A Compact and Flexible Signal Conditioning System for Data Acquisition

Because turbine test setups can have up to 1000 test points, special demands are placed on a data acquisition system that must fit a large number of measurement channels into a C-size VXIbus module.

by John M. da Cunha

The HP Model HD2000 data acquisition system is targeted for customers in the turbine test market. This market requires a variety of signal conditioning capabilities to make accurate measurements during turbine tests. Special needs include low cost per measurement point, high density, flexibility, and high performance. To take advantage of the HP HD2000 system's high common-mode rejection analog-to-digital converter (ADC), analog signal conditioning has to be fully differential. The variety of functions needed and constraints on cost, density, and the need for high performance presented quite a design challenge.

Customer Needs in Turbine Test

Turbine test customers use data acquisition systems to characterize, refine, and verify designs of new jet engines and to ensure that engines are performing to specification after overhaul or repair. A typical turbine test system consists of from 100 to 1000 measurement points taking data about engine temperatures, fuel consumption, thrust, pressures, and other items. Data gathered is displayed on control consoles where technicians running the tests can monitor the progress of the test. Data is also sent to disk for storage and later analysis. Because there are so many points in a typical test system, the cost of installing and maintaining each point is high. Thus, low cost per point is very desirable.

Because of the high measurement point count, customers desire that as many channels as possible be put in a single C-size VXIbus module. Therefore, we had to create a design that fits 64 channels of signal conditioning into a single C-size module along with the ADC and the VXIbus backplane interface. The HP HD2000's ADC also has full differential inputs with greater than 110-dB common-mode rejection. The density, cost, and full differential inputs require that signal conditioning circuits be small, inexpensive, and have very high common-mode rejection.

The form factor chosen for these signal conditioning circuits uses a plug-on module for each group of eight channels. Since the HP HD2000 has 64 channels total, this means that each single-width C-size module contains up to eight plug-on signal conditioning circuits with eight channels each (see Fig. 1). These boards are called signal conditioning plug-ons, or SCPs. Fitting eight SCPs into a single C-size slot meant that we had to create a design in which each SCP could only be 2.00 in by 4.075 in with 1.5 square inches of usable circuit area for each channel. Even using surface mount technology, these constraints proved very challenging for the higher-functionality SCPs.

Required Functions

The essential signal conditioning functions required by turbine test customers include the ability to:

- Pass a signal straight to the analog-to-digital converter
- Provide low-frequency, low-pass filtering
- Provide programmable gain and filtering for lower-noise measurements on thermocouples
- Provide temperature measurements with thermistors and resistive temperature devices
- Measure strain gauges.

The signal conditioning plug-ons (SCPs) in the HP Model HD2000 provide these basic functions.

Straight-Through SCP. The simplest function required of an SCP is to pass the input directly through to the multiplexer and analog-to-digital converter. We call this the straight-through SCP. The straight-through SCP has additional functionality. Customers want a way to detect an open transducer connection as well as an overvoltage condition. These functions are provided with simple yet effective circuits that yield very good overall results.

Open transducer detection is provided by a very large-value resistor (100 MΩ) which can be switched to the positive and negative supplies (see Fig. 2). The resistor provides a very small current that charges the input capacitance to the point where an overvoltage error or nonsensical reading will occur, thereby notifying the operator that there is something amiss with the transducer. Normally, open transducer detection is only switched on during calibration or system verification. The small amount of current will cause a slight degradation of measurement accuracy if used during a data gathering run. While it can be turned on during a data run with no other ill effects, such a practice is not recommended.

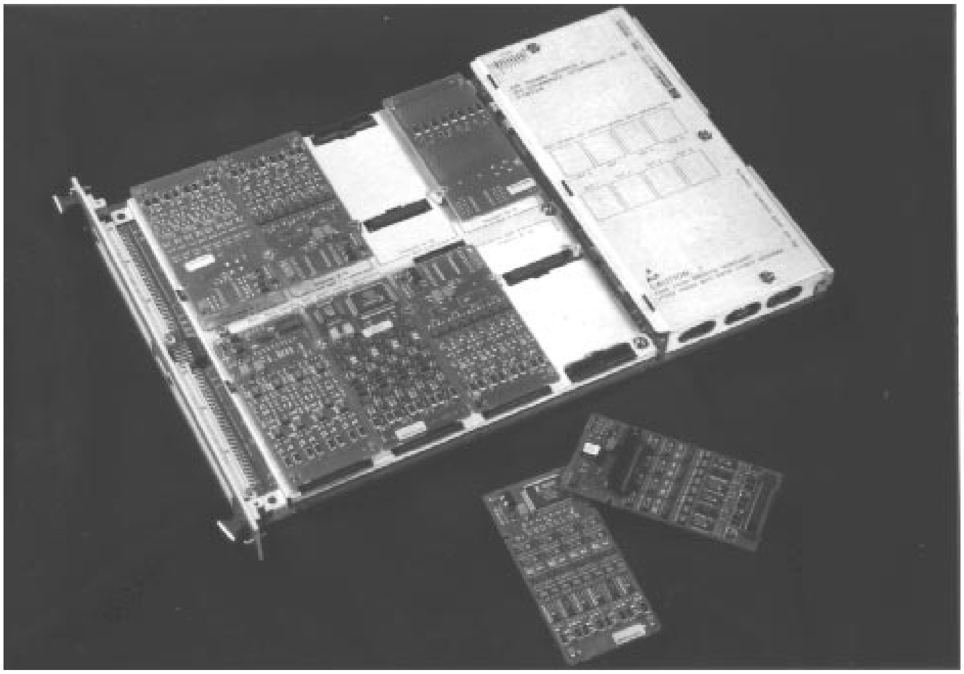


Fig. 1. An HP E1413 module with the cover off showing the eight (two are removed) signal conditioning plug-ons. Each plug-on has eight channels.

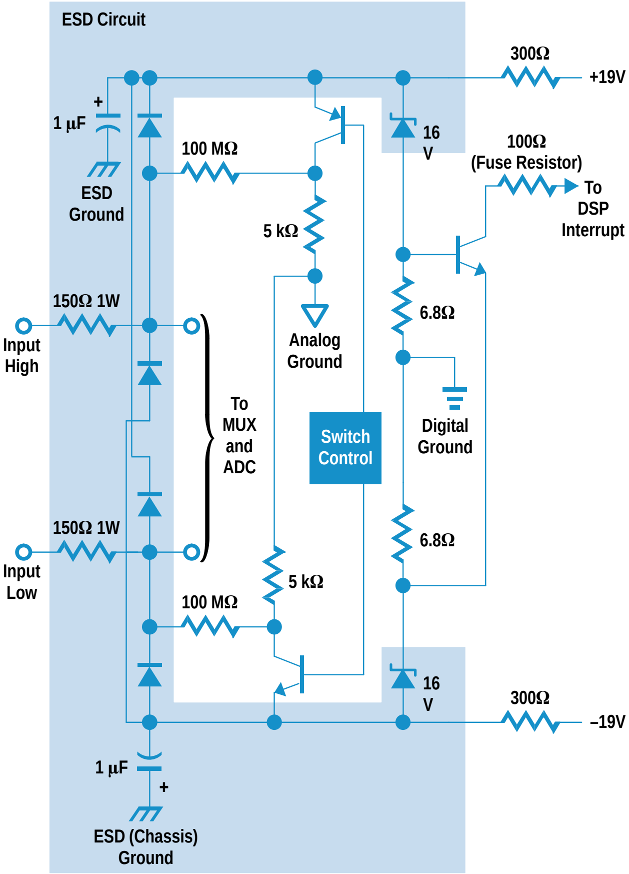


Fig. 2. Open transducer detect, ESD, and overvoltage protection circuit.

Overvoltage protection and ESD (electrostatic discharge) protection are combined into the same circuit for reduced board space and simpler circuitry. Judicious parts placement helped the functionality of the circuits a great deal. The ESD circuit consists of a Zener bias diode with its bias resistor and a large tantalum electrolytic capacitor placed near the ESD ground on the input connector. This provides bias for the diodes that dump static ESD current into the capacitors when the input voltage exceeds ±16.7 volts. ESD current is limited to a manageable value by the physically large, 1-watt, 150-ohm resistors in series with the diodes. Overvoltage protection is provided by monitoring the current through the Zener diode with a transistor. If sufficient current is dumped through the Zener diode, the transistor turns on, sending an interrupt to the digital signal processor (DSP). The DSP will then open protection relays provided on the main board to protect the SCP, the multiplexer, and the ADC. The overvoltage protection feature can also be overridden. Customers override the protection when the cost of stopping the test is more expensive than the measurement system. A fuse resistor is provided to protect the DSP from problems caused by very high overvoltages when the protection feature is overridden. The DSP input is protected by a pair of Schottky diodes that clamp the input. The fuse resistor will open if damage occurs to the input circuits that could put excessive voltage on the DSP input.

Each SCP looks like a memory address segment to the DSP. This memory address segment is called the digital interface address space (see Fig. 3). This address space is divided into two parts on each SCP. One part, called the module space, consists of 64 registers per SCP that are dedicated to addressing functions common to an entire SCP such as the plug-on identifier and scale registers. The other part of the address space, which is called the channel space, consists of 64 registers configured as eight registers per SCP channel.

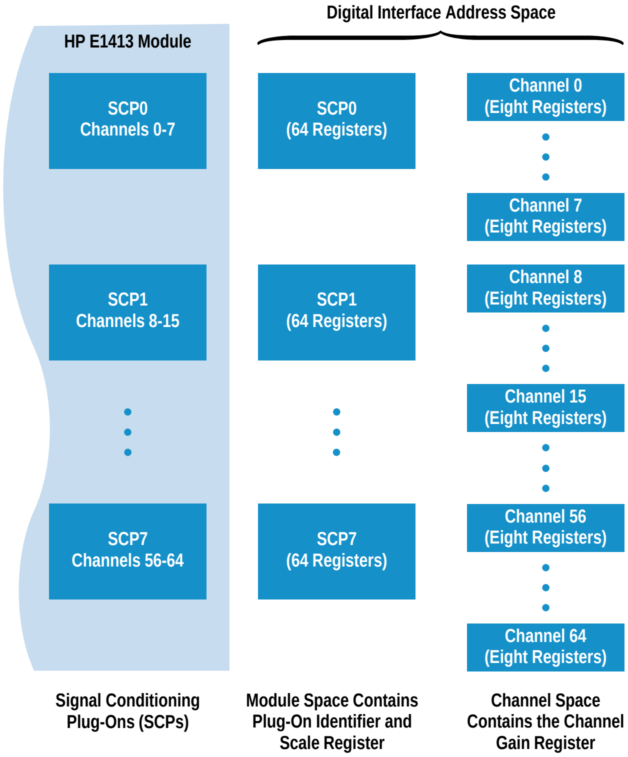


Fig. 3. Digital interface address space.

This address space is used to address functions unique to each of the eight SCP channels such as channel gain and filter setting.

Fixed Filter SCP. A second function required for turbine test is low-frequency, low-pass filtering. Many of the signals from the engine under test represent temperatures measured with thermocouples. Signal voltages are in the millivolt range and subject to high-frequency noise. Low-pass filters with cutoff frequencies of 10 Hz or below are required.

The HP E1413 has only one ADC. Thus, many SCP channels are scanned and multiplexed to the ADC (see Fig. 2 on page 8). With this setup channel-to-channel charge injection through the multiplexer causes errors during fast scanning with passive low-pass filters because the low-pass capacitors hold the charge and cannot dissipate the error charge except through the source and low-pass resistors. For example, if channel 10 on some SCP is holding 6 volts and channel 11 on the same SCP has −15 volts, there is a 21-volt swing when scanning from channel 10 to channel 11, which could cause an error during a fast scan. These errors make it necessary to reduce the scanning speed to achieve the required accuracy. The solution is to buffer the low-pass filter components with an amplifier to absorb the charge injection (see Fig. 4).

As previously stated, very high common-mode rejection must also be preserved in the differential signal path. While it is very desirable to have a sharp cutoff for the filter, there are no practical circuits that can provide a sharp cutoff with an RC type of filter and still produce 100 dB of common-mode rejection. The compromise solution is to use a two-pole passive RC filter in front of a unity-gain buffer. Care must be taken in choosing pole positions to provide low enough resistances so as not to introduce further errors caused by bias current offsets in the buffer amplifiers. Overvoltage protection and open transducer detection must also be provided. The total solution is a simple, but functional circuit that is very easily changed for different cutoff frequencies.

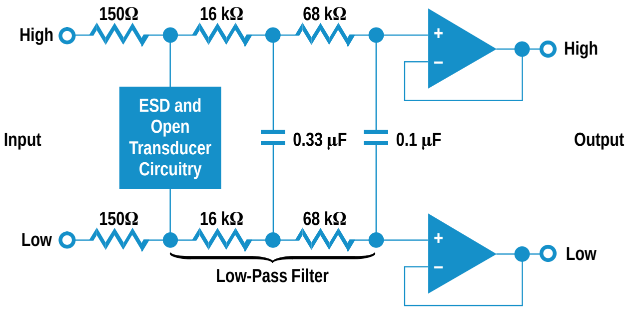
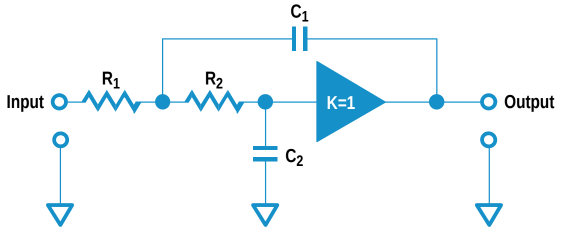


Fig. 4. Fixed filter SCP.

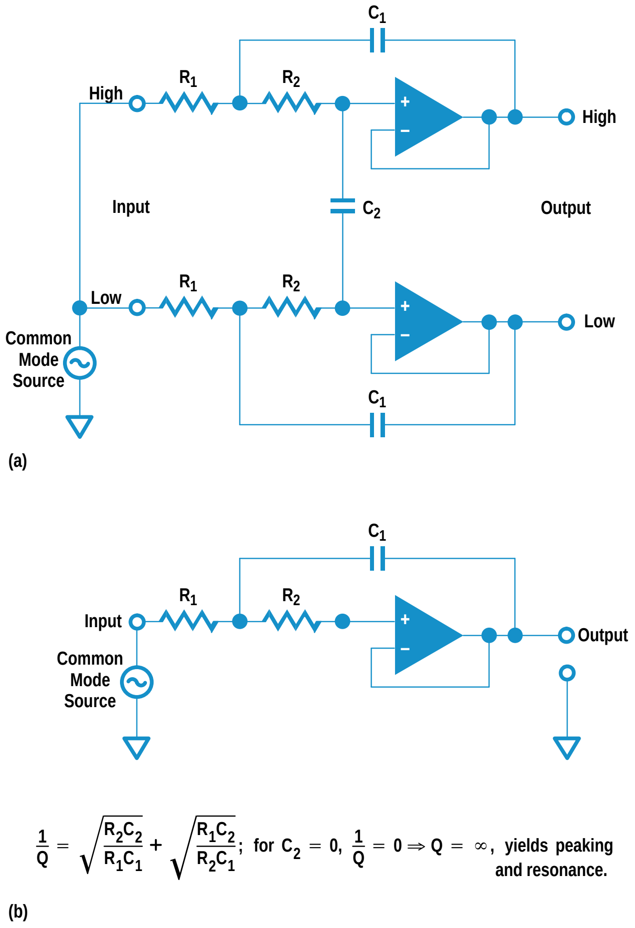
We encountered an interesting phenomenon while developing filter circuits for the fixed filter SCP. A reasonable approach to designing a differential filter is to begin with a single-ended filter (one with the common node at ground) and then transform it into a differential filter. This was the approach originally used to design the fixed filter. The original filter topology chosen was a traditional Sallen and Key structure[1] (see Fig. 5). This filter topology was chosen because of its low parts count and low sensitivities to finite operational amplifier gain-bandwidth and parts variations. The transformation to a differential filter was straightforward and yielded the circuit shown in Fig. 6a. This circuit performed as designed for differential signals but showed anomalies when tested for common-mode rejection.

A spectrum analyzer placed between either output and ground showed a resonance and severe peaking. This anomaly was originally believed to be the result of nonideal behavior in the circuit components. Further investigation showed that this was not the case. There are intrinsic problems with common-mode rejection when using a simple single-ended-to-differential transformation. The equivalent circuit of the



$$T(s) = \frac{K\omega_n^2}{s^2 + \left(\frac{\omega_n}{Q}\right)s + \omega_n^2}, \quad \text{where} \quad \begin{cases} \omega_n^2 = \dfrac{1}{R_1R_2C_1C_2} \\ \dfrac{1}{Q} = \sqrt{\dfrac{R_2C_2}{R_1C_1}} + \sqrt{\dfrac{R_1C_2}{R_2C_1}} \end{cases}$$

Fig. 5. Sallen and Key filter topology.



$$\frac{1}{Q} = \sqrt{\frac{R_2C_2}{R_1C_1}} + \sqrt{\frac{R_1C_2}{R_2C_1}};\ \text{for } C_2 = 0,\ \frac{1}{Q} = 0 \Rightarrow Q = \infty,\ \text{yields peaking and resonance.}$$

Fig. 6. (a) The circuit resulting from transforming the filter in Fig. 5 to a differential filter. (b) Equivalent circuit for one half of differential filter.

differential filter with a common-mode signal shows the problem (see Fig. 6b). The behavior of the circuit is such that the voltage drop across C_2 is essentially zero making it appear that C_2 does not exist. In the transfer function C_2 shows up in the damping factor of the complex poles in the half-circuit. As C_2 goes to zero, the damping of the poles goes to zero causing a resonance and the peaking observed. No practical alternative structure was found that did not have a similar difficulty in the transfer function for common-mode signals. As a result of this finding, the circuit in Fig. 4, which has the simpler passive filter with buffer topology, was chosen.

Programmable Gain and Filter SCP. Turbine test customers also want signal conditioning that includes gain as well as filtering to make lower-noise measurements on thermocouples. They want the flexibility to choose different gains and filter cutoff frequencies programmatically. They want this functionality in the same size and channel counts as the straight-through and fixed filter signal conditioning plug-ons. Including this additional functionality and all the other features mentioned above in the same space represented quite a challenge.

The ADC subsystem in the HP E1413 requires gain in powers of two for proper functioning of the engineering unit algorithm, which converts measured voltage data to units such as ohms or degrees (see article on page 21). Signal gains of 8 and 64 were chosen for the amplification factors. Gains of powers of two allow the engineering unit algorithm to adjust the ADC reading to the actual system gain by simply shifting bits up or down. Since a shift operation is faster to execute than a multiply, the engineering unit algorithm can work at the full speed of the ADC. Gains of 8 and 64 also provide sufficient gain to achieve significant noise reductions without overly complex circuitry.

Since programmability is a requirement, gain and frequencies are switched by analog IC switches. The circuit topology takes advantage of the switch density and configuration (dual 4:1 multiplexer). For the lowest-noise performance and most compact design, all the amplification is done in the first stage of the SCP (see Fig. 7). This allows the use of a single analog switch package to control the channel gain. An additional benefit is that the following low-pass filter section reduces the noise bandwidth of the system after the gain stage, thereby reducing the system noise. This topology is also used in other nonprogrammable gain and filter SCPs.

The filter circuit is the same circuit used in the fixed filter SCP, except that it is programmable. Different resistors are switched into the circuit to change cutoff frequencies. The resistors for the programmable gain and filter circuits are built into custom thin-film resistor packs to conserve space and improve thermal tracking performance. Putting all this circuitry into only 1.5 square inches of printed circuit board space required careful layout and frequent consultation with the production engineer assigned to the project. The resulting SCP stretches the limits of current surface mount technology yet still retains a good measure of producibility.

Current Source SCP. Turbine test customers need to measure temperatures with thermistors and resistive temperature devices, and resistances of certain types of sensors. To make these resistance measurements, a precision current source with high compliance is required. The design goals for the current source SCP were that the current source would not limit the input voltage range in a four-wire ohms measurement, and that it would provide 16-bit resolution and the ability to measure 100-ohm resistive temperature devices and 10-kohm thermistors. This required the current source to have ±16V compliance, better than 10-ppm resolution, and greater than 1-gigohm output impedance. For the engineering unit algorithm to work at full speed, the current source has to be calibrated and stable during the measurement cycle.

To aid in conversion of the voltage measurement into resistance, current source values of 488.3 μA and 30.52 μA are used. These sources are programmable to be able to change ranges and turn off the source. Both current sources exhibit low current noise to provide the necessary 16-bit resolution. To put all this capability in a circuit that occupies only 1.5 square inches, we had to design a circuit that used few parts.

Several circuit topologies were tried and discarded for various reasons before the final circuit was designed. The final circuit satisfies all the design goals with a minimum of parts and a simple design (see Fig. 8). It consists of a precision programmable current source driving a high-compliance

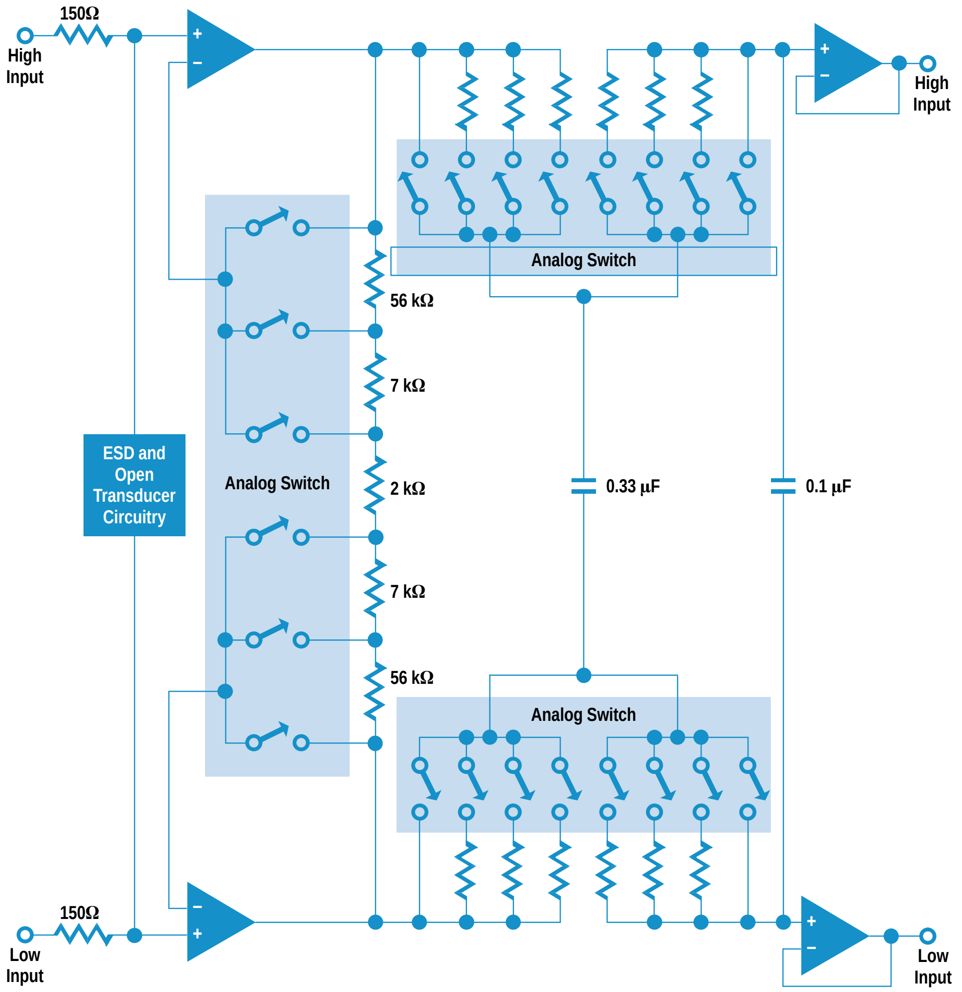


Fig. 7. Programmable gain and filter SCP.

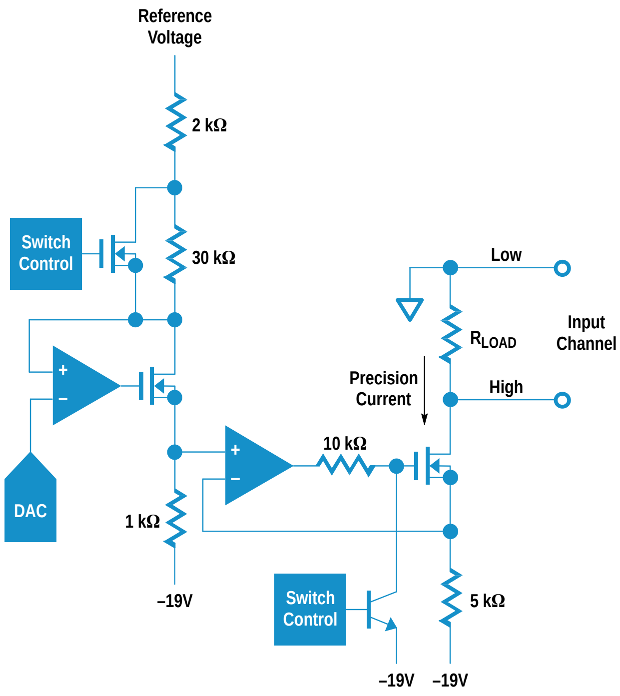


Fig. 8. Current source SCP.

current mirror circuit. The precision dc reference is available to the SCP from the ADC circuits. It is used to produce a precise and stable dc current that is adjusted with a digital-to-analog converter (DAC) and controlled by the operational amplifier. Current switching is performed by shunting the 30-kohm resistor to increase the current. The second part of the circuit reflects and scales this precision current and makes it available to the outside world through the MOSFET transistor. Compliance meets the ±16V goal at extremely high output impedance controlled by the gain of the operational amplifier. Note that this circuit is a current sink rather than a source. This was done to save parts and space.

Strain Completion with High-Accuracy Excitation Source.

Customers need to measure strain gauges to understand the stresses and loads on turbines. This measurement is typically made with one or more strain gauges configured in a Wheatstone bridge. An excitation supply is needed for the bridge along with completion resistors for making measurements using only one or two strain gauges.[2] To convert bridge voltage readings into strain gauge values, the bridge excitation voltage must be known or measured. To perform engineering unit conversions to strain gauge values at high speed, the excitation source has to be stable and calibrated to a known value to simplify calculations. The excitation supply must be able to source sufficient current to power all

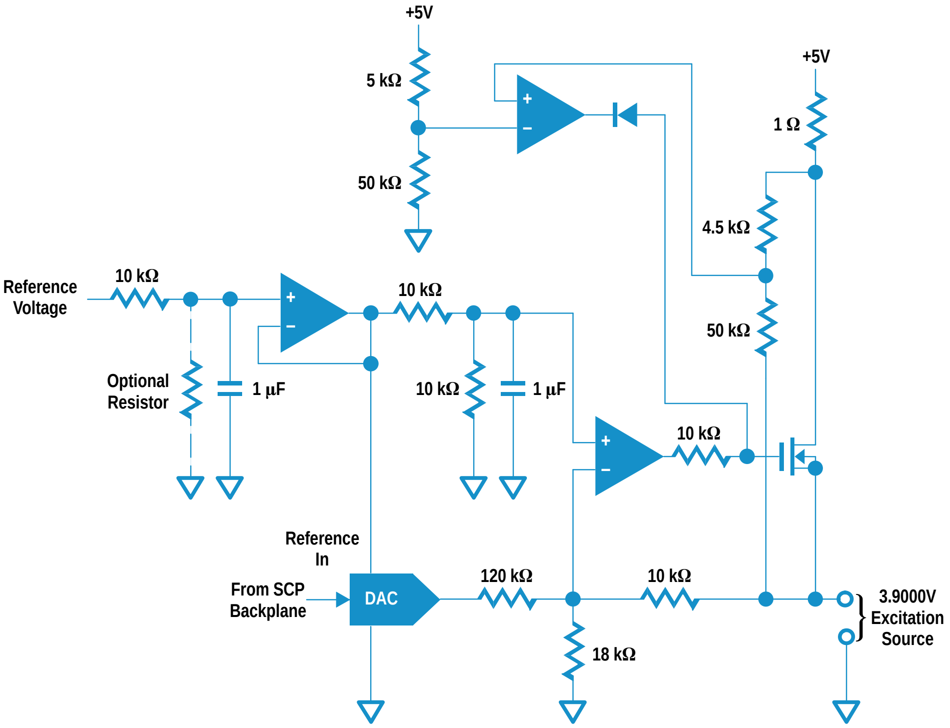


Fig. 9. Excitation supply for the strain gauge SCP.

eight strain bridges on an SCP and be able to survive an accidental short circuit without damage. Since only one excitation source was required for each SCP, space constraints were not as critical.

The circuit chosen provides >400 mA at 3.9000V for excitation (see Fig. 9). The output voltage is calibrated by a DAC to provide this level of resolution. The 3.9000V value was chosen to provide a near full-scale reading on the 4V range. In the event of a short circuit at the output of the excitation source, a fold-back circuit is activated to limit the output current to approximately 75 mA, thus preventing damage to the SCP. Again, the reference voltage provided from the ADC is used as the reference for the excitation supply. It is buffered and then divided down to provide a precise bias voltage for the operational amplifier. A calibration current is sourced at the summing node of the operational amplifier to adjust the output of the excitation source. Note that the calibration DAC uses the same reference as the operational amplifier. This allows the DAC to be used to calibrate any chosen output voltage with the same percentage of calibration span. Pads are provided on the printed circuit board to accommodate different, lower excitation voltages by dividing the reference before buffering. Calibration of the HP E1413 is described in the article on page 25.

When measuring strain gauges, customers often want to verify that the gauges are properly connected by putting a large-value resistor in parallel (shunt) with one resistor or strain gauge in the bridge. The bridge will then become unbalanced by a predictable amount. The bridge voltage can be measured and compared against the expected amount of deflection to determine if the bridge is operating properly. A large-value resistor and a programmable switch are provided on each channel to perform this task. The shunt resistor is usable in any bridge configuration (see Fig. 10).

Other Options

All of the SCPs are designed to accommodate future modifications to the original circuits. Different filter cutoff frequencies, different gains, different output currents, and different excitation source voltages can be accommodated in most cases by simply loading different parts on the printed circuit boards. Pads for other standard-size components are placed on the blank printed circuit boards at strategic nodes to provide for different customer needs with a minimum of additional design time or expense. This has proven to be a popular feature for customers since they can get a custom solution with a minimum of expense and effort.

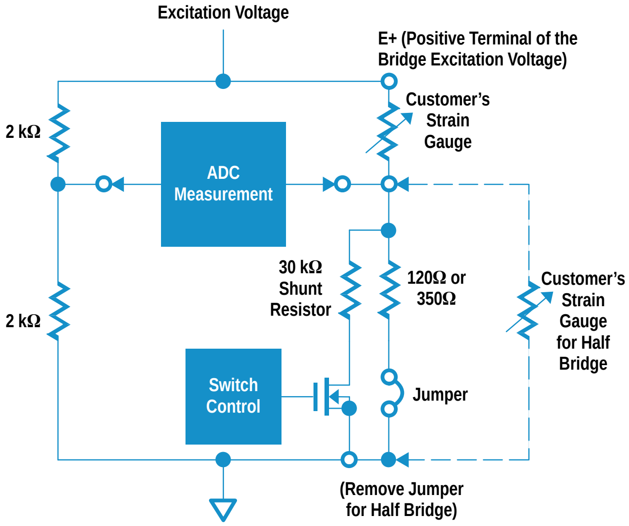


Fig. 10. Shunt resistor for strain gauges.

Conclusion

While the original design goals for the SCPs seemed to be well within reach, the implementation of high-performance circuits capable of providing the needed functionality in the space and at the circuit densities required presented quite a design challenge. High performance was extracted from simple, efficient designs by careful parts choices and placement on the printed circuit boards. Costs were kept low, consistent with the performance required by customers. The results met the original design goals in a way that provides the customer with lasting value.

Acknowledgments

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Reference

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2. HP Application Note 290-1, *Practical Strain Measurements,* Hewlett-Packard, Part Number 5952-8880, 1981.