Analog Measurement in the Digital Age

Despite tremendous gains in digital signal acquisition and processing, there is still much to be said for the benefits of an analog front end

Thomas P. Gerber, Douglas R. Firth, & Alan R. Szary

Introduction

Analog-to-digital converters (ADCs) and microprocessor-enabled digital signal processing (DSP) have closely followed Moore's Law for computational performance. These gains have brought fast, high-resolution digital acquisition systems (DAQs) to the instrumentation market at relatively low cost. It is now commonly assumed that modern DAQs with built-in signal conditioning obviate the need for stand-alone analog front ends (AFEs). Yet any measurement is fundamentally analog: the phenomenon of interest is sensed by a transducer, which produces an electrical waveform that contains a signal (desired information) and some noise (from the test environment).

Anyone concerned with making valid measurements, especially in harsh test conditions or variable field environments, should recognize the benefits of including a properly designed stand-alone AFE in their measurement system (Figure 1). Such benefits include not just traditional signal conditioning – which AFEs do very well – but also the ability to monitor and test the entire measurement chain from a single interface.

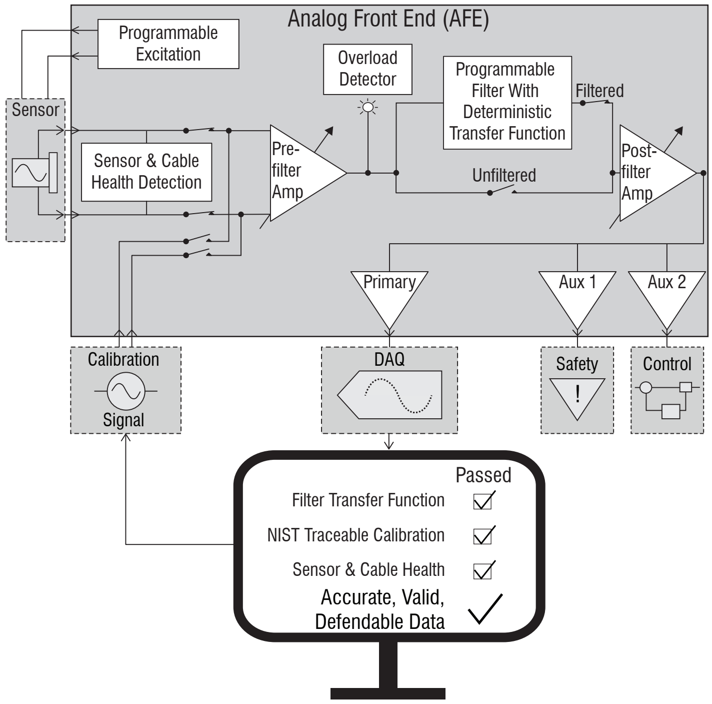

Figure 1. *Diagram depicting the role of a stand-alone Analog Front End (AFE) in a measurement system. Note that for the sake of illustration only one channel is shown. The AFE acts as the central hub in the system, linking the user interface to all components in the measurement chain. The AFE provides programmable excitation to external sensors and distributes signal amplification across both sides of a programmable filter with a deterministic transfer function. Quality control features in modern AFEs include dedicated circuitry for insertion of external calibration signals, monitoring circuits for overload detection and overall system health, and both primary and auxiliary outputs for digital acquisition and performance verification, respectively.*

Signal Conditioning and Shaping

Most measurement systems will require a low-pass analog filter to prevent aliasing in the sampled signal. If a measured transducer waveform contains spectral components greater than half the sampling frequency F_S, those components will corrupt in-band signals ($< F_S/2$) via their aliases. Once sampled, these aliases cannot be separated from the signals of interest. The relationship between a real spectral component and its baseband alias is fully determined by the sample rate. So if the amplitude response of the filter is known, the sample rate and filter cutoff frequency can be optimized for the desired level of alias attenuation and in-band response. By utilizing programmable filters to implement deterministic transfer functions with well-defined amplitude and phase response, AFEs provide precise and predictable alias protection.

In many test environments, the spectra of ambient noise sources are poorly constrained. In addition, noise can be generated by sensors with out-of-band resonances in their inherent response. When large, such noise sources can cause signal conditioning amplifiers to saturate, resulting in a clipped signal. If saturation occurs prior to a low-pass filter stage, then evidence of the saturation will be lost: the in-band signal of interest will be corrupted by clipping that is invisible at the filter output. If low-pass filters are not employed, then channel gain must be reduced to allow for the presence of unknown sources of noise in the signal; this can result in underutilization of the ADC's dynamic range.

An AFE can employ amplifier designs that distribute channel gain across both sides of the anti-aliasing filter, which can help minimize the risk of invisible clipping while ensuring the ADC's dynamic range is fully realized for the signal of interest. An example of conditioning a noisy signal that illustrates the effect of clipping is shown in Figure 2.

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Performance Verification, Versatility, and Life-Cycle Cost Efficiency

Run-time performance verification, periodic calibration of components, and system health monitoring are all critical to acquiring valid data from a measurement system. But in the absence of built-in test modules and software routines, end-to-end testing of the measurement chain (i.e. sensors, cables, conditioners, and ADCs) is laborious and time-consuming.

Modern AFEs can be equipped with hardware and software to provide numerous quality control features, such as: (i) Automated insertion of test signals at the input without the need to disconnect sensor cables; (ii) Multiple channel monitoring points along the signal path through signal conditioning circuitry; (iii) Built-in, NIST traceable Factory Acceptance Test (FAT) routines for in situ calibration of filter frequency response, common-mode rejection ratio, gain accuracy, and other performance characteristics; (iv) Fault-monitoring circuits for overload detection, sensor and cable health, and sensor excitation level; and (v) Multiple buffered outputs per channel to allow for simultaneous monitoring and measurement, including both filtered and unfiltered (wideband) outputs from a single channel.

An AFE with these features can save hundreds to thousands of hours per year in testing, calibration, and trouble-shooting. Moreover, a well-designed AFE is rather versatile: it can be easily configured to work with new sensor arrays and test configurations. Taking these savings into account, it is not difficult to see how the higher upfront cost of an AFE (when compared with a DAQ that includes minimal built-in signal conditioning) is easily amortized over its service life, which can span a decade or more of use.

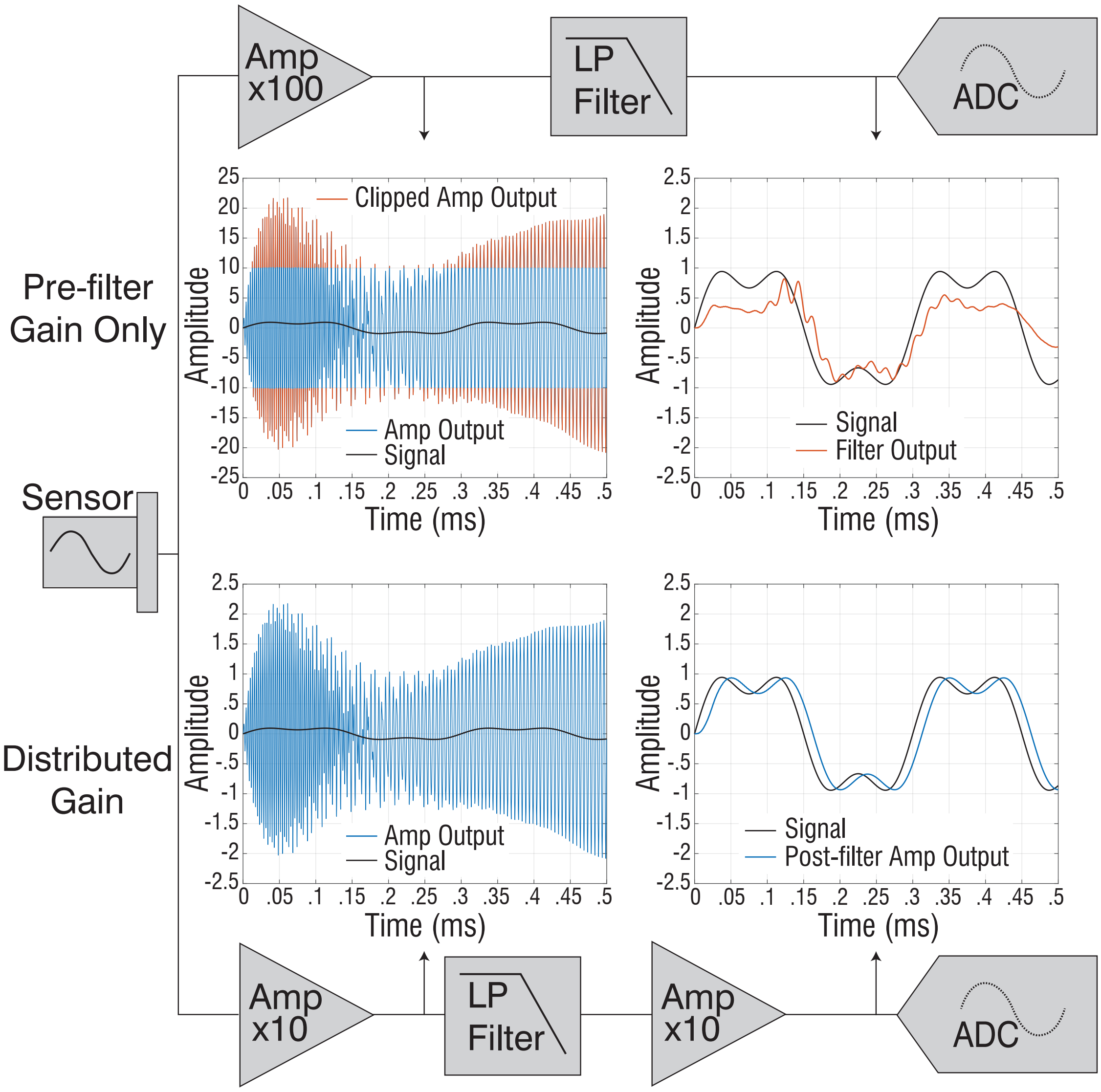

Figure 2. *Example of signal conditioning by an AFE to illustrate the effects of invisible clipping. A signal of interest (Signal) from the sensor is contaminated with out-of-band resonance and noise. The signal requires a gain of 100 to optimize the dynamic range of the analog-to-digital converter (ADC). If this gain is applied prior to low-pass filtering (top panels), the amplifier saturates on the total input. As a result, the input to the filter is clipped, and the recovered waveform (Filter Output) is a distorted version of the signal. If, however, the gain is distributed across both sides of the filter (bottom panels), no clipping occurs and the recovered waveform (Post-filter Amp Output) is an undistorted replica of the signal. Note that in this example, the time delay in the recovered waveform is constant (i.e. linear phase) and is determined by the filter's transfer function (here, the Precision Filters LP8P).*

PRECISION FILTERS, INC.
ISO 9001 CERTIFIED QUALITY

Precision Filters, Inc.
240 Cherry Street
Ithaca, New York 14850

Telephone: **607-277-3550**
E-mail: **pfinfo@pfinc.com**
Web Site: **www.pfinc.com**