

# Teaching Mixed-Signal Testing Concepts Using Low-Cost Test Equipment and LabVIEW™\*

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*As the number of transistors on an integrated circuit continues to grow, both analog and digital electronic systems are being built on a single chip. As the complexity of these chips increases, a firm grasp of mixed-signal test concepts is essential for the successful entry-level test or product engineer. This paper discusses a set of laboratory experiments being developed at Texas A&M University that introduces these concepts to students prior to graduation. The curriculum emphasizes the use of standard electronics bench equipment combined with additional low-cost personal computer technology to ensure that all interested academic institutions can afford to offer these labs. To demonstrate the type of experiments discussed, an example of one of the labs and its implementation using LabVIEW is also presented.*

## INTRODUCTION

THE ROLE OF mixed-signal components such as analog-to-digital converters (ADC) and digital-to-analog converters (DAC) is growing with the increasing use of digital signal processing in modern electronics. These components are often combined onto a single, highly dense integrated circuit (IC) [1] with other signal processing systems. Due to the sophistication of these ICs, they are often difficult to test in an efficient manner. To keep the cost of production tests down and time-to-market to a minimum, test engineers are expected to rapidly produce the hardware and software which are used in conjunction with automated test equipment (ATE) to guarantee the performance of mixed-signal devices as they are manufactured. With this in mind, industry expects higher education institutions to produce graduates that have a working knowledge of mixed-signal test engineering. Thus, graduates hired as test engineers can be productive as quickly as possible.

While the value of teaching digital test techniques in engineering has been known for several years [2], the focus in the area of mixed-signal devices has been on incorporating design rather than test into the curriculum [3, 4]. However, over the past several years there has been a drive from industry to emphasize mixed-signal test concepts in the classroom. This is confirmed by a textbook devoted to teaching mixed-signal testing [5] produced with the support of Texas Instruments. 'An Introduction to Mixed-Signal IC Test and Measurement', written by Mark Burns (Texas

Instruments) and Gordon Roberts (McGill University), covers all aspects of mixed-signal testing, from laboratory measurement techniques to the economics of production testing.

The Electronics Engineering Technology program at Texas A&M University currently offers two courses in mixed-signal testing based on the Burns and Roberts text. The aim of these courses is to teach semiconductor test techniques using industry-grade commercial automated test equipment (ATE). Through the donation of an ATE by Texas Instruments and Teradyne [6], students not only learn about test concepts, but also become familiar with the type of test hardware used in industry. However, the cost of an ATE is often in excess of one million dollars and is prohibitively expensive for widespread academic use. For this reason, a set of laboratory exercises is currently being developed that allows students to experiment with mixed-signal test techniques while leveraging the type of laboratory equipment typically found in academia.

As in the lecture component, the Burns and Roberts textbook was used as a guide for developing the laboratory exercises. Experiments were developed to cover most of the fundamental concepts presented in the text. One problem that occurs when implementing mixed-signal labs is that some of the measurement requirements differ from those of traditional analog (or digital) electronics labs. The first step in this development process was to identify the needs of a mixed-signal bench setup. These needs include the ability to: perform complex customizable post-processing calculations; source and capture analog and digital static and dynamic signals; and rapidly automate repetitive measurements. These criteria were then

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Table 1. Comparison of the mixed-signal test laboratory experiments to the text by Burns and Roberts

| Textbook Chapters                  | Laboratory Experiments   |
|------------------------------------|--|
| 1 Overview of Mixed-Signal Testing | —  |
| 2 The Test Specification Process   | —  |
| 3 DC and Parametric Testing        | L1—Continuity Testing<br>L2—Regulator Testing<br>L3—Making Impedance Measurements<br>L4—Measuring the DC Gain and Offset of Devices<br>L5—DC CMRR and PSRR Testing                                 |
| 4 Measurement Accuracy             | L6—Quantifying Measurement Error through Statistics<br>L7—Using Filtering to Increase Measurement Repeatability  |
| 5 Tester Hardware                  | —  |
| 6 Sampling Theory                  | L8—Using the Fourier Transform   |
| 7 DSP-Based Testing                | L9—The FFT and the Effects of Aliasing<br>L10—The FFT and the Effects of Noncoherent Sampling<br>L11—Synchronizing Signal Sources and Digitizers<br>L12—Making Meaningful Noncoherent Measurements |
| 8 Analog Channel Testing           | L13—Using Multitones to Make Frequency Response Measurements<br>L14—DSP Based Distortion and Noise Testing   |
| 9 Sampled Channel Testing          | L15—Setting up Digital Patterns  |
| 10 Focused Calibrations            | L16—Using a Focused Calibration to Transfer Instrument Accuracy  |
| 11 DAC Testing                     | L17—DC and Linearity Testing of DACS<br>L18—Alternative DAC Linearity Testing Techniques   |
| 12 ADC Testing                     | L19—The Statistical Nature of the ADC<br>L20—Search Techniques and ADC Linearity Testing<br>L21—ADC Testing using Histograms   |
| 13 DIB Design                      | L22—Propagation Delay and Termination Effects in Transmission Lines<br>L23—Time Domain Reflectometry   |
| 14 Design for Test                 | —  |
| 15 Data Analysis                   | L24—The Use of Guardbanding<br>L25—Statistical Yield Analysis and SPC Methods  |
| 16 Test Economics                  | —  |

used to identify potential equipment solutions that could be used to teach mixed-signal testing.

Once the equipment decisions were made, the creation of a laboratory curriculum was begun. To date, most of the experiments have been completed and tested. This paper discusses this curriculum, provides insights on how these experiments can be implemented using standard analog and digital electronic laboratory equipment, and presents an example of a typical laboratory exercise using National Instruments' LabVIEW and data acquisition hardware.

### MIXED-SIGNAL TEST LABORATORY CURRICULUM

Since the goal of these laboratory exercises is to demonstrate the concepts discussed in the text by Burns and Roberts, the flow of the experiments is designed to track the flow of the book. Table 1 shows a list of the labs currently being developed. Each lab is being designed as a standalone experiment; however, many of the labs inevitably depend on knowledge gained from previous exercises for successful completion. For example, being able to use multitones and perform DSP-based testing (labs 13 and 14) requires an understanding of the Fast-Fourier Transform (labs 8, 9, and 10).

While 25 different experiments have been proposed, combining consecutive lessons into one laboratory session can easily reduce the number. For example, the three laboratory exercises on the

Fast Fourier Transform could be combined into one lab session. Similarly, the two experiments on testing digital-to-analog converters could also be combined. Alternatively, these experiments could be used over a period of two semesters as part of a two-course sequence. In fact, that is the way this material is currently being taught in the Electronics Engineering Technology program at Texas A&M University. The first course covers the material in Chapter 8 and the second course covers the balance of the material.

While the labs have been designed specifically for teaching mixed-signal testing, many of the concepts discussed here are useful as general material on electronics testing. Traditional electrical engineering and engineering technology courses use labs to demonstrate theory, circuit analysis, and design techniques. Unfortunately, the concept of learning how to use laboratory instrumentation and perform meaningful measurements is often of less importance. Students are often taught the minimum testing skills necessary to successfully complete their labs. In addition, some of the measurements they learn to make are commonly taught incorrectly (or at least are based on some implicit assumptions). For example, few students learn that the correct method for making DC gain measurements is to use  $G = \Delta V_{out} / \Delta V_{in}$  (a two-point measurement) instead of simply using  $G = V_{out} / V_{in}$  (a single-point measurement). They also seldom get experience with measurement statistics and noise reduction techniques. By integrating some of the experiments proposed in this

paper into normal analog and digital electronics courses, the importance of making valid measurements can be stressed as an essential tool.

### MIXED-SIGNAL TEST BENCH SETUP

Before the labs could be designed, a test equipment setup that could be used for mixed-signal test experiments had to be configured. Typical analog electronic lab experiments usually rely on four pieces of standalone bench equipment: an oscilloscope, a power supply, a waveform generator, and a multimeter. The experiments are designed to allow students to take individual measurements and then post-process the data later when writing the lab report. It is becoming increasingly common to find computers incorporated into the lab station so that students can generate lab reports dynamically and so that they can use support software such as MS Excel for entering data or PSPICE for comparing simulations to actual measurement results.

In contrast, mixed-signal testing requires a more flexible bench setup. This is because many experiments require the ability to work with both DC and AC analog and digital signals simultaneously, the ability to perform large numbers of repetitive measurements rapidly (i.e. 256 measurements when testing an eight-bit DAC), and the ability to manipulate large amounts of data. Assuming the testing of eight-bit (or less) devices, the

following fundamental pieces of equipment were identified:

- For sourcing both precision DC and AC voltages, an analog source instrument is required. The instrument has to have enough resolution to measure eight-bit mixed-signal devices.
- For digitizing both DC voltages and dynamic waveforms, an analog capture instrument is needed. Again, the resolution has to be good enough to measure an eight-bit mixed-signal device.
- For sourcing both static digital codes and synchronous digital waveforms, an analog capture instrument is required. The instrument has to have a minimum of eight digital channels. Because some devices have a serial interface, the source had to be fast enough to source eight-bit serial signals as well.
- For capturing both static digital codes and digital waveforms with similar constraints to the above, a digital capture instrument is needed.
- Finally, for remotely controlling the instrumentation and for post-processing captured data, an automated measurement controller is needed. The controller must also use a flexible programming environment where students can make customized measurements during the lab.

With this in mind, several options ranging from the construction of a dedicated microcontroller-based measurement platform [7] to the use of separate pieces of networkable, high-end bench equipment

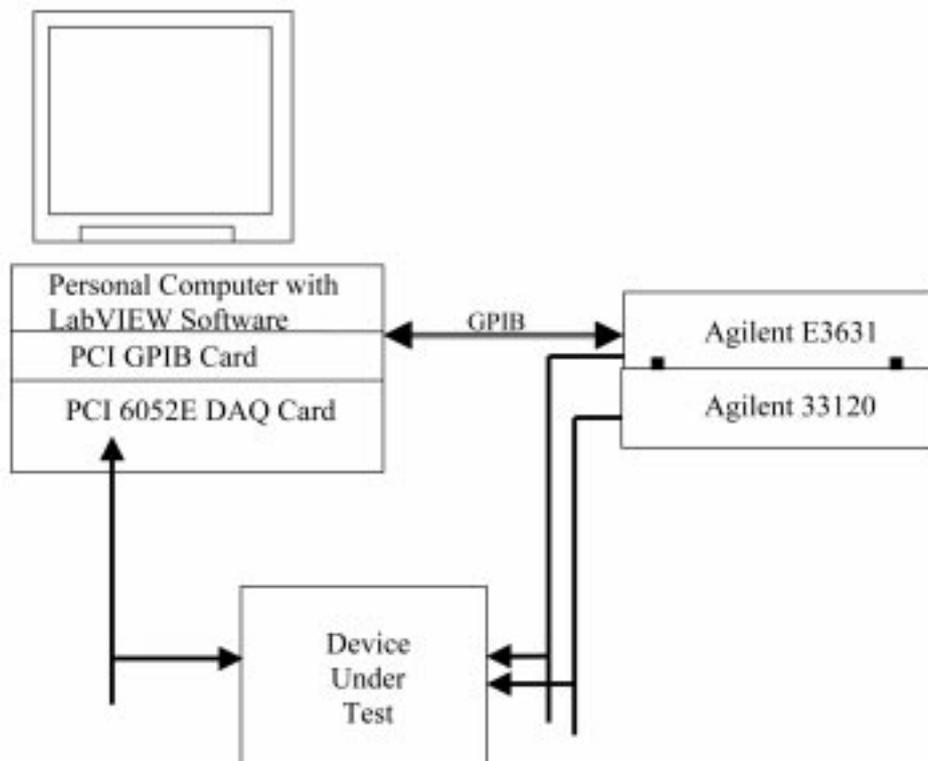


Fig. 1. Block diagram of the mixed-signal test system.

Table 2. Bench equipment needed for performing mixed-signal test experiments

|                     |   |
|---------------------|---|
| Controller          | Pentium III Personal Computer with LabVIEW (National Instruments) and a PCI GPIB interface (National Instruments)   |
| Analog Source<br>OR | PCI-6052E (National Instruments)—Two 16-bit D/A Analog Output Channels<br>33120A (Agilent)—GPIB Arbitrary Waveform Generator  |
| Analog Capture      | PCI-6052E (National Instruments)—Sixteen 16-bit A/D Digitizer Channels (can also be configured as eight differential channels)  |
| Digital Source      | OR<br>PCI-6024E (National Instruments)—Sixteen 12-bit A/D Digitizer Channels<br>PCI-6534 (National Instruments)—Thirty-two digital channels that can be configured as either digital inputs or outputs.<br>OR<br>PCI-6024E (National Instruments)—Eight channels configurable as asynchronous inputs or outputs.<br>OR<br>PCI-6052E (National Instruments)—Eight channels configurable as asynchronous inputs or outputs. |
| Digital Capture     | Same as above   |
| Power Supply        | E3631 (Agilent)—GPIB Controlled Triple Output Power Supply  |
| Optional Equipment  | 54622D (Agilent)—Mixed-Signal Oscilloscope  |

were explored. The final solution as seen in Fig. 1 optimizes cost while maintaining flexibility and ease of implementation. Table 2 summarizes the equipment identified as necessary for a complete mixed-signal test bench setup. The cost per bench for this type of setup runs between \$4000 and \$11,000. While this is still costly, a ten-station laboratory is still a small portion of the cost of a single ATE. Also, an unofficial survey of several electrical engineering and engineering technology programs showed that most institutions already have computers and GPIB programmable bench equipment as part of their standard analog electronics lab. This means that the only additional equipment needed is the PC-based data acquisition and GPIB cards.

With this equipment, all of the measurement requirements are satisfied. The PCI-6052E is a multifunction data acquisition card compatible with standard personal computers. The card has the ability to digitize and source signals with 16-bit resolution. This is more than sufficient for testing standard eight-bit mixed-signal devices. For high-frequency sourcing applications, one can use an arbitrary waveform generator such as the Agilent 33120A (since many electronics labs already have one of these) for sourcing analog waveforms and then purchase a less expensive data acquisition card, such as a PCI-6024E, for capturing analog waveforms and for sourcing DC voltages. On the digital side, a PCI-6534 is required if one wishes to perform dynamic tests on mixed-signal devices (i.e. S/THD or SNR measurements), otherwise the asynchronous digital lines on a standard multifunction data acquisition board can be used.

Because experiments such as measuring power supply rejection ratio require the ability to change power supply voltages, a networked power supply such as the E3631 is required. Finally, optional equipment such as a good digital oscilloscope allows students to make timing measurements such as propagation delay as well as to investigate concepts such as transmission line reflections. The controller was chosen to be a standard personal computer running Windows. This choice allows

students access to software packages such as Microsoft Word, Microsoft Excel, and Orcad PSPICE at the same workstation. National Instruments' LabVIEW virtual instrumentation environment [8] was chosen as the programming environment because it allows the development of intuitive graphical user interfaces.

The LabVIEW environment also creates a flexible, intuitive programming environment where students can modify existing mixed-signal test experiments and design new experiments. LabVIEW's graphical programming environment and use of modular subroutines facilitates the design of experiments where students supply a particular part of the program, such as their own data-processing routine. LabVIEW also supports drivers for all of the equipment discussed above, GPIB communications, and an inclusive library of data post-processing subroutines (i.e. FFT routines, time-domain windowing, histogram routines, etc.) required for producing mixed-signal measurements. Finally, since students on the engineering technology program are exposed to LabVIEW in other courses, this alternative has the advantage of not introducing a new learning curve into the class.

#### EXAMPLE: LINEARITY MEASUREMENT OF A DIGITAL-TO-ANALOG CONVERTER

##### Overview

When considering the types of mixed-signal integrated circuits that exist, the most common devices that come to mind include the digital-to-analog converter and the analog-to-digital converter. These are truly mixed-signal circuits in that they combine digital logic and analog electronics in the same device. They are also characteristic of the types of problem one encounters when testing mixed-signal systems, since they require both digital and analog test equipment and involve fairly complex test procedures. In this example, the linearity testing of a digital-to-analog converter is considered.

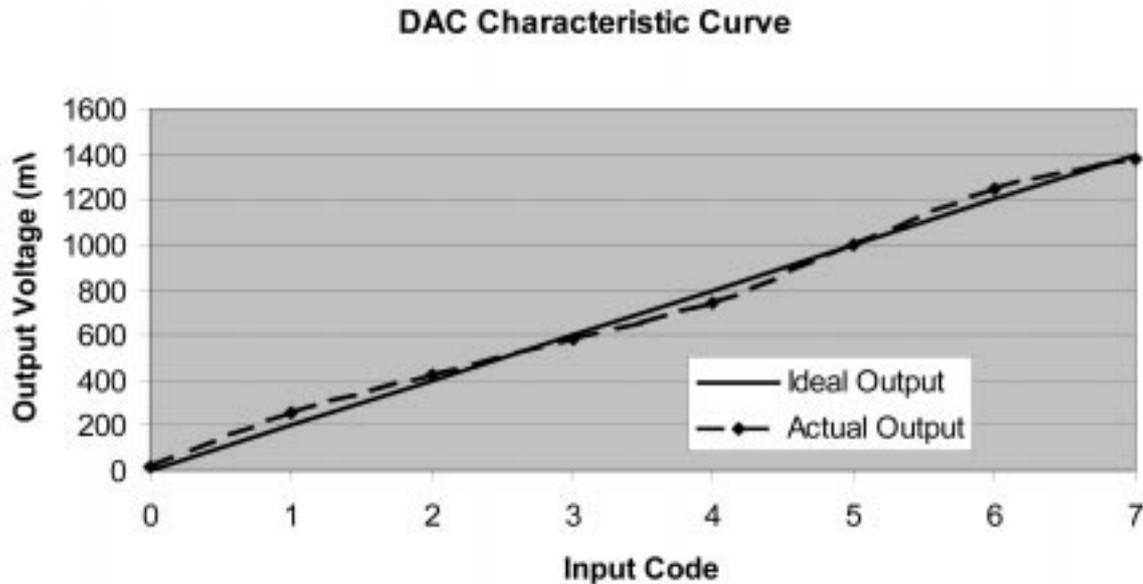


Fig. 2. Ideal versus actual digital-to-analog converter transfer curve.

#### Theory

In an ideal digital-to-analog converter, consecutive digital input codes cause the output to change in a perfectly linear fashion. As a result, the transfer function, or characteristic curve, relating input code to output voltage is a straight line, as in Fig. 2. However, due to non-idealities in the manufacture of the device, this is impossible to achieve in practice. Thus, the characteristic curve of a real digital-to-analog converter will not be linear, but will follow the general trend of the ideal curve (Fig. 2). This means two things:

- The change in output voltage between sets of consecutive input codes will fluctuate, resulting in differential non-linearity (DNL).

- For any given input code, the output will not be what is expected, resulting in integral non-linearity (INL).

To measure DNL and INL, the first step is to measure the device's characteristic curve. This is done by applying each possible input code in succession and measuring the output voltage. One can see that this would be a very cumbersome task using traditional bench equipment. For example, for an eight-bit converter one would have to perform 256 individual tests. However, using the setup discussed in this paper, the procedure can be automated and performed very quickly.

Once the data is collected, a curve-fitting routine is used to extract the best-fit line. The slope of this



Fig. 3. Picture of a complete lab station currently being used to deliver the mixed-signal laboratory curriculum.



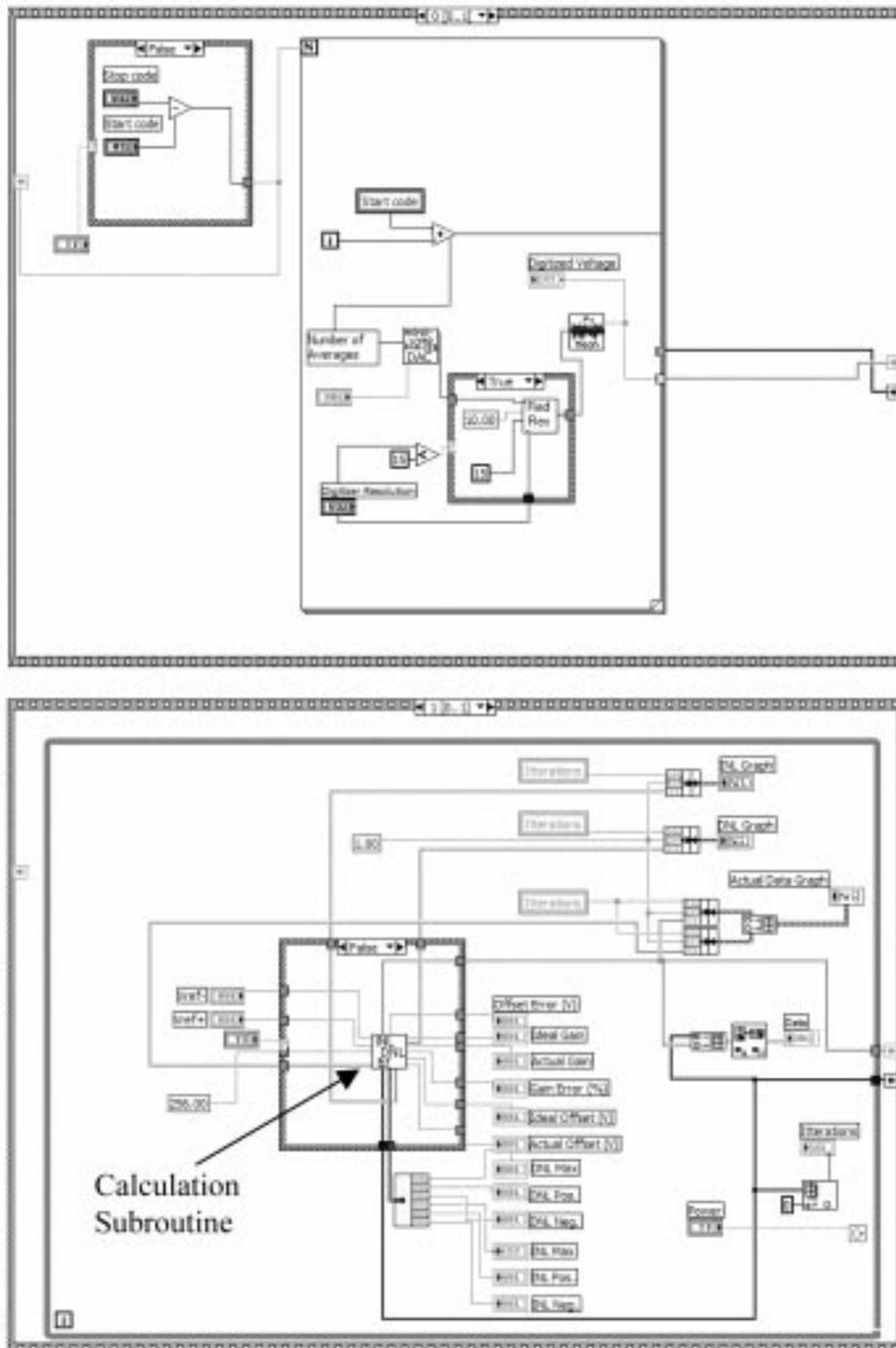


Fig. 5. Software diagram of the linearity test virtual instrument.

able to finish this experiment in the time allotted for the laboratory.

A second option for teaching this lab is to give the students the basic framework of the LabVIEW code, but to leave out a portion of the program, such as the calculation subroutine. Because of LabVIEW's modularity, this is very easy to do. One simply gives the students the 'footprint', or the pad layout, of the subroutine they are to write with the definitions of the inputs and outputs. Even by programming only the analysis portion of the

measurement VI, they are still required to think through the process of analyzing the data and the experiment can be performed in a fraction of the time mentioned previously.

Figure 6 shows the front panel of the test VI once the experiment is completed. Due to LabVIEW's graphical interface, it is very easy to present the data in an intuitive way. As in the figure, one can stack the DNL and INL plots so that the correlation between them can be readily seen.

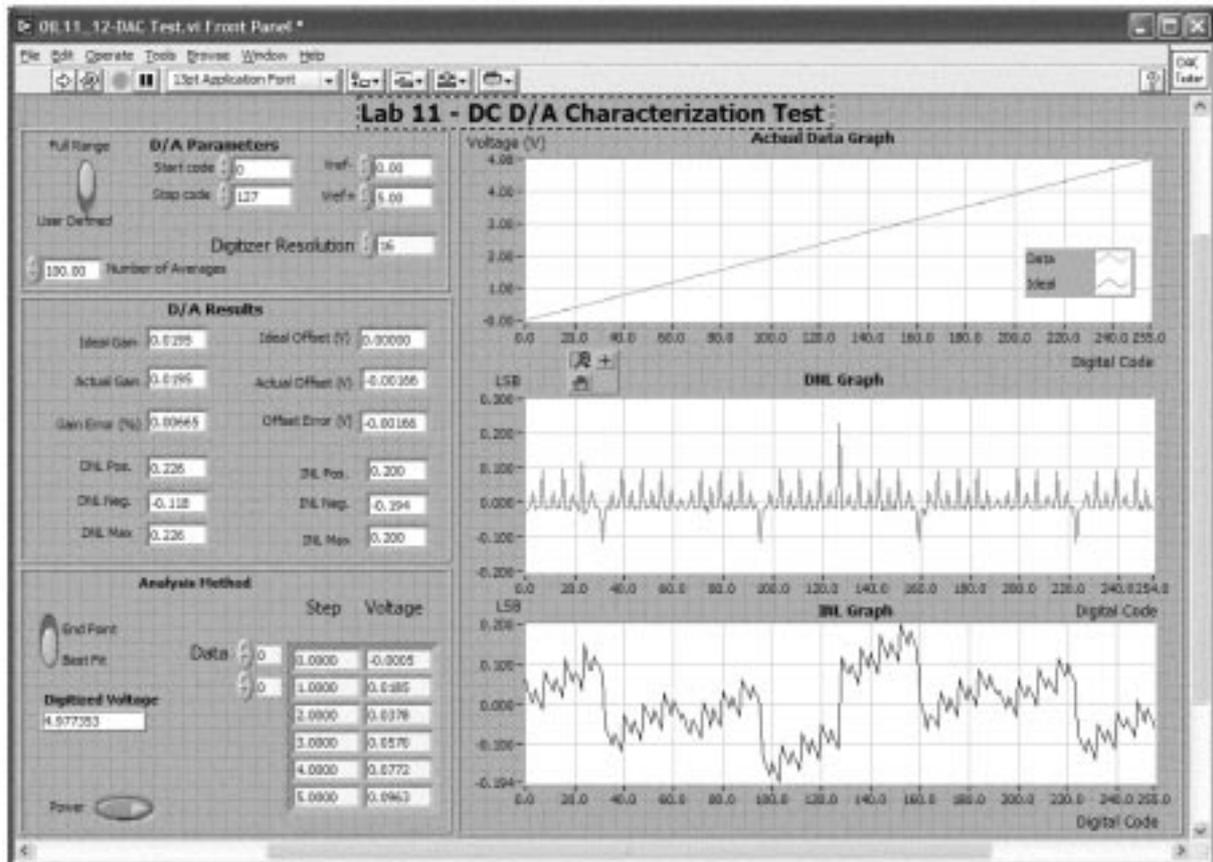


Fig. 6. Results from a linearity test of a digital-to-analog converter.

## CONCLUSION

Through the use of these experiments, students are being introduced to concepts that they would not normally see in a standard analog electronics laboratory. The response of the students to the new labs has been excellent and, after working through the concepts presented in the classroom, students are demonstrating a better comprehension of the material. Additionally, while these experiments are being designed specifically to better prepare students entering the field of test engineering after graduation, they are useful in giving all students a much better understanding of measurement concepts. Though students

normally learn to make simple measurements as a by-product of standard analog and digital labs, these experiments are specifically designed to teach the theory and implementation of most common measurements.

To continue this work, each of the experiments discussed is being tested both in the lab and in a classroom setting. Student and instructor feedback is then used to make continual improvements. Industry feedback is also being solicited. Finally, work is still continuing on the development of a complete standalone, low-cost mixed-signal tester. This tester has a targeted cost of \$500 and will substantially reduce the overall cost of a complete bench setup.

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