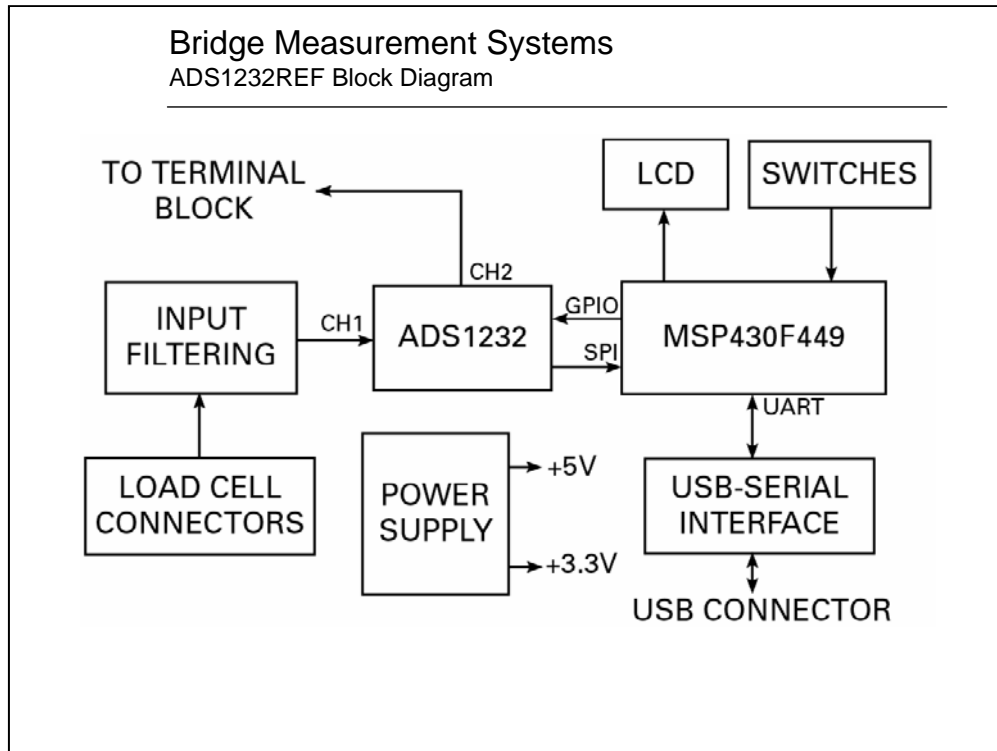


The ADS1232REF is a reference design for the ADS1232. It is designed to function as a weigh scale or load-cell meter, and has all of the components (except the case) which might be found in a real weigh-scale design.

It also serves as a general-purpose evaluation module for the ADS1232. It can be used either standalone or with a PC. The standalone modes display data from the board, and perform analysis on it. Software for the PC can read data from the board, perform analysis on it, and save it to disk.

The ADS1232REF can match and demonstrate all performance specifications shown in the datasheet for the ADS1232/34.

Precision Analog Applications Seminar

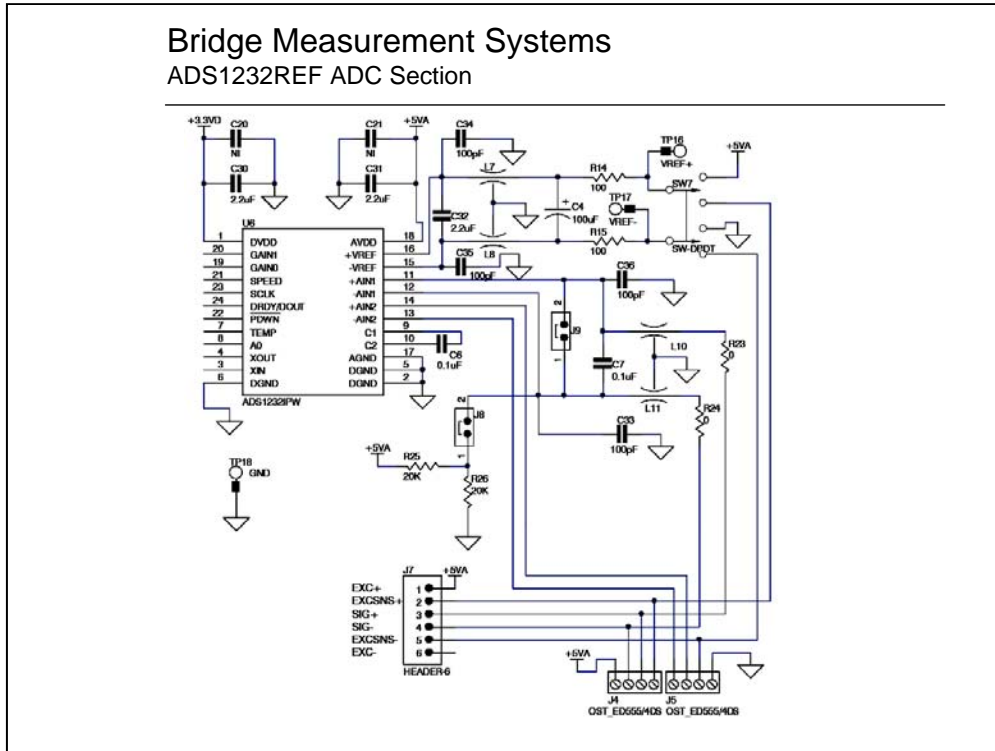


The ADS1232REF is based around an MSP430F449 microcontroller. This was chosen for its LCD driver, its multiplier, and its memory capacity.

The ADS1232 has three channels. Two are brought out to connectors, and the third reads an internal temperature diode. One of the channels is designed for connection to a load cell. One of the connectors has switchable excitation.

Precision Analog Applications Seminar

Bridge Measurement Systems ADS1232REF ADC Section



The ADC section demonstrates several features of good design for the ADS1232, and a few extra features to aid evaluation.

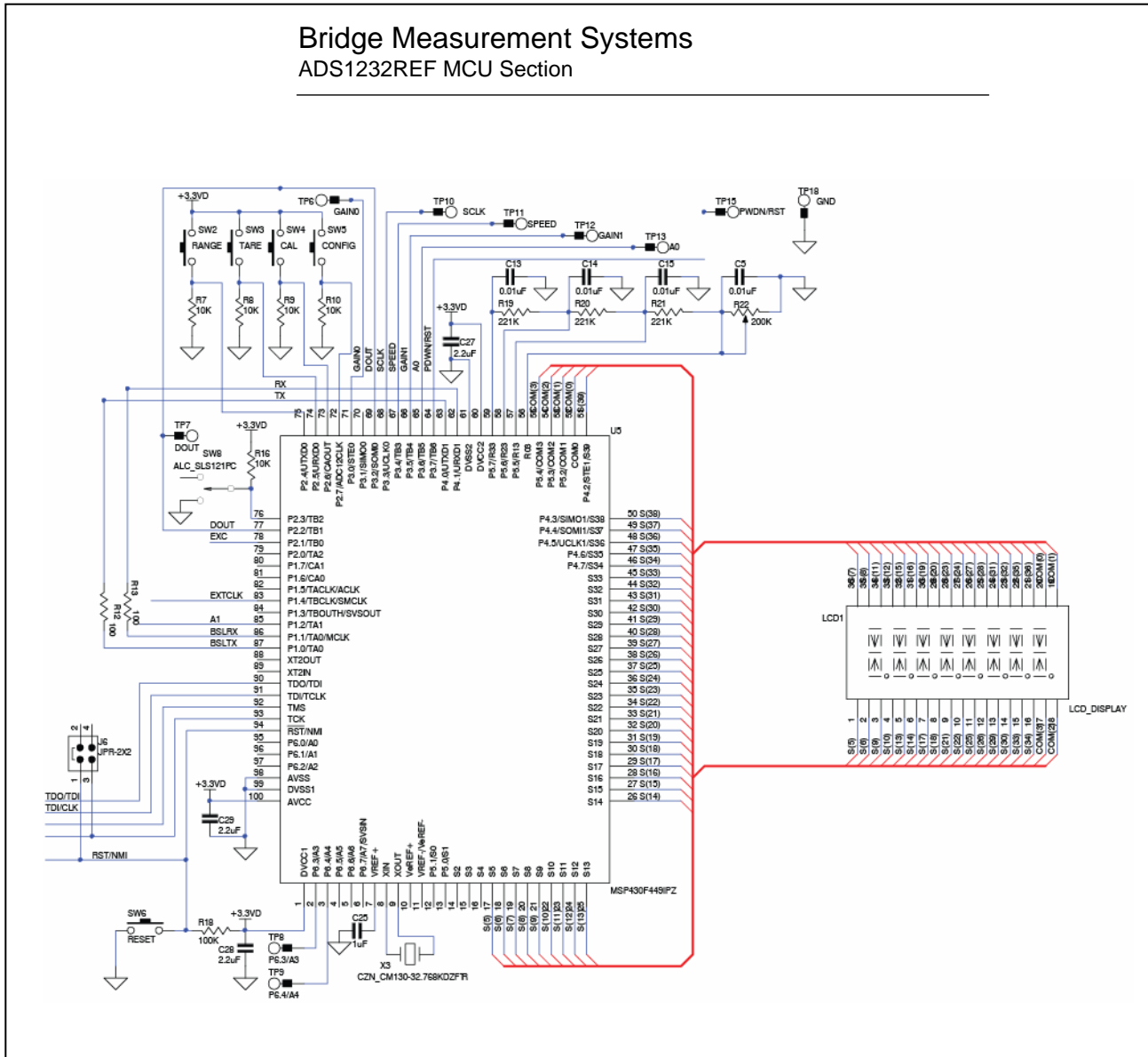
Input AIN1 is designed for load cells and is connected in two places; the screw-terminal block, and the header. It is filtered using through-caps and a differential capacitor. The input resistors are zero, since higher values increase noise.

The reference can be derived either from the 5V analog supply or from an external source – typically the excitation sense line from a six-wire load cell. The choice is made using switch SW7.

The reference is filtered by an elaborate network of capacitors and a pair of 100 ohm resistors. These help reject interference which may be picked up from a long cable.

Precision Analog Applications Seminar

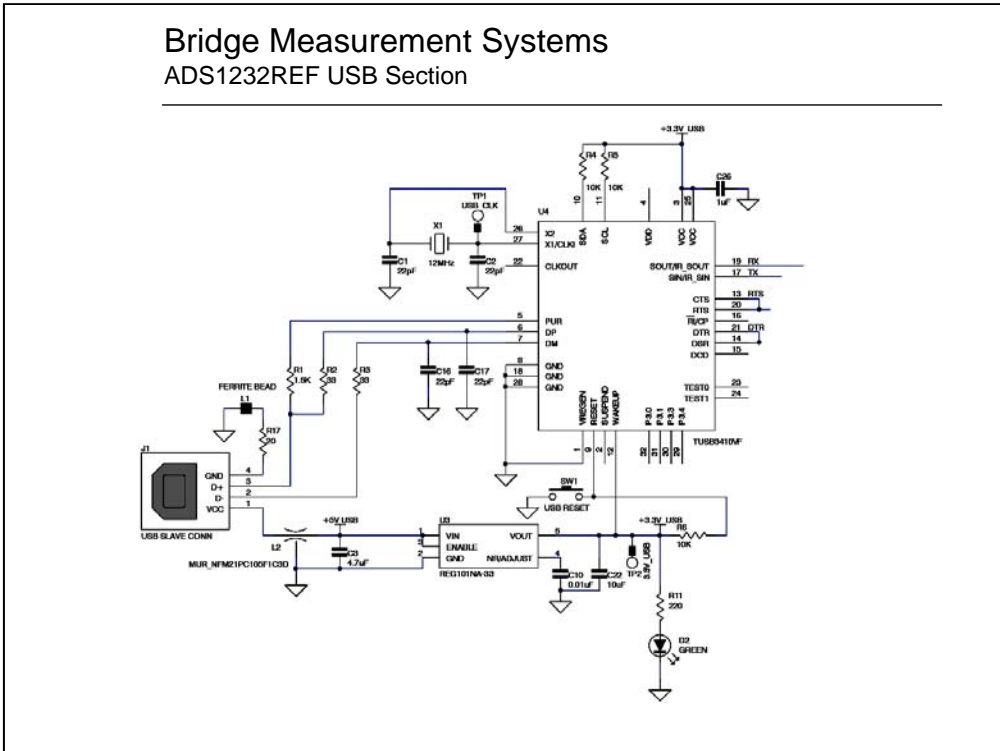
Bridge Measurement Systems ADS1232REF MCU Section



The MCU section is quite straightforward. An eight-digit starburst LCD occupies the LCD driver pins; five switches provide user interface. Programming comes from an (optional) JTAG connector or the serial bootstrap loader, which is connected to the USB to serial converter.

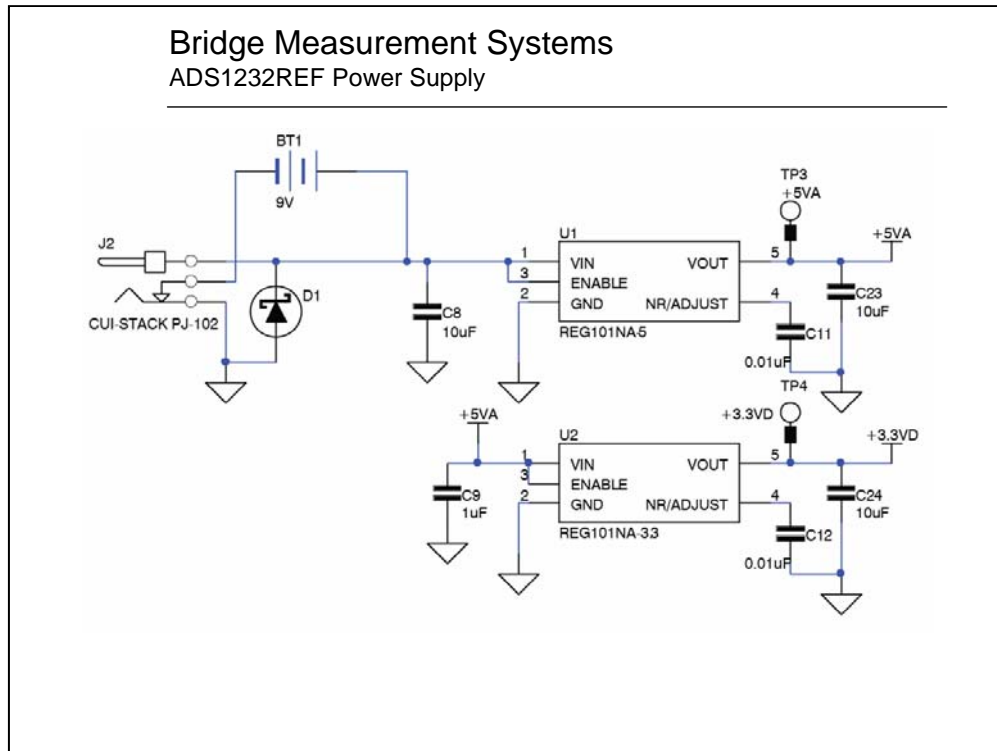
Precision Analog Applications Seminar

Bridge Measurement Systems ADS1232REF USB Section



The USB-serial converter is based around the TI TUSB3410. TI provides “virtual COM port” drivers for several operating systems, including Windows. This section is powered from USB, and is not powered when the USB cable is removed.

Precision Analog Applications Seminar

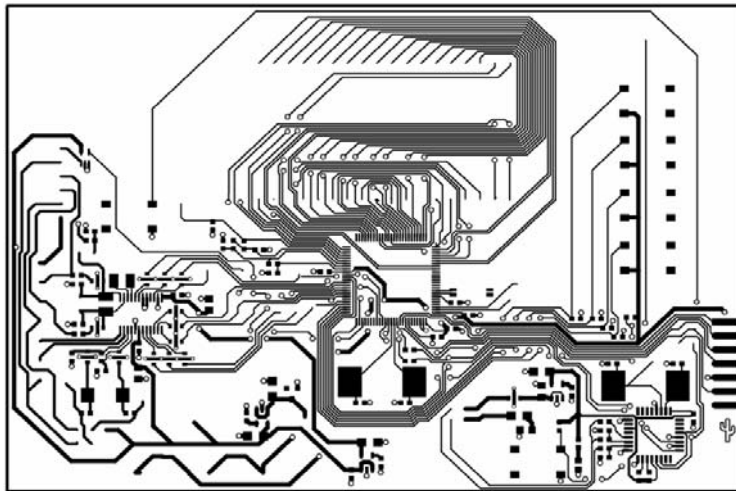


Power is supplied either from a wall-mount AC adaptor or a 9V battery. A switched connector causes AC connection to override the battery. To save battery power, there are no power-on LEDs.

Low noise is important, since the power supply is (optionally) used as the ADC reference. The power supply is thoroughly filtered on both input and output.

Precision Analog Applications Seminar

Bridge Measurement Systems ADS1232REF Layout: Top

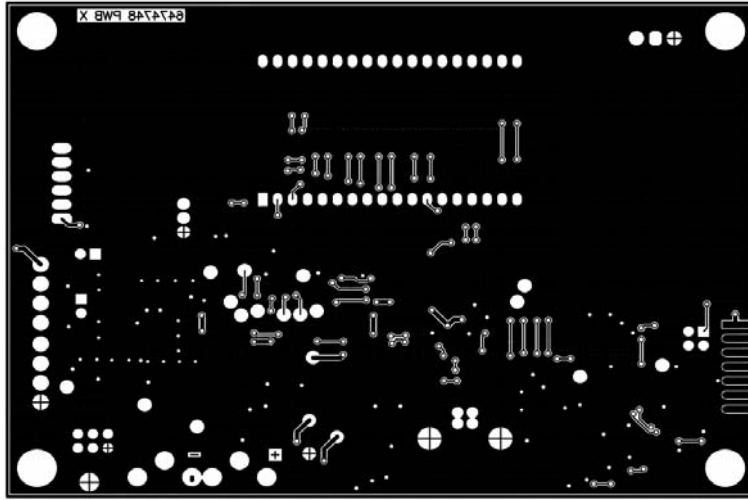


The ADS1232REF is laid out in two layers. This proves that good performance can be obtained with the ADS1232 even with a low-cost board process.

As many signals as possible are routed on the top layer, and the layout is arranged so that the microcontroller and fast digital components are kept away from the analog section.

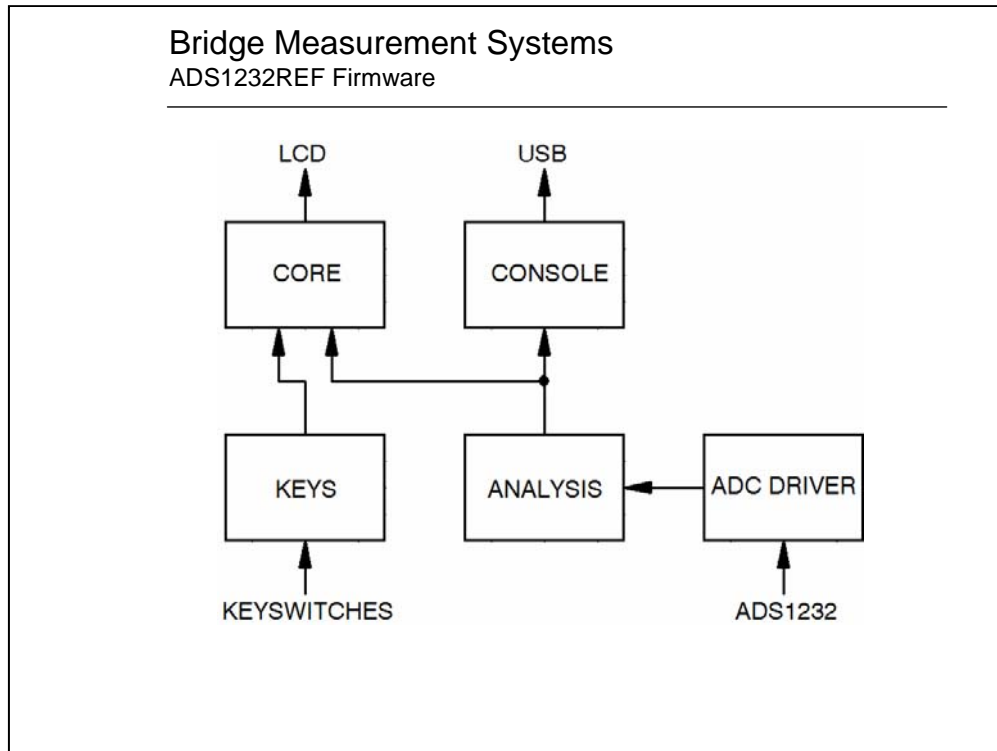
Precision Analog Applications Seminar

Bridge Measurement Systems ADS1232REF Layout: Bottom



The bottom side serves as a ground plane. As few signal traces as possible are routed on the bottom side. Since the layout is not high-speed, wide, direct paths for return current are more important than a continuous ground plane.

Precision Analog Applications Seminar



The ADS1232REF firmware is written using a real-time operating system called FreeRTOS. FreeRTOS is designed for small microcontroller systems, and is very simple. It provides a kernel, process switching, a simple synchronization mechanism, inter-process communication using queues, timing functions, and rudimentary memory management.

The firmware uses four processes. The primary controlling process is CORE. This runs the display, and provides the board's standalone user interface. It obtains information on keyswitch events from KEYS, which scans and debounces the key switches, translating key presses into events. CORE obtains ADC data and block analysis results from ANALYSIS. ANALYSIS obtains ADC data from the ADC driver, which is not a process, but a collection of routines and an ISR.

The fourth process, CONSOLE, implements a serial command-line console with single-letter commands. The PC software uses the command line to communicate with the board. The CONSOLE interface can also be operated via a serial dumb terminal, through the virtual COM port driver for the TUSB3410. Like CORE, CONSOLE obtains data from ANALYSIS and can change certain ADC parameters.

Precision Analog Applications Seminar

Bridge Measurement Systems Calculations

◆ RMS noise:

$$s_N = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \bar{x})^2}$$

◆ ENOB:

$$E = \begin{cases} 24 - \log_2 s_N & : s_N \neq 0 \\ 24 & : s_N = 0 \end{cases}$$

The ADS1232REF firmware provides RMS noise and ENOB calculations.

To calculate RMS noise, the standard deviation formula is used. The result of this is codes, which is converted into volts if necessary.

For ENOB, the base 2 logarithm is taken on the result of the RMS noise calculation, and subtracted from 24. If the standard deviation is 0, 24 bits is used.

Precision Analog Applications Seminar

Bridge Measurement Systems Summary

- ◆ Bridge sensors measure small changes in resistance using a pair of voltage dividers
- ◆ Delta-sigma ADCs are typically the best fit for bridge sensors
- ◆ Additional gain stages are optional with many delta-sigma ADCs
- ◆ Use ratiometric connections where possible
- ◆ Layout is important, but high-speed techniques are not usually needed