A Novel Set of Courses for Teaching Electrical System Analysis to Mechanical Engineering Students

Rico Picone and Paul E. Slaboch
Saint Martin's University, Lacey, WA

Abstract

For many years in the standard mechanical engineering curriculum, the topics of electrical system analysis, mechanical system analysis, and instrumentation have been taught as separate and sometimes disjoint courses. However, these topics are fundamentally related through the manipulation of electrical energy to produce a desired result, whether it be to turn on a light, turn an electric motor, or measure the stress in a beam. In an effort to more forcefully show the students how these subjects are related, a set of three courses, designed to be taken as co-requisites, was developed to integrate these topics. Two lecture-based courses, one covering mechatronics and the other covering instrumentation, as well as a laboratory course that applied the understanding gained in the lectures, were created and implemented during the fall semester of 2014 at Saint Martin's University. The students enrolled in these three courses were third-year students. The lectures for both topics were taught by one faculty member while a second faculty member taught the lab course. Close collaboration between the faculty members ensured that the topics covered in lecture kept pace with the labs so that students were able to first learn a theory, then apply it in laboratory practice. Assessment of course learning objectives revealed that students were better able to relate topics that were common between courses and had a stronger understanding of all topics. While the results of this first sequence were promising, there is room for improvement, and changes to some aspects of the lab and courses have been proposed to improve this novel set of courses.

Introduction

Every mechanical engineering (ME) student must learn the basics of electrical engineering concepts. Electrical systems are becoming more and more common in the mechanical world and the two systems can no longer be considered individually. It is important that all mechanical engineering students have the ability to deal with the union of these two disciplines.

Most mechanical engineering programs agree that electrical concepts are important to the ME students and require students to take an introductory course in electrical engineering (EE). This course is typically titled “Introduction to Electrical Circuit Design” or “Introduction to Electrical Engineering.” This course is also generally taught by the EE department. Having this course taught through the EE department offers significant advantages, most notably an opportunity for courses outside of the student’s major and exposure to a different way of thinking about electrical concepts. However, in learning about electronics as separate systems from the mechanical usage, students may have trouble combining these concepts later in their curriculum.

What happens if a particular university does not have an electrical engineering department? How should these important electrical topics be introduced in an ME department? The answer according to the ME department at St. Martin's University is to introduce these topics in a novel set of three courses meant to teach electrical concepts in concert with their mechanical components. The three-course set is comprised of Mechatronics, Instrumentation & Experimental Design, and a Laboratory Course that allows hands-on learning of electrical concepts.

In the past, the ME department at St. Martin's taught a course entitled "Introduction to Electric Circuit Design" which was a typical course in electric circuit design, but it was taught within the ME department. While this model has worked in the past and the students were able to learn all of the electrical concepts, it was decided that a curriculum change was necessary. During the last major curriculum revision at St. Martin's, the ME department wanted to change the way the electrical concepts were taught and this three-course set was designed. The driving force behind this decision was to more closely align and teach the electrical concepts that were most important to the areas of mechatronics and instrumentation. It was also very important to the faculty at St. Martin's that the hands-on component of the course was maintained as a laboratory that taught students how to work with mechatronics systems and how to use modern instrumentation systems and the electrical concepts behind them.

Another unique aspect of the set of three courses is that they are taken during the third year of the student's degree program. This allows the two lecture courses to have Differential Equations as a prerequisite. The introductory EE course or introduction to circuits is generally taught in the first or second years when students may not have had differential equations. This allows the lecture based courses to be taught using the full differential equations to model all of the systems and components.

This paper will discuss how the lectures in Mechatronics and Instrumentation were intertwined to teach all of the relevant electrical concepts in the context in which they will be used to either develop instrumentation or create mechatronic solutions to various problems. It will also discuss how the laboratory course was able to support both lecture courses and give students the hands-on experience of working with electric circuits in a problem-solving environment.

Description of the Set of Three Courses

Most mechanical engineers are introduced to electrical system analysis via an introductory physics course, followed by an electrical engineering course, and finally a course in instrumentation. Additionally, a course in system dynamics will typically incorporate some discussion of electrical systems. This sort of introduction tends to expose a student to a variety of methods of electrical system analysis, but leaves them unaware of the relations among methods and without a consistent approach to electro-mechanical system analysis.

The purpose of the set of three co-requisite courses described here is to introduce electrical system analysis to mechanical engineering students in a unified manner, such that it is contextualized and consistent. The three courses were entitled "Mechatronics," "Instrumentation and Experimental Design," and "Mechatronics and Measurement Systems Laboratory." The following sections detail the courses as taught in the Fall Semester of 2105, but also provide changes to the design of the courses in light of the experience of teaching them the first time.

The sections are presented in a thematic fashion to show how each theme may be integrated into the courses.

System Dynamical Theoretical Foundation

Electrical and mechanical systems analysis first developed independently in the 1940s, and were eventually unified in the 1950s into what is now called *system dynamics*, which has been extended to fluid, thermal, chemical, economic, biological, and demographic systems.[1] The teaching of a system dynamics course has become mainstream in mechanical engineering departments across the country, yet it remains largely ignored in the teaching of electrical, fluid, and thermal system analysis outside the single system dynamics course.

The set of three courses described here uses system dynamics as the basis for analysis. The Mechatronics course is the most analytical, and begins with lumped-parameter modeling through energy and power flow for simple electrical and mechanical systems.[†] Power flow variables are defined for each energy domain: voltage with current (electrical) and velocity with force (mechanical). Analogies are drawn between, for instance, massive mechanical elements and capacitive electrical elements. Elemental equations for each are defined in terms of power flow variables.

Linear graphs[1,2] are used as a unifying graphical technique, which allows mechanical and electrical systems to be expressed in the same manner. This is particularly useful when energy-transducing system elements, which cross energy domains (e.g. a motor/generator), are introduced. The energy-transducing elements can be included in the linear graph to link the electrical and mechanical linear graphs. State equation formulation via continuity and compatibility equations (Kirchhoff's current and voltage laws, respectively, for electrical systems) is then introduced. Note that simple resistive networks have been almost completely ignored with the assumption that students have learned this in their physics courses.

Operational methods for linear systems are then introduced, which include block diagrams, transformation between state space and classical form of system equations, and the system transfer operator (equivalent to the transfer function, but introduced in the time domain and without Laplace transforms). The course concludes with in-depth general solution techniques for system equations in state space and classical forms, with special emphasis on first- and second-order systems. Along the way, a number of electrical (e.g. sources, resistors, capacitors, inductors, diodes, transistors, and operational amplifiers), mechanical (e.g. one degree-of-freedom translational and rotational damping, elastic, and inertial elements), and electro-mechanical (e.g. motors, generators, and solenoids) system elements are mathematically modeled within the framework.

[†] The topical progression that follows is partially in keeping with the sequence of the text *System Dynamics* by Rowell and Wormley.[1]

The Instrumentation course is taught as fundamentally dynamical, itself.[‡] Ultimately, nearly every modern sensor's output is transduced into the electrical energy domain, making electrical system analysis foundational to the design of measurement systems. Furthermore, the physical variable of interest being measured is often of another energy domain, and therefore the measurement is viewed as the placing of one dynamical system in contact with another and observing the effect.

Instruments respond dynamically to their inputs, and understanding and characterizing this response is handled naturally in the analytical methods developed in the Mechatronics course. Both courses, then, are complemented by the Mechatronics and Measurement Systems Laboratory course. In the lab, students not only learn how to use various instruments of measurement to measure the response of dynamical systems, they discover that the instruments are themselves dynamical.

Electro-Mechanical Systems

The transduction between electrical and mechanical systems is a topic of special interest for mechanical engineering students learning electrical system analysis. Motors, generators, and solenoids, for instance, are some of the primary actuators used in mechanical engineering design; and yet their analysis can fall through the cracks between classes. This is one of the strengths of the Mechatronics course, which not only has a foot planted firmly in both the mechanical and electrical energy domains, but, with its system dynamical approach, can address the interface between these domains in a natural manner.

There is currently a class of seniors in Robotics and Automation designing an electro-mechanical system to be used by future classes of students in the Mechatronics and Measurement Systems Laboratory course. Using LabVIEW software as an interface, students will be able to actuate a second-order translational mechanical system via an electric motor with a crank-slider. This system includes digital electrical, analog electrical, electro-mechanical, rotational mechanical, and translational mechanical components. Moreover, various sensors will be included to monitor the system's state. Once again, the three courses are naturally united. Several laboratory assignments are planned for this device.

Signals and Signal Processing

Electrical signals are ubiquitous in all three courses. It is important, then, that the students have a solid understanding of signals in both the time-domain and the frequency-domain. Teaching signals in a piecemeal fashion is inefficient and a disservice to the students. Time-domain analysis of signals is formally introduced in the Instrumentation course, early on. This allows students to quickly begin analyzing electrical circuits in Mechatronics and laboratory procedures. It also grounds the concept of signals in a concrete measurements context.

[‡] This description is more design than report. It was taught during a transition semester in which it was being transitioned from the fourth-year to the third-year curriculum, and so a more traditional version of this course was actually taught.

Frequency-domain signal analysis is not immediately necessary in any of these courses, so it is introduced later, and in conjunction with the principle of superposition in Mechatronics. This is a natural progression because a system's steady-state response to a periodic input can be found by considering a Fourier Series of several sinusoidal inputs, and so superposition applies. Fourier and Laplace transforms can then be considered in the continuous frequency spectrum.

Signal processing in the form of basic sampling theory and A/D and D/A conversion are also considered in the Instrumentations course. Topics include the Nyquist-Shannon sampling theorem, aliasing, and the zero-order hold. These are explored further in the laboratory.

Signal Conditioning

Filters and amplifiers are excellent devices to introduce in Instrumentation, analyze in the Mechatronics course, and use in the laboratory. Operational and benchtop amplifiers are introduced once the Mechatronics course has proceeded far enough for their analysis.

Simple filters can be analyzed relatively quickly in the Mechatronics course, but they are best discussed in the frequency domain. For this reason, they are not discussed in detail until after frequency-domain signal analysis has been covered. Later laboratory procedures incorporate filtering via both operational and benchtop amplifiers.

Digital Electronics

After completing the first semester of teaching this set of courses, it became apparent that more time should be devoted to digital electronics. It fits most naturally in Instrumentation and the laboratory. Besides D/A and A/D conversion, binary number representations, Boolean logic, and logic gates are covered.

Hands-On Laboratory Experience

A fundamental component of any engineering education is the hands-on experiences students have applying principles learned in class to physical systems in the lab. The topics in mechatronics and instrumentation are no different. This section will describe the first iteration of the laboratory course and some of the lessons learned from this experience as well as plans to improve the course in the future.

This laboratory course was designed so that students would meet once a week for up to three hours to conduct the laboratory experiments. Some of the labs were longer than others, but all were meant to reinforce topics covered in either Instrumentation or Mechatronics, or both. It was assumed that students had some knowledge of various electrical test equipment, including multimeters and oscilloscopes. No prior knowledge of resistors or other electrical components was assumed.

The original intent of the lab course was to alternate weeks and focus on Instrumentation in one week and Mechatronics the next for the entire semester. It seemed plausible that laboratory experiments could be designed to reinforce the electrical concepts taught in both courses equally. However, the implementation of those plans proved to be rather challenging.

The courses started with simple electrical labs using a breadboard and various electrical components to reinforce the concepts being taught in Mechatronics. These concepts were covered in the early part of the course and have relatively easy lab procedures, requiring only a few components. Students had generally been exposed to these types of experiments before, so more attention was paid to the details and the technical writing of the students. These experiments progressed over the course of the semester into rather complex circuits that included resistors, capacitors, inductors, diodes, switches, counters, op-amps, and other such elements. Students would generally build a circuit according to some schematic and measure various voltages or currents at different points in the circuit and compare them to theoretical values. While these labs were valuable in terms of reinforcing the concepts, they did not combine the lessons learned in the Instrumentation course very effectively.

Other laboratory experiments were created to reinforce the Instrumentation concepts. Various instruments were discussed, including thermocouples, thermistors, differential pressure transducers, and strain gauges. The electrical bases for the operation of these instruments were discussed and then each instrument was used, in turn, to record some continuous data that was recorded via software. Experimental uncertainty, error analysis, and probability and statistical concepts were all reinforced by these laboratory experiments.

While these laboratory exercises were successful in reinforcing the concepts taught in the lectures, they were not as successful as was originally hoped in combining the material from the two lecture courses. The labs ended up being focused very heavily on just one course or the other and did not effectively demonstrate to students how all of these concepts were interrelated.

In the future, the laboratory course will be rearranged to focus on the basics of building electronic circuits early on before creating true mechatronic systems that can then be measured using the topics from the instrumentation course. Data from the mechatronic systems can then be analyzed and full uncertainty calculations can be undertaken during a formal error analysis. The difficultly in creating these labs is moving quick enough through the basics to arrive at the full mechatronic systems early enough in the course to allow time for instrumentation topics. Ideally the students should be programming and creating mechatronic systems by the tenth week of the semester to allow at least four to five weeks for instrumentation and data analysis. This compressed timeline will involve creating more intensive exercises early on that cover the basics of electric circuit design and analysis quickly.

Concluding Remarks

The set of three courses received positive evaluations from students. Some of the above that is more design than report is an attempt to respond to student criticism. The primary criticism of the Instrumentation course, as it was taught (in a more standard manner), was that the topics lacked a coherent theme. The dynamical perspective, as described above, should address this issue.

The students enrolled in this set of courses in the Fall Semester are now (Spring Semester) enrolled in the course System Analysis and Design, which spends the first half of the semester expanding on the system dynamics techniques learned the previous semester, and the second half of the semester on an introduction to classical automatic control theory.

The design and execution of these courses is complex because they are so intertwined and interdependent. It has been fruitful to consider them as fundamentally related and teach them from that perspective. The authors recommend this curriculum, and plan to explore this same unifying theme in other, related engineering courses. For instance, the distributed mathematical modeling of fluid and thermal systems should be explicitly related to the lumped-parameter modeling of system dynamics. We find that, too often, students are left with connecting the disciplines—which is the most difficult task.

Bibliography

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2. Richardson, J. L. (1971). *Introduction to System Dynamics.* Reading, Massachusetts: Addison-Wesley Publishing Company.