AC 2010-2256: A CIRCUITS COURSE FOR MECHATRONICS ENGINEERING

L. Brent Jenkins, Southern Polytechnic State University

A Circuits Course for Mechatronics Engineering

Abstract

A new course has been developed to serve as the sole circuit analysis course in a mechatronics engineering curriculum. Provision of adequate support for subsequent courses in the program required the omission of content traditionally found in *Circuits I*, the inclusion of content normally found in *Circuits II*, and the insertion of introductory material for some *Circuits II* content not covered in depth. Despite its unusual allocation of content, the course is also designed to serve as the first in a two-course sequence for electrical engineering majors, for whom the second course will cover topics that were either omitted or merely introduced in the first course.

This paper includes information such as the course prerequisites, description, outline, lecture coverage highlights, and outcomes. A brief discussion of the rationale for topic inclusion/exclusion is provided. The paper also includes information about the content of the course's concurrent laboratory component, such as lab titles and outcomes. A student survey is analyzed to provide a preliminary assessment of the effectiveness of the course.

Mechatronics Engineering

Mechatronics engineering is a relatively new degree program that integrates elements of electrical and mechanical engineering[1]. In essence, program graduates are prepared to design products in which circuits interact with mechanisms, especially in cases where the circuits provide digital control of the mechanisms. Robotics is a good example of a field that employs mechatronics engineers.

Course Development

Since it is impractical for students in a hybrid program to complete all the required courses in its component programs, it should come as no surprise that the mechatronics engineering curriculum was limited to a single circuits course. Despite this fact, *Circuits I* needs to prepare students for subsequent courses in analog electronics, digital electronics, electric machines, and control systems. Thus, the presence of conflicting constraints necessitated some hard choices.

A secondary objective that was applied during the development phase of *Circuits I* was the desire for it to be able to serve as the first of a two-course sequence in an electrical engineering program. The motivations underlying this objective were simple: to avoid the need to offer distinct but highly similar courses in support of the respective programs and to provide more scheduling flexibility to students.

After obtaining a "wish list" of topics from sources in both industry and academia, it was decided to omit the in-depth treatment of transient analysis typically found in *Circuits I* and replace it with an in-depth treatment of sinusoidal analysis and AC power. Support for subsequent courses is achieved by including intermediate-level coverage of transient analysis and introductory-level coverage of mutual inductance, ideal transformers, transfer functions, frequency response, resonance, filtering, and two-port networks. The impact of this intermediate- and introductory-level content is maximized through the inclusion of relevant exercises in the concurrent lab.

Figure 1 compares the coverage of topics in *Circuits I* to that of a traditional two-semester circuits sequence. "Extended" content is material normally associated with *Circuits II* that is being covered in *Circuits I*, while "shifted" content refers to material in the text that will be covered in a subsequent course. Please note that some of the "shifted" and "omitted" content is not normally associated with a two-semester circuits sequence.

	Classification	Topic
	Reduced coverage (intermediate-level instead of detailed)	Transient RL and RC circuits
Extended Content	Detailed coverage	Sinusoidal analysis AC Power
Extended Content	Introductory coverage	Mutual inductance Ideal transformers Transfer functions Frequency response Resonance Filters Two-port networks
Shifted Content	Topics to be taught in *Electronics*	Bandwidth and Q
Shifted Content	Topics to be taught in *Electric Machines*	Three-phase systems Linear transformers
Shifted Content	Topics to be taught in *Control Systems*	Complex frequency LaPlace transforms* Complex frequency plane/pole-zero plots Bode plots*
Omitted Content	Topics not explicitly introduced or covered in detail	Duality Transient RLC circuits Circuit analysis in the s-domain Scaling y, z, and h parameters Convolution* Fourier analysis*
*Topic in the text that is sometimes, but not always covered in an EE circuits sequence.		

Figure 1: *Circuits I* Coverage Compared to a Traditional Two-Semester Circuits Sequence

Figure 2 lists the labs associated with *Circuits I* content that is covered at either an intermediate- or an introductory-level. More information about labs in *Circuits I* follows in a subsequent section.

Topic	Lab(s)
Transient RC circuits	9
Transfer functions	12
Frequency response	11, 12
Resonance	11
Filters	12
Two-port networks	7

Figure 2: Labs that Reinforce Content Presented at an Introductory- or Intermediate-Level

Course Prerequisites and Description

The prerequisites for *Circuits I* are *Calculus I* and *Physics I*. Its course description is as follows:

> This course introduces and extends basic electrical quantities—techniques for analyzing resistive networks are heavily emphasized. The physical mechanisms underlying capacitance and inductance are examined, and the superposition, Thevenin's, Norton's, and maximum power transfer theorems are all applied to AC circuits. AC power and the power triangle are then investigated, followed by an introduction to such topics as transient response, two-port networks, transformers, frequency response, resonance, and filtering. Laboratory exercises reinforce the theoretical concepts presented in class and provide various opportunities to become proficient with standard instrumentation used in electrical engineering.

Course Outline

The course outline is provided in Figure 3.

Topics	Days
Introduction and Overview	0.5
I. Fundamentals A. Prefixed Engineering Notation B. Charge, Current, Voltage, Power C. Passive Sign Convention D. Ideal Sources 1. Independent Sources 2. Dependent Sources E. Ohm's Law, Resistance, and Power Absorption F. Resistivity and Conductivity G. Conductance H. Short Circuits and Open Circuits	2.5
II. Voltage and Current Laws A. Kirchhoff's Current Law B. Kirchhoff's Voltage Law C. Series Circuits D. Parallel Circuits E. Source Combination F. Resistor Combination G. Voltage Division H. Current Division	5
III. Analysis Techniques A. Nodal Analysis B. Mesh Analysis	7
C. Superposition Theorem	1

Figure 3: Course Outline

D. Practical Sources and Conversions E. Thevenin's Theorem F. Norton's Theorem G. Maximum Power Transfer Theorem H. Delta-Wye and Wye-Delta Conversion	6
IV. Reactive Elements A. Capacitors B. Inductors C. Element Combinations	2.5
V. Introduction to Transient Analysis A. RC Circuits B. RL Circuits	4
VI. Sinusoidal Steady-State Analysis A. Characterizing Parameters B. Lagging and Leading C. Differential Equation Approach D. Phasor Representation of Sources E. Phasor Voltage-Current Relationships for Passive Elements F. Impedance and Reactance G. Admittance and Susceptance	4.5
H. Analysis Techniques I. Phasor Diagrams	3
J. Introduction to Resonance	1
K. Introduction to Frequency Response and Filtering	1
VII. AC Power Analysis A. Instantaneous Power B. Average Power C. Effective Value D. Apparent Power E. Power Factor F. Complex Power and the Power Triangle	2
VIII. Introduction to the Ideal Transformer A. Symbol B. Dot Convention C. Voltage and Current Relations D. Impedance Reflection	1
Review and Wrap-up	3

Figure 3: Course Outline (Continued)

Lecture Coverage Highlights

The textbook that was selected for *Circuits I* is Engineering Circuit Analysis by Hayt, Kemmerly, and Durbin[2]. The course follows the level of the text for all topics in the outline that are not classified as "introductory." Despite its introductory label, transient analysis is covered at sufficient depth that students are able to complete most of the transient RC or RL problems in the text.

Nodal analysis is presented using three circuit-specific approaches—basic, extended, and supernode—followed by a summary that integrates these approaches. The *basic approach* is used for circuits that lack voltage sources, the *extended approach* is used for circuits that have reference-connected but not floating voltage sources, and the *supernode approach* is used for circuits that have floating voltage sources. Mesh analysis is presented in a similar fashion, depending on the presence and position of current sources.

The application of Thévenin's theorem is presented using three methods: "source-kill", v_{oc}/i_{sc}, and test source application. The *source-kill method* is applied to circuits that lack dependent sources, the *v_{oc}/i_{sc} method* is applied to circuits having both independent and dependent sources, and the *test source application method* is applied when all sources are dependent. Norton's theorem is presented in a similar fashion.

Transient RC circuits are analyzed using three equation-based methods: the charging case, the discharging case, and the general case. The form of the capacitor voltage and current equations that are used for the general case is:

$$v_C(t) = V_f + (V_i - V_f)e^{-t/\tau} \quad \text{and} \quad i_C(t) = I_i e^{-t/\tau},$$

where V_f is the final capacitor voltage [$t \to \infty$], V_i is the initial capacitor voltage [$t = 0^+$], τ is the time constant, and I_i is the initial capacitor current. The time constant is computed using the Thévenin resistance seen by the capacitor. A similar treatment is used for transient RL circuits.

Resonance is introduced by deriving the resonant frequency in a series resonant circuit; resonance is reinforced by activities in Lab 11 [see below].

Frequency response and filtering is introduced by deriving the transfer function of an RC high-pass filter; these topics are reinforced by activities in Lab 12, including a student derivation of the transfer function for an RC low-pass filter.

Course Outcomes

The course outcomes are provided in Figure 4.

Students who successfully complete this course will have demonstrated that they can:

1. Apply voltage division, current division, element combination, and/or source conversion to analyze* or simplify a circuit having series and/or parallel elements.

2. Use nodal or mesh analysis, employing either the supernode or supermesh approach, to write a complete set of equations for a circuit having voltage sources, current sources, and a dependent source.

3. Analyze or simplify a circuit using principles such as superposition, Thevenin/Norton equivalence, maximum power transfer, and delta-wye conversion.

Figure 4: Course Outcomes

4. Determine the voltage or current equation for an element in a transient RC or RL circuit having a non-zero initial and/or final voltage or current; compute the energy being stored in a capacitor or an inductor.

5. Apply knowledge of phasors and impedances to analyze a sinusoidal steady-state circuit.

6. Perform basic calculations related to resonance, RC filtering, or transformer action.

7. Compute the real power, reactive power, apparent power, and/or power factor for a circuit or element.

8. Derive the equation(s) needed to relate the behavior of a circuit to its circuit elements; select element values that will satisfy specifications for circuit behavior.

9. Use circuit simulation software, such as PSpice, to analyze a circuit; use mathematical computation software, such as MATLAB, to solve or plot circuit equations.

*As used in these outcomes, analyze means to compute the voltage(s), current(s), and/or power(s).

Figure 4: Course Outcomes (Continued)

Lab Titles and Outcomes

Laboratory coverage is summarized in Figure 5.

Lab	Titles and Outcomes
1	***Introduction to the Circuits Lab*** 1. Use Ohm's Law to predict the voltages and current in a series circuit. 2. Use PSpice to predict the voltages and current in a series circuit. 3. Use the resistor color code to identify resistor values. 4. Use a Digital Multimeter (DMM) to measure resistance, voltage, and current. 5. Adjust and connect a DC power supply for use in a circuit. 6. Use a protoboard to construct a circuit
2	***Maximum Power Delivered to a Resistive Load*** 1. Use a decade resistance box to implement a variable resistor. 2. Compute resistor power given voltage and resistance. 3. Plot load power versus resistance; determine the maximum power to the load and the resistance that produces it. 4. Derive the expression for the load resistance that absorbs maximum power from a particular circuit.

Figure 5: Lab Titles and Outcomes

Lab	Outcomes
	Introduction to Circuit Design
3	1. Apply Kirchhoff's Laws and Ohm's Law to select resistor values for a simple series-parallel circuit given voltage and current specifications. 2. Apply voltage division, current division, and resistor combination techniques to analyze a simple series-parallel circuit. 3. Use PSpice to determine voltages and currents in a simple series-parallel circuit. 4. Measure voltages and currents in a simple series-parallel circuit.
	Analysis, Simulation, and Measurement of a Multi-node Circuit
4	1. Use PSpice to simulate a multi-node circuit. 2. Write nodal equations to characterize the voltages in a circuit. 3. Use MATLAB to solve a set of simultaneous equations. 4. Construct a multi-node circuit, and then measure its node voltages.
	Analysis, Simulation, and Measurement of a Multi-loop Circuit
5	1. Write mesh equations to characterize the currents in a circuit. 2. Construct a multi-loop circuit, and then measure its mesh currents. 3. Compute the branch currents for a circuit given its mesh currents. 4. Compute the powers: supplied by a voltage source and absorbed by a resistor.
	The Superposition Theorem and Thévenin's Theorem
6	1. Apply the superposition theorem to a circuit. 2. Apply Thévenin's theorem to a circuit. 3. Construct a multi-source circuit. 4. Compare the responses produced by a circuit and its Thévenin equivalent.
	The Resistive T-Network from a Two-Port Network Perspective
7	1. Design a resistive T-Network to meet specifications. 2. Use PSpice to verify the T-network design. 3. Construct the T-Network to verify its operation. 4. Use a dependent source to develop a two-port network model for a T-network. 5. Use PSpice to verify the model previously developed.
	The Oscilloscope and the Function Generator
8	1. Use a function generator to produce a sinusoidal voltage. 2. Use an oscilloscope to measure the amplitude and phase of sinusoidal signals.
	Transient RC Circuits
9	1. Analyze and measure the voltage and current in a transient RC network. 2. Observe the behavior of transient circuits that have different time constants.
	Sinusoidal RLC Circuits
10	1. Calculate and measure the voltages in a sinusoidal RLC circuit. 2. Calculate and measure the impedances in a sinusoidal RLC circuit.
	Series Resonance
11	1. Compute and measure the resonant frequency of a circuit. 2. Use PSpice to plot the magnitude and phase of the input impedance versus frequency. 3. Measure and plot the magnitude of the input impedance versus frequency. 4. Use MATLAB to plot the magnitude of the frequency response using enumerated data.
	Low-Pass Filters
12	1. Derive the transfer function for an RC low-pass filter. 2. Use MATLAB to plot the magnitude and phase of the frequency response using equations and enumerated data. 3. Measure the magnitude and phase of the frequency response.

Figure 5: Lab Titles and Outcomes (Continued)

Assessment

At the end of the Fall 2009 semester, the students in *Circuits I* were given a Learning Outcomes Survey as part of an ongoing course assessment effort. A five-point Likert scale was used to construct the possible responses: 1-Strongly disagree, 2-Disagree, 3-Not sure, 4-Agree, and 5-Strongly agree. Participants were asked to select the response "that best describes your level of agreement" with each statement. The first eight statements in the survey were simply the respective course outcome statements (Figure 4) prefaced by "I am able to." Survey statements 9a and 9b, similarly prefaced, were obtained by separating the two clauses of Outcome 9 into separate statements: Statement 9a dealt with PSpice while Statement 9b related to MATLAB. A summary of the survey responses is tabulated in Figure 6 and the distribution of responses by statement is illustrated in Figure 7.

As shown in Figure 6, the sample means ranged from 3.90 to 4.67, which strongly suggests that most of the students were satisfied that they had met the course outcomes. A brief study of the solid bars in Figure 7 provides additional support for the same conclusion: the combined responses of "Agree" and "Strongly Agree" exceeded 90% on six of the statements and they exceeded 70% on all of the statements.

After defining a mean response of 3.5 or higher as a "tendency toward agreement," the t-distribution was used to compute, for each statement, the p-value associated with the hypothesis that *the population mean of the responses to a particular statement exceeds 3.5*. The results of these computations are recorded in the rightmost column of Figure 6. All statements generated p-values less than 0.05, indicating that the students "tended to agree" with those statements. In fact, the statistics show that an "agreement" hypothesis can be considered to be true to at least a 99% confidence level on nine of the ten statements. Thus, from a student perspective, the course was successful at meeting its outcomes.

Statement	Response					Statistics			
	1 Strongly disagree	2 Disagree	3 Not sure	4 Agree	5 Strongly agree	Total	Mean	Std Dev.	P-value
1	0	0	0	7	14	21	4.67	0.483	0.00000
2	0	0	0	8	13	21	4.62	0.498	0.00000
3	0	0	2	11	8	21	4.29	0.644	0.00001
4	0	0	2	11	8	21	4.29	0.644	0.00001
5	0	2	1	10	8	21	4.14	0.910	0.00207
6	0	1	0	12	8	21	4.29	0.717	0.00003
7	0	3	3	6	9	21	4.00	1.095	0.02472
8	0	1	4	12	4	21	3.90	0.768	0.01275
9a	0	1	2	10	8	21	4.19	0.814	0.00046
9b	2	0	0	11	8	21	4.10	1.136	0.01309

Figure 6: Survey Responses and Statistics

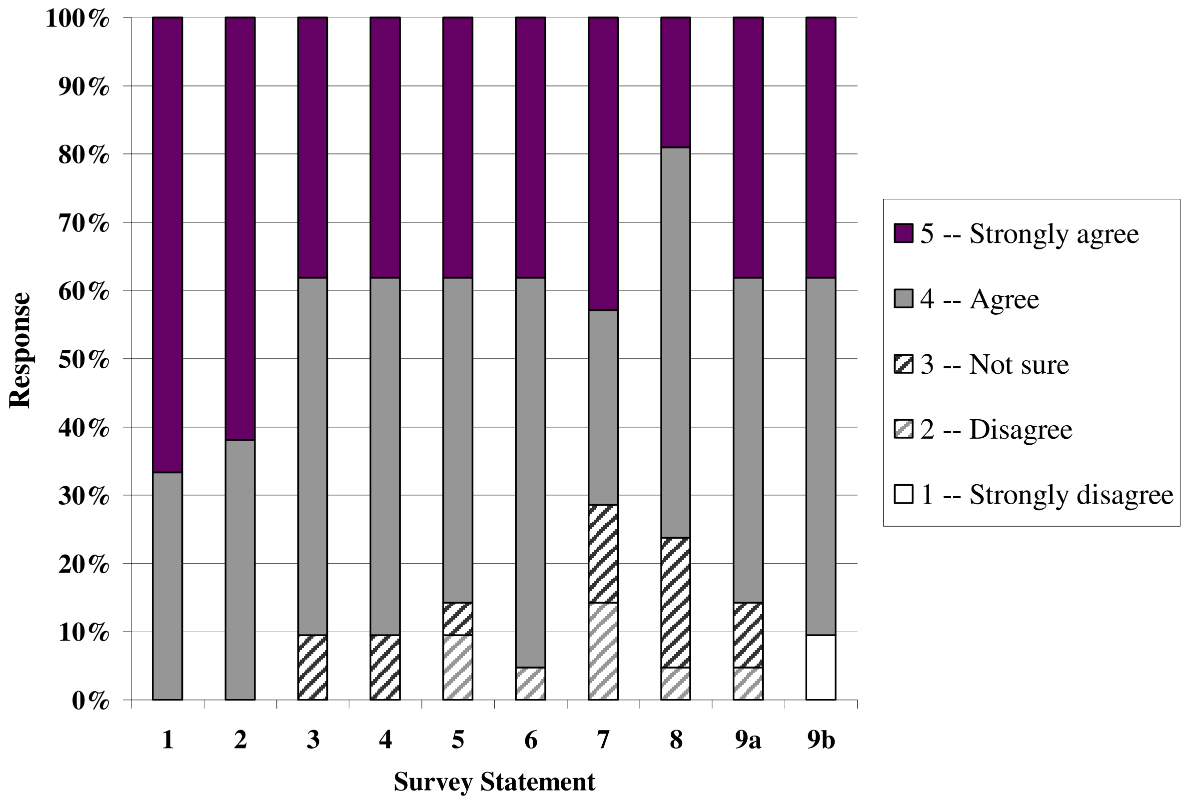

Figure 7: Response Percentages by Survey Statement

Future Work

As more of the courses supported by *Circuits I* are developed and taught, work will be needed to verify the appropriateness of its coverage. When possible, surveys of stakeholders other than current students should be conducted and analyzed to verify both course effectiveness and appropriateness of coverage. Stakeholders yet to be surveyed include instructors of subsequent courses, students who have completed subsequent courses, industrial advisory committee members, alumni, and employers of program graduates.

Conclusion

Details have been presented about a circuits lecture/lab course that is able to serve as both the sole circuits course in a mechatronics engineering program and as the first of a two-semester circuits sequence in an electrical engineering curriculum. Analysis of a student survey strongly supports a conclusion that the course met its outcomes. More work is needed to verify the appropriateness of the course's coverage.

Bibliography

1. "Mechatronics: where motors meet microprocessors," IEE Review, September 1991, pp. 315-318
2. Hayt, W. H., Kemmerly, J. E., and Durbin, S. M., Engineering Circuit Analysis, 7th edition, McGraw-Hill, New York, NY, 2007