Today
Lecture 1    Physics 262    Laboratory Electronics II    1/18/11

• **Go over course schedule and expectations**

• **Lecture**
  – Review circuit elements and linear circuits and their response to stimuli
  – Frequency response and complex analysis of circuit elements
  – Intro to complex voltage divider and Decibals

• **Homework**
  – HW1:
    • Horowitz and Hill: Exercises 1.1 (p.6), 1.2 (p.6), 1.3 (p. 6), 1.5 (p. 7), 1.10(p.13), 1.11(p.17), 1.12(p. 23), 1.15(P.27), and 1.17 (p. 33) (Mostly review)
    • Email me from your preferred email address (counts as quiz point)
    • Email me if you can’t make project presentation time (Friday 4/29/11 2-4pm)
  – All due Tuesday 1/25/11
  – Homework problems are NOT turned in (but I advice you do it!)

• **Reading in Horowitz and Hill**
  – Scan pages 1-28 in H&H by 1/20/10 (make sure you understand these 261 concepts)
  – Read pages 29-42 in H&H by 1/20/10

• **Lab this week**
  – Lab 1: Complex Impedance. Lab handout
  – Prelab due Thursday at start of lab.
Introduction

Spring 2011          Physics 262    Laboratory Electronics II

• Instructor – Randy Babbitt
  Physics Office: EPS 210, 994-6156 (EPS)
  Spectrum Lab Office:  994-1797
  Cell:  539-9751
  Email: Babbitt_teaching2011@physics.montana.edu

  Office hours –Tuesdays 1:00-2:00 and Thursdays 12:00-12:50
  or by appointment (just email or call me)

• Teaching Assistant – Harsh Bhatkar
  Physics office: EPS 226
  Email: Harsh [bhatkar@physics.montana.edu]
  Office hours: Thursdays 1-2 and Fridays 11-12

• Lectures: Tuesdays 9-9:50 in Roberts 121
• Lab:  Thursdays 8:00-10:50 or 2:10-5:00pm in EPS 228
• Final: Monday May 2, 2010 12-2pm  in Roberts 121
Requirements

Prerequisite:
Phsx 261, Laboratory Electronics I

Required texts:
“The Art of Electronics”, Horowitz and Hill, 2nd Edition

Reference text:
“The Analysis and Design of Linear Circuits”, Thomas/Rosa

Two lab notebooks required:

Roaring Spring brand #77108 5x5 quadrille lab books, sewn binding or equivalent

-Two notebooks are to be rotated with alternating labs
Web Site

- Course web site
  www.physics.montana.edu/faculty/babbitt/Physics262/phsx262.html

- Homework and Reading Assignments
- Schedule and Important Dates
- Lab Instructions
- Handouts
- Project Description, write ups, and due dates.
- Lectures and Lecture Notes
Course Policies

• Laboratory exercises are a critical part of this course
  – If you must miss a lab, you must schedule makeup time IN ADVANCE
  – You must get 50% or better on all labs to pass course

• HW1: Send me your email address (via my email address)
  – So I can contact you with additional course information and
    schedule/assignment/due date changes.

• Check web often
  – Important Date/Schedule/Assignment changes and hints on web

• Lab Notebooks due in Friday 10am one week after lab.
  – Will be returned next Tuesday in class or in lab on Thursday.
  – A Late Lab Notebook will have 20% penalty subtracted.

• Ethical behavior is expected
  – Sign and return cheating policy
  – Individual lab write-ups based on two person lab teams.
  – All other work is individual, unless specifically stated.
Homework and Quizzes

• Homework “due” each Tuesday
  – Homework is NOT turned in.
  – Due date reflects day a quiz or exam may be given that has similar problems on it.

• You can work together on homework.

• Ask questions in lab and office hours.

• Quizzes are quasi-weekly
  Short quiz at end of class/beginning of lab

• Quizzes are easy if you do the homework problems (tightly based on HW problems)

• Quizzes are open book/notes and your HW (no copies)
Grading

<table>
<thead>
<tr>
<th>Evaluation Method</th>
<th>Weight (%)</th>
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<tr>
<td>Lab Journal</td>
<td>45</td>
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<td>Final Project</td>
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<tr>
<td>Quizzes/Worksheets</td>
<td>15</td>
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<td>Final Exam</td>
<td>25</td>
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</tbody>
</table>
Laboratory Exercises

• **Pre-Lab exercises (up to 20% of lab grade)**
  – Pre-Lab and Lab exercises will be handed out during Tuesday lecture
  – Pre-lab due at start of lab on Thursday
  – Pre-lab will be checked by TA at start of lab.
    • It is your responsibility to make sure he checks you pre-lab at start of lab.

• **Lab write-ups (45% of course grade)**
  – Use two lab books (turn in alternating weeks, see lab schedule)
  – You must get 50% on ALL labs to pass course.
  – Lab write-up format and scoring rubric: See lecture from first lab
  – Work in pairs (but separate lab notebooks/write-ups)
    • Record your combined work in both your lab books
      – Division of labor is a good thing. Shows good lab skills.
      – HOWEVER, you must understand the work done by your partner.
      – Okay to copy partner’s data/graphs, but not their analysis/conclusions.
      – Your conclusions must be your own, in your own words.
Semester Project

• Several weeks devoted to the project (15% of course grade)
  – Project incorporates many concepts/activities of regular lab exercises.
  – Common problem but with different approaches
    • Developing a laser light show circuit driver
  – Use a single one of your lab notebooks for project (see lab schedule)

• Work in pairs (but separate lab notebooks/write-ups)
  – Record your work in both your lab books
    • Division of labor is a good thing. Shows good lab skills.
    • Record joint work in both of your lab books.
    • Okay to copy partner’s data/charts but not their reduction/conclusions from data.
  – Reference others work with proper acknowledgement in your lab book
  – Tape printed/copied pages neatly into your journal as needed
    • No loose papers. No loose edges. Tape all four corners. Okay to tape rotated.

• Project presentation time is a public light show driven by your circuits
  • Tentatively Friday April 29, 2011 2:00PM-4:00pm
  • You must email me by 1/25/10 if you can’t make this presentation time!!!!!

• More details later and on web site.
Resistors

Resister constraint independent of DC or AC circuit

- Voltage changes instantaneously with current

Resister provides resistance to current flow

- Introduces instant voltage drop in response to current

\[ i(t) = \frac{v(t)}{R} \]

\[ \frac{1}{R_{\text{Parallel}}} = \frac{1}{R_1} + \frac{1}{R_2} \]

\[ R_{\text{Series}} = R_1 + R_2 \]
Capacitors

- At DC, the capacitor looks like an open circuit.
- Capacitor voltage cannot change instantaneously.
- Capacitor response depends on changes in voltage.
- Capacitor reacts to a voltage change with current.
- At DC, the capacitor looks like an open circuit.

\[
Q = CV
\]
\[
I = \frac{dQ}{dt}
\]

\[
i_C(t) = C \frac{dv_C(t)}{dt}
\]

\[
\frac{1}{C_{\text{Series}}} = \frac{1}{C_1} + \frac{1}{C_2}
\]

\[
C_{\text{Parallel}} = C_1 + C_2
\]

- Capacitor voltage cannot change instantaneously.

\[
\begin{align*}
\text{if } \frac{dv_c(t)}{dt} &= 0 \text{ then } i_c(t) = 0 \\
\text{if } \frac{dv_c(t)}{dt} &= \infty \text{ then } i_c(t) = \infty
\end{align*}
\]
Inductors

- Inductor response depends on changes in current
- Inductor reacts to a current change with voltage
- At DC, the inductor looks like a short circuit.
  \[ \text{if } \frac{d}{dt}i_L(t) = 0 \text{ then } v_L(t) = 0 \]
- Inductor current cannot change instantaneously
  \[ \text{if } \frac{d}{dt}i_c(t) = \infty \text{ then } v_c(t) = \infty \]
RC Circuit

\[ v_s(t) = v_{R_1}(t) + v_{C_1}(t) \quad i_{R_1}(t) = i_{C_1}(t) \]

\[ i_c(t) = C \frac{dv_{C_1}(t)}{dt} \quad v_{R_1}(t) = R_1 i_{R_1}(t) \]

\[ v_s(t) = R_1 i_c(t) + v_{C_1}(t) \]

\[ = R_1 C_1 \frac{dv_{C_1}(t)}{dt} + v_{C_1}(t) \]

This suggests an exponential solution.
General RC Response
(Natural and Forced Responses)

\[ V_1 = 0V \]
\[ V_2 = 5V \]
\[ C_1 = 0.01uF \]
\[ R_1 = 5.1k \]

Capacitor Voltage Response

Response to step function voltage from \( V=0 \) to \( V=V_0 \) at \( t = t_0 \)

\[ v_C(t) = \left[ v_s(t < t_0) - v_s(t > t_0) \right] e^{-t/RC} + v_s(t > t_0) \]

\[ \Delta V_C(t) \]

Response to square wave between \( V=0 \) and \( V=V_0 \)

\[ \tau = RC \]
Let’s analyze RLC Circuit

\[ v_S(t) = v_R(t) + v_L(t) + v_C(t) \]

\[ v_R(t) = RC \frac{dv_C(t)}{dt} \quad \quad v_L(t) = L \frac{di_L(t)}{dt} \quad \quad i_C(t) = C \frac{dv_C(t)}{dt} \]

\[ v_L(t) = L \frac{d}{dt} \left( C \frac{dv_C(t)}{dt} \right) = LC \frac{d^2v_C(t)}{dt^2} \]

\[ v_S(t) = LC \frac{d^2v_C(t)}{dt^2} + RC \frac{dv_C(t)}{dt} + v_C(t) \]

• THERE MUST BE A BETTER WAY!!!!
Ordinary Differential Equation Solutions to Circuit Response

- Applied Voltages/currents
- Differential Equation
- Solve ODEs
- Solution Waveform
Fourier Method of Linear Circuit Analysis
(Laplace with Complex Frequency)
Linear Circuits

- In a linear circuit, the response, O(t) to a sum of inputs, A(t) & B(t), is the sum of the individual responses

  - IF \( A_{in}(t) \Rightarrow O_A(t) \) \( B_{in}(t) \Rightarrow O_B(t) \)

  - THEN \( A_{in}(t) + B_{in}(t) \Rightarrow O_A(t) + O_B(t) \)

- In a linear circuit, if the input is a sinewave at frequency \( f \), the output will also be sinusoidal at frequency \( f \)
  
  The phase and amplitude of the output may vary, but not the frequency.

- Any input can be decomposed into a sum of sinusoidal inputs, whose responses can be determined in a linear circuit analysis, and the output is the sum of these sinusoidal responses.

  Frequency Decomposition is Fourier Analysis

  Show excel demo
Complex Representation of Voltages and Currents

\[ V(t) = V(\omega) \cos(2\pi ft + \phi(\omega)) \]
\[ = V(\omega) \cos(\omega t + \phi(\omega)) \]
\[ = \text{Re}\left\{ V(\omega) \cos(\omega t + \phi) + jV(\omega) \sin(\omega t + \phi(\omega)) \right\} \]
\[ = \text{Re}\left\{ V(\omega) \exp(j(\omega t + \phi(\omega))) \right\} \]
\[ = \text{Re}\left\{ V(\omega) e^{j\phi(\omega)} e^{j\omega t} \right\} \]
\[ = \text{Re}\left\{ \tilde{V}(\omega) e^{j\omega t} \right\} \]

\[ \tilde{V}(\omega) = V(\omega)e^{j\phi(\omega)} \]

In general, \( V(t) \) is sum of sinusoidal inputs, but we can analyze them one at a time.
Complex Representation of Voltages and Currents

\[ \tilde{V}(\omega) = V(\omega)e^{j\varphi(\omega)} \]

The real and imaginary parts represent the cosine and sine components of the voltage

\[ V(t) = \text{Re}\left\{ \tilde{V}(\omega)e^{j\omega t} \right\} \]

\[ = \text{Re}\left\{ \tilde{V}(\omega) \right\} \cos(\omega t) - \text{Im}\left\{ \tilde{V}(\omega) \right\} \sin(\omega t) \]

Current also becomes complex

\[ i(t) = \text{Re}\left\{ \tilde{i}(\omega)e^{j\omega t} \right\} \]

\[ = \text{Re}\left\{ \tilde{i}(\omega) \right\} \cos(\omega t) - \text{Im}\left\{ \tilde{i}(\omega) \right\} \sin(\omega t) \]
Useful relationship

If you three complex numbers represented as:

\[ \tilde{A} = Ae^{j\varphi_A} \]
\[ \tilde{B} = Be^{j\varphi_B} \]
\[ \tilde{X} = Xe^{j\varphi_X} \]

Then if

\[ \tilde{X} = \tilde{A}\tilde{B} \]

The magnitudes and phases are related by

\[ X = AB \quad \varphi_X = \varphi_A + \varphi_B \]
Impedance of Capacitor

\[ V(t) = \text{Re}\{\tilde{V}(\omega)e^{j\omega t}\} \]

For a sinusoidal input

\[ = V(\omega)\cos(\omega t + \varphi) \]

\[ i(t) = C \frac{dV(t)}{dt} \]

\[ = -\omega CV(\omega)\sin(\omega t + \varphi) \]

\[ = \text{Re}\left\{\frac{V(\omega)e^{j\varphi}e^{j\omega t}}{1/j\omega C}\right\} \]

\[ = \text{Re}\left\{\frac{\tilde{V}(\omega)e^{j\omega t}}{Z_C(\omega)}\right\} \]

If \[ i(t) = \text{Re}\{\tilde{i}(\omega)e^{j\omega t}\} \]

then \[ \tilde{i}(\omega) = \frac{\tilde{V}(\omega)}{Z_C(\omega)} \]

where

\[ Z_C(\omega) = \frac{1}{j\omega C} = \frac{1}{\omega C}e^{-i(\pi/2)} \]
Impedance and Ohm’s Law

Resistor  
\[ Z_R(\omega) = R \]

Capacitor  
\[ Z_C(\omega) = \frac{1}{j\omega C} \]

Inductor  
\[ Z_L(\omega) = j\omega L \]

**Impedance** is the proportionality factor relating the complex voltage across an element to the complex current through the element.

\[ \tilde{i}(\omega) = \frac{\tilde{V}(\omega)}{Z(\omega)} \]

\[ \tilde{V}(\omega) = \tilde{i}(\omega)Z(\omega) \]

Devices in Series and Parallel

\[ Z_{\text{Series}} = Z_1 + Z_2 \]

\[ \frac{1}{Z_{\text{Parallel}}} = \frac{1}{Z_1} + \frac{1}{Z_2} \]
Impedance of ideal components in the Frequency Domain on Log-Log Plots

\[ Z_C(\omega) = \frac{1}{j\omega C} \]

\[ Z_R(\omega) = R \]

\[ Z_L(\omega) = j\omega L \]

Complete set of plots:
- Log-log gain plot
- Log-Lin phase plot
Simple Voltage Divider

**Current**

\[ i = \left( \frac{V_s}{R_1 + R_2} \right) = \left( \frac{V_s - V_{out}}{R_1} \right) \]

**Output Voltage**

\[ V_{out} = \left( \frac{R_2}{R_1 + R_2} \right) V_s \]

**Gain (or attenuation)**

\[ G = \left| \frac{V_{out}}{V_s} \right| = \left( \frac{R_2}{R_1 + R_2} \right) \]
Passive Filter: Generalized Voltage Divider

Current
\[ \tilde{i}(\omega) = \frac{\tilde{V}_s(\omega)}{Z_1(\omega) + Z_2(\omega)} = \frac{\tilde{V}_s(\omega) - \tilde{V}_{out}(\omega)}{Z_1(\omega)} \]

Output Voltage
\[ \tilde{V}_{out}(\omega) = \left( \frac{Z_2(\omega)}{Z_1(\omega) + Z_2(\omega)} \right) \tilde{V}_s(\omega) \]

Transfer Function \( \tilde{T}(\omega) \)
aka \( \tilde{T}(f) \)  
\[ f = \omega / (2\pi) \]

Gain
\[ \tilde{G}(\omega) = \left| \tilde{T}(\omega) \right| = \left| \frac{\tilde{V}_{out}(\omega)}{\tilde{V}_s(\omega)} \right| = \left( \frac{|Z_2(\omega)|}{|Z_1(\omega) + Z_2(\omega)|} \right) \]
Measuring an unknown $Z(\omega)$

If $Z_1$ is known, by measuring source and output voltage, complex impedance $Z_2$ can be determined.

$\Rightarrow$ Lab 1
Logarithmic Nomenclature

Decibel:

\[ dB = 20 \log_{10} \left| \frac{V}{V_0} \right| = 10 \log_{10} \left| \frac{P}{P_0} \right| \]

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<th>Voltage Factor</th>
<th>Power Factor</th>
<th>Voltage Factor</th>
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