2006-856: UPDATING MECHANICAL ENGINEERING MEASUREMENTS AND INSTRUMENTATION – A CASE STUDY

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Updating Mechanical Engineering Measurements and Instrumentation – A Case Study

Abstract

Measurement and instrumentation is a common course topic in many undergraduate mechanical engineering curricula. This paper summarizes changes to ME 370 – Engineering Measurements and Instrumentation at Iowa State University (ISU), which went through major course revisions from fall 2003 to spring 2005. Modifications to the course include the following: (i) incorporating virtual measurements and instrumentation into the lecture and laboratory, (ii) coupling the lecture and laboratory more closely through an on-line course manual, (iii) providing additional course resources through WebCT to enhance student learning, and (iv) updating and/or developing several new laboratory exercises to demonstrate key course learning objectives. An outline of the course before and after the course revisions will be presented, significant course changes will be summarized, the impact these changes have on mechanical engineering undergraduate education at ISU will be assessed, and lessons learned will be outlined.

1 Background

Mechanical Engineering Measurements and Instrumentation, commonly referred to as ME 370 at Iowa State University (identified as ME 370 for the remainder of this paper), is a required course in the mechanical engineering undergraduate curriculum. The course covers various measurement and instrumentation topics, as well as data acquisition and analysis. The course is usually taken in the second semester of the junior year and incorporates information from various courses in the ME curriculum, including mathematics, physics, statistics, dynamics, material science, and electrical circuits. It is typically the first such course students take that integrates topics from several courses. Since the course covers a wide variety of material from various disciplines, it has been taught in the past as a survey course, assuming the students have mastered the material in their courses leading up to this course.

Although ME 370 has a relatively recent history, a version of "Engineering Measurements and Instrumentation" has been taught in the ISU ME department for over 25 years because of it's importance to the mechanical engineering profession. The current ME 370 course was formalized with the 1999-2001 ISU course catalog as a result of changes in the ISU ME curriculum.

ME 370 has both lecture and laboratory components; it is composed of two 50-minute lectures each week and a 3-hour laboratory section. Total enrollment for the course averages between 100 and 120 students each semester, while the laboratory sections are limited to 12 students per section. There are six stations in each laboratory with student teams of two working at each station. Ideally, each station will have identical equipment, which is not always possible. Additionally, the 10-11 (typical) laboratory sections are supervised by teaching assistants.

Engineering Measurements and Instrumentation, as either ME 370 or a similar course, has never been a favorite course among ISU ME students. A fall 2002 graduating senior survey had over 60% of the respondents rate the educational value of ME 370 as "poor". Similar responses are found on senior surveys for prior versions of measurement and instrumentation. Hence, the overall goal of updating ME 370 was to increase the educational value of this course through various course innovations.

2 Course Structure

The previous ME 370 course syllabus was followed for approximately four years and is summarized in Table 1. The various laboratory exercises from spring 2003 are also identified in Table 1. ME 370 covered many topics in spring 2003 and used a measurement textbook by Beckwith et al.[1]; this textbook provides a great deal of information, but students thought it was too advanced and contained too much electrical engineering.

Table 1: ME 370 course syllabus in spring 2003.

Week	Lecture Topic	Laboratory Exercise
1	Overview, Measurement Systems, Data Acquisition	Excel and LabVIEW Tutorials
2	Digital Devices, A/D Conversion	Data Acquisition – Voltmeter
3	Probability and Statistics, Uncertainty	Data Acquisition – Voltmeter and Scanner
4	Time-Dependent Signals, Aliasing, 1st-Order Response	Calibration
5	2nd-Order Response, Readout Devices	1st-Order Response
6	Review, Exam	No Lab
7	Signal Conditioning	Readout Instruments – Oscilloscope
8	Voltmeters, Ammeters, Op-Amps	Filters
9	Resistance/Capacitance Sensors	Op-Amps
10	Linear Variable Differential Transformers, Thermocouples, Thermistors	Strain Gauges
11	Accelerometers, Exam	Thermocouples and Multi-channel Data Acquisition
12	Piezoelectric and Semiconductor Devices, Experimental Design	Accelerometers
13	Electrical Noise	LVDT "Design" Project
14	Standards and Codes, Review	LVDT "Design" Project
15	Optional Topics	No Lab
16	Final Exam Week	

The previous structure of ME 370 covered many topics that are important to measurement systems, but students felt there was a significant disconnect between the lecture topics and the laboratories. Also, the lecture topics "jumped around" from week to week and did not flow smoothly through the semester.

Course revisions identified three general topical areas on which to focus: (i) overall measurement systems, (ii) signal analysis and conditioning, and (iii) specific measurement examples. This allowed blending of the lecture topics between exams. Specific laboratory exercises to emphasize key lecture topics were also identified and more closely aligned to the lecture material; these are summarized in section 3.2.

The ME 370 syllabus after two years of modification is provided in Table 2. The laboratory exercises are also summarized and identified if they are new or revised versions of previous exercises. The topics covered in the modified course are fewer in number and more focused. A different measurement and instrumentation textbook by Figliola and Beasley[2] was also selected for this course and used beginning fall 2003.

Table 2: ME 370 course syllabus in spring 2005.

Week	Lecture Topic	Laboratory Exercise
1	Overview, Measurement Systems, Equipment	No Lab
2	Equipment, LabVIEW	Equipment Overview (**new**)
3	Probability and Statistics	LabVIEW Tutorial (**new**)
4	Uncertainty Analysis	Probability and Statistics (**new**)
5	System Dynamics	Calibration and Uncertainty (**revised**)
6	Catch-up, Review, Exam	No Lab – Exam Week
7	FFT Signal Analysis, Digital Sampling	1^{st}- and 2^{nd}-Order Response (**revised**)
8	Digital Devices, Data Acquisition	FFT Signal Analysis (**new**)
9	Op Amps, Filters	Op-Amps (**new**)
10	Noise, Bridge and Other Circuits	Electrical Noise (**new**)
11	Catch-up, Review, Exam	No Lab – Exam Week
12	Temperature Measurement	Multi-channel Data Acquisition (**new**)
13	Strain Measurement	Strain Gauges (**revised**)
14	Accelerometers	Accelerometers (**revised**)
15	Catch-up, Review	No Lab
16	Final Exam Week	

3 Significant Course Changes

Several changes were made to ME 370 between spring 2003 and spring 2005. The majority of these changes occurred in fall 2003, with minor modifications and improvements, based primarily on student and TA feedback, made in subsequent semesters. This section summarizes these changes.

3.1 New Laboratory Equipment

A lot of the equipment used in the ME 370 laboratory is in need of upgrading, but a significant capital investment is required. With limited funds, several selected pieces of equipment were purchased to be used in the new laboratory exercises. First, several identical low-cost handheld digital multimeters (DMM) were purchased (RadioShack 22-813; Fig. 1). A

DMM is a very versatile instrument and students are more likely to use this device than any other after they graduate. The students learned how to use this device in their first lab and then had access to it for the remainder of the semester if they needed to measure a voltage or resistance.

Fig. 1: Handheld multimeter.

Function generators are also used in several of the laboratory exercises, but we had three different function generators in the lab. We purchased six identical function generators (BK Precision; Fig. 2) and incorporated them into the new and modified laboratory exercises.

Seven National Instruments Educational Laboratory Virtual Instrumentation Suites (NI-ELVIS) were also purchased for modifications to the ME 370 laboratory. NI-ELVIS is a LabVIEW-based design and prototyping environment that can be used in measurement and instrumentation courses. It consists of LabVIEW-based virtual instruments, a multifunction data acquisition device, and a custom-designed bench top workstation and prototyping board (Fig. 3).

Fig. 2: Function generator.

The front panel of the NI-ELVIS workstation has controls for a variable power supply and a function generator, plus connections for a digital multimeter and oscilloscope. The actual front panel for the respective instruments can be found in LabVIEW VIs; hence, each instrument is actually a virtual instrument that can be modified as-needed by the user. Note that most instrumentation laboratories have stand-alone devices that perform these functions, but the devices are typically dated due to the upgrade costs (ME 370 at ISU included).

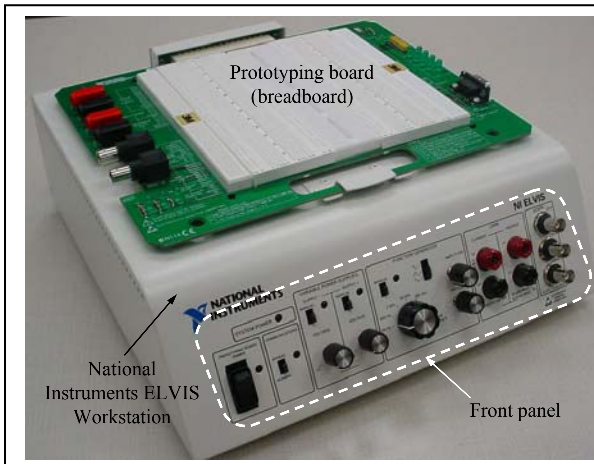

Fig. 3: NI-ELVIS workstation.

All instruments identified on the front panel of the NI-ELVIS workstation have corresponding connections on the prototyping board. The prototyping board also has connections for banana plugs and BNC cables that can be used as input and/or output. These connections correspond to areas on the breadboard that have to be connected to desired components for proper use.

The flexibility of the NI-ELVIS workstation allows for numerous laboratories to be developed as time permits, and some of this development is currently underway. Hence, the NI-ELVIS workstations will provide long-term flexibility to any ME 370 instructor.

3.2 New Laboratory Exercises

Seven new laboratory exercises were developed as part of the course modifications to ME 370. Many were implemented in fall 2003 and were further revised after student feedback; others were introduced in subsequent semesters. The laboratory exercises that were in place in spring 2005 and new since spring 2003 are summarized below. More details of selected laboratory exercises will be provided in future publications (e.g., Muff et al.[3]).

3.2.1 Equipment Overview

The purpose of this laboratory exercise is to familiarize the student with the basic functionality of a function generator, universal counter, oscilloscope, and digital multimeter. At the end of this exercise, students are able to:

1. Operate a B+K Precision 4011A function generator to set a given frequency, select a waveform, adjust the amplitude, and offset the function by a specified amount.
2. Use a HP 5216B universal counter to determine the frequency of a periodic input.
3. Operate a Tektronix 2236 oscilloscope to measure a voltage, find the amplitude of a periodic signal, measure the frequency of a periodic signal, compare two signals to each other, and determine the phase difference between two signals.
4. Use a HP 3456A digital multimeter and a RadioShack 22-813 digital multimeter to determine the AC and DC content of a voltage signal, measure an AC and DC current, and measure resistance.

3.2.2 Probability and Statistics

Students in this laboratory use a small data set to predict the characteristics of a larger population. Specifically, they measure the mass and diameter of 30 glass marbles to determine the average diameter and mass. They also determine if the sample population is normally distributed and if their results are statistically different from those of their lab partner.

The marble diameter and mass, and the associated specifications for the measurement instruments (i.e., a dial calipers and digital scale), are also used in the modified calibration and uncertainty laboratory. The students use their data to determine the density of the glass marble and an estimate of the uncertainty in their calculated density value. They also compare their calculated density with the tabulated density for glass and then offer an explanation for any differences.

3.2.3 LabVIEW Tutorial

In this tutorial, data acquisition and processing capabilities of LabVIEW 7.0 Express are highlighted. Students step through the process of using LabVIEW to turn a PC mounted data acquisition (DAQ) card into a total replacement for ordinary bench top devices. Students are given the opportunity to create their own virtual instrument that is able to function as a digital oscilloscope that can also measure AC-RMS and DC voltage, as well as fundamental frequency. Instruction is included on how to use LabVIEW to manually zoom in on important aspects of a captured waveform and/or automatically adjust the amount of information displayed in a graph of sampled data. In the process of building their virtual instrument, important concepts are covered such as simple debugging tips, and where to look for further help if they want to use functions not covered in the tutorial. When the virtual instrument is finally constructed, students are able to compare the results given by LabVIEW to the readouts of the traditional devices that are found at each lab station.

3.2.4 FFT Signal Analysis

This lab focuses on using the Fast Fourier Transform (FFT) to gain insight to the frequency domain information contained within a sampled signal. Students are given a MATLAB FFT program and are directed to apply inputs and interpret outputs from the program. In this manner, we focus on using an FFT as a tool for data analysis. Using MATLAB, students perform FFT operations on a sampled sine wave and note how sampling frequency and the number of data points directly influence the frequency range and resolution. Students also study non-ideal effects such as aliasing and spectral leakage. Students are also introduced to simple windowing functions that help alleviate some of the spectral distortion inherent with leakage. Advanced spectral analysis is also introduced with an example using Joint Time-Frequency domain Analysis (JTFA).

As a final exercise, students are given the opportunity to use spectral analysis techniques along with ASTM E 1876-01 Standard Test Method[4] to determine the mechanical properties of various rectangular metal bars. With the use of the defined test method, a single bar is supported and struck at an appropriate anti-node of a vibration mode. Using a microphone, the vibration can be measured and recorded by non-contact means. The data file is then analyzed using an FFT to identify possible natural frequencies. If more than one frequency is identified as a possible natural frequency, JTFA is used to determine the relative amount of damping present for each candidate frequency. The frequency with the least amount of damping is the true natural frequency of the vibration mode under test. Other possible frequencies can be ruled out and are likely a spurious mode that was accidentally excited.

Once the natural frequency of the vibration mode is determined, it can be correlated to either Young's or the shear modulus, depending on how the bar was supported. Using the method prescribed in ASTM E 1876-01, students are able to obtain material property results that are accurate within approximately 8% of tabulated values.

3.2.5 Operational Amplifiers

In this exercise, students are introduced to both ideal and non-ideal responses of a typical 741 operational amplifier. By using a NI-ELVIS workstation that is linked to a PC mounted data acquisition card, students are able to digitally sample and display voltage waveforms at the input and output of op-amp circuits under test.

Students explore the AC amplification characteristics of an inverting op-amp, voltage saturation and clipping, and slew rate limits. Students also investigate and measure the common mode rejection ability of a differential amplifier. Finally, students examine buffer amplifiers and their ability to isolate circuits from each other.

3.2.6 Electromagnetic Noise

In this exercise, three electromagnetic noise modes are presented including capacitive, inductive, and conductive coupling. More details of this exercise are provided by Muff et al.[3].

Students observe capacitive noise by applying various AC voltage potentials across a cable (the noise source), and then locating the cable close to wires that have a resistive load (a simulated transducer) while they measure the induced voltage across the load. Students record the induced voltage as a function of resistive load and noise source frequency. They also shield the wires with aluminum foil and determine the effect of grounding the shield.

Inductive coupled noise is demonstrated by generating a magnetic field with a coil of wire and then locating non-twisted and twisted wire pairs nearby. The induced voltage on the wires is compared. Finally, conductive coupled noise (ground loops) is demonstrated by connecting two instruments together and grounding each to a different ground location; the resulting voltage potential is then recorded.

3.2.7 Multichannel Data Acquisition

The primary goal of the multichannel data acquisition laboratory is to provide exposure to acquiring data in a loop, interchannel delay, and high speed data acquisition. Students examine issues important to acquiring data in a software timed loop. Students measure the maximum acquisition rate possible for their data acquisition card and determine if background processor tasks (e.g., operating a computer virus scan program) can affect maximum acquisition speed. Students also use a multiplexer to acquire data from different channels and measure the phase shift between channels to show that data are not taken at the same time.

3.3 Student Learning Aides

Several student learning aides were developed for ME 370 student use and provided through WebCT. WebCT (Web Course Tools) is a suite of educational tools that can be used to create a web-based learning environment. For ME 370, WebCT was used to create a course web page and provided a convenient location for students to access additional course material. For example, all lecture material was developed in PowerPoint slides and provided to the students before lecture. This allowed the students to focus on the material and not try to capture all the notes. Most students would print the notes out before lecture and embellish them during lecture. One exception to providing notes to the students was the example problems completed in class; the students were provided with the problem statement, but the solution was completed in class and not provided on WebCT.

The laboratory exercises and associated rubrics for each lab were provided in a separate folder on WebCT. This allowed for changes to be made to laboratory exercises during the semester and the most current version was available to the students. The lab rubrics were also provided before the lab so students knew exactly what was expected for each lab.

Several tutorials and examples were also developed and provided to the students through WebCT. Since ME 370 is usually the first course encountered by ME students where a lot of information is incorporated from prior courses and tied together, the subject matter of the tutorials and examples were typically from previous (required) courses in the ME curriculum (e.g., mathematics, physics, statistics, dynamics, material science, and electrical circuits). The tutorials and examples were provided to refresh the memories of the students. Additionally, they summarized important points from the previous courses that are important for successfully completing ME 370. Table 3 provides a list of the tutorials available to students in spring 2005.

Table 3: ME 370 tutorials provided to students in spring 2005 through WebCT.

Tutorial Title
Excel Example Data and Tutorial
Some Useful Math Relationships
V_{RMS} Calculation
Example – Sensitivity
An Introduction to LabVIEW
Z-Distribution Example
Example – Use of the Z-Distribution
Chi-Squared Example
Propagation of Uncertainty – Example 1
Propagation of Uncertainty – Example 2
Solutions to 1^{st} and 2^{nd} Order ODEs
Example – Second Order Systems
Nyquist Frequency
FFT, Sampling, and Frequency Resolution
Review of Simple Electrical Circuits
Op Amps, Noise, and CMRR
Loading Errors and Voltage Dividers
Thermocouples
Strain Gauges
Accelerometers

Other material provided on WebCT included suggested homework problems and solutions, sample exams and answers (full solutions were not provided), solutions to exams from the current semester, and homework assignments and solutions that were graded for credit.

4 Impact On Undergraduate Education

Between fall 2003 and spring 2005, 440 undergraduate students completed ME 370 at ISU. The impact the course modifications had on undergraduate education can be assessed both qualitatively and quantitatively. Qualitatively, student comments have been generally positive. The Mechanical Engineering administration was also extremely supportive, particularly in a time of tight budgets. Quantitative results can be measured using the standard end-of-semester course evaluations and graduating senior surveys.

The standard end-of-semester course evaluations address text and course issues, as well as instructor issues. One item the students are asked to rank is the “overall teaching effectiveness of the instructor” as it relates to the course material. Figure 4 shows this rating on a 5-point scale, with 1 = poor and 5 = excellent. Each data point represents the ME 370 instructor (open symbol) and department average for all courses that semester (solid symbol) to the response to overall instructor effectiveness. The data cover a period of five academic years and five different instructors. Data from multiple sections are provided during some semesters. Note, however, that ME 370 was always taught with 2-3 sections per semester prior to fall 2003, at which time a single large (~110 students) section was offered.

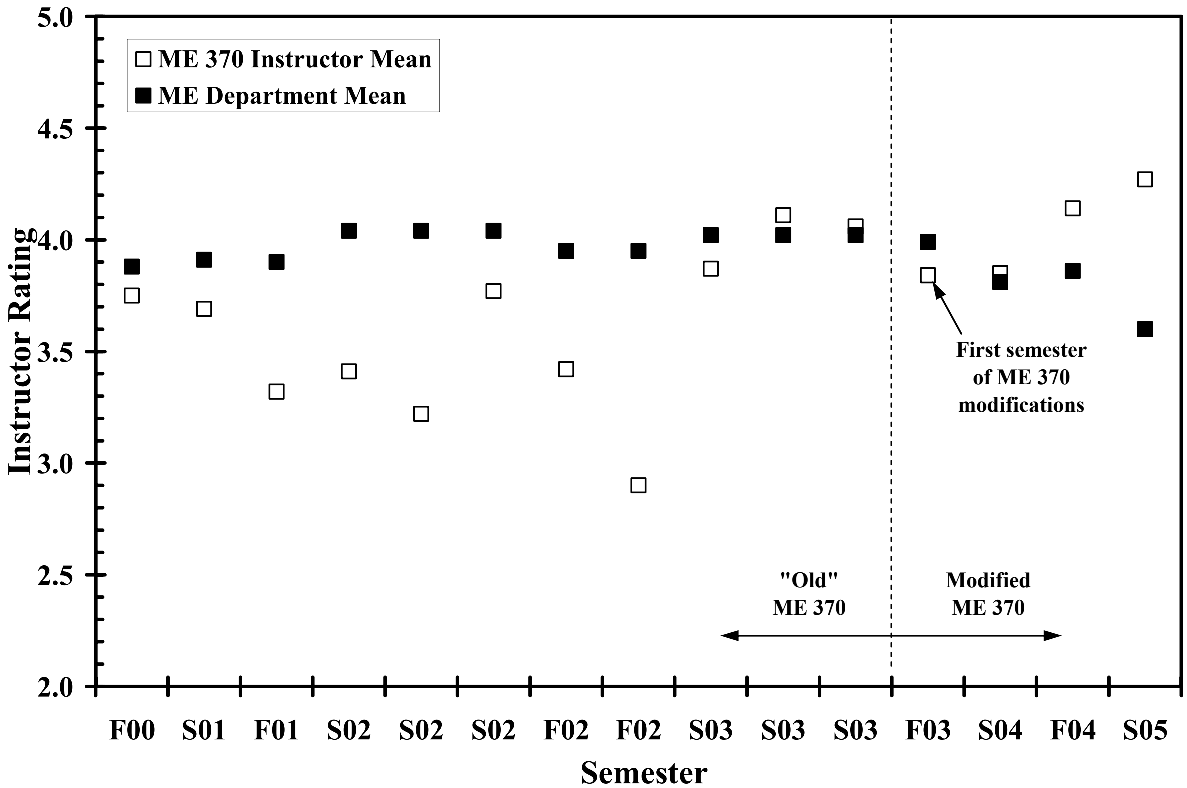

Fig. 4: Student response to overall teaching effectiveness relative to the course material. The semester represents five academic years and five different instructors. Teaching effectiveness is based on a 5-point scale with 1 = poor, 5 = excellent.

Figure 4 shows that since ME 370 was introduced in the ME curriculum, the “old” ME 370 course was consistently rated below the department average, with the exception of two sections in spring 2003; these two sections represent the first time this author taught the course, but the old syllabus was used. The student ratings were below the departmental average during the first semester the course modifications were implemented (fall 2003). The potential reasons for this drop relative to the previous semester for the same instructor include:

1. Some of the initial laboratory modifications were rushed and students felt they were “guinea pigs” when the laboratory did not go smoothly. The laboratories went better the second semester (spring 2004), and additional help was provided by the course instructor and TA during the first laboratory section of each week to quickly correct any problems that came about from laboratory modifications.

2. A new text was introduced at the same time course modification were being implemented. The text and solution manual had several typographical errors which frustrated the students (and the instructor). Most of these errors were identified by the second semester the text was used (spring 2004).
3. The course went from multiple sections of ~35-45 students per section and 2-3 sections per semester to a single large section of ~110 students per semester. With the large number of students, it was difficult to interact with each student on a personal level.

The above reasons caused the ratings drop during the first semester the modifications were initiated. The second semester shows the course ratings to be above the department average. Subsequent semesters, in which course and laboratory material were further refined, shows a consistent improvement.

Information from graduating senior surveys can also be used to quantitatively assess the impact of the ME 370 changes. Figure 5 shows the response to the question: “Please rate the educational value you received from ME 370” with possible responses of “Excellent”, “Adequate”, and “Poor”. The general trend is that over a 6 semester time frame, the percent of respondents who thought the educational value of ME 370 was “Poor” declined, while the percent of respondents who felt it was “Excellent” increased. Since ME 370 is typically a second-semester junior-level course, it seems reasonable that there is a 2-3 semester time lag between when the ME 370 modifications were initiated (fall 2003) and a change in the senior survey as a result of ME 370 modifications. This is particularly apparent in the S05 and F05 semester.

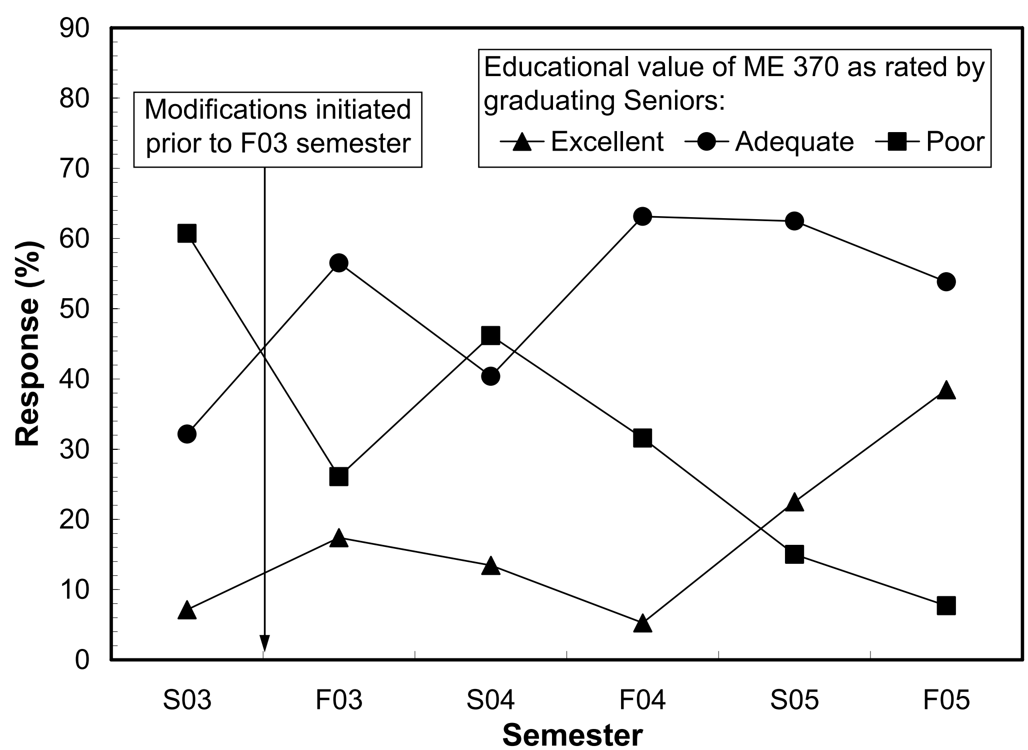

Fig. 5: Percent of graduating seniors who thought the educational value of ME 370 was either excellent, adequate, or poor.

5 Lessons Learned

Participating in this project was very rewarding. It allowed time to really think about a course, what is important to that course, and how much and how many of the important topics should be covered. Too often, faculty have more than one course and several research topics to think about, so major course philosophies are left to their own inertia.

The real challenge with this project was to stay ahead of the students, particularly during the first semester the course modifications were implemented. Three factors contributed to this dilemma. First, a new textbook was selected to be used in the course, so all the course notes had to be modified. Second, new problem assignments were also developed to correspond to selected problems in the new textbook. Although a solution manual was provided with the text, several errors were identified during fall 2003, so all problem solutions had to be checked. Finally, each laboratory exercise was either edited to correspond to material in the new textbook, revised to update the exercise, or developed from scratch. During the second semester of course modifications, additional laboratory modifications were implemented. The laboratory modifications took a lot more time to implement than originally planned, which was the most significant challenge in this project.

All of these changes made it frustrating (at times) for the students because the lecture notes, problem solutions, and/or laboratory exercises were made available only 1-2 days before they were covered. (As a side note, even when they were made available several days before they were covered, few students actually reviewed them beforehand.)

From the experience gained in this project, I would make modifications to a laboratory course on a different timeline next time. I would not select a new text at the same time extensive laboratory modifications are being made (unless adequate lead-time is available). I would also develop new laboratory exercises at least one semester before they are implemented and have someone else (e.g., the course TAs) go through them before they are introduced to the ME 370 students.

6 Conclusions

The required junior-level mechanical engineering course entitled ME 370 – Engineering Measurements and Instrumentation at Iowa State University went through significant changes from fall 2003 to spring 2005. Modifications to the course included (i) incorporating virtual measurements and instrumentation into the lecture and laboratory, (ii) coupling the lecture and laboratory more closely through an on-line course manual, (iii) providing additional course resources to enhance student learning through WebCT, and (iv) updating or developing several new laboratory exercises to demonstrate key learning objectives. These changes improved the course for ~110 students per semester. The improvement is most apparent in the graduating senior surveys, where more students feel the educational value of ME 370 is now "Excellent" and fewer students feel it is "Poor". Resources are also now in place to make continuous improvements by developing new laboratory exercises, particularly with NI-ELVIS workstations.

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