

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 L2—Regulator Testing L3—Making Impedance Measurements L4—Measuring the DC Gain and Offset of Devices L5—DC CMRR and PSRR Testing
4 Measurement Accuracy	L6—Quantifying Measurement Error through Statistics 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 L10—The FFT and the Effects of Noncoherent Sampling L11—Synchronizing Signal Sources and Digitizers L12—Making Meaningful Noncoherent Measurements
8 Analog Channel Testing	L13—Using Multitones to Make Frequency Response Measurements 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 L18—Alternative DAC Linearity Testing Techniques
12 ADC Testing	L19—The Statistical Nature of the ADC L20—Search Techniques and ADC Linearity Testing L21—ADC Testing using Histograms
13 DIB Design	L22—Propagation Delay and Termination Effects in Transmission Lines L23—Time Domain Reflectometry
14 Design for Test	—
15 Data Analysis	L24—The Use of Guardbanding 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

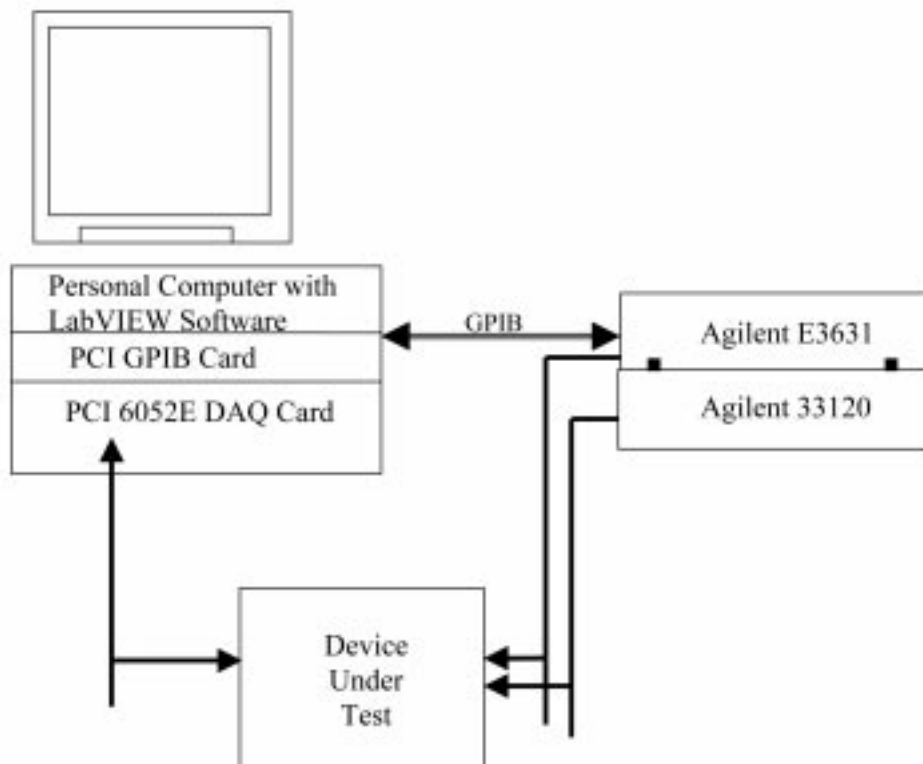


Fig. 1. Block diagram of the mixed-signal test system.

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 OR	PCI-6052E (National Instruments)—Two 16-bit D/A Analog Output Channels 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 PCI-6024E (National Instruments)—Sixteen 12-bit A/D Digitizer Channels PCI-6534 (National Instruments)—Thirty-two digital channels that can be configured as either digital inputs or outputs. OR PCI-6024E (National Instruments)—Eight channels configurable as asynchronous inputs or outputs. OR 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.

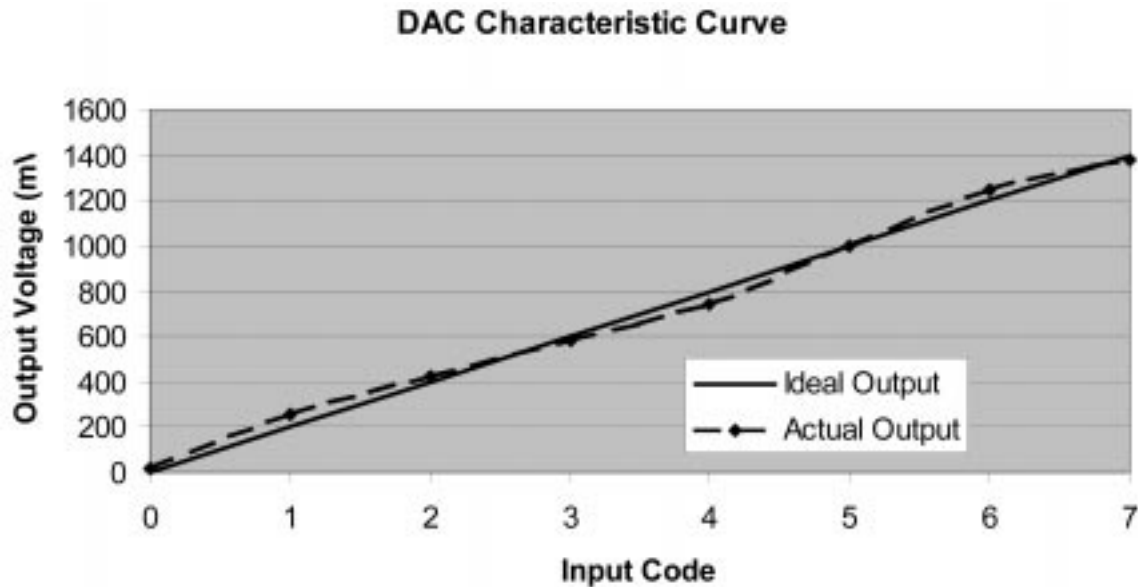


Fig. 2. Ideal versus actual digital-to-analog converter transfer curve.

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.

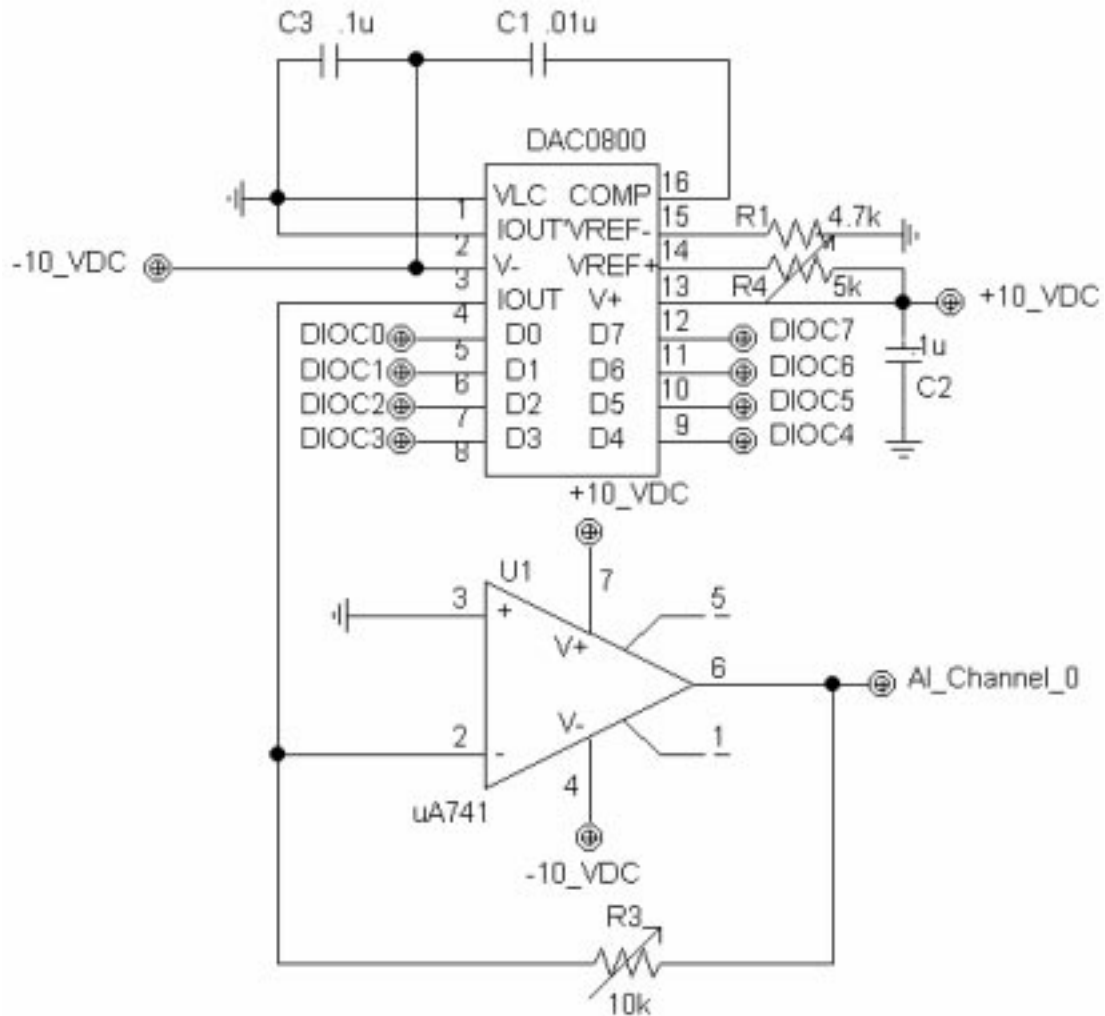


Fig. 4. Circuit diagram of a digital-to-analog converter test setup.

line is equivalent to the average width between two consecutive codes in volts, or the least significant bit (LSB) step size. DNL can be calculated by taking the discrete derivative of the characteristic curve, normalizing it by the LSB step size, and subtracting one. This gives a measure of how different the width between each set of consecutive codes is from the average LSB step size. To calculate INL, one simply performs a running integration of the DNL curve. Again, this gives a measure of how different the output voltage for a given code is compared to the ideal. Other measurements that can be made from the original data include gain, offset and monotonicity [5].

Test setup and LabVIEW VI

A picture of the test setup can be seen in Fig. 3. For this particular experiment, an eight-bit digital-to-analog converter (DAC0800) was measured. The device was connected as suggested in the data sheet [9]. The digital codes were sourced by the multi-function data acquisition card and the output voltage of the DAC was measured with one of the digitizer inputs of the data acquisition card. Because the DAC was an eight-bit device, either

the 12-bit or-16-bit data acquisition cards mentioned previously would work. The test circuit can be seen in Fig. 4. Using this system, all 256 codes were measured in approximately five seconds. To increase the accuracy of the measurement, the output voltage at each code was measured 100 times and averaged into a single value.

To automate the process, a LabVIEW VI was written, as shown in Fig. 5. As one can see, the VI is written in a modular form and is relatively simple. It is made up of a data acquisition sequence (first frame) and data analysis sequence (second frame). Since LabVIEW has many high-level subroutines for performing common analysis functions, processing the data for mixed-signal tests is typically simple to do. For example, in this experiment the Linear Fit.vi was used to provide the average LSB step size.

Because the students in Texas A&M's EET program learn LabVIEW as part of a computer-aided design course, they are able to write this level of code in about three hours. When taking this lab, students are asked to write the basic LabVIEW code before coming to class. They are then easily

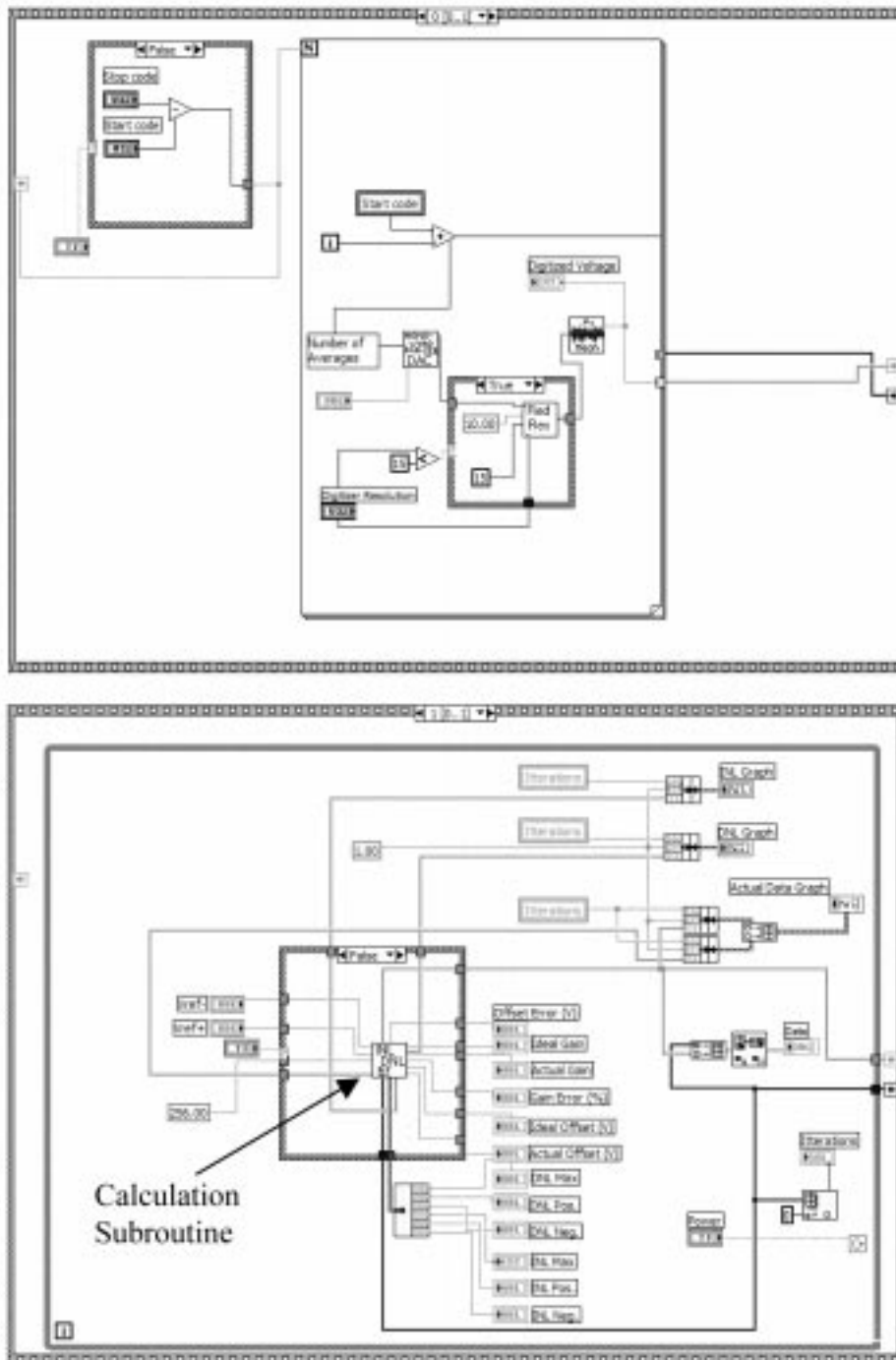


Fig. 5. Software diagram of the linearity test virtual instrument.

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.

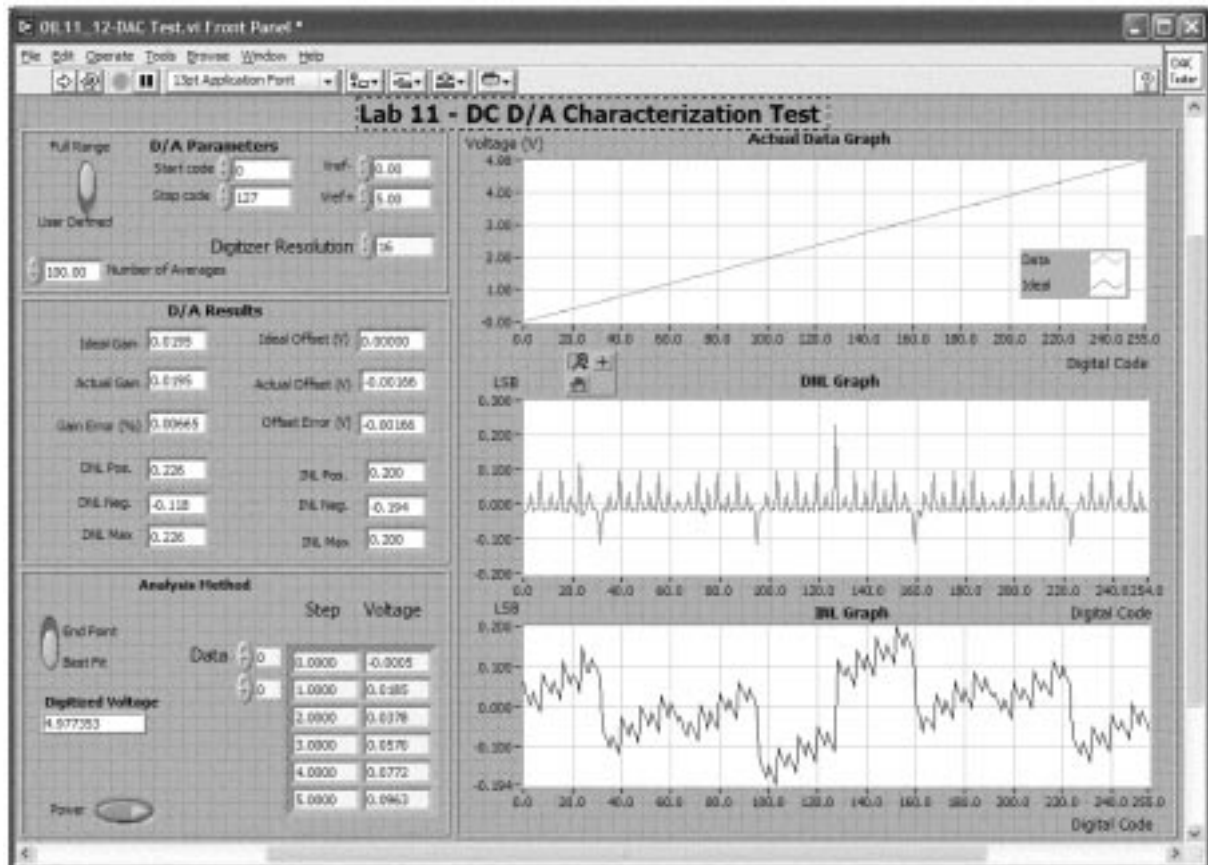


Fig. 6. Results from a linearity test of a digital-to-analog converter.

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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