Real Hardware Based Filter Laboratory Exercises for a Sophomore Linear Systems Course

Raymond G. Jacquot, Robert F. Kubichek and John E. McInroy
University of Wyoming

Abstract

The authors report here a modification to enhance a sophomore linear systems course. Students at the sophomore level are rather unsophisticated mathematically and need derivations and discussions of abstract concepts to be anchored in real systems that they can see and put their hands on. To this end the authors report in this paper a set of experiments which provide that foundation.

I. Introduction

At the University of Wyoming, electrical engineering sophomores a take a course in elementary linear systems immediately following their introductory circuit analysis course. The topics for this course are Laplace transforms, system modeling, transfer functions, convolution, frequency response, Fourier series, and filtering of periodic signals. Associated with the course is a laboratory which meets six times in the course of a semester. Due to the early time in the curriculum at which this course is taken, the authors have seen the need to couple the course concepts to physical systems in order to reduce mathematical abstraction. In the past, a paper was presented on a series of physical system experiments that involved a single vehicle suspension system[1]. This was done primarily as modeling, analysis and simulation with no real hardware on which students could hang their academic hats. Course evaluations were often critical that the laboratories would be better if they were based on some real hardware that students could touch and on which they could make measurements with real instruments. In this respect, this is a case of a well-intentioned effort which was not on target. To address these disturbing criticisms it was decided by the authors to construct several new laboratory exercises that were hardware based and that is the topic of this report. The hardware needed to be sufficiently complicated so that the modeling, analysis, and simulation tasks are not trivial. The hardware also needed to be such that results based on the model correlate well with measurements made on real hardware. To this end, a pair of active filters were designed and synthesized on a small printed circuit board. One of the filters is of first order while the other is of second order type. They may be treated individually or cascaded to form a single third order filter.

II. Course Setting

The course being discussed is a three semester hour course with three lectures weekly and a two hour lab six times during the semester. The course is taken by second semester sophomore electrical engineering majors. The prerequisite courses are a first course in circuit analysis plus ordinary differential equations. Table 1 below gives the topics in the course roughly in the order of coverage. The goal of the laboratory is to expose the students to systems computations employing MATLAB[2] and to introduce them to a modern system simulation package namely VisSim[3].

Table 1. Topic Outline for the Linear Systems Course

- Solution of Linear Equations
- The Unit Step Function
- The Dirac Delta Function
- The Laplace Transform
  - Development of Transform Pairs
  - Time and Exponential Multiplication
  - Partial Fraction Expansion
  - Linear Ordinary Differential Equations
- System Modeling
  - Mechanical Systems
  - Electrical Networks
- System Concepts
  - The Transfer Function
  - Poles, Zeros and System Stability
- The Frequency Response Function
  - Bode Plots
- First- and Second-Order Systems
- The Convolution Integral
- Fourier Methods
  - The Fourier Series
  - Mean Square Error and the Parseval Relation
  - Filtering of Periodic Signals
  - Complex Fourier Series
  - The Fourier Spectrum
- Introduction to the Fourier Transform

Filter A

Filter B

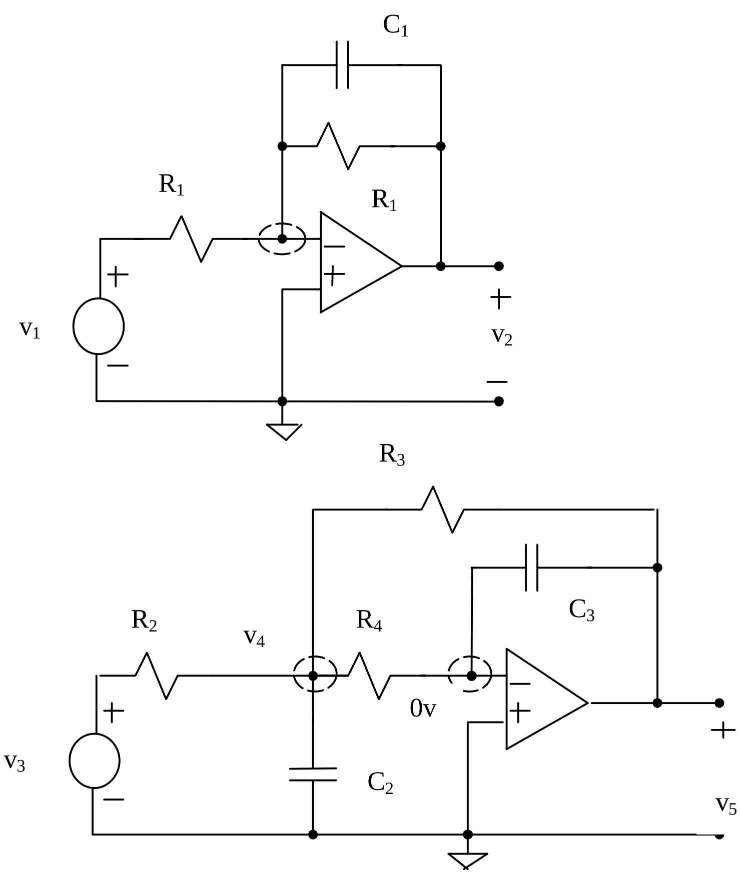

Figure 1. Filters Employed in the Exercises

Filter A is a first-order, lowpass filter with a nominal bandwidth of 5000 radians per second and unity d.c. gain. The nominal low frequency gain of Filter B is about 2.5.The filters differ from the above specifications because they are implemented with standard resistor and capacitor values. In addition each of the filters constructed may vary further from the nominal design because of the tolerances of the components employed (5% for the resistors and capacitors). The nominal resistor and capacitor values employed are:

Filter A	R_1 = 100 kΩ	C_1 = 0.0022 μF		
Filter B	$R_3 = R_4$ = 91 kΩ	R_2 = 36 kΩ	C_2 = 0.01 μF	C_3 = 470 pF

The filters are both on a single printed circuit board to which one must add a dual power supply, a signal generator and an oscilloscope.

IV. The Laboratory Exercises

Exercises one and two are designed to introduce the students to MATLAB and VisSim, which will be used extensively for the remainder of the course. Exercise six is a Fourier related exercise related to powerline harmonics and is not discussed here. Exercises three, four and five are those concerned with the filters and are examined in somewhat more detail below.

<u>Exercise 3-Step Response Predictions and Measurements</u>

This exercise is designed to introduce the students to system modeling and the calculation of system step responses using Laplace transforms and MATLAB. In addition the system is simulated using the general purpose simulation package VisSim. Step response measurements are made in the laboratory to give the students confidence that their analytical predictions yield results which correspond to physical responses of real systems.

(a) Write the three node voltage differential equations that relate input voltages v_1 and v_3 to respective output voltages v_2 and v_5.
(b) Solve the equations formulated in part (a) using the Laplace transform assuming the input to each filter is a 2 V step function.
(c) Solve the same equations using VisSim for the same step function input.
(d) Measure the response to a 90 Hz. square wave input and compare the results with the step responses given in parts (b) and (c).

<u>Exercise 4-Cascaded Filters</u>

This exercise is designed to introduce students to the input-output system model and the concept of poles and zeros. In addition, the concept of impulse response for the cascaded filters is reinforced by both analysis and simulation. Here students have to deal with a third order all-pole model .

(a) Given the three node voltage equations find the transfer function $G(s) = V_5(s)/V_1(s)$.
(b) Plot the poles in the complex s-plane.
(c) Find the impulse response function g(t) by inverting G(s).
(d) Find the impulse response function g(t) by simulating the filter with a narrow unit area pulse input employing VisSim.

Exercise 5-Frequency Response

This exercise is designed to emphasize the concept of steady-state response of linear, time-invariant systems to sinusoidal driving functions. The gain and phase character of such systems as functions of frequency is investigated and the concept of the Bode plot is reinforced.

(a) Evaluate the gain and phase shift character of the filter using the transfer function from Exercise 4 and MATLAB. Present results as linear plots and logarithmic plots.
(b) Simulate the filter for several frequencies and evaluate the gain and phase shift character of the filter at those frequencies to compare with the predictions of MATLAB.
(c) Measure the frequency response at 5 frequencies between 100 r/s and 8000 r/s and compare with the results with those of parts (a) and (b).

V. The Future

Having used the laboratory strategy mentioned above for only one semester, there are clearly modifications that must be made to improve the course. Some needed items are notably absent from the exercises. One item to be incorporated in the spring semester of 1999 is the experimental determination of the cascaded filter impulse response using a train of narrow, finite height pulses from a signal generator.

VI. Conclusion

After the first semester of offering this modified laboratory the students' reaction has been quite positive. They feel that they are now learning about theory and techniques that have applications to real physical systems in the real world.

Bibliography

1. Jacquot, R. G., Hamann, J.C. and Kubichek, R. F., *Modification of a Sophomore Linear Systems Course to Reflect Modern Computing Strategies*, Proc. 105th ASEE Annual Conference, Milwaukee, WI, June 15-18, CD Rom Paper 3220-02.
2. The Math Works, Inc., *MATLAB 5 Reference Guide*, Natick, MA, 1996.
3. Visual Solutions, Inc., *VisSim User's Guide—Version 3*, Westford, MA, 1998.

Raymond G. Jacquot

Ray Jacquot received his BSME and MSEE degrees at the university of Wyoming in 1960 and 1962 respectively. He was an NSF Science Faculty Fellow at Purdue University where he received the Ph.D. in 1969. He is a member of ASEE, IEEE and ASME and has been active in ASEE for the past two decades serving as Rocky Mountain Section Chair, PIC IV Chair and he currently serves as the Rocky Mountain Section Newsletter Editor. His professional interests are in modeling, control and simulation of dynamic systems. He currently serves as Professor of Electrical Engineering.

Robert F. Kubichek

Bob Kubichek received BS degrees in EE and Computer Science in 1976 and the M.S. in Electrical Engineering form the University of Wyoming in 1977. He was employed by Boeing Computer Services until 1979 developing CAD/CAM software and returned to the University of Wyoming to complete the Ph.D. in 1984. He was then employed by the BDM Corporation and then the U. S. Department of Commerce Institute for Telecommunication Sciences where he researched speech communication system performance measures. His current research efforts are in speech quality assessment, electomagnetic noise interference from power systems. He now serves as Associate Professor of Electrical Engineering.

John E. McInroy
John McInroy received his BSEE degree from the University of Wyoming in 1986. He received the M.S. and Ph.D. degrees in Electrical Engineering from Rensselaer Polytechnic Institute in 1988 and 1991 respectively with a focus in robotics. His professional interests are in robotic systems, sensor data fusion and precision motion control. He currently serves as Associate Professor of Electrical Engineering.