Class D Amplifiers

Acknowledgements: Developed by Palmerino Mazzucco, Faculty of Mesa Community College, Mesa, Arizona. Special thanks to Electronic Workbench for providing this simulation as a stand-alone activity.

Special Notes: This simulation should be completed after the section titled Class D Switching Amplifiers and the Class D Switching Amplifiers Drill Down. It should be completed before starting the Class D Switching Amplifiers Lab.

Approximate Time Required: 3 hours

Simulation Summary: The purpose of this interactive simulation is to prepare you for the class D amplifier hands-on laboratory. This circuit simulation lab introduces the operating characteristics typical of a class D amplifier and is provided by Multisim 7 software. The simulation describes smaller manageable block level discussions of the (a) Analog and Triangle Wave Input Generators, (b) Analog Comparator, (c) Power MOSFET Output, and (d) Low Pass Filter Output Modules. Improvements in current day MOSFET and manufacturing technology have made the integration of class D amplifiers into a single integrated circuit possible. Studying the operation inside these fully integrated circuits helps in understanding what is happening on the output side of the amplifier microchip.

Simulation Goal: Observe the operation of a representative class D amplifier circuit and perform measurements related to its operation.

Learning Objectives

1. Explain switching amplifier operation at the component level.
2. Determine the ratio of the analog input signal to the triangle wave input.
3. Describe the PWM pattern of a class D amplifier.
4. Determine the duty cycle of a circuit.
5. Compare the output of the simulation circuit when the input parameters are changed.

Grading Criteria: Your lab grade is determined by your performance on the simulation and the lab questions.

Simulation Preparation

1. Print this entire procedure to use as a reference, schematic, and workbook while completing the simulation.
2. Read the Introduction (below).
3. Review the Simulation Procedures (below).

Software Alert: When performing circuit simulations, failing to read and follow directions exactly can result in incorrect circuit operation and data measurements. For instance, if you fail to stop or pause the circuit at the appropriate times and leave circuits running, functions within Multisim 7 may become inoperative.

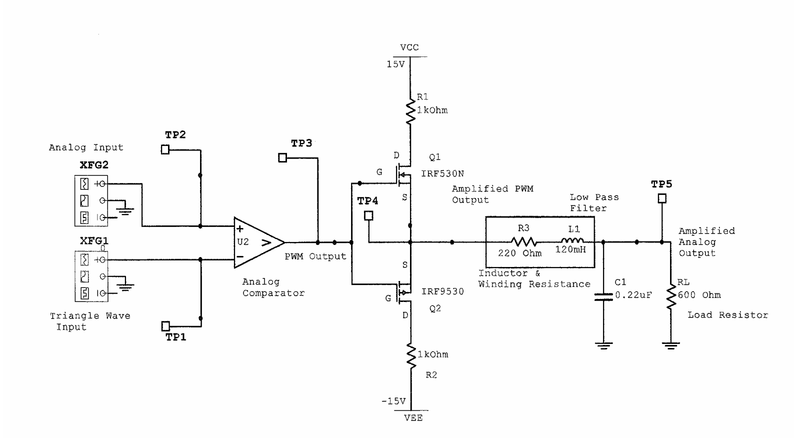
Introduction

In the past, class D amplifiers were considered inferior to many other amplifiers configurations and limited to lower bandwidth applications such as telephones and public address (PA) systems. Advances in semiconductor devices and consumer demand for higher battery power performance resulted in the advancement of class D technology.

Over the last several years, advances in semiconductor fabrication processes have made fully integrated class D amplifiers possible. The integration of analog circuitry with fast-switching, high input and low output impedance MOSFET (Metal Oxide Semiconductor Field Effect Transistor) devices has furthered the evolution of the class D amplifier. Discrete output power stages and supporting circuitry are integrated in one chip. The resulting class D device is an effective and highly efficient solution for battery powered amplifier applications.

Often, amplifiers are used in the audio frequency range (20 Hz to 20 kHz) where a signal wave is amplified to higher power levels. This type of amplifier, called an audio power amplifier, is optimized to drive low-impedance loads such as a headphones and stereo speakers. There are several amplifier topologies that amplify audio signals but the popularity of class D continues to rise due to its numerous advantages.

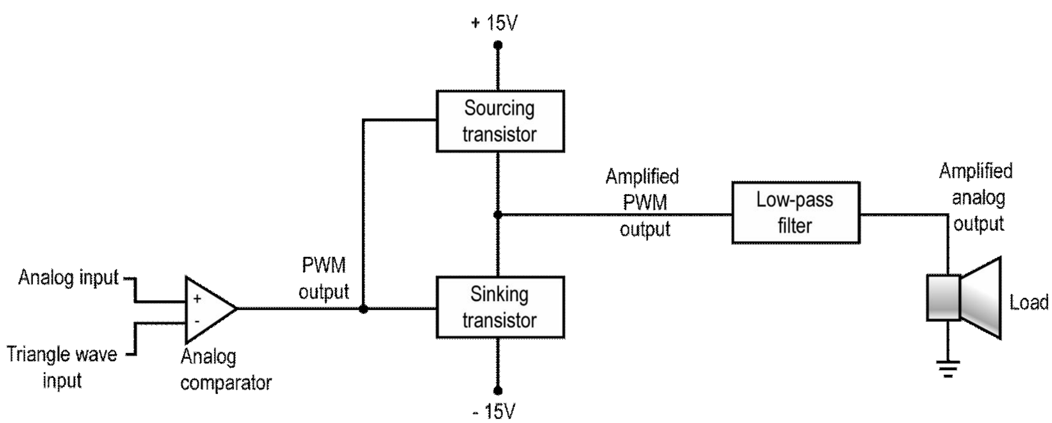
The class D amplifier used in this simulation can be divided into the following blocks or modules: (a) Analog and Triangle Wave Input Generators, (b) Analog Comparator, (c) Power MOSFET Output, and (d) Low Pass Filter Output Modules.



Class D Amplifier Schematic

Analog and Triangle Wave Input Generators Module

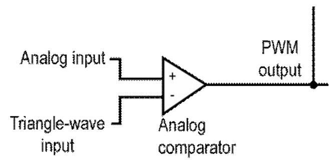
Amplifiers process input waveforms in the form of music, video, audio, or data that are output to the next system stage or delivered to a load such as a speaker. Our simulation input waveform will be a sine wave tone of a given frequency in the audio range. The class D amplifiers job will be to recover the sine wave tone at its output. In this simulation, the audio tone is the analog input in the schematic and the block diagram.



Class D Amplifier Block Diagram

A triangle wave input controls the pulse width modulation (PWM) operation of the class D amplifier and sets the sample rate of our amplifier. In many class D applications, the analog input signal is often music or speech operating in the 20 Hz to 20 kHz frequency range. For proper signal recovery at the amplifier output, the pulse width modulating triangle wave generator circuit must deliver a sampling rate a minimum of 10-12 times the highest input frequency to accurately reconstruct the analog input to its original form. Integrated class D amplifier circuits on the market today that are used in audio applications provide internally generated sample rates of 240 kHz or greater (20 kHz x 12 = 240 kHz). If higher input frequency signals are expected, the sample rate must be raised accordingly to ensure minimum signal distortion at the amplifier output.

Analog Comparator Module

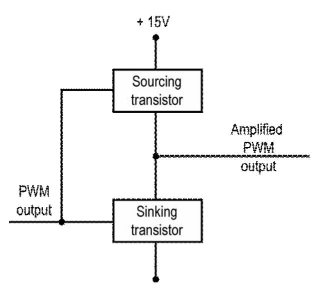


Analog Comparator

The analog input drives the positive (+) input of the comparator circuit while the triangle wave input is connected to the negative (–) input of the comparator. Comparator operation is rather simple. Its function is to compare the voltage levels applied between the input terminals. The analog input sinusoid is compared to the triangle wave. The comparator circuit switches its output HIGH or LOW based on the amplitudes of the two input signals. When the analog input amplitude exceeds the amplitude of the triangle wave, the output of the comparator switches HIGH or ON. It remains at the comparators HIGH voltage saturation level until the analog input sinusoid amplitude drops below that of the triangle wave. In effect, the comparator produces an output pulse with its width in duration proportional to the instantaneous voltage amplitude of the analog input tone at the particular sample time. As you might expect, if the sampling rate of the triangle wave were too slow, the sampled analog input tone could change several times before the next sample opportunity. This could result in incorrect instantaneous amplitude to pulse width conversion and signal distortion at the output of the class D amplifier.

Since the triangle wave frequency is selected based on the highest incoming analog input frequency, its conversions are consistent and linear from sample to sample. The relationship of the incoming analog input tone to the variable pulse widths produced in this system is perfectly linear if the triangle wave is stable.

Power MOSFET Output Module



Power MOSFET Output

The PWM output of the comparator connects to the gates of two complementary E MOSFETs (Enhancement Mode MOSFETS) which act as output transistors to drive the load (600 ohm resistor).

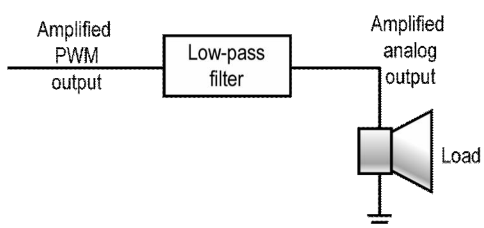
At the output of the comparator, the PWM signal is driven from ON to OFF repeatedly to trigger the operation of each MOSFET one at a time. The PWM output of the comparator swings quickly and freely between $+V_{CC}$ (+15 volts) and $-V_{EE}$ (-15 volts). MOSFET outputs offer fast switching speeds allowing fast transition between the ±15 volt power rails of the bipolar supply.

Each MOSFET operates as a switch and spends very little time operating in the power consuming linear region. Switching speed is the main reason for choosing MOSFET devices over bipolar junction transistors (BJT) to perform this function.

The circuit consists of two E MOSFET devices: a P channel MOSFET (IRF9530) and an N channel (IRF530N) MOSFET. As designed, the P channel device triggers with a negative gate to source voltage ($-V_{GS}$ bias), while the N channel MOSFET triggers with a positive gate to source voltage ($+V_{GS}$ bias). The comparator output transitions between ± 15 volts when operating. This ensures the PWM signal triggers the V_{GS} turn on requirements of each MOSFET at the appropriate time.

It is important to note, the exact implementation of the comparator function, MOSFET configurations, and power supply levels used in the switching function vary depending on application, power supply availability, and requirements. Also, many applications use fully integrated class D amplifier chips which compress much of the circuit functionality into one device.

Low Pass Filter Output Module



Low Pass Filter Output Module

The final stage of the class D amplifier is the low pass filter circuit. Most class D amplifiers utilize a Butterworth filtering scheme for simplicity and low cost. Many fully integrated class D amplifiers on a chip integrate the filter into the chip or make load characteristics part of the filtering scheme to save cost, parts, and complexity.

Critical to the low pass filter design is the selection of components that sufficiently suppress higher switching frequencies while passing the analog input signal. Some residual carrier switching frequency is always present after the filter but cannot be heard by humans at the applied higher frequencies. In addition to a good filter, high frequency decoupling capacitors are important at power supply outputs and across all integrated circuits. Good high frequency layout techniques are used to minimize electromagnetic interference (EMI) generation in class D amplifiers. As power levels rise, switching currents traveling along high impedance circuit traces can generate annoying electrical noise.

The output filter is essential for low pass filtering of the 1 kHz tone we use in simulation because it averages the carriers varying pulse width duty cycle into the original inputted content while attenuating carrier switching frequencies. Successful implementation of the low pass filter stage is very important and essential in maintaining maximum efficiency of class D amplification.

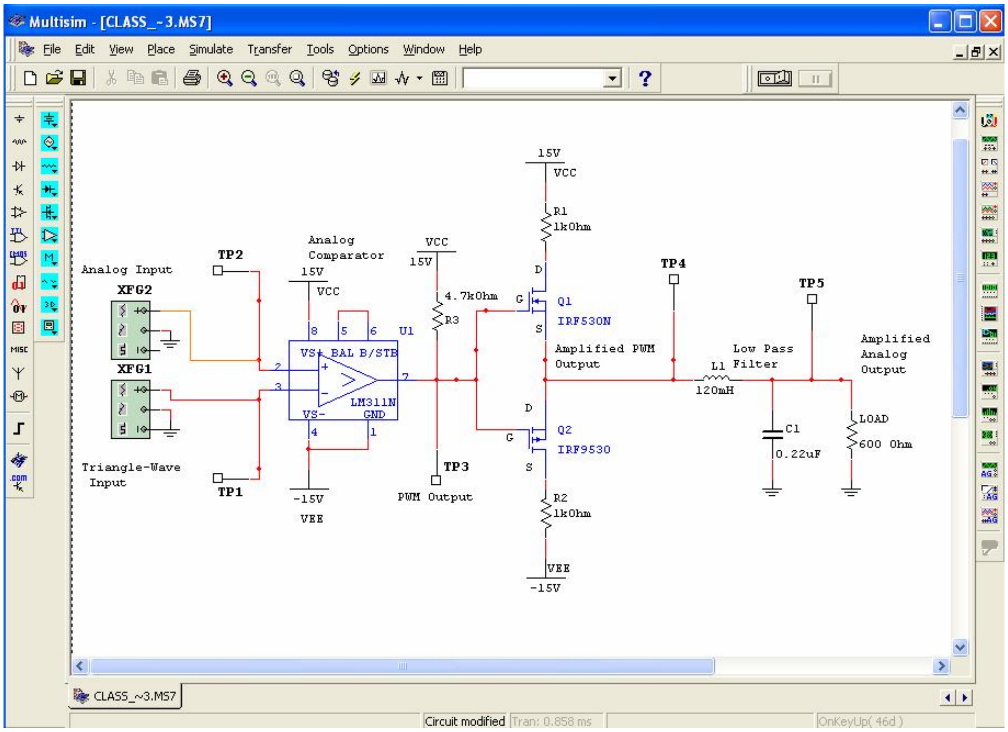
Many class D amplifier applications involve operation in the audio band (20 Hz to 20 kHz) in hearing aids, music, or voice applications. Dynamic range is attained by carrier switching frequency selection. A factor of at least 10 times the upper audio cutoff frequency is recommended. Thus the minimum triangle wave switching and sampling frequency for audio applications would be about 240 kHz. The higher the sample rate, the more “samples” of resolution become available for signal reproduction at the filter output. At rest (0 volt input to the comparator), the duty cycle of the switching frequency is 50%, or evenly divided, between ON and OFF.

Simulation Procedures

NOTE: The schematic, block diagram, lab questions, and table are at end of this document.

Using Multisim

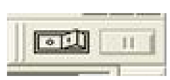
1. Download the Multisim demo from the WRE Module Learning Resource tab.
2. Open the file called Class_D.



   a. A simulation circuit is in the center of the screen.

NOTE: This is an example only. The circuit you are using is at the end of this procedure.

   b. The Run/Stop and Pause/Resume simulation buttons are on the tool bar near the Help (?) button. Run/Stop is on the left and Pause/Resume is on the right.



   c. The instrument toolbar is on the right border. As you move your mouse over the instrument, the name should appear. For this simulation, you will use the function generator, the two channel oscilloscope, and the four channel oscilloscope shown here.

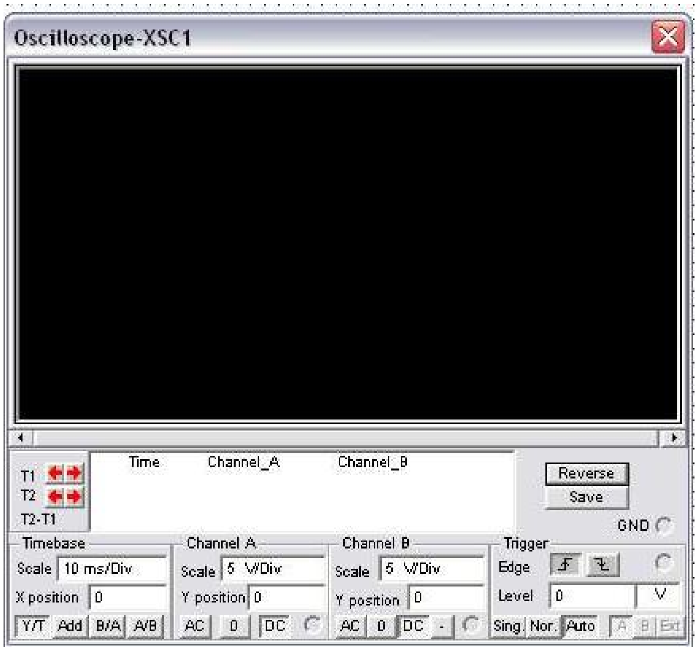
Function Generator, 2 Channel Oscilloscope, 4 Channel Oscilloscope

d. Double click on an instrument to transfer it to the circuit. Use your mouse to place it in position.

NOTE: For this simulation the function generator is already placed in the circuit.

e. Connect the wires by placing the mouse over the end of the wire connection for the instrument. A small bull's eye symbol will appear when you are in the correct position. Use your mouse and drag the wire it to the correct terminal point. Click once to connect.

f. To use an instrument, place your mouse over the instrument and double click. This will open the view like the oscilloscope shown here.

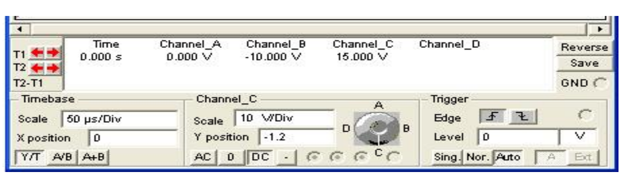


g. The slide bar below the oscilloscope screen can be used to move and adjust the wave image in the screen when the simulation is paused.

h. To set or change values, positions, or other parameters, place your mouse over the entry you want to change. When the hand appears, click once and up/down arrows will appear to allow you to scroll through preset values. Be sure to note the measurement units.

i. To get the most accurate reading, adjust the scale so the wave is as large as it can be without clipping.

j. On the four channel oscilloscope, a knob is used to switch from one channel to another. Place your mouse over the position indicator (white line pointing to C in the example below) on the knob. When the hand appears, click once and hold the mouse down as you move the indicator to the correct channel. Change the parameters for that channel. Rotate the knob and enter parameters for the other channels as needed.

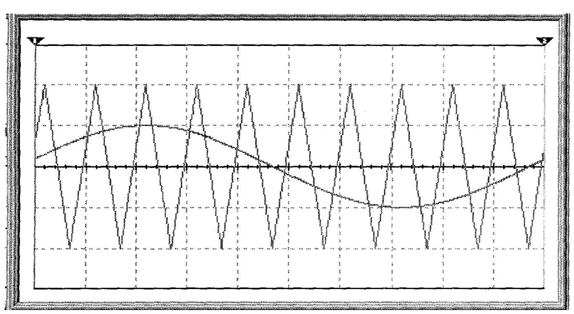


Analog and Triangle Wave Input Generators Module

3. Review the section on the Analog and Triangle Wave Input Generators in the introduction.
4. Double click the functional block called “Analog Input” on the circuit to reveal the pre-loaded configuration parameters for this device.
5. Record the analog input configuration parameters in the correct column of Table 1.

Note: The simulation uses peak voltage (V_p) for the amplitude.

6. Close the analog input configuration parameter window.
7. Double click the functional block called “Triangle Wave Input” to reveal the pre-loaded configuration parameters.
8. Record the triangle wave configuration parameters in the correct column of Table 1.
9. Close the triangle wave configuration parameter window.
10. Examine the parameters you have entered in Table 1. You should notice a 10X difference between the analog input signal and the triangle wave input signal. The 10X or greater sampling frequency is a requirement of the comparator and the triangle wave generator
11. Answer questions 1 and 2 before proceeding.
12. Drag a two channel oscilloscope onto the simulation window and connect Channel A to TP2 (Analog Input) and Channel B to TP1 (Triangle Wave Input).
13. Double click the oscilloscope graphic on the circuit to bring the oscilloscope simulation graticule into view.
14. Adjust the Channel A and B scale factors of the oscilloscope to 5v/div and the timebase scale factor to 100µs/div.
15. Activate circuit simulation by pressing the Run/Stop switch found in the top portion of Multisim.
16. After the screen fills with simulation cycles, stop the display by pressing the Pause/Resume button next to the Run/Stop button. Your simulation should look similar to the screen below. Use the slide bar to show a complete sine wave. Each waveform should be at the zero reference line of the grid allowing them to ride on top of each other for comparison.



17. Record your findings for the output function (sine, triangle, or square wave), frequency, and voltage levels of Channel A and Channel B under the appropriate simulation columns of Table 1. If your measurements are correct, both columns of data under “Configuration Parameters” should be similar. The same is true for the “Simulation Measurements” columns.

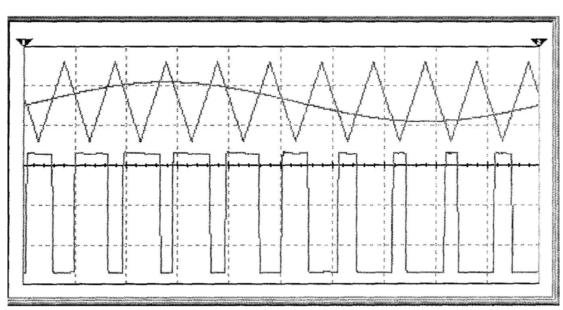
18. Count the number of triangle wave cycles (Channel A) that occur for one cycle of the sine wave input (Channel B). By now you should realize the ratio should be 10:1.
19. Press Run/Stop to stop the simulation.

Analog Comparator

20. Review the section on the Analog Comparator Module in the introduction.
21. Right click on the two channel oscilloscope and select cut to remove it from the circuit.
22. Double click on four channel oscilloscope and drag it into position.
23. Connect Channel A to TP2 to monitor the analog input line.
24. Connect Channel B to TP1 to view the triangle wave input.
25. Connect Channel C to TP3 to view the PWM output from the comparator.
26. Double click on the oscilloscope graphic to open.

Note: Review the section at the beginning of the procedure as needed for entering oscilloscope parameters.

27. Set the oscilloscope timebase to display 200µs div.
28. Set the oscilloscope vertical sensitivity at 10 v/div for all three channels.
29. Set the Y-position axis for each channel as follows:
    a. Channel A (analog input): +1.6
    b. Channel B (triangle wave input): +1.6
    c. Channel C (comparator pulse width modulator output): -1
30. Press the Run/Stop button to activate the simulation.
31. When the waveforms fill the screen, freeze the circuit by pressing the Pause/Resume button.
32. Observe the comparator square wave output voltage. This is the PWM output generated by the analog input signal and the triangle wave signal. This controls the ON/OFF switching of the MOSFET transistors in the next stage. The comparator is pre-set to operate from a bipolar ±15 volt supply. The positive rising and falling edge of each PWM signal turns ON MOSFET Q1 while the negative rising and falling edge turns ON MOSFET Q2. Your screen should look similar to the view shown here.



33. Observe the relationship between the analog input and the duty cycle or wave shape of the PWM signal. In particular, observe the pulse widths from the comparator output and how they relate to the sine wave.
34. Vary the analog and triangle wave voltage levels and observe the relationship of the comparator output and the sine wave. Remember to always keep the triangle wave voltage higher than the analog input voltage or the circuit may not operate correctly.
35. Press Run/Stop to stop the simulation.
36. Answer questions 3 and 4 before proceeding.

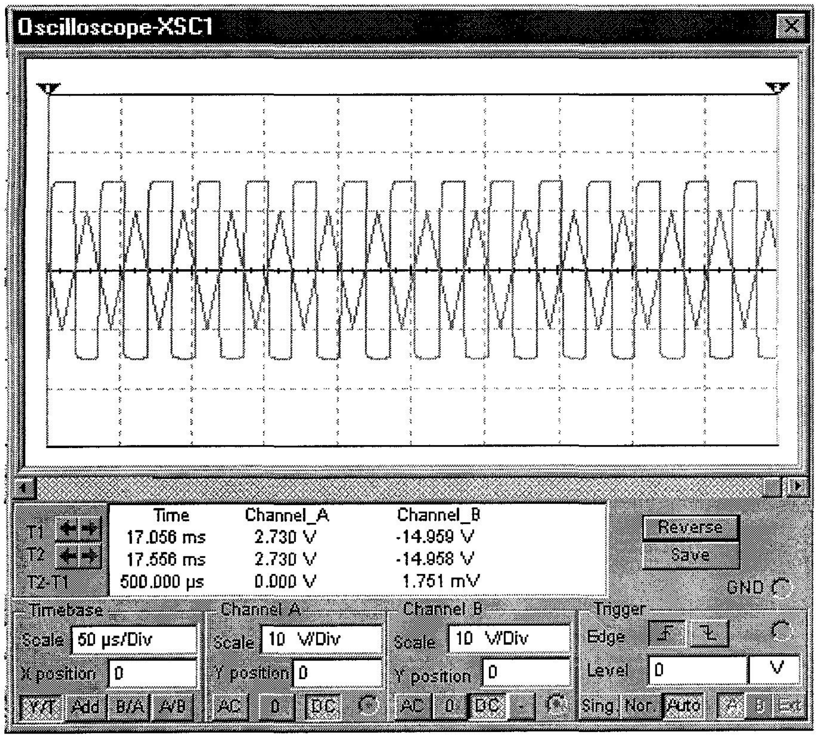
Power MOSFET Module

37. Review the section on the Power MOSFET Module in the introduction.
38. Replace the four channel oscilloscope with the two channel oscilloscope.
39. Connect Channel A oscilloscope test probe to TP 2 (analog input).
40. Connect Channel B oscilloscope test probe to TP4 (amplified PWM output).
41. Press Run/Stop to start the simulation.
42. Double click on the oscilloscope to view the window.
43. Adjust the timebase and oscilloscope channels A and B so that two complete waves and full signal amplitudes are in the viewing range.
44. Observe how the analog input signal voltage peaks and the PWM output pulses of the MOSFET driver circuit are the widest representing the maximum ON time while the time pulses narrow as the analog input reaches its negative maximum. It is the pulse width ON time that drives the filter stage of our class D amplifier where the original analog signal is recovered and delivered to the load.
45. Complete question 5 before proceeding.
46. Review the section on the Low Pass Filter Output Module in the introduction.
47. Verify class D amplifiers produce PWM switching frequencies with a 50% duty cycle with a 0 volt input.
    a. Double click the functional block called “Analog Input” on the circuit to reveal the pre-loaded configuration parameters for this device.
    b. Set the Amplitude (V_p) to 0.001 mV. This will effectively disconnect the analog input signal and force the + terminal of the comparator to ground. The triangle wave will rise and fall switching the comparator at the crossover voltage to control the switching of the MOSFET stage.

Note: You can type in the value instead of using the arrow keys.

48. Connect Channel A of the two channel oscilloscope to TP1 and Channel B to TP3 (PWM output).
49. Adjust the oscilloscope timebase to 50µs, and both Channel A and Channel B for 10v/div.
50. Change the Y position control of each channel to 0 so the waveforms share a common reference point on the scope.

51. Press Run/Stop to start the simulation.
52. Press the Pause/Resume button to pause the simulation. The image should look similar to the one shown here.



53. Answer question 6 and 7 before proceeding.

Low Pass Filter Output Module

54. Press Run/Stop to stop the simulation.
55. Double click the functional block called "Analog Input" on the circuit to reveal the pre-loaded configuration parameters for this device.
56. Set the Amplitude (V_p) to 5 volts.
57. Connect the oscilloscope probe for Channel B to TP 5(Amplified Analog Output).
58. Adjust the oscilloscope timebase to 500µs and both channel A and B to 2 v/div. The Y position should be set to 0 for each both channels.
59. Press the Pause/Resume button to resume the simulation.
60. Answer Question 8 before proceeding.
61. Press Run/Stop to stop the simulation.
62. Complete the Post Simulation Questions.

Simulation Questions: Table 1 and questions 1 through 8 should be completed during the simulation.

Table 1.0 Amplifier Input Configuration:

Parameters	**Analog Input (XFG2)** **(Video, audio etc.)**		**Triangle Wave Input (XFG1)**	
	Configuration Parameter	Simulation Measurement (Channel A)	Configuration Parameter	Simulation Measurement (Channel B)
Waveform				
Frequency:				
Amplitude V_p:				

1. From the data recorded in Table 1, what is the frequency ratio of the triangle wave to analog input?

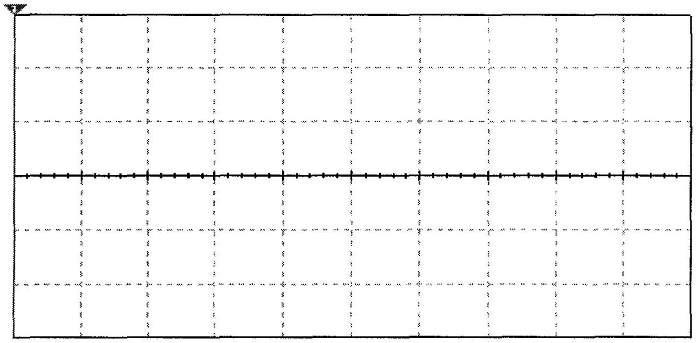
2. Is the predefined triangle to analog input ratio adequate? Why/Why not?

NOTE: If you are not sure, go back over the theory section of "Analog and Triangle Wave Input Generators Module" before moving on.

3. Describe what you observe.

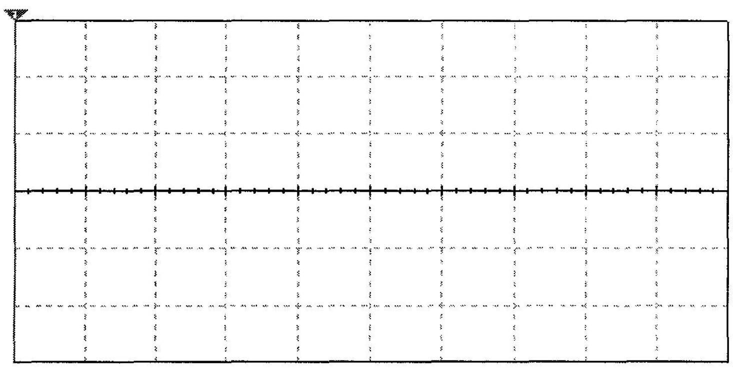
4. What would the PWM signal look like if the triangle wave were set to a higher frequency, say 20 kHz (double) or higher?

5. Draw a picture of TP1 vs. TP4 as seen on your oscilloscope screen.

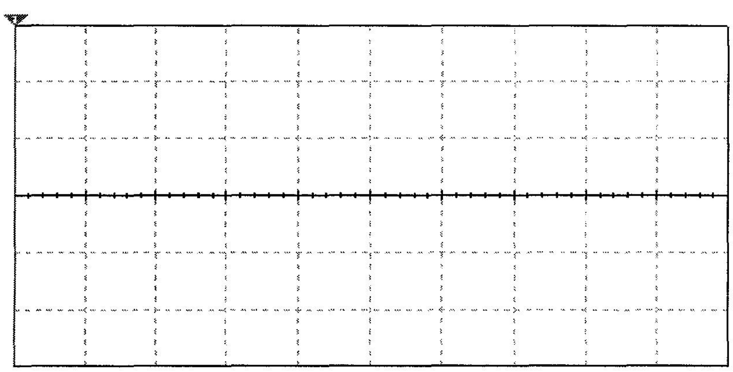


6. Simulate the circuit and observe the oscilloscope output. What is the duty cycle percentage? Is it what you expected from the theory presented?

7. Draw a picture of the triangle wave and PWM output you see on the oscilloscope screen. Is it what you expected?



8. Draw a picture of output you see on the oscilloscope. What is the oscilloscope displaying? Why is the amplified output so raggedy looking? Refer to your schematic and block diagram as required.



Post Simulation Questions: These questions should be completed after the simulation.

1. Describe each of the following modules used in the simulation.
   a. Analog and Triangle Wave Input Generators:

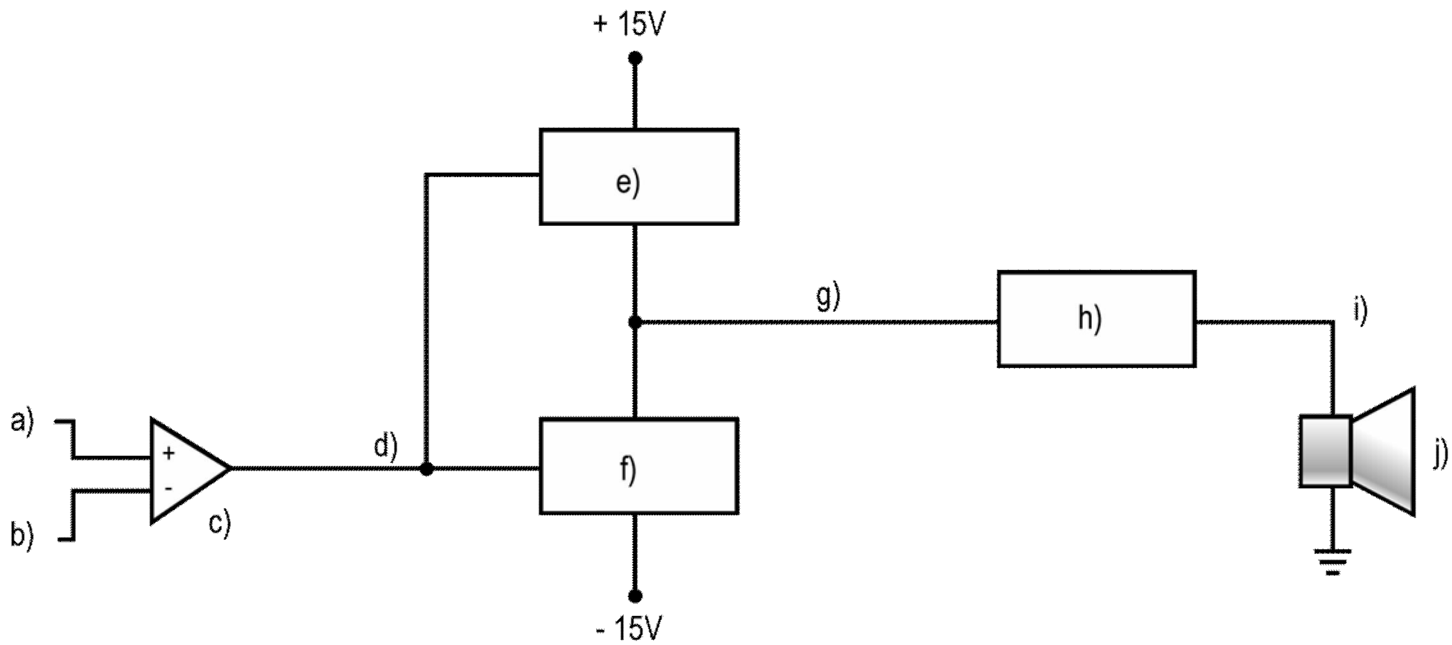
   b. Analog Comparator

   c. Power MOSFET

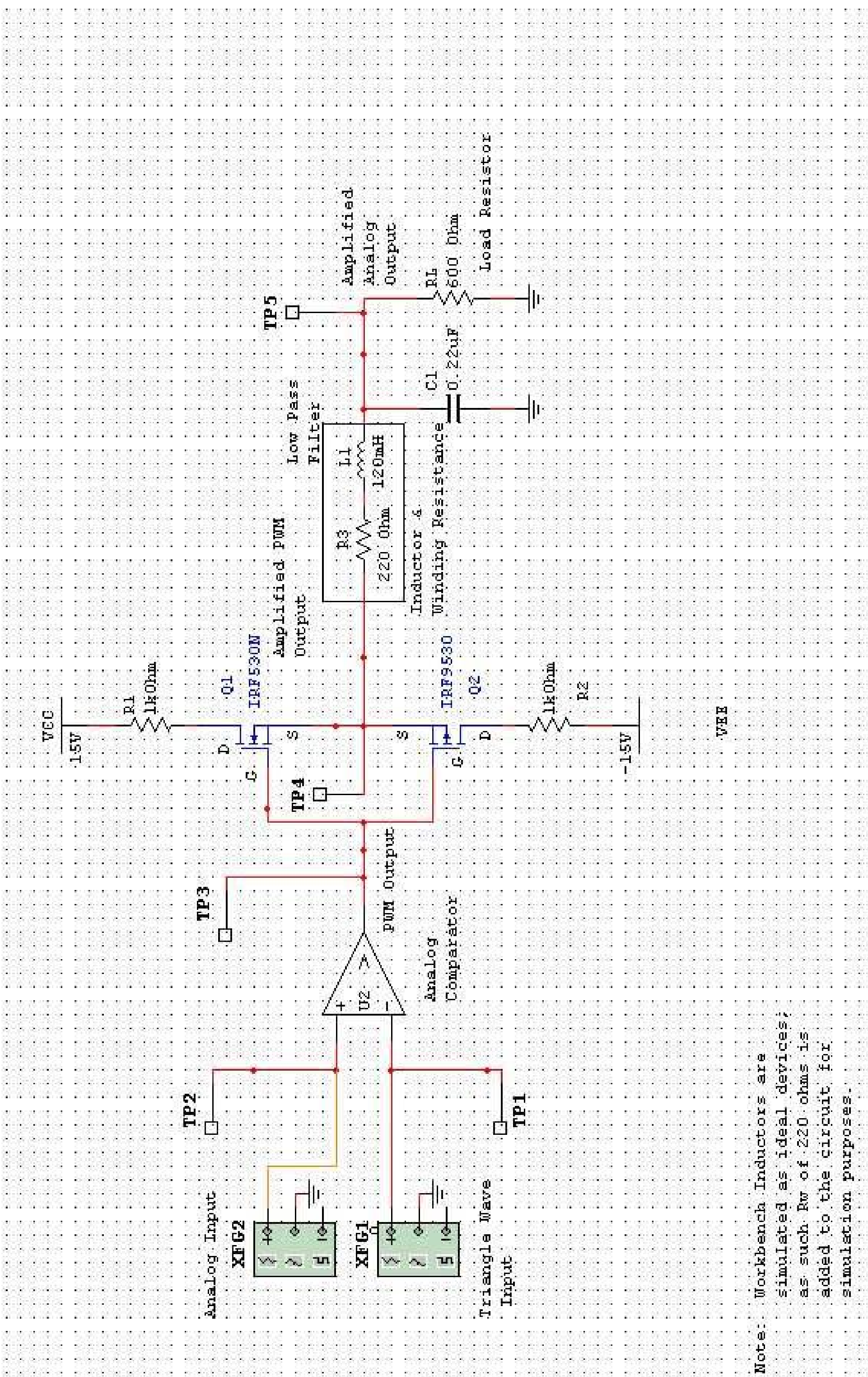
   d. Low Pass Filter

2. What would happen if the sampling rate of the triangle wave were too slow?

3. Identify the following components on the block diagram.
   Amplified analog output
   Amplified PWM output
   Analog comparator
   Analog input
   Load
   Low pass filter
   PWM output
   Sinking transistor
   Sourcing transistor
   Triangle wave input



Class D Amplifier Schematic



Class D Amplifier Block Diagram