Session 1668

Virtual Instruments Revitalize an Undergraduate Measurements and Instrumentation Course

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Abstract

Measurements and Instrumentation (M&I) is a 3-hour, required, junior-level course in the Aerospace Engineering curriculum at The University of Texas at Austin. In Fall 1994 a major restructuring of the course occurred that was centered around the shift to digital data acquisition through the use of virtual instruments (VI's) based on the LabVIEW™ software.[1] This paper discusses the development of the VI's used in the course, the laboratory exercises that comprise the course, and the improvements in student morale and report-writing skills that have resulted from the restructuring of the course.

1. Introduction

Measurements and Instrumentation (M&I) is a 3-hour, required, junior-level course in the Aerospace Engineering curriculum at The University of Texas at Austin. A confluence of circumstances occurred in the early 1990's that led to a major restructuring of the course: the early medical retirement of the principal course instructor; the need to incorporate use of the the computer in the measurements course both for data acquisiton and for report preparation; the need to incorporate digital signal processing concepts in the course; and the desire to form a close working relationship with National Instruments, a local Austin company that was (and is) in the forefront of virtual instrumentation technology. The revised course was first offered in Fall 1994, but revision is still in process.

Five major objectives were set for the reorganized *M&I* course: (1) to introduce the students to the fundamentals of digital signal processing, (2) to provide the students with several VI's with which to acquire and save data for later inclusion in their formal reports, (3) to introduce the students to modern methods of modal testing of structures, (4) to have students design a measurement system, incorporating product information acquired via the internet, and,

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[1] LabVIEW is a trademark of National Instruments, Austin, TX.

finally, (5) to require a substantial upgrading of the quality of the technical reports produced by the students. The revised course admirably meets all of these objectives.

Reference 1 provides a survey of modern computer-based experiments, several of which are similar to the lab exercises described in this paper. The reader will find numerous proceedings papers and web resources for computer-based labs, such as Refs. 2 and 3, respectively.

The catalog description of the course is:

> Design of measurement systems; standards; calibration; digital signal processing, time-domain and frequency-domain representation of data; transducers and signal conditioning; measurement of acceleration, displacement, force, length, strain, and temperature; safety. Written reports. Two lecture hours and three laboratory hours a week for one semester.

The prerequisites for the course are:

> EM 319 *(Mechanics of Solids)*, EE 331K *(Electric Circuits and Electronics)*, and credit or registration for an approved communication elective.

2. Course Syllabi

As noted in the catalog description given above, there are two 50-minute lectures per week and one 3-hour, hands-on laboratory session per week. There are five lab stations with identical equipment, and the students work in two- or three-person teams. Although a few topics, such as lab safety, are touched upon in the lectures, the course is primarily defined by the topics of the laboratory exercises. Prior to the F94 revision, the topics covered by lab exercises were:

1) Introduction to Electronic Instrumentation
2) First-Order System Behavior
3) Second-Order System Behavior
4) Measurement of Length and Displacement
5) Force and Inertia Measurement
6) Strain Measurement
7) Dynamic Strain Measurement
8) Acceleration Measurement
9) Fluid-Flow Measurement
10) Temperature Measurement (Thermocouples)

Figure 1. Laboratory Exercises Prior to Revision of the Course

The principal data-recording instruments were pencil and paper, and a digital oscilloscope fitted with a Polaroid camera. Four “formal” lab reports were written by each student to satisfy the university’s Substantial Writing Component requirement, which is discussed later; the remaining lab reports were “informal,” consisting of the answering of several homework exercises employing data taken in the lab.

The lab topics covered in the revised course are:

1) Introduction to Electronic Instrumentation
2) First-Order System Behavior
*3) Second-Order System Behavior; Virtual Oscilloscope
4) Measurement of Length and Displacement
*5) Digital Signal Processing; Virtual Two-Channel Spectrum Analyzer
*6) Measurement of Force and Acceleration; Ratio Calibration
*7) Beam Vibration
†8) Measurement of Strain
†9) Measurement of Temperature (Thermocouples)
* New, or substantially revised, in F94. † Currently under revision.

Figure 2. Laboratory Exercises After Revision of the Course

Because the students have other required fluid-flow labs, in order to make room for the new digital signal processing topic the fluid-flow measurement topic was dropped completely. The total number of labs was reduced by one to make it possible to “stiffen” the formal-report requirement and to introduce a design exercise.

3. Virtual Instruments

A *virtual instrument* (VI) is essentially software that allows a personal computer to act as a laboratory instrument (e.g., an oscilloscope, a data-logger, a function generator, etc.). Analog input/output operations may be handled various ways, for example, by the computer’s PCI bus or serial port, through a GPIB interface, or through a plug-in board. The LabVIEW software was used to modify two sample VI’s to produce a virtual oscilloscope, *V’scope*, and a virtual two-channel spectrum analyzer, *Spectrum Analyzer*, for the Apple Macintosh IIci computers that were purchased for the Measurements Lab. The I/O operations for these two VI’s are handled by a National Instruments NB-A2150F dynamic signal acquisition (DSA) board. Each VI consists of three main parts: the front panel, the block diagram, and the icon/connector. The front panel contains buttons, knobs, and switches that are similar to those on a conventional piece of hardware. These controls are operated by using the computer’s mouse or by entering numerical values directly at the keyboard. The block diagram represents the source code of the VI. Mathematical functions, I/O operations, etc. are represented as icons, and data is transferred through connecting “wires.” The icon/connector acts as the representation of the VI and as the calling interface when multiple VI’s are linked together. Figure 3 shows the front panel of the new *Strain Analyzer* (See Section 7), and Fig. 4 shows its block diagram.[4]

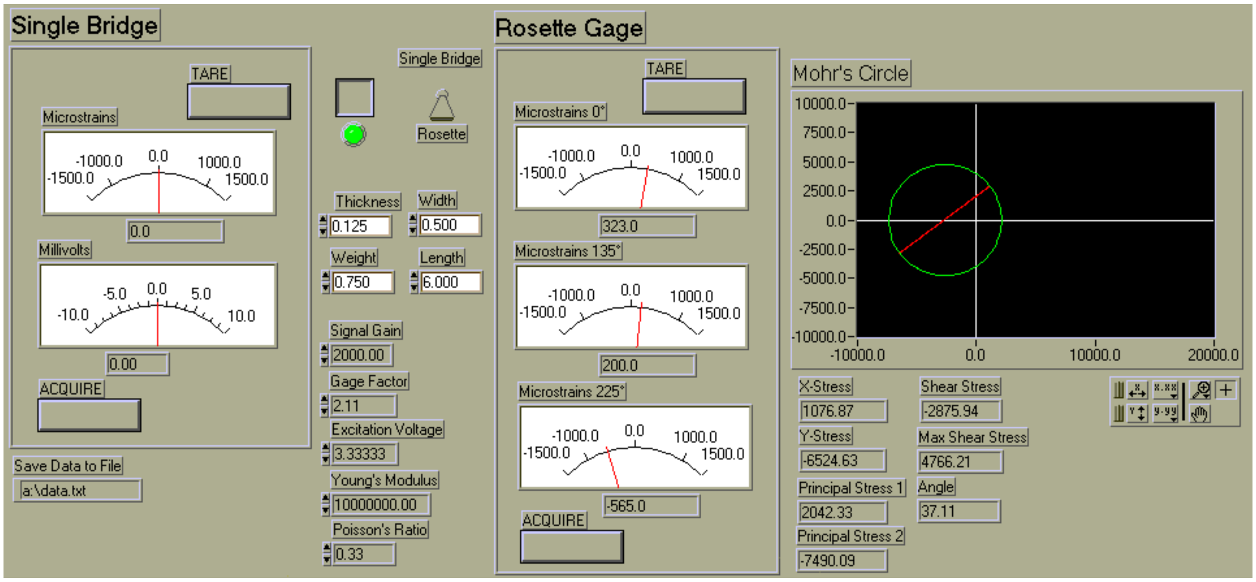

Figure 3. The Front Panel of the LabVIEW *Strain Analyzer* Virtual Instrument.

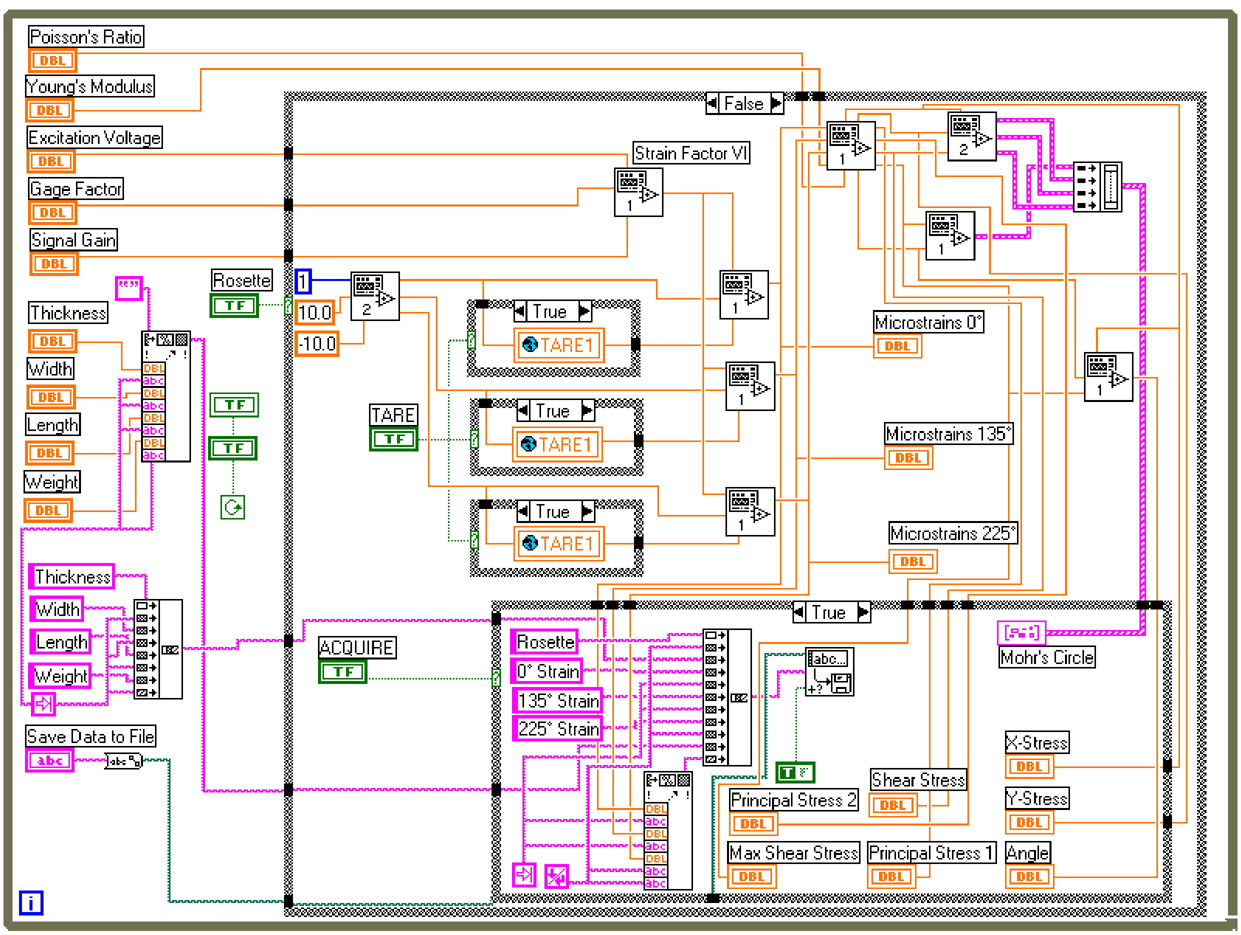

Figure 4. Block Diagram of the LabVIEW *Strain Analyzer* Virtual Instrument.

During the semester prior to the F94 first offering of the revised course, a graduate research assistant was employed 20 hrs/wk to work with the first author in defining the functions to be incorporated in the two custom VI's and to carry out the programming of the VI's. Development of the two VI's and development of the new and revised lab exercises proceeded simultaneously, with the first author developing the lab exercises and specifications for the VI's, and the RA developing the VI's. The graphical programming environment is much more intuitive than text-based programming, and the ability to collapse code into sub-VI's, which can be called by other VI's, makes applications modular and easy to modify. In fact, both *V'scope* and *Spectrum Analyzer* were constructed by modifying existing VI's that were supplied along with the LabVIEW software. Once completed, the two VI's were "compiled," and the two executable files were saved on each of the lab computers. Students are expected to use the VI's much as they would a conventional instrument, and are not required to do any LabVIEW programming.

4. Formal Reports; Substantial Writing Component Course Requirements

One of the objectives of the revision of the *M&I* course was to institute a substantial upgrading of the quality of the formal technical reports produced by the students. The University of Texas at Austin has a university-wide writing requirement that each student must satisfy. Beyond freshman English, the student is required to pass so-called Substantial Writing Component courses, in, or closely related to, the student's major. The three courses that Aerospace Engineering students take to meet the Substantial Writing Component requirement are:

- CE 333T -- *Technical Writing* (or equivalent)
- ASE 369K -- *Measurements and Instrumentation*
- ASE 363Q -- *Design and Testing of Aerospace Structures*

Yes, all of these are engineering courses! But the Civil Engineering faculty person in charge of CE 333T has a Ph.D. in English, as do the faculty of the other similar engineering courses. Two of the above courses, CE 333T and ASE 363Q, also have public speaking requirements in addition to the writing requirement. The ASE-EM Visiting Committee members now rave about the quality of the student presentations, undergraduate as well as graduate, at each meeting of the committee.

The ASE courses have strict requirements on the amount of writing required; the students' reports must be graded by an "English" TA as well as graded for technical content; and a report must be submitted to the Dean of Engineering at the end of every semester. At present, the writing requirement in ASE 369K is met by having each student write three formal technical reports (i.e., computer-generated reports), do a re-write of the first report, and produce a brief formal writeup of the design of a measurement system. Strong emphasis is placed on the "engineering" format of the report -- equations, tables, figures, references, etc. Sample pages from a formal lab report and a final design project report are included in the Appendix.

5. The New/Revised Labs

The new, or substantially revised, laboratory exercises are listed below, along with the major new features that were incorporated:

Lab	Status	New Feature(s)
3) Second-Order System Behavior; Virtual Oscilloscope	Rev.	*V'scope*
6) Digital Signal Processing	New	DSP topics; *Spectrum Analyzer*
7) Measurement of Force and Acceleration; Ratio Calibration	New	Piezo. F&A; FRF's; Ratio Calib.; *Spectrum Analyzer*
8) Beam Vibration	New	FRF's; Modes and frequencies

Figure 5. Features of New or Revised Laboratory Exercises, F94.

++ Lab 3: *Second-Order System Behavior; Virtual Oscilloscope* -- Lab 1, *Introduction to Electronic Instrumentation*, and Lab 2, *First-Order System Behavior*, were not changed in F94. The digital oscilloscope was retained in Lab 2 so that students would have some experience with a conventional instrument-type oscilloscope. Measurement of the response of an RC circuit to a step voltage input and response to a sinusoidal voltage input enable students to learn concepts such as rise time, frequency response, phase lag, etc. The topics covered in Lab 3 are:

- Virtual Oscilloscope -- a familiarization exercise in the use of the *V'scope* VI
- Frequency Response of a Second-Order System -- use of scope cursors to measure response amplitude and phase lag of an RLC circuit subjected to sinusoidal input
- Response of a 2nd-Order System to a Square-Wave Input -- an exercise to demonstrate the effect of the RLC circuit on a square-wave input

Except for during the summer term, Lab 3 forms the basis for the first formal technical report. In conjunction with the assignment of this report there is one lecture on English grammar, etc., by the English TA, and one lecture by the instructor on elements of a formal engineering technical report. Plots that have been saved to disk by the VI are included as figures in this report. After copies of this report have been graded separately by the instructor and by the

English TA, the students are permitted (encouraged) to re-write this report, hopefully for a better grade.

++ Lab 5: *Digital Signal Processing: Virtual Two-Channel Spectrum Analyzer* -- This new subject was added because of its critical importance in many aspects of aerospace engineering, from structural dynamics, to controls, to satellite communications. Among the topics treated in lecture are: time domain, frequency domain, Fourier transforms, sampling, leakage, aliasing, and frequency response functions. The topics covered in the laboratory exercise for Lab 5 are:

- Virtual Spectrum Analyzer -- a familiarization exercise in the use of the *Spectrum Analyzer* VI
- Periodic Signals -- an exercise to compare theoretical and measured Fourier coefficients of a square-wave signal, and also of a saw-tooth signal
- Leakage -- an exercise to demonstrate the effect of the length of the data-acquisition time window in relationship to the period of a sinusoidal signal
- Nyquist Sampling Theorem; Aliasing -- an exercise to illustrate the effect of sampling frequency on the spectrum of a signal, and to illustrate the need for the anti-aliasing filter on the data-acquisiton board (NB-A2150F)

This lab is usually written up as the second formal lab report. Again, plots that have been saved to disk by the VI are included as figures in this report. For illustration of the phenomenon of leakage, Fig. 6 shows the front panel of the *Spectrum Analyzer* VI with the time-domain and frequency-domain representations of a sinusoidal signal that is periodic in the time window. Figure 7 shows how the corresponding plots for a sinusoidal signal that is not periodic in the time window might appear in a student's report.

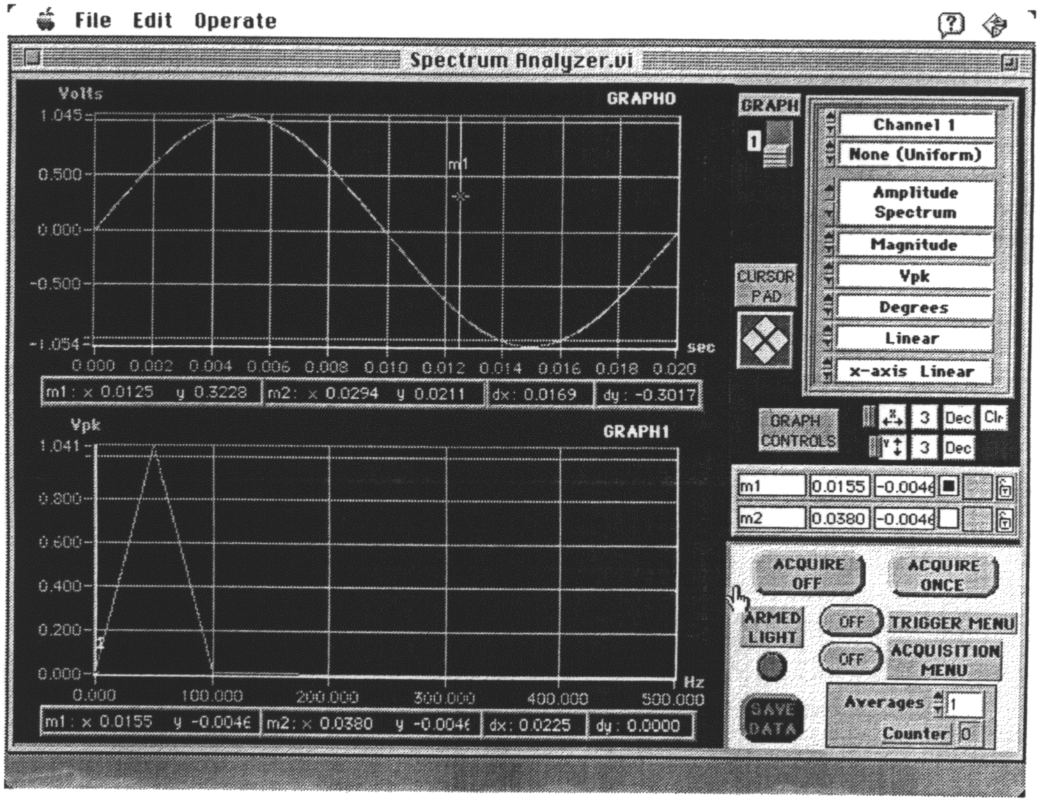

Figure 6. Front Panel of the *Spectrum Analyzer* VI; Illustration of Leakage Phenomenon

++ Lab 6: *Measurement of Force and Acceleration; Ratio Calibration* -- This new subject was added because of the importance of piezoelectric transducers of various types, including force cells and accelerometers; the importance of frequency response functions in system identification; and the use of a modern frequency-domain calibration technique, ratio calibration. Among the topics treated in lecture are: principles of seismic accelerometers, and characteristics of piezoelectric transducers for measuring frequency response. The topics covered in the laboratory exercise for Lab 6 are:

- Time-Domain Windows -- introduction to the “force window” and the “exponential window”
- Impulse-Force Hammer; Spectrum of an Impulse -- an exercise to demonstrate how a force impulse can be created by use of a hammer with an attached piezoelectric force cell, and to demonstrate the effect of tip hardness on the spectrum of the impulse force
- Ratio Calibration -- a calibration exercise based on $F(f)=mA(f)$ that employs an impulse hammer, an accelerometer, and a calibration mass, and uses the *Spectrum Analyzer* VI to form the frequency response function of A/F

This lab is usually written up as the third formal lab report. Again, plots that have been saved to disk by the VI are included as figures in this report.

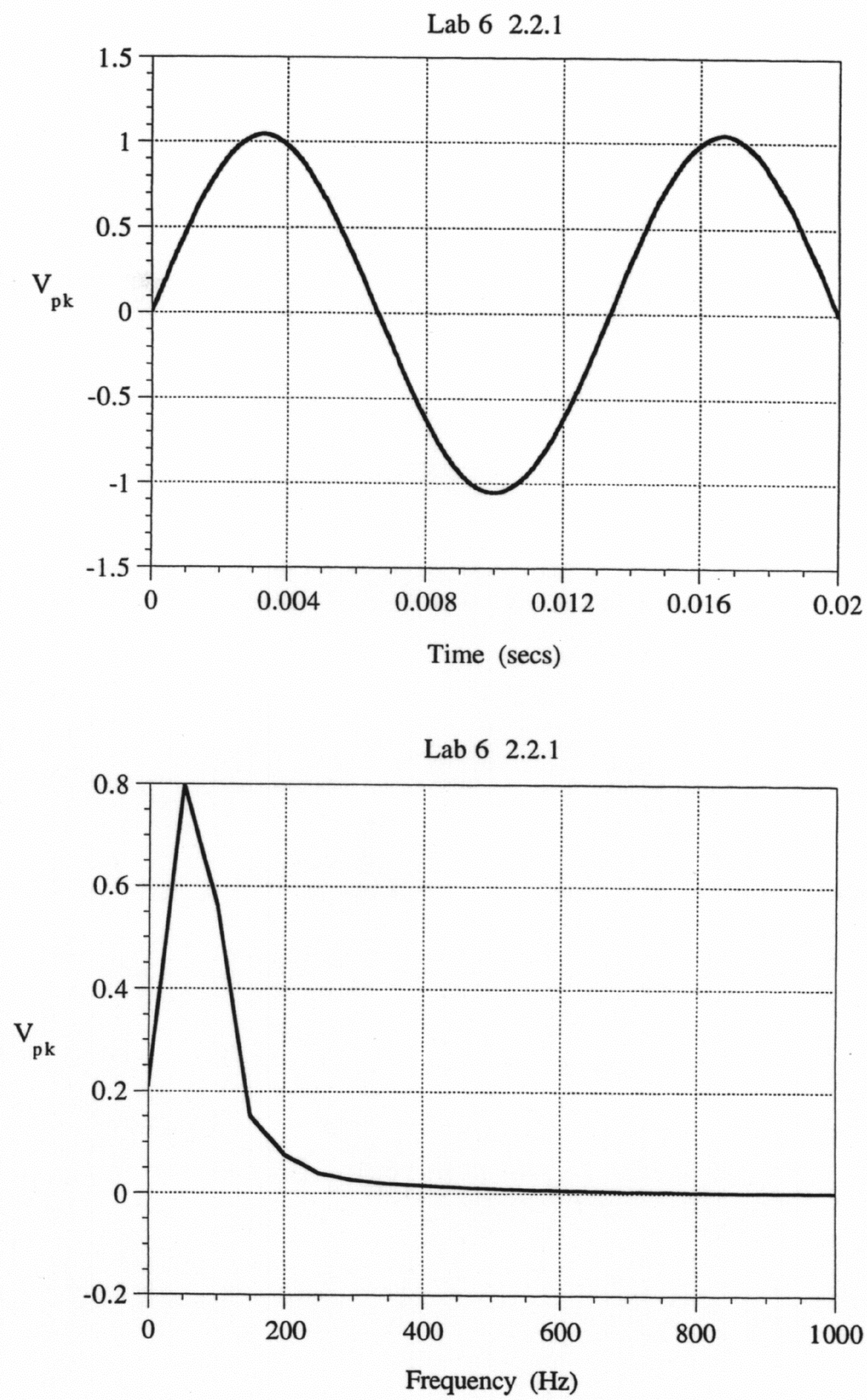

Figure 7. Leakage Resulting from a Signal not Periodic in the Time Window.

++ Lab 7: *Beam Vibration*-- This new subject, a follow-on to Lab 6, was added as an introduction to experimental modal analysis, that is, to the experimental determination of the natural frequencies and mode shapes of a simple structure. In the ASE 363Q senior design course, *Design and Testing of Aerospace Structures*, a number of design teams have projects that make use of this introduction to modal testing. The lab exercise involves the use of the impulse hammer and accelerometer to acquire acceleration/force frequency response functions for a simple cantilever beam. Natural frequencies and mode shapes are estimated from these FRF's and are compared to modal parameters based on theory. This lab is sometimes written up as the third formal lab report.

6. End-of-Semester Design Project

At the end of the semester the students are assigned a design project that is to be researched and written up on the computer. Students are expected to use the Internet to obtain product information to include in their reports. Topics that have been assigned include a strain-gauged support for a spacecraft vibration test setup, use of piezoelectric strain gauges and conventional foil gauges to measure dynamic strain in a snowboard, and measurement of strain in the shaft of a golf club. The last page of this paper is a sample page from a golf-club report.

7. Subsequent Revisions and Revisions in Progress

In the fall of 1997 a decision was made to replace the MAC IIci's with Dell PC's and to use the oscilloscope and spectrum analyzer in the National Instruments *VirtualBench*[2] suite of VI's. The reasons that motivated these changes were the dominance of PC's over MAC's in the entire field of engineering computations and measurements, and the desire to be VI-compatible with off-the-shelf National Instruments VI's. At the same time, National Instruments agreed to replace the MAC DSA boards with newly designed DSA boards for the PC's. In the spring of 1998 PC's were acquired for the Measurements Lab, and Lab 3 was converted from *V'scope* to the *VirtualBench-Scope*. Hardware delays and software incompatibility have delayed replacement of the MAC-based *Spectrum Analyzer*, but PCI-4451 boards have been acquired, and the transition is expected to occur by the summer of 1999.

As noted in Fig. 2, Lab 8 -- *Measurement of Strain* and Lab 9 -- *Measurement of Temperature (Thermocouples)* are currently undergoing revision. Although the content of these labs will not be changed substantially, virtual instruments will be employed for data acquisition. In fact, a three-person team in the senior design course, ASE 363Q -- *Design and Testing of Aerospace Structures*, worked on revision of the strain-gauge lab and developed the LabVIEW VI illustrated in Figs. 3 and 4 above. This team worked with National Instruments to develop recommendations for the new signal-conditioning hardware to be acquired.

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[2] *VirtualBench* is a registered trademark of National Instruments, Austin, TX.

8. Benefits and Drawbacks

As indicated by the title of this paper, significant benefits have accrued from the revisions incorporated in the *Measurements and Instrumentation* course. Among them are:

- Students use the computer extensively throughout the entire ASE curriculum, and it is natural for them to use the computer in this course.
- Students benefit from this exposure to virtual instruments.
- The LabVIEW VI's provide a very useful instrument for teaching the concepts of digital signal processing, frequency response, etc.
- The LabVIEW VI's make it possible for students to save data to computer files for later use in their formal reports.
- The quality of the formal reports, which are graded for both technical content and for English, has improved "1000%," since all text, equations, tables, and plots are computer generated. (See the first page of the Appendix.)

Several drawbacks should be mentioned:

- Because so much is now possible in terms of experiments to run and report features to expect, it is very tempting to overload the course.
- Plagiarism can be a problem! It becomes an easy matter for students to "borrow" computer files containing "A" reports. Some students, even top students, don't seem to be able to resist the temptation.
- Computers are not fool-proof! The lab computers stand idle a good bit of the week because there is too much likelihood that the files necessary to run the VI's and other applications during the *M&I* labs would be messed up if general use of the computers were to be permitted.
- Maintenance of the computers and software can, particularly if left to the TA's, be difficult. Taking advantage of new hardware or software can pose compatibility problems.

9. Conclusions

The benefits of using LabVIEW-based data acquisition in the Aerospace Engineering *Measurements and Instrumentation* course have far outweighed the drawbacks. Students in general have reacted very favorably to the course in its present form; their main complaint has been the amount of effort they must expend to produce the formal reports.

10. References

1. Neebel, D. J., Blandino, J. R., and Lawrence, D. J., *A Survey of Modern Computer-Based Experiments,* Part No. 321884B-01, National Instruments, Austin, TX, March 1998.

2. Eibeck, P. A., “Multimedia Courseware Support for the Instruction of Engineering Experimentation,” *Proceedings of Frontiers in Education 23rd Annual Conference*, sponsored by ASEE and IEEE, Washington, D.C., Nov. 6-9, 1993, pp. 135-139.

3. Hewlett-Packard website: www.tmo.hp.com/tmo/iia/edcorner/English/

4. Sierra, A., Linehan, D., and Thornton, D., *ASE 369K Strain Gage Lab Employing a LabVIEW VI Design Project - Final Report*, ASE-EM Department, The University of Texas at Austin, Austin, TX, Dec. 1998.

Biographical Information

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Roy R. Craig, Jr. is a Professor of Aerospace Engineering and Engineering Mechanics at The University of Texas at Austin. He joined the UT-Austin faculty in 1961, and currently holds the John J. McKetta Energy Professorship in Engineering. Dr. Craig has received numerous teaching awards, including the J. Leland Atwood Award, bestowed jointly by the ASEE and the American Institute of Aeronautics and Astronautics in 1997. He is the author of two textbooks, *Structural Dynamics - An Introduction to Computer Methods* and *Mechanics of Materials*, and of papers on modeling, identification, and control of flexible structures, and the use of computers in engineering education. Dr. Craig received a B.S. degree in Civil Engineering from the University of Oklahoma, and M.S. and Ph.D. degrees from the University of Illinois at Urbana-Champaign. He is a Fellow of AIAA and holds membership in ASEE, ASME, and SES.

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Edward McConnell is the Computer-Based Instruments Marketing Manager for National Instruments. His job responsibilities include the strategic marketing and product management of the company's computer-based instruments. He joined National Instruments in 1990 after working as a design engineer for BTS, Inc. in Germany. He holds a B.S. in electrical engineering and a B.A. in philosophy, both from Rice University. McConnell is a member of the IEEE, Eta Kappa Nu, and Tau Beta Pi.

Appendix

Sample pages that illustrate the quality of the formal lab reports and the design project report are reproduced here.

2.0 Theory

2.1 Second-Order Systems

2.1.1 Transient Response

Craig [1] shows that the equation governing a second-order system has the general form

$$\ddot{y} + 2\zeta\omega_n\dot{y} + \omega_n^{\,2}y = \omega_n^{\,2}Ku \qquad (2.1)$$

where

u = input (as a function of time),
y = output (as a function of time),
ζ = damping ratio (unitless),
ω_n = undamped (angular) natural frequency (rad/s), and
K = static sensitivity (output units/input units).

Equation 2.1 is a linear, second-order differential equation. For a step input u_0, Eq. 2.1 can be solved for y, which yields

$$y(t) = K u_0\left[1 - \frac{e^{-\zeta\omega_n t}}{\sqrt{1-\zeta^2}}\cos(\omega_d t - \beta)\right] \qquad (2.2)$$

where

$$\omega_d = \omega_n\sqrt{1-\zeta^2} \qquad (2.3)$$

$$\beta = \arctan\left(\frac{\zeta}{\sqrt{1-\zeta^2}}\right) \qquad (2.4)$$

ω_d = damped (angular) natural frequency (rad/s)
β = phase angle (rad)

Equation 2.2 represents the transient response of a second-order system.

2.1.2 Frequency Response

For a periodic input

$$u(t) = u_0\cos\Omega t \qquad (2.5)$$

the steady-state solution of Eq. 2.1 is

$$y_{ss}(t) = \frac{1}{\sqrt{(1-r^2)^2 + (2\zeta r)^2}}K u_0\cos(\Omega t - \phi) \qquad (2.6)$$

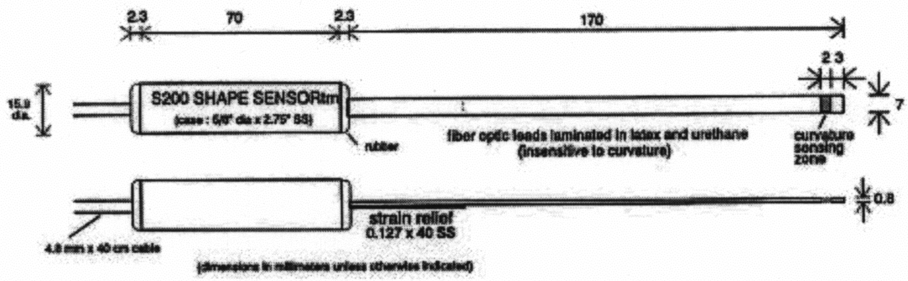

Figure 3
Dimensions of Measurand Inc. S200 Shape Sensor™

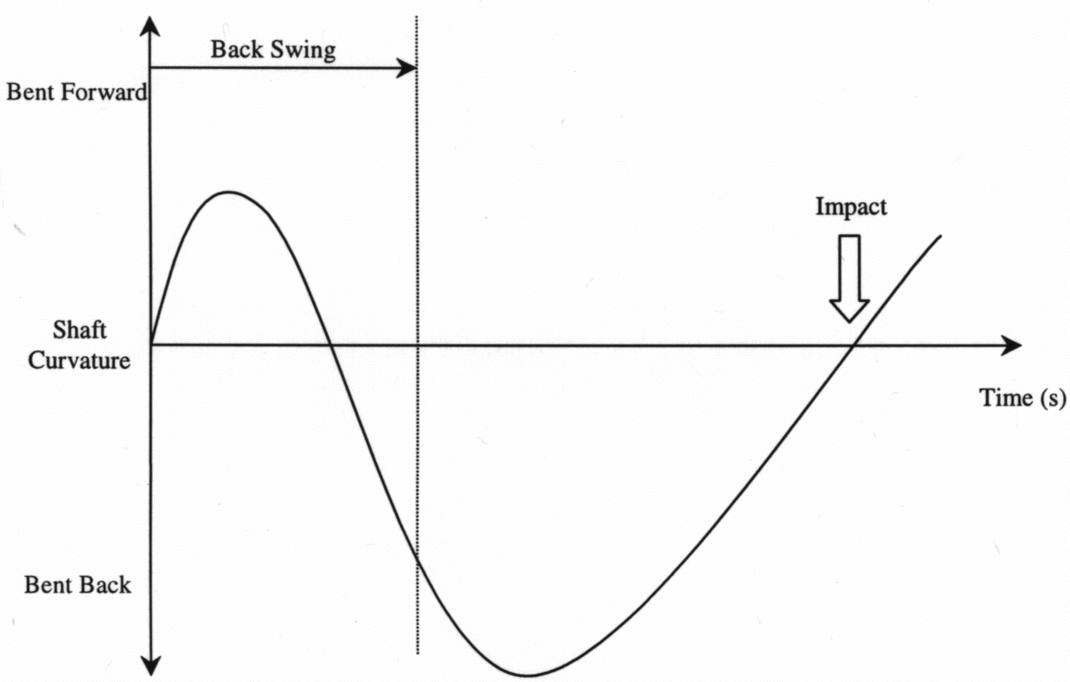

Figure 4
Possible System Output