Application Brief:

Signal Conditioning for Rocket Engine Testing

Introduction

Testing rocket engines is a tricky business. Hundreds of sensors measure thrust, fuel flow, pressure, vibration, strain, temperature and other variables in extreme conditions. Thousands of feet of cable are routed through the test stand to the engine and some sections of cable are often subjected to a harsh daily outdoor environment. Specialized measurement techniques are required to minimize the effects of the environment on data quality.

Given the expense of conducting rocket engine tests, failure to collect data is not an option. Redundant sensing and data recording are often utilized to validate data. Furthermore, sensor data is used to control the engine and to determine whether or not a test should be aborted to prevent damage to the test article or for safety concerns.

With so much at stake, strict protocol dictates rigorous pre-test verification and validation of both the measurement system and the data collected from it. The calibration certificates and data sheets of the instruments and sensors are insufficient proof of measurement system validity. Pre-test routines are required to verify crucial measurement system specifications, including those of the sensors and cabling, as proof of data validity.

This application brief discusses specific measurement challenges related to rocket engine and similar propulsion testing and describes Precision Filters' (PFI's) solutions for them. From the raw sensor signal to reliable, accurate, and valid data, PFI products play a critical role in transforming the raw measurement to signals that are data acquisition ready.

Contents

- **Signal Conditioning for Rocket Engine Measurements**
  - Thrust, pressure, and other bridge sensor measurements
  - Temperature
  - Vibration and dynamic pressure
  - Flow
  - Fatigue
- **Signal Filtering and Amplification**
  - Tailoring the system transfer function to the measurement
  - Elimination of out-band noise through distributed gain
  - Maintaining bandwidth with resonant sensors
- **Verification of Cables and Sensor Health**
  - In situ cable roll-off measurement
  - Resistive gage real time health monitoring
  - Piezoelectric charge and IEPE sensor health
  - Muting faulty sensors
- **Self-Test and Calibration**
  - Yearly calibration
  - Pre-test verification
- **Life Cycle Costs**

Rocket Engine Measurements

Many different sensor types are involved in the testing of rocket engines. Static and dynamic pressure sensors measure direct and delta pressures on cryogenic and hot gases. Piezoelectric and integrated electronics piezoelectric (IEPE) transducers measure vibration and pressure at high and low temperatures over wide bandwidths. RMS to DC converters provide DC signals that are proportionate to vibration levels for feedback to control systems. Strain gage based pressure sensors measure static and dynamic pressures throughout the facility and engine. High-temperature static and dynamic strain gages characterize engine fatigue while precision load cells measure engine thrust. High-accuracy resistive temperature devices (RTDs) and thermocouples characterize engine and facility temperature. Magnetic pickups incorporating Hall Effect sensors are utilized to determine shaft rotational speed. Rotary flow sensors accurately measure the volumetric flow rate of an engine's fuel/oxidizer consumption to determine specific impulse.

For each sensor type, a signal conditioning strategy is required that minimizes unwanted noise and maximizes data quality. The hardware must be flexible, universal and not require a separate card type or plug-on module for each transducer type. This simplifies operation and spare hardware by reducing the number of unique cards in the system. The signal conditioning must be stable with long calibration intervals to allow tests to be run in rapid succession with confidence. The software must provide unique verification routines for each type of sensor. These routines, initiated remotely at the push of a button by personnel thousands of feet away from the test stand, perform an accurate and comprehensive checkout of the system immediately prior to firing the engine. The verification data must be recorded by the signal conditioning system as essential proof of test data validity for test certification.

PFI developed its suite of signal conditioning products to meet the stringent and demanding requirements of rocket engine testing. The products incorporate unique and proprietary signal conditioning technology that provides unmatched data quality for both dynamic and static sensor measurements. They further incorporate equally innovative methods to perform in situ instrument, sensor, and cable validation that no other system provides.

In the following sections, we discuss the specific measurement requirements common to rocket engine testing as well as how these challenges are addressed with PFI technology.

Pressure, Thrust and Other Bridge Sensor Conditioning

Bridge type sensors are often used for development and production testing on rocket engines. A key concern is the engine thrust produced via igniting propellant in the combustion chamber of the engine. Precision load cells are used to characterize the thrust that the engine develops. Strain gage based pressure sensors are used to measure the combustion chamber pressure that is important for validating engine thrust performance. Pressure measurements are also made on the purge subsystems and hydraulic actuators.

PFI's rocket engine test suite of signal conditioning products provides a universal solution for static and dynamic full-bridge pressure sensors and load cells. The Precision 28124, 28144, and 28154 signal conditioners feature a fully programmable interface for sensors requiring Wheatstone bridge conditioning with constant voltage excitation. The highly accurate excitation and DC gain supports the challenging requirements of the load cell based thrust measurement system. The rock-solid stability of the excitation source means an end to costly calibration and manual adjustments between test runs or engine swaps. Remote sense capability eliminates excitation voltage drops caused by cable lead resistance and ensures accurate excitation is delivered to the sensor. Balanced excitation minimizes the common mode voltage to the amplifier and allows full use of the available common mode range. With optional open circuit detectors, open circuit measurements are forced to positive full scale to allow quick identification.

Pressure sensors with 4-20 mA current outputs are supported by a 28 V unipolar excitation mode. A precision 250 Ω sense resistor converts this current to a voltage that is measured by the differential amplifier input.

The Precision 28000 System provides NIST traceable test methodology for end-to-end system calibration. Two shunt calibration methods for span verification may be utilized. For sensors with built-in shunt calibration resistors, a programmable contact closure is supported. For bridge type sensors, 255-step precision bipolar shunt calibration is provided. The built-in test bus enables injection of external calibration signals, while the internal traceable DC reference may be set to a unique level per channel and injected at the amplifier input under program control. Verification of zero is easy and automated with PFI's "test mode short" that, when activated, applies a ground connection at the amplifier input to reveal any DC offset errors.

Real-time sensor health monitors alert the operator to sudden changes in sensor resistance or excitation level enabling timely pre-test remediation and providing confidence that "all systems are go" prior to engine ignition and the start of the test. Sensor "mute" mode ensures that faulty sensors or unused channels are terminated in the quietest state, preventing noise coupling to properly functioning channels.

To optimize system performance at any operating ambient temperature, PFI's products feature fully automated built-in calibration routines for excitation, amplifier gain, offset and common-mode rejection. The routines may be run on the unit in place and at any time.

PFI Features

- **Support for both static and dynamic full-bridge pressure sensors**
- **Bridge conditioning with constant voltage excitation**
- **Highly stable and accurate excitation source**
- **Remote sense capability for accurate sensor excitation**
- **Precision shunt calibration support for span verification**
- **External calibration signal injection via built-in test bus**
- **Diagnostic input "short" mode reveals channel offset and noise**
- **Real-time sensor health monitoring of resistance and excitation level**
- **Mute eliminates faulty sensor noise coupling to other channels**

Conditioning for Temperature Measurements

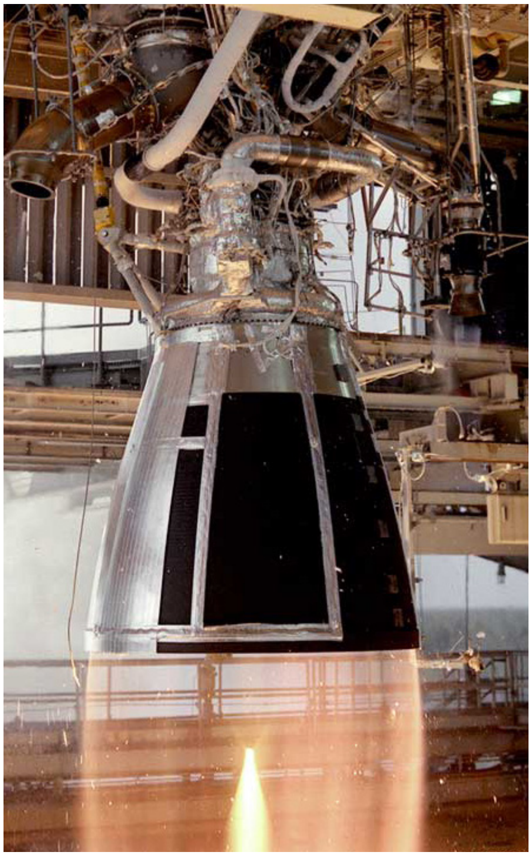
Rocket engine testing requires diverse techniques for the measurement of temperatures at both hot and cold extremes. From the cryogenic temperatures of propellants to the high engine exhaust temperatures, reliable and accurate temperature measurements are critical.

Resistance Temperature Detectors

The accurate measurement of propellant temperature is crucial to the calculation of specific impulse.

For cryogenic temperature measurements, silicon diodes are frequently utilized. The programmable HC10 RTD configuration module provides accurate constant current necessary in diode thermometry, typically 100 µA.

For higher accuracy, a platinum RTD can be used to achieve less than 0.1° C error of its variable resistance sensing element. To translate this variable resistance at the far end of a 300 foot cable exposed to extremes of temperature, moisture, EMI, and vibrations into an accurate and stable voltage signal suitable for data acquisition requires specialized measurement techniques.



An RS-68 engine under going hot-fire testing at NASA Stennis Space Center.

Conversion of the variable resistance to a measurable voltage requires a precise constant current excitation source with excellent stability and low noise. The excitation levels should be kept low, typically 1 mA or lower, to prevent self-heating. A balanced connection to the RTD is required to minimize pick-up from electrostatic noise sources. PFI's proprietary push-pull Balanced Constant Current™ (BCC™) excitation source topology with HC10 RTD configuration module satisfies all of these requirements.

At PFI, we understand that run-time verifications of the measurement system are crucial to overall success of the test program. The costs of a test run are very high and a faulty or improperly configured measurement system during rocket engine test firing is unacceptable. The HC10 module includes built-in precision RTD substitution resistors with five convenient points for ITS-90 temperature scale interpolations between 62.5 Ω and 2 kΩ. The five 0.01% RTD substitution resistors are calibrated to NIST traceable standards by in situ software routines. When the resistors are substituted for the active RTD, signal conditioner to recorder correction factors may be determined to account for excitation errors, amplifier gain and offset errors as well as A/D errors.

Thermocouples

For temperature measurements requiring less accuracy, such as engine and facility temperature monitoring, lower-cost thermocouples are often appropriate. While the accuracy of these measurements may not be as demanding, it is still imperative to obtain reliable and valid data on all thermocouple channels specified in the test protocol. Low DC drift and stable gain accuracy are required, while a differential input stage with high common mode rejection ratio (CMRR) is needed to reject ground noise when the thermocouple is grounded to the test article. The low-drift input stage of Precision's HC10-equipped signal conditioners when used in conjunction with a remotely located isothermal block satisfies these requirements.

While voltage substitution is the most reliable way to verify the span of a channel, it is often difficult to distribute accurate mV-level DC calibration signals from a remotely located signal source to the inputs of multiple channels. Insertion losses, gain errors, DC offsets, and noise all work to corrupt these low-level signals. The thermocouple mode of the HC10 module has mV-level DC calibration voltages built directly into the input stage of each channel. The thermocouple simulation voltage substitution is programmable from 1 to 125 mV in 100 µV steps with a calibrated accuracy of 0.07%. The advantage to this topology is that all thermocouples channels can be calibrated simultaneously and at different voltage insertion levels. The DC calibration feature can also be used for other non-standard measurements where no other form of end-to-end calibration may be possible.

For thermocouple applications where high density and low cost are needed, the Precision 28208A thermocouple conditioner provides eight channels of programmable, DC-stable filter/amplifiers with integral reference junction compensation. An isothermal block with an integral digital temperature sensor provides better than 0.15 °C accuracy in reference junction compensation.

PFI Features

- **Precise constant current excitation source with high accuracy, excellent stability and low noise**
- **Balanced Constant Current (BCC™) topology for minimal electrostatic noise pickup**
- **NIST traceable built-in 0.01% substitution resistors for RTD calibration**
- **Low DC drift input stage and stable gain accuracy**
- **High CMRR for ground noise rejection**
- **Programmable thermocouple simulation voltage substitution for calibration**

Conditioning for Vibration and Dynamic Pressure Measurements

A variety of piezoelectric sensors are used to measure dynamic pressure and vibration in the facility and on engine. Accelerometers and dynamic pressure sensors are mounted on or in run ducts to characterize propellant flow to the engine and record any flow instability, such as cavitation, that can affect engine performance. Accelerometers are also mounted at the interface to the facility to characterize the vibration transmitted to the vehicle and its payload. For example, if the payload is a satellite, it is the responsibility of the launch provider to advise satellite manufacturers of the payload vibration environment which affects satellite design. Accelerometers and dynamic pressure sensors are also mounted at various locations on or in the engine including the turbo-pump, the gas generator, and the main combustion chamber. These sensors characterize the rotating machinery performance to monitor for excessive vibration levels that could damage the engine and record any pop combustion instability that may need to be evaluated.

Piezoelectric sensors are available as both charge output devices and IEPE sensors with integral electronics for charge conversion. While there are many differences between the two types of sensors, the decision to use charge versus IEPE often comes down to the temperature in the environment of the sensor. IEPE devices are limited to approximately 250 °C while charge sensors function to 800 °C and beyond. The Precision 28304 conditioner for dynamic measurement of pressure and vibration has two modes for use with either charge mode or IEPE sensors.

Charge Mode Sensors

Piezoelectric charge mode sensors are often used for dynamic pressure and vibration measurements on rocket engines due to their ability to survive the extremely harsh environments while continuing to produce valid, accurate, and reliable data. The management of the connection path between the charge mode sensor and the measurement electronics requires great care. It is important to maintain very high insulation resistance when cabling to charge mode sensors, as signal to noise ratio (SNR) and low frequency data accuracy can be very seriously compromised if cable insulation resistance is not maintained. Unfortunately, this is often difficult and challenging to do. Often, the cable run from the sensor to the instrumentation requires long distances, several bulkhead penetrations, multiple patch panels, and exposure to corrosive gases, steam, vibrations, and temperature extremes, both hot and cold. The ingress of steam or corrosive gas into a connector or compromised cable section works over time to break down the insulation properties of the various materials leading to leakage paths of 1 MΩ or lower.

The use of general-purpose charge amplifier products that are intolerant of low insulation resistance can result in severely degraded SNR and low frequency measurement data with amplitude errors of 50% or more. Without knowledge of this issue, the distorted data could be accepted as valid and lead to erroneous test conclusions. The PFI charge conditioner products incorporate charge amplifiers that are designed to be tolerant of insulation resistance break-down as low as 100 kΩ.

Another possible source of error with charge mode sensors results from either intentionally or unintentionally grounding the sensor cable shield to the test article. If a standard single-ended charge amplifier is used, substantial noise pickup can result from the formation of a ground loop. PFI charge conditioners feature a programmable isolated or grounded input mode adaptable to any sensor mount configuration. For grounded sensors, the isolated input mode breaks the ground connection and prevents ground loops and their associated noise.

IEPE Mode Sensors

For low temperature vibration measurements (below 250 °C), IEPE type sensors are often used. The integration of charge-to-voltage circuitry in these sensors provides a low impedance output signal that allows for the utilization of standard coaxial cabling but at the cost of restricted dynamic range.

Common signal conditioners for IEPE sensors connect the sensor “low” to ground at the channel input. This is usually the most appropriate connection since the low input is often the shield of the coaxial cable. Occasionally however, the IEPE low connection is grounded at the sensor. This can be a troublesome situation, as it creates a ground loop since the low side is also connected to ground at the signal conditioner. Triaxial accelerometers present similar problems because the sensor often provides a common shield connection for the X, Y and Z-axis coaxial cables. If each cable shield is grounded by a basic single-ended signal conditioner, three ground loops are created possibly leading to significant noise and degradation in SNR.

To solve these problems, PFI’s signal conditioners incorporate a programmable input stage that can either be grounded or isolated from the channel ground. In isolated mode, the low connection can be grounded at the distant sensor location and no ground loops will be created. Proprietary IEPE circuitry assures that all IEPE current will be returned through the floating low connection and not through the chassis earth ground connection.

PFI’s signal conditioners accommodate high frequency signals with long cable runs by supporting programmable IEPE current up to 12 mA. Further, their channel input stages continually monitor the sensor DC bias voltage level, which serves as a useful indicator of sensor, cable, and connector health. This voltage level is displayed for each channel and is compared to user-programmable upper and lower threshold limits to alert the user to a sudden shift of the bias level. A system bias level report can be requested at any time creating a file for pre-test gage health documentation.

PFI Features

- **Dual-mode compatibility for charge mode and IEPE**
- **Charge mode measurement tolerant of cable leakage**
- **Remote in situ T-Insertion test to detect sensor fault or cable damage**
- **Ground loop free measurement of grounded sensors and triaxial accelerometers**
- **Long-Distance TEDS (LDTEDS™) for communication with distant TEDS sensors**
- **Low latency RMS/DC conversion for redline control systems**
- **Programmable analog band-pass filtering to set bandwidth of interest**

Long-Distance TEDS

TEDS (Transducer Electronic Data Sheet) capable sensors, in conformance with IEEE Standard 1451.4, provide information—such as manufacturer name, serial number, and calibration data—that is readable by the data acquisition system for use in system scaling, identification, bookkeeping, troubleshooting, and other functions. Conventional TEDS readers in signal conditioners have been limited to a maximum cable run of 400 feet to the TEDS sensor due to the communication protocol and design of the 1-wire memory devices. However, rocket testing applications often require cable runs in excess of 1000 feet, precluding the use of TEDS equipped sensors. PFI offers proprietary Long-Distance TEDS (LDTEDS™) technology that digitizes the TEDS waveforms and utilizes digital signal processing to read the TEDS data, enabling communication with TEDS sensors at distances up to 1500 feet.

Redline Safety Monitoring

Facility and engine measurements are monitored during testing for unsafe operational levels. Of critical importance are the vibration levels of the rotating machinery, including pumps and turbo-pumps, which if left unchecked can easily destroy the engine. The maximum safe vibration level is commonly referred to as the "redline" and exceeding this level may require an abort of the test run.

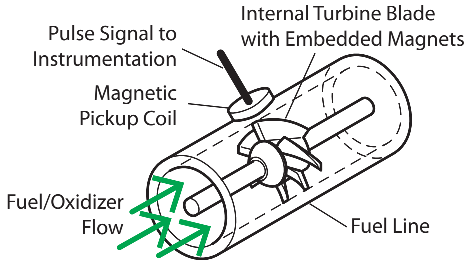
A common redline monitoring technique for vibration measurements is to convert the RMS energy in the critical frequency band to a DC voltage that is fed to the redline control system. An analog RMS/DC converter module is easily fitted to any PFI conditioner card and the analog band-pass filters may be set to examine the vibration levels in the bandwidth of interest. The RMS/DC solution is designed for extremely low latency and is customizable to user requirements.

Measurements typically include redundant redline sensors and employ voting to prevent one failed channel from causing a test cut. It is critical to know how an open circuit channel is going to respond so that it can be identified and properly managed in the voting. The PFI 28124 HC10 includes an optional open circuit detector that forces a wandering channel to full scale, preventing the channel from being perceived as valid.

Conditioning for Flow Measurements

Flow meter data is used to understand propellant consumption, which is critical to the measurement of specific impulse. Flow meters are also used to verify propellant mixture ratio and hydraulic flow. Rocket turbopumps are used to move the fuel and oxidizer into the combustion chamber at high volumetric flow rates. The performance of turbopumps are typically monitored by a turbine flow meter positioned in the fuel line, providing a measurement of fuel/oxidizer consumption.

Rotary flow meters have an internal turbine that turns as fluid flows across the blades. Magnetic pickups incorporating Hall Effect sensors generate electrical pulses in response to blade movement. The frequency of these pulses gives a measure of the rotational speed of the shaft of the flow meter which is proportional to the volumetric flow of fuel and oxidizer to the engine.



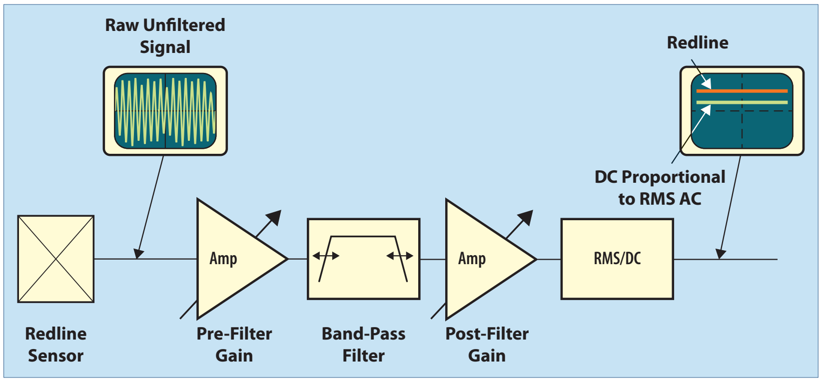
Simplified Diagram of a Rotary Flow Meter

A similar technique may be used to measure the rotational speeds of the shafts of the turbopump and the turbine that drives it. Rotational shafts create pulse signals that often have a broad noise spectrum along with overshoot and ringing that can cause false triggering and erroneous measurements. Further, variability in noise content from sensor to sensor creates new and evolving signal conditioning challenges.

The Precision 28608B filter/amplifier and 28524 frequency-to-voltage converter together comprise a complete fuel flow monitoring system. The 28608B filter/amplifier is used for amplification and band-pass filtering of the pulse signals from the Hall Effect sensor. The band-pass filter is effective at cleaning up the raw sensor signal harmonics and noise prior to frequency conversion. The 28524 frequency-to-voltage converter accurately measures the frequency of the sensor signal and outputs a precise DC level proportional to frequency. The DC output range can be independently programmed for each channel allowing the user to scale the DC output to the frequency range of interest. The 28524 has four averaging time constants for the DC output allowing the user to select smoothed or rapid output response. To deal with the most difficult flow meter or speed sensor signals, the 28524 card features a configurable trigger. Programmable trigger polarity (positive or negative), trigger hold-off (in microseconds), and trigger level settings allow for reliable measurement of frequency for signals with ringing, overshoot, crossover distortion, or glitches.

PFI Features

- **Amplification and band-pass filtering of pulse signals for flow measurement**
- **Effective removal of raw sensor signal harmonics and noise prior to conversion**
- **Precise frequency measurement; proportional DC level voltage output**
- **Multiple averaging time constants for smoothed or rapid output response**
- **Configurable trigger for reliable measurement of frequency from challenging signals**



Redline Safety Monitoring System

Conditioning for Fatigue Measurements

Strain measurements are critical for validation of new rocket engine designs. Overall strength, low cycle fatigue (LCF) and high cycle fatigue (HCF), must be very well understood to certify both the engine system and components such as rotors, pressure vessels, and major load-carrying structures. Accurate and defendable measurements of static and dynamic strain are crucial for live fire qualification testing as well as for validating analytical models used for fatigue life assessments.

Many factors must be considered when making strain measurements in the harsh environment of rocket engines. While the common ¼ bridge circuit can be used successfully for the heavily filtered measurement of static strain at moderate temperatures and with short cable runs, this methodology is unsuitable for the frequency rich assessment of dynamic strain on rocket engine structures. The inherently unbalanced nature of cabling to a remotely located ¼ bridge arm renders the measurement extremely sensitive to electrostatic noise pick-up from hostile ambient noise sources. In extreme cases the hostile ambient noise sources can even mask the dynamic strain signal of interest.

PFI's proprietary Balanced Constant Current (BCC) topology is a totally balanced architecture and results in the most noise-immune topology for a remotely located strain gage. Additionally, the use of constant current excitation prevents any loss of gage sensitivity due to long cable runs, a problem that plagues both static and dynamic ¼ bridge measurements.

For strain measurements employing two arms with a known strain relationship, the Wheatstone ½ bridge configuration is often used. This configuration is very useful for bending beam, Poisson, or single active gage type measurements. Unfortunately, the ½ bridge circuit is also susceptible to the same noise pick-up and loss of gage sensitivity problems as the ¼ bridge circuit, discussed above. A five-wire configuration can be used to compensate for the loss of sensitivity due to long cable runs, but since heavy filtering is needed to eliminate the noise pick-up it is very difficult to obtain high-fidelity dynamic data from a remote ½ bridge circuit.

PFI's proprietary BCC topology can be configured for "Push-Push" ½ bridge mode to solve both gage sensitivity and noise pick-up. Since constant current excitation is used rather than constant voltage, there is no loss of gage sensitivity even with extremely long wires. Further, since the BCC cabling connection to the ½ bridge is totally balanced, noise pick-up is eliminated by CMRR of the differential amplifier and not by heavy filtering. This allows simultaneous static and noise-free dynamic data from the same ½ bridge.

One special case of the ½ bridge circuit is apparent strain compensation in high temperature static strain measurements. Here, the active gage experiences both the thermally induced (apparent) strain and the desired mechanical strain. The second gage is subjected to the apparent strain of the base metal but not any mechanically induced strain. The ½ bridge circuit serves to cancel the effect of apparent strain in the measurement. PFI's fully balanced BCC ½ bridge topology achieves excellent apparent strain compensation and its high degree of noise immunity allows both dynamic and static data from the same active strain gage.

PFI Features

- **Totally balanced BCC topology offers the most noise-immune topology for a remotely located strain gage**
- **BCC topology configurable for both ¼ bridge and ½ bridge strain measurements**
- **Constant current excitation prevents any loss of gage sensitivity due to long cable runs**
- **Enables simultaneous static and dynamic data from the same ½ bridge with high noise immunity**
- **Real-time health monitoring of excitation and loop resistance**

Conditioner Card Selection Guide for Rocket Engine Testing

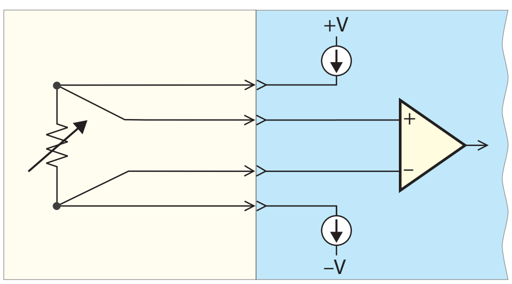
Card	Type	Chan.	Applicable Transducer	Interface	Excitation
28124	AC/DC Voltage, Bridge, Static or Dynamic Resistance	4/card	Static or dynamic strain, pressure, RTD, load, accel, AC/DC filter/amp, any bridge type sensor, IEPE (opt. HC14)	Prog. Bridge Completion, Shunt Cal, 2/4 Wire Constant Current	Constant V: 0 to 20.475 V; BCC: 0 to 20.475 mA; Opt. HC10 BCC: 0 to 1.023 mA
28144	AC/DC Voltage, Bridge, Static or Dynamic Resistance	4/card	Static or dynamic strain, pressure, RTD, load, accel, AC/DC filter/amp, any bridge type sensor, IEPE (opt. HC14)	Prog. Bridge Completion, Shunt Cal, 2/4 Wire Constant Current	Constant V: 0 to 20.475 V; BCC: 0 to 20.475 mA; Opt. HC10 BCC: 0 to 1.023 mA
28154	AC/DC Voltage, Bridge, Static or Dynamic Resistance, 300 Vcm	4/card	Static or dynamic strain, pressure, RTD, load, accel, AC/DC filter/amp, any bridge type sensor, IEPE (opt. HC14)	Prog. Bridge Completion, Shunt Cal, 2/4 Wire Constant Current	Constant V: 0 to 20.475 V; BCC: 0 to 20.475 mA; Opt. HC10 BCC: 0 to 1.023 mA
28208A	DC Voltage with Cold Junction Compensation	8/card	Thermocouple, low-level DC voltage	2-wire w/ shield	N/A
28304	SE Charge, IEPE (GND or ISO) w/ Long Distance TEDS	4/card	Piezoelectric or IEPE Sensor, Remote Charge Converter, AC Voltage	2-wire coaxial on Combo-D	IEPE Current: 0, 4, 8, 12 mA
28524	Freq. to Voltage, Pulse Rate Conditioner	4/card	Frequency counter, pulse rate, flow rate, Hall effect sensors	2-Wire w/Shield	N/A
28608B	AC/DC Voltage	8/card	Low-Level AC or DC amps and LP, HP or BP filtering	2-wire w/ shield	N/A

Conditioning for Other Measurements

Tests on rocket engines can involve a variety of other measurements, including acoustics, displacement, current, and voltage. Piezoresistive microphones measure sound intensity from the time-dependent engine noise sources that occur during static firing. Noise is characterized from inlet and outlet ducts well as that from the plume. The effectiveness of a noise suppressing water deluge system may also be evaluated.

The Precision 28124, 28144, and 28154 signal conditioners with voltage and current excitation employ precise constant voltage excitation to the microphones to convert resistance to voltage. Programmable FLAT/PULSE filter technology with distributed gain amplifies the in-band signal while protecting against internal clipping. Resonance compensating REZCOMP technology may be employed to extend the response of resonant sensors such as microphones. Both FLAT/PULSE filter and REZCOMP technologies are discussed further below.

Intrinsically safe DC Linear Variable Differential Transformers (LVDTs) and Rotary Variable Differential Transformers (RVDTs), powered via the 28124's 28 Vdc optional unipolar excitation mode, are used to measure the position of valves and actuators. The 28124 also functions as a precision DC or AC voltage amplifier and is used for measurement of a wide variety of signals, including voltages from the engine control unit (ECU).



PFI proprietary Balanced Constant Current provides excellent noise immunity RTD's, strain gauges and other resistance sensors in either 2 or 4-wire configurations.

Signal Filtering and Amplification

An integral aspect of signal conditioning is the filtering and amplification of raw transducer signals to reduce noise and boost signal level. Selection of an appropriate filter for the type of analysis being performed is important. A filter designed for spectral analysis will provide overshoot and ringing on transient impulsive signals. Conversely, a filter designed for good transient response will result in insertion loss in the bandwidth of interest. The primary concern of amplification is to keep out-of-band noise from saturating the amplifier while boosting the signal of interest to the required full-scale level. For certain transducers, such as accelerometers and recessed sensors, inherent resonances can restrict usable measurement bandwidth. PFI's signal conditioning capabilities address these issues, as discussed in the following sections.

Tailoring the System Transfer Function to the Measurement

Care must be taken to select the correct measurement system transfer function as dictated by test requirements. Precision's FLAT/PULSE filter technology allows the user to program the frequency response characteristics of the signal conditioner. For transient tests or tests where time-domain wave shape preservation is important, the PULSE mode provides linear phase response, as well as time-domain wave shape reproduction and outstanding transient response with low overshoot and ringing. For frequency domain analysis, the FLAT mode provides outstanding transfer function flatness and a sharp selective filter response.

The PULSE filter mode is often required for rocket engine testing as engine start and power level transitions represent highly transient test conditions. The PULSE mode transient response accommodates challenging transient signals by minimizing filter overshoot and ringing. Further, for signal processing on low speed measurements during development testing, the constant time delay provided by

Conditioner Card Selection Guide for Rocket Engine Testing

Card	Bandwidth	Gain	Filter	Cutoff Frequencies	Outputs
28124	250 kHz	x1/16 to x8192 w/ vernier	4-poles; PULSE/FLAT LP	FLAT: 2 Hz to 100 kHz PULSE: 1 Hz to 100 kHz	(3) Buffered Prog WB/Filtered SE outputs per channel w/ ground reference
28144	500 kHz	x1/16 to x8192 w/ vernier	4, 8-poles; PULSE/FLAT LP, REZCOMP	FLAT: 2 Hz to 204.6 kHz PULSE: 1 Hz to 102.3 kHz	Single-ended w/ ground reference
28154	250 kHz	x1/16 to x8192 w/ vernier	4-poles; PULSE/FLAT LP	FLAT: 2 Hz to 100 kHz PULSE: 1 Hz to 100 kHz	(3) Buffered Prog WB/Filtered SE Outputs per channel w/ optional Isolated Output (opt. 0)
28208A	10 KHz	x1, 10, 100, 1000	3-pole Bessel LP	1, 10, 100 Hz and Wideband	Single-ended or Differential (Opt. T)
28304	0.25 Hz to 450 kHz	x1/16 to x8192 w/ vernier	4, 8-poles; PULSE/FLAT LP or BP REZCOMP	FLAT: 2 Hz to 204.6 kHz PULSE: 1 Hz to 102.3 kHz	(2) Buffered Single-ended outputs per channel
28524	1 Hz to 50 kHz	Input Range 10 mV to 100 V	Band-Pass	1 Hz to 50 kHz, Programmable	Single-ended DC output w/ ground reference; Single-ended Pulse output
28608B	500 kHz	x1/16 to x8192 w/ vernier	4, 8-poles; PULSE/FLAT LP or BP	FLAT: 2 Hz to 204.6 kHz PULSE: 1 Hz to 102.3 kHz	Single-ended w/ ground reference

the PULSE mode is often desired. Use of the PULSE mode minimizes the total time delay through the data acquisition system (DAS), which is a critical concern, as a rocket engine can destroy itself in less than a second.

Elimination of Out-Band Noise through Distributed Gain

Some transducers, such as piezoresistive pressure transducers, can have very high resonant frequencies that can be excited by transient events, leading to out-of-band signals that can be larger than the signal of interest. Further, sources of unwanted low frequency noise can exist, such as engine sub-harmonics, triboelectric noise from cable whip or pyroelectric noise from the sensor caused by large temperature gradients during engine start-up.

The amplifier gain is distributed around the filter in both “pre-filter” and “post-filter” gain stages in the 28000 System, to allow the filter to remove out-of-band signals, such as transducer resonance, while still achieving the required full-scale in-band signal level. The 28000 “reserve” feature allows the user to specify the required protection against out-of-band noise and the pre- and post-filter gain are then automatically distributed to provide this protection. The pre-filter gain is set to achieve the required amplifier headroom for out-of-band signals prior to the filter while maximizing dynamic range. After the filter removes out-of-band signals, the post-filter gain is set to achieve the desired full-scale output. Maximum protection against high- and low-frequency noise sources is provided when distributed gain is combined with cascaded high-pass and low-pass filters to form a band-pass filter configuration.

Maintaining Bandwidth with Resonant Sensors

For applications where the sensor cannot be mounted flush with the flow field due to temperature and other constraints, the sensor is often recessed at the end of a tube. The tube produces an organ-pipe resonance that amplifies the pressure signal by 20 dB or more depending on the length of the tube and other properties. This resonance limits the useful measurement bandwidth to about 20% of the first resonance or about 1 kHz for a 1” tube.

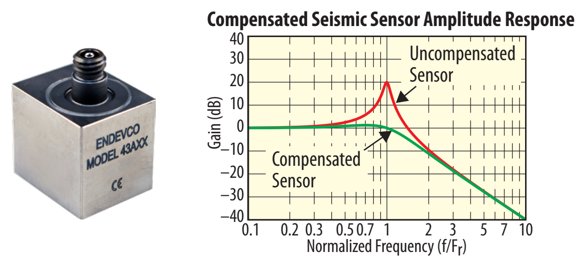
A similar bandwidth limitation occurs with charge and IEPE accelerometers, which are mechanical structures that have a well-known under-damped seismic resonance of the sensing mass. The mounted response of the accelerometer is limited by its frequency response, often modeled as a simplified damped spring mass second order system. A generally accepted rule is to limit the useable response of the accelerometer to only 20% of the sensor resonance where the response will have approximately 5% of amplitude peaking and 5 degrees of phase non linearity. This constraint under-utilizes the native sensor bandwidth that may contain important information about the test article.

Precision Filters, in collaboration with Kulite Semiconductor Products, developed the patented REZCOMP® technology to extend the frequency response of pressure sensors, accelerometers, microphones and other resonant sensors in real time without a need for post-processing. Using data provided by the sensor manufacturer, the user enters the frequency and Q characteristics of the resonance to compensate the transducer for a flat sensor amplitude response and a linear phase response. The application of REZCOMP technology typically extends useable sensor bandwidth by 200-300% or more.

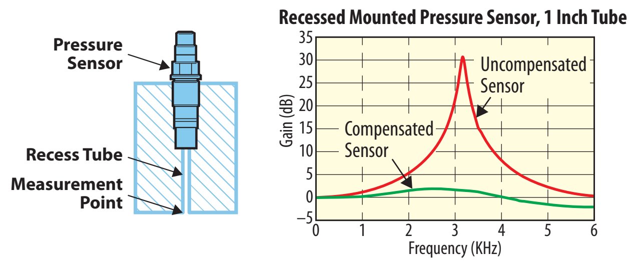
Multiple Buffered Outputs

Often the outputs of the signal conditioner must feed multiple destinations such as primary and secondary recording systems, control systems and safety systems. Simply “teeing” a single analog output to drive multiple destinations leads to ground loop and ground referencing problems and a short at the tee’d output will mean loss of data for all systems connected to that output.

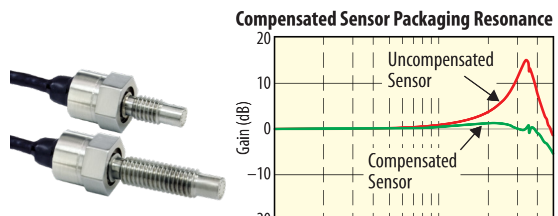
PFI’s 28124 and 28154 cards have three independently buffered outputs per channel to drive three independent destinations. Each output supports ground sensing for driving grounded single-ended loads without introducing ground loops and may be independently programmed for filtered or wideband operation.



Accelerometer Mechanical Resonance



Recessed Mounted Pressure Sensor Resonance



Kulite XTL-190

Microphone/Sensor Packaging Resonance

Verification of Cables and Sensor Health

Long cable runs impose a bandwidth restriction due to cable roll-off that is difficult to characterize but is crucial to understand. Cable breakdown or sensor failure can lead to measurement error or loss of data and require timely identification and corrective action. Piezoelectric charge and IEPE sensor health should be continually checked, ideally from the control room. It is imperative to prevent sensor faults from becoming noise sources that corrupt other channels. PFI provides solutions to address all these challenges, as discussed in the following sections.

In Situ Cable Roll-off Measurements

Due to the harsh nature of rocket engine testing, instrumentation is usually placed at a distance from the test article to protect the sensitive electronics from adverse conditions. While robust sensors can be chosen to survive harsh test environments, long cable runs of several hundred feet or more are needed to connect to the measurement electronics in the control room. The capacitance of long cables unfortunately leads to a roll-off restriction on the bandwidth of resistance-based sensor measurements, such as strain gages, RTDs, bridge-based load cells, accelerometers, and pressure sensors. A measurements engineer making dynamic measurements of resistive-based sensors must understand and document the exact cable roll-off characteristics of each cable.

The measurement of cable roll-off of installed cables is a difficult task, requiring stimulation of the sensor end of the cable with a signal generator whose output impedance matches that of the sensor. PFI's bridge and strain conditioners for rocket engine testing have the unique ability to measure in situ cable roll-off using the installed sensor impedance.

For strain gages and RTD's, a variable-frequency AC current can be injected into the cable, where the current reacts with the actual sensor resistance to create a sensor-based AC voltage.

For bridge-based sensors, PFI's proprietary AC Shunt Calibration allows the user to perform in situ dynamic shunt calibration against the actual bridge impedance. The measurement system then responds as if it were measuring an actual sensor-based signal. The frequency of the stimulus signal can be increased to determine the roll-off characteristics of the installed cable and attached sensor. This feature is available on Precision 28124, 28144, and 28154 signal conditioners in voltage excitation mode for bridge-based load cells, static strain gages and pressure sensors, and in current excitation mode for dynamic strain gages and RTD sensors.

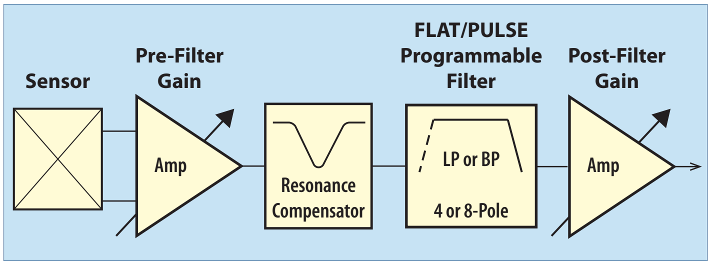
Resistive Gage Real-Time Health Monitoring

As time in engine test stands becomes more expensive and test results more critical, modern day test protocols often include significant pre-test setup and equipment verification steps. An effective pre-test validation would consist of a sensor resistance check, excitation level check, and cable and connector integrity check. Manual techniques, using a handheld digital multimeter to perform these verification steps, are both error prone and time consuming. Further, a significant time lapse can occur between verification and the actual test run, during which undetected problems can arise.

Rocket engine measurements often require complicated wiring schemes. Long cable runs, multiple connection points, and environmental factors combine to cause uncertainty in the sensor connection. A sudden increase in sensor resistance is indicative of pending failure. PFI's signal conditioners provide continual real-time monitoring of the total loop resistance of the sensor and cable circuit. This loop resistance reading can be compared to preset limits to alert the user to unexpected resistance shifts, as well as gross short and open conditions. The excitation voltage or current delivered to the sensor is continually monitored and reported to the user on the fly and flagged if out of tolerance. In addition, an excitation current limit indication is provided in order to alert the user to take timely corrective action to prevent loss of data. Possible causes of current limit include an incorrect excitation setting or a damaged transducer.

Piezoelectric Sensor Health

The Precision 28304 charge amplifier has built-in "T-Insertion" capability to electronically stimulate the connected piezoelectric sensor to produce an output charge signal. The charge output of a stimulated sensor is dependent on its electrical properties and those of its connecting cable. This output is extremely repeatable and can be used to detect any change resulting from a sensor fault or cable leakage issue. T-Insertion can be used to quickly and easily gather information on all sensor channels from the convenience of the control room. Pre and post T-Insert measurements can be compared to greatly enhance quality assurance documentation and add a new level of test validity documentation.



Distributed Gain Topology for Optimizing Dynamic Range

IEPE Sensor Health

A common measure of IEPE sensor health has always been the bias level. Traditionally, a front panel analog VU meter would give a visual indication of the bias level for each channel. However, the physical size and analog nature of the VU meter have driven its disappearance from modern computer-controlled instruments. PFI 28000 IEPE conditioners not only provide continual real-time monitoring of IEPE bias levels, but also allow the user to enter upper and lower comparison limits to detect and alert to a sudden shift in bias.

A second predictor of IEPE sensor failure is a sudden shift of output resistance, Z-out, of the FET transistor at the sensor output. The 28000 IEPE conditioner's "Z-out" feature has the ability to measure the output resistance of all attached IEPE sensors. By comparing Z-out readings to pre-programmed baseline readings, a shift in Z-out can be detected. Both Z-out and bias level can be documented as a report to be included in test quality or validity documentation.

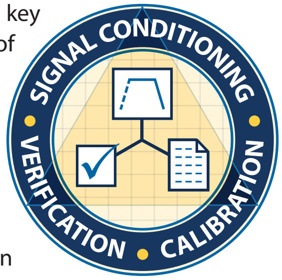
Muting Faulty Sensors

While most attention is paid to properly functioning sensors, a "real world" perspective forces one to also consider sensors that are NOT functioning properly. Often, a malfunctioning sensor can cause noise or fault currents that can corrupt other properly functioning channels. One common example of this phenomenon is "chatter" caused by sensors with intermittent connections.

Due to the extremely harsh environment of sensors on rocket engines, it is not uncommon for a sensor such as a strain gage to eventually fatigue and fracture, creating an open circuit condition. When the gage loop becomes open circuited, the connecting wires suddenly drift to the power supply rails of the signal conditioner. A gross fault in a strain gage resulting in a permanent open condition does not cause a noise problem. However, an intermittent gage condition, in which the connecting wires continually switch between the high voltage and low voltage levels, will create gage chatter. This chatter condition creates a hostile noise source for any other gage extension wires in the vicinity of the hostile cable. Unterminated or floating amplifier inputs are a potential source of "self-inflicted" noise. With high input impedance and potentially high channel gain it is possible to create a hostile rail-to-rail noise signal which could couple to neighboring channels.

Depending on the sensor type, various techniques must be used to quiet the channel's input and output circuits and ensure that no gage chatter and attendant noise coupling occurs. Precision's 28000 signal conditioners incorporate a "mute" feature that places a problematic channel in its quietest state, thereby eliminating the possibility of coupling noise to properly functioning channels.

Self-Test and Calibration



Since the signal conditioner is a key component in the critical path of important test data, performance specifications must be rigorously proven and documented. Yearly calibration is only the minimum requisite for defendable test data. Continual setup, tear down and reconfiguration of sensitive test equipment demands a rigorous test protocol that demonstrates that every channel is working properly prior to an actual test. At Precision, we know that verification tests are seldom run if the difficulty of doing so outweighs the perceived advantage. The PFI 28000 Self-Test Subsystem can conduct both rigorous yearly calibrations as well as quick Go/No-Go tests—all at the push of a button, and all without removing the system from the equipment rack.

Yearly Calibration

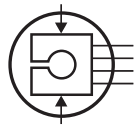
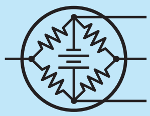
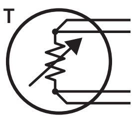
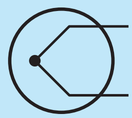
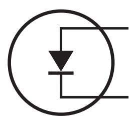
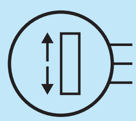
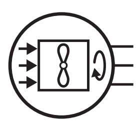
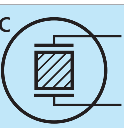
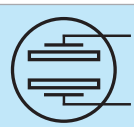
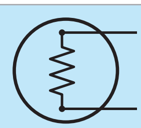
All test and measurement systems require periodic calibration. Typically, this means that test systems are dismantled and cards uninstalled and shipped either to an in-house calibration lab or back to the manufacturer.

PFI's built-in test hardware and software allows the user to perform NIST traceable calibration tests on-site without removing the system from the equipment rack. Traceability is afforded by the use of a high performance digital multimeter (DMM) kept in calibration by a third-party metrology test lab. Test software incorporated in the 28000 graphical user interface (GUI) first verifies calibration and traceability information of the DMM before proceeding step by step through an extensive test routine designed specifically for each card type. Every card function is exercised and all data-critical performance characteristics are accurately measured and compared to published specifications. Tests have been designed to assure a Test Uncertainty Ratio (TUR) of 4 or greater with a 95% confidence level. These calibration tests are the same rigorous measurement routines that are performed in the factory prior to shipment and serve as an excellent Factory Acceptance Test (FAT) to be used by a customer upon receipt of new equipment.

Performance characteristics measured by the 28000 FAT are shown below.

- Filter Frequency Response
- Channel to Channel Phase and Amplitude Match
- Gain Accuracy
- Offset Voltage
- AC/DC Coupling
- Max Level
- Noise
- CMRR
- Overload Detectors
- Amplifier Stage (Wide-Band) Frequency Response
- Excitation
- Auto-Balance
- Shunt Calibration

Sensor Types and Signal Conditioner Selection Chart

Measurement	Sensor	Connection	Applicable Card	Important Features
Horizontal and Vertical Thrust	Load Cell 	4 or 6-wire bridge with optional shunt cal (3-wires) plus shield	28124-HC10, 28154-HC10	Contact closure for internal sensor shunt resistor. Accurate and stable amplifier excitation and DC gain are critical.
Pressure – Engine, Hydraulic, Propellant, Purge	Bridge Type Pressure Sensor 	4 or 6-wire bridge with optional shunt cal (3-wires) plus shield	28124-HC10, 28154-HC10	Contact closure for internal sensor shunt resistor. Bridge auto balance.
Temperature - Propellant	RTD T 	4-wire plus shield	28124-HC10, 28154-HC10	Stable constant current excitation and DC gain. Accurate resistor substitution.
Temperature – Engine and Facility Temperatures	Thermocouple 	2-wire plus shield	28124-HC10, 28154-HC10, 28208A	Accurate and stable amplifier DC gain. Accurate voltage substitution (HC10).
Temperature – Cryogenic temperatures	Silicon Diode 	2 or 4-wire plus shield	28124-HC10, 28154-HC10	Stable constant current excitation and DC gain.
Displacement – Valve position	DC LVDT 	3 or 4-wire plus shield	28124-HC10, 28154-HC10	Constant voltage excitation, current output sensing (4-20 ma), Zero Suppress.
Flow – Propellant consumption, Hydraulic flow, rotational speed	Rotary Flow Meter, Magnetic Pick-ups 	2-wire plus shield	28524, 28608B	Flexible triggering, Programmable Band-pass filtering to eliminate unwanted harmonics of input signal.
Vibration – High Temperature	Piezo-Electric (Charge) Accelerometer C 	Coaxial	28304	Distributed gain amplifier to prevent clipping. Charge converter tolerant to sensor shunt resistance.
Vibration	Integral Electronics (IEPE) Accelerometer V 	Coaxial for single axis, multi-pin connector for triaxial	28304, 28316C	Ability to isolate or ground signal conditioner to avoid noise due to ground loops.
Vibration – low frequency	Capacitance Accelerometer 	4-wire	28124, 28154	Zero-suppress to remove initial sensor bias.
Red line on vibration, pressure, etc.	Any sensor **RL**	Sensor dependent	28124, 28304 or 28608B with RMS/DC output adapter module	Ability to add RMS to DC conversion at any sensor output to provide a DC signal proportional to engine vibration or other EU.
Fatigue	Strain Gage 	2 to 10-wire	28124-HC14, 28144-HC14, 28154-HC14	Ability to handle any configuration. Balanced topology for reduced EMI interference.

Pre-Test Verification

While yearly calibration shows basic compliance to quality standards, it does little to reveal a problem that may have developed between tests. Finding a bad channel in a yearly calibration can be too late, especially if that channel was potentially used on many tests throughout the year. The most rigorous test protocols require that additional tests are run before and sometimes after every test. In order to keep these tests viable within the time constraints of actual testing, they must be crafted to be quick and easy with minimal delay to actual engine testing.

The 28000 suite of Go/No-Go tests has been designed with speed and simplicity in mind. While the FAT verifies all channel parameters, the Go/No-Go routine quickly verifies only the present run-time settings of each channel. Gain, filter setting, DC offset and excitation levels are quickly measured, verified and presented in report form. The Go/No-Go report is an excellent addition to a quality assurance report and explicitly demonstrates that the equipment was functioning properly at time of test.

Example Pre-Test Verification Regimen

The Precision 28000 Signal Conditioning System can be completely set-up and operated from the provided Windows based GUI or programmed via the Ethernet interface. Ethernet programming allows the system to be interfaced with control systems that perform functions like transducer venting to atmosphere prior to performing a system calibration and preventing a system calibration when it is unsafe to do so. It also provides the capability to completely set up the signal conditioners and utilize the available internal test modes to perform a signal conditioner to recorder NIST traceable DC system calibration of offset and gain. Pressure transducers, load cells, RTDs, thermocouples and other measurements can be calibrated simultaneously by utilizing one of the many sensor specific test modes for zero and span conditions. Similarly, AC measurements can be verified operational and scaled from the signal conditioner to the recorder by applying a known signal to the signal conditioner input via the wideband 28000 system test bus. Verification of charge mode measurements are facilitated by the built-in NIST traceable shunt calibration capacitors.

Life Cycle Costs

The life cycle cost of a test system is the total cost of owning, operating and maintaining the system over its period of service. Included in this cost are the purchase cost, the installation cost, the acceptance testing cost, the operating cost, and the cost of ongoing maintenance and calibration. Also included, if typically overlooked, is the cost of acquiring bad data. While the up-front purchase cost is significant, the cost of operation and maintenance of the system over its lifetime will usually far exceed the purchase cost. The cost of bad data, even for one rocket engine test, can exceed the purchase price of the entire data system many times over.

Precision's 28000 Signal Conditioning System significantly reduces both operating and maintenance costs while providing tools to aid the user in validating test data to reduce or eliminate the possibility of bad data. The computer-controlled setup of the 28000 System reduces test setup time. Sensors and cables are verified using the 28000 System's built-in transducer health monitoring. Since sensor and cable health is monitored and reported on the fly during the test run, timely corrective action can be taken to potentially save critical data. Channels with faulty sensors can be placed in "mute" mode and data from these channels tagged as suspect.

The programmed settings of the 28000 System are directly measured and verified via automated Go/No-Go tests. Go/No-Go tests may be run before and after each engine test run to verify the integrity of the signal conditioning system. The built-in Factory Acceptance Test (FAT) allows the user to NIST traceably calibrate the system on-site in the equipment rack, reducing the expense of off-site calibration and system downtime.

Using the capabilities of the 28000 System, the user can rapidly perform system and sensor verification. For example, sensor loop resistances can be collected in a matter of seconds in contrast to tedious manual measurements that can take several hours for large channel count systems. Full reports are stored on the host server and may be presented as proof of test data validity.

Conclusion

When a "systems approach" is used in the design of a signal conditioning system, it appeals to all members of the measurements team. The metrology department, responsible for maintaining high quality test equipment in-spec and traceable year after year, appreciate the built-in NIST traceable calibration capabilities of the 28000 System. Test engineers, routinely challenged to defend their test data, appreciate the automated reports generated by the 28000 sensor and cable health Go/No-Go tests. Data analysts appreciate the quality, highly accurate and validated output data. Finally, project engineers, responsible for staying on budget and always concerned with the yearly "bottom line", appreciate the low life-cycle cost and low overall cost of ownership of Precision's 28000 System.

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ISO 9001 CERTIFIED QUALITY

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