

# Analog Dialogue

A forum for the exchange of circuits, systems, and software for real-world signal processing

**SSB UPCONVERSION OF QUADRATURE DDS SIGNALS TO THE 800-TO-2500-MHz BAND (page 46)**

**Fundamentals of DSP-Based Control for AC Machines (page 3)**

**Transducer/Sensor Excitation and Measurement Techniques (page 33)**

Complete contents on page 1



## About *Analog Dialogue*

*Analog Dialogue* is the free technical magazine of Analog Devices, Inc., published continuously for thirty-four years, starting in 1967. It discusses products, applications, technology, and techniques for analog, digital, and mixed-signal processing.

Volume 34, the current issue, incorporates all articles published during 2000 in the World Wide Web editions [www.analog.com/analogdialogue](http://www.analog.com/analogdialogue). All recent issues, starting with Volume 29, Number 2 (1995) have been archived on that website and can be accessed freely.

*Analog Dialogue's* objectives have always been to inform engineers, scientists, and electronic technicians about new ADI products and technologies, and to help them understand and competently apply our products.

The frequent Web editions have at least three further objectives:

- Provide timely digests that alert readers to upcoming and newly available products.
- Provide a set of links to important and rapidly proliferating sources of information and activity fermenting within the ADI website [[www.analog.com](http://www.analog.com)].
- Listen to reader suggestions and help find sources of aid to answer their questions.

Thus, *Analog Dialogue* is more than a magazine: its links and tendrils to all parts of our website (and some outside sites) make its bookmark a favorite “high-pass-filtered” point of entry to the [analog.com](http://www.analog.com) site—the virtual world of Analog Devices.

Our hope is that readers will think of ADI publications as “Great Stuff” and the *Analog Dialogue* bookmark on their Web browser as a favorite alternative path to answer the question, “What’s new in technology at ADI?”

Welcome! Read and enjoy!

We encourage your feedback\*!



Dan Sheingold  
dan.sheingold@analog.com  
Editor, *Analog Dialogue*

\*We've included a brief questionnaire in this issue (page 55); we'd be most grateful if you'd answer the questions and fax it back to us at 781-329-1241.

## IN THIS ISSUE

*Analog Dialogue* Volume 34, 2000

	Page
Editor's Notes: New Fellow, Authors . . . . .	2
<i>Fundamentals of DSP-Based Control for AC Machines</i> . . . . .	3
<i>Embedded Modems Enable Appliances to Communicate with Distant Hosts via the Internet</i> . . . . .	7
<i>Adaptively Canceling Server Fan Noise</i> . . . . .	10
<i>Fan-Speed Control Techniques in PCs</i> . . . . .	16
<i>Finding the Needle in a Haystack—Measuring Small Voltages Amid Large Common Mode</i> . . . . .	21
<i>Demystifying Auto-Zero Amplifiers—Part 1</i> . . . . .	25
<i>Demystifying Auto-Zero Amplifiers—Part 2</i> . . . . .	28
<i>Curing Comparator Instability with Hysteresis</i> . . . . .	30
<i>Transducer/Sensor Excitation and Measurement Techniques</i> . . . . .	33
<i>Advances in Video Encoders</i> . . . . .	38
<i>Selecting an Analog Front-End for Imaging Applications</i> . . . . .	40
<i>True RMS-to-DC Measurements, from Low Frequencies to 2.5 GHz</i> . . . . .	45
<i>Single-Sideband Upconversion of Quadrature DDS Signals to the 800-to-2500-MHz Band</i> . . . . .	46
<i>VDSL Technology Issues—An Overview</i> . . . . .	50
Authors (continued from page 2) . . . . .	53
Feedback Questionnaire . . . . .	55

## Editor's Notes

We are pleased to note the introduction of Dr. David Smart as new Fellow at our 2000 General Technical Conference. Fellow, at Analog Devices, represents the highest level of achievement that a technical contributor can achieve, on a par with Vice President. The criteria for promotion to Fellow are very demanding. Fellows will have earned universal respect and recognition from the technical community for unusual talent and identifiable innovation at the state of the art. Their creative technical contributions in product or process technology will have led to commercial success with a major impact on the company's net revenues.



Attributes include roles as mentor, consultant, entrepreneur, organizational bridge, teacher, and ambassador. Fellows must also be effective leaders and members of teams and in perceiving customer needs. Dave's technical abilities, accomplishments, and personal qualities well qualify him to join Bob Adams (1999), Woody Beckford (1997), Derek Bowers (1991), Paul Brokaw (1979), Lew Counts (1983), Barrie Gilbert (1979), Roy Gosser (1998), Bill Hunt (1998), Jody Lapham (1988), Chris Mangelsdorf (1998), Fred Mapplebeck (1989), Jack Memishian (1980), Doug Mercer (1995), Frank Murden (1999), Mohammad Nasser (1993), Wyn Palmer (1991), Carl Roberts (1992), Paul Ruggerio (1994), Brad Scharf (1993), Jake Steigerwald (1999), Mike Timko (1982), Bob Tsang (1988), Mike Tuthill (1988), Jim Wilson (1993), and Scott Wurcer (1996) as Fellow.

### NEW FELLOW

**Dave Smart** is the chief technologist behind ADICE, our highly successful analog and mixed-signal circuit simulator, which is widely used by chip designers in Analog Devices. Dave joined ADI in 1988, assuming responsibility for ADICE. He made numerous contributions to the robustness, accuracy, and features of the simulator, winning the praise of Analog Devices' demanding analog IC designers. To meet the challenges of designing large mixed-signal chips in the 1990s, Dave led a small team in the development and deployment of a completely new version of ADICE with innovative techniques for the effective simulation of mixed-signal circuits using mixed levels of modeling abstraction. He is currently working on tools and methods for the design of RF and high-speed ICs. The work of Dave and his team has been a key element of the design of nearly every analog and mixed-signal product developed by Analog Devices in the past decade.

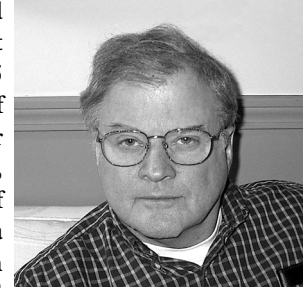


Dave developed an interest in analog circuits as a teenager growing up in Skokie, Illinois. Before receiving any formal education in electronics, he and a friend designed and built an audio mixing board for their high school auditorium to be used in theatrical productions. While pursuing his study of circuits as an undergraduate at the University of Illinois at Urbana-Champaign in the early 1970s, he became aware of the power of digital computers and imagined their use to take some of the tedium and guesswork out of circuit

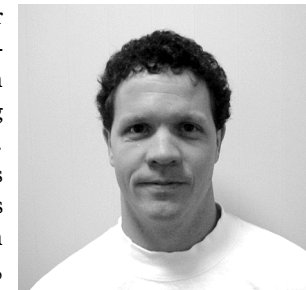
design. Once he met Professor Tim Trick, who was active in the field of computer-aided design of circuits, Dave's career direction was set. After receiving BS and MS degrees from the University of Illinois, he worked on circuit simulation at GTE Communication Systems for seven years. He returned to the University of Illinois, researching parallel algorithms for circuit simulation with Professor Trick, and he obtained his PhD degree prior to joining ADI in 1988.

### THE AUTHORS

**Rick Blessington** (page 7) rejoined ADI as a Business Development Manager in April of 1999, after 15 years in the sales and marketing of communication products for major electronics companies. At present, he is involved in development of inventive new products under a contract collaboration between Sierra Telecom (So. Lake Tahoe) and Analog Devices. Rick holds BA and MA degrees in Technology from California State University at Long Beach. In the early years of his career, Rick taught electronics in Southern California. He and his family now live in Walpole, MA; his hobbies include sailing and skiing.



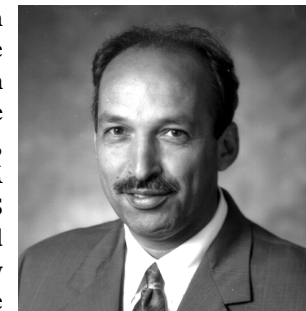
**Kevin Buckley** (page 40) is a Senior Applications Engineer in the High-Speed Converter Division, in Wilmington, MA, working on analog front ends for imaging applications. He joined Analog Devices in 1990 as a technician for the Microelectronics Division and received a BSEE in 1997 from Merrimack College, North Andover, MA. In his spare time he plays hockey and soccer, coaches his son's soccer team, and enjoys chasing his baby daughter around the house.



**Paschal Minogue** (page 10) is the Engineering Manager of the Digital Audio Group in Limerick, Ireland. He graduated from University College Dublin, with a B.E. Electronic Engineering degree (First Class Honors) and joined the Design Department at Analog Devices in Limerick, Ireland, in 1981. Since then, he has worked on standard converters, noise cancellation, communication products, and most recently audio-band and voice-band products.



**Reza Moghimi** (page 28) is an Applications Engineer for the Precision Amplifier product line in Santa Clara, CA. He is responsible for amplifiers, comparators, temperature sensors, and the SSM audio product line. He holds a BS from San Jose State University and an MBA from National University (Sunnyvale, CA). His leisure interests include playing soccer and traveling with his family.



[more authors on Page 53]

# Fundamentals of DSP-Based Control for AC Machines

by Finbarr Moynihan,  
Embedded Control Systems Group

## INTRODUCTION

High-performance servomotors are characterized by the need for smooth rotation down to stall, full control of torque at stall, and fast accelerations and decelerations. In the past, variable-speed drives employed predominantly dc motors because of their excellent controllability. However, modern high-performance motor drive systems are usually based on three-phase ac motors, such as the ac induction motor (ACIM) or the permanent-magnet synchronous motor (PMSM). These machines have supplanted the dc motor as the machine of choice for demanding servomotor applications because of their simple robust construction, low inertia, high output-power-to-weight ratios, and good performance at high speeds of rotation.

The principles of vector control are now well established for controlling these ac motors; and most modern high-performance drives now implement digital closed-loop current control. In such systems, the achievable closed-loop bandwidths are directly related to the rate at which the computationally intensive vector-control algorithms and associated vector rotations can be implemented in real time. Because of this computational burden, many high-performance drives now use digital signal processors (DSPs) to implement the embedded motor- and vector-control schemes. The inherent computational power of the DSP permits very fast cycle times and closed-loop current control bandwidths (between 2 and 4 kHz) to be achieved.

The complete current control scheme for these machines also requires a high-precision pulswidth modulation (PWM) voltage-generation scheme and high-resolution analog-to-digital (A/D) conversion (ADC) for measurement of the motor currents. In order to maintain smooth control of torque down to zero speed, rotor position feedback is essential for modern vector controllers. Therefore, many systems include rotor-position transducers, such as resolvers and incremental encoders. We describe here the fundamental principles behind the implementation of high-performance controllers (such as the ADMC401) for three-phase ac motors—combining an integrated DSP controller, with a powerful DSP core, flexible PWM generation, high-resolution A/D conversion, and an embedded encoder interface.

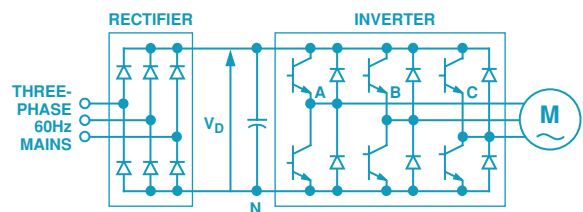
## VARIABLE SPEED CONTROL OF AC MACHINES

Efficient variable-speed control of three-phase ac machines requires the generation of a balanced three-phase set of variable voltages with variable frequency. The variable-frequency supply is typically produced by conversion from dc using power-semiconductor devices (typically MOSFETs or IGBTs) as solid-state switches. A commonly-used converter configuration is shown in Figure 1a. It

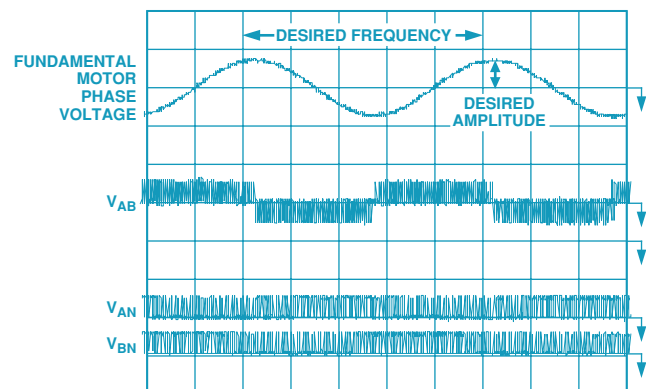
is a two-stage circuit, in which the fixed-frequency 50- or 60-Hz ac supply is first rectified to provide the dc link voltage,  $V_D$ , stored in the dc link capacitor. This voltage is then supplied to an inverter circuit that generates the variable-frequency ac power for the motor. The power switches in the inverter circuit permit the motor terminals to be connected to either  $V_D$  or ground. This mode of operation gives high efficiency because, ideally, the switch has zero loss in both the open and closed positions.

By rapid sequential opening and closing of the six switches (Figure 1a), a three-phase ac voltage with an average sinusoidal waveform can be synthesized at the output terminals. The actual output voltage waveform is a pulswidth modulated (PWM) high-frequency waveform, as shown in Figure 1b. In practical inverter circuits using solid-state switches, high-speed switching of about 20 kHz is possible, and sophisticated PWM waveforms can be generated with all voltage harmonic components at very high frequencies; well above the desired fundamental frequencies—nominally in the range of 0 Hz to 250 Hz.

The inductive reactance of the motor increases with frequency so that the higher-order harmonic currents are very small, and near-sinusoidal currents flow in the stator windings. The fundamental voltage and output frequency of the inverter, as indicated in Figure 1b, are adjusted by changing the PWM waveform using an appropriate controller. When controlling the fundamental output voltage, the PWM process inevitably modifies the harmonic content of the output voltage waveform. A proper choice of modulation strategy can minimize these harmonic voltages and their associated harmonic effects and high-frequency losses in the motor.



a. Typical configuration of power converter used to drive three-phase ac motors.



b. Typical PWM waveforms in the generation of a variable-voltage, variable-frequency supply for the motor.

Figure 1.

## PULSEWIDTH MODULATION (PWM) GENERATION

In typical ac motor-controller design, both hardware and software considerations are involved in the process of generating the PWM signals that are ultimately used to turn on or off the power devices in the three-phase inverter. In typical digital control environments, the controller generates a regularly timed interrupt at the PWM switching frequency (nominally 10 kHz to 20 kHz). In the interrupt service routine, the controller software computes new duty-cycle values for the PWM signals used to drive each of the three legs of the inverter. The computed duty cycles depend on both the *measured* state of the motor (torque and speed) and the *desired* operating state. The duty cycles are adjusted on a cycle-by-cycle basis in order to make the actual operating state of the motor follow the desired trajectory.

Once the desired duty cycle values have been computed by the processor, a dedicated hardware PWM generator is needed to ensure that the PWM signals are produced over the next PWM-and-controller cycle. The PWM generation unit typically consists of an appropriate number of timers and comparators that are capable of producing very accurately timed signals. Typically, 10-to-12 bit performance in the generation of the PWM timing waveforms is desirable. The PWM generation unit of the ADMC401 is capable of an edge resolution of 38.5 ns, corresponding to approximately 11.3 bits of resolution at a switching frequency of 10 kHz. Typical PWM signals produced by the dedicated PWM generation unit of the ADMC401 are shown in Figure 2, for inverter leg A. In the figure, AH is the signal used to drive the high-side power device of inverter leg A, and AL is used to drive the low-side power device. The duty cycle effectively adjusts the average voltage applied to the motor on a cycle-by-cycle basis to achieve the desired control objective.

In general, there is a small delay required between turning off one power device (say AL) and turning on the complementary power device (AH). This dead-time is required to ensure the device being turned off has sufficient time to regain its blocking capability before the other device is turned on. Otherwise a short circuit of the dc voltage could result. The PWM generation unit of the ADMC401 contains the necessary hardware for automatic dead-time insertion into the PWM signals.

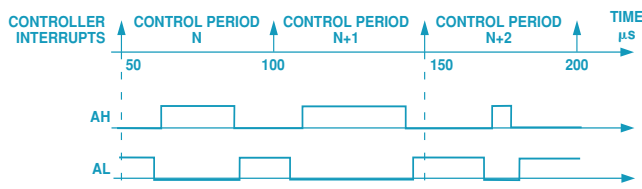


Figure 2. Typical PWM waveforms for a single inverter leg.

### General Structure of a Three-Phase AC Motor Controller

Accurate control of any motor-drive process may ultimately be reduced to the problem of accurate control of both the torque and speed of the motor. In general, motor speed is controlled directly by measuring the motor's speed or position using appropriate transducers, and torque is controlled indirectly by suitable control of the motor phase currents. Figure 3 shows a block diagram of a typical synchronous frame-current controller for a three-phase

motor. The figure also shows the proportioning of tasks between software code modules and the dedicated motor-control peripherals of a motor controller such as the ADMC401. The controller consists of two proportional-plus-integral-plus-differential (PID) current regulators that are used to control the motor current vector in a reference frame that rotates synchronously with the measured rotor position.

Sometimes it may be desirable to implement a decoupling between voltage and speed that removes the speed dependencies and associated axes cross coupling from the control loop. The reference voltage components are then synthesized on the inverter using a suitable pulsewidth-modulation strategy, such as *space vector modulation* (SVM). It is also possible to incorporate some compensation schemes to overcome the distorting effects of the inverter switching dead time, finite inverter device *on*-state voltages and dc-link voltage ripple.

The two components of the stator current vector are known as the *direct-axis* and *quadrature-axis* components. The direct-axis current controls the motor flux and is usually controlled to be zero with permanent-magnet machines. The motor torque may then be controlled directly by regulation of the quadrature axis component. Fast, accurate torque control is essential for high-performance drives in order to ensure rapid acceleration and deceleration—and smooth rotation down to zero speed under all load conditions.

The actual direct and quadrature current components are obtained by first measuring the motor phase currents with suitable current-sensing transducers and converting them to digital, using an on-chip ADC system. It is usually sufficient to simultaneously sample just two of the motor line currents: since the sum of the three currents is zero, the third current can, when necessary, be deduced from simultaneous measurements of the other two currents.

The controller software makes use of mathematical vector transformations, known as Park Transformations, that ensure that the three-phase set of currents applied to the motor is synchronized to the actual rotation of the motor shaft, under all operating conditions. This synchronism ensures that the motor always produces the optimal torque per ampere, i.e., operates at optimal efficiency. The vector rotations require real-time calculation of the sine and cosine of the measured rotor angle, plus a number of multiply-and-accumulate operations. The overall control-loop bandwidth depends on the speed of implementation of the closed-loop control calculations—and the resulting computation of new duty-cycle values. The inherent fast computational capability of the 26-MIPS, 16-bit fixed-point DSP core makes it the ideal computational engine for these embedded motor-control applications.

### ANALOG-TO-DIGITAL CONVERSION REQUIREMENTS

For control of high-performance ac servo-drives, fast, high-accuracy, simultaneous-sampling A/D conversion of the measured current values is required. Servo drives have a *rated operation* range—a certain power level that they can sustain continuously, with an acceptable temperature rise in the motor and power converter. Servo drives also have a *peak* rating—the ability to handle a current far in excess of the rated current for short periods of time. It is possible, for example, to apply up to six times the rated

current for short bursts of time. This allows a large torque to be applied transiently, to accelerate or decelerate the drive very quickly, then to revert to the continuous range for normal operation. This also means that in the normal operating mode of the drive, only a small percentage of the total input range is being used.

At the other end of the scale, in order to achieve the smooth and accurate rotations desired in these machines, it is wise to compensate for small offsets and nonlinearities. In any current-sensor electronics, the analog signal processing is often subject to gain and offset errors. Gain mismatches, for example, can exist between the current-measuring systems for different windings. These effects combine to produce undesirable oscillations in the torque. To meet both of these conflicting resolution requirements, modern servo drives use 12-to-14-bit A/D converters, depending on the cost/performance trade-off required by the application.

The bandwidth of the system is essentially limited by the amount of time it takes to input information and then perform the calculations. A/D converters that take many microseconds to convert can produce intolerable delays in the system. A delay in a closed-loop system will degrade the achievable bandwidth of the system, and bandwidth is one of the most important figures of merit in these high-performance drives. Therefore, fast analog-to-digital conversion is a necessity for these applications.

A third important characteristic of the A/D converter used in these applications is *timing*. In addition to high resolution and fast conversion, simultaneous sampling is needed. In any three-phase motor, it's necessary to measure the currents in the three windings of the motor at *exactly the same time* in order to get an instantaneous "snapshot" of the torque in the machine. Any time skew (time delay between the measurements of the different currents) is an

error factor that's artificially inserted by the means of measurement. Such a non-ideality translates directly into a ripple of the torque—a very undesirable characteristic.

The ADC system that is integrated into the ADMC401 provides a fast (6-MSPS), high-resolution (12-bit) ADC core integrated with dual sample-and-hold amplifiers so that two input signals may be sampled simultaneously. (As noted earlier, this allows the simultaneous value of the third current to be calculated.) The ADC core is a high-speed pipeline flash architecture. A total of eight analog input channels may be converted, accepting additional system or feedback signals for use as part of the control algorithm. This level of integrated performance represents the state-of-the-art in embedded DSP motor controllers for high-performance applications.

### POSITION SENSING AND ENCODER INTERFACE UNITS

Usually the motor position is measured through the use of an encoder mounted on the rotor shaft. The incremental encoder produces a pair of quadrature outputs (A and B), each with a large number of pulses per revolution of the motor shaft. For a typical encoder with 1024 lines, both signals produce 1024 pulses per revolution. Using a dedicated quadrature counter, it is possible to count both the rising and falling edges of both the A and B signals so that one revolution of the rotor shaft may be divided into 4096 different values. In other words, a 1024-line encoder allows the measurement of rotor position to 12-bit resolution. The direction of rotation may also be inferred from the relative phasing of quadrature signals A and B.

It is usual to have a dedicated encoder interface unit (EIU) on the motor controller; it manages the conversion of the dual quadrature

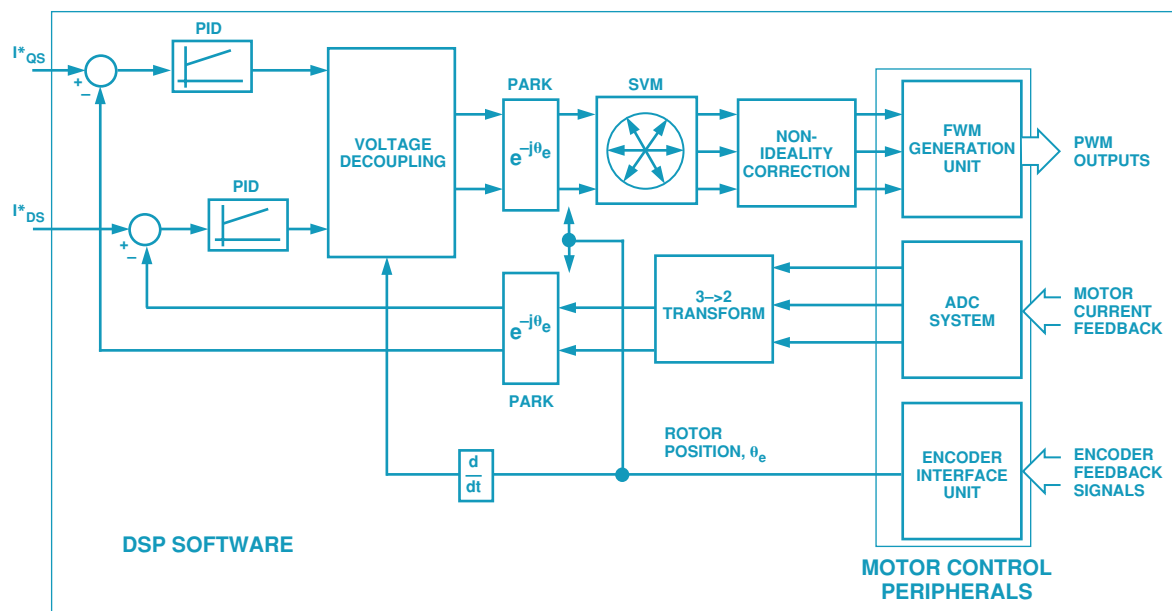


Figure 3. Configuration of typical control system for three-phase ac motor.

encoder output signals to produce a parallel digital word that represents the actual rotor position at all times. In this way, the DSP control software can simply read the actual rotor position whenever it is needed by the algorithm.

This is all very well, but there is an increasing class of cost-sensitive servo-motor drive applications with lower performance demands that can afford neither the cost nor the space requirements of the rotor position transducer. In these cases, the same motor control algorithms can be implemented with estimated rather than measured rotor position.

The DSP core is quite capable of computing rotor position using sophisticated rotor-position estimation algorithms, such as extended Kalman estimators that extract estimates of the rotor position from measurements of the motor voltages and currents. These estimators rely on the real-time computation of a sufficiently accurate model of the motor in the DSP. In general, these sensorless algorithms can be made to work as well as the sensor-based algorithms at medium-to-high speeds of rotation. But as the speed of the motor decreases, the extraction of reliable speed-dependent information from voltage and current measurements becomes more difficult. In general, sensorless motor control is applicable

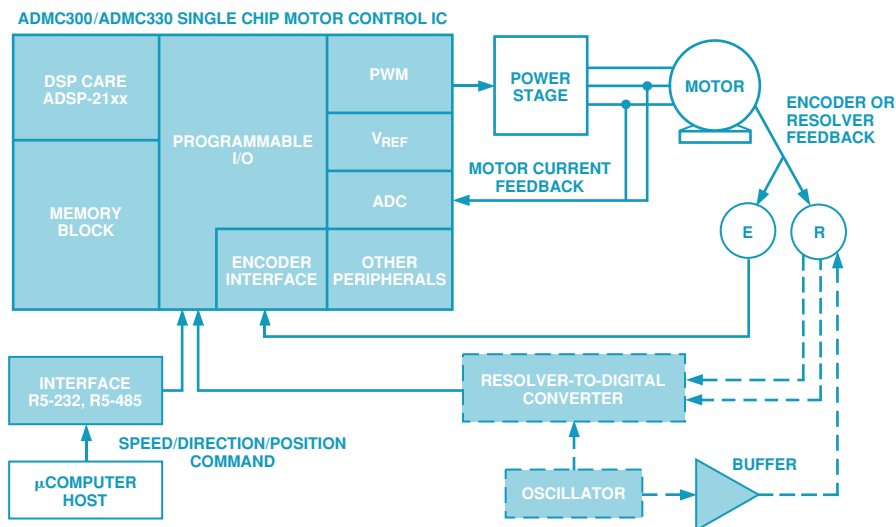
principally to applications such as compressors, fans, and pumps, where continuous operation at zero or low speeds is not required.

### Conclusions

Modern DSP-based control of three-phase ac motors continues to flourish in the market place, both in established industrial automation markets and in newer emerging markets in the home appliance, office automation and automotive markets. Efficient and cost-effective control of these machines requires an appropriate balance between hardware and software, so that time-critical tasks such as the generation of PWM signals or the real-time interface to rotor position transducers are managed by dedicated hardware units. On the other hand, the overall control algorithm and computation of new voltage commands for the motor are best handled in software using the fast computational capability of a DSP core. Implementing the control solution in software brings all the advantages of easy upgrading, repeatability, and maintainability, when compared with older hardware solutions. All motor-control solutions also require the integration of a suitable A/D conversion system for fast and accurate measurement of the feedback information from the motor. The resolution, conversion speed, and input sampling structure of the ADC system need to be strictly targeted to the requirements of specific applications.



## Mixed-Signal Motor Control Signal Chain



NOTE:  
SELECT THE BLUE SIGNAL CHAIN<sup>SM</sup> BLOCKS OR THE  
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Using Mixed-Signal Motor Control ICs



# Embedded Modems Enable Appliances to Communicate with Distant Hosts via the Internet

by Rick Blessington  
Software & Systems Technology Division\*

## INTRODUCTION

Today's smart appliances do much more than shut off the dryer when the clothes are dry or display a new photograph when one has been shot. For example: they provide status information indicating when a vending machine needs to be filled or a drop box emptied; they run remote diagnostics when needed, and automatically upgrade their settings and download software upgrades to stay current; they schedule and request maintenance to avoid malfunctions; they add intelligence to the appliances that harbor them.

Any equipment that does not require an embedded PC, but relies on data or fax to communicate with a remote host, is likely to require an embedded modem. Internet appliances designed solely to provide information via email or the Web need embedded modems to provide the communications link to the Internet. Set-top boxes for interactive cable and satellite television require embedded modems to communicate billing information, interactive programming, pay-per-view, and home shopping orders. Appliances and handheld computers (or PDAs) become much more useful when they can link to remote hosts.

The Handspring Visor™, for example, can maintain schedules and calendars, contact lists and telephone directories, expense logs and time sheets, stock portfolios, and sports team statistics. To be completely useful, however, the information must be both current and identical to the information in the user's computer, company database, and administrative assistant's office tools and paper files. With its Springboard modem, from card access, which uses an Analog Devices embedded modem chipset, the Visor can be connected to a telephone line and automatically update both itself and its user's host computer. In this way, the Visor becomes the accurate, timely, and functional information appliance its users need. Its embedded modem makes all of these capabilities possible by linking it to a remote host without loading the PDA, because of the Analog Devices DSP used in the embedded modem.

The Visor required its modem to have low power, small size, high reliability, standalone form factor, and ease of Internet interfacing. The resulting Springboard modem fits entirely inside the Visor package, operates from the Visor's existing batteries without significantly shortening their life, and automatically connects to

the Internet when connected to a telephone line. It makes the Visor an extension of its user's computer network.

## Embedded Modem Components

Embedded modems contain a data pump, DAA (data access arrangement), and modem code. They may or may not include a controller, Internet protocol stack, and SDRAM. The number of chips depends on the application requirements, including the need for any additional functions. They connect to telephone lines, and include all the necessary hardware and software.

A *data pump* includes a processor (DSP) that translates data to a standard protocol (fax or Internet), at a specific bit rate, such as V.32, V.34, V.90, employing *modem code*. A *DAA* provides the physical and software interface to a POTS (plain old telephone service) line. A *silicon DAA* performs this function without external codecs, relays, optocouplers, and transformers. An *Internet protocol (IP) stack* implements the Internet protocols (such as PPP, TCP, HTTP, POP3, FTP, etc.) on the modem's DSP. This permits file downloads, standard Web-page hosting, and email capability for the device to which the modem is *connected without the use of a PC, microcontroller, or other processor*. Thus the DSP executes both the modem code and the IP stack.

## Modem Architecture Trade-Offs

Embedded modems may be either controller-based (parallel) or operate without a controller. In both cases they need a fixed-point DSP data pump and DAA. The modem code can either run on the DSP data pump, or on a Pentium® or RISC processor (for host-based or software modems), or on a multifunction programmable DSP (such as an ADSP-218x). For comparison, modem architectures may be divided into two host-based classes (with and without on-board processing), and two standalone classes (microcontroller- and DSP-based). Their characteristics and advantages/disadvantages are compared in Table I.

The *controller-based designs* work without hosts, so they don't care about operating systems or whether the host has crashed. This standalone approach assures greater redundancy, since the modem operates independently of the host computer and its operating system. Their downside is they need a microcontroller and its memory, as well as DSP memory, to run the supervisory code. This entails additional parts count, real estate and power, and consequently added cost and risk. Also, their modem software is usually hard-coded and consequently not upgradeable.

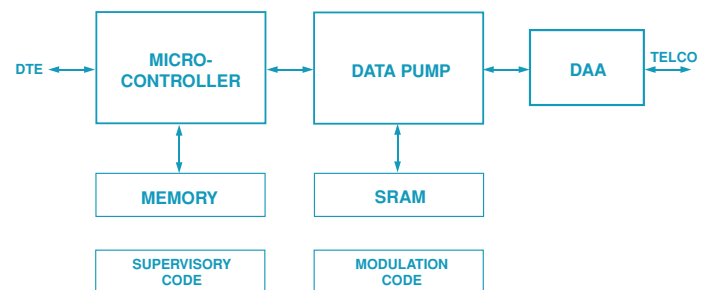


Figure 1. Controller-based modem.

\*For more details, contact willie.waldmann@analog.com or  
ajai.gambhir@analog.com.

**Table I. Modem Architecture Overview**

Type Trade-Offs (+ and -)	Controller-Based— Parallel	Controllerless—Serial (or Winmodem)	Software—Host-Based	Multifunction Programmable—DSP-Based
Requires Host	No	Yes	Yes	No
Redundancy	Best. Stays alive when host crashes.	None. Relies on host.	None. Relies on host.	Best. Stays alive when host crashes.
Upgradeability	None	Depends on host.	Least	Best
Cost	Most	Moderate	Lowest	Moderate
Downside(s)	Needs microcontroller with memory to run supervisory code.	Needs host to run supervisory code. Data pump still needs memory.	Requires more power. Limited to Pentium and Windows applications.	Ongoing price competition with host-PC pricing erosion.
Uniqueness	Operating-system neutral	Memory resides on host.	Software only. Supervisory code and DSP runs on host.	No host or operating system dependencies. Integrated controller and data pump.

Controllerless (software-controlled, or win-) modems, offer lower cost, real estate, and power since the memory resides on the PC and no microcontroller (nor memory for it) is needed. However, they require a PC to run the supervisory code, so these winmodems are heavily dependent on the PC operating system. Consequently, uptime of the PC host is important to their operation, and they are affected by the typical PC install/support issues. Their performance suffers when the host is heavily loaded with other jobs. They still require a data pump with memory. Code upgrades and diagnostics are dependent on the reliability of the PC host, with no redundancy. Software upgrades are limited by the modem's fixed amount of memory.

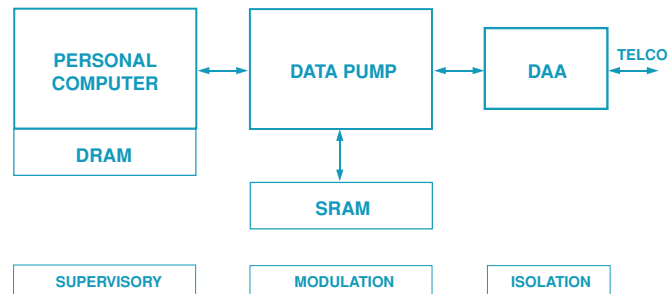


Figure 2. Controllerless modem (ISA and PCI).

Software, host-based or soft-modems operate without a DSP or microcontroller, since their supervisory and data pump code runs on the PC host. This approach has been promoted by PC processor manufacturers to take advantage of the “free” unused MIPS of the increasingly more powerful host processors, since the modems do not significantly load the host, but at the same time they help justify the need to upgrade to it. These modems are very low cost because they use the existing host. On the other hand, if the cost of upgrading to a sufficiently fast host to handle the modem functions is taken into consideration, the result will far surpass the cost of either a controller-based or controllerless design. Host-based modems are also heavily dependent on their host's reliability, as well as concurrency issues encountered when running many operations simultaneously. In addition, this approach typically limits the modem to communicating only Windows and Pentium applications, limiting the “free” MIPS (millions of instructions per second) on the host to particular functions. The power drain

and cost-per-MIPS for a Pentium is much higher than for a DSP-based design, so the power used by the board must be taken into account, even if the cost is not. The cost of modem IP must still be paid, so the concept of “free” is not accurate.

A multifunction DSP-based embedded modem incorporates a programmable DSP, such as an ADSP-218x. By integrating the controller, memory, and data pump on a single chip, real estate (board space), cost, and power are reduced. No separate microcontroller or associated memory is required. A software-based UART is used, further reducing the hardware cost, real estate, and power. The standalone design operates independently of the host and operating system, offering redundancy and remote software upgradeability via the included FLASH memory. The codec adds international capabilities, accommodating country-specific parameters. Three modulation speeds are possible, each using the same components but a different Internet protocol (IP): up to 14.4 kbps, up to 33.6 kbps and up to 56 kbps.

The Analog Devices programmable DSP-based embedded modems capture the advantages of all the above approaches with few of their disadvantages. Even as PC prices fall while host PC performance increases, embedded DSP MIPS will always remain less expensive, more reliable, and independent of host processing.

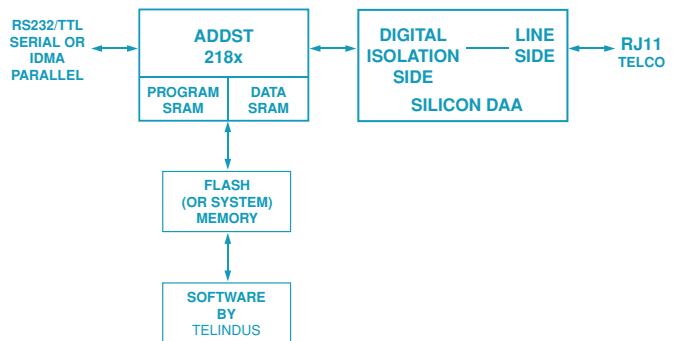


Figure 3. Multifunction DSP-based modem.

All of the alternatives, except the host-based design, have the disadvantage of facing competition with continuing PC host price erosion. As the PC host price decreases relative to that of the standalone modem, host-based modems become more cost effective. The trade-off between redundancy and cost, however, will continue.

### DAA Approaches

The DAA (data access arrangement) supports country-specific Call Progress and Caller ID, which must be specified for each country. Different DAA components are available to support worldwide operation of a subset of countries. The DAA handles TIP and RING telephone connections—and includes a second codec for nonpowered lines, such as leased lines and wireless. Multiple DAAs can be supported by a single DSP for use in multi-line applications.

The state-of-the-art international silicon DAA with integral codec eliminates the cost and real estate of transformers, optoisolators, relays, and hybrids. All of this is replaced with two small TSSOP packages that directly connect to the DSP, improving reliability and manufacturing ease while decreasing real estate and cost. The design improves performance, since the signals are digitally transmitted over the isolation barrier. The silicon DAA includes international support in a single design and supports both U.S. and international caller ID without relays, via software programmability, for different countries. No hardware modification is required. Advanced power management, caller ID, and *sleep* mode save power and offer green compliance, enabling a smaller power supply and longer battery life. Monitor output and microphone input support voice and handset applications.

Each modem design also supports legacy DAAs used for unpowered telephone line applications, such as wireless and leased lines.

### Software Development

Analog Devices' embedded modems include modem code supplied by Telindus. Product-specific software can be obtained from modem partners of Analog Devices. For example, one can automatically link the Handspring Visor to the Internet by adding a Springboard modem from Card Access. One can enable a Lavazza e-esspresso coffee machine to send and receive emails (to trigger maintenance checks and restocking visits, and display weather or traffic reports) by adding an Internet modem from Analog Devices that executes a TCP/IP stack from eDevice.

### Modem Reference Designs

The Analog Devices embedded modem development platform includes an ADSP-218x programmable DSP and a silicon DAA. It consumes under 200 mW maximum power at 3.3 V. No customer

code is required. The development platform includes modem software from ISO 9001-certified Analog Devices' technology partner Telindus. The board comes with connectors for EZ-ICE, JTAG, and RS-232 I/O for modification and testing of the AT command set and S registers.


### Embedded Modem Applications

The products that use embedded modems for communication include vending machines (which can communicate levels of inventory and when they need to be filled), kiosks, POS terminals, security and surveillance systems, games, and drop boxes that can communicate when they have shipments to be picked up. The ways in which the basic product communicates via these standalone modems are established by programming in relevant web content and communication data. The results for designers are products with such characteristics as built-in investment protection, appliances that “know” and communicate when they need to be serviced, fixed, filled, emptied, updated, or picked up. Products that use the Internet to provide customer information and communications can be located wherever needed. Industrial equipment can indicate when it needs to be serviced. Refrigerators can display recipes containing only the ingredients on their shelves.

Standalone embedded modems can reduce operating costs at the same time that they make possible new product categories with features to spur new sales. With new Internet-enabled power, these products can create new opportunities for e-commerce, e-service, and e-information vendors.

Standalone embedded modems offer complete and flexible design alternatives for worldwide communications in a variety of approaches. Each approach can be configured on as few as three chips, offers a choice of speeds, and can be implemented inexpensively with low power and real estate requirements. Embedded modems can bring the power of Internet information and communications to both new and installed devices and can add automatic software upgrades and remote diagnostics at the same time.

### For Further Information

For additional help, contact [systems.solutions@analog.com](mailto:systems.solutions@analog.com), or visit Analog Devices Software & Systems Technologies on the Web. Or contact Analog Devices' modem partners: Card Access and eDevice. 

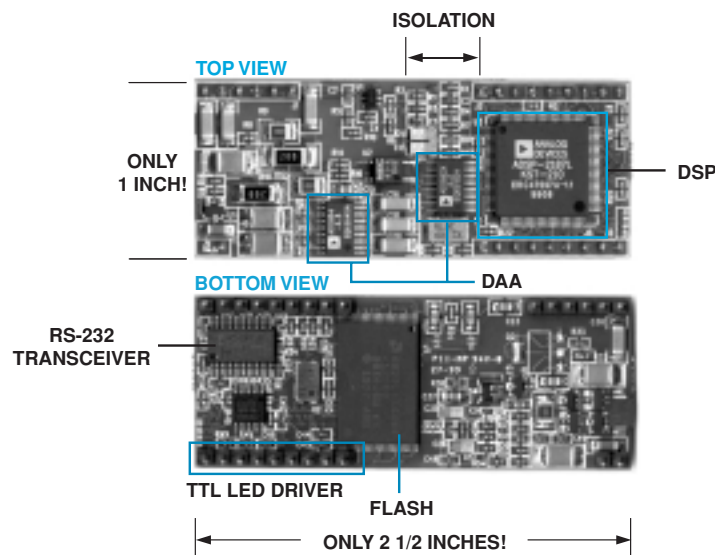


Figure 4. V.90 standalone embedded modem reference design.

# Adaptively Canceling Server Fan Noise

## Principles and Experiments with a Short Duct and the AD73522 dspConverter

by Paschal Minogue, Neil Rankin, Jim Ryan

### INTRODUCTION

In the past, when one thought of noise in the workplace, heavy industrial noise usually came to mind. Excessive noise of that type can be damaging to the health of the worker. Today, at a much lower level, though not as severe a health hazard in office environments, noise from equipment such as personal computers, workstations, servers, printers, fax machines, etc., can be distracting, impairing performance and productivity. In the case of personal computers, workstations and servers, the noise usually emanates from the disk drive and the cooling fans.

This article is about the problem of noise from server cooling fans, but the principles can be applied to other applications with similar features. Noise from server cooling fans can be annoying, especially when the server is located near the user. Usually, greater server computing power means higher power dissipation, calling for bigger/faster fans, which produce louder fan noise. With effective fan noise cancellation, bigger cooling fans could be used, permitting more power dissipation and a greater concentration of computer power in a given area.

### DESCRIPTION OF PROBLEM

Typically, server cooling-fan noise has both a random and a repetitive component. A spectrum plot of the fan noise of the Dell Poweredge 2200 server illustrates this (Figure 1). Also, the profile of the fan noise can change with time and conditions; for example, an obstruction close to the fan will affect its speed and thus the noise that it generates.

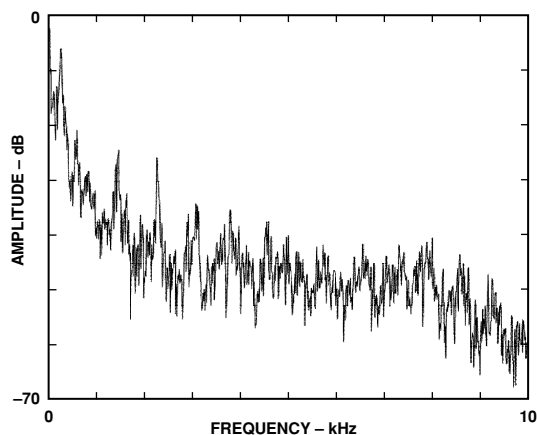


Figure 1. Profile of server fan noise.

### ONE SOLUTION

One solution is to confine the propagation of much of the fan noise to a duct, and then use *active noise control* (ANC) to reduce the strength of the fan noise leaving the duct [1].

A block diagram of a basic ANC system as applied to noise propagating inside a duct is illustrated in Figure 2. The noise propagating down the duct is sampled by the upstream reference microphone and adaptively altered in the electronic feed-forward path to produce the antinoise to minimize the acoustic energy at the downstream error microphone. However, the antinoise can also propagate upstream and can disrupt the action of the adaptive feedforward path, especially if the speaker is near the reference microphone (as is always the case in a short duct). To counteract this, electronic feedback is used to neutralize the acoustic feedback. This neutralization path is normally determined off-line, in the absence of the primary disturbance, and then fixed when the primary noise source is present. This is done because the primary noise is highly correlated with the antinoise.

There are many problems associated with short-duct noise cancellation [2, 3, 4]. Acoustic feedback from antinoise speaker to reference microphone is more pronounced; the number of acoustic modes increases exponentially; duct resonances can cause harmonic distortion; and the group delay through the analog-to-digital converters, processing unit, and digital-to-analog converters can become significant [5]. This paper concentrates on the latter problem in particular.

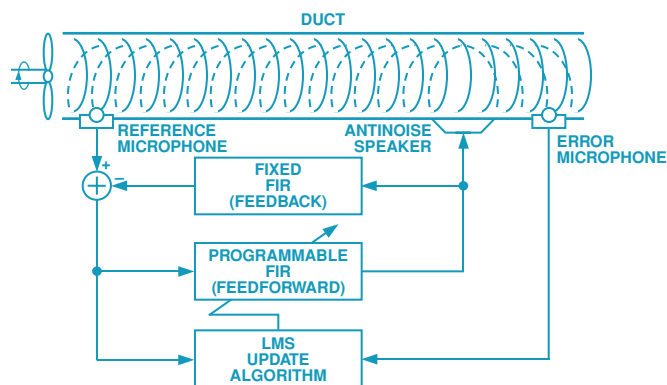


Figure 2. Basic duct ANC system.

### THE IMPORTANCE OF GROUP DELAY

To provide an unobtrusive and viable solution in terms of size and cost, the smaller the duct is made the better; ideally, it should fit inside the server box—which would result in a very short acoustic path. To maintain causal relationships, the delay through the entire (mostly electronic) feedforward path has to be less than or equal to the delay in the forward acoustic path if broadband primary noise is to be successfully cancelled.

$$\delta_{ff} \leq \delta_{ap} \quad (1)$$

where  $\delta_{ff}$  is the delay through the feedforward path and  $\delta_{ap}$  is the primary acoustic delay.

In cases where the secondary speaker is recessed into its own short duct, the feedforward path will also include the acoustic delay through this secondary duct.

$$\delta_{ff} = \delta_e + \delta_{as} \quad (2)$$

where  $\delta_e$  is the electronic part of the feedforward path and  $\delta_{as}$  is the acoustic delay in the secondary duct.

The electronic delay in the feedforward path consists of group delay through the microphone, anti-aliasing filter and A/D converter (ADC); processing delay (+ digital filter group delay) in the DSP; group delay through the D/A converter (DAC) and anti-imaging filter; and finally the delay through the secondary speaker.

$$\delta_e = \delta_{mic} + \delta_{adc} + \delta_{dsp} + \delta_{dac} + \delta_{spkr} \quad (3)$$

Therefore, from causality:

$$\delta_{mic} + \delta_{adc} + \delta_{dsp} + \delta_{dac} + \delta_{spkr} + \delta_{as} \leq \delta_{ap} \quad (4)$$

To minimize  $\delta_{ap}$ , and thereby the length of the duct,  $\delta_{ff}$  (and all its various components) should be made as small as possible. Let's assume that delays through the microphone, speaker and secondary duct path have already been minimized. Then, the remaining quantity to be minimized is  $\delta_{adc} + \delta_{dsp} + \delta_{dac}$ .

$\delta_{adc}$  can be minimized by using an oversampled ADC with low group-delay-decimation filtering;  $\delta_{dsp}$  can be minimized by using a DSP with sufficiently high-MIPS and an efficient instruction set;  $\delta_{dac}$  can be minimized by using an oversampled DAC with interpolation filtering having low group delay. The latter should be capable of being bypassed to further minimize the group delay.

Furthermore, the processor should use the most recent ADC sample as soon as it becomes available, and the DAC should use the latest DSP output result as soon as it becomes available. To achieve this, it must be possible to advance the timing of the DAC relative to the ADC in some fashion.

High-speed gain taps in parallel with the main processing path can help to ease the situation, especially in the case of practical short ducts where the noise can flank the acoustic path via the duct hardware itself.

Although a feedforward cancellation technique with a very low group delay is required to cancel the random component when using a relatively short duct, a feedback approach can be applied to cancel the repetitive component using an rpm sync signal as the reference input.

### ANC ARCHITECTURE

Less group delay through the cancellation system means that a shorter duct can be used, making the approach more feasible and acceptable. To achieve very low group delay, a heavily oversampled sigma-delta converter technique is employed at the *analog front-end* (AFE) section of the system. Furthermore, both an *analog gain tap* (AGT) and a *digital gain tap* (DGT) can be utilized to provide even lower group delay in the processing path.

With no high-speed gain taps, a 2-ADC/1-DAC configuration (Figure 3) can be used, as all the processing is done digitally and at a relatively low rate. In Figure 3, each conversion channel is shown with its sample-rate conversion in a separate block: a

decimator block in the case of the ADC channel and an interpolator block for the DAC channel.

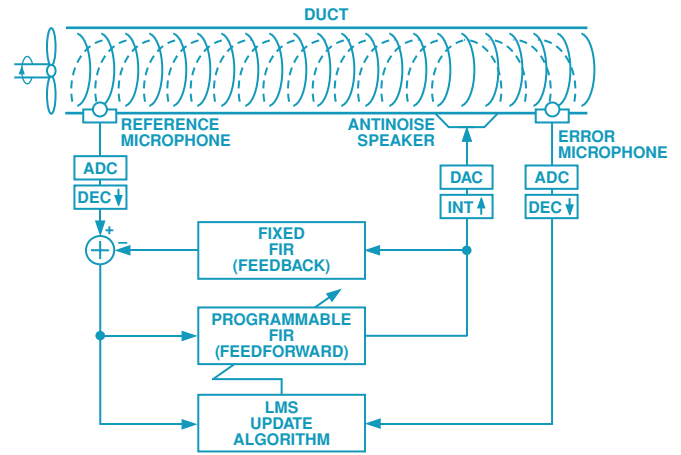


Figure 3. A 2-ADC/1-DAC configuration with no high-speed gain taps.

The introduction of gain taps is illustrated in Figure 4. Filters with gain taps can be thought of as just single-tap FIR filters. The feedforward tap is programmable and adapted during cancellation; the feedback tap is fixed and determined off-line.

Note that the DGTs act on the high-rate output of the ADC and their outputs are combined with the high-rate input to the DAC.

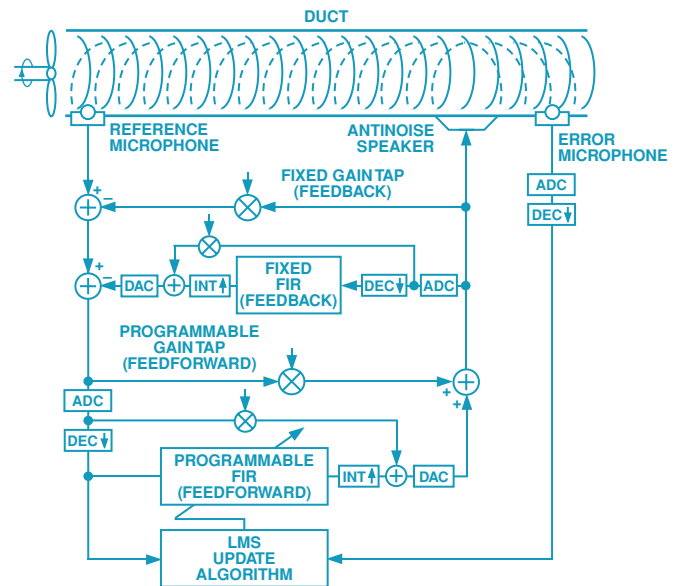


Figure 4. ANC system with high-speed analog and digital gain taps.

## ANC ALGORITHM

The standard filtered-x LMS (FXLMS) algorithm was used to update the ANC coefficient for the feedforward cancellation,

$$h_{k+1} = h_k + 2 \mu \times e_k \times x'_k \quad (5)$$

where  $x'_k$  is filtered by the secondary path model. Other adaptive algorithms have been suggested for improved performance on fixed-point DSPs [6].

The modeling for the secondary path and feedback neutralization path is done off-line; then fixed versions are used in the active-cancellation mode. In addition, each microphone input is processed through an adaptive dc tap, and a leakage component is optionally part of the feedforward-path coefficient update algorithm.

## ANC HARDWARE AND SOFTWARE REQUIREMENTS

The short-duct ANC hardware should include an AFE with at least two ADC channels and one DAC channel. The reference signal ADC and the antinoise DAC need to have inherently high sample rates and low group delay. The sampling timing of the antinoise DAC should be capable of being advanced relative to the sample timing of the reference ADC. The AFE should also have both high-speed analog and digital gain taps to provide an ultra-short delay path. The error-signal ADC also needs to be low in group delay, as its delay contributes to the delay through the secondary path as seen by the processor from the antinoise speaker to the error microphone. As this secondary path model has to be run by the processing block as well as the main feedforward path, it should be as short as possible. The main processing block should have as high a MIPS rate as possible (with an efficient instruction set) to reduce the delay, keeping within the general requirement for a low-cost solution. Finally, a single-package embodiment of the main signal conversion and processing functions should make the ANC solution more flexible yet cost-effective.

One such ANC solution with a single integrated circuit package can be obtained using the AD73522 dspConverter.

## AD73522 PRODUCT INFORMATION

The AD73522 (Figure 5) is a single-device *dspConverter* incorporating a dual analog front end (AFE), a microcomputer optimized for digital signal processing (DSP) and a *flash*-based boot memory for the DSP.

The AFE section features two 16-bit ADC channels and two 16-bit DAC channels. Each channel provides 77-dB signal-to-noise ratio over a voiceband signal bandwidth with a maximum sample rate of 64 ksp/s. It also features an input-to-output gain network in both the analog (AGT) and digital (DGT) domains. The low group-delay characteristic (typically 25  $\mu$ s per ADC channel and 50  $\mu$ s per DAC channel) of the AFE makes it suitable for single- or multi-channel active control applications. The ADC and DAC channels feature programmable input/output gains with ranges of 38 dB and 21 dB respectively. An on-chip reference voltage is included to allow single-supply operation.

The AD73522's 52-MIPS DSP engine combines the *ADSP-2100 family* base architecture (three computational units, data address generators and a program sequencer) with two serial ports, a 16-bit internal DMA port, a byte DMA port, a programmable timer, flag I/O, extensive interrupt capabilities, and on-chip program- and data memory.

The AD73522-80 integrates 80 Kbytes of on-chip memory configured as 16K 24-bit words of program RAM and 16K 16-bit words of data RAM. The AD73522-40 integrates 40K bytes of on-chip memory configured as 8K words of 24-bit program RAM and 16-bit data RAM.

Both devices feature a Flash memory array of 64 Kbytes (512 Kbits) connected to the DSP's byte-wide DMA port (BDMA). This allows nonvolatile storage of the DSP's boot code and system data parameters. The AD73522 runs from a 3.3-V power supply. Power-down circuitry is inherent to meet the low-power needs of battery-operated portable equipment.

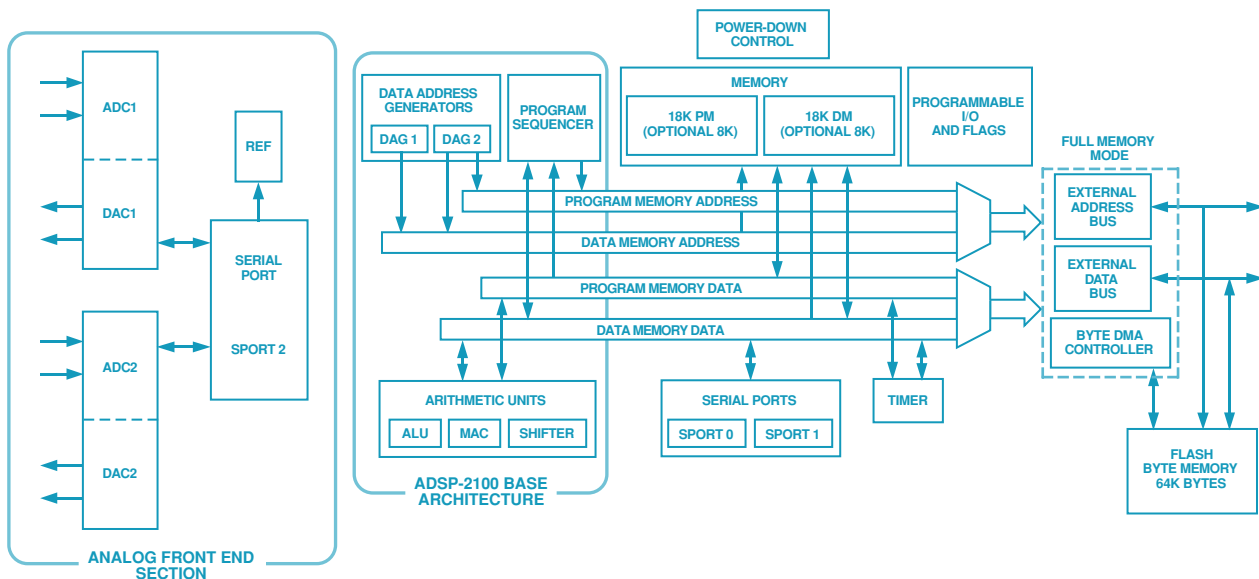


Figure 5. AD73522 dspConverter.

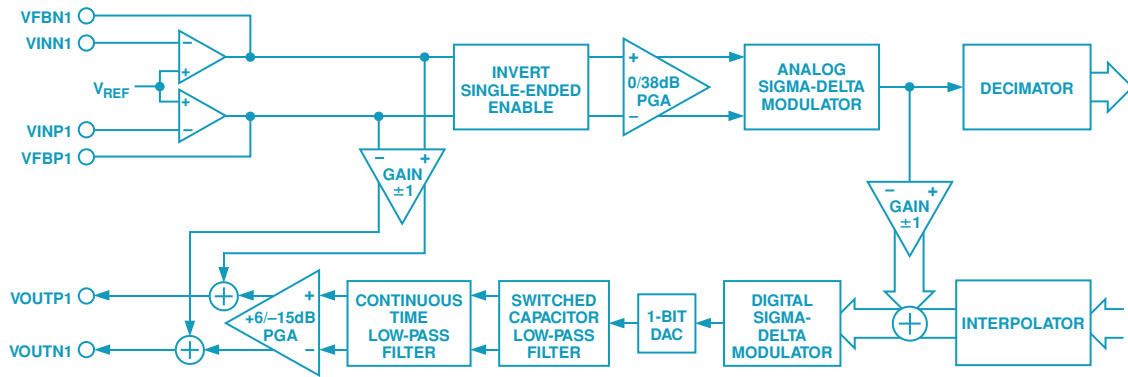


Figure 6. Analog front-end subsection of the AD73522 dspConverter.

### SIGMA-DELTA ADC AND DAC ARCHITECTURE

The conversion technique adopted in the AFE is of the sigma-delta type. An analog sigma-delta modulator is used in the ADC channel and a digital sigma-delta modulator is employed in the DAC channel. A sigma-delta modulator is a heavily oversampled system that uses a low-resolution converter in a noise-shaping loop. The quantization noise of the low-resolution, high-speed converter is inherently high-pass filtered and “shaped” out of band. The output of the modulator or noise shaper is then low-pass filtered to reduce the sample rate and remove the out-of-band noise.

The AFE conversion channels used in the AD73522 are shown in Figure 6. The ADC section consists of an analog second-order,  $32\times$  to  $256\times$  oversampling, 1-bit sigma-delta modulator, followed by a digital sinc-cubed decimator (divide-by-32 to divide-by-256). The DAC section contains a digital sinc-cubed interpolator, a digital, second-order,  $32\times$  to  $256\times$  oversampling, 1-bit sigma-delta modulator, followed by an analog third-order switched-capacitor LPF and a second-order continuous-time LPF.

The group delay through the ADC channel is dominated by the group delay through the sinc-cubed decimator and is given by the following relationship:

$$\delta_{dec} = Order \times \frac{M-1}{2} \times \delta_{ds} \quad (6)$$

where *Order* is the order of the decimator (= 3), *M* is the decimation factor (= 32 for 64-kSPS output sample rate) and  $\delta_{ds}$  is the decimation sample interval (=  $1/2.048E6$  s)

$$\begin{aligned} \Rightarrow \delta_{dec} &= 3 \times \frac{32-1}{2} \times \frac{1}{2.048E6} \\ \Rightarrow \delta_{dec} &= 22.7 \mu\text{s} \end{aligned} \quad (7)$$

for a 64-kSPS output sample rate.

The group delay through the DAC channel is primarily determined by the group delay through the sinc-cubed interpolator and the group delay through the third-order switched-capacitor LPF. The inherent group delay through the interpolator is identical to that through the decimator and equals  $22.7 \mu\text{s}$  for 64-kSPS input sample rate. However, the interpolator can be optionally bypassed to

avoid this inherent group delay at the expense of reduced out-of-band rejection.

The z-transform of both the sinc-cubed decimator and interpolator is given by:

$$\left[ \frac{1 - z^{-M}}{1 - z^{-1}} \right]^3 \quad (8)$$

The group delay through the analog section of the DAC is approximately  $22.7 \mu\text{s}$ .

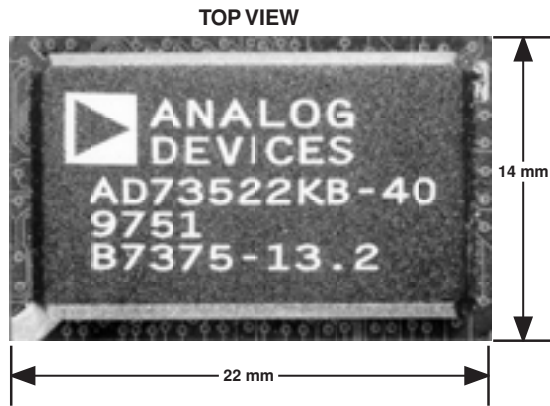
Notice that with sample rates of only 8 kSPS the inherent group delays through both the decimator and interpolator increase to  $186.8 \mu\text{s}$ . Therefore, it is very important to run the converters at as high a rate as possible to reduce the inherent group delay.

The AFE features high-speed analog and digital feedforward paths from ADC input to DAC output via the AGT and DGT respectively. The AGT is configured as a differential amplifier with gain programmable from  $-1$  to  $+1$  in 32 steps and a separate *mute* control. The gain increment per step is 0.0625. The group delay through the AGT feedforward path is only  $0.5 \mu\text{s}$ . The DGT is a programmable gain block whose input is tapped off from the bit-stream output of the ADC’s analog sigma-delta modulator. This single-bit input is used to add or subtract the digital gain tap setting, a 16-bit programmable value, to the output of the DAC’s interpolator. The group delay through the DGT feedforward path is only  $25 \mu\text{s}$ .

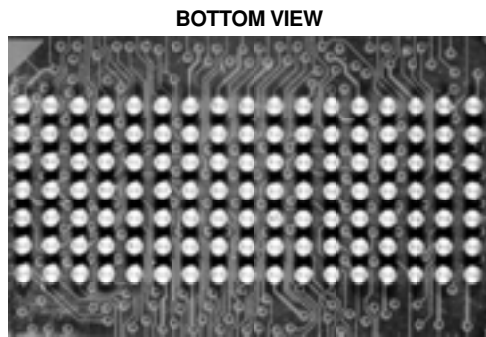
The loading of the DAC is normally internally synchronized with the unloading of the ADC data in each sampling interval. However, this DAC load position can be advanced in time by up to  $15 \mu\text{s}$  in  $0.5\text{-}\mu\text{s}$  steps. This facility can be used to further minimize the feedforward delay from analog input to analog output via the DSP.

### AD73522 PACKAGING

The three main processing elements (AFE, DSP and Flash memory) are combined in a single package to give a cost-effective, self-contained solution. This single package is a 119-ball plastic ball grid array (PBGA), as shown in Figure 7. It measures  $14 \text{ mm} \times 22 \text{ mm} \times 2.1 \text{ mm}$ , and the solder balls are arranged in a  $7 \times 17$  array with a 1.27-mm (50 mil) pitch.



a.



7 ROWS × 17 COLUMNS OF SOLDER BALLS

b.

Figure 7. AD73522 plastic ball grid array (PBGA) packaging.

### AD73522 EVALUATION BOARD

The AD73522 dspConverter evaluation board (Figures 8 and 9) combines all of the front-end analog signal conditioning with a

user-friendly programming platform that allows quick and easy development. The board, interfacing to the serial port of a PC, comes with Windows® 95-compatible interface software that allows the transfer of data to and from all memory, including the Flash sections. All of the dspConverter pins are available at the output connectors. The board has an EZ-ICE® connector for advanced software development. Other features include a microphone with conditioning circuitry on one input channel and speaker amplifiers on the output channels.

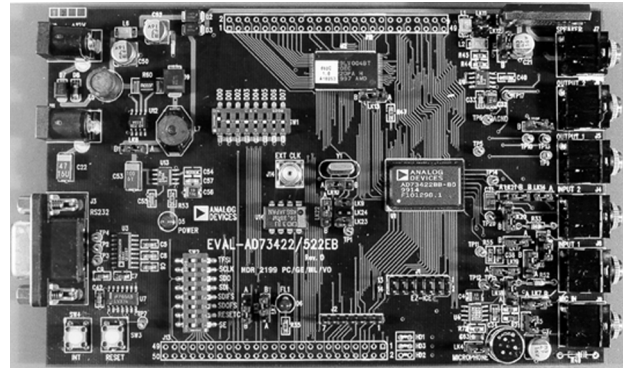


Figure 8. AD73522 dspConverter evaluation board.

### EXPERIMENTAL SETUP

The experimental setup (Figure 10) consists of a server box (containing just a fan and power supply), a plastic duct (with reference and error microphones and secondary loudspeaker), and the AD73522 evaluation board. The server fan was 5 inches (about 13 cm) in diameter. The T-shaped duct and the speaker measured 6 inches (about 15 cm) in diameter. The duct length was adjustable down to a minimum of 12 inches (30.5 cm).

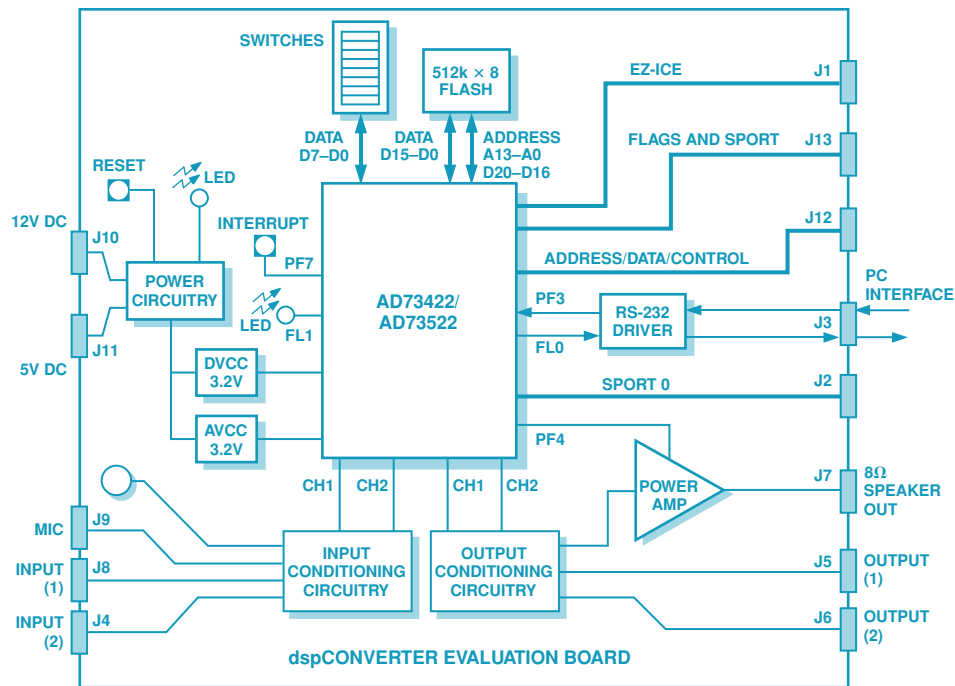


Figure 9. Block diagram of the AD73522 dspConverter evaluation board.

Windows is a registered trademark of Microsoft Corporation.  
EZ-ICE is a registered trademark of Analog Devices, Inc.



During experimentation, the AD73522 evaluation board was hooked up to a PC for debug. Also, internal variables were written out to unused DAC channels for monitoring. Initially, the system was set up using a primary speaker instead of the actual server fan to allow testing with programmable tones and broadband signals.

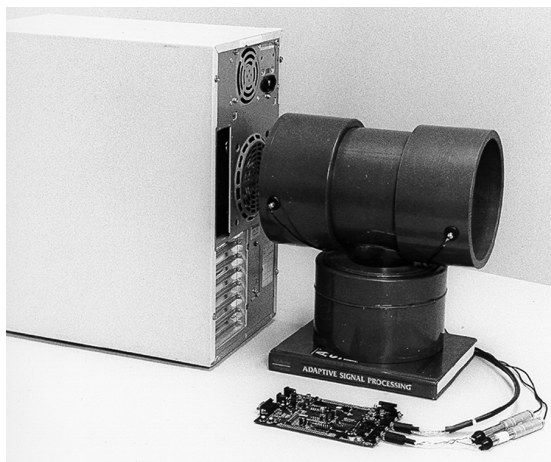
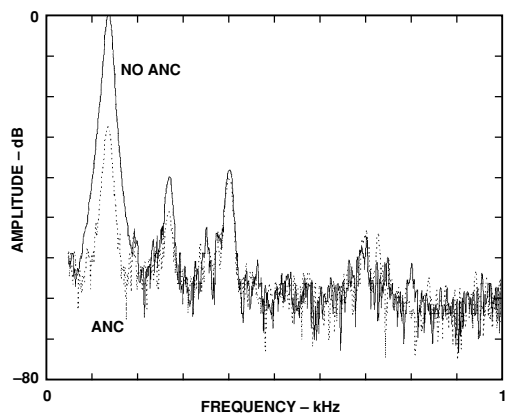


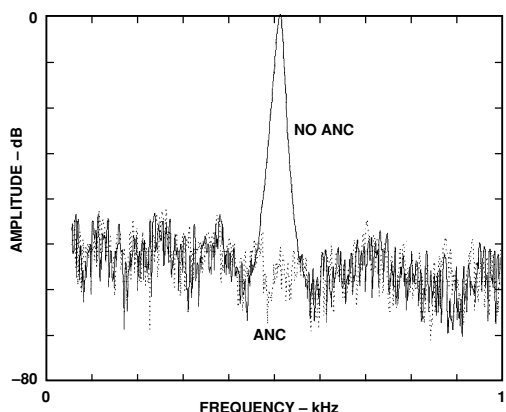
Figure 10. Server fan experimental setup.

## RESULTS

The performance of the experimental setup with a single-tone disturbance from the primary speaker is shown in Figure 11. The main tone is reduced by a factor of 30 dB. When the primary speaker delivers a broadband disturbance, the reduction factor is about 20 dB, as illustrated in Figure 12.



a. 136-Hz performance, with and without ANC.



b. 510-Hz performance, with and without ANC.

Figure 11. Noise spectra with single-tone disturbance.

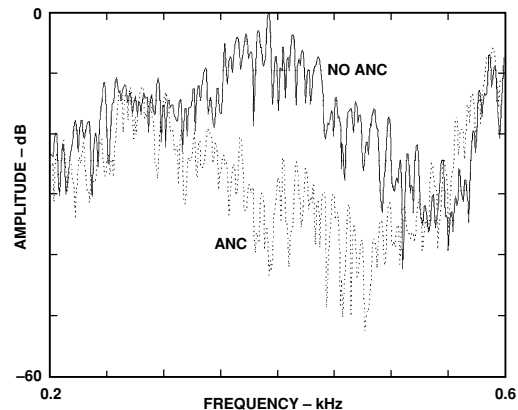


Figure 12. Performance with broadband disturbance.

## CONCLUSIONS

An approach combining an analog gain tap (AGT) and digital gain tap (DGT) allows the use of sigma-delta techniques in low-group-delay ANC applications. A single-package embodiment combining analog and digital functions, like the AD73522 dspConverter, should provide an ANC solution that is both flexible and cost-effective.

## ACKNOWLEDGEMENTS

Dell Computer, Limerick, Ireland, for the Poweredge 2200 server box used in the experimental setup.

Cork Institute of Technology, Cork, Ireland, for the duct construction used in the experimental setup and a kick-start in the code development.

The Institute of Sound and Vibration Research (ISVR) and Digisonix, Inc., for an excellent introduction to active noise control.

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# Fan-Speed Control Techniques in PCs

by David Hanrahan

Analog Devices offers a comprehensive set of hardware-monitoring products for use in desktop and notebook PCs and servers. Intelligent systems-monitoring devices make possible sophisticated fan speed control techniques to provide adequate cooling and maintain optimal thermal performance in the system. During the past year a family of products has been developed, including the ADM1029 Dual PWM Fan Controller and Temperature Monitor, the ADM1026, and ADM1030/ADM1031 Complete, ACPI-Compliant, Dual-Channel  $\pm 1^\circ\text{C}$  Remote Thermal Monitor with integrated fan controller for one or two independent fans. They build on the core technology used in the ADM102x PC System Monitor product portfolio (see also *Analog Dialogue* 33-1 and 33-4). Providing fan speed control based on the temperatures measured within the system, these new products offer more complete thermal-management solutions. We discuss here the need for this level of sophisticated control and the issues inherent in providing it.

## BACKGROUND

As the new millennium dawns, processors are achieving speeds of 1 GHz and more. Their impressive improvements in speed and system performance are accompanied by the generation of increasing amounts of heat within the machines that use them. The need to safely dissipate this heat, along with moves in the computing industry to develop “Green PCs” and user-friendly machines (as Internet appliances become mainstream), has driven the need for, and development of, more sophisticated cooling and thermal management techniques.

PCs have also begun to become smaller and less conventional in size and shape—as can be seen in any of the latest concept PCs or slim-line notebooks on the market. Rigid power dissipation specifications such as “Mobile Power Guidelines ’99” (Ref. 1) stipulate how much heat may be safely dissipated through a notebook’s keyboard without causing user discomfort. Any excess heat must be channeled out from the system by other means, such as convection along heat pipes and a heat-spreader plate, or the use of a fan to move air through the system. Clearly, what is needed is an intelligent, effective approach to thermal management that can be universally adopted. Various industry groups have assembled to address these and other issues, and have developed standards such as ACPI (advanced configuration and power interface) for *notebook PCs* and IPMI (intelligent platform management interface) for *server* management.

## INDUSTRY STANDARDS

The development of the new thermal management/speed control products was motivated by the *ACPI* and *IPMI* standards.

The *Advanced Configuration and Power Interface*—ACPI (Ref 2) was defined by Intel, Microsoft, and Toshiba primarily to define and implement power management within notebook PCs.

**Power management** (Ref. 2) is defined as “Mechanisms in hardware and software to minimize system power consumption, manage system thermal limits, and maximize system battery life. Power management involves trade-offs among system speed, noise, battery life, processing speed, and ac power consumption.”

Consider first a notebook-PC user who types trip reports while flying across oceans or continents. Which characteristic is more important, maximum CPU performance or increased battery life? In such a simple word-processor application, where the time between a user’s keystrokes is almost an eternity in CPU clock cycles, maximum CPU performance is nowhere near as critical as continuous availability of power. So CPU performance can be traded off against increased battery life. On the other hand, consider the user who wants to watch the latest James Bond movie in full-motion, full-screen, mind-numbing sound and brightness, on digital versatile disk (DVD). It is critical that the system operates at a level of performance to decode the software fast enough, without dropping picture or audio frames. In this situation CPU performance cannot be compromised. Therefore, heat generation will be at top levels, and attention to thermal management will be of paramount importance to obtain top performance without impairing reliability. Enter ACPI.

What then is ACPI? ACPI is a specification that describes the interface between components and how they behave. It is not a purely software or hardware specification since it describes how the BIOS software, OS software, and system hardware should interact.

The ACPI specification outlines two distinct methods of system cooling: *passive cooling* and *active cooling*. Passive cooling relies on the operating-system (OS) and/or basic input/output-system (BIOS) software to reduce CPU power consumption in order to reduce the heat dissipation of the machine. How can this be achieved? By making intelligent decisions such as entering *suspend* mode if no keystroke or other user interaction has been detected after a specified time. Or if the system is performing some intensive calculations, such as 3D processing, and is becoming dangerously hot, the BIOS could decide to throttle (slow down) the CPU clock. This would reduce the thermal output from the machine, but at the cost of overall system performance. What is the benefit of this *passive*-type cooling? Its distinct advantage is that the system power requirement is lowered silently (fan operation is not required) in order to decrease the system temperature, but this does limit performance.

So, what about active cooling? In an actively cooled system, the OS or BIOS software takes a direct action, such as turning on a CPU mounted fan, to cool down the processor. It has the advantage that the increased airflow over the CPU’s metal slug or heat-sink allows the heat to be drawn out of the CPU relatively quickly. In a passively cooled system, CPU throttling alone will prevent further heating of the CPU, but the thermal resistance of the heat sink to “still air” can be quite large, meaning that the heat sink would dissipate the heat to the air quite slowly, delaying a return to full-speed processing. Thus, a system employing active cooling can combine maximum CPU performance and faster heat dissipation. However, operation of the fan introduces acoustic noise into the system’s environment and draws more power. Which cooling technique is better? In reality, it depends on the application; a

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versatile machine will use both techniques to handle differing circumstances. ACPI outlines the cooling techniques in terms of two different modes: *performance mode* and *silent mode*. The two modes are compared in Figures 1 and 2.

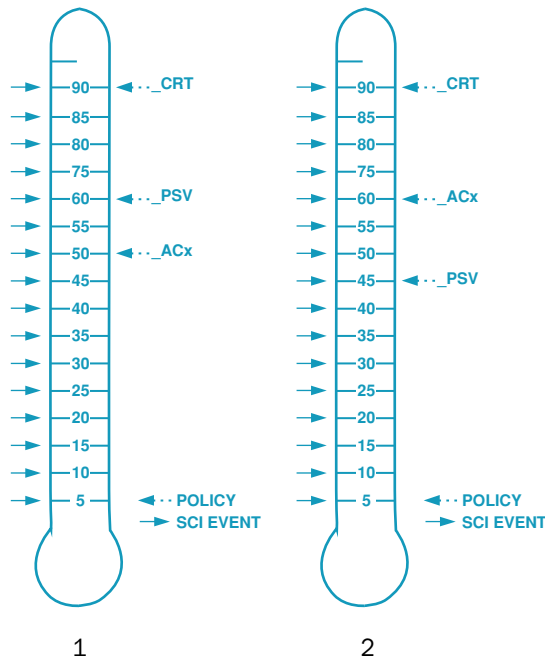


Figure 1. Performance preferred. Active mode (\_ACx, fan on) is entered at 50°, passive mode (\_PSV, throttle back) is entered at 60°. Shutdown occurs at the critical temperature (\_CRT) 90°. Fan speed may increase at levels above ACx. Figure 2. Silence and battery economy preferred. Passive mode is first entered at 45°, and fan is not turned on until 60°.

Figures 1 and 2 are examples of temperature scales that illustrate the respective trade-offs between performance, fan acoustic noise, and power consumption/dissipation. In order for a system-management device to be ACPI-compliant, it should be capable of signaling limit crossings at, say, 5°C intervals, or *SCI* (system-control interrupt) events, that a new *out-of-limit* temperature increment has occurred. These events provide a mechanism by which the OS can track the system temperature and make informed decisions as to whether to throttle the CPU clock, increase/decrease the speed of the cooling fan, or take more drastic action. Once the temperature exceeds the \_CRT (critical temperature) policy setting, the system will be shut down as a fail-safe to protect the CPU. The other two policy settings shown in Figures 1 and 2 are \_PSV (passive cooling, or CPU clock throttling) and \_ACx (active cooling, when the fan switches on).

In Figure 1 (performance mode), the cooling fan is switched on at 50°C. Should the temperature continue to rise beyond 60°C, clock throttling is initiated. This behavior will maximize system performance, since the system is only being slowed down at a higher temperature. In Figure 2 (silent mode), the CPU clock is first throttled at 45°C. If the temperature continues to rise, a cooling fan may be switched on at 60°C. This reduced-performance mode will also tend to increase battery life, since throttling back the clock reduces power consumption.

Figure 3 shows how the limits of the temperature measurement bands track the temperature measurement. Each limit crossing produces an interrupt.

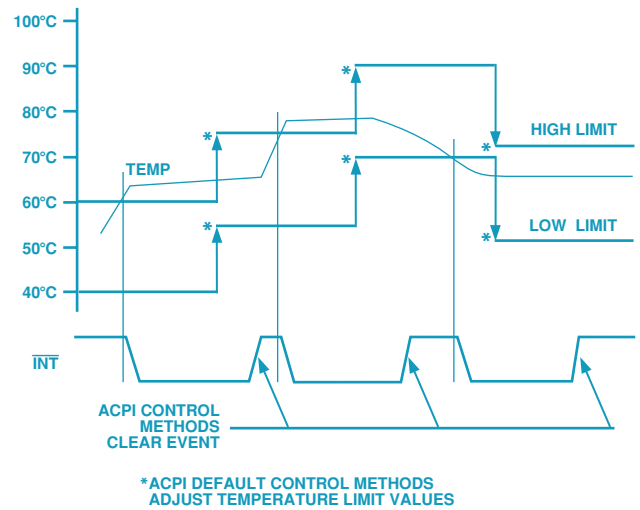


Figure 3. Tracking temperature changes by moving limits and generating interrupts.

The *intelligent platform management interface* (IPMI) specification (Ref. 3) brings similar thermal management features to servers. IPMI is aimed at reducing the *total cost of ownership* (TCO) of a server by monitoring the critical “heartbeat” parameters of the system: temperature, voltages, fan speeds, and PSUs (power-supply units). Another motivation for IPMI is the need for interoperability between servers, to facilitate communication between baseboards and chassis. IPMI is based on the use of a 5-V I<sup>2</sup>C bus, with messages sent in packet form. Further information on IPMI is available from the Intel website at <<http://developer.intel.com/design/servers/ipmi/>>

All members of the Analog Devices Temperature and Systems-Monitoring (TSM) family are ACPI- and IPMI-compliant.

### TEMPERATURE MONITORING

The prerequisite for intelligent fan-speed control within PCs is the ability to measure both system and processor temperature accurately. The temperature monitoring technique used has been the subject of many articles (for example, see *Analog Dialogue* 33-4) and will only be briefly visited here. All Analog Devices system-monitoring devices use a temperature monitoring technique known as *thermal diode monitoring* (TDM). The technique makes use of the fact that the forward voltage of a diode-connected transistor, operated at a constant current, exhibits a negative temperature coefficient, about -2 mV/°C. Since the absolute value of V<sub>BE</sub> varies from device to device, this feature by itself is unsuitable for use in mass-produced devices because each one would require individual calibration. In the TDM technique, two different currents are successively passed through the transistor, and the voltage change is measured. The temperature is related to the difference in V<sub>BE</sub> by:

$$\Delta V_{BE} = kT/q \times \ln(N)$$

- where:  $k$  = Boltzmann’s constant
- $q$  = electron charge magnitude
- $T$  = absolute temperature in kelvins
- $N$  = ratio of the two currents

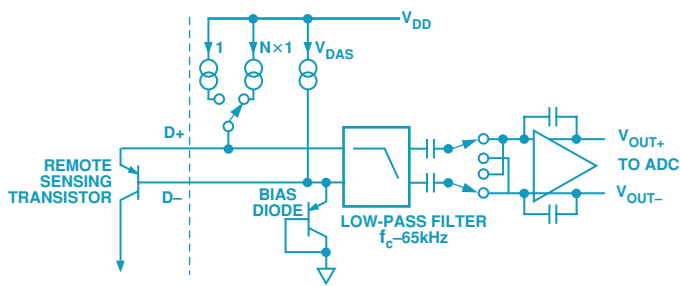


Figure 4. Basic TDM signal-conditioning circuit.

In any CPU, the most relevant temperature is that of the “hot spot” on the die. All other temperatures in the system (including the heat-sink temperature) will lag the rise in this temperature. For this reason, practically every CPU manufactured since the early Intel Pentium® II processors contains a strategically located transistor on its die for thermal monitoring. It gives a true, essentially instantaneous, profile of die temperature. Figure 5 shows temperature profiles in a system repeatedly entering and waking up from *suspend* mode. It compares the temperatures measured by a thermistor attached to the CPU’s heat sink and by the substrate thermal diode. In the short interval for the actual die temperature to change back and forth by about 13°, the heat sink thermistor cannot sense any change.

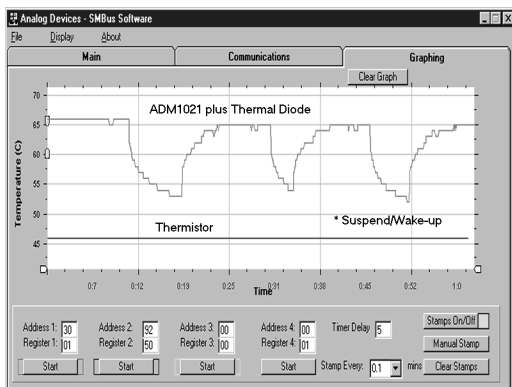


Figure 5. Comparison of temperatures measured by a heat sink thermistor and by TDM during a series of entrances to and exits from *suspend* mode.

## TEMPERATURE TO FAN CONTROL

With an accurate temperature monitoring method established, effective fan control can be implemented! The technique, in general, is to use TDM to measure temperature, with the sensing transistor either integrated on-chip or externally placed as near as possible to a hot-spot, and setting the fan speed at a level that will ensure sufficient heat transport at that temperature. Various operating parameters of the control loop will be programmable, such as minimum speed, fan start-up temperature, speed versus temperature slope, and turn on/off hysteresis. The speed control approaches described will include on-off, continuous (“linear”), and pulsewidth modulation (PWM).

**Fan-control methods:** Historically, the range of approaches to fan-speed control in PCs is from simple on-off control to closed-loop temperature-to-fan speed control.

*Two-step control:* This was the earliest form of fan-speed control adopted in PCs. The BIOS would measure the system temperature (originally using a thermistor in close proximity to the CPU) and decide whether to switch a cooling fan fully on or off. Later, PCs used more accurate TDM-based temperature monitors to implement the same two-step fan control.

*Three-step control:* The BIOS or Operating System again measures the temperature using a thermistor or thermal diode and, based on software settings, decides whether to turn the fan fully on, fully off, or set it to run at half-speed.

*Linear fan-speed control:* This more recent method of fan-speed control is also known as *voltage control*. The BIOS or OS reads the temperature from the TDM measurement circuit and writes back a byte to an on-chip DAC, to set the output voltage in order to control the speed of the fan. An example of an IC fan controller of this type is the ADM1022, which has an 8-bit DAC on-chip with an output voltage range of 0 V to 2.5 V. It works with an external buffer amplifier having appropriate design ratings for the chosen fan. The ADM1022 also contains default automatic hardware trip points that cause the fan to be driven at full-speed in the event that its TDM circuit detects an over-temperature condition. The debut of these types of devices signified the emergence of *automatic fan-speed control*, where some of the decision-making is moved from OS software to system-monitoring hardware.

*Pulsewidth-modulation fan-speed control:* In ADI’s systems-monitoring product line, these PWM types are the most recent fan control products. The BIOS or OS can read the temperature from the TDM device and control the speed of the cooling fan by adjusting the PWM duty cycle applied to it.

It is worth noting that all of the above methods of fan-speed control rely on CPU or host intervention to read the temperature from the TDM device over the 2-wire System Management Bus. The thermal management software executed by the CPU must then decide what the fan speed should be and write back a value to a register on the system’s monitor IC to set the appropriate fan speed.

An obvious next step in the evolution of fan-speed control is to implement an *automatic fan-speed control loop*, which could behave independently of software and run the fan at its optimum speed for a given chip temperature. There are many benefits to such closed-loop speed control.

Once the system’s monitoring device has been initialized (by loading limit registers with required parameters), the control loop is then completely independent of software, and the IC can react to temperature changes without host intervention. This feature is especially desirable when a catastrophic system failure occurs, from which the system is unable to recover. If the PC crashes, the power management software in the OS is no longer executing, which results in loss of thermal management! If the PC cannot read the temperature being measured (since the PC has crashed), it cannot be expected to set the correct fan speed to provide the required level of cooling.

The other tangible benefit of a closed-loop implementation is that it will operate the fan at the optimum speed for any given temperature. This means that both acoustic noise and power consumption are reduced. Running a fan at full speed maximizes both power consumption and acoustic noise. If the fan speed can

be managed effectively through loop optimization, running only as fast as needed for a given temperature, power drain and audible fan noise are both reduced. This is an absolutely critical requirement in battery-powered notebook PC applications where every milliamperere of current, or *milliamp-second of charge*, is a precious commodity.

### AUTOMATIC FAN-SPEED CONTROL LOOP

Here's how one might implement an automatic fan-speed control loop, which will measure temperature using TDM techniques and set the fan speed appropriately as a function of temperature. Programmable parameters allow more complete control of the loop. The first register value to be programmed is  $T_{MIN}$ . This is the temperature (corresponding to  $ACx$ ) at which the fan will first switch on, and where fan speed control will begin. Speed is momentarily set at maximum to get the fan going, then returned to the minimum speed setting (see Figure 6). The parameter that allows control of the slope of the temperature-to-fan speed function is the range from  $T_{MAX}$  to  $T_{MIN}$ , or  $T_{RANGE}$ . The programmed values for  $T_{MIN}$  and  $T_{RANGE}$  define the temperature at which the fan will reach maximum speed, i.e.,  $T_{MAX} = T_{MIN} + T_{RANGE}$ . Programmed temperature range is selectable: 5°C, 10°C, 20°C, 40°C, and 80°C. In order to avoid rapid cycling on and off in the vicinity of  $T_{MIN}$ , *hysteresis* is used to establish a temperature below  $T_{MIN}$ , at which the fan is turned off. The amount of hysteresis that can be programmed into the loop is 1°C to 15°C. This fan control loop can be supervised by OS software over the SMBus and the PC can decide to override the control loop at any time.

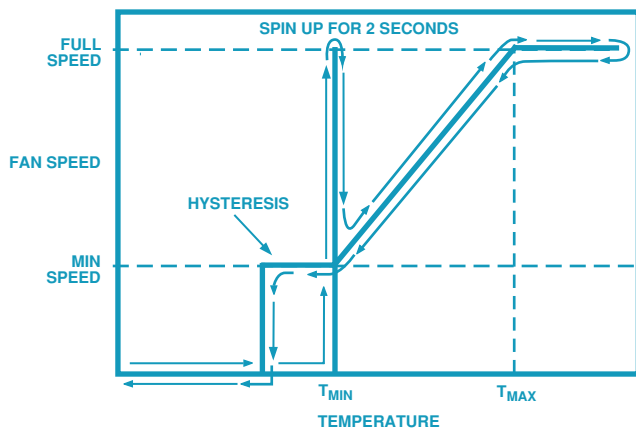


Figure 6. Fan speed programmed as an automatic function of temperature.

### PWM vs. LINEAR FAN-SPEED CONTROL

One might ask why pulsewidth modulation is desirable if linear fan-speed control is already in widespread use.

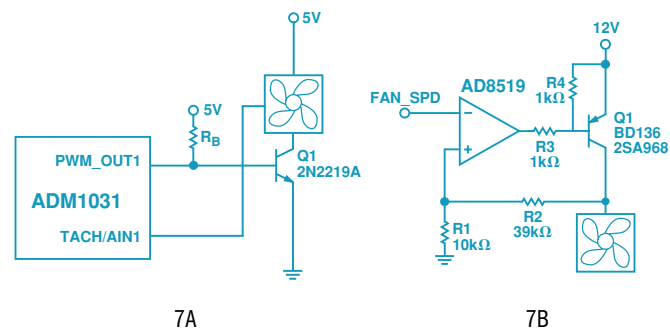
Consider a 12-V fan being driven using linear fan-speed control. As the voltage applied to the fan is slowly increased from 0 V to about 8 V, the fan will start to spin. As the voltage to the fan is

further increased, the fan speed will increase until it runs at maximum speed when driven with 12 V. Thus the 12-V fan has an effective operating window between 8 V and 12 V, with a range of only 4 V available for use in speed control.

The situation becomes even worse with the 5-V fan that would be used with a notebook PC. The fan will not start until the applied voltage is about 4 V. Above 4 V, the fan will tend to spin near full speed, so there is little available speed control between 4 V and 5 V. Thus, linear fan-speed control is unsuitable for controlling most types of 5 V fans.

With pulsewidth modulation, maximum voltage is applied for controlled intervals (the *duty cycle* of a square wave, typically at 30 Hz to 100 Hz). As this duty cycle, or ratio of high time to low time, is varied, the speed of the fan will change.

At these frequencies, clean tach (tachometer) pulses are received from the fan, allowing reliable fan-speed measurement. As drive frequencies go higher, there are problems with insufficient tach pulses for accurate measurement, then acoustic noise, and finally electrical spikes corrupting the tach signal. Therefore, most PWM applications use low frequency excitation to drive the fan. The external PWM drive circuitry is quite simple. It can be accomplished with a single external transistor or MOSFET to drive the fan (Figure 7). The linear fan-speed-control equivalent, driven by an analog speed voltage, requires an op amp, a pass transistor, and a pair of resistors to set the op amp gain.



Figures 7A and 7B. PWM drive circuit compared with a linear drive circuit.

How is the fan speed measured? A 3-wire fan has a tach output that usually outputs 1, 2, or 4 tach pulses per revolution, depending on the fan model. This digital tach signal is then directly applied to the tach input on the systems-monitoring device. The tach pulses are not counted—because a fan runs relatively slowly, and it would take an appreciable amount of time to accumulate a large number of tach pulses for a reliable fan speed measurement. Instead, the tach pulses are used to gate an on-chip oscillator running at 22.5 kHz through to a counter (see Figure 8). In effect, the tach *period* is being measured to determine fan speed. A high count in the tach value register indicates a fan running at low speed (and vice versa). A limit register is used to detect sticking or stalled fans.

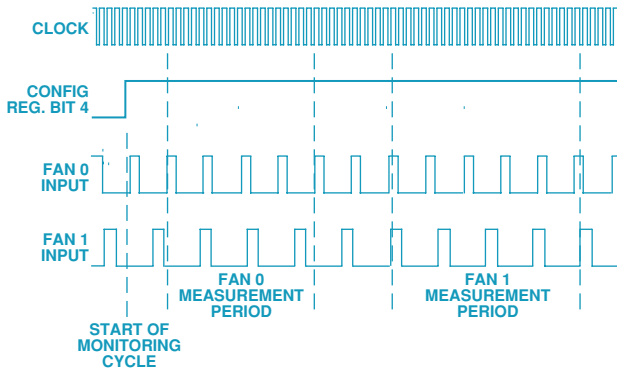


Figure 8. Fan-speed measurement.

What other issues are there with fan-speed control?

When controlling a fan using PWM, the minimum duty cycle for reliable continuous fan operation is about 33%. However, a fan will not start up at 33% duty cycle because there is not enough power available to overcome its inertia. As noted in the discussion of Figure 6, the solution to this problem is to spin the fan up for two seconds on start-up. If the fan needs to be run at its minimum speed, the PWM duty cycle may then be reduced to 33% after the fan has spun up, and it is protected from stalling by the hysteresis.

#### FAN STALLS AND FAN FAILURES

Nevertheless, the possibility can arise that a fan may stall at some time while used in a system. Causes may include a fan operating too slowly, or dust build-up preventing it from spinning. For this reason, the Analog Devices systems monitors have an on-chip mechanism based on the fan's tach output to detect and restart a stalled fan. If no tach pulses are being received, the value in the Tach Value register will exceed the limit in the Tach Limit Register and an error flag will be set. This will cause the controller

to attempt to restart the fan by trying to spin it up for two seconds. If the fan continues to fail, for up to five attempted restarts, a catastrophic fan failure is acknowledged to exist, and a FAN\_FAULT pin will assert to warn the system that a fan has failed. In two-fan dual-controller systems, the second fan can be spun up to full speed to try to compensate for the loss in airflow due to the failure of the first fan.

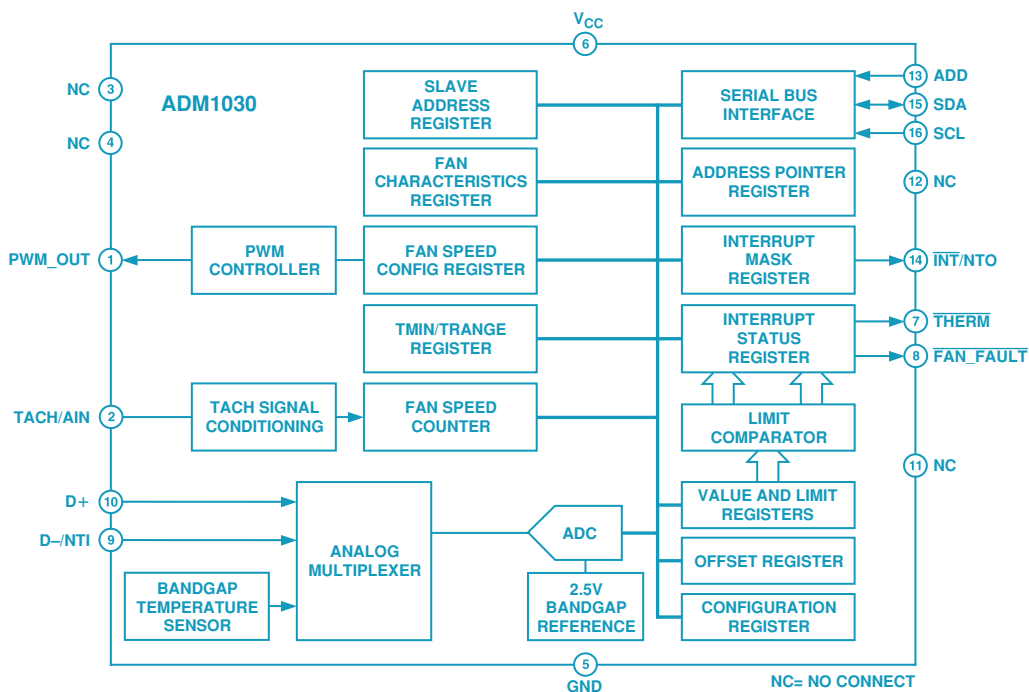
#### SUMMARY

Superior thermal-management solutions continue to be developed and offered to the computing industry by Analog Devices. The techniques developed for the ADM1029, ADM1030/ADM1031, and ADM1026 take thermal management within PCs to a new level. These devices are packed with features such as temperature monitoring, automatic temperature control in hardware, fan-speed measurement, support for backup and redundant fans, *fan-present* and *fan-fault* detection, programmable PWM frequency, and duty cycle. As power guidelines become more stringent, and PCs run significantly hotter, more sophisticated temperature-measurement and fan-speed-control techniques are being developed to manage the systems of the future more effectively.

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2. *Advanced Configuration and Power Interface Specification*, Revision 1.0b, Intel Corporation, Microsoft Corporation, Toshiba Corp. <http://www.teleport.com/~acpi/DOWNLOADS/ACPIspec10b.pdf>
3. *Intelligent Platform Management Interface: "What is IPMI?"* Intel Corporation. <http://developer.intel.com/design/servers/ipmi/ipmi.htm>

## ADM1030 Functional Block Diagram



# Finding the Needle in a Haystack:

## Measuring small differential voltages in the presence of large common-mode voltages

by Scott Wayne

### INTRODUCTION

In applications such as motor control, power-supply current monitoring, and battery cell-voltage monitoring, a small differential voltage must be sensed in the presence of a high common-mode voltage. Some of these applications require galvanic isolation, others do not. Some applications use analog control, others use digital control. Four cases of such measurements will be considered, each requiring unique considerations. They are:

- 1) galvanic isolation with analog output;
- 2) galvanic isolation with digital output;
- 3) no galvanic isolation, analog output;
- 4) no galvanic isolation, digital output.

### Differential Signals Versus Common-Mode Signals

Figure 1 shows the input of a measurement system.  $V_{DIFF}$  represents the *differential voltage*, the signal of interest.  $V_{CM}$  represents the *common-mode voltage*, which contains no useful information about the measurement and could in fact reduce the measurement accuracy. The common-mode voltage could be an implicit part of the measurement system, as in a battery cell-voltage monitoring application, or it could be created by a fault condition where the sensor accidentally comes in contact with a high voltage. In either case, that voltage is unwanted, and it is the job of the measurement system to reject it, while responding to the differential-mode voltage.

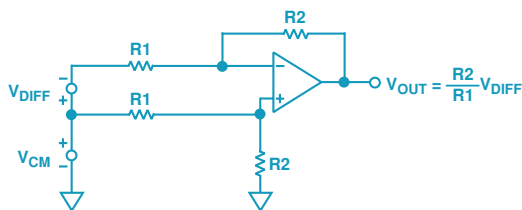


Figure 1. Measurement system with differential and common-mode voltages.

### Common-Mode Rejection (CMR)

The measurement system has both a differential-mode gain and a common-mode gain. The differential-mode gain is usually greater than or equal to one, while the common-mode gain is ideally zero. Resistor mismatches cause the dc gain from the inverting input to differ slightly from that of the noninverting input. This, in turn, results in a dc common-mode gain that is nonzero. If the differential

gain is  $G = \frac{R_2}{R_1}$ , the common-mode gain will be

$\frac{\%mismatch}{100} \times \frac{G}{G+1}$ . The *common-mode rejection ratio* (CMRR) is the differential-mode gain divided by the common-mode gain, or  $\frac{100}{\%mismatch} \times (G+1)$ . The logarithmic equivalent (CMR—in dB), is  $20 \log_{10} \left[ \frac{100}{\%mismatch} \times (G+1) \right]$ .

In real-world applications, external interference sources abound. Pickup will be coupled from the ac power line (50/60 Hz and its harmonics), from equipment switching on and off, and from radio-frequency transmission sources. This type of interference is induced equally into both differential inputs, and therefore appears as a common-mode signal. So, in addition to high dc CMR, instrumentation amplifiers also require high ac CMR, especially at line frequencies and their harmonics. DC common-mode errors are mostly a function of resistor mismatch. In contrast, ac common-mode errors are a function of differences in phase shifts or time delays between the inverting and noninverting inputs. These can be minimized by using well-matched high-speed components, and they can be trimmed with a capacitor. Alternatively, in low-frequency applications, output filtering can be used if necessary. While dc common-mode errors can usually be removed through calibration or trimming. AC common-mode errors, which can reduce the resolution of the measurement, are generally of greater concern. All Analog Devices instrumentation amplifiers are fully specified for both dc and low-frequency ac common-mode rejection.

### Galvanic Isolation

Some applications require that there be no direct electrical connection between the sensor and the system electronics. These applications require galvanic isolation in order to protect the sensor, the system, or both. The system electronics may need to be protected from high voltages at the sensor. Or, in applications requiring intrinsic safety, the sensor excitation and power circuitry may need to be isolated to prevent sparks or the ignition of explosive gases that could be caused by a fault condition. In medical applications, such as electrocardiograms (ECG), protection is required in both directions. The patient must be protected from accidental electric shock. If the patient's heart stops beating, the ECG machine must be protected from the very high voltages applied to the patient by emergency use of a defibrillator in an attempt to restore the heartbeat.

Galvanic isolation is also used to break ground loops where even a small resistance between two system grounds may produce an unacceptably high potential. This could occur in precision conversion systems where milliamperes of current flowing through a few hundredths of an ohm could create hundreds of microvolts of ground error, which could limit the resolution of the measurement. Or it might occur in industrial installations where thousands of amperes of current could create hundreds of volts of ground error and a potentially hazardous situation.

Galvanic isolation may use magnetic fields (transformers), electric fields (capacitors), or light (opto-isolators). Each method has its own advantages and disadvantages. For all types, though, isolated power supplies (or batteries) are usually necessary for powering the floating side of the isolator. This can easily be combined with signal isolation in isolators that use transformer isolation barriers. Other methods may require separate transformer-coupled dc-to-dc converters, which increase cost.

## High Impedance Versus Galvanic Isolation

Many applications need the ability to sense a small differential voltage in the presence of a high common-mode voltage, but do not require the intrinsic safety or the ability to break ground loops that are provided by galvanic isolation. These applications require a high-CMR amplifier that can accept high common-mode voltage. This type of amplifier, sometimes called a “poor man’s isolation amplifier,” isolates the sensor from the system with a high impedance, rather than with a galvanic isolation barrier. While not isolation in the true sense, it can serve the same purpose in some applications at much lower cost. In addition, a dc-to-dc converter is not required, since the whole system is powered from the same power supply.

Figure 2 shows the AD629, a high-common-mode-voltage difference amplifier that was designed for these types of applications. It seems simple enough. It’s “just” an op amp and five resistors. Can’t users “roll their own?” Yes, but the resistors would have to be matched to better than 0.01% and would have to track to better than 3 ppm/°C. Resistor self-heating would degrade dc CMR, while capacitive strays would degrade ac CMR. Performance, size, and cost would all be sacrificed compared to what could be obtained in an 8-lead DIP or SOIC.

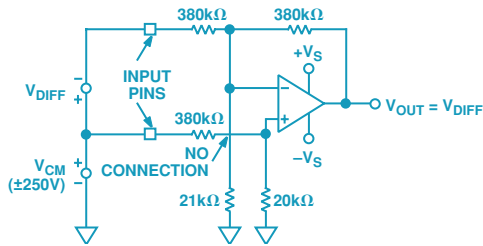


Figure 2. AD629 High-common-mode-voltage-difference amplifier.

Applications such as simple industrial process-control loops with analog inputs and outputs that require galvanic isolation could use the AD202/AD204. These are complete isolation amplifiers with galvanic isolation between the input and output stages. Transformer coupling means that they can also provide isolated power to the input stage, eliminating the need for an external dc-to-dc converter. The AD202/AD204 provide an uncommitted op amp for input signal conditioning, have CMR of 130 dB at a gain of 100, and 2000-V-peak CMV isolation. Figure 3 shows an AD202 circuit\* to measure a  $\pm 5$ -V full-scale signal riding on a common-mode voltage of up to 2000 V. For applications that require isolated bridge excitation, cold-junction compensation, linearization, and other signal-conditioning functions, the 3B, 5B, 6B, and 7B series provide a family of complete, well-isolated signal conditioners.

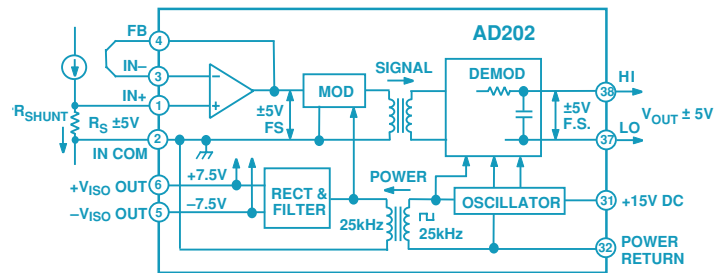


Figure 3. AD202/AD204 used in application requiring galvanic isolation and analog outputs.

Some industrial sensor applications require galvanic isolation, combined with the digital output of a smart sensor. Digital isolation, rather than analog isolation, could be used more cost-effectively but an external dc-to-dc converter is required. An example of this sort of application is in motor control, where a

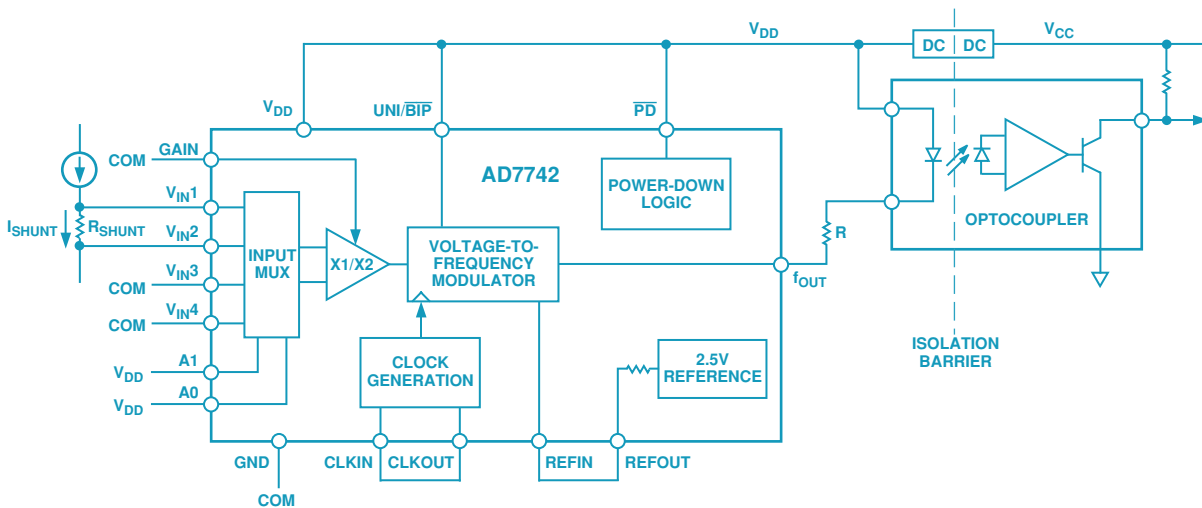


Figure 4. AD7742 used in application requiring galvanic isolation and digital outputs.

\*These Figures are illustrative examples; they are not detailed schematics of tested applications. Please consult product data sheets for more information. You will also find the online seminar notes, Practical Analog Design Techniques, and the book, *Practical Design Techniques for Sensor Signal Conditioning* (available from ADI), to be useful sources of design information. Use extreme caution when working with high-voltage circuits.



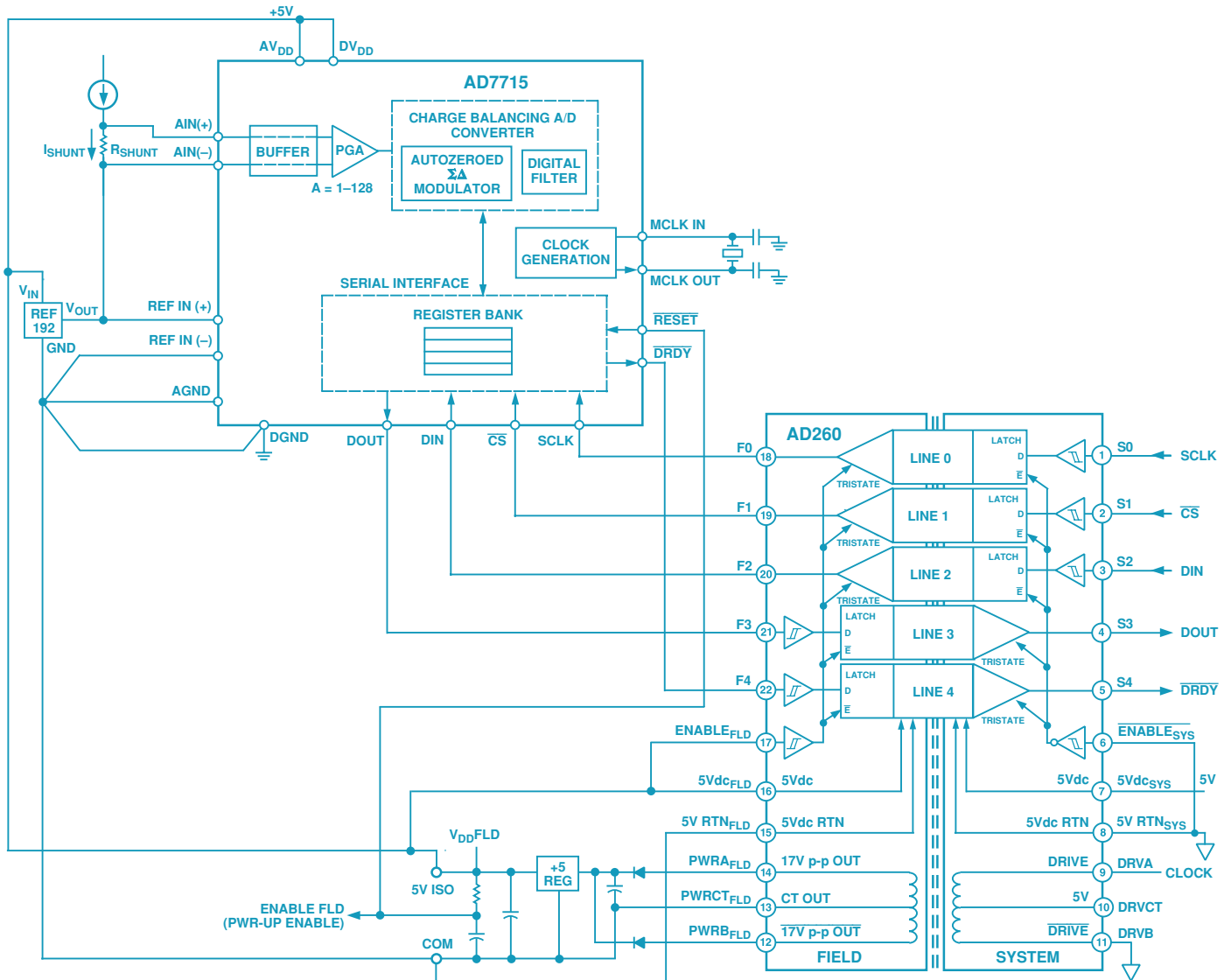


Figure 5. AD7715/AD260 used in application requiring galvanic isolation and digital outputs.

fault condition in the motor could destroy the control electronics. The AD7742 synchronous voltage-to-frequency converter could be used, together with an opto-coupler and a dc-to-dc converter, as shown in Figure 4. A remote AD7742 can be interfaced with a system microprocessor or microcontroller to complete the A/D conversion. For stand-alone applications the serial-output AD7715 analog front end, a 16-bit sigma-delta A/D converter, could be used, but it has five digital lines to isolate, rather than the single digital output from the V/F converter. However, instead of five opto-couplers and a dc-to-dc converter, an AD260 five-channel high-speed logic isolator with its own on-board transformer could be used. Figure 5 shows the AD7715 and AD260.

When galvanic isolation is not required, the situation becomes simpler. An example of this type of application is in battery cell voltage monitoring. An AD629 is used both to measure the voltage of an individual cell, and to reject the common-mode voltage provided by the stack of series-connected cells. No dc-to-dc converter is required, since the high impedance of the resistance

network protects the inputs of the op amp, even though its power supply voltage is much lower than the common-mode voltage. Figure 6 shows the AD629 measuring the voltage of a 1.2-V cell that is part of a 120-V battery.

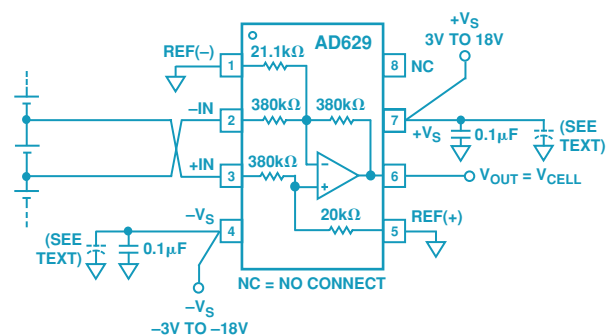


Figure 6. AD629 used in analog application where galvanic isolation is not required.

Finally, there are applications that do not require galvanic isolation, but where digital outputs are desired. An example of this application is supply-current monitoring of a microprocessor-controlled power supply. Here the AD629 is used with an AD7887 12-bit ADC. The AD629 provides the signal conditioning and

common-mode rejection, while the AD7887 provides the digital output. Again, no dc-to-dc converter is required because of the high input impedance and common-mode attenuation of the AD629. Figure 7 shows the AD629/AD7887 in a power-supply current monitoring application. ▶

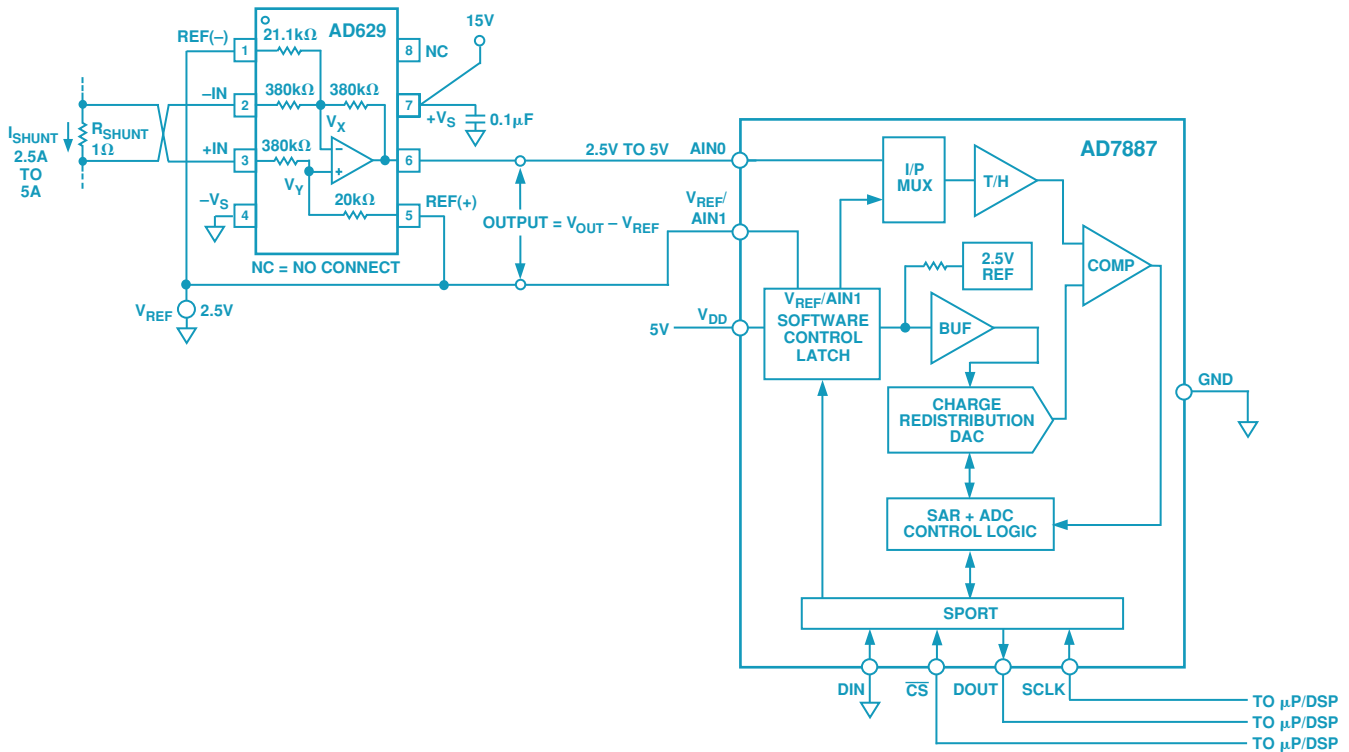
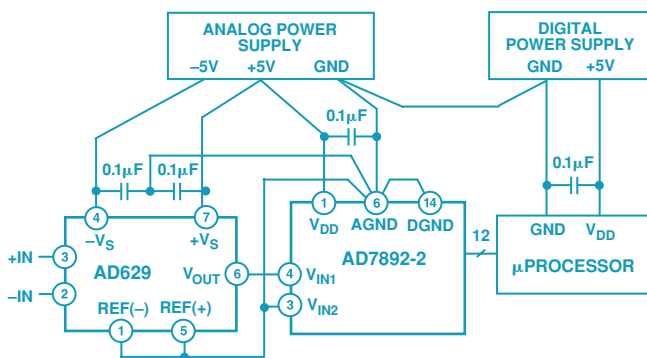
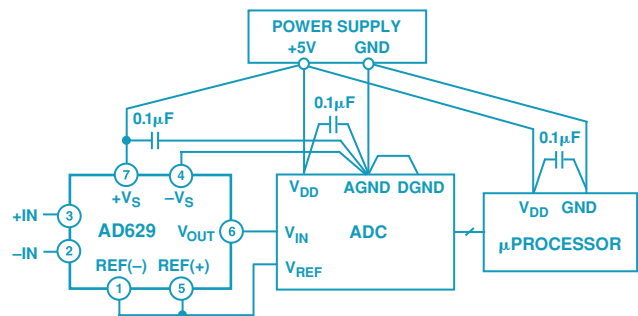


Figure 7. AD629/AD7887 used in digital application where galvanic isolation is not required.

## Optimal Grounding Practice



Optimal Grounding Practice for a Bipolar Supply Environment with Separate Analog and Digital Supplies



Optimal Grounding Practice in a Single Supply Environment

# Demystifying Auto-Zero Amplifiers—Part 1

**They essentially eliminate offset, drift, and 1/f noise. How do they work? Is there a downside?**

by Eric Nolan

## INTRODUCTION

Whenever the subject of auto-zero or chopper-stabilized amplifiers comes up, the inevitable first question is “How do they really work?” Beyond curiosity about the devices’ inner workings, the real question in most engineers’ minds is, perhaps, “The dc precision looks incredible, but what kind of weird behavior am I going to have to live with if I use one of these in my circuit; and how can I design around the problems?” Part 1 of this article will attempt to answer both questions. In Part 2, to appear in the next issue, some very popular and timely applications will be mentioned to illustrate the significant advantages, as well as some of the drawbacks, of these parts.

## Chopper Amplifiers—How They Work

The first chopper amplifiers were invented more than 50 years ago to combat the drift of dc amplifiers by converting the dc voltage to an ac signal. Initial implementations used switched ac coupling of the input signal and synchronous demodulation of the ac signal to re-establish the dc signal at the output. These amplifiers had limited bandwidth and required post-filtering to remove the large ripple voltages generated by the chopping action.

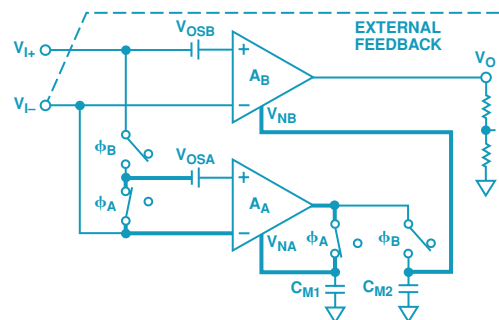
Chopper-stabilized amplifiers solved the bandwidth limitations by using the chopper amplifier to stabilize a conventional wide-band amplifier that remained in the signal path\*. Early chopper-stabilized designs were only capable of inverting operation, since the stabilizing amplifier’s output was connected directly to the non-inverting input of the wide-band differential amplifier. Modern IC “chopper” amplifiers actually employ an auto-zero approach using a two-or-more-stage composite amplifier structure similar to the chopper-stabilized scheme. The difference is that the stabilizing amplifier signals are connected to the wide-band or main amplifier through an additional “nulling” input terminal, rather than one of the differential inputs. Higher-frequency signals bypass the nulling stage by direct connection to the main amplifier or through the use of feed-forward techniques, maintaining a stable zero in wide-bandwidth operation.

This technique thus combines dc stability and good frequency response with the accessibility of both inverting and noninverting configurations. However, it may produce interfering signals consisting of high levels of digital switching “noise” that limit the usefulness of the wider available bandwidth. It also causes intermodulation distortion (IMD), which looks like aliasing between the clock signal and the input signal, producing error signals at the sum and difference frequencies. More about that later.

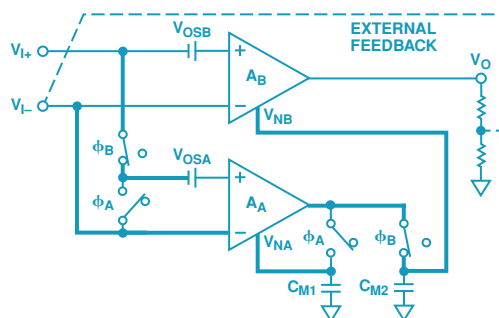
## Auto-Zero Amplifier Principle

Auto-zero amplifiers typically operate in two phases per clock cycle, illustrated in Figures 1a and 1b. The simplified circuit shows a nulling amplifier ( $A_A$ ), a main (wide-band) amplifier ( $A_B$ ), storage capacitors ( $C_{M1}$  and  $C_{M2}$ ), and switches for the inputs and storage capacitors. The combined amplifier is shown in a typical op-amp gain configuration.

In *Phase A*, the auto-zero phase (Figure 1a), the input signal is applied to the main amplifier ( $A_B$ ) alone; the main amplifier’s nulling input is supplied by the voltage stored on capacitor  $C_{M2}$ ; and the nulling amplifier ( $A_A$ ) auto-zeros itself, applying its nulling voltage to  $C_{M1}$ . In *Phase B*, with its nulling voltage furnished by  $C_{M1}$ , the nulling amplifier amplifies the input difference voltage applied to the main amplifier and applies the amplified voltage to the nulling input of the main amplifier and  $C_{M2}$ .



a. Auto-Zero Phase A: null amplifier nulls its own offset.



b. Output Phase B: null amplifier nulls the main amplifier offset.

Figure 1. Switch settings in the auto-zero amplifier.

Both amplifiers use the trimmable op-amp model (Figure 2), with differential inputs and an offset-trim input.

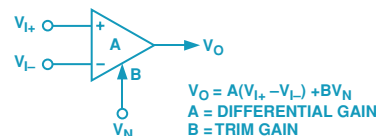


Figure 2. Trimmable op-amp model.

In the nulling phase (Phase A—Figure 1a), the inputs of the nulling amp are shorted together and to the inverting input terminal (common-mode input voltage). The nulling amplifier nulls its own inherent offset voltage by feeding back to its nulling terminal whatever opposing voltage is required to make the product of that

\*Edwin Goldberg and Jules Lehmann, U. S. Patent 2,684,999: Stabilized dc amplifier.

voltage and the incremental gain of the nulling input approximately equal to  $A_A$ 's input offset ( $V_{OS}$ ). The nulling voltage is also impressed on  $C_{M1}$ . Meanwhile, the main amplifier is behaving like a normal op amp. Its nulling voltage is being furnished by the voltage stored on  $C_{M2}$ .

During the output phase (Phase B—Figure 1b) the inputs of the nulling amplifier are connected to the input terminals of the main amplifier.  $C_{M1}$  is now continuing to furnish the nulling amplifier's required offset correction voltage. The difference input signal is amplified by the nulling amplifier and is further amplified by the incremental gain of the main amplifier's nulling input circuitry. It is also directly amplified by the gain of the main amplifier itself ( $A_B$ ). The op amp feedback will cause the output voltage of the nulling amplifier to be whatever voltage is necessary at the main amplifier's nulling input to bring the main amplifier's input difference voltage to near-null. Amplifier  $A_A$ 's output is also impressed on storage capacitor  $C_{M2}$ , which will hold that required voltage during the next Phase A.

The total open-loop amplifier dc gain is approximately equal to the product of the nulling amplifier gain and the wide-band amplifier nulling terminal gain. The total effective offset voltage is approximately equal to the sum of the main-amplifier and nulling-amplifier offset voltages, divided by the gain at the main amplifier nulling terminal. Very high gain at this terminal results in very low effective offset voltage for the whole amplifier.

As the cycle returns to the nulling phase, the stored voltage on  $C_{M2}$  continues to effectively correct the dc offset of the main amplifier. The cycle from nulling to output phase is repeated continuously at a rate set by the internal clock and logic circuits. (For detailed information on the auto-zero amplifier theory of operation see the data sheets for the AD8551/AD8552/AD8554 or AD857x amplifiers).

### Auto-Zero Amplifier Characteristics

Now that we've seen how the amplifier works, let's examine its behavior in relation to that of a "normal" amplifier. First, please note that a commonly heard myth about auto-zero amplifiers is untrue: the gain-bandwidth product of the overall amplifier is *not* related to the chopping clock frequency. While chopping clock frequencies are typically between a few hundred Hz and several kHz, the gain bandwidth product and unity-gain bandwidth of many recent auto-zero amplifiers is 1 MHz–3 MHz—and can be even higher.

A number of highly desirable characteristics can be easily inferred from the operating description: dc open-loop voltage gain, the product of the gains of two amplifiers, is very large, typically more than 10 million, or 140 dB. The offset voltage is very low due to the effect of the large nulling-terminal gain on the raw amplifier offsets. Typical offset voltages for auto-zero amplifiers are in the range of one microvolt. The low effective offset voltage also impacts parameters related to dc changes in offset voltage—dc CMR and PSR, which typically exceed 140 dB. Since the offset voltage is continuously "corrected," the shift in offset over time is vanishingly small, only 40 nV–50 nV per month. The same is true of temperature effects. The offset temperature coefficient of a well-designed amplifier of this type is only a few nanovolts per °C!

A less obvious consequence for the amplifier's operation is the low-frequency "1/f noise" characteristic. In "normal" amplifiers, the input voltage noise spectral density increases exponentially

inversely with frequency below a "corner" frequency, which may be anywhere from a few Hz to several hundred Hz. This low-frequency noise looks like an offset error to the auto-correction circuitry of the chopper-stabilized or auto-zero amplifier. The auto-correction action becomes more efficient as the frequency approaches dc. As a result of the high-speed chopper action in an auto-zero amplifier, the low-frequency noise is relatively flat down to dc (no 1/f noise!). This lack of 1/f noise can be a big advantage in low-frequency applications where long sampling intervals are common.

Because these devices have MOS inputs, bias currents, as well as current noise, are very low. However, for the same reason, wide-band voltage noise performance is usually modest. The MOS inputs tend to be noisy, especially when compared to precision bipolar-processed amplifiers, which use large input devices to improve matching and often have generous input-stage tail currents. Analog Devices AD855x amplifiers have about one-half the noise of most competitive parts. There is room for improvement, however, and several manufacturers (including ADI) have announced plans for lower-noise auto-zero amplifiers in the future.

Charge injection [capacitive coupling of switch-drive voltage into the capacitors] occurs as the chopping switches open and close. This, and other switching effects, generates both voltage and current "noise" transients at the chopping clock frequency and its harmonics. These noise artifacts are large compared to the wide-band noise floor of the amplifier; they can be a significant error source if they fall within the frequency band of interest for the signal path. Even worse, this switching causes intermodulation distortion of the output signal, generating additional error signals at sum and difference frequencies. If you are familiar with sampled-data systems, this will look much like aliasing between the input signal and the clock signal with its harmonics. In reality, small differences between the gain-bandwidth of the amplifier in the nulling phase and that in the output phase cause the closed-loop gain to alternate between slightly different values at the clock frequency. The magnitude of the IMD is dependent on the internal matching and does not relate to the magnitude of the clock "noise." The IMD and harmonic distortion products typically add up to about –100 dB to –130 dB plus the closed-loop gain (in dB), in relation to the input signal. You will see below that simple circuit techniques can limit the effects of both IMD and clock noise when they are out of band.

Some recent auto-zero amplifier designs with novel clocking schemes, including the AD857x family from Analog Devices, have managed to tame this behavior to a large degree. The devices in this family avoid the problems caused by a single clocking frequency by employing a (patented) spread-spectrum clocking technique, resulting in essentially pseudorandom chopper-related noise. Since there is no longer a peak at a single frequency in either the intrinsic switching noise or "aliased" signals, these devices can be used at signal bandwidths beyond the nominal chopping frequency without a large error signal showing up in-band. Such amplifiers are much more useful for signal bandwidths above a few kHz.

Some recent devices have used somewhat higher chopping frequency, which can also extend the useful bandwidth. However, this approach can degrade  $V_{OS}$  performance and increase the input bias current (see below regarding charge injection effects); the design trade-offs must be carefully weighed. Extreme care in both design and layout can help minimize the switching transients.

As mentioned above, virtually all monolithic auto-zero amplifiers have MOS input stages, tending to result in quite low input bias currents. This is a very desirable feature if large source impedances are present. However, charge injection produces some unexpected effects on the input bias-current behavior.

At low temperatures, gate leakage and input-protection-diode leakage are very low, so the dominant input bias-current source is charge injection on the input MOSFETs and switch transistors. The charge injection is in opposing directions on the inverting and noninverting inputs, so the input bias currents have opposing polarities. As a result, the *input offset current is larger than the input bias current*. Fortunately, the bias current due to charge injection is quite small, in the range of 10 pA–20 pA, and it is relatively insensitive to common-mode voltage.

As device temperature rises above 40°C to 50°C, the reverse leakage current of the input protection diodes becomes dominant; and input bias current rises rapidly with temperature (leakage currents approximately double per 10°C increase). The leakage currents have the same polarity at each input, so at these elevated temperatures the input offset current is smaller than the input bias current. Input bias current in this temperature range is strongly dependent on input common-mode voltage, because the reverse bias voltage on the protection diodes changes with common-mode voltage. In circuits with protection diodes connected to both supply rails the bias current polarity changes as the common-mode voltage swings over the supply-voltage range.

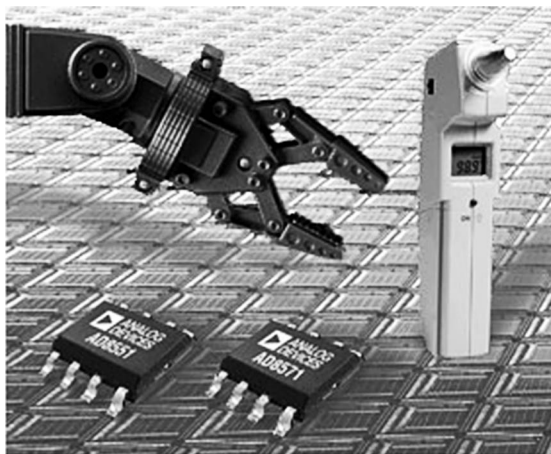
Due to the presence of storage capacitors, many auto-zero amplifiers require a long time to recover from output saturation (commonly referred to as overload recovery). This is especially true for circuits using external capacitors. Newer designs using internal capacitors recover faster, but still take milliseconds to recover. The AD855x and AD857x families recover even faster—at about the same rate as “normal” amplifiers—taking less than 100 μs. This comparison also holds true for turn-on settling time.

Finally, as a consequence of the complex additional circuitry required for the auto-correction function, auto-zero amplifiers require more quiescent current for the same level of ac performance (bandwidth, slew rate, voltage noise and settling time) than do comparable nonchopped amplifiers. Even the lowest power auto-zero amplifiers require hundreds of microamperes of quiescent current; and they have a very modest 200-kHz bandwidth with broadband noise nearly 150 nV/√Hz at 1 kHz. In contrast, some standard CMOS and bipolar amplifiers offer about the same bandwidth, with lower noise, on less than 10 μA of quiescent current.

### Applications

Notwithstanding all of the differences noted above, applying auto-zero amplifiers really isn't much different from applying any operational amplifier. In the next issue, Part 2 of this article will discuss application considerations and provide examples of applications in current shunts, pressure sensors and other strain bridges, infrared (thermopile) sensors, and precision voltage references. ▶

## Maintain Zero Drift in a Wide Range of Applications



Our Precision Chopper Amplifiers Maintain Zero Drift in a Wide Range of Applications

# Demystifying Auto-Zero Amplifiers—Part 2

**They essentially eliminate offset, drift, and 1/f noise. Here are some design ideas.**

by Eric Nolan and Reza Moghimi

Part 1 of this two-part article explains how auto-zero amplifiers work and identifies their important characteristics. As promised, this installment will discuss a few application ideas that are particularly well suited to auto-zero amplifiers.

Applying auto-zero amplifiers really is not much different from applying any operational amplifier. Most new designs have the same pinout and functionality as any other amplifier. DC closed-loop gain is set by resistors in the same manner; functions such as filtering, integration, and the like can be done in the same way. In most applications, the principal accommodation will be limiting the bandwidth to exclude the chopping noise and IMD artifacts from the passband. For auto-zero amplifiers with fixed-chopper frequency, this generally limits their application to dc or low-frequency signals below 1 or 2 kHz.

## PRECISION CURRENT SHUNTS

A precision shunt current sensor benefits by some of the unique attributes of auto-zero amplifiers used in a differencing configuration (Figure 1). Shunt current sensors are used in precision current sources for feedback control systems. They are also used in a variety of other applications, including battery fuel gauging, torque feedback controls in electric power steering and precision power metering.

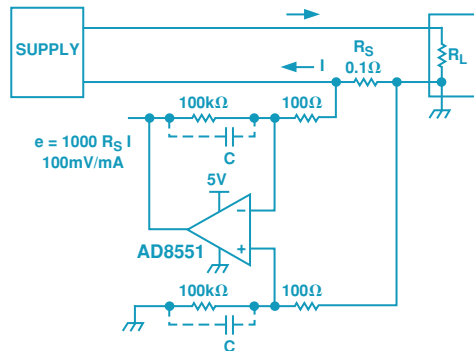


Figure 1. Current shunt amplifier.

In such applications, it is desirable to use a shunt with very low resistance to minimize the series voltage drop; this minimizes the waste of power and allows the measurement of high currents without significant voltage drop. A typical shunt might be 0.1 Ω. At measured current values of 1+ amperes, the shunt's output signal is hundreds of millivolts, or even volts, and amplifier error sources are not critical. However, at low measured current values in the 1-mA range, the 100-μV output voltage of the shunt demands a very low offset voltage and drift to maintain absolute accuracy. Low input bias currents are also needed, so that "injected" bias current does not become a significant percentage of the measured current. High open-loop gain, CMR, and PSR all help to maintain the overall circuit accuracy. As long as the rate of change of the

current is not too large, a fixed-frequency auto-zero amplifier can be used with excellent results.

It is generally desirable to limit the signal bandwidth to the lowest value needed, since this minimizes the effect of the chopping clock noise and also minimizes total noise. Remember that total voltage noise for an auto-zero amplifier is proportional to the square root of the signal bandwidth ( $E_N = e_N \times \sqrt{BW}$ ). A simple low-pass filter can be created by adding optional capacitors (C) in parallel with the feedback resistors. Additional gain and filtering at amplified voltage levels can be provided by an additional stage using ordinary amplifiers. With their high open-loop gain, auto-zero amplifiers can easily provide closed-loop gains of 100× to 1000×, permitting inexpensive CMOS amplifiers with several millivolts of offset and fairly high voltage noise to be used in the following stage without sacrificing system accuracy. Using a high stage gain for the auto-zero amplifier can also add an extra pole to the filter roll-off if the amplifier's gain-bandwidth divided by the stage gain is less than half the chopping clock frequency. However, filter performance will be affected by variations in GBW from amplifier to amplifier.

If the signal frequency exceeds about half the chopping clock frequency, an auto-zero amplifier type with a pseudorandom clock rate, such as the AD8571, can be used. In this case, the maximum overall accuracy will be slightly degraded due to the slightly higher wideband noise and the higher bandwidth; but the chopping clock will not produce a large error term at the clock frequency, and the effects of IMD will be minimized.

## STRAIN BRIDGES

Another common application, where the low offset and related low-frequency performance help to achieve wide dynamic range, is with strain bridges. Used in force and pressure sensors and in weigh scales, these bridges usually produce a relatively small output voltage level, even at full scale. In this example, three of the four amplifiers in a quad AD8554 are used for excitation and differential amplification (see Figure 2). The full-scale output may be a few tens of millivolts. In this case, the very low offset voltage of the auto-zero amplifier contributes minimal error to the measured signal. The long sample times of weigh scales benefit from the lack of 1/f noise. The low long-term drift of the amplifiers also minimizes or eliminates recalibration requirements.

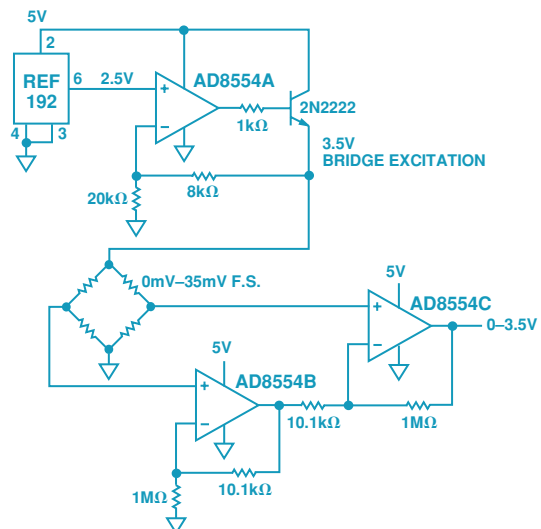


Figure 2. Single-supply strain-gauge bridge amplifier.

Pressure sensor systems, which usually require linearization to produce accurate output values, benefit from the low offset and drift. A well-characterized sensor can be scaled and linearized without concern for interaction with the amplifier, since the added amplifier error terms are negligible. The low input bias currents enable the use of higher bridge impedances, too; this can significantly improve system power consumption in portable or loop-powered applications, because the bridge excitation current can be much lower for the same output range. The lower bridge excitation current also minimizes errors due to bridge self-heating. Most strain-gauge bridge applications are low-frequency by nature, so the limited useful bandwidth of fixed-frequency auto-zero amplifiers is not an issue. The use of bridges with higher frequency outputs or with ac excitation can be accommodated through the use of randomly clocked auto-zero amplifiers.

### INFRARED (IR) SENSORS

Infrared (IR) sensors, particularly thermopiles, are increasingly being used in temperature measurement for applications as wide-ranging as automotive climate controls, human ear thermometers, home-insulation analysis and automotive-repair diagnostics. The relatively small output signal of the sensor demands high gain with very low offset voltage and drift to avoid dc errors. If interstage ac coupling is used (Figure 3), the low offset and drift prevents the input amplifier's output from drifting close to saturation. The low input bias currents generate minimal errors from the sensor's output impedance. As with pressure sensors, the very low amplifier drift with time and temperature eliminates additional errors once the temperature measurement has been calibrated. The low 1/f noise improves SNR for dc measurements taken over periods often exceeding 1/5 second. Figure 3 shows an amplifier that can bring ac signals from 100 to 300 microvolts up to the 1 to 3-V level.

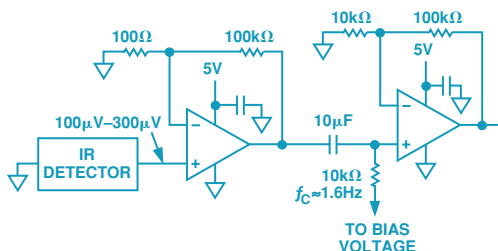
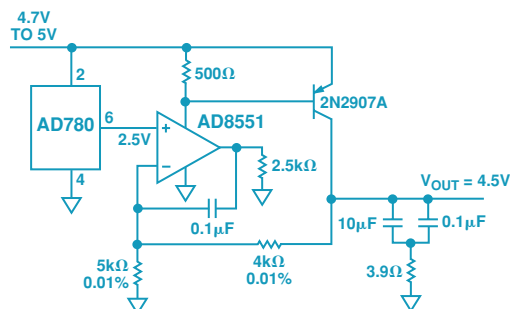


Figure 3. High-input-impedance ac-coupled preamplifier for thermopile.

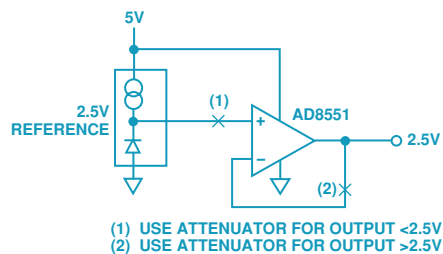
### PRECISION REFERENCES (FIGURE 4)

Precision voltage reference ICs in low-voltage systems may lack the flexibility to handle all the jobs they are called upon to do. For example, (a) they may require low dropout voltage, or (b) they may have to handle sourcing and sinking load currents, or (c) the system in which they are used may simply need a negative reference in addition to the positive reference. With their extremely low offsets and drift, their output drive capability, and the use of active

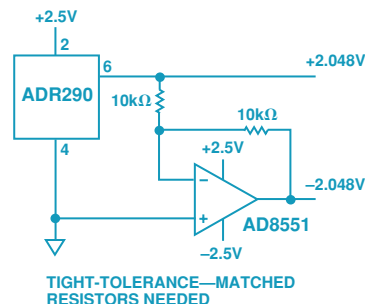
feedback, auto-zero amplifiers teamed up with precision references can provide effective solutions to these problems.



a. Regulated 4.5 V from a supply as low as 4.7 V.



b. Simple buffering.



c.  $\pm 2.048\text{-V}$  reference from  $\pm 2.5\text{-V}$  supply.

Figure 4. Precision amplifiers enhance flexibility of precision references.

The above are just a few ideas to suggest the wide applicability of auto-zero amplifiers. Almost any application that deals with small input signals and wide dynamic range over a moderate signal bandwidth is worthy of consideration for performance improvement using an auto-zero amplifier. Systems that are calibrated and must maintain performance over extended periods without maintenance will also benefit. Any application requiring tight channel-to-channel matching of dc performance is also a candidate. The dc error contributions of high-gain auto-zero amplifiers are so small that using multichannel, or even single-channel, devices will not substantially degrade the matching of multiple input channels. Multiple devices (duals and quads) will also be helpful with matched low-frequency ac inputs. ▶

# Curing Comparator Instability with Hysteresis

by Reza Moghimi

## ABOUT COMPARATORS

Comparator ICs are designed to compare the voltages that appear at their inputs and to output a voltage representing the sign of the net difference between them. In a comparator circuit, if the differential input voltage is higher than the input offset voltage ( $V_{OS}$ ), plus the required overdrive, the output swings to a voltage representing *logic 1*. In effect, a comparator can be thought of as a one-bit analog-to-digital converter. Besides being key components of A/D converters, comparators are also widely used in level detection, on-off controls, clock-recovery circuits, window detectors, and Schmitt triggers.

Operational amplifiers (op amps) can be—and frequently are—used as comparators, either open-loop or in a high-gain mode, but a better way is to use the special integrated circuits that are optimized for this purpose. The output stage of a *comparator* is wired to be more flexible than that of an *op amp*. Op amps use push-pull outputs that ordinarily swing as close to the power supply rails as feasible, while some comparators may have an open collector output with grounded emitter. This permits the pull-up voltage source for the output stage to vary over a wide range, allowing comparators to interface to a variety of logic families or load circuits. A reduced value for the pull-up resistor, providing increased current, will yield improved switching speed and noise immunity, but at the expense of increased power dissipation. Comparators often have a *latch* that permits strobing the input at the right time and a *shutdown* function that conserves power when the comparator is not needed.

Built to compare two levels as quickly as possible by running essentially “open-loop,” comparators usually lack internal Miller compensation capacitors or integration circuitry and therefore have very wide bandwidth. Because of this, comparators are usually configured with no negative feedback (or with very small amounts if a controlled high gain is desired).

This absence of negative feedback means that, unlike that of op amp circuits, the input impedance is not multiplied by the loop gain. As a result, the input current varies as the comparator switches. Therefore the driving impedance, along with parasitic feedbacks, can play a key role in affecting circuit stability. While negative feedback tends to keep amplifiers within their linear region, positive feedback forces them into saturation.

## What's the Role of Hysteresis?

Even without actual feedback circuitry, capacitive strays from the output to an input (usually the noninverting input), or coupling of output currents into ground (to which the noninverting input is often connected) may cause the comparator circuit to become unstable. Guarding high-impedance nodes and paying careful attention to layout and grounding can help to minimize these coupling effects. Latching is also helpful.

But it is not always possible to prevent instability by these measures. An often-effective solution is to use positive feedback to introduce

a small amount of hysteresis. This has the effect of separating the up-going and down-going switching points so that once a transition has started, the input must undergo a significant reversal before the reverse transition can occur.

When processing slowly varying signals with even small amounts of superimposed noise, comparators tend to produce multiple output transitions, or bounces, as the input crosses and recrosses the threshold region (Figure 1). Noisy signals can occur in any application, and especially in industrial environments. As the signal crosses the threshold region, the noise is amplified by the open loop gain, causing the output to briefly bounce back and forth. This is unacceptable in most applications, but it can generally be cured by introducing hysteresis.

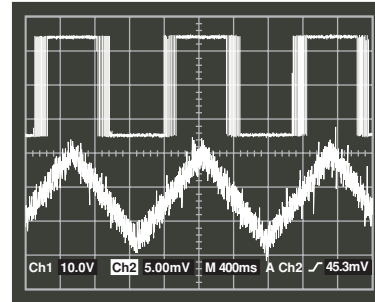
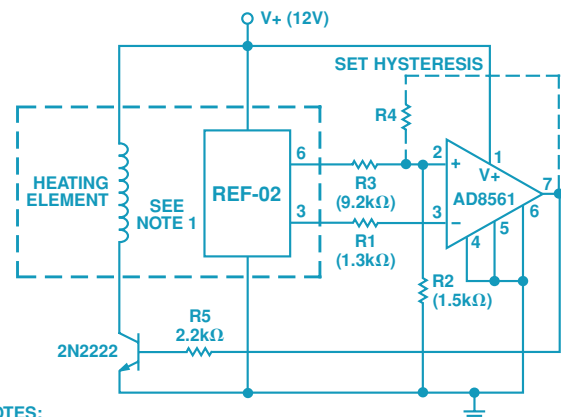


Figure 1. Noise causes multiple transitions.

## Where to Use Hysteresis

Besides comparator noise reduction, *system* hysteresis is used in on-off control to avoid overly frequent cycling of pumps, furnaces and motors. In the simplest applications a controller turns an actuator on and off as a system parameter falls below or rises above a reference set point. With hysteresis, the actuator remains on until the parameter rises somewhat above the set point, switches, and then remains off until the parameter falls to a value below the set point. The levels at which switching occurs are called the high and low threshold voltages,  $V_{th}$  and  $V_{tl}$ . An example of set-point hysteresis is the home thermostat, which uses some form of comparator to turn the furnace on or off. Allowing hysteresis for a few degrees of temperature change reduces unnecessary cycling adequately for home environments. Figure 2 shows a typical circuit for a comparator IC used in temperature control.



- NOTES:
1. REF-02 SHOULD BETHERMALLY CONNECTED TO SUBSTANCE BEING HEATED.
  2. NUMBERS IN PARENTHESES ARE FOR A SETPOINT TEMPERATURE OF 60°C.
  3.  $R1 = R2 || R3 || R4$

Figure 2. Temperature-control circuit with REF02 reference/sensor and AD8561 comparator. Hysteresis is introduced as needed via positive-feedback resistor, R4.



### Designing Comparator Circuits with Hysteresis

Hysteresis is applied by feeding back to the positive input a small fraction of the output voltage (which is at an upper or a lower limit). This voltage adds a polarity-sensitive offset to the input, increasing the threshold range.

With a chosen comparator, the designer must determine whether to use it in an inverting or noninverting configuration, i.e., whether a positive overdrive will switch the output to a negative or positive limit. Some comparators have positive and negative outputs, imparting a great deal of flexibility to their use in a system. Hysteresis can be applied by connecting the positive input terminal to the tap of a two-resistor voltage divider between the positive output and the reference source; the amount of output voltage fed back depends on the resistance ratio. This frees the *inverting input* for direct connection of the input signal, as in Figure 2.

If the signal is applied to the *noninverting input*, its source impedance should be low enough to have an insignificant effect on either the input scaling or the hysteresis ratio. To get the maximum performance out of a device, the hysteresis should be large enough to overcome the  $V_{OS}$  (over the entire operating temperature) plus the required overdrive, as determined from the manufacturer's data sheet. Increasing the overdrive reduces the propagation delay of the part. The level of overdrive required increases with ambient temperature.

Figures 3 and 4 show the use of hysteresis with dual supplies. In Figure 3, the signal is applied to the inverting input. The output vs. input plot shows the vicinity of the switching point.  $R_2$  is usually much higher in resistance than  $R_1$ . If  $R_2$  were infinite, there would be no hysteresis, and the device would switch at  $V_{REF}$ . The hysteresis is determined by the output levels and the resistance ratio  $R_1/(R_1 + R_2)$ , and the switching-point voltage is offset slightly from  $V_{REF}$  by the attenuation ratio  $R_2/(R_1 + R_2)$ .

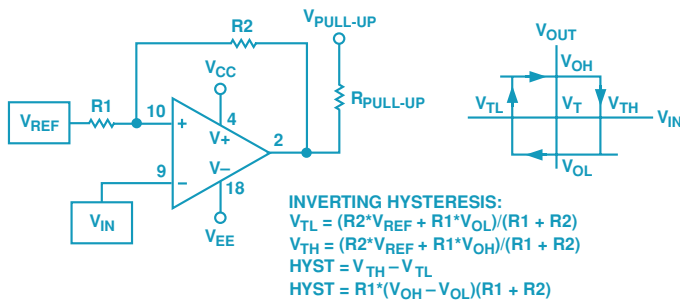


Figure 3. Comparator using inverting input, dual supplies.

In Figure 4, the signal is applied to the noninverting input via  $R_1$ . Because the input signal is slightly attenuated, the hysteresis will be slightly larger than in the inverting case.

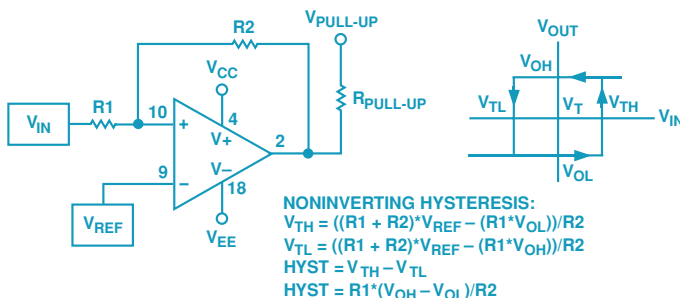
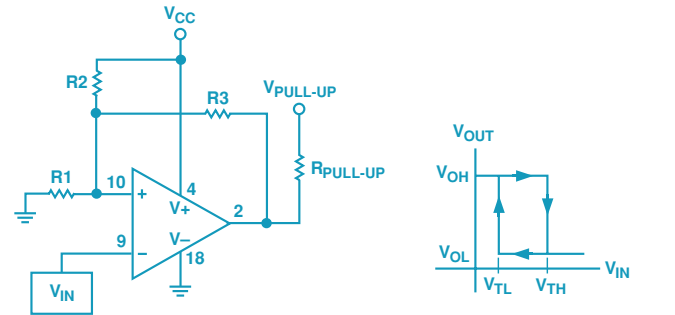


Figure 4. Comparator using noninverting input, dual supplies.

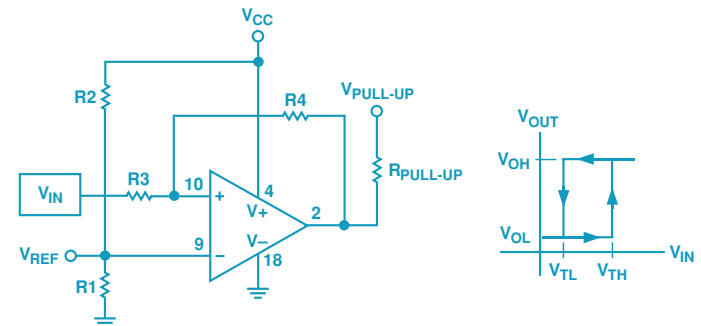
If the reference voltage is midway between the comparator's high and low output voltages (as is the case with a symmetrical power supply and ground reference), the introduction of the hysteresis will move the high and low thresholds equal distances from the reference. If the reference is nearer to one output than the other, the thresholds will be asymmetrically placed around the reference voltage.

In *single-supply* comparator operations, the need arises to offset the reference, so that the circuit operates entirely within the first quadrant. Figure 5 shows how this can be achieved. The resistor divider ( $R_2$  and  $R_1$ ) creates a positive reference voltage that is compared with the input. The equations for designing the dc thresholds are shown in the figure.



**SINGLE-SUPPLY INVERTING HYSTERESIS:**  
 $V_{TL} = (R_1 \parallel R_3) \cdot V_{CC} / ((R_1 \parallel R_3) + R_2) + (R_1 \parallel R_2) \cdot V_{OL} / ((R_1 \parallel R_2) + R_3)$   
 $V_{TH} = (R_1 \parallel R_3) \cdot V_{CC} / ((R_1 \parallel R_3) + R_2) + (R_1 \parallel R_2) \cdot V_{OH} / ((R_1 \parallel R_2) + R_3)$   
 $HYST = V_{TH} - V_{TL}$   
 $HYST = (R_1 \parallel R_2) \cdot (V_{OH} - V_{OL}) / (R_1 \parallel R_2 + R_3)$

(a)



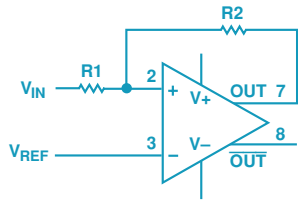
**SINGLE-SUPPLY NONINVERTING HYSTERESIS:**  
 $V_{REF} = V_{CC} \cdot R_1 / (R_1 + R_2)$   
 $V_{TH} = ((R_3 + R_4) \cdot V_{REF} - (R_3 \cdot V_{OL})) / R_4$   
 $V_{TL} = ((R_3 + R_4) \cdot V_{REF} - (R_3 \cdot V_{OH})) / R_4$   
 $HYST = V_{TH} - V_{TL}$   
 $HYST = R_3 \cdot (V_{OH} - V_{OL}) / R_4$

(b)

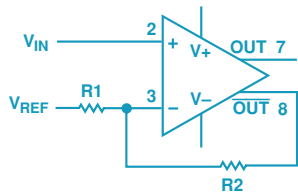
Figure 5. Comparators in single-supply operation.

Placing a capacitor across the feedback resistor in the above configurations will introduce a pole into the feedback network. This has the "triggering" effect of increasing the amount of hysteresis at high frequencies. This can be very useful when the input is a relatively slowly varying signal in the presence of high-frequency noise. At frequencies greater than  $f(p) = 1/(2\pi C_f R_f)$ , the hysteresis approaches  $V_{TH} = V_{CC}$  and  $V_{TL} = 0V$ . At frequencies less than  $f(p)$ , the threshold voltages remain as shown in the equations.

For comparators having complementary (Q and  $\bar{Q}$ ) outputs, positive feedback, and therefore hysteresis, can be implemented in two ways. This is shown in Figure 6. The advantage of Figure 6b is that a positive input-output relationship can be obtained without loading the signal source.



a. Unloaded reference.



b. Unloaded input.

Figure 6. Complementary-output comparators.

Figure 7 shows a circuit for comparing a bipolar signal against ground, using a single-supply part.

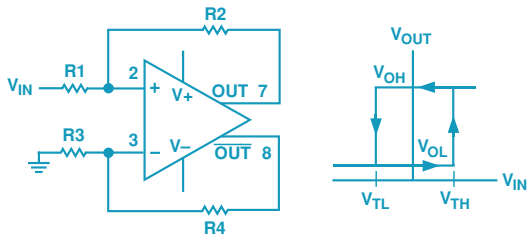


Figure 7. Single-supply comparator with bipolar input.

### Variables Affecting Hysteresis

The offset voltage, input bias currents, and finite gain in the linear region of the comparator all limit the accuracy of the switching thresholds,  $V_{TH}$  and  $V_{TL}$ . The input bias current is normally not a problem, since most applications use small source resistors to take advantage of the high speed of the comparators. Although it reduces power dissipation, high source resistance increase the propagation delay of the comparator. In order to keep the required overdrive low, the offset should be as small as possible. Open-loop amplifiers could be used in place of comparators when extremely low offsets are required in the design.

The trip-point accuracies (with hysteresis) are also affected by the device-to-device variation of  $V_{OH}$  and  $V_{OL}$ . One possible remedy is to use a programmable reference, but this process can become costly and time consuming. A better way, though still somewhat cumbersome, is to use precision clamp circuitry to keep the output at a fixed value when it goes high (Figure 8).

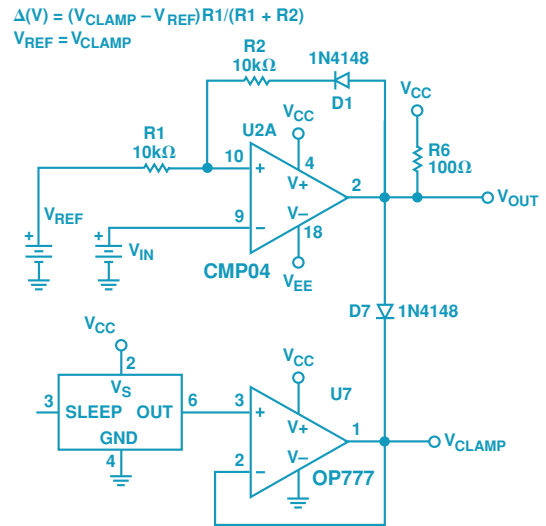


Figure 8. Precision clamp circuit.

### CONCLUSION

Designers can use hysteresis to rid comparator circuits of instabilities due to noise. Hysteresis is reliable and can be applied predictably using small amounts of positive feedback. ▶

# Transducer/Sensor Excitation and Measurement Techniques

by Albert O'Grady

## INTRODUCTION

Input transducers, or *sensors* are classified as either active or passive. *Passive* sensors, such as thermocouples or photodiodes (in the voltage-output mode) are two-port devices that directly transform physical energy to electrical energy, generating output signals without the need for an excitation source. *Active* sensors (like active circuits in general) require an external source of excitation. Examples can be found in the class of resistor-based sensors, such as thermistors, RTDs (resistance-temperature detectors), and strain gages; they require a current or voltage for excitation in order to produce an electrical output.

This article will consider a variety of excitation methods that can be used in active sensor/transducer applications and will show some typical circuits. The discussion includes the benefits and shortcomings of ac and dc excitation techniques using current and voltage. Accurate measurement of low-level analog signals with a data-acquisition system generally requires more than simply wiring the output of the transducer to the signal conditioning circuitry and then to the analog-to-digital converter. To maintain high-resolution and accuracy within the measurement system, the designer must exercise care in selecting the excitation source for the transducer—and in the field-wiring scheme used in conveying the low-level analog signal from the transducer to the A/D converter. Figure 1 shows a generalized block diagram of a transducer-based data acquisition system. The integrity of the data acquired in these systems depends on all parts of the analog signal path shown here.

For a given excitation source, the system designer is faced with the challenge of measuring the output signal and dealing with the issues that may arise. For example, wiring resistance and noise pickup are among the biggest problems associated with sensor-based applications. A variety of measurement techniques are available for employment in quest of optimum performance from the measurement system. Principal choices include ratiometric vs. non-ratiometric operation, and 2-wire vs. 3- and 4-wire Kelvin force/sense connections.

## EXCITATION TECHNIQUES

Active transducers can be excited using a controlled current or

voltage. The choice between voltage and current excitation is generally at the discretion of the designer. In data-acquisition systems, it is not uncommon to see constant-voltage excitation used for strain and pressure sensors, while constant current excitation is used to excite resistive sensors such as RTDs or thermistors. In noisy industrial environments, current excitation is generally preferable due to its better noise immunity.

AC or dc excitation sources can be used in transducer applications; each offers advantages and disadvantages. The advantages associated with dc excitation include simplicity of implementation and low cost. The downside of dc excitation includes the difficulty of separating the actual signal from unwanted dc errors due to offsets and parasitic-induced thermocouple effects. DC offsets are not fixed; they vary unpredictably due to temperature drift and both thermal and 1/f noise sources.

Although ac excitation techniques are more expensive to implement, they offer many performance benefits. AC excitation operates similarly to the chopping scheme used in precision amplifiers; it is used advantageously in transducer signal-conditioning circuits to remove offset errors, average out 1/f noise and eliminate effects due to parasitic thermocouples. With decreased sensitivity to 1/f-noise, a discernible output signal can be produced with much lower excitation currents or voltage. Decreased excitation means that the self-heating effects of current flow in resistive sensors can be greatly reduced. Since a relatively narrow bandwidth is involved, it is also likely that ac excitation also offers greater immunity to RF interference than dc excitation.

There are two major factors in selecting an excitation source that will enhance overall system performance. First, resolution: the magnitude of the excitation should be sufficient that the minimum change in the variable being measured produces an output from the transducer that is large enough to overcome the noise and offset in the system. Second, power level: if the sensor is resistive the designer must ensure that the self-heating effects of excitation current flowing through the transducer do not adversely affect the measured results.

## RATIOMETRIC VS. NON-RATIOMETRIC OPERATION

Figure 2 shows a ratiometric configuration in a bridge transducer application. The same reference source is used for both the transducer excitation and the A/D converter. A given percentage change in excitation is countered by the same percent change in the conversion process (or vice versa). The ADC output code,  $D_{OUT}$ , is a digital representation of the ratio of the converter's input,  $A_{IN}$ , to its reference,  $V_{REF}$ . Since the input to the converter and its reference are derived from the same excitation source, changes in the excitation do not introduce measurement errors. Thus, in ratiometric configurations, if the variable being measured by the transducer is unchanged, the digital output code from the ADC is immune to variations in the bridge excitation.

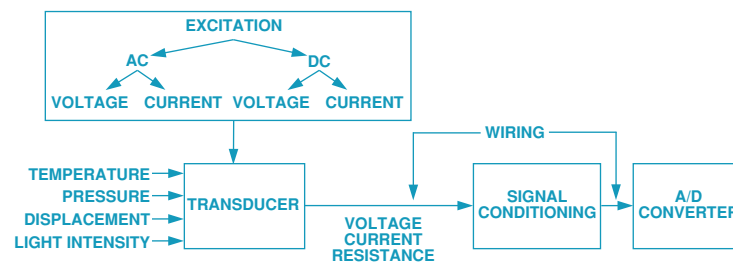


Figure 1. Typical transducer-based data acquisition system.

For this reason, an accurate stable reference is not necessary to achieve accurate measurements. Ratiometric operation is very powerful; it permits measurement and control, using the system analog supply, to obtain accuracy independent of the stability of voltage references or excitation supplies. Because the power supply rejection of most ADCs is fairly high, drifts in the power supply voltage do not adversely affect the measurement.

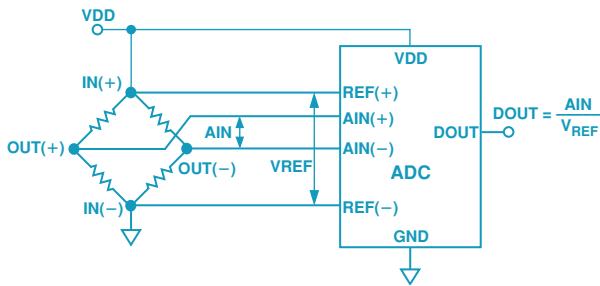


Figure 2. Ratiometric operation in a bridge transducer application.

Figure 3 demonstrates the disadvantage of dc non-ratiometric operation. It shows a typical non-ratiometric configuration in a bridge transducer application. As in the previous application, the ADC outputs a digital code,  $D_{OUT}$ , the ratio of  $A_{IN}$  to  $V_{REF}$ . In this example, the output code is sensitive to relative changes between the bridge excitation and reference voltage. Any change in the excitation voltage results in a change in the analog input voltage seen by the ADC. Since the reference is independent of the excitation, the digital output code will reflect the changed excitation. Non-ratiometric circuits are principally suitable for applications requiring measurements against an absolute reference—or where a single converter serves a variety of unrelated analog inputs. Since changes in reference, excitation, etc., will not be removed but will be reflected in the measurement, highly accurate, precise, and stable references and excitation sources are required for most applications.

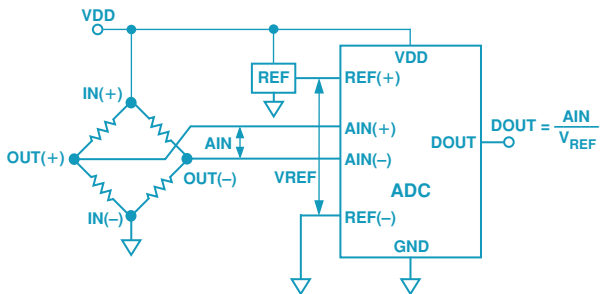


Figure 3. Non-ratiometric operation in a bridge-transducer application.

In the design of high-resolution data-acquisition systems, designers should always keep in mind the cost-effectiveness of ratiometric operation wherever its use is feasible.

### WIRING CONFIGURATIONS

There are a variety of wiring configurations that can be employed when connecting to resistive sensors such as RTDs and thermistors in temperature-measurement applications. The basic 2-, 3- and 4-wire connections are shown in Figure 4. Why are these formats available, with their various complexities and costs? Lead-wire resistance can introduce significant measurement errors if adequate

precautions are not taken to eliminate them, particularly in low-resistance 100- $\Omega$  RTD applications. In RTD circuits a controlled (usually constant) current is passed through the sensor, a resistor whose resistance increases gradually, repeatably, and approximately linearly with temperature. As its resistance increases, its voltage drop increases and, though small, can be measured without difficulty.

In an ideal application the voltage measured should only include the increase in resistance of the sensor itself. In practice, though, especially in 2-wire configurations, the actual resistance between the sensor terminals at the point of measurement includes the resistances of both the sensor and the lead wires. If the lead-wire resistance were to remain constant, it would not affect the temperature measurement. However, the wire resistance does change with temperature; and as the ambient conditions change, the wire resistance will also change, introducing errors. If the sensor is remote and the wire is very long, this source of error will be significant in RTD applications, where the nominal sensor value will be 100  $\Omega$  or 1 k $\Omega$ , and incremental changes are typically of the order of 0.4%/°C. Thermistor applications, where nominal sensor resistance values are higher than for RTDs, tend to be less sensitive to lead-resistance, since the leads contribute less error.

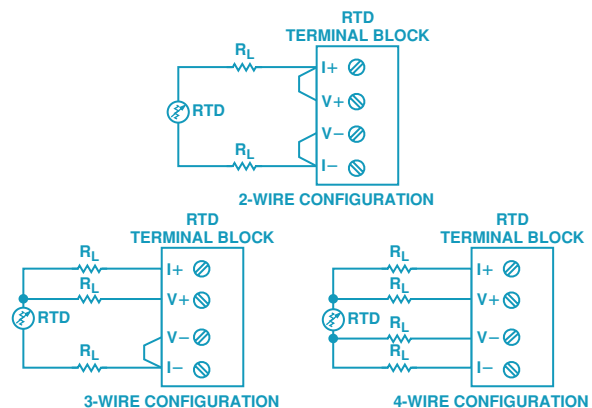


Figure 4. Typical wiring configurations for resistance based sensors.

The 2-wire configuration is the least accurate of the three systems shown above, because the lead wire resistance,  $2R_L$ , and its variation with temperature contribute significant measurement errors. For example, if the lead resistance of each wire is 0.5  $\Omega$  in each wire,  $R_L$  adds a 1- $\Omega$  error to the resistance measurement. Using a 100- $\Omega$  RTD with  $\alpha = 0.00385/^{\circ}\text{C}$ , the resistance represents an initial error of 1  $\Omega$ /(0.385  $\Omega/^{\circ}\text{C}$ ) or 2.6°C, and variation of the lead resistance with ambient temperature contributes further errors.

The 3-wire configuration in Figure 4 offers significant improvements over the 2-wire configuration due to the elimination of one current-carrying lead wire. If the measurement wire returning to  $V(+)$  feeds into a high impedance node, no current flows in this wire and no wiring error is introduced. However, the lead resistance and thermal characteristics of the RTD return wire to  $V(-)$  and  $I(-)$  still introduces errors, so the errors have been reduced to one-half the error in a 2-wire system.

The 4-wire configuration in Figure 4 offers the best performance, in terms of accuracy and simplicity, compared to the 2- and 3-wire configurations. In this application, the errors due to the lead-wire resistance and thermal heating effects are removed by measuring the temperature right at the RTD. The return wires

from the RTD are generally buffered by a high-impedance circuit (amplifier/analog to digital converter), and thus no current flows in the return wires and no error is introduced.

If two matched current sources are available, it is possible to design 3-wire systems that essentially eliminate any wiring resistance or thermal effects. An example, using the AD7711 converter, is shown in Figure 5. The excitation is furnished by current from the upper 200- $\mu$ A current source, flowing through the resistance of the connecting wire,  $R_{L1}$ . The lower current source provides a current flowing through the other measurement wire, with resistance  $R_{L2}$ , creating a voltage drop essentially equal and opposite to the drop across  $R_{L1}$ , cancelling it when measured differentially. The sum of the two currents flows harmlessly through the return wire ( $R_{L3}$ ) to ground (the differential measurement ignores the common-mode voltage). The 200- $\mu$ A current, flowing through the series 12.5-k $\Omega$  resistor, develops a voltage that is used as a reference for the converter, providing a ratiometric measurement.

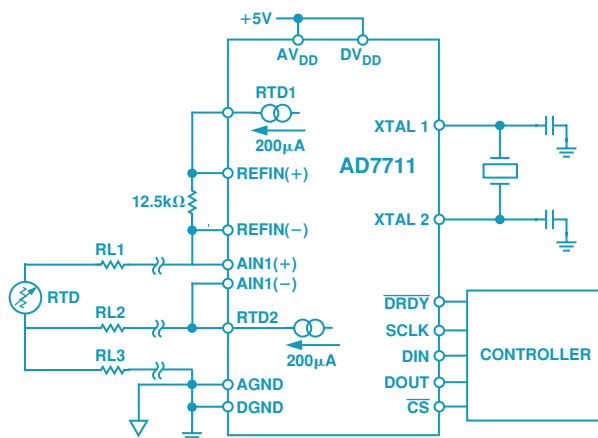


Figure 5. Eliminating errors due to field-wiring resistance in 3-wire RTD applications.

The AD7711, a high-resolution sigma-delta ADC, converts the voltage from the RTD to digital. The AD7711 is an ideal choice of converter for this application; it offers 24-bit resolution, an on-chip programmable gain amplifier and a pair of matched RTD excitation current sources. As is evident from the example, a complete solution can be built without the need for extra signal conditioning components.

### AC EXCITATION

Figure 6 shows some of the system error sources associated with dc-excitation and measurement in a bridge sensor application. In this bridge circuit, it is not possible to distinguish how much of the amplifier's dc (and low-frequency) output is actually from the bridge and how much is due to error signals. Errors introduced by 1/f noise, parasitic thermocouples, and amplifier offsets cannot be dealt with unless some method is used to differentiate the actual signal from these error sources. AC excitation is a good solution to this problem.

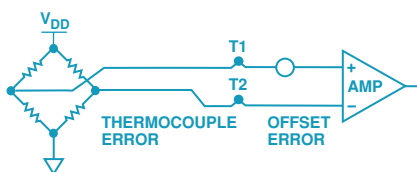


Figure 6. Error sources associated with dc-excitation in a bridge transducer measurement system.

The signals from a bridge transducer, which depend on the excitation, are typically small. If the excitation is 5 V and the bridge sensitivity is 3 mV/V, the maximum output signal is 15 mV. Sources of degradation for the information provided by these low-level signals include noise (both thermal and 1/f), voltage from parasitic thermocouples and amplifier offset errors. For example, parasitic thermocouples exist in normal circuit wiring. Junctions between tin-lead solder and copper PC board traces can introduce thermocouple effects of 3 to 4  $\mu$ V/ $^{\circ}$ C, if thermal gradients exist across the circuit. Thermocouple junctions will also exist between the copper traces of the circuit board and the Kovar pins of the amplifier, creating voltage errors as large as 35  $\mu$ V/ $^{\circ}$ C. In a high-resolution data-acquisition system, these thermocouple errors, along with the amplifier offset errors and the noise in the system, will all add up to significant dc and low-frequency error.

AC excitation is a powerful approach to separating these errors from the signal. By using a square wave for ac-excitation, with the polarity of the excitation signal reversed between measurements, the induced dc errors can be effectively cancelled. This chopping scheme also has the effect of removing 1/f noise, which is dominant at low frequencies (dc to a few Hz) in these applications.

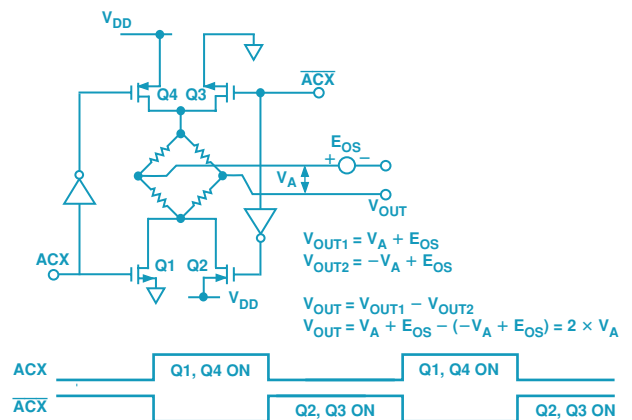


Figure 7. Typical bridge configuration employing ac excitation.

Figure 7 shows how a bridge can be configured for ac-excitation. The polarity of the excitation voltage to the bridge is reversed on alternate cycles, using transistors Q1 to Q4 to perform the switching. All the induced dc and low-frequency errors have been lumped together as  $E_{OS}$ . During phase 1, Q1 and Q4 are on while Q2 and Q3 are off; the output,  $V_{OUT1}$ , is given by  $(V_A + E_{OS})$ . During phase 2, Q2 and Q3 are on while Q1 and Q4 are off, with the output,  $V_{OUT2}$ , represented by  $(-V_A + E_{OS})$ . The actual output is the sum of the two phases, giving  $V_{OUT} = 2 \times V_A$ . The control signals for the ac-excitation must be non-overlapping clock signals. This scheme removes the errors associated with dc excitation at the expense of a more complex design.

Figure 8 shows a bridge-transducer application using the AD7730 bridge-transducer ADC, which includes on-chip all the necessary circuitry to implement ac excitation and produce the computed output result following the switching of the excitation.

The AD7730 sigma-delta ADC is a complete analog front-end for weigh-scale and pressure-measurement applications. Operating from a single +5-V supply, it accepts low-level signals directly from a transducer and outputs a serial digital word. The input signal is applied to a proprietary programmable gain front end, based on an analog modulator. A low-pass programmable digital filter with

adjustable filter cutoff, output rate, and settling time processes the modulator output. There are two buffered differential programmable-gain analog inputs, as well as a differential reference input. It accepts four unipolar and bipolar analog input ranges from 10 mV to 80 mV full-scale.

The peak-to-peak resolution achievable directly is 1-in-230,000 counts. An on-chip 6-bit DAC allows compensation for tare voltage in weigh-scale applications. The device's serial interface can be configured for 3-wire operation and is compatible with microcontrollers and digital signal-processors. The AD7730 contains self-calibration and system calibration options, and features an offset drift of less than 5 nV/°C and a gain drift of less than 2 ppm/°C. With this level of drift performance, calibration in the field is usually unnecessary.

In Figure 8, transistors Q1 to Q4 perform the switching of the excitation voltage. These transistors can be discrete matched bipolar or MOS transistors—or a dedicated bridge-driver chip such as the 4427 from Micrel can be used to perform the task.

Since the analog input voltage and the reference voltage are reversed on alternate cycles, the AD7730 must be synchronized with these reversals of the excitation voltage. For synchronous switching, it provides the logic control signals for switching the excitation voltage. These signals are the non-overlapping CMOS outputs, ACX and  $\overline{\text{ACX}}$ . One of the problems encountered with ac-excitation is the settling time of the analog input signals after switching, especially in applications where there are long leads from the bridge to the AD7730. The converter could produce erroneous data because it is processing signals that are not fully settled. Accordingly, the user is allowed to program a delay of up to 48.75  $\mu\text{s}$  between the switching of the ACX signals and the processing of data at the analog inputs. The AD7730 also scales the ACX switching frequency in accordance with the output update rate. This avoids switching the bridge at an unnecessarily faster rate than the system requires.

The ability of the AD7730 to handle reference voltages which are the same as the excitation voltages is particularly useful in ac-excitation, where resistor divider arrangements on the reference input add to the settling time associated with the switching.

AC-excitation can be effectively used to eliminate the effects of self-heating in temperature-measurement applications using resistive sensors. When measuring temperature using an RTD, the excitation current itself (however small) produces  $I^2R$ , or Joule heating, producing an indicated temperature somewhat higher than the temperature being measured. The degree of self-heating greatly depends on the medium in which the RTD is immersed. An RTD will self-heat to a much higher temperature in still air than in moving water.

With commonly used dc excitation, the excitation current through the sensor must be large enough so that the smallest temperature change to be measured results in a voltage change that exceeds the system noise, offset, and drift of the system. The excitation currents required to overcome these errors are typically 1 mA or greater. The power dissipated in the RTD causes its temperature to rise, introducing drift errors in the measurement, which reduces system accuracy. For example, using a 1-mA dc excitation source with a 1-k $\Omega$  RTD having a self-heating effect of 0.05°C/mW results in a drift error of 0.5°C.

Since an ac-excitation source will reduce offset and drift effects, much smaller excitation currents can be used in many applications. Thus, decreased excitation current not only reduces the self-heating effects in the RTD (by the square of the current reduction!); it also reduces the associated dc and low-frequency output errors as noted above.

Figure 9 shows the AD7730 high-resolution sigma-delta converter used for ac-excited RTD measurement. In this application, the AD7730 is operated with split supplies, i.e.,  $\text{AV}_{\text{DD}}$  and  $\text{DV}_{\text{DD}}$  are at separate potentials, and AGND and DGND are at separate potentials. With this arrangement, it is necessary that  $\text{AV}_{\text{DD}}$  or  $\text{DV}_{\text{DD}}$  not exceed AGND by 5.5 V. Therefore, when operating with  $\pm 2.5\text{-V}$  analog supplies the  $\text{DV}_{\text{DD}}$  must be restricted to +3 V with respect to digital ground, which is the system ground.

The AD7730's ACX output, which controls the reversing of the current in this application, is established with respect to the  $\text{AV}_{\text{DD}}$  and AGND supplies. When ACX is high, a current of 100  $\mu\text{A}$  flows through the RTD in one direction; when ACX is low, the 100- $\mu\text{A}$  current flows in the opposite direction through the RTD. The

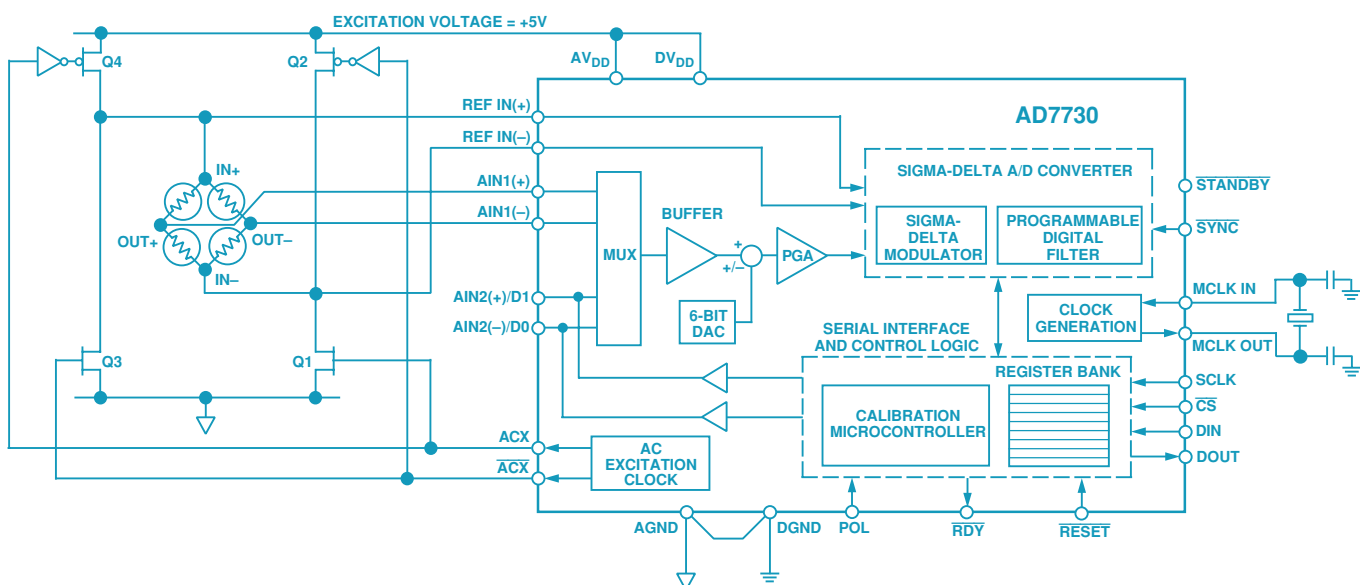


Figure 8. AC-excited bridge application using AD7730 sigma-delta converter.

switched-polarity current source is developed using op-amps U1 and U2 in a standard voltage-to-current conversion configuration. The AD7730, configured for its ac-excitation mode, produces a square wave at its ACX output. During the conversion process the ADC takes two conversion results—one on each phase of the ACX signal—and combines them within the ADC to produce one data output word representing the measured temperature.

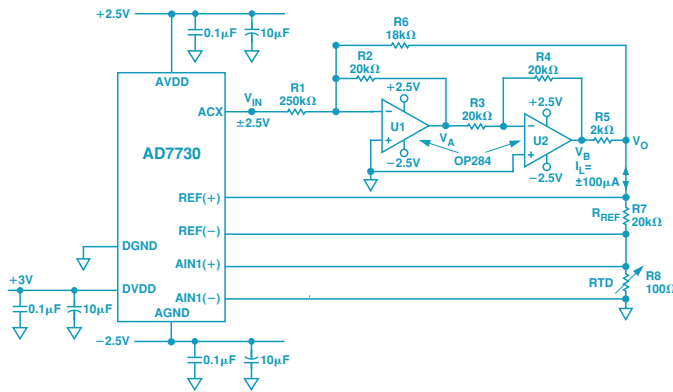


Figure 9. Eliminating self-heating effects in RTD temperature measurement applications using ac excitation and the AD7730 ADC.

For example, if the RTD output during phase one of the ACX signal is 10 mV, and a 1-mV circuit induced dc-error exists due to parasitic thermocouples, the ADC measures 11 mV. During the second phase the excitation current is reversed and the ADC measures  $-10$  mV from the RTD, and again sees +1-mV dc-error, giving an ADC output of  $-9$  mV during this phase. These measurements are processed within the ADC  $(11\text{ mV} - (-9\text{ mV}) / 2 = 10\text{ mV})$ , thus removing the dc-induced errors within the system. AC-excitation allows currents in the vicinity of 100  $\mu\text{A}$  to be effectively used in RTD applications, as shown in Figure 9, reducing self-heating effects substantially.

Because the converter's reference voltage is developed using the excitation current, the RTD's resistance is measured ratiometrically. Thus, the external resistance values in the voltage-to-current converter do not affect system accuracy, as the exact value of the drive current is not critical, about 1%. Therefore, 100-ppm/ $^{\circ}\text{C}$  resistors will suffice. However, the resistance of  $R_{\text{REF}}$ , which uses the current to develop the ADC reference voltage, must be stable over temperature to avoid reference-induced errors in the measurement output. With the circuit shown, measured temperature ranges from  $-200^{\circ}\text{C}$  to  $+200^{\circ}\text{C}$  can be easily accommodated.

Since line-frequency pickup can produce offsets if chopping is at line frequency (50 or 60 Hz), chopper operation is suggested at an asynchronous 57 Hz (where a filter null occurs). Resolutions of 16-bit peak-to-peak are achievable when using the AD7730 in its unipolar 0–20-mV range with an update rate of 57 Hz. Another

important benefit of using the AD7730 in RTD applications is its immunity to both radiated electric fields and fast transient bursts (EFT). When operating in a noisy environment it is recommended using the AD7730 in its chop mode. The chopper stabilization techniques used within the AD7730 eliminate offset and minimize offset drift. When the AD7730 is operated in CHOP mode the signal chain, including the first stage filter, is chopped. This reduces the overall drift performance to less than  $5\text{ nV}/^{\circ}\text{C}$ . The AD7730 can be operated in the presence of electric fields (1 V/m to 3 V/m) from 30 MHz to 1 GHz with flat offset across the frequency range. Without chopping, the offset performance degrades in the presence of an electric field and drifts with frequency.

## SUMMARY

In designing high-resolution data acquisition systems care must be exercised in selecting the method of excitation, the excitation source for the transducer, and the field wiring scheme used in conveying the low-level analog signal from the transducer to the A/D converter.

Transducers can be excited with either ac or dc current or voltage. DC is more widely used than ac for excitation, because systems using dc excitation are easier to implement and troubleshoot; but they have a number of drawbacks. The excitation magnitude at the sensor must be enough so that the smallest change to be measured results in a voltage change that exceeds the noise, offset and drift of the system.

If large dc errors and low-frequency noise are expected, ac excitation is useful. The excitation source is switched on alternate cycles, and the resulting amplitudes are measured and averaged to provide a conversion result. AC excitation thus removes the effects of  $1/f$  noise and dc induced parasitic thermocouple effects in a signal chain. This allows the excitation to be greatly reduced, in turn reducing the errors introduced from self-heating in resistance-based sensors. These benefits usually exceed the disadvantages of somewhat higher implementation cost and the care that must be taken to ensure adequate settling before a measurement is made.

Choices of sensor wiring configurations are available, involving from two to four wires, depending on the required accuracy. Four-wire configurations offer the best accuracy by eliminating the errors due to the lead wire resistance and thermal effects in the wiring. Systems can be configured with common excitation and references (ratiometric), or with independent references (non-ratiometric). Ratiometric is preferred because it permits measurement and control with accuracy greater than the stability of voltage references or excitation supplies. Measurements are insensitive to excitation variations.

Conclusion: Where possible, the best designs of high-resolution data-acquisition systems should use 4-wire configurations and exploit the benefits of ratiometric operation and ac excitation. ▶

# Advances in Video Encoders

by Christine Bako

*Foreword to the reader: Video technology uses many special terms that may be unfamiliar to those not in the field. We've provided a 32-page glossary (Application Note 548, in PDF, 112 KB) to help readers who want to understand video terminology. It may be helpful to print out a copy to have on hand as a reference. A printed version of the glossary may also be ordered from Literature Distribution.*

## INTRODUCTION

Digital video signals from sources such as MPEG codecs must be appropriately encoded and converted to analog before they can be displayed by analog TVs and VCRs. In general, encoding means to convert from one format or signal to another. For video encoders, this means converting from 4:2:2 YCrCb digital video data into YUV, RGB, or CVBS analog video signals. YCrCb is a component digital signal, where Y is the luminance signal, which contains the black-and-white signal information, Cr is red minus the luminance (R-Y), and Cb is blue minus the luminance (B-Y). YUV is a scaled version of YCrCb. This scaling is necessary prior to combining the YUV signals into composite video, so that it will be contained within the amplitude limits of signal-processing and recording equipment. This YUV signal should not be confused with the *analog* YUV inputs found on high-end TVs. CVBS (Color, Video, Blank, and Sync) is a composite analog signal. In this format, a single analog video signal includes information on sync, color, and luminance. Composite signals are used in standard TVs and VCRs. The component formats provide a sharper picture with less noise than a composite signal because the modulation required to produce the CVBS signal is eliminated.

The ADV719x family (Figure 1) is a new generation of video encoders. They provide all of the features of other members of ADI's video encoder family, plus 4× oversampling, digital noise reduction (DNR), gamma correction and, in the ADV7194, Xtended-10™ technology (see below). A key feature of the ADV719x is the ability

to input progressive scan signals in 3 × 10-bit 4:2:2 YCrCb format. On-board DACs convert these signals into an analog YPrPb format that can be viewed on a progressive scan monitor.

**4× Oversampling:** In A/D converters, oversampling means using a sampling rate that is higher than the Nyquist rate, that is, sampling at a rate more than twice that of the highest frequency of the incoming signal. For a D/A converter, oversampling is actually an interpolation process, accomplished by computing the average value between consecutive samples.

Video data is clocked into the ADV719x at a 13.5-MHz rate. It is first interpolated up to 27 MHz, and interpolated again up to 54 MHz. The video data is then sent to the six 10-bit DACs. The interpolation process allows a given signal quality to be reached using less-expensive components with looser tolerances. In this case, interpolation allows the use of reconstruction filters with a gentler roll-off slope. This, in turn, means less-complex filter designs and lower cost. Phase nonlinearity and passband ripple are less likely to cause problems. Interpolation also allows the resolution of converters to be extended. In an ideal system, if the bandwidth of the signal is doubled, the same amount of information can be conveyed down a channel with an SNR of 6 dB or less. Therefore, raising the sampling rate allows the word length in each sample to be reduced without information loss.

Figure 2 shows the reconstruction filter requirements when 2× oversampling and 4× oversampling are used.

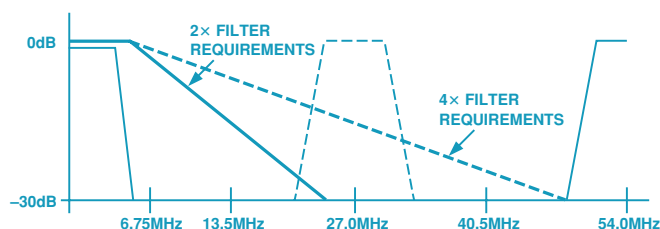


Figure 2. Low-pass filter requirement with 2× and 4× oversampling.

**Digital Noise Reduction:** Noise is generally visible as “snow,” or small dots that make the picture look fuzzy, and can be caused by bad transmission or low-quality equipment. Noise is more visible

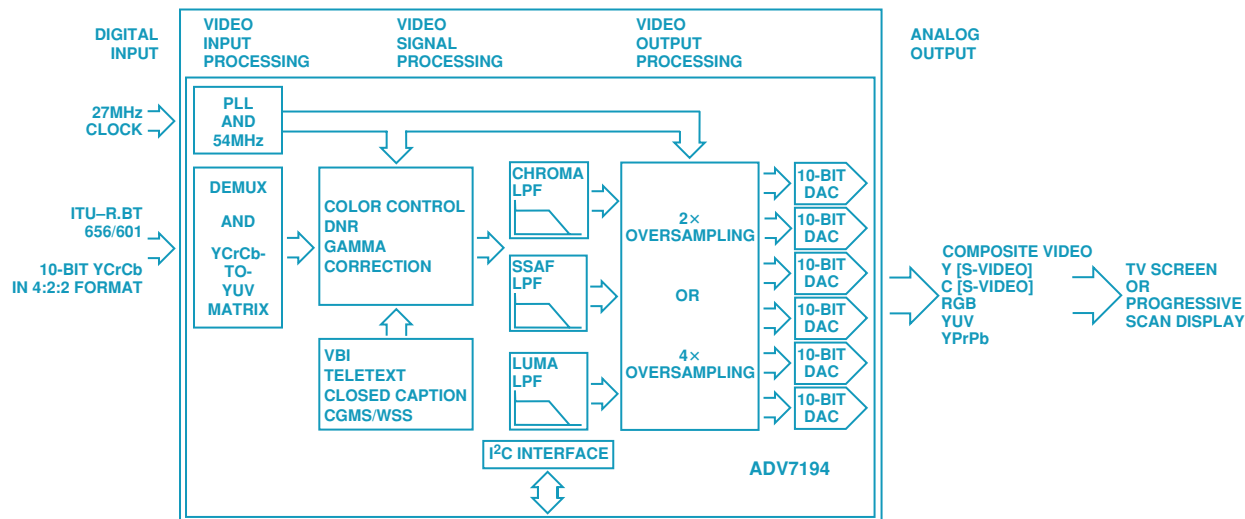


Figure 1. Functional block diagram of the ADV7194.



on pictures with significant high frequency content; that is, pictures that contain lots of detail and color. The digital noise reduction (DNR) used on the ADV719x effectively reduces noise in the picture, and also has the ability to reduce noise that results from the MPEG compression. MPEG compression splits the video data contained in one frame into compressed blocks of  $8 \times 8$  pixels. Several of these blocks make up a field. The border areas of these blocks cause noise to be visible on the TV picture, which makes it generally less sharp. This type of signal degradation is typical of MPEG compression. In the ADV719x family of video encoders, the amount of noise reduction applied to the transition areas is programmable.

Video noise characteristically combines high frequencies and low amplitudes. The ADV719x makes use of this fact by analyzing the incoming signal for its high-frequency, low-amplitude content. This noise signal is then subtracted from the original signal, resulting in improved picture quality. Depending upon the noise requirements, the user can program a threshold value that determines the amount of noise attenuation applied.

Additionally, programming allows high-frequency signals to be enhanced. When received, high-frequency signals with high amplitudes are assumed to be valid data. Applying a programmable gain to these signals and adding them to the original signal results in an improvement in picture sharpness.

Figure 3 shows a simulation of an input signal (light trace) and the resulting output signal (heavy trace) when digital noise reduction is applied.

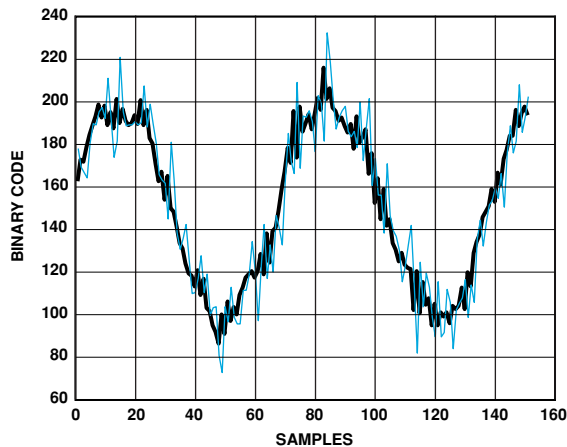


Figure 3. Effect of digital noise reduction. Heavy trace is output waveform.

**Gamma Correction:** Gamma is the exponent applied to a signal voltage in an approximation of the nonlinear transfer function of a display device (e.g., a cathode-ray tube screen). Gamma = 1.0 would produce a perfectly linear plot, i.e., the output as a linear function of the input. In CRTs the intensity of light produced on the screen of a CRT is a nonlinear function of the voltage applied at the input, with a typical gamma value of 2.3 to 2.6.

Gamma correction, a process of compensating for this nonlinearity, is necessary for reproducing good color with the correct intensity in order to meet standards for picture appearance on a given screen.

The nonlinearity of the CRT should also be considered if an image is to be coded in such a way as to make maximum perceptual use of a limited number of bits per pixel and to minimize the visibility of noise. If uncompensated, the nonlinearity would create errors

known as contouring or banding. These are visible on simple pictures having large areas of smoothly varying shades. This is effectively the same as the visible distortion caused by quantization error introduced at low levels of modulation.

Display devices, such as liquid crystal displays (LCDs) and CRTs, have differing nonlinearity characteristics. The ADV719x allows the user to program gamma values so that appropriate compensation curves can be applied to the incoming signal. Gamma correction in the display device is especially useful in cases where the video source doesn't provide a gamma-corrected signal.

Figure 4 shows responses of the gamma correction circuit to a linear ramp signal for several values of gamma.

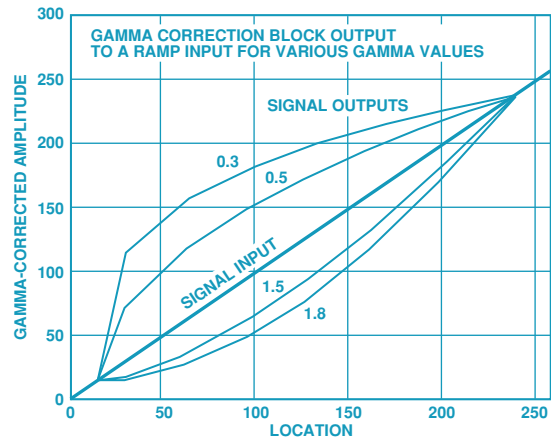


Figure 4. Gamma correction curves.

**Xtended-10 Technology:** Many video encoders, including the ADV7175/ADV7176, ADV7175A/ADV7176A, ADV7177/ADV7178, ADV7170/ADV7171, and ADV7172/ADV7173, allow for data to be input in 8-bit format, processed at 8 or 10 bits, and output to 10-bit DACs. With Xtended-10 technology, the ADV7194 allows data to be input in 10-bit format, processed at 10 bits, and output to six 10-bit DACs. The 10-bit processing available in the ADV7194 is of especial value in professional video applications.


#### THE ADV719x FAMILY

The ADV719x image processing facilities are unsurpassed. The user has control over brightness, color, contrast, chroma, and luma, as well as delay and programmable adjustment of sync pulsewidth and position. There are seven programmable luma filters, seven programmable chroma filters, and an extended SSAF™ filter with 12 programmable responses.

The ADV719x also provides features such as TTX, CGMS, Macrovision, master/slave timing modes, VBI (vertical blanking interval) programming, and closed captioning.

The technical performance of the ADV719x is outstanding, resulting in excellent signal quality. Errors in differential gain and phase are 0.2% and 0.4°, respectively. SNR of up to 75 dB can be achieved.

The ADV719x runs on a single +5-V, +3.3-V, or +3-V supply. The ADV7190 is packaged in a 64-lead LQFP. The ADV7192 and ADV7194 are packaged in 80-lead LQFPs.

Evaluation boards are available. The user simply connects the board to the TV monitor when used with internal color bars, or a YCrCb signal source can be used. A PC running Windows® 95/98 is required. User-friendly software is provided. 

# Selecting an Analog Front-End for Imaging Applications

by Kevin Buckley

## INTRODUCTION

Every imaging system starts with an image sensor. The signal from the sensor must be processed in the analog domain, converted to digital, and further processed in the digital domain. This allows the image to be analyzed, manipulated, and enhanced, prior to storage, display, transmission, and/or further processing. Imaging applications typically involve three chips—an image sensor, an analog front-end (AFE), and a digital ASIC. The AFE conditions the analog signal received from the image sensor and performs the analog-to-digital (A/D) conversion. The digital ASIC contains image-processing and timing-generation circuitry. Figure 1 shows a block diagram of a typical imaging system. Additional application-specific circuitry following the digital image-processing ASIC depends upon whether the imaging system is a camera, scanner or copier.

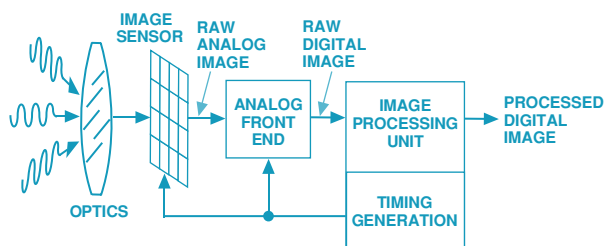


Figure 1. Block diagram of a typical imaging application.

**Analog front-ends.** A typical AFE starts with an input clamp. The common-mode level of the image sensor's output signal could range from 0 V to more than 9 V, so the signal must be ac-coupled to the AFE. The input clamp restores the dc level of the signal to an optimum point within the supply range of the AFE.

A sampling function follows the input clamp. AFEs designed to work with charge-coupled devices (CCDs) use a correlated double sampler (CDS). The CDS takes two samples of each pixel, one at the reset level and one at the video level, and performs a differential measurement between the two. The CDS improves the signal-to-noise ratio (SNR) by eliminating the correlated  $kT/C$  noise associated with the output stage of the CCD, and by attenuating

low frequency drift. Contact image-sensors (CIS) and focal-plane arrays (FPA) used in commercial infrared (IR)-imaging applications typically output a single-ended, ground-referenced signal, and do not require a differential measurement. AFEs designed to work with these sensors use a sample-hold amplifier (SHA) in place of the CDS. A coarse black-level offset-correction stage is integrated with the CDS or SHA.

A programmable- (or variable-) gain amplifier (PGA or VGA) follows the CDS to amplify the signal and better utilize the full dynamic range of the A/D converter (ADC). If black-level offset correction is not performed ahead of the PGA, the dynamic range of the imaging system will suffer. A high-speed ADC converts the conditioned analog image signal to the digital domain, allowing for additional processing by a digital ASIC.

The AFE is programmed via a standard serial port that easily interfaces with most off-the-shelf microcontrollers or the digital ASIC. The PGA-gain registers, offset-correction registers, and sampling modes are all programmed through this interface.

The choice of an AFE for an imaging application depends on many factors, including: the type of sensor being used, dynamic range, resolution, speed, noise, and power requirements. This article is intended to provide a guide to making appropriate AFE choices for imaging applications.

## DIGITAL VIDEO AND STILL CAMERA APPLICATIONS

Digital video and still cameras are among the fastest-growing segments in consumer electronics today. Camera manufacturers continually need to create higher-performance cameras at lower cost in order to remain competitive. This need has driven IC manufacturers to higher levels of circuit integration in order to reduce the size and cost of camera components.

The first step in this process was to integrate all of the analog circuitry into a single chip. Figure 2 shows a simplified block diagram of a digital camera. Although each application will have different requirements for sampling rate, noise performance, power consumption, image resolution, and operating modes, the AFE is a crucial link in establishing and maintaining system performance.

**Need for speed.** In standard analog video applications, VGA (640 × 480) resolution is common, so 300 kpixel CCDs are used. With an NTSC-standard transmission rate of 30 frames per second (fps) and interlaced CCD arrays, an AFE would have to process pixels at a rate of almost 10 MHz. For higher-definition applications, such as digital TV (DTV), progressive scanning is used. Using a progressive-scan CCD with 300 kpixels, the analog front-end needs to run at speeds approaching 20 MHz (300,000 × 30 × 2 = 18 MHz).

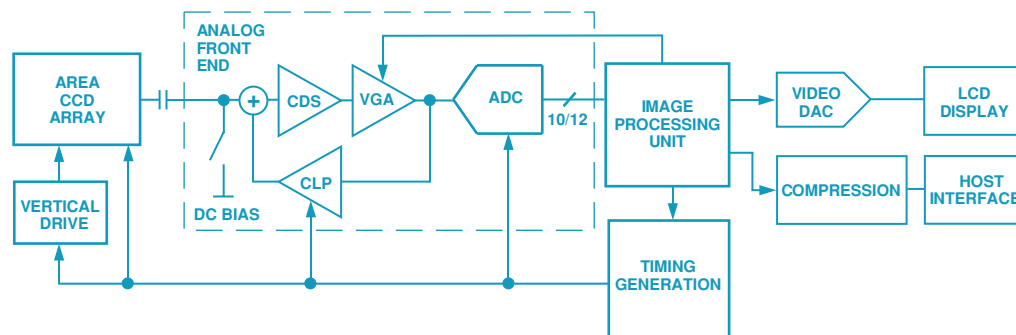


Figure 2. Simplified block diagram of a digital camera.

Applications such as security and high-speed analysis require even higher speeds. An AFE running at 36 MHz can process 100 fps of a 360-kpixel CCD. Multifunction digital cameras and camcorders, such as camcorders with still-shot capability and digital still cameras with video capability, require high-resolution CCDs (one megapixel or greater) to combine the still-shot capability with the high-speed video capability. A one-megapixel video camera that has still-shot capability and operates at the standard 30 fps will need a progressive scan CCD in order to transfer a full frame at a time while taking still pictures, and an AFE that can operate at speeds of at least 30 MSPS.

**High resolution.** Historically, camcorders and digital cameras for the consumer market have required 10-bit intensity-signal resolution. Recent advancements in image processing technology have created a need for higher resolution to allow for additional image editing and manipulation, and to ensure minimal loss of image integrity. In addition to the existing high-speed 10-bit AFEs for the camera market, Analog Devices has recently developed the AD9842 and AD9844 12-bit AFEs to satisfy higher-resolution requirements.

**Noise and nonlinearity.** Noise generated within the AFE must be minimized because it directly affects the *dynamic range* of the imaging system. The dynamic range of a system is determined by comparing the maximum signal that can be processed to the minimum resolvable signal. The AFE noise consists of wideband noise from the analog signal processing circuitry plus the quantization noise of the A/D converter.

Because imaging signals are rarely pure sine waves, classical converter specifications such as SNR and signal-to-noise-and-distortion (SINAD) are not directly applicable to an imaging system. Instead, SNR can be defined in a somewhat different manner, based on wideband noise. The wideband noise of an AFE can be measured by using a “fixed-input histogram” test. In an ideal system, a fixed input should produce a single output code. Noise in the system will produce a range of codes; from their distribution, the rms noise value can be statistically calculated. The rms wideband noise can then be compared with imager noise, and the overall system SNR can be calculated.

The linearity of the AFE is also important to the performance of an imaging system. *Differential nonlinearity* (DNL) is the difference of the actual code width and the ideal code width (quantum step) between adjacent digital levels. If the converter has large DNL errors it could transform smooth changes in luminosity to “steps” or lines visible to the human eye. Acceptable DNL performance is typically of the order of 0.5 least-significant bits (LSBs). *Integral nonlinearity* (INL) is also important. Abrupt transitions in the INL, concentrated around a small number of codes, can contribute to noticeable image artifacts. But if the transfer function of the INL is smooth, the nonlinearity will be gradually spread out over the entire range of the converter, and moderate errors will be less objectionable to the human eye. However, large “smooth” INL errors can sometimes cause errors in the digital image processing, leading to color artifacts in the final picture.

**Automatic black-level offset correction.** Ideally the reset and video levels of the CCD would be identical when there is no light

being applied to the CCD. However, the inherent CCD *dark current* causes a black-level offset that can exceed 100 mV. This offset must be corrected before any gain is applied to the signal in order to utilize maximum dynamic range of the ADC. The AFE includes an automatic black-level correction loop that samples the black level, determines the black-level offset, and applies the proper offset correction to the signal prior to the gain stage.

With an area-CCD array, the dark current will vary from line to line, so this process must be done for each line in the array. The AFE does this automatically, so the calibration coefficients for the entire area do not need to be stored. CCD arrays provide optical black pixels at the beginning of each line to allow the automatic black-level correction loop to determine the correction needed on a line-by-line basis.

**Pixel-rate gain adjustment.** A pixel in a CCD is not inherently able to distinguish between colors. In order to separate incoming light into a series of colors, color filters are placed individually over each pixel of a CCD array in a mosaic pattern. The specific pattern and selection of colors depends on the manufacturer.

CCD arrays typically output data in a serial fashion from a single channel. The sequence in which the color information comes out of the CCD depends on the filter pattern and scanning technique. For example, a progressive-scan CCD that uses a Bayer filter will output data in the following order:

R	G	R	G	Line 0
G	B	G	B	Line 1
R	G	R	G	Line 2
G	B	G	B	Line 3

The responsivity to each color in this array will be different. With white light, the green pixels, for example, may be much stronger than the red or blue pixels. In order for each pixel to be able to utilize the full dynamic range of the ADC, a variable-gain amplifier (VGA) is required before the ADC. This VGA must be able to switch gain settings to the appropriate value for each color at the pixel rate. If the VGA were not capable of changing gain at the pixel rate, the gain would have to be fixed such that the “strongest” color would utilize the full dynamic range of the ADC. At this gain setting, the “weaker” colors would have a smaller dynamic range and SNR relative to the “stronger” color.

Analog Devices has addressed this issue by developing a pixel-rate-gain amplifier (*PxGA*<sup>™</sup>). The AD9841 and AD9842 are 10- and 12-bit 20 MHz AFEs that use *PxGA* technology to switch gain-coefficients into the VGA individually at the pixel rate. Using the example of the progressive-scan CCD with the Bayer filter, each R, G, and B pixel would have its own gain coefficient applied, allowing each color to utilize the full dynamic range of the ADC, maximizing SNR. Furthermore, the effect of any nonlinearity in the analog domain will be reduced, because all colors are being processed at similar amplitudes.

Figure 3 is an example of *PxGA* employed with a CCD array having 4-color filtering.

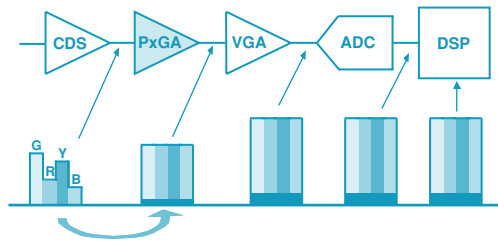


Figure 3. Signal path with PxGA.

### AD984x Family of analog front-ends

The AD984x family is a group of high-speed, low-power CMOS analog front-ends for imaging applications that use area-CCD arrays. They feature industry-leading lows in noise, nonlinearity, and power consumption at speeds of up to 36 MHz. The AD984x family is ideal for low-voltage, high-speed, portable imaging applications, such as digital still cameras and digital video camcorders—as well as any other imaging system using interlaced or progressive-scan area-CCD arrays (including machine vision, security cameras, scientific spectroscopy, video conferencing, and digital copiers).

The signal chain consists of an input clamp, correlated double sampler (CDS), pixel-rate gain amplifier (*PxGA*—on AD9841 and AD9842), digitally controlled variable-gain amplifier (VGA), automatic or programmable black-level offset calibration, and A/D Converter. Figure 4 shows a block diagram of the AD9841/AD9842 products, which contain a *PxGA*. The AD9845A, a 12-bit, 30-MSPS AFE with *PxGA* technology, is scheduled for release in December, 2000.

The 10-bit AD9840, AD9841, and AD9843 have exceptionally low noise, (~0.2 LSB rms of output noise, 74 dB SNR), operate at speeds of up to 36 MHz, and are ideal for progressive-scan CCD and high frame-rate video applications. The 12-bit AD9842 and AD9844 have 77 dB SNR and are ideal for high-end, high-resolution applications. For battery-powered applications, the AD9840 offers the lowest power consumption available, 75 mW at 20 MHz and 140 mW at 36 MHz. Although the AD984x AFEs are single-channel products, their digital output bus has three-state outputs—so several AFEs can be used in multichannel high-speed applications. Table 1 lists the critical specifications.

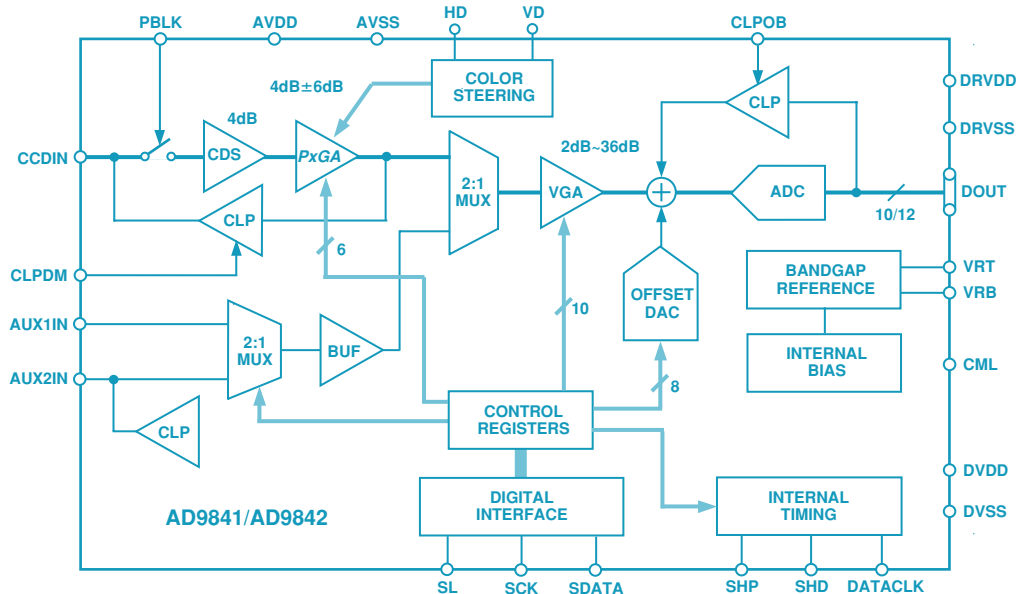


Figure 4. Block diagram of the AD9841/AD9842.

Table 1. Critical Specifications of the AD984x Family of Analog Front-Ends

Generic	Resolution (Bits)	$F_s$ Max (MSPS)	DNL Typ (LSB)	SNR Typ (dB) <sup>1</sup>	Power (mW)	Input Range (V p-p)	PGA Gain Range (dB) <sup>2</sup>	PxGA	PGA Control Type	Black Level Adj. (LSB)	Aux Video Inputs
AD9840	10	36	± 0.5	74	140	1.0	0 – 34	no	digital	0 – 64	2
AD9841	10	20	± 0.4	74	75	1.0	0 – 34	yes	digital	0 – 64	2
AD9843	10	20	± 0.4	74	75	1.0	0 – 34	no	digital	0 – 64	2
AD9842	12	20	± 0.5	77	75	1.0	0 – 34	yes	digital	0 – 255	2
AD9844	12	20	± 0.5	77	75	1.0	0 – 34	no	digital	0 – 255	2
AD9845	12	30	± 0.5	77	140	1.0	0 – 34	yes	digital	0 – 255	2

<sup>1</sup>SNR is calculated as  $20\log_{10}$  (full-scale output/rms output noise).

**Auxiliary modes.** The AD984x series AFEs offer two auxiliary inputs for applications that require other functions besides the standard CCD input. AUX1 samples, biases, amplifies (0 dB to 36 dB variable gain) and converts ac-coupled continuous waveforms to digital in applications for purposes such as diagnostics of the imaging system. AUX2 samples analog video-type waveforms, such as NTSC or PAL signals, providing black-level clamping, 0 dB to 18 dB variable gain, and A/D conversion.

### SCANNING, COLOR COPYING AND VERY HIGH-END IMAGING APPLICATIONS

There are many imaging applications with AFE needs that, though similar, are different from those of the camera market. Scanners, color copiers, fax machines, bar-code readers and professional imaging applications—such as graphic arts scanners and scientific imaging systems—all have their own sets of requirements. The major differences are the image sensor being used and the interface that connects to the back end of the AFE. The analog front-end for each of these systems may have different input requirements, offset correction techniques, dynamic-range requirements, and speed requirements—and are best served by a different type of AFE than is used by the digital still-camera and camcorder market.

**Multichannel requirement.** In an area-CCD array, color images are created by placing filters over each pixel, with the pixel values fed out from a single channel serially. In a linear CCD array or CIS module, three linear arrays are used to create color images; one line is used for each color (R, G, or B). The outputs of these three arrays are transferred simultaneously from three output channels. Color scanning applications such as document scanners, multifunction peripherals (MFP) and digital color copiers use this type of imager. The ideal AFE for these types of applications will have three sampling channels operating simultaneously.

**Black-level offset correction for a linear CCD array.** Unlike camera applications that use area-CCD arrays, an AFE that interfaces with a linear CCD array does not need an automatic black-level correction loop. Since there is only one line of up to a few thousand pixels, a single black-line calibration can be performed to determine the black-level offset once at the start of

every scan. A black-level offset correction factor can then be programmed into the AFE as an input word to the DAC, which will apply the coarse black-level offset correction to each pixel for the entire scan. This circuitry is much simpler to implement than the automatic black-level calibration loop used in a camera AFE.

**High-end scanning.** Professional scanning applications use the best CCDs available today. Graphic-arts scanners and film scanners may also use cooling mechanisms to control the temperature of the CCD, maximizing the SNR. Integration times will be as long as reasonable to maximize the dynamic range of the CCD output signal and increase the SNR. With CCD signals of up to 4 V commonly available in these applications, true 13- or 14-bit performance is achievable. In any imaging system, the AFE should not be the limiting factor in performance, so for these high-end applications a true 14-bit AFE is necessary. The AD9814 provides a true 14-bit no-missing-codes solution with 0.55 LSB rms noise at the 14-bit level (89 dB SNR) and a 4 V input range.

**Low-to-mid-range scanning.** Low-end scanners have progressed from 30-bit color systems (10 bits/channel) a few years ago, to 36- and even 42-bit color systems (12 and 14 bits/channel). While the CCDs in these low-end scanners can't achieve the 14-bit performance of the high-end scanners, the digital post-processing algorithms still require 14-bit resolution from the ADC. The AD9822, a lower-cost version of the AD9814, is ideal for these applications; it provides 1.5 LSB rms noise performance at the 14-bit level (80 dB SNR).

**Speed requirements.** The scan-speed for a stand-alone scanner has historically been limited by the host interface, whether it's EPP, USB, or even SCSI. With the scanner's ability to transmit a maximum of only a few megabytes per second to the host, the image sensor and AFE only need to operate at several megapixels per second or less. Most AFEs for scanner applications offer sample rates of 6 MHz, corresponding to 2 MHz/color. In a digital copier, the host interface is not needed. The maximum sample rate of the scan will be limited by the digital image processing and the speed of the print engine, both of which can currently operate much faster than host interfaces. Looking ahead,

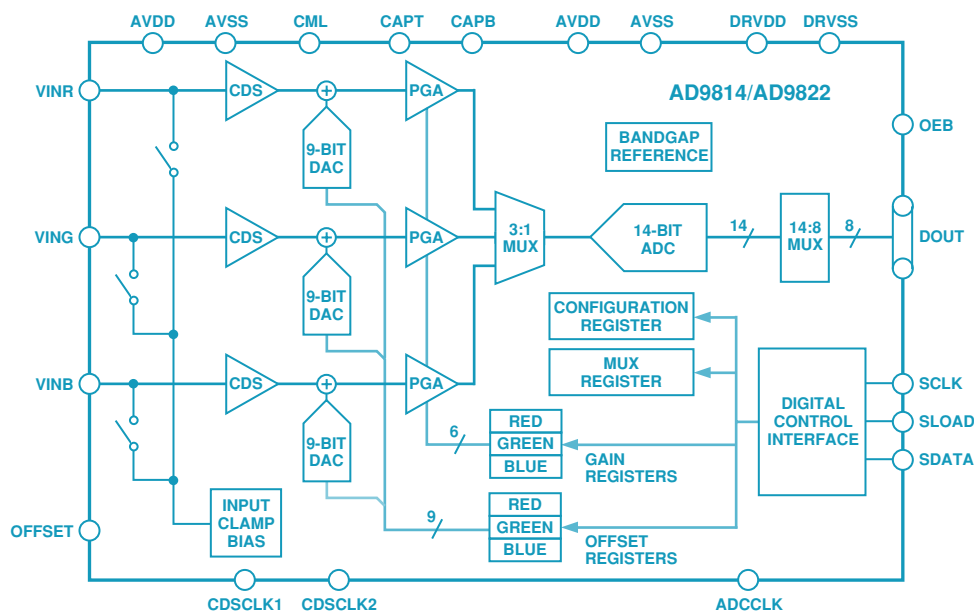


Figure 5. Block diagram of the AD9814/AD9822

IEEE-1394 (Firewire, iLink) is starting to gain market acceptance and a spec for USB 2.0 is taking shape. The host interface could potentially operate at up to 800 MHz and would no longer be the bottleneck that it is now.


To look more closely at the speed requirements for the AFE, consider typical copying specifications. For standard copying, a 300 dots-per-inch (dpi) scan is adequate. For a letter-sized document, color scanning at 300 dpi yields roughly 30 million pixels. Allowing for some processing overhead, scanning at a sample rate of 6 MHz (2 MHz/color) takes about 6 seconds, for a page rate of 10 pages per minute (ppm). To achieve 20 ppm, a sample rate of 12 MHz is needed—double the sample rate of most currently available scanner AFEs.

A multifunction peripheral (MFP), which integrates the scanner/fax/copier functions in a single unit, typically requires a higher-speed AFE than a flatbed document scanner, but it still needs to function as a good-quality scanner (600 dpi or more). For this case, the resolution needed for a letter-sized document is approximately 120 million color pixels. For this resolution, a 6-MHz AFE can produce only about 2.5 ppm, and a 12-MHz AFE increases the throughput to about 5 ppm. Many newer MFPs on the market can support 8–10 ppm in color-copy mode, at 600 dpi resolution; this requires an AFE sampling rate of around 20 to 22 MHz. With its 14-bit performance at 15 MSPS and 10-bit performance at up to 30 MSPS, the AD9822 is ideal for these applications. Figure 5 shows a block diagram of the AD9814/AD9822.

The 14-bit AD9814 and AD9822, operating at 6 and 30 MSPS, are at the high end of an Analog Devices family of three-channel AFEs with 10-bit to 14-bit resolution and sampling rates from 6 MSPS to 30 MSPS.

The AD9814 provides true 14-bit performance with high dynamic range for high-end imaging applications such as film scanners and graphic arts scanners. The AD9822 can operate at up to 30 MSPS with 10-bit performance for high-speed scanning applications. It is ideally suited for imaging applications that use trilinear color CCDs or CIS modules. At 15 MSPS, it provides high-speed, 14-bit, no-missing-codes performance, suitable for low- to midrange document scanners, digital color copiers, and MFPs.

In 2001, scanners that boast 48-bit color scanning will hit the shelves; they require a 16-bit AFE. To meet this need, the AD9826, to be released in November, 2000, is a 16-bit, 15 MSPS AFE that will operate at speeds up to 30 MSPS with 10-bit performance.

The family of 3-channel AFEs, tabulated below (Table 2), has the low-noise and high dynamic range necessary for graphic-arts scanners and spectroscopy systems. It has the speed necessary to work in digital color copiers and MFPs. It also has a programmable single-channel mode that would be useful in machine vision systems, bar code readers, and infrared (IR) imaging systems. The input voltage range of these products is as high as 4 V p-p, which is ideal for many document- and transparency-scanning applications. 

**Table 2. Critical Specs of the Family of 3-Channel Analog Front-Ends**

Generic	Resolution (Bits)	# of Channels	F <sub>s</sub> Max (MSPS)	DNL Typ (LSB)	INL Typ (LSB)	Input Referred Noise (LSB rms)	Power (mW)	Input Range (V p-p)	PGA Gain Range (V/V)	Offset Correction Range (mV)	Digital Shading and Offset Correction
AD9805	10	3	6	± 0.25	± 0.75	0.1	450	2/4	4	-80/+20	yes
AD9807	12	3	6	± 0.4	± 1.5	0.3	450	2/4	4	-80/+20	yes
AD9816	12	3	6	± 0.4	± 1.5	0.5	420	1.5/3	6	± 100	no
AD9814	14	3	10	± 0.5	± 4.0	0.55	350	2/4	6	± 300	no
AD9822	14	3	15	± 0.65	-10/+2	1.5	380	2	6	± 350	no
AD9826	16	3	15	±0.75	±16	3	380	2/4	6	± 300	no

# NOW—True RMS-to-DC Measurements, from Low Frequencies to 2.5 GHz

Whatever the waveform, the AD8361 TruPwr™ detector IC extracts the rms value at low cost, using supply voltages from 2.7 V to 5.5 V

The AD8361 is a root mean-square (rms)-responding true-power-detector analog IC for use in high-frequency receiver and transmitter signal chains. Computing the rms value of simple and complex waveforms containing frequencies up to 2.5 GHz, it is particularly useful for measuring the rms level of high-crest-factor (peak-to-rms-ratio) signals, such as occur in systems employing ordinary and wideband code-division multiple-access (CDMA and W-CDMA). Fabricated on a proprietary high- $f_T$  silicon bipolar process, it is housed in an 8-lead  $\mu$ SOIC package and specified for operation from  $-40$  to  $+85^\circ\text{C}$ .

The AD8361 is the newest development in a line of dedicated rms-to-dc conversion integrated circuits that started in 1977 with the advent of the AD536 (*Analog Dialogue* 11-2). Prior to that time, large dedicated rms modules, such as Model 440, existed, but the only ICs available in that class were analog multipliers, which can be used for rms in cumbersome, expensive circuits employing squaring and division.

The AD8361 can convert a modulated RF signal with a complex waveform, containing frequencies up to 2.5 GHz, into a varying “dc” voltage representing the rms level of the signal. Highly linear and stable with temperature, it is useful for the detection of signals using CDMA, quadrature amplitude modulation (QAM), and other complex modulation schemes, with a 30-dB dynamic range. Measurement accuracy is to within 0.25 dB over a 14-dB range, and 1 dB over a 23-dB range. It requires only 4 mA from a 2.7-V to 5.5-V power supply (and has a 1- $\mu\text{A}$  power-down mode for conserving battery power when not in use). An evaluation board is available (AD8361-EVAL). The AD8361 is priced at \$3.75 in 1,000s.

## WHY AN RMS IC

RMS ICs compute the true rms value of a waveform, performing a running solution of the equation,

$$V_{RMS} = \sqrt{\frac{1}{T} \int_{t_1}^{t_2} (V_{IN})^2 dt}$$

They produce a faithful measure of the average power in a resistive load regardless of the waveshape, with greater accuracy than devices that compute simple averages—and in a much simpler implementation—at lower power and lower cost, than devices that make use of heating effects. Typical applications are found in transmitter power control and received signal strength indicators (RSSIs).

The AD8361 achieves this function through the use of a proprietary feedback technique in which the outputs of two identical squaring cells are balanced by the action of a high-gain error amplifier (Figure 1).

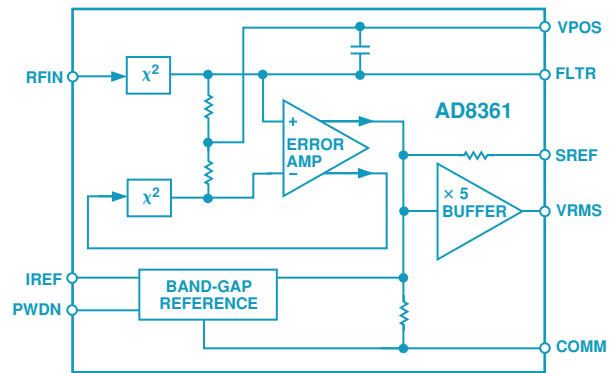


Figure 1. Functional block diagram.

**How it works:** The signal to be measured is applied to the input of the first squaring cell, which presents a nominal resistance of 225 ohms between the input pin (RFIN) and COMM (connected to the ground plane). Since the input pin is at a bias voltage of about 0.8 V above ground, a coupling capacitor is required. Because this capacitor is an external component, it can be chosen to permit the measurement range to be extended to arbitrarily low frequencies.

The squaring cell generates a current proportional to  $V_{IN}^2$  and applies it to a parallel R-C. Because of the low-pass filtering, the voltage developed across the resistor is proportional to the average value of  $V_{IN}^2$  (and the power dissipated in the device’s input resistance). Additional capacitance can be connected externally to increase the filtering time constant as desired.

This mean-square voltage is applied to one input of a high-gain error-sensing amplifier. The amplifier’s other input is the output of a second squaring cell, which computes the square of the (feedback) output of the amplifier. At equilibrium then, the amplifier’s output is required to be proportional to the square root of the average value of  $V_{IN}^2$  (i.e., the rms value of the input). A buffered version of this amplifier output becomes the device output.


The squaring cells have very wide bandwidth and are capable of responding to frequencies from dc to microwave. Because they are essentially identical and tend to track with temperature, the conversion gain is pretty much independent of their individual gains and is stable with temperature.

The AD8361 responds to inputs of up to 390 mV rms with a 3-V supply and 660 mV rms with a 5-V supply. It has a nominal conversion gain of 7.5 V/Vrms. Three operating offset modes are available, to accommodate a variety of A/D converter requirements:

- Ground-referenced mode, with zero offset;
- Internal reference mode, offsetting the output 350 mV above ground;
- Supply reference mode, offsetting the output to  $V_S/7.5$ .

## REFERENCES

John Greichen and Eamon Nash, “Revolutionary IC performs rms-to-dc conversion,” *Microwaves & RF*, September, 1999, pp. 140–146. ([www.mwrf.com](http://www.mwrf.com))

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# Single-Sideband Upconversion of Quadrature DDS Signals to the 800-to-2500-MHz Band

by Rick Cushing, NI7X

## INTRODUCTION

Direct digital syntheses (DDS) technology is advancing rapidly, but *direct* synthesis of UHF and microwave output frequencies is not yet practical or economically feasible. Current state-of-the-art commodity DDS ICs—such as the 300-MHz AD9852 Single- and AD9854 Quadrature Complete-DDS chips—offer *usable* outputs to the lower VHF spectrum, approximately 120 MHz. Sampling speed limitations of the DDS and output DAC form the major bottleneck; fundamental DDS output signals must not be greater than one-half the sample frequency. The next generation of high-speed DDS ICs from Analog Devices will challenge those limitations with 900-MHz sample rate and 360-MHz usable fundamental output.

In order to take advantage of DDS attributes at UHF and microwave frequencies, a DDS is commonly integrated with a phase-locked loop (PLL) or upconverted in a mixer. Unfortunately, multiplication using PLLs compromises signal integrity, frequency resolution, and agility. Also, upconverting a DSB (double-sideband) signal to single-sideband at a higher frequency, using a mixer, may require difficult or impossible output filtering as well as a high-quality fixed-frequency local oscillator (LO). Methods used to overcome these shortcomings usually result in the need for multiple PLL or mixer/filter/oscillator stages.

The following is an improved and economical approach to *single-stage* upconversion to the frequencies from 800-to-2500-MHz, using the above-mentioned AD9854 Quadrature Complete-DDS and a new device, the AD8346 Quadrature Modulator, which has phase accuracy to within 1 degree and amplitude balance to within 0.2 dB at 1900 MHz. The upconverted suppressed-carrier, single-sideband signal displays >36-dB typical rejection of LO and undesired sideband frequencies over the entire frequency range. Moreover, *all* DDS signal qualities are preserved, while the unwanted products of upconversion are minimized. 36-dB rejection is adequate for many applications, and this 4000× suppression of unwanted signal power will greatly reduce output filter complexity or alternatively improve the feasibility of effective filtering in more-demanding applications.

To choose between the upper and lower sidebands, one simply reverses or exchanges the quadrature DDS signals, I for Q and Q for I, at the AD8346 modulator input pins. The AD8346 modulator input pins. The AD8346 modulator has a variety of modulation modes (AM, FM, PSK, and FSK) available. This enhances the utility of this application by providing digital and analog communications capability in addition to agile, single-frequency signals.

Upconversion of quadrature DDS signals is just one example of what can be done with the AD8346 Quadrature Modulator. It can in fact upconvert *any* quadrature analog baseband signal (dc to 70 MHz) with similar sideband suppression.

## QUADRATURE SSB UPCONVERSION

The AD8346 Quadrature Modulator provides impressive SSB upconversion performance, permitting baseband signals to directly modulate local-oscillator (LO) frequencies from 800 MHz to 2.5 GHz with typically 36 dB rejection of redundant sideband and LO frequencies. The upconverted signal may be frequency-hopped, spread-spectrum or stationary; and unmodulated or wide-band modulated, within the allowable input bandwidth. For upconverting quadrature signals synthesized by DDS, the block diagram in Figure 1 shows how AD9854 output signals would be applied to the AD8346 differential “baseband modulation” inputs for SSB upconversion near the LO frequency.

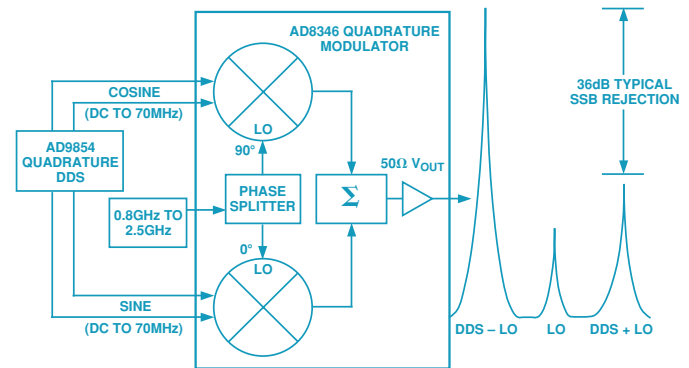


Figure 1. Quadrature DDS SSB Upconversion.

In quadrature upconversion, two mixers are driven with sine and cosine LOs, which are internally derived from a single-ended high-quality oscillator, provided by the user. The mixers are fed sine and cosine baseband signals (filtered DDS output signals) to be symmetrically upconverted about the fixed LO. The two mixer outputs are summed internally to add in-phase components and reject quadrature components of the mixer outputs. The end result (without additional filtering) is a suppressed-carrier, single-sideband, voltage output at -10 dBm and 50-ohm impedance, at a frequency that is either the sum or difference of the LO and baseband signal, plus suppressed remnants of the LO and opposing sideband.

Quadrature modulation, which requires precise phase relationships, is not a new concept. Fifty years ago, one of the first uses of quadrature modulation was to produce single-sideband radio-telephony signals; it was called the “phasing method.” However, the “filter method” came to be preferred because maintaining quadrature phase relationships over appreciable bandwidth is not easily accomplished with *analog* methodology. Both methods were used primarily at low IF frequencies, with the aim of removing the redundant sideband and eliminating the “carrier.”

The AD9854 DDS produces *digitally precise* quadrature output signals (typical accuracy two-tenths of one degree) from dc to >120 MHz, using a 300-MHz clock source. In the example shown in Figure 1, the clock can be derived from the high-quality LO if divided down appropriately. The quadrature phase error of the AD8346 is typically 1 degree over its 800-to-2500-MHz output



range. These devices comprise a “chipset” that can serve well in many wideband digital and analog communication schemes, from spread-spectrum to television.

A more complete explanation, including a basic mathematical analysis of analog and digital quadrature modulation and SSB upconversion, is available in an article written by Doug Smith, “Signals, Samples and Stuff: A DSP Tutorial (Part 1)” in the March/April, 1998, issue of *QEX: Forum for Communications Experimenters* magazine. For more information contact the American Radio Relay League, 225 Main Street, Newington, CT 06111, <www.arrl.com/qex.>

To gain a greater appreciation of the merits of quadrature upconversion, it may be instructive to compare two popular methods for generating UHF and microwave DDS-based signals: *DDS/PLL frequency multiplication* and *single-stage mixer upconversion*.

### PLL/DDS MULTIPLICATION

PLL multiplication of a DDS signal to UHF and microwave frequencies is easily and economically accomplished, but at a cost: the advantages provided by DDS will be degraded in practically every desirable attribute, including the phase-noise specification, new-frequency acquisition time, frequency resolution and spurious-free dynamic range (SFDR). Combinations of PLL/DDS/mixer/filter that reduce the signal degradation do exist, but the complexity and cost of such multiple-stage implementations may not be tolerable. Figure 2 shows a typical DDS/PLL implementation.

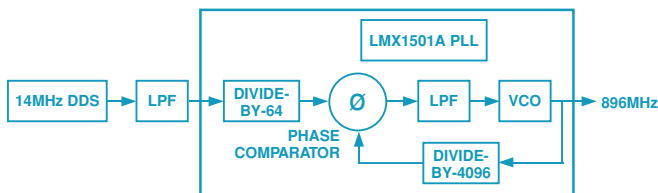


Figure 2. Example of a DDS and PLL integration using an LMX1501A PLL evaluation board and an AD9851 DDS.

PLL output phase noise is an obvious and easily observed phenomenon; its magnification will degrade performance in proportion to the multiplication factor of the PLL (expressed in dB,  $20 \log f_{OUT}/f_{IN}$ ). For example, if the frequency of a DDS signal at 10 MHz is multiplied by 100, to yield an output of 1 GHz from a PLL, the output phase noise within the PLL loop bandwidth will be approximately 40 dB greater than with the original input signal. Furthermore, spurious signals, or “spurs” within the PLL loop bandwidth will be increased by the same amount. This may result in *unacceptable* spur levels that are up to 40 dB greater than those of the DDS input signal.

Spectral plots easily show how the phase noise of a DDS signal suffers after being multiplied by 64 in the PLL circuit in Figure 2. Figure 3 shows the DDS input signal to the PLL at 14 MHz and Figure 4 shows the PLL-multiplied DDS signal at 896 MHz. The wide noise “skirt” is the signature of degraded phase noise.

To illustrate the effect of PLL multiplication on spur levels, the DDS signal was modulated to produce an abundance of low-level spurs close to the fundamental. Figure 5 shows the modulated DDS signal that was fed to the PLL, while Figure 6 shows how these spurs within the 30 kHz loop bandwidth of the PLL have been magnified. Note that >60 kHz away from the carrier, spur amplitudes are not affected. The phase noise has not been altered nor have any other parameters been changed.

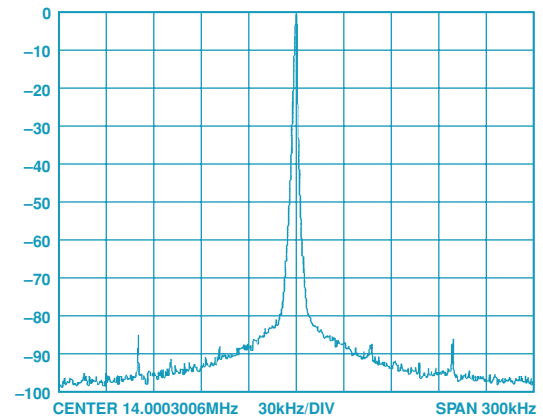


Figure 3. 14 MHz DDS input signal.

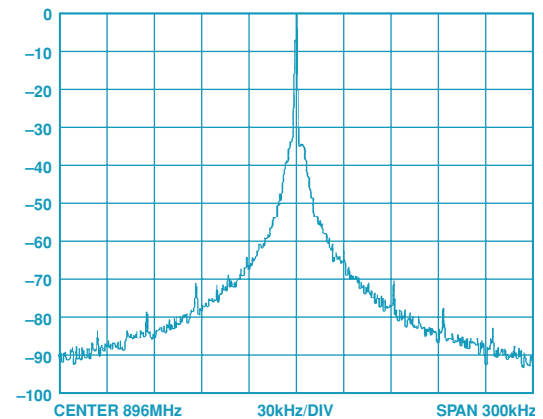


Figure 4. 896 MHz PLL output signal.

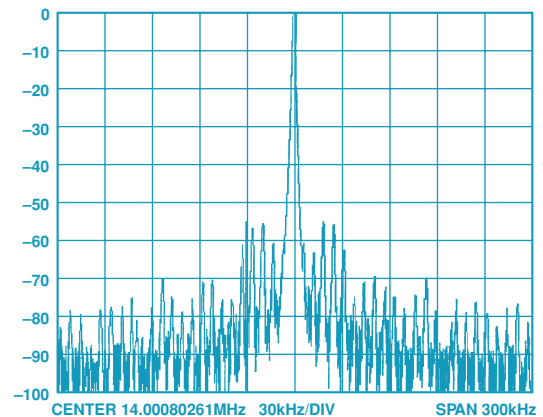


Figure 5. Modulated 14 MHz DDS signal to PLL.

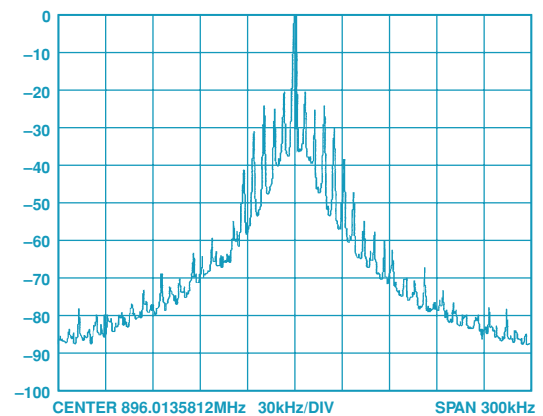


Figure 6. 896 MHz PLL output signal.

In addition to phase noise, timing jitter, and spur-level degradation, many other desirable DDS attributes, including frequency agility and resolution, will be adversely affected with PLL multiplication. Even frequency resolution will become  $N$  times worse than the DDS resolution, and new-frequency acquisition will be limited by the PLL's settling time (which can be as much as 10,000 times greater than that of the DDS).

### DDS/MIXER UPCONVERSION

A better option available to the designer is to upconvert a DDS signal to UHF/microwave frequencies using a mixer. Upconverting does not significantly increase either the spur levels or the phase noise. Furthermore, frequency agility and resolution remain unaffected. The largest obstacle to overcome is the presence of the double-sideband (DSB) output:  $LO + DDS$  and  $LO - DDS$ , and any LO feedthrough that occurs.

Figure 7, showing a 200-MHz region of spectrum of a suppressed carrier (LO), single-upconversion mixer output, demonstrates this problem with upconversion. The two sidebands are 50 MHz apart, with LO feedthrough at a frequency midway between the two at 1.04 GHz. This 50-MHz spread is only 5% of the 1-GHz output frequency. Filtering the signals to remove the unwanted sideband and LO feedthrough will be extremely difficult. If the output frequency is increased to 2 GHz, it may complicate matters to the point where filtering is impractical. To overcome this problem, designers traditionally incorporate multiple stages of mixing and filtering to produce a DSB signal with larger sideband spacing at UHF/microwave that will be more easily filtered but at far greater expense and complexity.

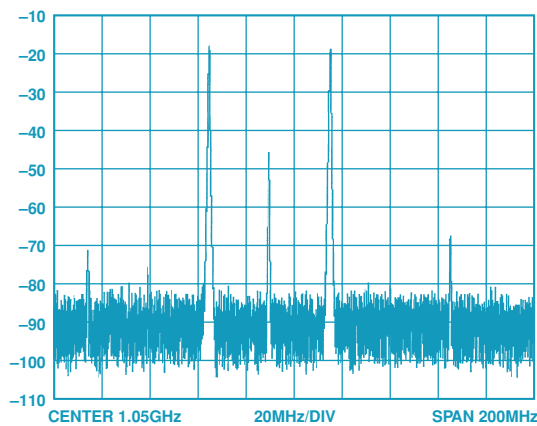


Figure 7. DSB output from typical mixer.

### DDS UPCONVERSION LAB RESULTS

A quadrature implementation of the SSB upconverter was accomplished in the lab using the evaluation boards for the AD9854 and the AD8346. Modifications to the AD8346 evaluation board were required to accept the filtered, quadrature, *single-ended* signals provided by the AD9854 evaluation board. The output voltage levels also needed to be increased to suit the AD8346 input requirements. A diagram of the lab hook-up and modifications is seen in Figure 8. Modifications are as follows:

1. Add two 1:16 center-tapped impedance-step-up transformers (Mini-circuits T16-6T) to convert single-ended quadrature signals to differential signals and to provide a 1:4 voltage step-up. Use of the center-tapped secondary allowed a dc offset voltage of 1.2 volts to be added to the differential signals to comply with the AD8346 input-biasing requirements.

2. Add 1000-ohm termination resistors across each transformer output.
3. Add a 1.2-volt dc bias source consisting of two silicon diodes forward-biased from the 3.3 volt supply voltage through a 2000-ohm current-limiting resistor. Connect to center-tap of both I- and Q-channel transformer secondary windings.

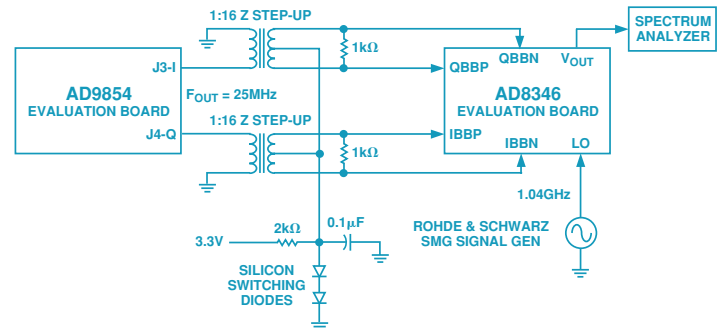


Figure 8. Hookup and modification of Analog Devices evaluation boards for lab evaluation.

Tests of this setup verified the performance expectations conveyed in the AD8346 data sheet when the quadrature input signals from the AD9854 were properly adjusted to compensate for quadrature phase error and I & Q amplitude imbalance. See Figures 9 and 10.

Errors in the I & Q quadrature phase relationship are introduced—*after* the signals exit the AD9854 IC—by the filters, unequal cable and PCB trace lengths, transformer differences, etc. System phase errors cannot be corrected through programming changes of the AD9854. Its outputs are *fixed in accurate quadrature*. Phase errors can be corrected by adjusting cable lengths from the AD9854 to the AD8346 evaluation board. Amplitude inequalities can be corrected using the AD9854's 12-bit, independent sine and cosine (I & Q), digital amplitude multiplier stages.

Figure 9 shows a 200-MHz segment of the output spectrum of the AD8346 centered around 1.05 GHz. The DDS “modulating” upper and lower sideband signals are seen 25 MHz away on either side of the LO at 1.04 GHz. A difference of  $-40$  dB is indicated between the suppressed upper sideband (USB) and the favored lower sideband (LSB) amplitudes. The 40-dB differential equates to a power ratio of about ten-thousand to one. This level of sideband suppression is indicative of approximately 1 degree of input-signal phase mismatch.

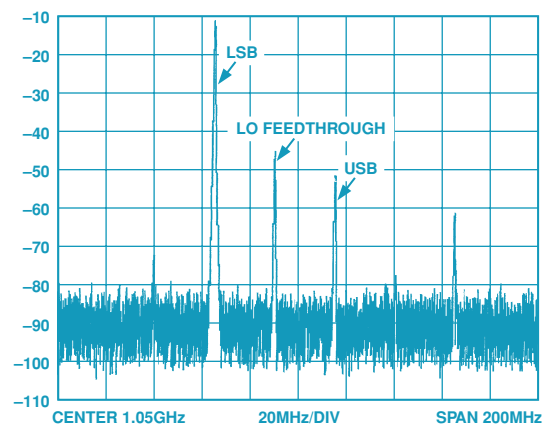


Figure 9. Output spectrum of AD8346 modulator.

A close-in view (Figure 10) of the lower sideband (LSB) at 1.015 GHz shows excellent signal integrity. It is in striking comparison to the PLL-multiplied signal in Figure 4. As noted earlier, the sine and cosine DDS signals to the quadrature modulator can be exchanged to cause the complementary sideband to be favored.

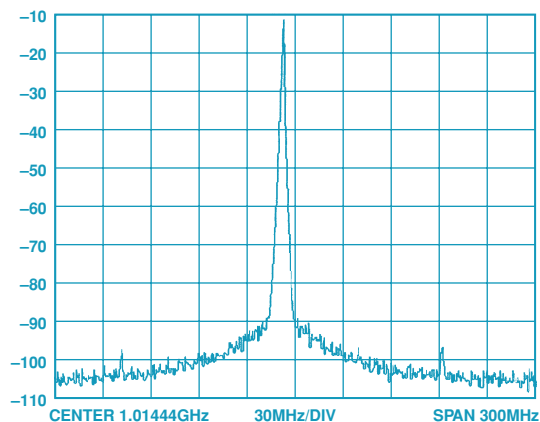


Figure 10. Close-in look at the LSB.

LO feedthrough amplitude (−36 dB) is greater than the suppressed sideband in this setup. LO feedthrough level is not affected by either the phase or amplitude of the DDS I & Q input signals. To reduce the significance of LO feedthrough, the voltage levels of the I & Q input signals should be maximized (1V p-p) at each differential input pin.

### CONCLUSION

Quadrature modulation is a well-established and economical method of DDS upconversion to UHF and microwave frequencies, without losing any of the desirable attributes of DDS technology or compromising signal quality. The AD8346 quadrature modulator simplifies the process. It is a “natural” match to the AD9854 DDS, with its differential quadrature

outputs. With a high-quality LO, UHF and microwave SSB output is readily achievable.

With the AD9854’s variety of modulation modes, this application supports a (nearly) complete AM, FM, PSK, FSK exciter at microwave output frequencies. With minor additional signal processing of the AM suppressed-carrier I & Q DDS outputs, SSB voice or other amplitude modulation schemes become possible. Figure 11 shows how the ICs would be interconnected with external modulating sources and controlling devices to perform communications functions.

The 36-dB (typical) sideband and LO rejection is directly usable in many applications, and output filtering becomes a much less formidable task in more-demanding applications. Appropriate adjustment of the DDS I & Q signal phase relationship and amplitude balance can increase sideband suppression even further.

Although it was specifically designed to provide the appropriate output signals without the need for multiple DDSs to achieve this function, the AD9854 in the application described here is not the only way to combine DDS and quadrature modulation. Other DDS ICs, such as the AD9850, AD9851 and the AD983x series, might also be used in quadrature pairs. If two DDSs can be synchronized, it is likely that they can be programmed to achieve quadrature outputs using internal phase-offset circuitry. See the DDS Information center at [www.analog.com/dds](http://www.analog.com/dds) for a complete listing of DDS and digital modulator products, and for access to technical notes and data sheets. It is also worth noting that the AD9854’s independently programmable I & Q output amplitudes make output matching a simple software routine.

The relative simplicity and economy of quadrature DDS SSB upconversion to over 2 GHz should encourage readers to consider adding this technique to their repertoire. It preserves every desirable DDS attribute at microwave frequencies, and at the same time drastically reduces the undesirable redundant sideband of conventional double-sideband-mixer upconversion. ▶

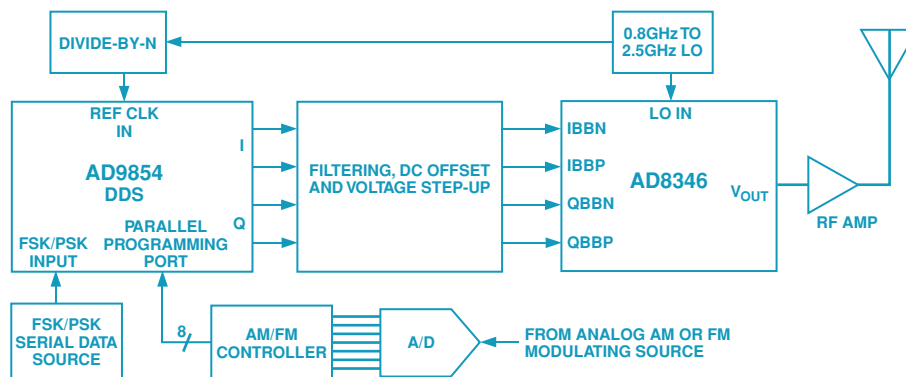


Figure 11. Block diagram depicting the stages needed for an RF exciter producing AM, FM, FSK, PSK modulated signals in the 800 to 2500 MHz frequency band.

# VDSL Technology Issues—An Overview

by Vladimir Friedman

## ABSTRACT

The very-high-speed digital subscriber-line (VDSL) technology makes possible delivery of information to speeds up to 52 Mb/s. The high-frequency band used (up to 20 MHz) raises many challenges not existing in the present DSLs, among them spectral allocation, transmission in a FEXT (far-end-crosstalk) noise environment, RF interference sources. We discuss here the issues pertinent to the deployment of VDSL technology.

## INTRODUCTION

VDSL is capable of delivering data rates comparable with cable modems. Optical fiber is used to transport data to the residential area; from there data is transmitted over the existing copper infrastructure. Efforts to establish standards for this technology are currently under way in the US (ANSI T1E1), Europe (ETSI) and the International Telecommunication Union (ITU). The wide frequency bandwidth used (up to 20 MHz) raises several technical challenges. The most important ones are presented below, as they are discussed in the standardization committees.

## VDSL DEPLOYMENT CONFIGURATIONS

Due to the large attenuation of high-frequency signals on twisted-pair lines, the deployment of VDSL is limited to a loop length of less than 4500 feet from the signal source. Figure 1 shows two possible configurations. For customers close to the central office (CO), VDSL can be deployed over copper wiring from CO (Figure 1a); this configuration is called fiber to the exchange (FTTEx). For more-distant customers the fiber is run to an optical network unit (ONU), from which the data is distributed using the existing infrastructure (Figure 1b). This configuration is called fiber to the cabinet (FTTCab).

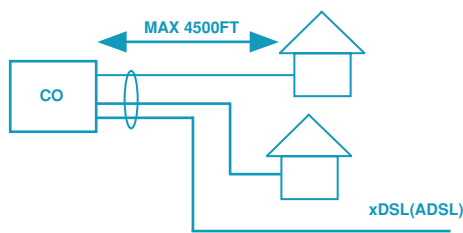


Figure 1a. FTTEx configuration.

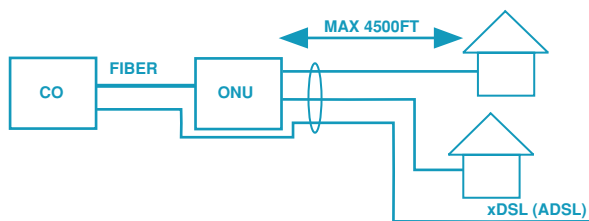


Figure 1b. FTTCab configuration.

The present spectrum allocation proposals use the ADSL downstream frequency band for VDSL downstream as well. From the point of view of the crosstalk between ADSL and VDSL, there is a subtle difference between the two configurations of Figure 1. In the FTTEEx case, the presence of the VDSL does not affect ADSL performance because VDSL power spectral density (PSD) is less than ADSL PSD. Conversely, the presence of ADSL in the same binder may have a serious impact on VDSL performance. In FTTCab configuration the situation is reversed. VDSL signals from the ONU may generate unacceptable noise levels for the ADSL downstream signal, as it becomes heavily attenuated along the path from CO to ONU. (Reference 1)

## DATA RATES AND SPECTRUM ALLOCATION

Table 1 depicts some of the data rates considered in the US for standardization at one time or another.

Table 1. VDSL Data Rates

Profile	Asymmetric Services Data Rate		Symmetric Services
	Downstream Mb/s	Upstream Mb/s	Each Direction Mb/s
Short Loop (1500 ft.)	51.84	6.48	25.96
	38.88	4.32	19.44
Medium Loop (3000 ft.)	25.92	3.24	12.96
	19.44	2.43	9.72
	12.96	1.62	6.48
Long Loop (4500 ft.)	6.48	1.62	

The asymmetrical services expected to dominate in the US market include video distribution—including HDTV—and Internet applications. In Europe there is more interest in the symmetrical services, which are directed towards business applications. Within each category of services, the data rate depends on the distance from the customer premises to the ONU (CO).

Frequency-division multiplexing (FDM) was chosen as the multiplexing method for separating the upstream and downstream data transmission. For asymmetrical services the ratio between the downstream and upstream data rate is close to 10:1, thus most of the bandwidth should be allocated for downstream. For symmetrical services the bandwidth should be allocated equally to the two directions. A requirement of the standards is that both types of services should coexist on the same cable. Under these conditions, no spectral allocation method can simultaneously optimize both the asymmetrical and symmetrical services data rates.

One solution is to define two spectrum allocations: One is optimized toward the asymmetrical services, while accommodating certain symmetrical data rates as a secondary goal; the other is geared more towards symmetrical services. Also, because the short loop profile requires considerable bandwidth, it was recognized that it will be difficult to accommodate them in the same binder with the rest of the services. This is why the standardization effort is presently focused on medium loop profiles; this spectral allocation is also suitable for the long loop case. An agreement in principle was reached within ITU for a spectrum allocation that

contains four bands (two downstream and two upstream) in the 138-kHz-to-12-MHz frequency range. An example of such a spectrum allocation for North America (Reference 2) is shown in Figure 2. The reach is 2500 ft for 22/3 Mb/s asymmetrical services and 1700 ft for 13/13 Mb/s symmetrical services. For lower data rates on longer loops the first upstream/downstream bands can be used. Future allocation of the spectrum above 12 MHz will allow the transmission of higher data rates on short loops.

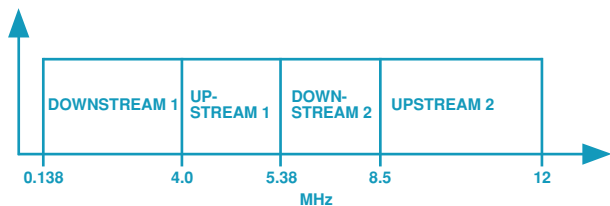


Figure 2. VDSL frequency plan for North America.

### BRIDGED TAPS

Figure 3 shows a loop with a bridged tap and its attenuation for different tap lengths,  $L = 0, \lambda/4, 5\lambda/4, 101\lambda/4$ , where  $\lambda$  is the wave length. The shortest bridged tap creates a deep null in the channel

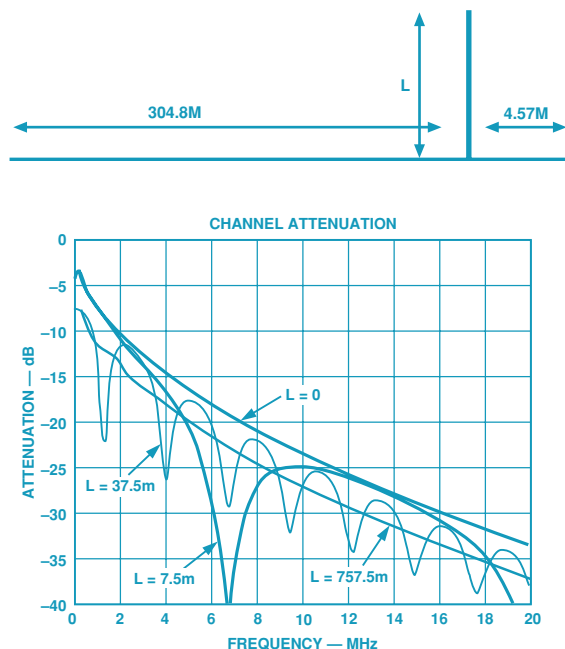


Figure 3. Magnitude response of a bridged-tap loop.

characteristic. For the VDSL spectral plan, from Figure 2, such a bridged tap will significantly reduce the data rate in the Downstream 2 channel. The ratio between downstream and upstream data rates will be significantly affected by short bridged taps. The longer bridged taps have less of an impact because the reflected wave is attenuated by the losses in the line. There is still an SNR loss because the transmitted signal power is split between the line and the bridged tap at the insertion point. The difference is that on long bridged taps the SNR loss is evenly distributed between the two directions. This is the reason why the ETSI standard does not have provisions for bridged taps; however, they are still part of US standard requirements.

### CROSSTALK NOISE SOURCES

Figure 4 illustrates the crosstalk noise sources on a twisted-pair wire. The near-end crosstalk (NEXT) noise is generated between signals travelling in opposite directions. NEXT is proportional to frequency at power 1.5. Because the incoming signal is attenuated at the receiver input, only one such interferer will reduce the VDSL performance significantly. This noise source can be contained by allocating different frequency bands for upstream and downstream direction (Figure 2).

The far-end crosstalk (FEXT) noise is generated between signals travelling in the same direction in a cable. FEXT is the dominant crosstalk noise source in VDSL. Its power spectral density:

$$PSD_{FEXT} = k L f^2 |H_{ch}(f)|^2 \cong k L f e^{-(2 L \alpha(f))}$$

depends on the frequency,  $f$ , the length of the cable segment,  $L$ , that the two signals run in parallel, and the channel transfer function  $H_{ch}(f)$ . Because the channel transfer function is an exponential function of  $L$ , the power spectral density of the FEXT noise is small for large values of  $L$  and is relatively high for low  $L$ . In the upstream direction (Figure 4), transmitter Tx4US is much closer to ONU than Tx2US and Tx3US. Tx4US will inject a relatively high level of FEXT noise in pairs 2 and 3. The upstream signals from these pairs are heavily attenuated at the point where the FEXT noise is injected. The result is that in the upstream direction the FEXT noise from sources close to the ONU (CO) will degrade significantly the SNR of the sources far away from ONU, collocated in the same binder. The solution consists in reducing the transmit power, depending on the distance from the transmitter location to the ONU (CO). This problem does not exist in the downstream direction (all the transmitters are located at ONU/CO).

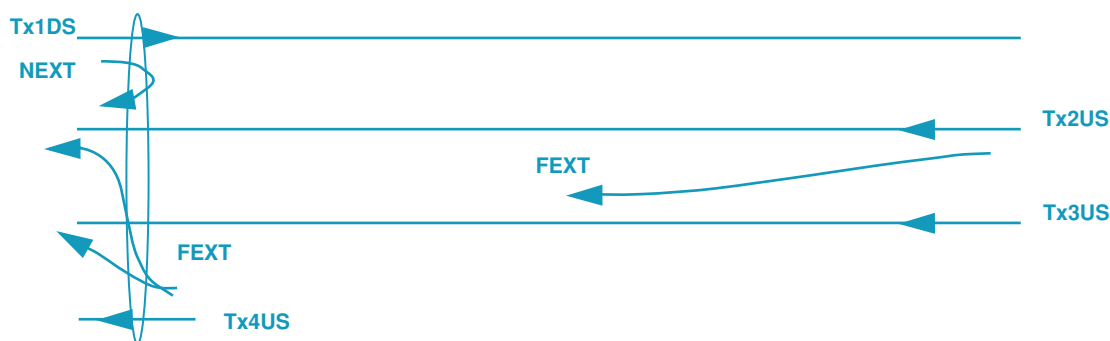


Figure 4. Twisted-pair crosstalk noise sources.

## RF INTERFERENCES

Both the European and US standards allow six relatively narrow (100 kHz–200 kHz) amateur radio bands within the VDSL spectrum. Significant interference can exist between the VDSL signal and signals from amateur radio stations. Causes include improper (lack of) shielding, decrease in the balance of the phone line at high frequencies (it can go as low as 10 dB–30 dB), and use of untwisted drop wires. There are three problems manifested by these interference sources:

- *egress suppression*. VDSL interference in the radio amateur bands can be restricted by limiting the power spectral density of the VDSL signal in these bands to 80 dBm/Hz.
- *ingress suppression*. The amateur-radio signal interference can be as high as 0 dBm at the VDSL receiver input. It is highly desirable to attenuate such interference before converting to digital, otherwise a high-resolution ADC able to handle both the signal and the interfering signals is necessary.
- the amateur radio signal is a non-stationary signal, characterized by ON/OFF periods. Eliminating the effects of this signal (even attenuated) in the digital domain is not a simple task.

## LINE-CODE

Three proposals for the line-code were submitted to the standards organizations:

- *single carrier modulation (QAM)*, the input data is split into two streams that modulate an in-phase and a quadrature sine wave; this method is presently used in most of the modems. It must be noted that with a frequency band allocation such as that in Figure 2, two such systems are necessary for each upstream and downstream direction.
- *discrete multitone modulation (DMT)*, the frequency band is split into a large number of channels; each individual channel uses QAM modulation. An efficient method for coding/decoding makes use of the IFFT at the transmitter and FFT at the receiver; it also ensures orthogonality between the carriers. This modulation method is used in ADSL.
- *filtered multitone (FMT) modulation* (Reference 3), can be viewed as a combination of the other two methods. The modulation is achieved by splitting the data into several streams, each of them applied to one of the inputs of a filter-bank. Because of implementation complexity, the number of channels is considerably less than in DMT. The sharp filters allow the elimination of guard bands used in QAM. Linear or decision-feedback equalizers are necessary for eliminating inter-symbol interference (ISI).


QAM and DMT modulation are compared below in the light of VDSL's specific problems. In most of the cases the reader will be able to extrapolate the results for FMT.

- The DMT signal has a Gaussian amplitude distribution. A peak-to-average ratio (PAR) of 15 dB is necessary to reduce the clipping to an acceptable level. Accommodating such high signal peaks requires an extended range for the transmitter buffer and increases the power consumption in the analog front end. Some of the single-carrier modulation's advantage is lost, because the line signal is the sum of two QAM channels (see Figure 2).
- Two QAM transmitters/receivers are necessary in each direction for single-carrier modulation; the DMT requires frame synchronization and supervision, and timing recovery is more difficult. As a result, the complexity is about the same for the two methods.
- The data rate losses due to cyclic prefix/suffix (DMT modulation) and guard bands (QAM) are similar.
- *RF egress*. In order to reduce the transmit PSD to –80 dBm/Hz for each of the radio amateur bands falling within the transmit band, notch filters are necessary for single modulation systems. These filters make the equalization more difficult. In DMT systems, the bins falling within amateur radio bands are not used. As a general observation, DMT modulation's greater flexibility in controlling PSD across the VDSL spectrum may translate into higher performance.

## CONCLUSION

VDSL allows the transmission of high data rates, up to 52 Mb/s, using the existing twisted-pair wires. An agreement was reached in the standards organizations on using frequency division multiplexing with four frequency bands (two for upstream and two for downstream) in the 138-kHz-to-12-MHz frequency range. The details of the spectrum allocation are yet to be determined. The FEXT noise is the major crosstalk impairment. It requires power-backoff in the upstream direction. Short bridged taps can significantly alter the ratio between the upstream and downstream data rate, which is the reason they are not specified in the ETSI standard; however, they are still part of the US standard. Finally, T1E1 and ETSI agreed to include all three line codes in the present standards. In the long term the standards may evolve to the line code most capable of facing the difficult technical problems posed by VDSL.

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**Christine Bako** (page 38) is an Applications Engineer at ADI's facility in Limerick, Ireland, since August, 1998. She supports video products, principally encoders. She is a graduate of the University of Salford, Manchester, UK, with a BE. In her spare time she engages in skydiving and edits the Irish Parachute Club newsletter.



**Vladimir Friedman** (page 50) has received a Dipl. Eng. Degree from Polytechnic Institute of Bucharest, Romania, and an MSEE degree from the Polytechnic Institute of New York. He has worked at the Telecommunications Research Institute of Bucharest, Romania, in the area of CW wide-band FM systems; at ITT Advanced Technology Center, Shelton, CT, designing VLSI circuits for switching systems and DSP; and at AT&T Bell Laboratories developing architecture and signal processing algorithms for sigma-delta data conversion and ISDN and ADSL CAP modems. He joined Analog Devices in 1996, where he is involved with ADSL and VDSL modems using DMT modulation.



**Eric Nolan** (pages 25, 28) is the Marketing Manager for amplifiers and analog audio products in ADI's Precision Amplifier group. Earlier, he held various engineering and management positions in product engineering, product development, and key-account management. Eric holds a BSEECs degree from the University of California, Berkeley (1981). Favorite activities include reading, music, woodworking, golf, and baseball.



**Scott Wayne** (page 21) is ADI's Senior Technical Editor and Contributing Editor for *Analog Dialogue*. With an SBEE from MIT, Scott joined Analog Devices as a Design Engineer in 1978, and has designed a variety of precision A/D and D/A converters using modular, hybrid, and monolithic technologies. He is the author of several articles and holds two patents. In his free time Scott volunteers as a Big Brother, and enjoys sailing, hiking, and golf.



**Neil Rankin** (page 10) joined Analog Devices in September 1997 after graduating from Middlesex University, in London. Since joining, he has worked as a Design Evaluation Engineer for the Digital Audio product line, based in Limerick, Ireland. He is a licensed private pilot and enjoys hopping around Ireland.



**Rick Cushing** (page 46) was a Design Engineer for the High-Speed Converter product line in the Analog Semiconductor division at Analog Devices, Greensboro, NC, until his recent retirement. When most recently heard from, he was cruising under sail in the Atlantic Ocean.

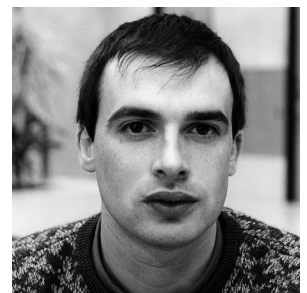
**David Hanrahan** (page 16) is an Applications Engineer for the Temperature and Systems Monitoring Group (TSM) at ADI's Limerick, Ireland, facility. David joined the Applications Group in August, 1998, after completing his B. Tech. in Electronic Engineering at Waterford Institute of Technology. Before joining ADI, David worked as a research assistant at the National Center for Laser Applications at National University of Ireland, Galway. His interests include walking, reading, working on his radio controlled helicopter (no, it hasn't flown yet!), and weekends with friends and family.



**Dr. J. Finbarr Moynihan** (page 3) is a Senior Systems Manager for the Motion Control Group at Analog Devices. He was graduated with a bachelor's degree from University College Cork, in Ireland, and subsequently received a Master's of Engineering Sciences degree and a PhD, also from University College Cork. His doctoral thesis was on the application of DSPs in motor-control systems. He has published many papers on motor control, given seminars at international conferences, lectured at University College Cork, and has been a visiting lecturer at the University of Padua, in Italy.



**Albert O'Grady** (page 33) is a Senior Engineer with the Applications Group, in Limerick, Ireland, where he provides customer support and new-product definitions for high-resolution, low-bandwidth, sigma-delta ADCs and general-purpose DACs. Albert holds a B. Eng. from the University of Limerick. In his spare time, Albert enjoys reading and plays badminton and tennis.



**Jim Ryan** (page 10) is a Staff Applications Engineer in the Digital Audio group at Analog Devices, Limerick, Ireland, where he is responsible for digital audio converters and voiceband codecs. Jim, who joined ADI in 1988, has a B.Sc. (Electronics) and a M.Eng. (Computer Systems), both from the University of Limerick. Previously, he had worked at Westinghouse Electric, Intepro Systems, and LDC/Milton Roy in a product-development role. When not at work, he enjoys hill walking, rugby, reading, and listening to music. ▶







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