AC 2007-407: AN INTEGRAL ANALYTICAL-NUMERICAL-EXPERIMENTAL PEDAGOGY FOR A SYSTEM DYNAMICS AND CONTROL COURSE

Benjamin Liaw, City College of the City University of New York

Professor Liaw received his Ph.D. degree from the University of Washington in 1983. After a year of post-doctoral research study at University of Washington, he joined the faculty of the City College of the City University of New York (CCNY) in 1984, where he is a Full Professor at Department of Mechanical Engineering. During 2000-2002 he was also appointed Acting Associate Dean for Undergraduate Studies, School of Engineering. His interests include (1) the design, analysis, manufacturing and testing of composites and smart materials, and (2) improving engineering education through innovative teaching and research techniques, with emphasis on attracting under-represented minorities and women. Through years he has published more than 70 refereed papers with funding support from NSF, NASA, ARPA, AFOSR, ARO, U.S. Army TACOM-TARDEC and ARDEC-Picatinny Arsenal, AT&T, Digital Equipment Corporation, Alliant Techsystems, Frontier Performance Polymers, NYS GRI and PSC CUNY. In addition to being active in research, he had also served as the ECSEL Project Director at CCNY in 1993-2001. The main charge of the NSF-funded ECSEL Coalition is to improve undergraduate engineering education through design across the curriculum.

Ioana Voiculescu, City College of the City University of New York

Professor Ioana Voiculescu received a Ph. D. degree in Mechanical Engineering from Politehnica University, Timisoara, Romania, in 1997 in the field of Precision Mechanics. She finished her second doctorate in 2005, also in Mechanical Engineering, but with the emphasis in MEMS. She has worked for more than five years at the U.S. Naval Research Laboratory, in Washington, DC in the area of MEMS gas sensors and gas concentrators. Currently, she is developing a MEMS laboratory in the Mechanical Engineering Department at City College University. She is an IEEE member, an ASME member and a reviewer for IEEE Sensors Journal in 2004, 2005 and 2006

An Integral Analytical-Numerical-Experimental Pedagogy for a System Dynamics and Control Course

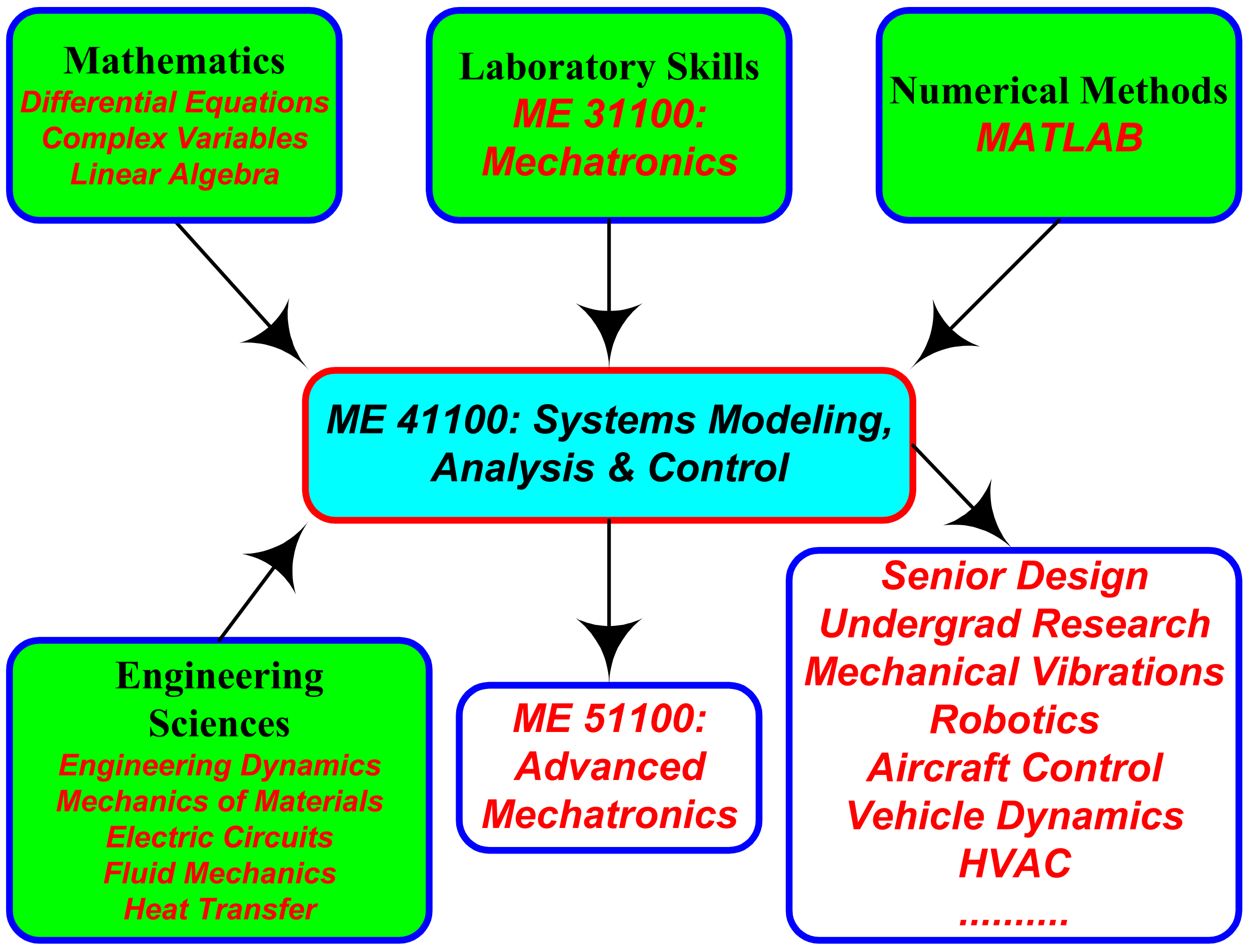
Abstract

An integral analytical-numerical-experimental pedagogy was adopted to reform the teaching-learning method in a junior systems dynamics and control course in the Mechanical Engineering program at The City College of New York. The main objective of the course reform is to help students acquire knowledge and abilities necessary for the success in students' future professional careers (including graduate studies) and life-long learning. In lieu of the conventional textbook-based homework and exams for a traditional engineering science course, three approaches were adopted for the reform of this system dynamics and control course: (1) comprehensive homework linking the training of mathematical skills, computational techniques and engineering design capabilities, (2) an integral analytical-numerical-experimental approach to solve engineering problems, and (3) student initiated final group presentations and reports. Once completed the course, students are expected to have developed abilities to identify and formulate real-world engineering problems, to carry out background research, to think creatively, to work individually and in teams, to synthesize information of various attributes, to assess results, and to communicate with others effectively. As an evidence, the reform result is very encouraging. The score of the internal ABET course survey of the course has shown drastic improvement.

1. Introduction

The study of System Dynamics and Control requires a genuine multi-disciplinary approach to integrate principles in various engineering disciplines (mechanical, electrical, computer, information technology, etc.) to develop optimal strategy for solving a contemporary engineering problem. Many educators have developed various forms of pedagogy for the improvement of teaching-and-learning of this important subject[1-10]. This paper presents part of results of the recent NSF-funded departmental-level undergraduate curriculum reform at the Department of Mechanical Engineering, The City College of The City University of New York. The current effort adopted an integral analytical-numerical-experimental pedagogy for a required course – **ME 41100: Systems Modeling, Analysis and Control** (4 credits, 3 lecture hours and 3 laboratory hours), which is one of three courses in the area of mechatronics and controls offered in this curriculum. The other two courses are ME 31100: Fundamentals of Mechatronics (required, 3 credits, 2 lecture hours and 3 laboratory hours) and ME 51100: Advanced Mechatronics (technical elective, 3 credits, 2 lecture hours and 2 laboratory hours). Results of the curriculum reform in other courses had been reported elsewhere[11-13].

As shown in the figure on next page, ME 41100 lies at the center of the Mechanical Engineering curriculum. The pre-requisites required for this courses include mathematics (calculus, differential equations, complex variables, linear algebra, etc.), engineering sciences (dynamics, mechanics of materials, fluid mechanics, heat transfer, electric circuits, etc.), MATLAB-based computer and numerical techniques, and mechatronics-based laboratory techniques (e.g., knowledge of various electro-mechanical-optical sensors, digital data acquisition, characteristics of measurement systems, engineering statistics and regression analyses, etc.). In short, this course serves as the culmination of our engineering science portion of curriculum. Students are expected to apply the knowledge acquired from this course to almost all advanced courses during their senior year. These courses include, but are not limited to, senior design projects, advanced mechatronics, mechanical vibrations, robotics, aircraft stability and control, vehicle dynamics, HVAC, etc.



One of the major activities the Department undertook for the preparation of ABET visit in Fall 2004 was the reform of ME 41100. Previously, this course was split into two required courses - ME 42100: Systems Modeling, Analysis and Control (3 credits, 3 lecture hours) and ME 54300: Dynamics and Controls laboratory (1 credit, 3 laboratory hours). These two courses were sequential; that is, ME 42100 is the pre-requisite of ME 54300. As illustrated in the above figure, students need extensive background in analytical, numerical and experimental skills to learn well in ME 42100, the system dynamics and control course. However, in the old curriculum, this course was offered as a traditional engineering-science type of course with only 3 hours for lecture, which was not enough to cover the whole gamut of mechanical-engineering related systems, such as translational, rotational, electrical, electromechanical, pneumatic, hydraulic, thermal systems, etc.

The reform result is very encouraging. The score of our ABET course survey of ME 41100, in comparison with those of ME 42100 and ME 54300, has risen steadily from below 60 to around 80. Such a drastic change is NOT merely due to the change of sequential offering of ME 42100 and ME 54300 to the version of parallel offering. Details of these ABET course survey results will be discussed at the end of this article. It is our belief that the improvement is mainly due to the implementation of several educational-reform activities into the new version of ME 41100. The implementation of these reforms, sponsored by an NSF-funded curriculum reform grant, is reported below.

2. Objectives and Strategies of the Course Reform

The main goal of the course reform in ME 41100: System Modeling, Analysis and Control is to help students gain useful knowledge and skills in the general area of system dynamics and control. Such knowledge and skills are necessary for the success in students' future professional careers (including graduate studies) and for the continuation of their life-long learning. In order to achieve this goal, students in this class solve problems and explore issues in system dynamics and control using engineering analysis, computation and experimental techniques. Once completed the course, students are expected to have developed abilities to identify and formulate real-world engineering problems, to carry out background research, to think creatively, to work individually and in teams, to synthesize information of various attributes, to assess results, and to communicate with others effectively.

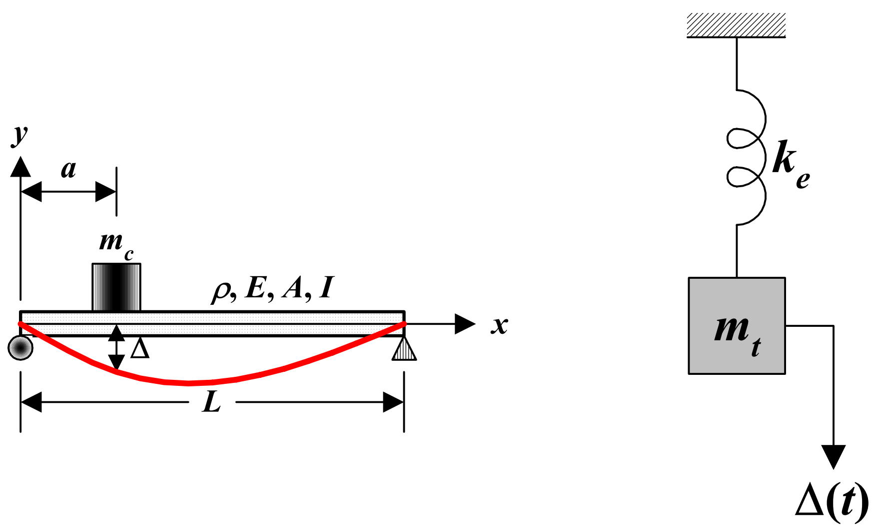
To accomplish these objectives, we adopted a strategy emphasizing: (1) collaborative learning by student teams for problem solving, (2) just-in-time integral learning using analytical, computational and experimental approaches, (3) close linkage between mathematics skills and engineering applications, (4) student-initiated knowledge exploration, including exposure to emerging technologies. In short, this course reform places learning in students' own hands; emphasize communication skills (both oral and written); encourage team work and development of people skills; and expect an ability for life-long learning.

The first step taken in this course reform activity was the revision of grading system. In the old mode when the course was split in two sequential courses: ME 42100 (3 credits, 3 lecture hours) and ME 54300 (1 credits, 3 laboratory hours). The grading system for the former was: homework (10%), mid-term exams (60%), and final Exam (30%), whereas for the latter the grading system was: exam (20%) and lab reports (80%). In the current mode: ME 41100 (4 credits, 6 lecture-laboratory hours), the grading distribution is homework (36%), lab reports (18%), exams (25%) and final group presentation and report (21%).

Traditionally exams are used as the main assessment tool to evaluate a student's progress. However, since most of, if not all, students tend to prepare for an exam seriously only a few days before the exam, their learning usually is sporadic and the hastily acquired knowledge may be easily forgotten after the exam. Hence, two exams, each counts as 12.5% toward the course grade, are held in the course to test students' accumulated knowledge in the middle and at the end of the semester. On the other hand, in order to reflect the new grade distribution system, the current course reform stresses on comprehensive homework assignments, integral analyticalcomputaional-experiemntal lab reports and final group presentation and report, which together count for 75% of the course grade. We believe that knowledge gained through these three non-exam oriented assessment tools will ingrain into students' memory more permanently and pave way for the course to achieve the afore-mentioned educational objectives.

3. Comprehensive Homework Approach

As stated above, homework assignment in the old mode counts only a small fraction of the grade, the problems were frequently taken out of textbook directly. In general each problem represents a simple practice and is only intended to present a single concept of the chapter. To get the answer very often students need only to choose a proper equation given in the chapter. Since these concepts, though closely connected, may appear independently among those dispersive homework problems, hence for most of students it may be difficult for them to see the overall picture showing how these concepts related with each other and linked with other subjects in the curriculum, i.e., the pre- and co-requisites. In this course reform, innovative homework assignments were designed to induce students' learning from past experience, i.e., prerequisites as well as future advanced study. For instance, in one of the homework assignments, students were asked to find the equivalent spring constant and mass of a simply-supported beam loaded with a concentrated mass, as shown in the figure below.



The problem is related to one of the prerequisites of the course: ME 33000: Mechanics of Materials. In order to find the equivalent spring constant and mass, students will need the results of beam deflection due to an equivalent concentrated force. Such a beam deflection may be obtained from a conventional Mechanics of Materials textbook. To demonstrate that background knowledge from Mechanics of Materials is needed, students are asked to solve this problem through the following steps:

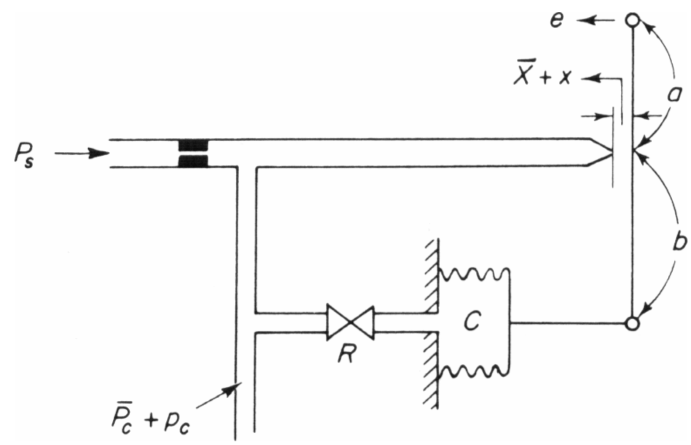
(a) Generate a free-body diagram to determine if the beam is statically determinate or indeterminate.

(b) Find the reactions and the shear and moment distributions if the beam is statically determinate.

(c) Obtain the beam deflection and slope based on the results in Step **(b)** if the beam is statically determinate. On the other hand, if the beam is statically indeterminate, obtain the reactions, the shear and moment distributions, and the beam deflection and slope using the more complicated approach.

(d) Determine the equivalent spring constant and mass of the beam using the concept of energy equivalence.

In the old mode of teaching, Steps **(a)** to **(c)** were considered covered in our ME 33000: Mechanics of Materials. Only Step **(d)** was considered to be belonging to the course of system dynamics and control. However, without a thorough review of Steps **(a)** to **(c)** and acquiring the segmented knowledge by executing only Step **(d)**, a typical student may have difficulty to visualize the full picture linking these two basic subjects in engineering science: the Mechanics of Materials and the System Dynamics and Control.



Another feature of the comprehensive homework approach is to guide students through unchartered water. In this approach, students were asked to work on homework assignment based on not only the knowledge they acquired in this course, but also additional reading assignment taken from advanced study in system dynamics and control. For instance, the textbook adopted in this course is: K. Ogata, *System Dynamics*, 4th ed., 2004, which is suitable for a junior course such as ME 41100. In this textbook students learned basic dynamics for pneumatic systems as well as fundamental concepts in the proportional-integral-derivative (PID) control. In one of their homework assignments: Pneumatic PD Controller (as shown in the figure above), students are asked to study the section of Control of Pneumatic Systems, taken from an advanced textbook by the same author, *Modern Control Engineering*, 4th ed., 2002, *pp*. 158-175, which is more suitable for a first-year graduate level course in feedback system control. The functions, construction, applications and limitation of a pneumatic proportional (P) controller is explained fully in this <u>self-study</u> reading assignment. Students are asked first to learn this advanced, yet related, subject by themselves, then to apply this self-study knowledge to explain the pertinent attributes of a pneumatic proportional-derivative (PD) controller.

4. Integral Analytical-Computational-Experimental Learning

In the old sequential mode of curriculum, students did not conduct experiments in system dynamics and control until they had completed the learning of all theories and analytical/numerical techniques. As commonly known, “seeing is believing”. Without hands-on experimental experience, some students, if not all of them, may be hampered from acquiring knowledge in engineering. Furthermore, since theories and experiments were learned in two separate courses: ME 42100 (theories) and ME 54300 (experiments), in the past a few students, though in minority, postponed the taking of ME 54300 several semesters after they have taken ME 42100, thus diminishing the effect of learning the subject in continuation.

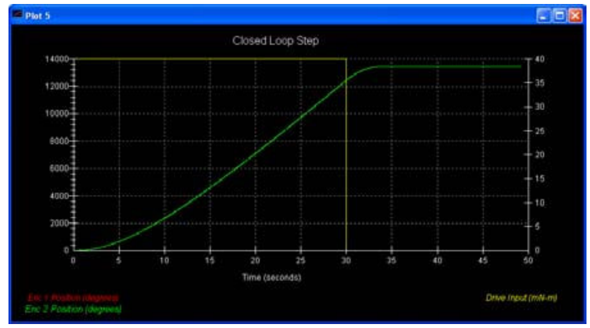
With the augmented credits and hours in this reformed course, we now have the flexibility to teach subjects in an integral analytical-computational-experimental approach and make easy for students to have full understanding of the subjects. As an example, the figures depicted on next page show the experimental apparatus of an unrestrained torsional mechanical system, Educational Control Products (ECP) Model 205 Torsional Dynamic/Control System, as well as its experimental and numerical (MATLAB) time responses due to a step torque input.

5. Final Group Presentation and Report

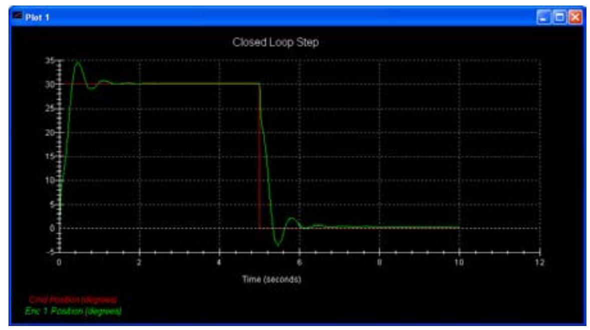
In lieu of traditional final exam, students were asked to make a final group presentation with a report. Indeed, the team, which usually constitutes three to four students, was formed at the beginning of a semester and is the basis for the afore-mentioned collaborative learning and experimental group. Topics of the final presentation must be related to proportional-integral-derivative (PID) control. Each student team needs to define its engineering problem and comes up with the governing equations of the problem for analysis and design. Specifically, the presentation should be conformed to feedback control of a physical plant subject to reference, disturbance and noise inputs in the form of step, ramp and parabolic functions. The resultant controlled output and the actuating error signal are of particular interest. Strong encouragement was given to topics of interdisciplinary nature and/or applications in emerging technologies (e.g., MEMS/mechatronics, nanotechnology, intelligent systems, smart structures, adaptive materials, biomedical engineering, innovative energy-power systems, etc.). The rationale of having this learning activity at the culmination of a semester, as mentioned earlier, are to help students develop abilities to identify and formulate real-world engineering problems, to carry out background research, to think creatively, to work individually and in teams, to synthesize information of various attributes, to assess results, and to communicate with others effectively. In a nutshell, it places learning in students’ own hands after they have accumulated enough background knowledge. Such training is very crucial for their capability for life-long learning in the future. In this past semester (Fall 2006) the following topics were studied:

- Lateral Directional Dynamic Stability and Control of an Aircraft
- PID Controller Tuning for a CVD Process
- Control of Turbine Blade Vibration
- Deck Stabilization Using Hydraulic Circuit
- Control Optimization of Nonlinear Dynamic System: Rocket Trajectory
- Yaw Control of a Wind Turbine

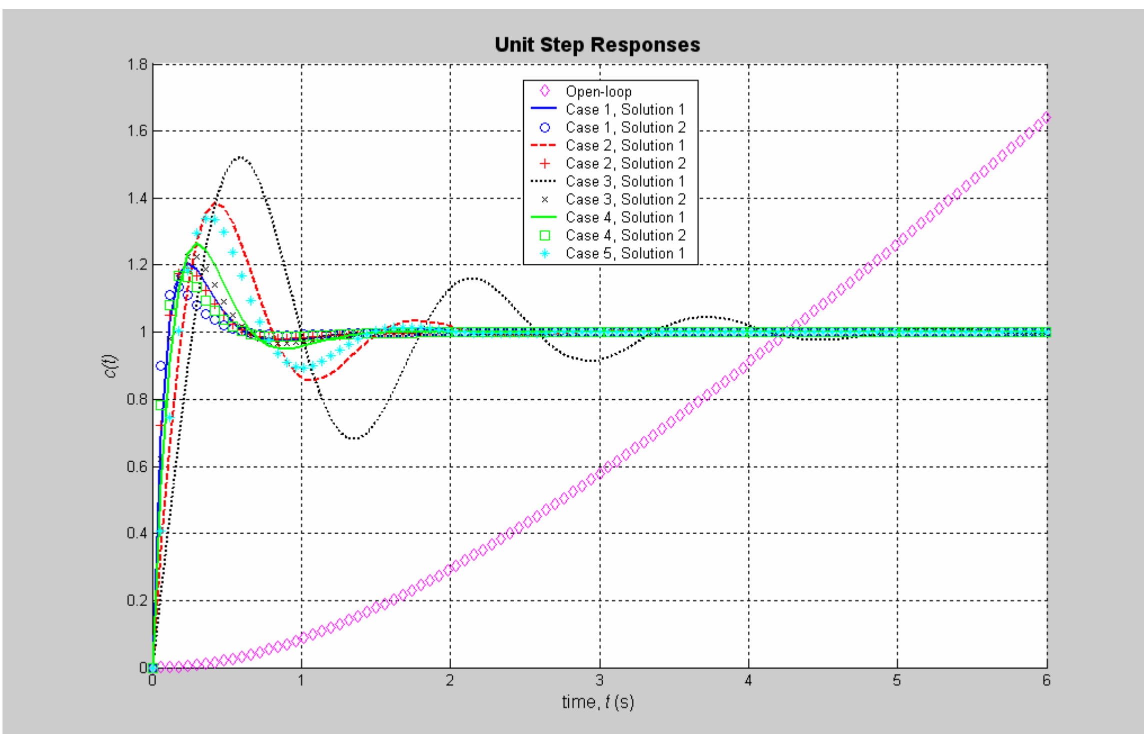
An unrestrained torsional mechanical system



Open-loop time response in disk position



Closed-loop PD response in disk position



Analytical-computational (MATLAB) solutions.

6. ABET Course Survey

Since Spring 2002, the Department requires ABET course survey being conducted for each class section, as one of our ABET assessment tools. The survey questions, called Course Outcomes, of a given course were designed by a faculty coordinator, who may not always be the instructor. Results of the survey of this system dynamics and control course in the Fall 2006 semester are tabulated below:

	Survey Question (Course Outcome)	N	Knowledge Gain			
			Percentage of N			Mean
			None	Partial	Strong	
1	Ability to model various physical systems using techniques of differential equations. Ability to model and analyze these systems using MATLAB,	20	0	30	70	88
2	Knowledge of time-domain responses of first and second order systems. Ability to solve time response problems using MATLAB.	20	0	30	70	88
3	Knowledge of control systems in time domain, etc. Ability to use MATLAB for design and performance prediction of control systems in time domain.	**19**	**0**	**70**	**30**	**72**
4	Knowledge of frequency-domain responses of dynamic systems and vibration problems. Ability to solve frequency response and vibration problems using MATLAB.	**20**	**0**	**70**	**30**	**72**
5	Knowledge of control systems in frequency domain. Ability to use MATLAB for design and performance predictions in frequency domain.	**20**	**5**	**65**	**30**	**69**
6	Ability to conduct time-domain mechanical system experiments and compare with theoretical prediction.	20	0	40	60	84
7	Ability to conduct frequency-domain vibration experiments and compare with theoretical prediction.	20	0	55	45	78
8	Ability to conduct various control experiments and compare with theoretical prediction.	20	0	35	65	85
	Average		**1**	**49**	**50**	**80**

In the table above, the means were calculated by giving a weight of 1.0, 0.6 and 0.0 to the Strong, Partial and None answers, respectively. As shown in the last row of the table, about half of the class felt they had gained strong knowledge/ability whereas the other half considered they had acquired partial knowledge/ability of system dynamics and control from the course. Students also felt more comfortable when the knowledge/ability is in time domain (Questions 1, 2, 6 and

8) while they felt somehow lost when dealing with problems in frequency domain (Questions 4, 5 and 7). This is understandable due to the two facts:

(a) Most of us are more intuitive in time domain, rather than in frequency domain.

(b) The subjects in frequency domain are covered in the last three weeks, which are only one-fifth of the contact hours of the course. That means students did not have enough time to digest what they had just learned before taking the survey, which is usually given at the end of the semester.

Finally, the two tables below summarizes the ABET course surveys from Spring 2002 till Fall 2006. Other than the Spring 2002 semester, all the remaining classes were taught by this author. The first table shows results of the ABET course surveys conducted according to the old pedagogy; whereas the second table depicts results for semesters with the reform pedagogy being implemented. As one can see from these two tables, the survey mean (which is proportional to the students' confidence in their knowledge gain) improves drastically from a score of 56.7 to 78.8 while the over all academic performance has also improved impressively.

ME 41100 ABET Course Survey Results (Before Reform)

Semester	Students Enrolled	Students Surveyed	Survey Mean	Grade					
				A	B	C	D	F	W
2002 Spring*	19	16	**51**	1	6	6	4	1	1
2002 Fall	24	18	**56**	6	9	7	1	0	1
2003 Spring	14	14	**64**	0	9	3	1	1	0
	57	**48**	**56.7**	**7**	**24**	**16**	**6**	**2**	**2**

Note: (*) The Spring 2002 class was taught by another instructor.

ME 41100 ABET Course Survey Results (After Reform)

Semester	Students Enrolled	Students Surveyed	Survey Mean	Grade					
				A	B	C	D	F	W
2003 Fall	5	5	**81**	2	1	1	1	0	0
2004 Spring	8	8	**86**	2	4	2	0	0	0
2004 Fall	20	16	**79**	7	6	4	2	0	1
2005 Spring	26	25	**74**	6	15	4	0	0	1
2005 Fall	23	19	**80**	4	9	10	0	0	0
2006 Spring	11	7	**79**	3	3	3	0	0	2
2006 Fall	22	20	**80**	5	10	7	0	0	0
	115	**100**	**78.8**	**29**	**48**	**31**	**3**	**0**	**4**

6. Conclusions

In summary, pedagogical reform has been carefully planned, implemented and executed in a system dynamics and control course. Through 10-semester student surveys, the results show significant improvement in students' overall knowledge gain and academic performance. It is believed that the improvement of teaching-and-learning in this course will pave ways for partial fulfillment of the Department's mission and goals in undergraduate education; that is, once completed the course, students are expected to have developed abilities to identify and formulate real-world engineering problems, to carry out background research, to think creatively, to work individually and in teams, to synthesize information of various attributes, to assess results, and to communicate with others effectively.

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