EC 200 — Circuits & Systems
Laboratory Manual

Rose-Hulman Institute of Technology
Spring 1999

Circuits & Systems

Lab 0 – General Information

What's the purpose of a laboratory? Or at least a laboratory for students? Some might say that it's to get students as frustrated as possible and convince them that they don't ever want to be technicians! There's some truth in that, but the job of an engineer often involves making measurements.

So the purpose of this part of the course is to introduce you to the basics of working in an electrical laboratory. These will include the use of the most common instruments: oscilloscopes, meters, signal generators, power supplies, and so on. You should complete this course with a knowledge of these instruments, and especially of their limitations.

Another purpose is to let you see that some of the things you learn in the classroom really do exist in the physical world. You'll find that much of what you've studied on paper really does work. But you'll also discover that this isn't exactly true, that the things you've learned about are imperfect. So this hands-on experience is important because it helps you develop a better understanding of how the theoretical and the practical fit (or don't fit) together.

There's a third purpose to the lab that we sometimes don't like to admit. A lot of the learning in the lab takes place by encountering problems with equipment and devices. Yes, the op-amp is a very nice device for many things, but it sometimes takes a long time to discover that you've powered it wrong and burned it out. Call it perversity of inanimate objects or whatever you want, you'll have plenty of opportunity to encounter this principle! But don't be put off by your discovery – debugging is merely another form of logical problem-solving.

Course Materials

You'll need three things for this course, this pile of paper that includes the experiments, the expendable parts that you'll use in those experiments, and a lab log book in which you'll keep all your records.

Each of the experiments in this collection is designed for one or two lab sessions. The description of each experiment includes the goals of that lab, some prelab work, what you are to do in the lab, and what you are to hand in at the end. The early experiments describe your activities in some detail; the later ones are more sketchy. Note that the lab book is *always* due at the end of a particular experiment.

At the beginning of the course you should purchase a circuit board and a wire stripper from the Instrument Room. All of the small parts you'll need will be purchased *a la carte* as you need them. Most labs use less than a dollar's worth of parts.

You need to get a lab log book in which you'll take data in the lab. The Bookstore has the acceptable book: Lab Book, 10x7$^7/_8$, 80 sheets, 5x5 quadruled, #26-251. In this book you'll complete all prelab requirements, collect all lab data, analyze what you get, sketch results, and answer questions.

You may also need some graph paper from the bookstore for plots that require more carefully drawn graphs. Individual experiments will mention this.

Equipment

Each bench in the lab has three pieces of measuring equipment on it. These will provide you with most of the apparatus you'll need. All of it is industrial-grade equipment that will perform very well:

- Tektronix frame, sometimes called "The Rack," with six instruments :

  DM501 Digital Multimeter: volts (200 mV – 1000

V dc, 200 Mv – 500 V ac), 200 μA – 2 A ac/dc, 200 Ω – 20 MΩ, temperature).

FG501A Function Generator: sine, square, triangle, ramp, and pulse waveforms, 2 mHz – 2 MHz, ±13 V dc offset.

DC504A Counter/Timer: frequency to 100 MHz, pulse width and period to 2.5 MHz.

SG505 Oscillator: sinewave 10 Hz – 100 kHz ungrounded or grounded.

PS501-1 Power Supply: 0–20 V dc floating, 5 V dc fixed grounded.

PS503A Dual Power Supply: –20 – 0 and 0 – +20 V dc floating, 5 V dc fixed grounded.

- Tektronix 2235 Oscilloscope: 100 MHz, 2 mV – 5 V/div, 50 ns – 0.5 s/div.
- Triplett 4800 True RMS Digital Multimeter: volts (250 mV – 1000 V dc, 250 mV – 750 V ac), 250 μA – 10 A ac/dc, 250 Ω – 25 MΩ, frequency to 10 MHz, period 10 μs – 100 ms, temperature.

What is Expected of You

First and foremost, professional work is the norm in the lab just as it is in the other parts of the course. It might be wise to review the course handout.

The experiments themselves contain three different tasks that you will be expected to perform:

- Prelab work is assigned for many of the experiments. This is to help you prepare for the actual measurements in the lab so that you can use your time more efficiently Do all prelab work in your lab log. A photocopy of your work is due at the beginning of the second class preceding the lab.
- Actual laboratory work involves connecting circuits and equipment, observing results, recording data, and so on. The earlier labs specify this in some detail, while the later ones say much less. You should be thinking about what you are investigating and what kind of observations are appropriate. For example, if you are making measurements of resistance, you should record a description of the resistor (coded nominal value, wattage, condition, etc.) even if these aren't asked for.
- Postlab work involves some consideration of the results. Be sure to check the lab sheets to see what is required and leave enough time at the end of the lab session to do it.

Additional reporting is due for some of the labs. Your reports will be like you might present to an employer.

One word of caution: You are expected to know and understand the procedures and requirements. "I didn't know we were supposed to do that," won't work.

Grading Policy

Your final grade, which provides 20% of the final course grade, will be composed of all the written work that the labs require. Late work is not acceptable unless you have a very substantial reason for the lateness. In addition, you must have a passing grade in the lab to pass the course.

Lab Log Book

Your lab book is similar to the record kept by an engineer in a laboratory where developments are taking place. It provides not only the record of what was done and how, but also serves as a legal document in such matters as obtaining patents. The lab book you are using meets all but one of the common requirements for such a record: it lacks printed page numbers (we've omitted those to save money!).

Since the lab log will be turned in at the end of each experiment, each partner will need a book. Otherwise, a book may not be available for the prelab or lab work for the next session.

One partner in the lab group should do all the work in the lab book for one experiment while the other builds the circuit, sets up equipment, and reads instruments. These duties should rotate for each lab experiment. Your grade on the lab is a joint grade.

You are asked to do two seemingly contradictory things when you carry out and record your experiment. The first is to follow directions to the letter, both the directions listed here and those that go with each experiment. Following these directions makes your work easier to grade and will also get you into some good habits.

The second thing you must do is think for yourself. The lab instructions are usually not a cookbook. At times you will be expected to do something, yet not be told to do it. For example, if the lab says, "Compare your experimental and theoretical results," you are expected to calculate an experimental error; you could lose points if you don't.

Section 5.1 of the ECE Department's *Guidelines and Standards for Writing Assignments* contains some general instructions that you are expected to follow. Here are some additional instructions for recording your experiment in your lab log:

1. The lab book is a journal. Record all observations and results in the book **as you are doing** the experiment. Keep accurate records that would enable someone else to repeat the experiment. Show all of your calculations. If in doubt, write it down.

2. Make all entries in your lab book in ink. If you make a mistake, neatly cross it out with a single line and write the correction beside it. Don't erase because it may turn out that what you wrote the first time was important. The one exception to this rule is that you may, if you wish, draw graphs in pencil; they are often difficult to get right the first time.

3. Never tear out any pages. In general, use only the fronts of pages.

4. The first page of each experiment is the title page. Put the title of the experiment in big, easy-to-spot letters. Next, list the team members. Finally, record instrument and equipment identification for each piece of equipment used. This will make it possible for someone to repeat your experiment. It also helps in identifying malfunctioning equipment.

5. Do prelab work in your lab book. This comes after the title page and before the lab work. A photocopy of this is due at the beginning of the last class before lab.

6. Make sure complete, labeled circuit diagrams are included for all circuits used.

7. When drawing what you are looking at on a scope, always draw the whole screen. Use two divisions in your lab book for each major division on the scope. Label all scales and make clear where zero is located on the vertical axis.

8. All tables should have column headings and appropriate units. A column labeled *Comments* or *Notes* is useful to record extra things, such as a change of scale on an instrument.

9. Many of your graphs can be drawn in the notebook. Each graph should have a title, labeled axes, and appropriate units. If a different grid is needed (semi-log, for example) or a graph has to be saved for another experiment, use good-quality graph paper. Permanently attach this graph to the notebook as shown in Fig. 1. Do not leave loose pages in your lab book.

10. When you start a new section of the lab, label this new section in your book. Number your answers just as the lab sections are numbered.

11. Each member of the lab team must sign the book on the last page of the experiment. Include the date. Secure the already-graded pages with a rubber band to make easy for the grader to find the most recent experiment.

12. Finally, neatness counts. Your lab work must be organized, easy to read, and easy to follow. This is not to say you will be penalized for crossed-out words, spelling errors, or hurried lettering, nor does it say you'll gain extra credit for work that looks like it was done on a word processor. However, despite the fact that this is *your* journal, it is being written for someone else to read, whether it be the grader, the court deciding your patent dispute, or you five years from now. If your journal is difficult to read or follow, your work could be wasted.

Some Ways to Look Good

While "everyone knows that spelling counts and that you shouldn't smudge your ink," some of what you know about writing doesn't quite apply to your lab notebook. But paying attention to some other things will make you

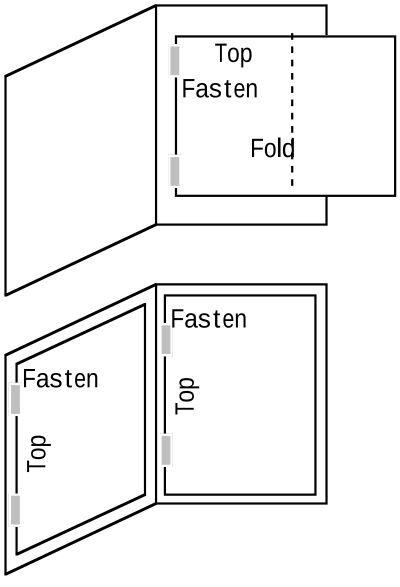


Fig. 1—Fastening papers in lab log

look good.

Since this notebook is a "stream" of what is happening, neatness, grammar, and spelling are only minimal factors. It's "nice" if you are neat, spell well, and write perfect sentences, but it is much more important that you record what is happening, both on the bench and in your mind.

If you really want to look good, pay attention to the following points:

- Use tables to present data, not sentences. Make sure the tables have clear column headings.
- Put units at the top of the column in a table to save writing them on every line.
- Make tables large. There should be enough space in the table to line out one entry and put in a correction without crowding.
- Cross out a mistake with one line. Don't obliterate the error.
- Graphs should be large enough to read, with plenty of room for labels on curves and axes.
- Use "good" axis calibrations such as steps of 1, 2 or 5. Steps of 3 are hard to read, as are peculiar numbers like 1 1/4.
- Be sure that axes have names and units.
- Avoid labeling a graph with calibrations such as "10 volts per division." Label the divisions themselves.
- Oscilloscope sketches should be about the same size as the scope screen. This means using, in a typical notebook, four little squares for each scope screen square.
- Calibrate the axes of a scope drawing in the same way that a graph is done.
- Show the zero-level line in scope drawings.
- All work should read from the bottom of the notebook if possible. If you need to turn something sideways, it is *always* read from the *right* side of the book.

Schematic Diagrams

A drawing of a circuit is a very important "tool" to have when you are wiring that circuit. Without the drawing, you don't know where you are supposed to be, and you can't see on paper what the circuit is supposed to look like.

The general rule in this course is, "Draw 'em before you hook 'em!" This means a completely labeled schematic that includes all element values, all sources, and labels on all pins of integrated circuits.

A proper schematic diagram is *not* a depiction of the physical layout of a circuit. It is what its name says, a *scheme* that shows the electrical, not the physical form of the circuit. The drawing in Fig. 2 is a properly laid-out schematic diagram of an op-amp inverter. Notice a number of things about it:

- The schematic is laid out from left to right in the direction the signal is flowing.
- Standard symbols for devices are used, not outlines of their physical shapes.
- All parts are labeled with enough information to permit you to build the circuit from the drawing.
- Semiconductor pin numbers are included.
- Power supply voltages are labeled (although in schematics of digital logic, the power wires are often completely omitted).
- Input and output terminals are clear, with input on the left and output on the right.
- Integrated circuits are labeled with their standard numbers (LM747) or "U" numbers to reference a listing elsewhere.
- The "A" on "U1A" means that this is a portion of the integrated circuit U1; the other half of this device would be labeled "U1B."

If you modify the circuit during your testing in the lab, be sure to modify the schematic. For simple changes, such as a change in a resistor's value, this change can be made on the original drawing. But for large changes, you'll need to make a new drawing.

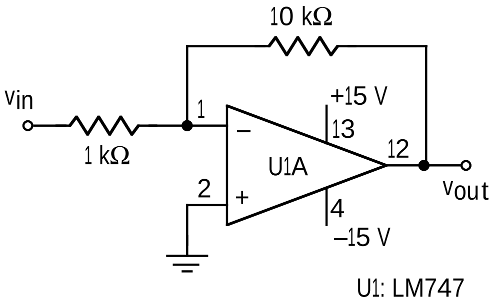


Fig. 2—Proper schematic diagram

Your instructor will not help you with a circuit unless you have a schematic drawing of it that is up to date.

Wiring a Breadboard

There are as many ways to construct a circuit on a breadboard as there are students doing it. But a few simple standards will help by keeping the circuit orderly, reducing wiring errors, preventing the circuit from falling apart, and generally making life simpler..

Here are some simple things you can do in planning your board layout that will help reduce the “spaghetti” and make your board easier to work with:

- Built circuits in advance, then use tape for flags to label power, inputs, and outputs.
- Power goes at the top, ground at the bottom.
- Build your circuit from left to right in the same direction as the “flow” of the signal through the circuit.
- Don’t crowd. You need space to work.
- Flatten humps of wire so that they don’t get caught and pulled out as you make measurements.
- Use wire, not pins for power connections.
- Try never to push pins into holes in the middle of the board – put them at the ends only. (The pins weaken connectors, damage that appears as non-working connections in later courses.)

If you wire a board using a spaghetti layout, ignoring basic principles of orderliness, your instructor will probably refuse to help you debug a circuit.

Good Scoping

The oscilloscope is the most valuable instrument in the laboratory. If you were allowed just one instrument for all your work, the scope would have to be your choice. But the scope is a complicated piece of equipment. Paying attention to a few conventions will help you get good results:

- Channel 1 should display the input signal. This signal should generally be the one to which the scope sweep is synchronized. The trace should be toward the upper half of the screen.
- Channel 2 should display the output signal. The trace should be toward the lower half of the screen.
- Use the whole screen to display as large a waveform as possible. For example, don’t display six periods of a pulse when you need to see only one.

Electrical Safety

Electricity has the ability to kill or injure you. You will be working with “electricity” in the lab this quarter. So you must pay attention to where it and you are at all times.

Electricity is nothing to be feared, no more than an automobile. The automobile can kill or injure, but you try to drive in such a way that you minimize the chances of having something go wrong. The same is true when working with electricity: act in ways that minimize the chances of getting hurt.

What’s the problem with electricity? Some people say, “It’s the current that kills.” Others say, “The voltage is the problem.” But since you can’t separate these two effects (i.e., the voltage pushes the current through your body), it makes little difference how you think about the effects of electricity on the body.

We can classify the effects of electric shock by noting what the shock does. Damage to the body may be caused by current that disturbs the rhythm of the heart or interferes with the nervous system. Damage may be caused by heat due to current flowing through the resistance of the body, especially the skin. Damage may also be caused by current that causes involuntary muscle contractions that make your body do something like falling.

But all these results come about because your body became part of an electrical circuit, allowing current to flow through it in some way. Hence the conclusion is that, to remain safe, **you must not become part of the circuit.**

How do you avoid becoming part of a circuit? The obvious way is not to have “electricity” in the first place! To say that another way, **turn off the circuit before working on it**. This isn’t quite enough, though, because the circuit might get turned on and put you in a dangerous position. So, while you should not work on energized circuits, you need to go further.

Treat the circuit as if it were energized, even if you “know” the circuit is off. This way, you won’t be hurt if the circuit happens to be on. Remember that a circuit is a closed path, so for you to become part of the circuit, you must be part of the closed path. **Never put more than one hand into the circuit;** make sure that the rest of your body (don’t forget your feet!) is not touching the circuit or ground. Then you'll be less likely to have a current path through you.

But something still could happen. That's when you want help around. So another safety rule is that you should **never work on a circuit alone**. This way, if something unexpected happens, somebody is there to help you or to get help.

So the three rules for electrical safety are pretty simple:

- **Don't work on live circuits.**
- **Don't assume the circuit is dead, ever.**
- **Don't work alone.**

Ah, you say, we couldn't be working with voltages in this lab that could hurt us. Wrong! Under the right conditions, only a few volts can push enough current through your body to cause muscle contractions or, if in the right path, tangle up the heart's rhythm. So these safety rules apply no matter what the voltage. Besides, how can you be sure that the power supply that is providing this "little voltage" won't malfunction and issue a blast of energy?

Treat electricity the way you treat an automobile: if you don't pay attention to what you are doing, you can get hurt. Or worse.

Writing Assignments

The course includes writing assignments such as formal reports, memos, and instruction manuals. These may be assigned at various times with a variety of topics. You will be graded on the quality of your writing. This means that you may wish to get help from the Learning Center or from other students.

All of your written work must conform to the Department's *Guidelines and Standards for Writing Assignments*.

Your work must be typed or, preferably, produced using a word processor. Be aware that the computer can lead you to doing things that aren't proper. For example, a computer-drawn graph is an easy way to present data, but the computer often chooses peculiar or improper axes.

Correct usage of the English language is essential. This means that spelling, punctuation, grammatical structure, and word usage must be correct. Nothing marks you more quickly as inept than misuse of the language. The word-processor can help you considerably here, so this is another reason to use it.

Sometimes you hear that you must avoid personal pronouns. Use them! Do not try to write in a formal style, which is becoming less common except in scholarly journals. But don't slip too far into a "familiar" way of writing. Note that "I" means you, while "we" means a group of people. As an example of this style, write, "I applied current to the resistor and it immediately exploded," instead of, "Current was applied to the resistor in the manner specified in the laboratory instructions and it was observed to undergo rapid and complete self-destruction, accompanied by a loud and disturbing report, followed by a random scattering of segments of the device over the upper portion of the work surface."

Acknowledgment

Lab manuals and the like involve lots of past history in the form of previous labs. What you have here is therefore a melding of the work of many people, but the historical thread is hard to unravel.

Wm. J. Eccles

Circuits & Systems

Lab 0.5 – Reading Resistors and Capacitors

Small electronic parts don't have much room for printing, so labeling them with values is often done in code. Resistors and capacitors can be particularly difficult to read if you haven't been initiated into the society.

Resistors

A simple code using colored bands gives the resistance of small resistors. There are twelve colors in common use, ten for decimal digits and two primarily for percentage tolerances. The colors have the following meanings:

Black	0	Blue	6
Brown	1	Violet	7
Red	2	Grey	8
Orange	3	White	9
Yellow	4	Silver	10^{-1},10%
Green	5	Gold	10^{-2},5%

Resistors generally have four bands. Start reading from the band nearest the end of the resistor.

1st band – The tens digit of an integer.

2nd band – The units digit of an integer.

3rd band – The multiplier as a power of 10.

4th band – Percent tolerance (20% if no band).

For example, suppose the bands are red-violet-orange-gold. The resistor's value is found via red = 2, violet = 7, orange = 3, and gold = 5%. So the nominal resistance is 27×10^3 = 27 kiloohms = 27 kΩ. The tolerance of 5% means the actual value is 27 kΩ ± 5%, or somewhere between 25.65 and 28.35 kΩ.

Here are some other examples:

brown-black-brown = $10\text{x}10^1$ = 100 Ω

green-blue-brown = $56\text{x}10^1$ = 560 Ω

orange-orange-red = $33\text{x}10^2$ = 3.3 kΩ

brown-green-orange = $15\text{x}10^3$ = 15 kΩ

brown-black-green = $10\text{x}10^5$ = 1 MΩ

grey-red-silver = $82\text{x}10^{-1}$ = 8.2 Ω

Capacitors

Capacitors have strange markings that are by no means as simple to decode as those on resistors. It's easy to think you have a 20-pF when you actually have a 0.2-μF capacitor. Reading capacitors is an ancient and mystic art! Here are some general rules that work 98.39% of the time:

Rule 1 – If the value printed on the capacitor has a decimal point in it, you can be reasonably assured that the value is in microfarads (μF, which is 10^{-6} farad). There may be exceptions to this rule for small-valued capacitors; e.g., you may encounter a capacitor marked 4.7. You can usually tell by its size whether its value is given in microfarads or picofarads.

Rule 2 – If the value printed on the capacitor has no decimal point and either has fewer than three digits or has a zero as its last digit, the number is the capacitance in picofarads (pF, which is 10^{-12} farad).

Rule 3 – If the value printed on the capacitor has no decimal point, has more than two digits, and has as its last digit a number other than zero, the value is in picofarads, like this:

- The first two digits are the first two digits of the capacitance.
- The last digit is the number of zeros to attach.
- It's like the color code for resistors, but with numbers instead of colors.

Rule 4 – If the value printed has two digits with a letter between them, the letter is the decimal point and the value is in picofarads.

Examples

2.2	2.2 µF	Rule 1
150	150 pF	Rule 2
472K	4700 pF	Rule 3
10	10 pF	Rule 2
104M	0.1 µF	Rule 3
4R7D	4.7 pF	Rule 4

(This set of rules is based on the works of Prof. Derry.)

RETMA Standard Resistors

Standard	**20%**	**10%**	**5%**
Percent step	~ 40%	~ 20%	~10%
Multiplier	$\sqrt[6]{10} = 1.46$	$\sqrt[12]{10} = 1.21$	$\sqrt[24]{10} = 1.10$
	10	10	10
	–	–	11
	–	12	12
	–	–	13
	15	15	15
	–	–	16
	–	18	18
	–	–	20
	22	22	22
	–	–	24
	–	27	27
	–	–	30
	33	33	33
	–	–	36
	–	39	39
	–	–	43
	47	47	47
	–	–	51
	–	56	56
	–	–	62
	68	68	68
	–	–	75
	–	82	82
	–	–	91
	100	100	100

Resistors are generally available for multipliers that give values from 1.0 Ω to 10 MΩ.

Available Parts

The Instrument Room has most 5% values of resistors available, especialy in the decades from 100Ω to 100 kΩ. Resistors cost 5¢ each.

Capacitors (non-polarized) are available in many standard values as follows:

1.8 pF
2.2
5.0
7.5
10
12
18
22
27 pF
33
47
68
100
220
330
470
0.001 µF
0.0015
0.0022
0.0047
0.01
0.022
0.033
0.047
0.1 µF
0.22
0.33
0.47
1.0

Capacitors cost from 10 to 40¢ each.

Circuits & Systems

Lab 0.7 – LM 747 Op-Amp

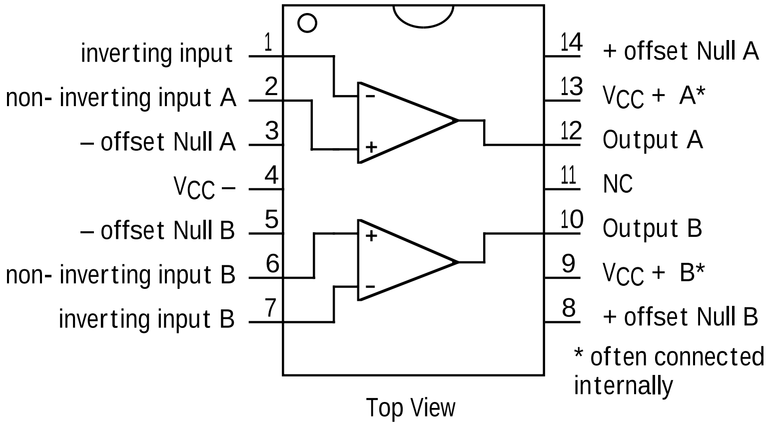


Fig. 1—LM747 pin diagram

The operational amplifier, op-amp for short, has many applications in electronic circuits. This “lab” gives you data on the LM 747 and includes models of five popular op-amp applications.

Package

The LM 747 comes in a 14-pin DIP, which stands for *dual inline package*. The two rows of seven pins are arranged with 0.1 inches between pins and 0.3 inches between rows. The pin diagram is shown in Fig. 1. This diagram is the top view of the chip. Notice that the end of the chip with the #1 pin is identified, in this example by both the notch and the dot.

Power

The LM747 requires a dual power supply in most applications. That is, we must supply to the V_{CC}+ pins a voltage that is positive with respect to ground and a voltage to the V_{CC}– pin negative with respect to ground. The power-supply ground itself is not needed by the chip. It is, however, needed by your signals. So the proper power connections need to be made as shown in Fig. 2.

Models

Figures 3, 4, 5, 6, and 7 (on the next page) show five common applications of a single op-amp with their input/output relationships.

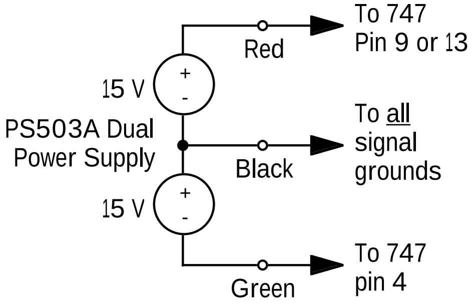


Fig. 2—Supplying power to LM747

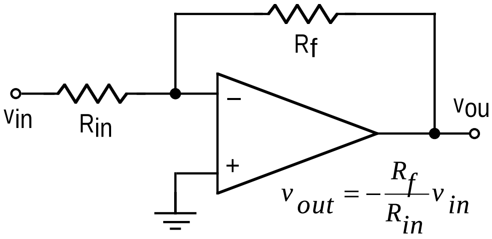


Fig. 3—Inverter

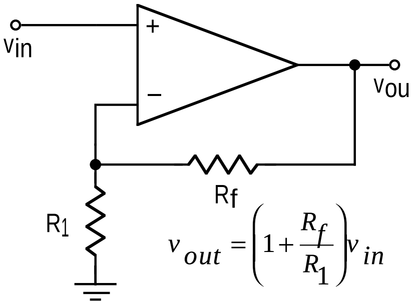


Fig. 4—Non-inverter

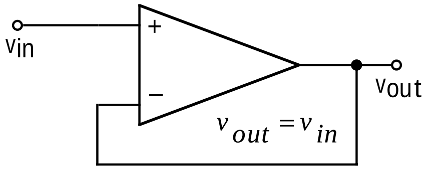


Fig. 5—Voltage follower

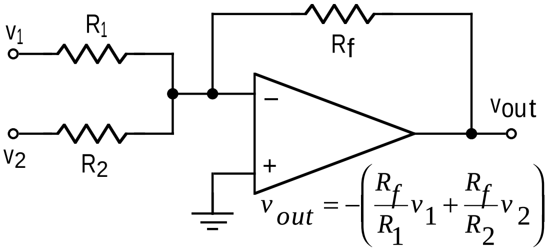


Fig. 6—Summer

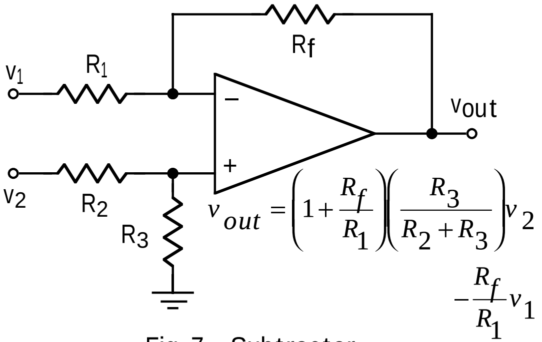


Fig. 7—Subtractor

Proper Wiring

Figure 8 shows the power way to wire a board that has an op-amp. Notice a number of things:

- The LM 747 straddles the gutter in the board, using the first row of holes on either side of that gutter.
- Components and wires don’t cross over the chip. This makes it possible to remove the chip without moving things.
- Power is supplied at the top, in this case on both rows because of the two supplies that the LM 747 needs.
- Ground is at the bottom.
- Input and output leads are some distance from the chip itself. This helps to keep those longer leads from knocking loose something else in the circuit.

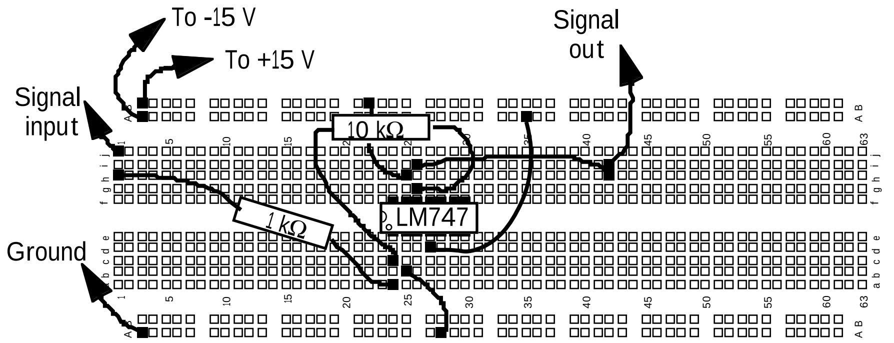


Fig. 8—Proper layout of inverter

Circuits & Systems

Labs 1 & 2 – Active Circuit Design

In Electrical Systems you studied the operational amplifier, or *op-amp* for short. In this pair of introductory labs for Circuits and Systems, you are going to design a circuit using op-amps. But the circuit you design is going to be rather different from what you have studied before.

Be sure to look at Lab 0.7, for here you'll find a description of the LM 747 integrated-circuit op-amp that you'll use for your circuit. You'll also find circuits for five commonly-used op-amp circuits.

Overview

The op-amp is a very nice building block for creating circuits that have properties beyond those of passive circuits. For example, an op-amp with a capacitor performs integration. In this lab we are going to design some of these more unusual circuits.

We have several reasons for doing this:

- design experience,
- continuing use of op-amps, and
- introduction of switches into our circuits.

Equipment

This lab will make use of the standard instruments that you have on your bench. You will need to purchase a "DIP switch" with eight individual switches in it, an LM 747 dual op-amp, and the resistors for your design (about $2).

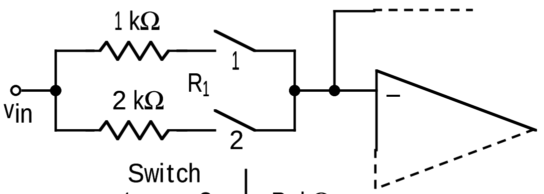
Prelab

The first step in this lab is to get with your lab partner. If you don't have one, please locate one after the end of the first class. The circuit that you'll be designing is a joint design.

Next, determine which circuit you are to design. Do this by adding your five-digit Rose-Hulman student number to that of your partner. Then divide this result by 3. Select the project from the projects listed as *Code 0*, *Code 1*, and *Code 2* based on the remainder of the division.

Finally, get started on your design. Be sure that you note the requirements in *Lab 0 – General Information*.

You might like a clue about how switches can be used to select resistors. The drawing below shows how two switches can be used to select among four resistance values:



Switch		
1	2	R_1 kΩ
off	off	∞
on	off	1
off	on	2
on	on	0.667

Fig. 1—Switching resistor values

Design Projects

For your selected project you are to design an active op-amp circuit that provides the output specified:

Code 0 – Provide a switch-selectable voltage from the 5V fixed supply. The required voltages are 0, 3, 6, and 9 volts within 10%.

Code 1 – Provide a switch-operated adder that will produce V_{in1}, V_{in2}, $(V_{in1} + V_{in2})/4$, or $(V_{in1} + V_{in2})/2$ within 5%. Note that there is no inversion.

Code 2 – Provide a switch-operated adder that will produce $V_{in} + 0.5$, $2V_{in} + 1$, or $4*V_{in} + 2$ within 5%. Note that the input voltage is not inverted.

There are some other specifications:

- The number of parts is to be kept as small as possible. (Each circuit can be done with no more than a single LM747.)
- Use single resistors to achieve the required resistances. In other words, don't combine two resistors in either parallel or series to get a desired value. (The Instrument Room has all standard values as listed on page 10.)
- The sources of the various signals (V_{in}) have very low output resistance, while the load to be driven by the output of your circuit is an open circuit.
- The op-amp is to be powered from +15V and –15V.
- Simulate V_{in} using the variable 5-V power supply.

Results

By the end of the period for Lab 2, you must have demonstrated the correct operation of your design to your instructor, who will initial your lab journal at that time to show that your circuit was working correctly. But your instructor won't look at what you have done unless you have a properly drawn schematic (see Lab 0) for the circuit you present.

The End

Your lab journal is due at the end of the lab session. Be sure that it is complete and that it conforms to the requirements of *Lab 0 – General Information*.

Circuits & Systems

Lab 3 – Nodal Analysis

Nodal analysis is a formal approach to writing equations for a circuit. In this lab we'll verify nodal-analysis via laboratory measurements.

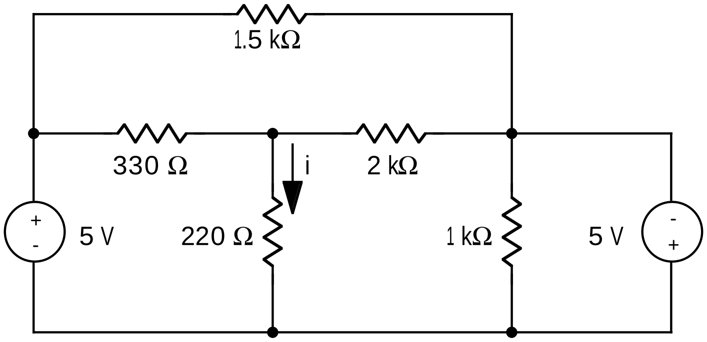


Fig. 1—Circuit for analysis

Goals

Our goal in this lab is to verify nodal analysis by constructing and testing circuits after analyzing them using nodal analysis.

Prelab

For each of the three circuits shown in *Procedure*, find the output variable using formally-applied nodal analysis. You may do this using a computer if you wish, but be sure the results are included in your journal in an understandable way.

Don't forget that prelab work is due at the beginning of class on the second day before your lab session.

Equipment

The sources in The Rack, the oscilloscope, and the meters on the bench are needed. You'll need resistors—220 Ω, 330 Ω, 1 kΩ, 1.5 kΩ, 2 kΩ, 10 kΩ, 20 kΩ (2),—and 2 0.01-µF capacitors, about $1.

Procedure

For the circuit shown in Fig. 1, find the current i by direct measurement. Compare the result with your theoretical result.

Do the same for the circuit shown in Fig. 2, finding the output voltage v. While you don't have a real current source on your bench, you can make one with a variable voltage source and an ammeter, adjusting the voltage so that the current is the proper value. Check the ammeter to make sure the current remains at the desired value—*and* that it is going in the right direction!

Build the circuit shown in Fig. 3 (on the next page). Apply a 10-V peak sinusoid at 1 kHz. Measure the peak amplitude (magnitude) and phase of the node voltages you predicted with nodal analysis. Repeat this procedure at 5 kHz. (Remember that $\omega = 2\pi f$, where ω is in radians per second and *f* is in hertz.)

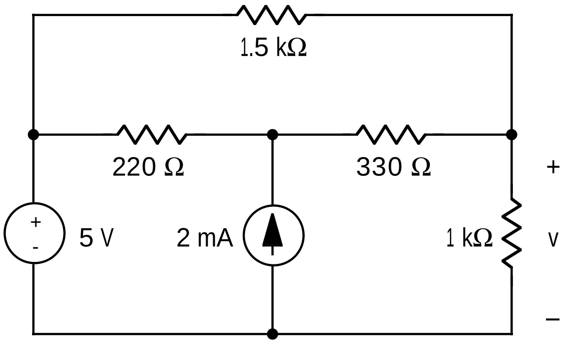


Fig. 2—Another circuit for analysis

The End

Your lab journal is due at the end of the lab session.

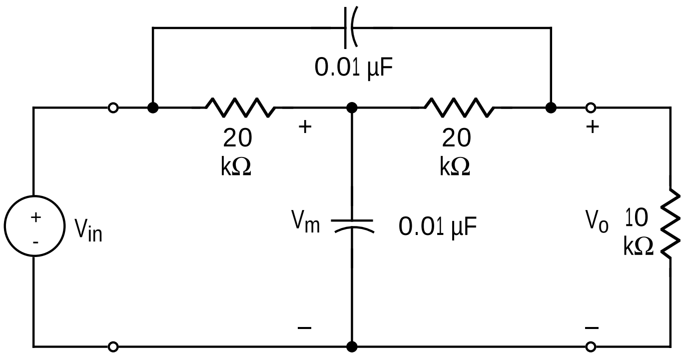


Fig. 3—Bridged-T filter with load

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Lab 4 – Linearity

Linearity is fundamental to everything we do in this first circuits course. Superposition very much requires the circuit to be linear. In this lab we will investigate some examples of linear circuits and superposition.

Goals

Superposition is a useful tool in many situations, but it can't be applied unless the system is linear. This lab has three goals:

- experiment with linear circuits involving more than one source,
- see what happens when a circuit is not linear, and
- get practice making circuits measurements and comparing them with theory.

Prelab

For the circuits in Figs. 1 and 3, make calculations to determine the labeled voltage under three different conditions:

a) one source active, the second source dead;

b) the second source active, the first one dead; and

c) both sources active.

Determine R_x in Fig. 2 so that $v_o = 0$.

Be prepared to compare the results of your calculations with the results of your measurements. (Hint: "Close" is not an acceptable comparison!)

you might want to get parts and built the circuits before coming to lab to save time in lab.

Equipment

You'll need sources and meters in The Rack, along with a number of components: 150 Ω, 470 Ω, 0.047 µF, and a 1N4148 diode (about 50¢ total). You have the other parts from previous labs.

Procedure

This lab is rather long, so you will probably want to set up circuits quickly and carefully, make measurements efficiently, record results carefully, and make appropriate comparisons. Remember that your team's lab journal is due at the end of the lab period.

1. Superposition—d-c

Measure the voltage v_o in the circuit of Fig. 1 under three conditions: the 5-V source active and the 3-V source dead (don't forget what "dead" means!), the 5-V source dead and the 3-V source active, and both sources active.

When you have your data, make sure that you have presented it in an understandable form (a table, perhaps?). Then compare results with what superposition says and also what the theoretical calculations have said. (Hint: "Compare" means numbers.) (Hint^2: This is the last time you'll be specifically told to compare things. In the fu-

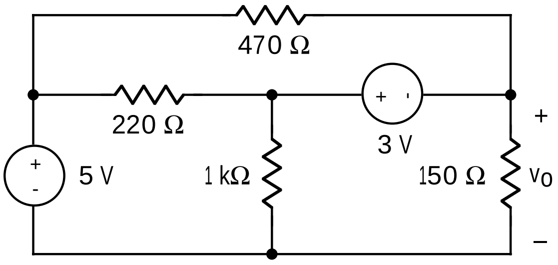

Fig. 1—Circuit for superposition—d-c

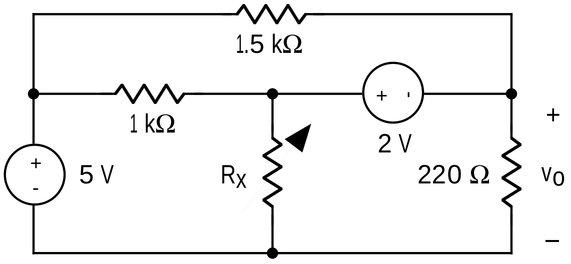

Fig. 2—Circuit for cancellation

ture, when you have data for the same thing but from two different sources, you'll be expected to know that intelligent comparisons are required.)

2. Superposition—d-c cancellation

Find the value of R_x in Fig. 2 that will reduce v_o to zero. You probably should use a decade resistance box for the resistance R_x. But don't accept the dial readings as gospel—lab equipment has a tendency to get out of calibration. In other words, use your ohmmeter to verify the dial reading when you are finished.

3. Superposition—a-c

Measure the voltage V_o in Fig. 3 under three conditions: d-c source active and a-c source dead, d-c source dead and a-c source active, and both sources active.

This set of measurements can be done with The Rack's DMM, since you can measure d-c and also rms values for a-c. But be sure to observe V_o on your scope as well. In particular, note how d-c and a-c combine.

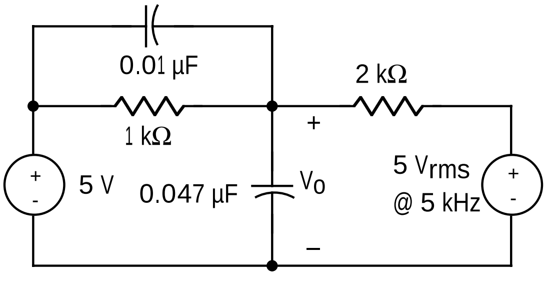

Fig. 3—Circuit for superposition—a-c

4. Diode data

Obtain a 1N4148 diode. A diode conducts current only one way: positive current flows out the cathode, which is the marked end (a black band). It does not conduct current readily in the opposite direction.

Set up a circuit (*not* the circuit of Fig. 4) so that you can measure the current-voltage characteristic of your diode. Keep in mind that pushing the diode above 250 mA will probably burn it out!

Collect enough data to get a good plot of current versus voltage between 0 and 200 mA. Plot the current on the vertical axis of your graph. Plot your points as you collect data; this way, you can choose the spacing of the points, wide where the curve is straight, closer together when the curve is changing rapidly.

Plot your graph directly in your lab journal. Don't crowd things! The voltage axis should occupy most of the width of your page. You might want to read about graphs in Lab 0.

5. Nonlinear circuit

Measure the voltage v_d and the current i_d for the circuit of Fig. 4. Then double the source to 10 volts and repeat your measurement. You have enough data to compute the resistance of the diode under each condition. Is there agreement with your graph? Did v_d and i_d double when you doubled the source voltage?

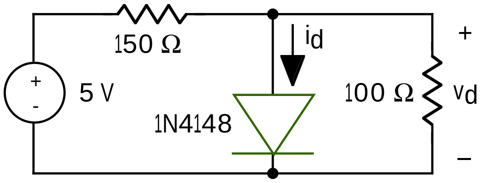

Fig. 4—Nonlinear circuit

The End

Be sure that you have completed all the parts of this lab, that each page of your journal is initialed by both team members, and that the last page is signed by both and dated. Turn in your journal by the end of the lab period.

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Lab 5 – Thévenin and Matching

Does Thévenin's Theorem really work? Or is it just some classroom exercise that we do so that all our students have something to get confused about? How "matched" are things when we apply the theory? How critical, how touchy is this match? In this lab we'll try a couple of circuits and see what we get.

Goals

Thévenin's Theorem tells us how to find a simple equivalent at the terminals of a linear circuit. To this we have added the concept of matching, which means extracting the maximum possible power from a circuit. In this lab we'll experiment with this concept.

The lab has four goals:

- try matching a load to a source, both for a d-c circuit and in the a-c steady state;
- measure or calculate power to a load, both for d-c and for a-c (remember that "power" almost always means *average power*);
- see how critical these matches are; and
- plot data on semilog paper.

Prelab

Do three things for each of the circuits (Figs. 1 and 2):

1) Find the Thévenin equivalent.
2) Determine the proper load to extract maximum power from the circuit.
3) Compute the maximum power that the load absorbs.

Now determine how to find the power delivered to the load in both cases. What can you measure in the lab and how is power computed from those measurements?

Get the necessary parts and construct the circuits on your breadboard so that you are ready for lab. (The 33-mH inductor will be available in lab.)

Finally, come to lab with two pieces of three-decade semilog graph paper. (The bookstore has this.)

Equipment

You'll be using various items in The Rack, along with the scope for a-c measurements. On your bench will be a 33-mH inductor, a decade resistor box, and a capacitor substitution box. You will need a 3.3-kΩ resistor also.

Procedure

Both parts of this lab are roughly the same. You'll connect the matched load to your circuit, measure the power, and then plot power versus another parameter using semilog paper.

1. D-c matching

Using the circuit of Fig. 1, find the power delivered to your matched resistance. Then vary the load resistance from 0.05 R_L to 20 R_L and plot the power versus R_L on

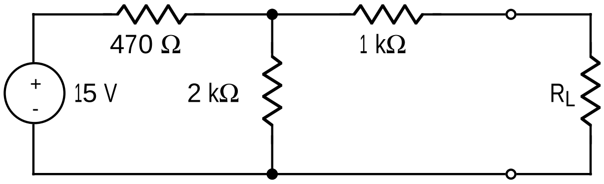


Fig. 1—Circuit for d-c matching

semilog paper. Use the logarithmic axis for R_L in ohms. Indicate the maximum power and the corresponding resistance on your graph.

2. A-c matching

Using the circuit of Fig. 2 with V_s set to 4 kHz at approximately 3 volts rms, find the power delivered to your matched load. For your load capacitance you will probably want to use either the decade capacitor box or the capacitor substitution box that will be on your bench.

After determining the maximum power, vary the frequency from 200 Hz to 20 kHz and plot the power delivered to the load versus the frequency. Use semilog paper with the logarithmic axis for the frequency in hertz. Indicate the maximum power and the corresponding frequency on your graph.

Is the maximum on your graph at 4 kHz? Show this result to your instructor and explain what's going on.

The End

Your lab book is due as usual at the end of the lab session. Be sure that your graphs are properly done (see Lab 0) and that they are fastened into your lab journal correctly.

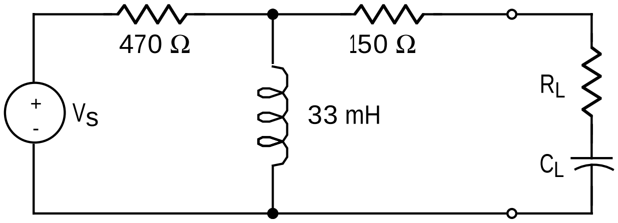


Fig. 2—Circuit for a-c matching

Circuits & Systems

Lab 6 – Step Response Design

This lab uses the step response of a circuit in a peculiar way – to fit a particular waveshape specification. In other words, the step response itself is specified and the circuit to produce it is to be designed.

[This lab includes many ideas from *Lab Manual* by John C. Getty, a book developed to accompany Thomas & Rosa, *The Analysis and Design of Linear Circuits*.]

Goals

Our goal is to make use of what we know about RC and RL circuits to produce a certain waveshape.

Equipment

Use the function generator for the step input and the scope for the output. Parts needed will depend on your design but their cost shouldn't exceed 50¢. If you need an inductor, the only reasonable one available is 33 mH.

Prelab

Add your Rose-Hulman student number to your lab partner's. Divide the result by 4 and use the remainder to select the template on the next page.

Design an RC or RL circuit and its input signal to fulfill the requirement imposed by the selected template.

Procedure

The circuit that you design is to contain only one energy storage element, either a capacitor or a 33-mH inductor. While you may use as many resistors as you wish, the best circuits will have very few resistors.

The output waveform must fit entirely in the clear squares of the template. It must not touch the solid squares at any point. Notice that the template is specifically calibrated on both axes.

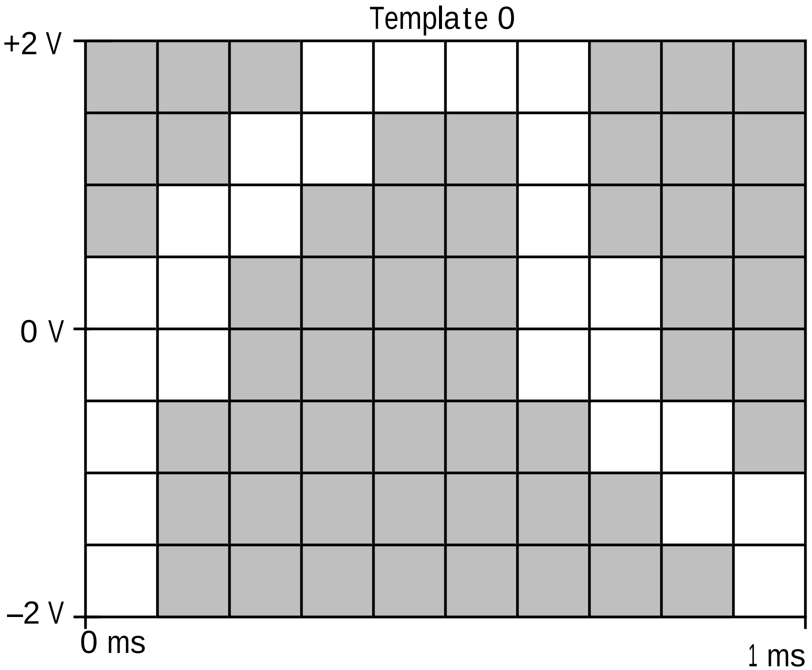
When you have finished your testing, present your results for grading Your instructor will have a plastic template that will fit over the screen to show that the waveform meets the specifications. S/he'll also want to check the calibration of your scope. You may *not* have the test template until you are ready to be graded on your result.

The End

While you must keep a proper lab journal that contains your design, your tests, any changes you make, and the final result, your final grade will be based on only four points:

- whether your prelab work was done completely by the beginning of the previous class,
- whether the waveform fits the template correctly, and if not, how close it comes,
- whether your journal is a reasonable record of your work, and
- the simplicity of your circuit.

Nothing will be handed in at the end of the lab session.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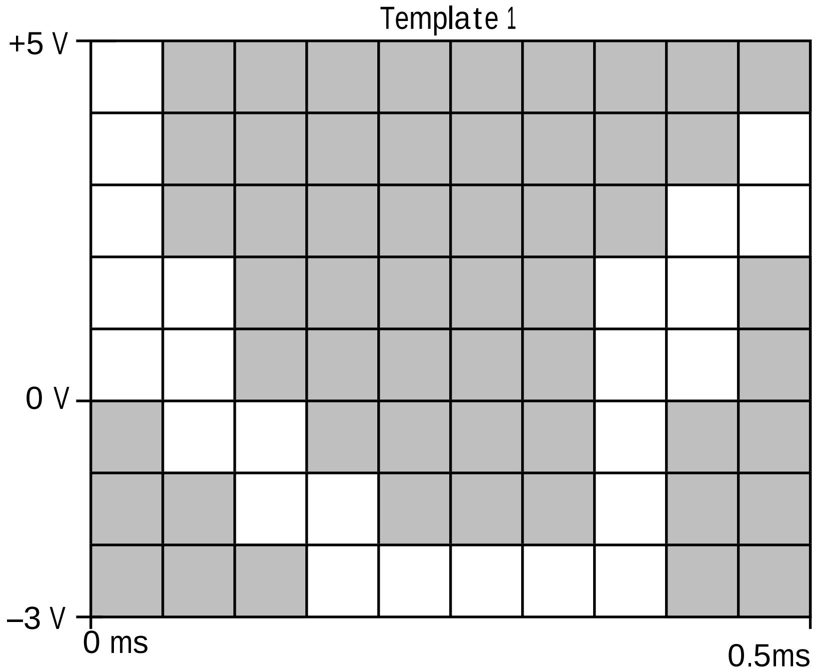
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–3 V
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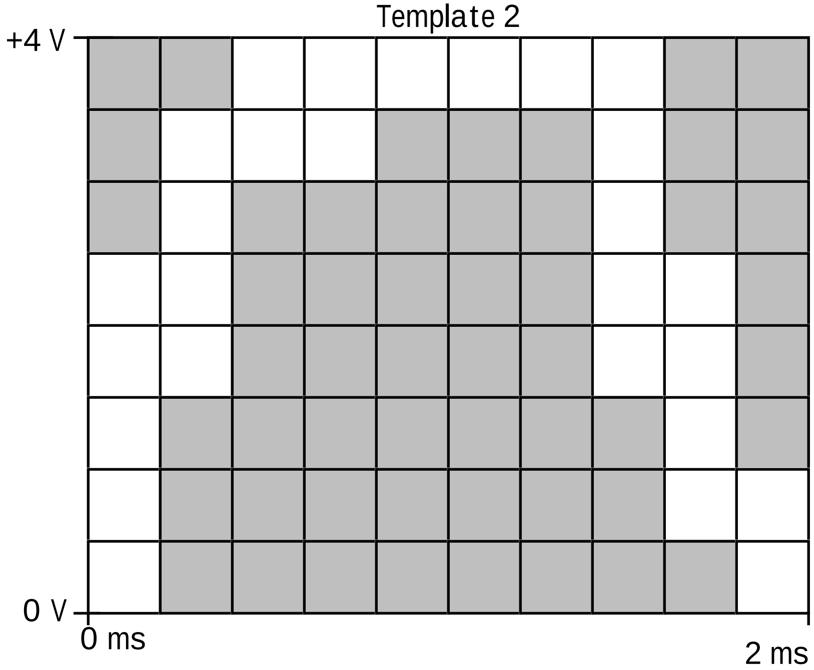
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0 ms
2 ms

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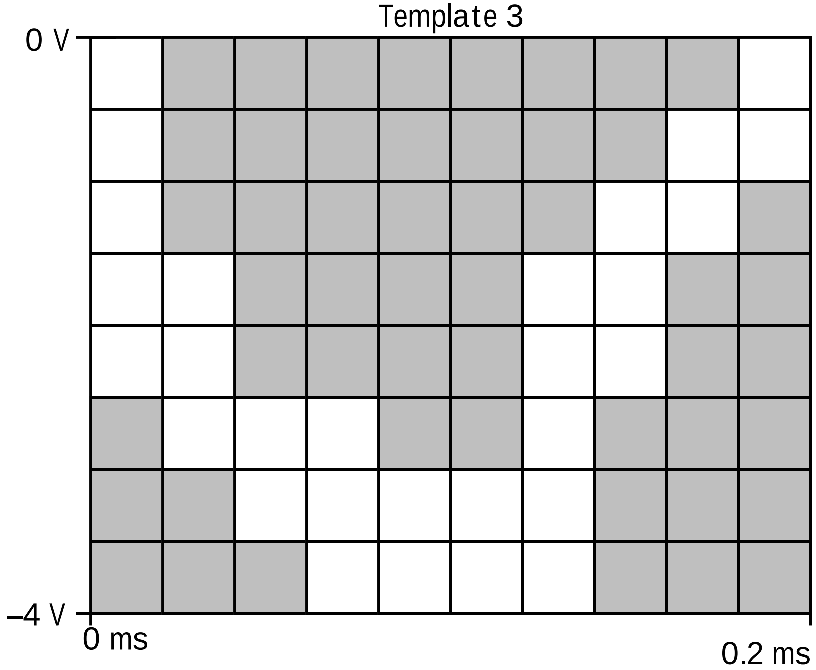
Template 3
0 V
–4 V
0 ms
0.2 ms

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Circuits & Systems

Lab 7 – Steps & Steady State

A circuit's step response and the way it handles signals are very closely related. You've learned some of the mathematics that supports this concept, so let's take a look at that relationship in the laboratory.

Goals

There are four topics that we are going to address here:

- what is the step response of an op-amp circuit that contains a capacitor,
- what is the response of the same circuit to sine waves of various frequencies,
- what is the relationship between these, and
- how do we plot sinusoidal responses versus frequency?

Equipment

Most of your measurements will be made using the oscilloscope while driving the op-amp circuit with the function generator. (We choose the function generator because it has a lower R_{Th} than the oscillator.)

Use the DC504A Counter-Timer, not the dial of the FG501 Function Generator, to set frequencies.

You should already have all the needed small parts.

Prelab

For the circuit of Fig. 1, calculate the step response (output due to an input of a step of height 1 V) so that you know the time constant as well as the complete output function. Do the same for the circuit of Fig. 2.

Obtain log-log graph paper for plotting the results of your sinusoidal measurements. You will need one sheet for this lab, 3 decades by 3 decades. Homemade paper will probably be unsatisfactory. Excel plots are also generally unsatisfactory (lack of a smooth curve through the points, inadequate grid lines, strange axes calibrations).

Procedure

1. Step response

Construct the op-amp circuit of Fig. 1 and measure its step response (output due to a unit-step input—use 1 V), comparing your result with the calculations you made in the prelab. Be sure to measure the time constant accurately.

2. Sinusoidal response

Measure the sinusoidal response of the op-amp circuit of Fig. 1. Keep the input at 1 V peak. Start at 100 Hz and go up in frequency until the output is down to about 1/50th of the output in the long flat region.

The DMM is not a satisfactory instrument for measuring voltages in this case because the frequency is going too high. The DMM is satisfactory, according to the manufacturer's manual, to 10 kHz.

Plot the magnitude of your circuit's gain on a sheet of log-log paper. Since the horizontal axis is the log of frequency, choose your data points to make sense on that axis. For example, you might select 100, 200, 400, 700, 1000, 2000, 4000, 7000, 10,000, … Hz to get a fairly uniform spacing on the axis. Plot the curve as you go along so you know where to put points closer together.

Your curve should have a long flat region and then "roll off" at the upper frequencies. The point at which this roll-off begins is by convention the point at which the output is $1/\sqrt{2}$ of its "flat" value.

Determine the roll-off frequency for this circuit. (This frequency is commonly called the *cutoff frequency*.) Now compare this frequency (in radians per second, not hertz) with the reciprocal of the time constant. They should be the same!

3. Another op-amp circuit

Repeat your step-response and sinusoidal-response measurements for the circuit of Fig. 2. Plot your result on the same graph paper as in the previous part. Notice that this time the roll-off is at the low-frequency end of the response curve.

Make the same comparison between the roll-off frequency (in radians per second) and the reciprocal of the time constant. Again, they should be the same.

The End

Reporting on this lab will be in the form of a memo, so you won't be handing in your lab journal at the end of the session.

One member of the team is to write a memo giving the *results* of this lab. The memo is to your lab instructor in the role of your supervisor in an industrial lab. Your supervisor wants to know what your results are, so give *results*. Don't forget that the graphs are part of these results.

The memo is due at the beginning of the second class following the lab session.

The other member of your team will write a memo for another lab. Hence the memo for today's lab will not be returned until later.

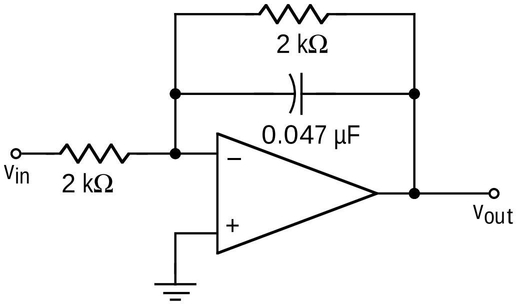

Fig. 1—Low-pass filter

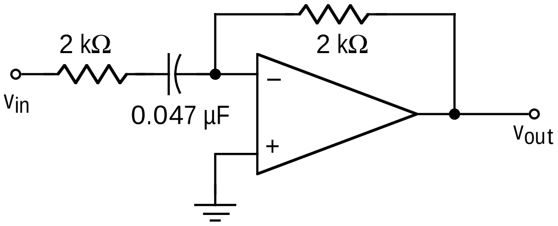

Fig. 2—High-pass filter

Circuits & Systems

Lab 8 – Phase Measurement

Measurement of the amplitude of a signal versus frequency is fairly easy, at least until you get to very high frequencies like a megahertz. But amplitude is only half the story for a sinusoid. We also need phase information. In this lab we'll work on measurement of phase versus frequency.

Goals

1. Practice measuring phase.
2. Measure the phase response of an all-pass filter.
3. Measure the characteristics of an inductor.
4. Measure the phase response of an RLC circuit.

Equipment

LM747, 33-mH inductor, parts from your kit, and two sheets of three-decade semilog paper. You should have all the small parts except a 0.1-µF capacitor.

Prelab

Develop a procedure for measuring the phase difference between two sinusoids displayed on an oscilloscope. Describe how to maximize the accuracy of your measurement. You may wish to refresh your memory about the definition of phase shift between two sinusoids, especially the distinction between positive and negative phase shift.

Calculate the phase shift of the op-amp all-pass filter of Fig. 1 at 170 Hz, 1700 Hz, and 17 kHz.

Estimate the resonant frequency f_o (in hertz) of the impedance in Fig. 2. (The resonant frequency for our purposes is where the phase angle goes rapidly through 0° or 180°.) For your calculations, assume that the inductor has nominal values of $L = 33$ mH and $R_L = 35\ \Omega$.

Build the circuit of Fig. 1 on your breadboard.

Obtain two sheets of three-decade semilog paper.

Procedure

1. All-Pass Filter Amplitude and Phase

The all-pass filter (Fig. 1) passes all signals unchanged in terms of amplitude, but introduces a frequency-dependent phase shift.

Implement the all-pass filter of Fig. 1. Use a 1-V-peak sinusoidal input signal, verifying that the input remains at the same amplitude as you change frequency.

Plot the amplitude response and the phase response on the same sheet of semilog paper over the frequency range 100 Hz to 100 kHz. Make sure you collect enough data to clearly show what is happening.

Based on your results, what do you expect the phase to be at d-c and at very high frequencies?

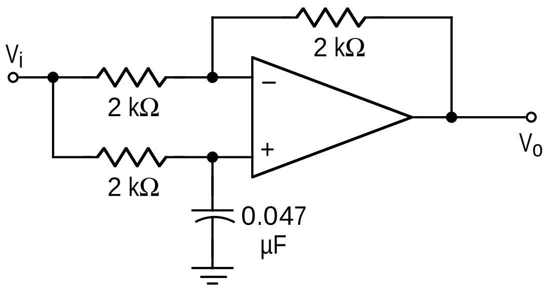

Fig. 1—All-pass filter

Record the phase shift at 170 Hz, 1700 Hz, and 17 kHz. Compare your results with theoretical values.

2. Resonant RLC Circuit

Build the circuit of Fig. 2 using the 33-mH inductor on your bench. Then measure and plot both the magnitude and the phase angle of the impedance Z(jf) for frequencies from 300 Hz to 30 kHz. Plot both curves on the same piece of three-decade semilog graph paper. Plot as you go along, collecting extra points where the curve changes rapidly.

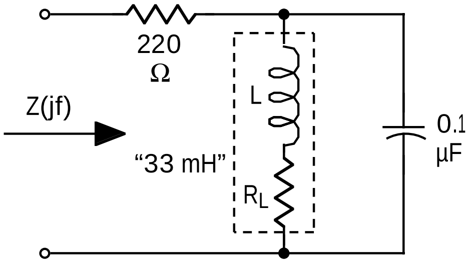

Fig. 2—RLC resonant circuit

The End

This lab ends with a memo, just as the last one did, but this time written by the other member of the team. Go back to the previous lab and review the instructions given there.

Circuits & Systems

Lab 9 – s-Plane Design

Sometimes we know what we want out of a circuit by what its s-plane looks like. We can often design that circuit by considering where the poles and zeros are to be located on the s-plane. In this lab we are going to start with the s-plane and end with a circuit.

One approach to the design of a circuit from the s-plane is trial-and-error. But this needs to be an orderly process:

- Note all the poles and zeros on the s-plane.
- Find a circuit with the correct *pattern* of poles and zeros. This can be done by trying various combinations of parts, starting with the simplest combinations that look like they might have a chance of working. Some designers use letters like R_1 and C; others just assign the value “1” to each element and scale the elements later.
- Adjust or scale the element values so that the poles and zeros fall at the correct places.
- Readjust the element values to make use of commercial parts.
- Build and test the circuit to show that it meets specifications.

Goals

Our goal is to design an *active* circuit that matches the given s-plane, build that circuit with commercial parts, and show that it meets specifications.

Equipment

Parts for your design, The Rack, and the oscilloscope.

Prelab

Design a simple *active* circuit that has the s-plane arrangement for H(s) as shown in Fig. 1:

- poleat the origin (hint: this means that there is infinite gain at d-c, which says d-c causes saturation);
- single simple zeroat $-2\pi 2000\ s^{-1}$ (hint: this means that there is probably only one energy-storage element); and
- gain magnitude of 10 at f = 1 kHz (hint: meet this specification last).

One more hint: there are only three specifications, one zero, one pole, and one gain, so it is possible that they can all be met with just three components (plus the op-amp).

Your design should use commercially available parts. Use only single resistors (i.e., don’t try to get a more precise value by combining resistors to get one resistance).

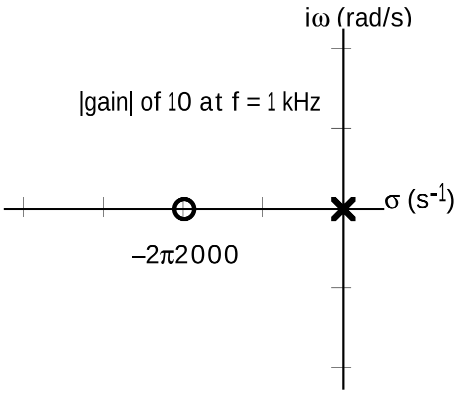

Fig. 1—s-plane for design

Procedure

Build and test your circuit. Be sure to show that you do indeed have a zero at $-2\pi2000$ s^{-1} and a pole at the origin.

The End

Your lab journal is due as usual at the end of the session.

Circuits & Systems

Lab 10 – Bode Diagram Design

In Lab 9 we started with an s-plane and designed a circuit to provide the specified poles and zeros. In this lab we are going to do almost the same thing, but this time the specifications are in the form of a Bode diagram. We'll start with the Bode diagram and end with an *active* circuit that produces such a plot.

You might want to review the general steps at the beginning of Lab 9. The only addition will be a step at the beginning of the list:

- Determine where poles and zeros would be on an s-plane to produce the specified Bode diagram.

Goals

Our goal is to design an active circuit that matches the given Bode magnitude diagram, build that circuit with commercial parts, and show that it meets specifications.

Equipment

Parts for your design (less than 75¢), The Rack, and the oscilloscope. You will also need one sheet of three-decade semilog graph paper.

Prelab

Design a simple *active* circuit that has the Bode magnitude diagram for H(s) shown in Fig. 1. Here are a few suggestions:

- What is the circuit's response at d-c? What does this tell you about a d-c path through the circuit?

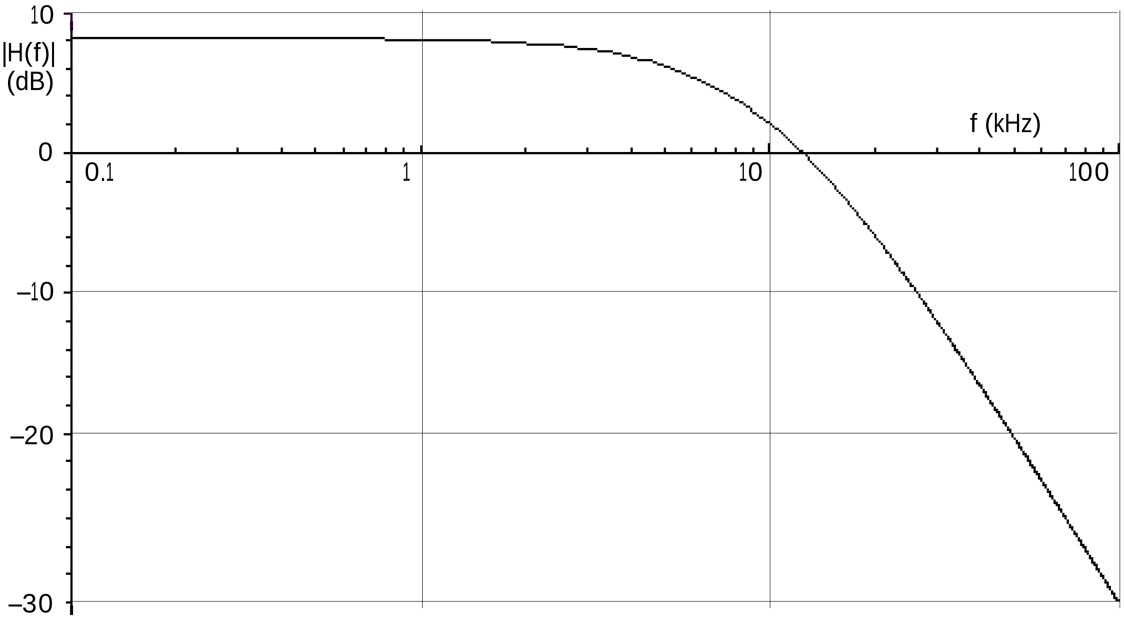

Fig. 1—Bode diagram for design

- Each “break” (a change in slope of 20 dB/decade) in a Bode magnitude diagram probably represents one pole. How many poles are there in H(s)?
- Complex pairs of poles often produce peaks or sharp humps. Does this diagram have any of those? So are the poles complex conjugates?
- The pole at a break is located at the half-power point. How many dB is “half power”? Where are these points? Where are the poles?
- You need to know that this circuit is a “minimum phase” circuit, which means there are no singularities in the right half-plane. This means the phase angles will be in the ±90° range (ignoring the 180° inversion provided by the op-amp). Also, recall that, to be stable, all poles must be in the left half-plane.
- What is the “midband gain”? This gain can be adjusted as the last step in the design.
- A circuit will probably need one independent part (R, L, or C) for each separate specification. This design can probably be done with six components plus the op-amp.

Again, design your circuit so that it can be built with parts from your kit. Don’t use electrolytic capacitors. Use only single resistors for a desired resistance. You may, however, want to use two capacitors for one capacitance because of the wide spread between values in your kit.

Procedure

Build and test your circuit. Draw the Bode magnitude plot to show how well you have met specifications.

The End

Present your lab journal, with the graph properly attached, at the end of the session. It will be graded on the spot and returned, so never leave lab without it.