Georgia Institute of Technology
School of Electrical and Computer Engineering
ECE 4435 Op Amp Design Laboratory

Lab Instructor: ______________________ Office: ______________________

Office Hours: ______________________ Email: ______________________

Laboratory Objectives

Each student will individually design, simulate, test, and evaluate at least three circuits employing operational amplifiers. These circuits will be designed to accomplish a prescribed function or serve a particular application. Students will predict the expected ideal response of their design. They will also simulate their circuits using a practical op amp model and compare and evaluate these theoretical predictions against the results obtained in the laboratory.

Laboratory Evaluation

Design Project One	50 points
Design Project Two	50 points
Design Project Three	50 points
Total	150 points

A report will be required for each design project. The report will reflect:

1. Your analysis of the problem to be solved.
2. An explanation of the design philosophy you used to achieve the performance required.
3. A computer simulation of your design using SPICE or other programs as appropriate.
4. Your experimental data properly presented.
5. Verification of a workable circuit by the lab instructor.

Each report will be due on the date specified. A penalty of two points per day (including weekends) will be made for late reports. Your design report should be bound in a binder with the "Summary Evaluation Sheet" as the first page of the report. Arrange the pages in the following order:

1. "Summary Evaluation Sheet" from the Laboratory Experiment Handout.
2. "Handout Sheet" describing the problem.
3. "Design Analysis & Philosophy" describing the approach you took.
4. "Computer Simulations" with results neatly summarized and presented.
5. "Experimental Results," neatly summarized in graphs, figures, tables, etc., as appropriate.
6. "Economics" of your design with explanation and justification.
7. "Conclusions" describing experimental results, comparing numerically expected and actual performances, economic considerations, etc.

8. Graded pre-laboratory explanation.

Secure a large enough binder or folder so that you will be able to file all three of the design projects together with the most recent always first. After grading your solution, the complete binder will be returned to you.

Ten Requirements for a Technical Engineering Report

1. Folder
2. Order as given above with pages numbered.
3. All figures numbered and titled, all equations numbered, and references included properly. See any IEEE journal as an example for style and format.
4. Written in third person.
5. Complete circuit diagrams included with component values given for all elements and IC pin numbers given. Also, SPICE node numbers indicated.
6. SPICE simulation properly condensed and presented.
7. Percent errors and differences determined.
8. Graphs and tables as necessary showing theoretical, simulated, and experimental results, preferably on the same graph for easy and ready comparison.
9. Explanation of testing procedure.
10. Strong conclusions – percent and sources of error, economics, testability, improvements, what was learned, etc.

Design Problem Ethics

You are free to discuss general approaches to the problem with any class member. You can feel that your cooperation with other students is fair and ethical if all exchanges of ideas are entirely verbal as opposed to written. In addition, only general ideas rather than implementation details may be discussed. You will need the lab instructor to witness and verify the operation of your design. He should sign your report in the designated place.

Some DO's and DONT's for the Lab

- **DON'T** remove any test equipment, laboratory supplies, parts, hardware, instruction manuals, etc., from Room C-348.
- **DO** help keep up with the equipment in this room by immediately reporting any missing equipment to the lab instructor.
- **DON'T** ask the technicians for help with your design project or to repair equipment you believe is faulty.
- **DO** a double check on your test set up. If still in trouble, seek help from the lab instructor. If he or she cannot solve the problem, then discuss it with the course instructor.
- **DO** follow special instructions posted from time to time in the lab.
- **DON'T** ask faculty or graduate students with keys to open the lab if the door is locked.

- **DON'T** ask to use the laboratory "after hours," on weekends, or for special arrangements on an individual project.
- **DON'T** make the solution to any design problem a "team effort" which really reflects only one student's design.
- **DO** feel free to discuss the requirements of each project and the general approaches you are considering with other students in the class. However, your specific solution should be yours, and yours alone.

IC Op Amps, Wire Kits, and Breadboards

You must purchase a wire kit and a breadboard for your lab projects. These can be purchased in the Ga. Tech Bookstore or the Engineer's Bookstore. The venerable 741 type op amp will suffice for most applications. However, the LF351 (single), LF353 (dual), and LF347 (quad) are superior and are recommended. Because of potential oscillation problems, the LF356 is not recommended.

Personal Laboratory Supplies

Some of you may have already begun to establish your own assortment of electronic parts, supplies, hardware, etc., which you can use in this laboratory. Others may wish to use this course and laboratory as a way of acquiring materials for a "home shop" which will be helpful not only in ECE 4435 but also in future courses and individual projects. Some items that you will find helpful and should consider acquiring are listed as follows:

Solderless Breadboards	Needle-Nose Pliers
1/4 W Resistor Assortment	Diagonal Cutters
Capacitor Assortment	Wirestrippers
Alligator Clips	#22 Solid Hookup Wire
Vector Board Flea Clips	Storage or Tackle Box
IC Sockets	Hemostats or Forceps
Low-Power Soldering Iron	Rosin Core Solder

Misc. Supplies such as Potentiometers, ICs, Diodes, Transistors, Magnifying Glass, Soldering Paste, Small Magnet, IC Extractors, Hand-Held Multimeter, etc.

Practical Considerations in the Lab

The theoretical side of electronic design must be balanced by the practical side. This is why laboratory experience is so valuable. In your design work, you will encounter problems not addressed in the text. The following suggestions are intended to supplement the text in the area of circuit design and testing, especially involving breadboards and op amps. Always be sure that:

1. Wires and component leads are short and neatly dressed.
2. All power supply lines are bypassed to ground with capacitors on the breadboard. During initial testing and debugging, it is a good idea to put a small value resistor in series with each power supply lead between the power supply and the decoupling capacitor. This will limit the current and prevent blowing out an op amp or a polar electrolytic capacitor in case you make a mistake. Suggested values for these elements are $100\,\mu$F and $100\,\Omega$, respectively.
3. Always connect the breadboard common, usually called circuit or signal ground, to the power supply common and connect the ground reference of all test equipment on the bench to the breadboard common.
4. Resistors associated with op amps are in the range of $100\,\Omega$ to $1\,\text{M}\Omega$.

5. Op amps are operated well within their input common-mode ranges and within their output swing capabilities.

6. Op amps are not required to sink or source more than 10 mA.

You should make the above points a checklist for every design. Following these suggestions and using other conservative design techniques will greatly reduce the time spent debugging and redesigning. The above points are described more thoroughly in the following:

1. Wires and Component Leads
   Wires and leads can act as antennas that pick up electromagnetic interference (EMI) from nearby sources. These sources include fluorescent lights, TV stations, radio stations, amateur radio broadcasts, computers, etc. The higher the impedance at a given circuit node, the greater the susceptibility to EMI. Therefore, high-impedance points, such as those found frequently in active filter circuits (Lab 3), should receive special consideration. The lengths of interconnecting wires and component leads should be kept short to minimize EMI pickup. Good power supply decoupling and a grounded metal plane beneath the breadboard are other preventative measures.

2. Power Supply Decoupling
   An ideal power supply is a voltage source with zero output impedance. However, no practical power supply has an output impedance of zero. In most cases, the equivalent circuit of the output impedance of a regulated power supply consists of several resistors, capacitors, and inductors. Often, these are approximated by a single resistor in series with a single inductor. The resistor models the output impedance at very low frequencies. The inductor models the output impedance at very high frequencies. Part of these elements are associated with the power supply itself while part is associated with the wiring between the power supply and the circuit.
   When signal currents flow through the output impedance of the power supply, a voltage drop is generated which causes the power supply rails in the circuit to have signal related voltage fluctuations. This can cause undesirable coupling between different stages in the circuit which can cause the circuit to oscillate or have other undesirable characteristics. Power supply bypass capacitors are the solution to this problem. A single bypass capacitor to ground having a value in the range of $1\,\mu$F to $100\,\mu$F at the point where each power supply lead connects to the breadboard is often all that is required. In some cases, additional bypass capacitors at the points where the power supply rails connect to each op amp are required. In some rare cases, separate RC decoupling networks may be required on the power supply rails to some of the op amps in the circuit.

3. Grounding
   To the beginner, grounding can sometimes be the major reason that circuits do not work properly. Unfortunately, the word “ground" has two meanings. The first meaning refers to the power system ground, usually called safety ground. The chassis of AC powered equipment is connected via the third prong on the power cord to the power system safety ground to prevent accidental shocks. Often a safety ground terminal or binding post is on the front of a piece of equipment, e.g. a power supply, which is labeled with a ground symbol. However, the terminal may not be connected to the circuit inside the equipment.
   The second meaning refers to signal ground or signal common in a circuit. For our purposes, this is the ground reference on your breadboard. The power supply common, the oscilloscope common, the signal generator common, etc., all connect to it. If a connection is missing between the common on your breadboard and the common on a piece of test equipment on

the bench, something will not work unless the commons happen to be connected to each other back through the third prong of the AC line cords. In the latter case, the connection will not be a low impedance path at high frequencies and measurements may not be accurate. To avoid these problems, always connect the signal ground or signal common on each piece of test equipment to the signal common on your breadboard.

4. Resistor Values
   Resistor values should be restricted for two main reasons. The first has to do with the input bias currents of the op amps. These currents are often neglected in design equations. If their effects are to be negligible after the circuits are built, the external resistances through which they must flow must be small enough so that the voltages generated will not perturb the circuit. As an example, suppose the Thévenin source impedance in series with the input of a 741 op amp is $1\,\mathrm{M}\Omega$. The 741 input bias current is approximately $80\,\mathrm{nA}$. This current flowing through a $1\,\mathrm{M}\Omega$ resistor will generate a voltage of $80\,\mathrm{mV}$. This voltage at the input to a high gain op-amp circuit can cause a significant DC offset voltage at the output of the circuit. An additional problem with high impedance circuits is noise pickup. By keeping resistor values less than about $1\,\mathrm{M}\Omega$, noise pickup can be minimized.
   The second reason for restricting resistor values is the limited output current capability of the op amp. Typically, this is about $10\,\mathrm{mA}$. This places a lower limit on the effective load impedance which the op amp can drive. For example, if a $13\,\mathrm{V}$ peak output voltage is required and the maximum output current that can be delivered is $10\,\mathrm{mA}$, it follows that the effective load impedance on the op amp must be $1.3\,\mathrm{k}\Omega$ or greater. The effective load impedance includes the actual load in parallel with the input impedance of the feedback network. In the case of capacitive load impedances, the current demand is proportional to the time rate of change of the output voltage. Thus one must make sure that the capacitor charging current does not exceed the available current or the frequency response of the circuit will be affected.

5. Power Supply Limitations
   Op amps may be operated over wide ranges of power supply voltages. For a 741 op amp, these are typically $\pm 4\,\mathrm{V}$ to $\pm 18\,\mathrm{V}$ for bipolar supplies and $8\,\mathrm{V}$ to $36\,\mathrm{V}$ for a unipolar supply. Regardless of the power supply voltages used, the op amp cannot accept input voltages at its $+$ and $-$ inputs which lie outside its common mode input range. For the 741, this range is $(V_L + 2)$ V to $(V_H - 2)$ V, where V_L is the lower power supply voltage and V_H is the upper power supply voltage. For example, if the 741 is operated at power supply voltages of $V_L = 2\,\mathrm{V}$ and $V_H = 13\,\mathrm{V}$, the common-mode input voltage must lie between $4\,\mathrm{V}$ and $11\,\mathrm{V}$. The common-mode input voltage is defined as one-half the sum of the voltages at the $+$ and $-$ inputs to the op amp. In its linear range, the op amp maintains a virtual short circuit between these two inputs so that the common-mode voltage becomes equal to the voltage at either input. This voltage is the sum of the DC and AC components.
   In addition to having an effect on the allowable common-mode input voltage, the power supply voltages have an effect on the maximum available signal swing at the output of the op amp. For the 741, the output voltage swing is limited to be within $2\,\mathrm{V}$ of the power supply voltages. That is $V_L + 2 \leq V_O \leq V_H - 2$, where V_O is the output voltage. If an output voltage swing from $-12\,\mathrm{V}$ to $+12\,\mathrm{V}$ is required, for example, power supply voltages of $\pm 14\,\mathrm{V}$ minimum must be used.

Design Evaluation Criteria for Laboratory Design Projects

1. Design approach, philosophy, and clarity of explanation. Follow suggestions given above.

2. Achievement of design specifications.
3. Documentation of design performance.
4. Design simplicity and economics. Evaluate the cost of your design according to the following key:

   (a) Fixed 5% Resistors = 1 cost unit (cu) each
   (b) Fixed Capacitors = 4 cu each
   (c) Variable Resistors
       1. Single-turn (course) = 8 cu each
       2. Ten-Turn (fine) = 10 cu each
       3. Ganged= 20 cu each
   (d) 741 and LF351 Op Amps = 6 cu each (9 cu each for dual, 12 cu each for quad)
   (e) Small-Signal Diodes = 4 cu each
   (f) Zener Diodes = 5 cu each
   (g) Bipolar Transistors (NPN or PNP) = 4 cu each
   (h) Field-Effect Transistors = 6 cu each

Assume that your design is to be used in an application requiring large quantity production using off-the-shelf components.

Other Components: If you are considering using some special device or component, determine the cost and availability of a tested and guaranteed unity from a reliable vendor. With this information, your laboratory GTA will determine the equivalent cost units.

Point Distribution for Design Projects

Prelab Submitted on Time	5 points
Laboratory Attendance	10 points
Explanation of Design Approach & Insight Into Design Block Diagram of Circuit Derivation of Transfer Function for Each Stage Derivation of Design Equations Derivation of Half-Power Cutoff Frequencies Input and Output Impedance Considerations, etc.	10 points
Results & Presentation of SPICE Simulations Preliminary Simulation “Signed Off" in Second Week of Lab Simulation of Final Overall Circuit Presentation	5 points
Economics & Cost Analysis Justify Design Choices Total Component Cost	5 points
Presentation of Experimental Results Complete Documentation of Results Verified in Lab Comparison of Theoretical, SPICE, and Experimental	5 points

Results (In Tabular Form with % Errors)
Explanation of Results
Explanation of Measurement Techniques

Experimental Results Obtained 5 points
Accuracy with which Design Specifications are Achieved
Accuracy of Half-Power Cutoff Frequencies
Accuracy of Transfer Function Pole and Zero Frequencies
Input & Output Impedances

Conclusions 5 points
Sources of Error
Proposed Improvements to Circuit
General Comments on Whether Specifications are Reasonable
General Comments on Whether Measuring Techniques are Reasonable