Experiment 7

Mini-Project Exercise

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Now it's time to apply what you've learned and attempt to design a circuit to perform some assigned function. What follows is a "menu" of design problems; your Prelab exercise will be to design a circuit to accomplish the task assignment you've chosen from the menu. During your lab period you will assemble and test your circuit, making any slight adjustments required for the circuit to be a success. You will demonstrate your circuit's performance at the end of the lab session, and you will provide a more detailed description of its performance in your lab write-up.

THE DESIGN PROBLEM MENU

Here they are! Each subsection here will provide a performance specification for an application whose circuit must be designed (with all component values assigned) which will satisfy the performance requirements. Examine them all, and then pick one to do for your lab.

1. *Swept-frequency function generator*

Implement a function generator (square and triangle outputs) that has an output frequency which increases linearly through a factor of ten, then rapidly resets to the original lower frequency, and then starts the linear increase again, repeating this process indefinitely. The circuit must also generate a "sync" signal which is high while the output frequency is sweeping upward and low which the frequency is being reset to its starting value (see Figure 7-1).

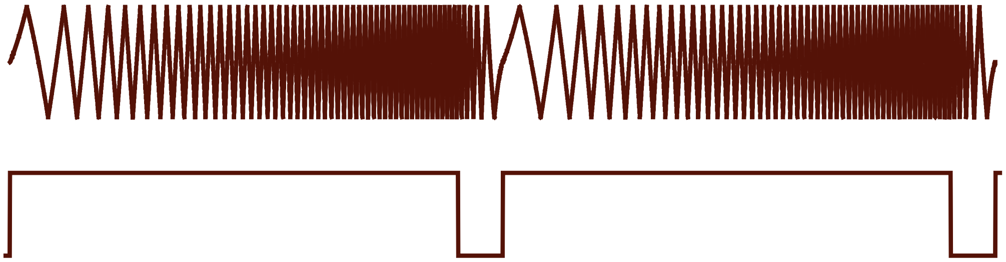


Figure 7-1: Sample output of the *swept-frequency function generator*. Top trace: generator output sweeping up through a 10-fold frequency range and then rapidly resetting to its original frequency and repeating (triangle output shown, but a sweeping square output should be available as well). Bottom trace: the accompanying "sync" signal which could be used to synchronize an oscilloscope to the output sweep.

Circuit specification details:

1. Both triangle and square outputs should be available, and their peak-to-peak amplitudes should be somewhere in the 2V to 10V range (these need not be adjustable, and the two output amplitudes need not match).
2. The sweep must cover a factor of ten in output frequency, frequency must increase linearly, and the sweep should take 1 to 2 seconds to complete. The starting (lowest) frequency of the sweep should be $\sim 100\,\text{Hz}$.
3. The time required for the circuit to reset its output frequency to its lowest value and begin another sweep should be $\ll 1$ second.
4. The "sync" output must be 4.5–5.0V when *high* (during each sweep) and 0.0–0.4V when *low* (while frequency is resetting for another sweep).

2. Amplifier with automatic gain control (AGC)

Implement an amplifier with a gain which is continuously, automatically adjusted so that its mean-square output voltage matches a control input DC voltage:

$$\overline{V_{out}^{2}} / 10\text{V} = V_{control}$$

The amplifier's gain should be adjusted slowly, taking a few seconds to settle to a new gain following a change in the input signal amplitude or a change in the control voltage setting. Similarly, the time over which the amplifier's output is averaged should be on the order of a few seconds. Otherwise, the frequency response of the amplifier should cover the *audio* range: 20Hz to 20kHz.

The resulting behavior of the circuit is that it should amplify a voice or music input signal without distortion, but the gain will be such that the output will always have the same average power (over intervals of a few seconds) regardless of the input signal power (this behavior is called *automatic gain control* or *AGC*).

Circuit specification details:

1. A nominal input voltage of 8V peak-to-peak should be near the middle of the input voltage range for effective operation of the *AGC* amplifier.
2. The *AGC* should be effective over a range of about a factor of 5 variation in the mean squared input voltage (about a factor of 2 or 3 in the input peak-to-peak amplitude).
3. The range of $V_{control}$ for effective circuit operation should be around 3V to 5V.
4. The time constant both for averaging the squared output voltage and for adjusting the circuit gain should be 3sec to 5sec.
5. The *AGC*'s input impedance should be at least 100kΩ.

Note and hint: the most effective approach to solve this problem is to generate an error signal proportional to:

$$V_{control} - \left(\overline{V_{out}^{2}} / 10\text{V} \right)$$

and then use this error signal to control the gain of the amplifier which generates V_{out}. See the section ***Circuit design hint: error signal generation and control loops*** for some comments about error signals and their uses in control loops such as the one needed for this circuit.

3. Audio tone controls

Consider the circuit shown below, an inverting amplifier whose gain is adjustable by changing the potentiometer wiper position. Moving the wiper through its range would result in an inverting gain range of $1/11 < -G < 11$; with the wiper in its center position the gain would be -1 (you should make sure you agree with these numbers).

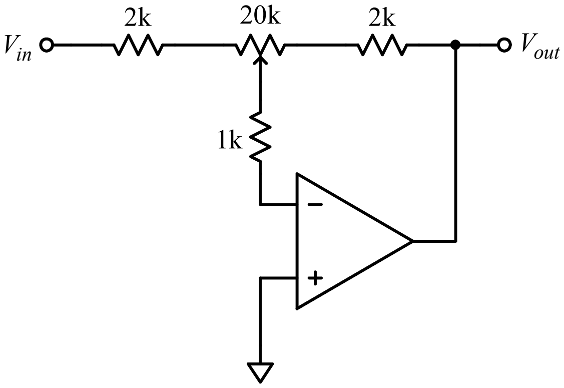


Figure 7-2: Inverting amplifier with an adjustable gain. With the potentiometer wiper all the way to the left, the gain would be −22k/2k = −11; wiper all the way to the right would result in a gain of −2k/22k = −1/11. This circuit will form the basis of a tone control; adding capacitors in strategic spots could make the gain adjustment only affect a subset of frequencies in the input signal.

By cleverly adding a couple of capacitors to this basic circuit (and maybe another resistor or two, you could use the resulting *RC* filtering to restrict the action of the potentiometer gain adjustment to only a certain range of frequencies, while for other frequencies the gain would stay at -1, independent of the wiper position. If the circuit is to be used at *audio* frequencies (20Hz to 20kHz), then the result is a tone control (e.g. *Bass* or *Treble*). An example of the frequency response of a modified circuit for a bass control is shown in Figure 7-3.

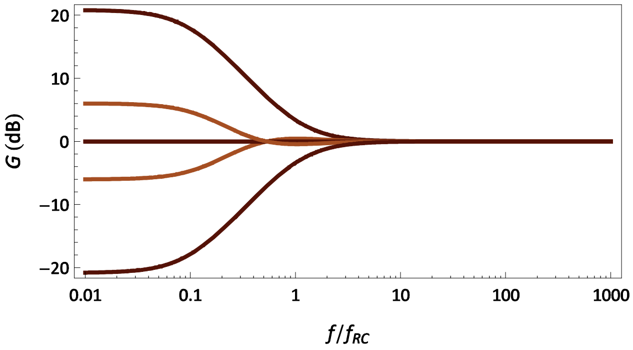


Figure 7-3: An example of a *Bass* (low frequency) *tone control* based on the circuit of Figure 7-2 with two capacitors added to restrict the action of the potentiometer to only affect a range of frequencies. For a typical bass tone control, f_{RC} would be 220Hz or so. A Treble control would be designed to affect frequencies above an f_{RC} of about 1800Hz. The curves shown are for *full boost* and *full cut*, 30% *boost* and *cut*, and potentiometer centered (no effect on the frequency response).

Your design task is to develop modifications to the circuit in Figure 7-2 to create a bass tone control or a treble tone control. A truly clever circuit could incorporate potentiometers for both functions into a single op-amp inverting amplifier circuit. The gain of the circuit when the potentiometer wiper is centered should be −1 at all frequencies in the audio range specified above. If you attempt a design which incorporates both bass and treble control in a single amplifier, then you may find it wise to use different resistance values for the two potentiometers. In this case the available potentiometer values are 1k, 20k, and 100k.

4. Window comparator

Design a comparator-type circuit which outputs a *high* level while its analog input signal lies between two adjustable threshold voltages (an *upper* and a *lower* threshold, which define the comparator's *window*), and outputs a *low* level when the analog input signal voltage lies outside the voltage window defined by the two thresholds.

The comparator should also respond to a *gate* input such that it will only output a high level signal in response to the analog input voltage level *while the gate input is high*; otherwise the output will remain low even if the analog input signal is within the comparator's voltage window. This gate input should have two additional features: it should incorporate hysteresis (implement using a Schmitt trigger), and it should act as though the gate were always high (the gate is *open*) if no external signal is attached to the circuit's gate input.

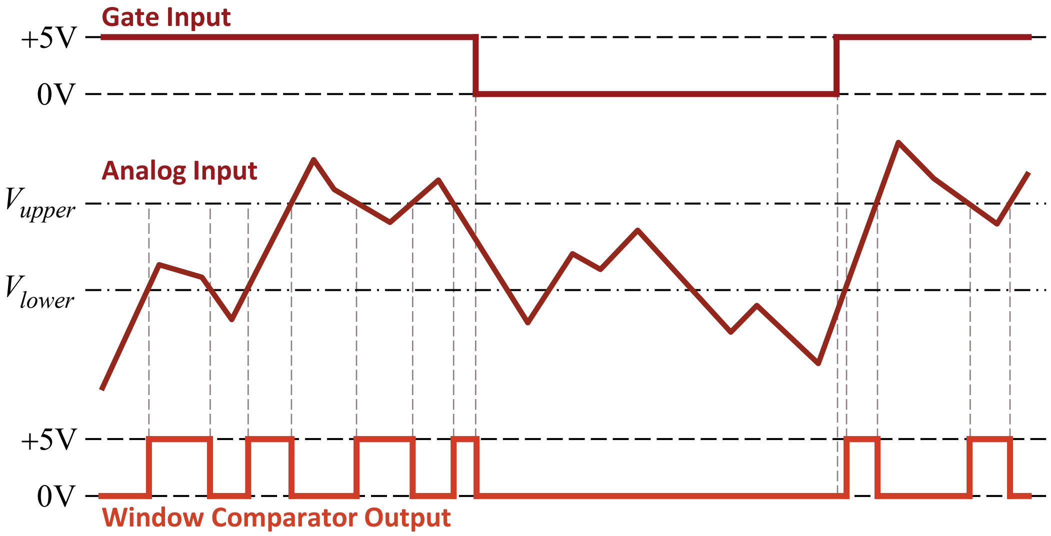


Figure 7-4: Sample *window comparator* behavior. The comparator's output is active only while its *Gate* input is high (or disconnected). When active, the comparator's output is high whenever its analog input signal voltage falls within the window defined by two adjustable thresholds, V_{lower} and V_{upper}.

Circuit specification details:

1. The valid analog signal input range should be at least −10V to +10V. The upper and lower thresholds should be adjustable to any two voltages within this range.
2. The comparator output must be 4.5–5.0V when *high* and 0.0–0.4V when *low*.
3. The gate input should incorporate hysteresis on its input such that the gate signal must go above +2V when going from *low* to *high* (to enable the comparator output), and it must go below +1V when going from *high* to *low* (to disable the comparator output).
4. The valid gate input voltage range should be at least −10V to +10V, but the hysteresis thresholds described above will determine what voltage levels define a high and low gate input (the 0V and +5V levels for the gate input shown in Figure 7-4 would meet the hysteresis threshold requirements, but are not mandatory).
5. Both the analog and gate inputs should have an input impedance of at least 100kΩ.

5. Pulse-width modulator and demodulator

Design a circuit which will accept an input signal and use its instantaneous voltage value to control the *duty cycle* (symmetry) of a high-frequency square-wave signal generated by your circuit. The duty cycle should be 50% when the input signal is 0V; the duty cycle should increase toward 100% (output always high) as the input signal becomes more positive and decrease toward 0% (output always low) as the input signal becomes more negative. This variation in the duty cycle of a high-frequency square-wave in response to an input signal is called *pulse-width modulation* (Figure 7-5).

You also must design a circuit which will accept a pulse-width modulated signal (such as the upper trace in the left-hand image in Figure 7-5) and *demodulate* it to reproduce the original

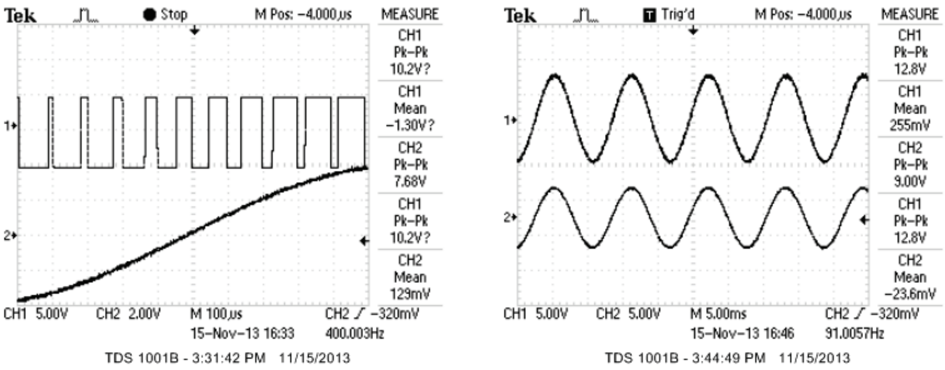


Figure 7-5: *Pulse-width modulation*. Left: the input signal level (CH2, lower trace) controls the *duty cycle* of a high-frequency, square-wave *carrier* output signal (CH1, upper trace); the *frequency* of the carrier is not affected by the input signal. Right: the *demodulated* carrier signal (CH1, upper trace) *recovers* (reproduces) the original input signal (CH2, lower trace).

input signal source (demodulated output shown in the upper trace of the right-hand image in Figure 7-5).

Circuit specification details:

1. The valid analog signal input range which will not *saturate* the modulated square wave (duty cycle reaches 100% or 0%) should be at least −8V to +8V.
2. The square-wave carrier frequency should not change as long as the input signal does not saturate it (see above requirement). Only the output duty cycle should change, not the output frequency.
3. The square wave frequency should be at a fixed value somewhere in the range of 20kHz to 80kHz.
4. The demodulated output should faithfully reproduce the input signal (not show significant distortion) for any input signal with a frequency of less than 1/20 of the carrier (square-wave) frequency and an amplitude of less than 90% of the saturation amplitude. A residual bit of the carrier frequency may show up in the demodulated output as a slight ripple in the output (less than 5%).

Note and hint: no multipliers, diodes, or transistors should be needed for this circuit; only op-amps, resistors, and capacitors. The demodulator is particularly simple.

Circuit design hint: error signal generation and control loops

A common circuit design problem, especially in such applications as industrial process control, automatic stability and guidance systems, or signal frequency or amplitude control, is to design a circuit so that some characteristic of a dynamic system output is automatically, quickly, and precisely adjusted by the circuit to match some value determined by an independent control parameter input to it. The field of study of the most effective way to implement systems to meet this requirement is part of the subject known as *control theory* (Caltech even offers an undergraduate minor in this subject: Control and Dynamical Systems). For example, the use of negative feedback to ensure that an op-amp's output is a linear function of its inputs is an implementation of a basic method studied by students of control theory.

Consider the abstract representation of a simple *control loop* shown in Figure 7-6. The control loop continually monitors the system's output by comparing it to a control *set-point* input. The difference in the set-point and the circuit output values becomes the *error signal* which is used to generate a *control command* to adjust the system's behavior. The object of the loop is to drive the error signal toward 0 in a *prompt and well-controlled manner* until the error is acceptably small.

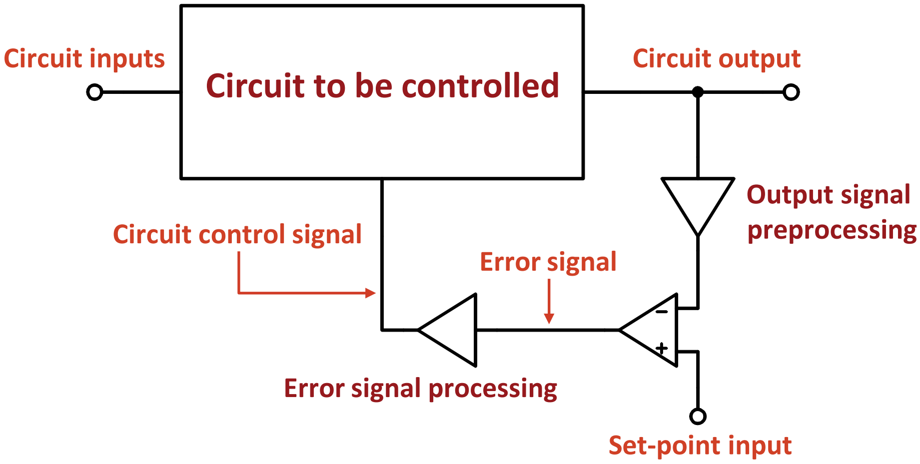
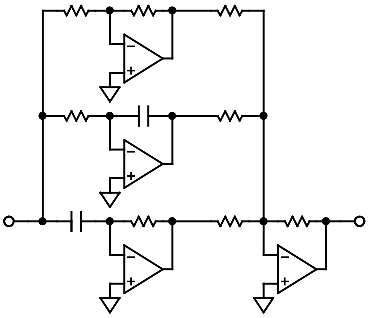


Figure 7-6: An abstract representation of a simple *control loop*. The main circuit or process to be controlled produces some output which is a function of its inputs; this function is adjusted based on the value of the loop's *circuit control signal*. The control loop monitors the circuit's output by comparing it to a *set-point*; the difference in the set-point value and the circuit output becomes an *error signal*. The error signal is processed by amplifiers and filters to adjust the circuit control signal until the error signal becomes acceptably small.

For the control loop to be effective, the error signal must be properly generated and carefully handled; even once it has succeeded in driving the error to a sufficiently small value, changes in the system's inputs, perturbations to and noise in the system itself, and changes in the set-point input value will require the control loop to continue to adjust the circuit control signal. The control loop may fail by: (1) generating control signals of insufficient range or quickness to reduce the error signal enough to control the circuit's output error; (2) commanding the system's adjustments in the wrong direction, so that the error grows rather than shrinks; or (3) overcorrecting the system by making adjustments which are too large and too slow, so that the error overshoots and oscillates about 0 rather than converging on 0 with time.

Avoiding these errors in the control loop design requires careful consideration of how you handle the error signal and control signal calculations. As shown in Figure 7-6, some preprocessing of the circuit output monitor (such as scaling or filtering) may be required before it is subtracted from the set-point value to generate an error signal. This error signal in turn may require significant amplification, filtering, and other signal processing actions in order to convert it into the control signal required to adjust the system's performance.

A common error signal processing system is called a *PID* loop, for *Proportional-Integral-Differential* control: the error signal is amplified, integrated, and differentiated by parallel op-amp circuits. These circuits' outputs are then added by a summing amplifier; the weight of each term in the sum is then adjusted to provide the best control loop response to changes in the system or the set-point (Figure 7-7).



$$V_{out} = \left(k_P + k_I \int dt + k_D \tfrac{d}{dt}\right) V_{in}$$

Figure 7-7: A PID operator circuit commonly used to process an error signal. The weights of the individual terms may be adjusted by selecting appropriate values for the input resistors in the final summing amplifier.

PRELAB EXERCISES

1. Carefully read the Experiment 8 notes, particularly the section titled **DEVELOPING THE SYSTEM DESIGN**. Come up with an idea for your final project and develop an initial performance specification for it. Draw a tentative system block diagram of the signal flow through your circuit and the operation each sub-circuit must perform. Use this to make a rough estimate of the numbers of op-amps, multipliers, timers, other ICs, and/or transistors you may need to complete the project.

2. Pick one of the design problems from the menu of choices presented and design a circuit that will perform that task. Provide a complete schematic with component values assigned, using only the types of op-amps, multipliers, and other circuit elements you've used in previous experiments, except that you may include potentiometers in your design to set the variable parameters the circuit may require (such as the audio tone control design task, or the adjustable thresholds in the window comparator design task).

Available potentiometer values are 1k, 20k, and 100k.

LAB PROCEDURE

Implement and test your circuit

Construct and test the circuit you've designed to satisfy the requirements of your chosen design problem. You may use the components preinstalled on the analog trainer circuit board in addition to components you need to install in the breadboard areas.

Practice good component layout techniques when you use the breadboard area: identify the rails you'll use for power supply voltages and ground; determine the most effective positioning of the ICs on the breadboard so that the wiring will be clean and easy to check; double and triple check the pin number assignments shown on the IC data sheets; make the power supply and ground connections to each IC before installing other components; add IC pin numbers to your schematic so that you can quickly add components and check you connections.

Lab results write-up

As always, include a sketch of the schematic with component values for each circuit you investigate, along with appropriate oscilloscope screen shots. Make sure you check the performance of your circuit against each of the design problem specifications.