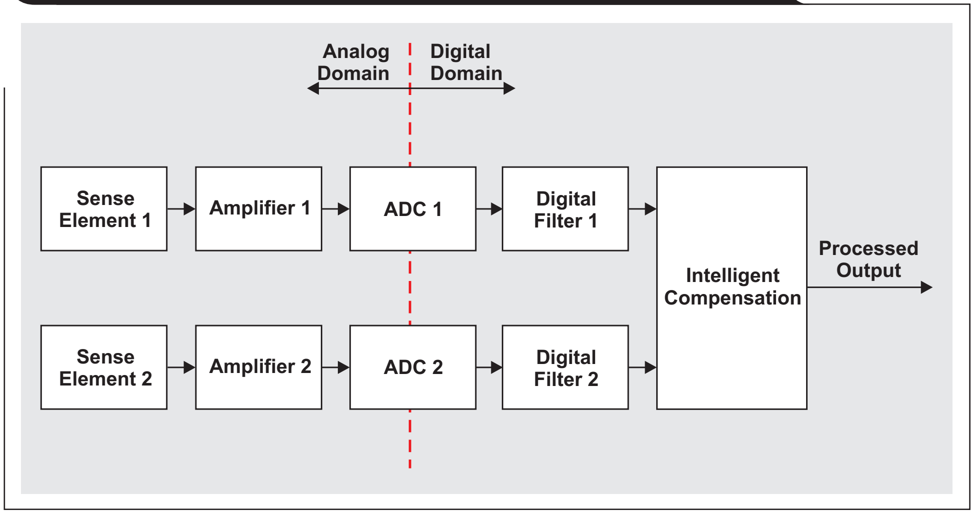
Exploring anti-aliasing filters in signal conditioners for mixed-signal, multimodal sensor conditioning

By Arun T. Vemuri
Systems Architect, Enhanced Industrial

Introduction

Some sensor-signal conditioners are used to process the output of multiple sense elements. This processing is often provided by multimodal, mixed-signal conditioners that can handle the outputs from several sense elements at the same time. This article analyzes the operation of anti-aliasing filters in such sensor-signal conditioners.

Figure 1. Multimodal, mixed-signal sensor-signal conditioner



Basics of sensor-signal conditioners

Sense elements, or transducers, convert a physical quantity of interest into electrical signals. Examples include piezoresistive bridges used to measure pressure, piezoelectric transducers used to detect ultrasonic waves, and electrochemical cells used to measure gas concentrations. The electrical signals produced by sense elements are small and exhibit nonidealities, such as temperature drifts and nonlinear transfer functions.

Sensor analog front ends such as the Texas Instruments (TI) LMP91000 and sensor-signal conditioners such as TI's PGA400/450 are used to amplify the small signals produced by sense elements into usable levels. The PGA400/450 include complete signal-conditioning circuits as well as circuits that generate stimuli for sense elements, manage power, and interface with the external controllers. Furthermore, devices such as the PGA400 provide the ability to correct for the nonidealities of the sense elements.

Multimodal signal conditioning

Often, for the purpose of signal conditioning or higher-level monitoring, there is a need to measure outputs of more than one sense element. For example, processing the output of a typically piezoresistive bridge requires measuring the outputs of both the bridge and a temperature sensor. Similarly, processing the output of a thermocouple requires measuring the outputs of both the thermocouple and a sensor that measures the connector temperature. The connector temperature is measured in order to perform cold-junction compensation. The scenario where more than one sense element is processed by the same signal conditioner is called *multimodal signal conditioning*.

Mixed-signal signal conditioning

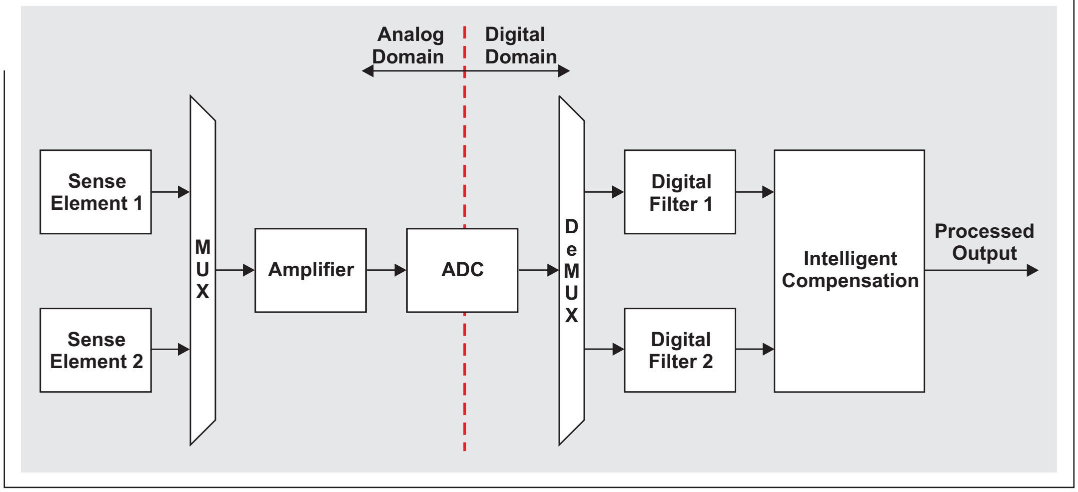
Another aspect of sensor-signal conditioning is the electrical domain in which the signal conditioning occurs. TI's PGA309 is an example of a device where the signal conditioning of resistive-bridge sense elements occurs in the analog domain. In devices such as the PGA400, the signal conditioning occurs in both the analog and the digital domains. The latter scenario is called *mixed-signal signal conditioning*.

A critical component of mixed-signal conditioners is the analog-to-digital converter (ADC). Figure 1 shows a block diagram of a multimodal, mixed-signal sensor-signal conditioner. This figure shows that the two sense elements have independent signal paths until the signals reach the intelligent compensation block. This block then combines the two signals to produce the processed output.

Nyquist criterion

A key aspect of mixed-signal sensor-signal conditioning is the discretization of the continuous-time analog-domain signal into a discrete-time digital-domain signal. In other words, mixed-signal conditioners are sampled systems. Hence, the well-known Nyquist criterion of sampling is applicable to mixed-signal sensor-signal conditioning. This

Figure 2. Analog signal paths sharing an amplifier and an ADC



criterion simply states that the sampling frequency has to be double the signal bandwidth of interest. For Figure 1 it is assumed that the amplifiers in each signal path limit the bandwidth of the signal in order to satisfy the Nyquist criterion. In other words, the amplifiers amplify the signals while at the same time providing the necessary anti-aliasing, or limiting of bandwidth, to satisfy the criterion.

Figure 1 also shows digital filters in the signal paths. The digital filters are used to reduce the signal bandwidths further to help improve the system's signal-to-noise ratio (SNR).

Unwanted sinusoid signals

For some applications, it may be desirable to reduce the cost of the circuit shown in Figure 1. Figure 2 shows a more cost-effective example wherein the two analog signal paths share an amplifier and an ADC. The signal paths in either circuit could have out-of-band sinusoid components introduced into either the sense element (for example, due to electromagnetic interference) or the signal path itself (for example, due to interference from adjacent circuits). Because of the common signal path in Figure 2, the digital filters may not be effective in eliminating out-of-band or unwanted sinusoid components. This section analyzes this problem.

For this analysis it is assumed that the circuits in Figures 1 and 2 share the same conditions:

- ADC sampling rate: 10 kHz
- Amplifier bandwidth to satisfy Nyquist criterion: 5 kHz
- Signal band of interest or digital-filter bandwidth: 2.5 kHz
- Unwanted sinusoid component at 3 kHz in sense element 1's path

In the circuit in Figure 1, the unwanted 3-kHz signal is effectively attenuated by the digital filter. This is because the 3-kHz signal is not aliased into the baseband. That is, the 3 kHz will show up at 3 kHz—even in the digital domain.

However, if the same 5-kHz amplifier is used for the circuit in Figure 2, and if the signals from the two sense elements are alternately sampled, the digital filter will be ineffective in attenuating the unwanted 3-kHz signal. This is because the effective sampling frequency of the signal from sense element 1 is only 5 kHz, even though the ADC sampling rate is 10 kHz. Thus, the 3 kHz will alias into the baseband (or appear as an in-band signal), rendering the digital filter ineffective in removing the unwanted signal.

It is noted that in order to prevent aliasing of the unwanted signal and to satisfy the Nyquist criterion, the amplifier bandwidth has to be lowered to 2.5 kHz. In this case, a 2.5-kHz digital filter is not needed any more; the digitized signal's bandwidth is limited to 2.5 kHz by the analog amplifier.

Unwanted wideband white noise

The signal paths in Figures 1 and 2 can produce unwanted wideband white noise. To investigate and clearly understand this, it will be assumed that the signal path does not have any unwanted sinusoid components. It will also be assumed that the signal path's white noise is the dominant source of noise compared to the quantization noise, which is usually the case in such signal paths.

Anti-aliasing filters for white noise: Case 1

With the independent signal paths shown in Figure 1, each 5-kHz amplifier acts as an anti-aliasing filter to limit the white-noise bandwidth of the respective signals to 5 kHz. The digital filters further reduce these bandwidths to 2.5 kHz, thus achieving a certain signal-to-white-noise ratio.

With the two analog signal paths in Figure 2 sharing a 5-kHz amplifier, sense element 1's effective sampling frequency is once again 5 kHz, assuming that the two sense-element outputs are sampled alternately. In this case, all analog-domain noise from 2.5 to 5 kHz aliases into the 0- to 2.5-kHz range, which is the frequency band of interest. However, the root mean square (RMS) noise in this frequency range is not affected! In other words, the SNR is the same for this circuit as for that in Figure 1.

Anti-aliasing filters for white noise: Case 2

For Case 2, it is assumed that the signal band of interest is 1.25 kHz, which is half the band of interest used in Case 1. That is, the signal band is reduced because there is no signal content beyond 1.25 kHz that is wanted, and because limiting the noise bandwidth improves the SNR. Assuming that the 5-kHz amplifier is used for anti-aliasing, one will naturally conclude that a 1.25-kHz digital filter will reduce the bandwidth and achieve the same SNR for the circuit in Figure 1 as for the one in Figure 2. However, this is not the case. While it is true that, with the 5-kHz anti-aliasing filter, the RMS noise in the sampled domain is the same in both architectures, their noise densities are different. With the independent signal paths, the noise density of the sampled signals is $\text{Noise}_{\text{RMS}}/\sqrt{5\text{ kHz}}$, while the noise density for the common signal path is $\text{Noise}_{\text{RMS}}/\sqrt{2.5\text{ kHz}}$. Thus, using a 1.25-kHz band-limiting filter in the common analog signal path results in RMS noise of $\sqrt{1.25\text{ kHz}} \times \text{Noise}_{\text{RMS}}/\sqrt{2.5\text{ kHz}}$ at the digital filter's output. This noise is higher than the RMS noise in the independent signal paths, which is $\sqrt{1.25\text{ kHz}} \times \text{Noise}_{\text{RMS}}/\sqrt{5\text{ kHz}}$. That is, the SNR in the common signal path is worse than that in the independent signal paths. Note that these RMS calculations assume ideal filters, which are filters with 0-dB gain in the passband and infinite attenuation in the stopband.

Simulation model

Figure 3 shows a MATLAB®/Simulink® model used to analyze the effect of signal-path architectures on unwanted wideband white noise. The model includes both the circuit with independent signal paths and the circuit with a common signal path. Note that the downsample-by-2 block is used to represent the effects of alternate sampling of the common signal path. The analog amplifier is assumed to have a gain of 10 and is a fourth-order elliptical low-pass filter. The FDA tool in MATLAB/Simulink was used to design the digital filters in Figure 3, which are also fourth-order elliptical low-pass filters.[1]

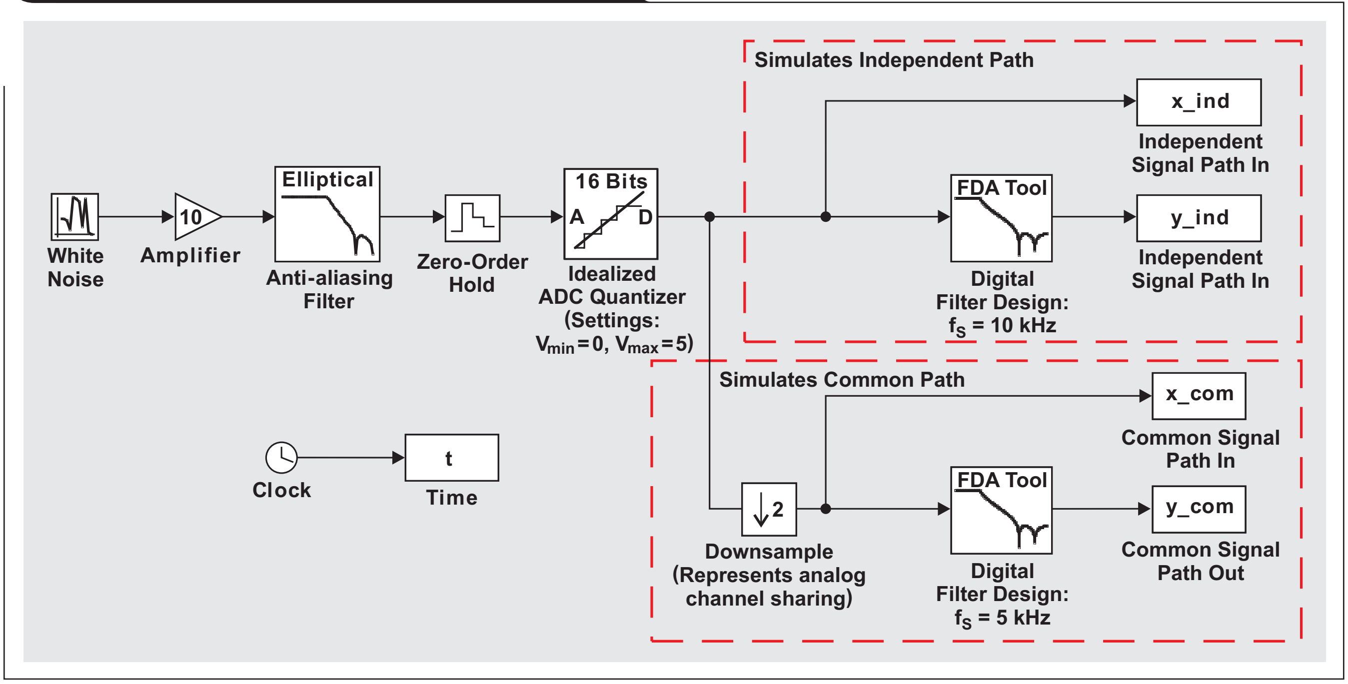
Table 1. RMS noise of the independent and common signal paths

AMPLIFIER BANDWIDTH (kHz)	std(x_ind)	std(y_ind) WITH DIGITAL FILTER	std(x_com)	std(y_com) WITH DIGITAL FILTER
5	7018	3250	7004	4806
2.5	4934	3300	4938	3365

Table 1 summarizes the RMS noise of the 1.25-kHz digital filter when the amplifier bandwidth is 5 kHz or 2.5 kHz. The MATLAB "std" function was used to calculate the RMS noise.

For the amplifier bandwidth of 5 kHz, the RMS value of the ADC output and its downsampled-by-2 value shown in the "std(x_ind)" and "std(x _com)" columns, respectively, are about the same. That is, the downsampling does not

Figure 3. MATLAB®/Simulink® simulation model



affect the RMS value. Therefore, if the downsampled value is used directly without further digital filtering, then the signal-to-white-noise ratio for the common signal path is the same as for the independent signal path.

For the amplifier bandwidth of 2.5 kHz, the RMS values of the digital-filter outputs are shown in the "std(y_ind)" and "std(y_com)" columns. From the data in these columns, it is clear that the effect of the 1.25-kHz digital filter depends on the frequency of the analog anti-aliasing filter. If the anti-aliasing filter's bandwidth is 2.5 kHz, which corresponds to half of the sampling frequency in the common signal path, then the noise at the output of the common-path digital filter matches the noise at the output of the digital filter in the independent signal path. If, however, the anti-aliasing filter's bandwidth is 5 kHz, then the RMS values of the digital-filter outputs are very different, resulting in different signal-to-white-noise ratios.

Conclusion

For multimodal, mixed-signal sensor-signal conditioners, the bandwidths of anti-aliasing filters have to be chosen appropriately to remove unwanted signals and to achieve the desired SNRs. If a sigma-delta modulator ADC is used, ADC samples that are unsettled after switching have to be discarded. This reduces the effective sampling rate even more.

Reference

1. Alan V. Oppenheim and Ronald W. Schafer, *Digital Signal Processing*. Englewood Cliffs, NJ: Prentice-Hall, 1975.

Related Web sites

Amplifiers: Op Amps:
www.ti.com/amplifier-aaj

www.ti.com/lmp91000-aaj
www.ti.com/pga309-aaj
www.ti.com/pga400-q1-aaj
www.ti.com/pga450-q1-aaj

Subscribe to the AAJ:
www.ti.com/subscribe-aaj

TI Worldwide Technical Support

Internet

TI Semiconductor Product Information Center Home Page

support.ti.com

TI E2E™ Community Home Page

e2e.ti.com

Product Information Centers

Americas	Phone	+1(512) 434-1560
Brazil	Phone	0800-891-2616
Mexico	Phone	0800-670-7544
	Fax	+1(972) 927-6377
	Internet/Email	support.ti.com/sc/pic/americas.htm

Europe, Middle East, and Africa

Phone

European Free Call	00800-ASK-TEXAS (00800 275 83927)
International	+49 (0) 8161 80 2121
Russian Support	+7 (4) 95 98 10 701

Note: The European Free Call (Toll Free) number is not active in all countries. If you have technical difficulty calling the free call number, please use the international number above.

Fax	+(49) (0) 8161 80 2045
Internet	www.ti.com/asktexas
Direct Email	asktexas@ti.com

Japan

Phone	Domestic	0120-92-3326
Fax	International	+81-3-3344-5317
	Domestic	0120-81-0036
Internet/Email	International	support.ti.com/sc/pic/japan.htm
	Domestic	www.tij.co.jp/pic

Asia

Phone

International	+91-80-41381665
Domestic	Toll-Free Number

Note: Toll-free numbers do not support mobile and IP phones.

Australia	1-800-999-084
China	800-820-8682
Hong Kong	800-96-5941
India	1-800-425-7888
Indonesia	001-803-8861-1006
Korea	080-551-2804
Malaysia	1-800-80-3973
New Zealand	0800-446-934
Philippines	1-800-765-7404
Singapore	800-886-1028
Taiwan	0800-006800
Thailand	001-800-886-0010

Fax	+8621-23073686
Email	tiasia@ti.com or ti-china@ti.com
Internet	support.ti.com/sc/pic/asia.htm

A090712

IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as “components”) are sold subject to TI’s terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI’s terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers’ products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers’ products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI’s goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or “enhanced plastic” are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have ***not*** been so designated is solely at the Buyer's risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

Products		**Applications**	
Audio	www.ti.com/audio	Automotive and Transportation	www.ti.com/automotive
Amplifiers	amplifier.ti.com	Communications and Telecom	www.ti.com/communications
Data Converters	dataconverter.ti.com	Computers and Peripherals	www.ti.com/computers
DLP® Products	www.dlp.com	Consumer Electronics	www.ti.com/consumer-apps
DSP	dsp.ti.com	Energy and Lighting	www.ti.com/energy
Clocks and Timers	www.ti.com/clocks	Industrial	www.ti.com/industrial
Interface	interface.ti.com	Medical	www.ti.com/medical
Logic	logic.ti.com	Security	www.ti.com/security
Power Mgmt	power.ti.com	Space, Avionics and Defense	www.ti.com/space-avionics-defense
Microcontrollers	microcontroller.ti.com	Video and Imaging	www.ti.com/video
RFID	www.ti-rfid.com		
OMAP Applications Processors	www.ti.com/omap	**TI E2E Community**	e2e.ti.com
Wireless Connectivity	www.ti.com/wirelessconnectivity		

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265