Class D Audio Power Amplifier

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Abstract

There is always a push to create amplifiers that are more efficient. High efficiency translates to less power wasted, lower operating temperatures, and longer battery life in portable applications. For audio amplifiers, it is also imperative to have excellent sound quality by maintaining low distortion through the entire audio range.

This class D audio power amplifier achieves high efficiency while retaining exceptional sound quality, making it an outstanding audio power amplifier. It achieves high efficiency by using a pulse width modulation (PWM) scheme to convert the analog input into a stream of "pulses." These pulses control power transistors that allow current to flow through the load and turn the transistors either completely on or completely off keeping wasted energy to a minimum. There is very little audible distortion introduced by this class D audio power amplifier.

Our class D audio power amplifier has an output power of 71.25 W for a 9 Ω load, far above the specified 10 W. We calculated an efficiency of 86.9% which exceeds the required 50% efficiency. The necessary frequencies of operation from 200 Hz - 10 kHz are easily amplified; this amplifier performs well over the entire audio band.

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1 Introduction

Our electrical engineering design project is a class D audio power amplifier that is used to convert small electrical signals into large ones while retaining a high efficiency.

The intended application of our amplifier is sound amplification. The class D audio power amplifier receives an electrical signal from the output of a portable compact disc (CD) player that would normally only be able drive a load such as headphones (150 Ω – 1000 Ω). Our project amplifies the electrical input signal so that it can drive smaller loads, such as an eight ohm speaker, with large currents to produce loud sounds. Throughout this text, we will assume the input to be an electrical audio signal from a portable CD player.

Figure 1 below presents the overall block diagram of the class D audio power amplifier.

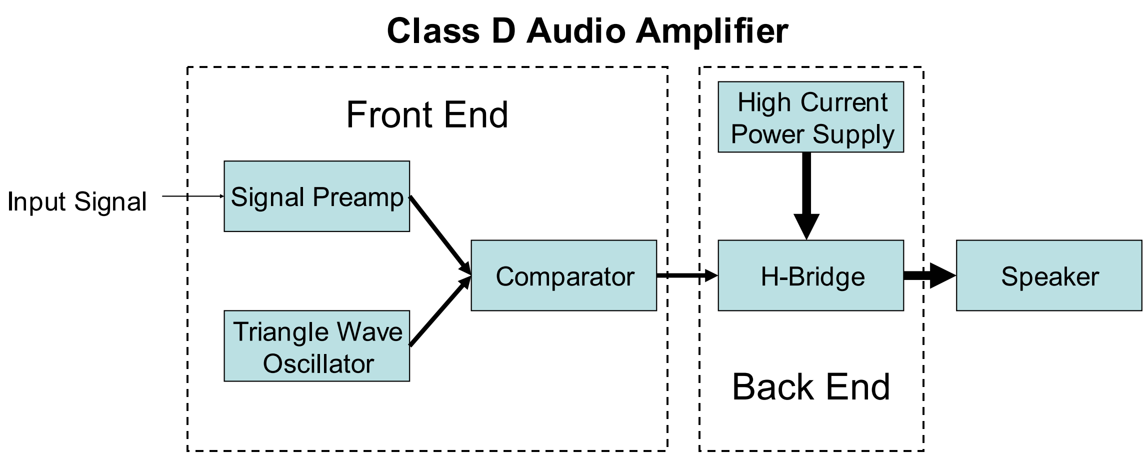


Figure 1 – Class D Block Diagram

The input signal shown in Figure 1 above is amplified by the signal preamplifier to reduce noise later in the circuit. The comparator compares the amplified input signal to a triangle wave oscillating at a constant frequency. The output of the comparator is either a “high” voltage or a “low” voltage. The two logic levels at the output of the comparator represent two situations at the input to the comparator: the amplified input signal voltage level was higher than the voltage level of the triangle wave, or the amplified input signal voltage level was lower than the voltage level of the triangle wave. The "high" and "low" voltage levels at the output of the comparator control the power transistors in the H-bridge. When a "high" voltage level is sent from the comparator to the H-bridge, the high current power supply is directed by the H-bridge to drive the speaker with the current flowing in one direction. When a "low" voltage level is sent from the comparator to the H-bridge, the high current power supply is directed by the H-bridge to drive the speaker with the current flowing in the opposite direction. This constantly changing current through the load produces sound.

This text describes in detail the class D audio power amplifier that we designed and built.

1.1 Inputs

The inputs to our project are an audio signal and a 120 V_{AC} line (the common electricity found in the United States). The audio input signal jack is a 1.5mm stereo jack commonly used for portable CD players. The 120 V_{AC} line supplies power to both the front end (low power) and back end (high power) circuitry.

The front end runs off $\pm$ 10 V_{DC}. We designed the power supplies to be able to supply up to 0.5 A if needed. Typically, much less than .1 A is drawn. The back end needs a 24 V_{DC}, 3 A power supply to allow a loud volume to be heard through the speaker at the output. The current demand from the back-end power supply is much greater than the demand on either front-end supply.

The AC voltage is stepped down using a 12 V_{RMS} center tapped transformer for the $\pm$ 10V supplies and a 30 V_{RMS} transformer for the 24 V supply. The signal is then full wave rectified using circuit components appropriate for the desired DC voltage output. These two transformers are in parallel, so only one cord must be plugged into the wall. There is a slow blow fuse in series with the plug going into the wall. In case something goes wrong (i.e. the high current power supply becomes shorted to ground) and the amplifier draws a large amount of current for a certain time, the fuse will blow. This will prevent human contact with dangerously high voltages. As another safety precaution, all high voltage contacts are covered with insulating material.

1.2 Output

The output of our project is a pulse width modulated (PWM) signal that is a representation of the analog electrical input. The output is fed to a speaker which converts the electrical signal into sound. The speaker acts as a low-pass filter so any signal energy present at high frequencies is not converted into sound energy. The average current through the speaker represents an amplified version of the input signal.

1.3 Specifications

Our project converts the inputs (120 V_{AC} and an electric audio signal) into a single amplified output signal. When the output signal is connected to a speaker, the distortion introduced by the class D audio amplifier is very low.

The frequency of operation is over the entire audio band detectable by humans. We examined different frequencies using audio CDs with sine wave "tracks" oscillating at frequencies from 20 Hertz to above 20,000 Hertz. We were not able to hear noises at such extreme frequencies due to limitations of the speaker. However, we viewed the output signal of the class D amplifier on the oscilloscope and confirmed that it was correctly amplifying the input signal.

The output power of our amplifier is 71.25 Watts for a 9 Ω resistive load. This purely resistive load allows an accurate total output power measurement, as opposed to an audio speaker, which has a non-linear impedance characteristic over a range of frequencies.

The class D amplifier is remarkable in that its efficiency is much higher than both class A and class B amplifiers. Due to the pulse width modulated waveform, the amplifier's power transistors are either completely on or completely off, which increases efficiency by allowing minimal power dissipation in the transistors. Theoretically, the efficiency of a class D amplifier can be as high as 98%, losing power only in the switching of the transistors. We were able to measure an efficiency of 86.9% (including the power at the switching frequency).

2 Design Overview

This class D audio amplifier can easily be simplified by considering the process as a set of interconnected blocks of functions. Figure 1 on page 1 shows the overall block diagram of the class D audio amplifier and is reprinted below in Figure 2 for convenience.

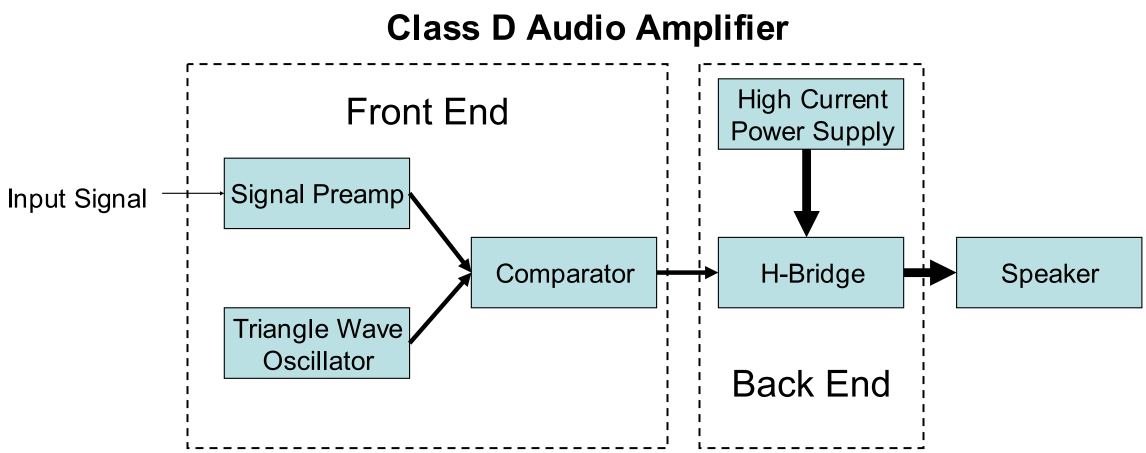


Figure 2 – Class D Block Diagram

As presented in the block diagram, the class D amplifier is split into two smaller sections: the front end circuitry and the back end circuitry. The front end circuitry deals with the signal-level manipulation and generation of a PWM waveform, which will in turn drive the back end. The back end is responsible for both the generation of an amplified, identical PWM waveform, and the delivery of the PWM waveform to the load.

2.1 Front End Circuitry

The front end of the class D audio amplifier is responsible for the generation of a PWM waveform. The input signal is first pre-amplified by an op-amp to implement a volume control. Also, an oscillator creates a triangle-wave at a set frequency, which is much higher than the maximum audio frequency (20 kHz). The frequency of the oscillator sets the switching frequency of the H-bridge transistors in the back end circuitry. The PWM signal is created by comparing the pre-amplified input signal to the oscillating triangle waveform. The resulting locked anti-phase PWM signal is a constant period, varying duty cycle representation of the input signal. The front end circuitry is run from a relatively small power supply that is entirely independent of the back end circuitry's power supply.

2.2 Back End Circuitry

The back end circuitry is responsible for switching the PWM signal across the speaker by using an H-bridge. An H-bridge is a four transistor configuration in which the transistors act much like switches. This configuration can be seen below in Figure 3.

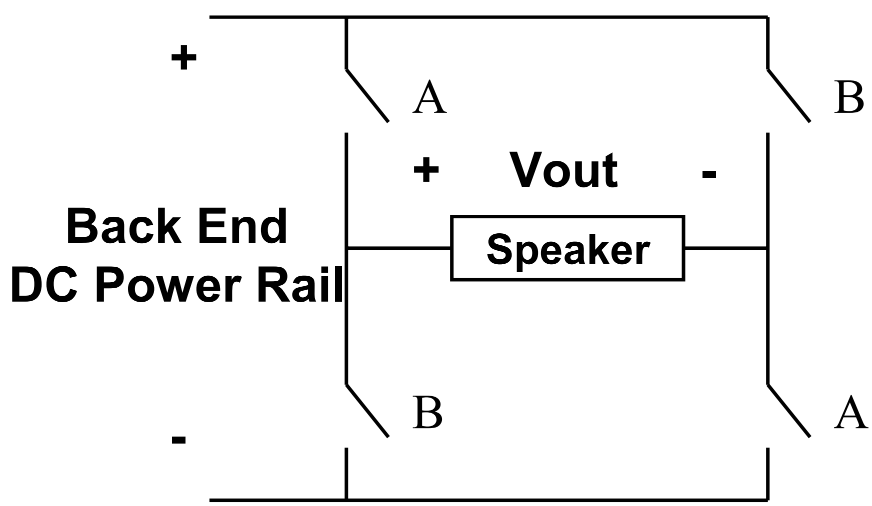


Figure 3 – H-Bridge Overview

The power transistors are shown above with either an "A" or "B" next to them, and as you can see from the figure, the H-bridge is used to switch the entire power rail (minus a small voltage drop across each transistor in the current path) onto the speaker. Current flows through the speaker in either direction depending on the logic level of the PWM signal. Gate drive circuitry controls the transistors so the H-bridge can easily be used to switch the front end PWM signal across the speaker. Note that it is extremely important that both transistors "A" and "B" on the same side of the speaker are never on at the same time. This would short the DC power rail to ground and surely destroy the H-bridge. The back end circuitry is run by a high-voltage, high-current power supply that is entirely independent of the front end's power supply.

3 Front End

3.1 Triangle Wave Oscillator Circuit

The LM566 IC provides a simple and accurate triangle wave oscillator when configured as shown below in Figure 4.

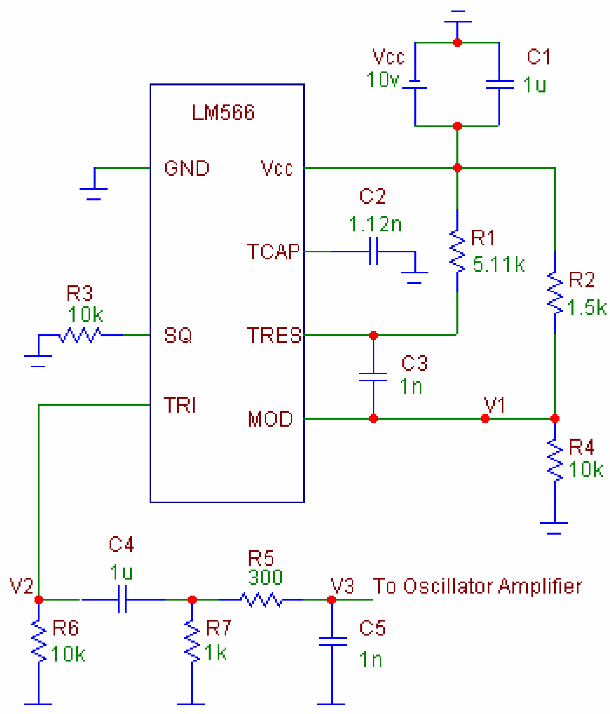


Figure 4 – LM566 Triangle Wave Oscillator Circuit

The LM566 data sheet provides an AC test circuit and equation to design and select component values. Equation 1 below expresses the output frequency f_o for the triangle wave in terms of the component values shown in Figure 4 above.

$$f_o = \frac{2.4 \cdot (V_{cc} - V_1)}{V_{cc} \cdot R_1 \cdot C_2}$$

Equation 1

where 2 kΩ<R_1<20 kΩ

The normal range of human hearing is from 20 Hz to 20 kHz. In order to satisfy Nyquist's criteria, the frequency of the triangle wave must be at least twice the highest frequency we wish to amplify. This means f_o must be at least 40 kHz. We choose f_o to be 65 kHz to be sure we are sampling the input signal above the Nyquist rate. V_{cc} is shown in Figure 4 on page 6 as 10 V. Performing nodal analysis on Figure 4, V_1 is 8.7 V. We select R1 to be 5.11 kΩ to find a reasonable value of 1.12 nF for C2.

Capacitor C1 in Figure 4 is a 1 μF tantalum capacitor in parallel with V_{cc}. The wire connection between the LM566 and the capacitor is much shorter than the wire connection between the LM566 and V_{cc}. Quick changes in current demanded from V_{cc} (dI/dt) multiplied by the inductance (L) of the relatively long wire connecting the LM566 to V_{cc} create a voltage drop ($V = L \cdot \frac{dI}{dt}$). This voltage drop can become significant when the current is changing at a high frequency, such as supporting a 65 kHz triangle wave generator. Tantalum capacitors perform effectively at high frequencies because they respond quickly to the increased current demand and hold the voltage at V_{cc} for a short time. Throughout this text, all 1 μf capacitors in parallel with either Vcc or –Vcc are present to squelch voltage transients due to high frequency switching.

The triangle wave at node V_2 (Figure 4, page 6) with respect to time is shown in Figure 5 below.

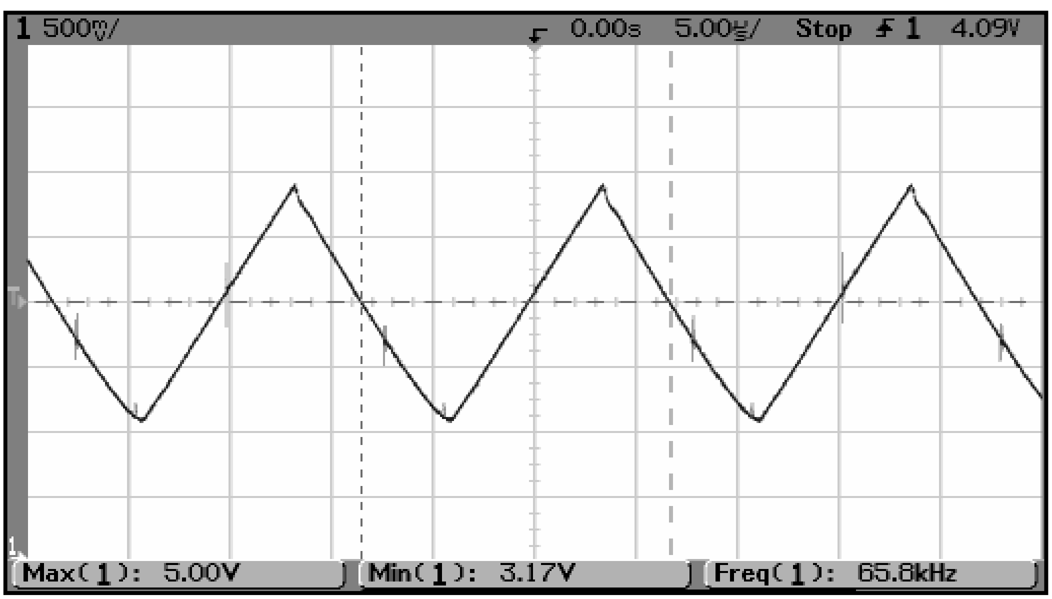


Figure 5 – Voltage at Node V_2 in Figure 2 with Respect to Time

The R7/C4 network shown in Figure 4 on page 6 is a high-pass filter that blocks the 4.09 V_{DC} offset shown in Figure 5 on page 7. This high-pass filter produces a corner frequency of 159.15 Hz that is below the low end of the audio band and will effectively block the dc component. The R5/C5 network low-passes the triangle waveform at a corner frequency of 530.5 kHz. This rounds the peaks of the triangle wave by removing high frequency components.

In order for the comparator to properly control the H-bridge, the voltage range of the triangle waveform must exceed the voltage range of the preamplified audio signal. The triangle wave oscillator output must be amplitude adjusted to encompass all possible input signal amplitudes. The oscillator amplifier circuit is shown in Figure 6 below.

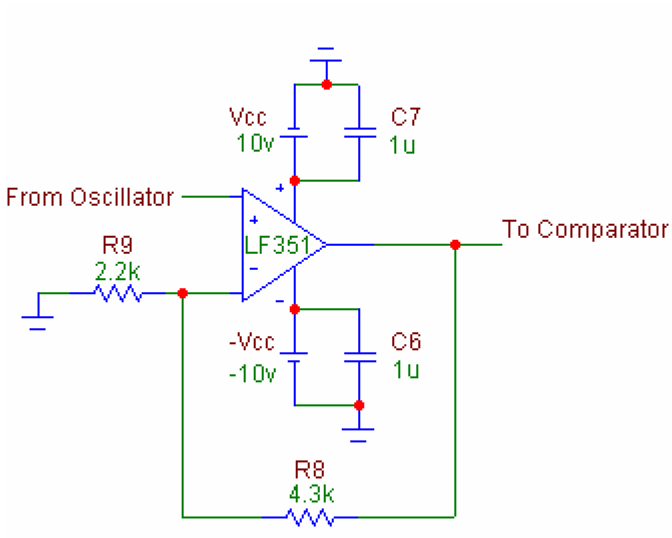


Figure 6 – Oscillator Amplifier

The LF351 op amp is in the non-inverting configuration in Figure 6 above. Resistors R8 and R9 provide a gain of 3 V/V. The amplified triangle wave is now -2.44 V to 2.69 V as shown in Figure 7 on page 9.

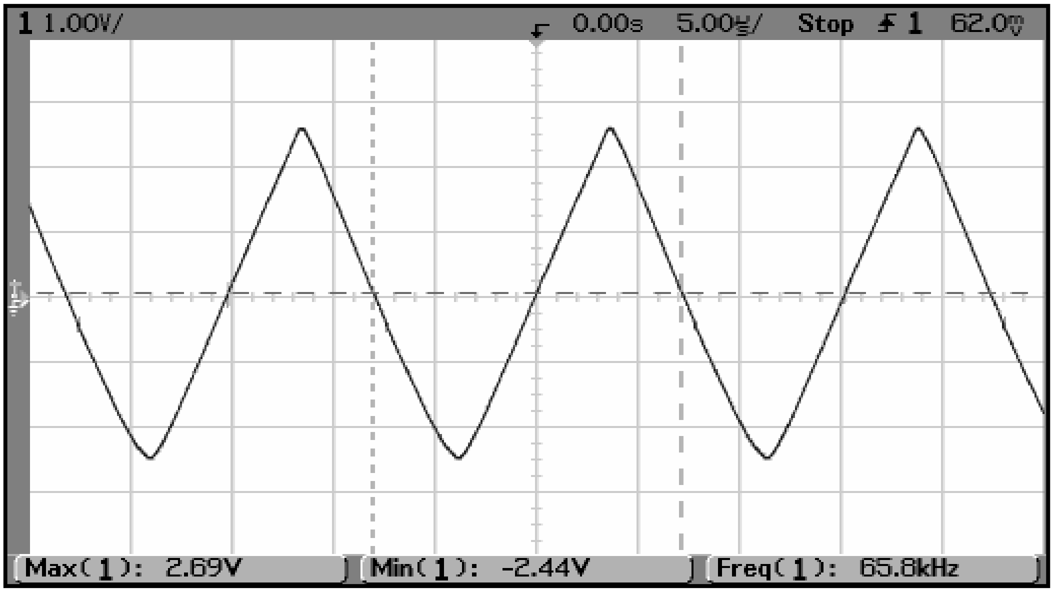


Figure 7 – Amplitude Adjusted Triangle Wave

The amplified triangle wave shown above in Figure 7 is fed to the negative terminal of the comparator. The frequency of the wave is 65.8 kHz and satisfies Nyquist's criteria for sampling.

3.2 Audio Signal Preamplifier Circuit

The preamplifier circuit shown in Figure 8 below combines the right and left channels of the portable CD player output to produce a mono audio signal. The sound quality is "fuller" with the signals combined than it would be with only one channel.

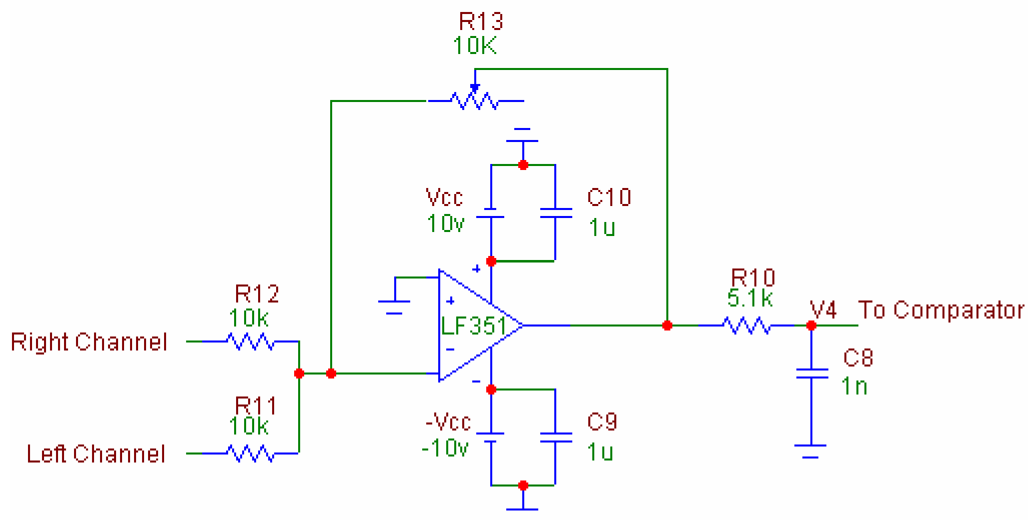


Figure 8 – Audio Signal Summer and Preamplifier Circuit

The signal preamplifier circuit shown in Figure 8 above employs an LF351 op-amp in the inverting configuration. The logarithmic potentiometer in the feedback path allows the user to control the magnitude of the audio signal gain which is proportional to the volume at the output of the class D audio amplifier.

The audio signal is low-pass filtered by the R10/C8 network shown in Figure 8 above to reduce noise introduced by the audio preamplifier circuit. This network has a corner frequency of 31.2 kHz and allows the entire audio band to pass. The voltage signal at node V_4 is shown in Figure 9 on page 11.

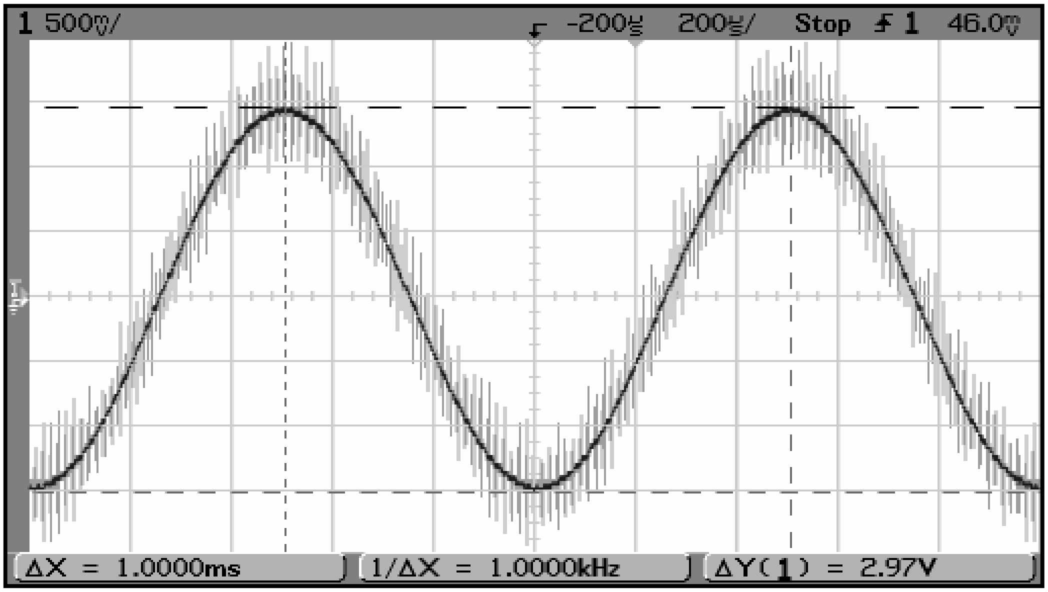


Figure 9 – Amplified Audio Input Signal

Figure 9 above shows the voltage at node V_4 in Figure 8 on page 10 with respect to time. The audio input was a 1 kHz sine wave, and the graph above shows that the frequency has been maintained. The peak to peak voltage is 2.97 V and the wave is centered at approximately 0 V. As required, the voltage range of the output of the signal preamplifier does not exceed the voltage range of the amplified triangle wave (5.13 V) shown in Figure 7 on page 9. The noise being introduced to the signal is caused by the large currents being switched at a fast rate (65.8 kHz) by the power transistors in the H-bridge. These constantly switching currents produce a magnetic field that interferes with any electrical signal in the proximity of the H-bridge. To test this, shielded probes were placed near the H-bridge and they picked up the noise through air. Notice that there are 65 or 66 spikes in each period of the 1 kHz signal. This is because every time the H-bridge transistors switch (at a rate of 65.8 kHz) a noise spike is created.

3.3 Comparator Circuit

The reliability and availability of the LM311 make it a good comparator to use to generate the locked anti-phase pulse width modulation driving the H-bridge. Figure 10 below shows the configuration of the LM311 used to compare the amplified triangle waveform to the amplified signal input.

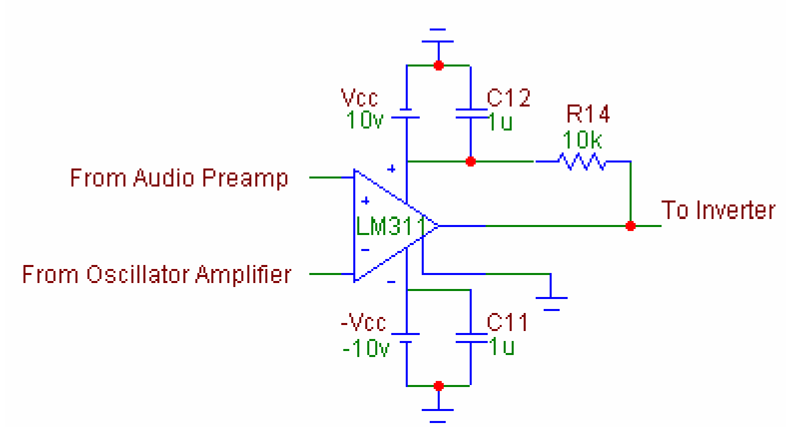


Figure 10 – Voltage Comparator

The comparator output is connected to the V_{cc} supply through R14 as shown in Figure 10 above. The balance and strobe pins are tied together (not shown), and the ground pin is connected to common ground.

An example of what a PWM signal looks like is shown below in Figure 11. In this example, the audio input is a sine wave.

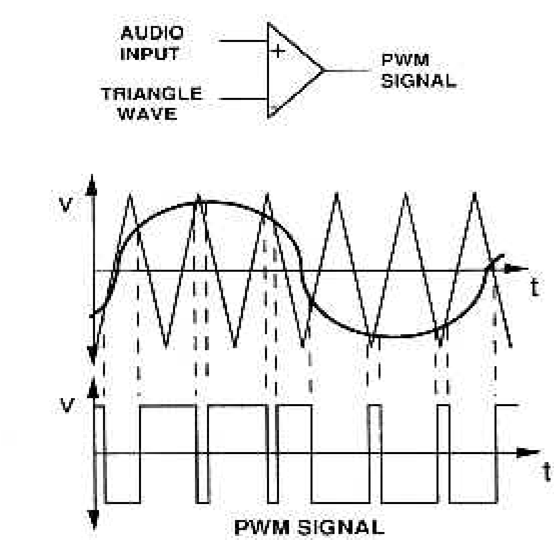


Figure 11 – Pulse Width Modulation

As shown in Figure 11 on page 12, the output of the comparator in Figure 10 on page 12 goes high (V_{cc}) when the audio signal is higher than the triangle waveform, and the output goes low (0 V) when the audio signal is lower than the triangle waveform. Note that the audio signal is never allowed to go outside the limits of the triangle wave; this would result in an erroneous PWM value. It is also important that the transition time of the PWM signal is very short because the only two allowable values are "high" and "low." Figure 12 below shows the output of the comparator with 0 V_{DC} input.

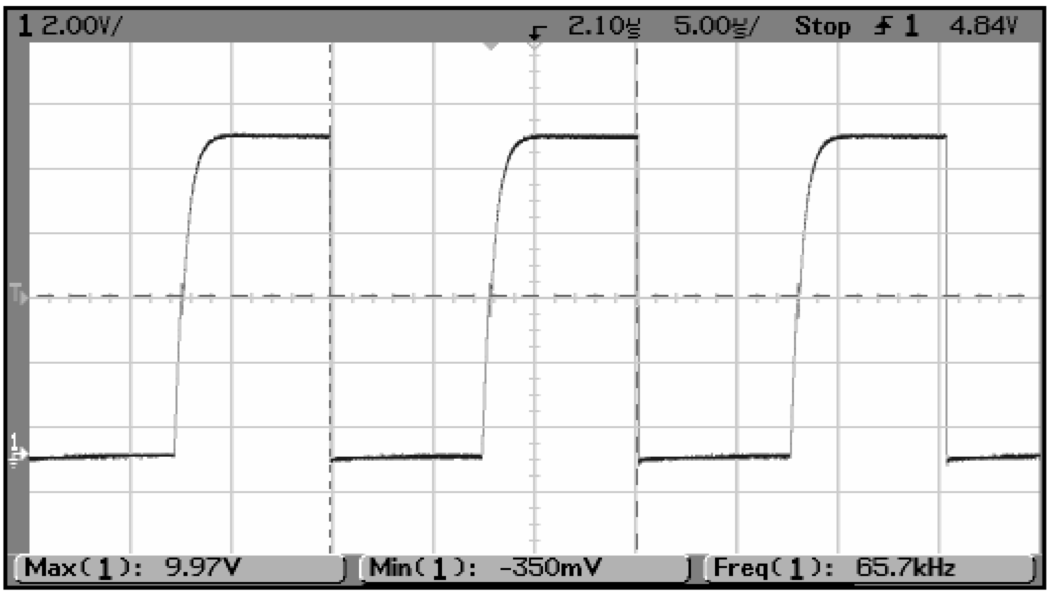


Figure 12 – Comparator Output

The undesirable qualities of the comparator output are obvious in Figure 12 above. The smooth corner on the rising edge increases the transition time between "low" and "high" states. This decreases the "high" time and distorts the signal. A Schmitt trigger will be used to correct this problem.

The PWM signal is important because it controls the state of the H-bridge, which delivers power to the load. For our application, the load is an 8 Ω speaker.

3.4 Inverter with Schmitt Trigger Circuit

The (inverted) PWM signal driving the inverters is approximately V_{cc} or ground at all times (Figure 12, page 13). The inversion of the signal is not detectable by the human ear, so it is not necessary to use an inverter to return the audio signal to the original state. It is necessary, however, to ensure the PWM signal has fast transition times. Therefore, the output of the comparator is fed to the MM74HC14, an inverter with Schmitt trigger inputs, in order to decrease the rise time of the PWM signal. The inverter circuit is shown below in Figure 13.

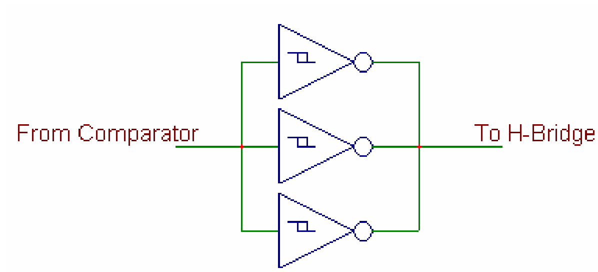


Figure 13 – Inverter with Schmitt Trigger Circuit

The attractive features of the MM74HC14 are hysteresis and quick response time. Hysteresis ensures that small noises in the input signal in either the high or low state will not cause false output values. The quick response time cleans up the signal by reducing transition time.

We encountered a problem with the chip overheating when we used just one inverter. To combat this problem, we hooked up three of the possible six inverters on the chip in parallel as shown in Figure 13 above. This reduced the power dissipation in each inverter and caused the chip to run much cooler. Recently, we discovered that we mistakenly used the MM74HC14 Hex Schmitt Trigger with the MM74C14 Hex Schmitt Trigger datasheet. This is a problem because our rails do not exceed the maximum supply rating (15 V) for the MM74C14 Hex Schmitt Trigger but do exceed the maximum supply rating (7 V) of the MM74HC14 Hex Schmitt Trigger. We strongly recommend the substitution of the MM74C14 for the MM74HC14 Hex Schmitt Trigger.

Using three inverters in parallel further promotes a decrease in rise and fall times of the PWM signal. Figure 14 on page 15 shows the dramatic improvement realized by using the inverter with a Schmitt trigger.

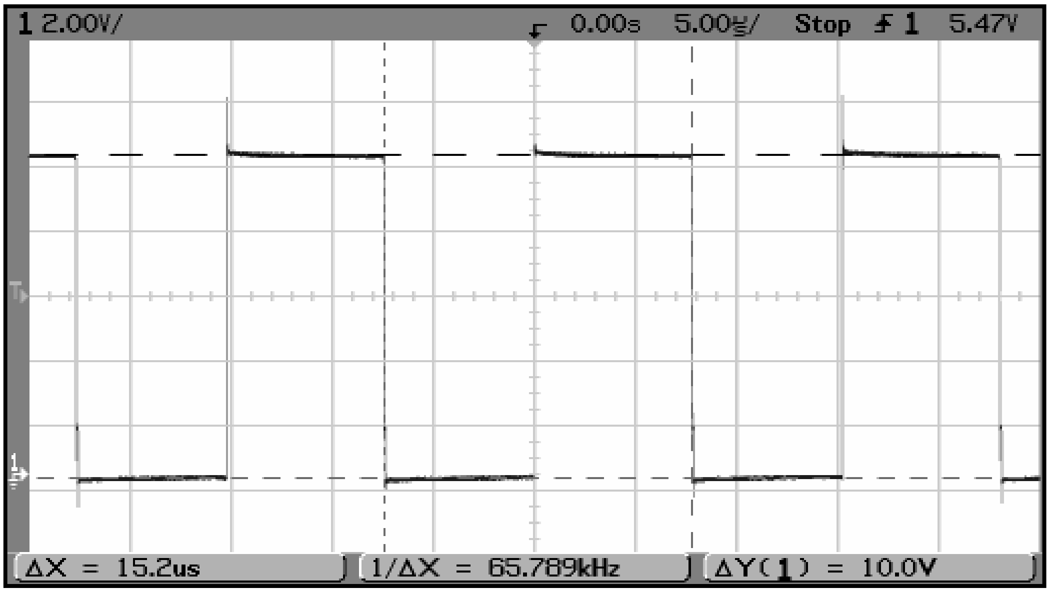


Figure 14 – Inverter with Schmitt Trigger Output

In Figure 14 above, no audio input signal was applied, and the duty cycle of the PWM waveform is 50%. Note also that the estimated frequency is 65.8 kHz, and the logic levels of the PWM signal are ground (0 V) and V_{cc} (10 V) with sharp transitions.

Figure 15 below shows the audio input signal and the corresponding PWM waveform produced by this class D audio power amplifier.

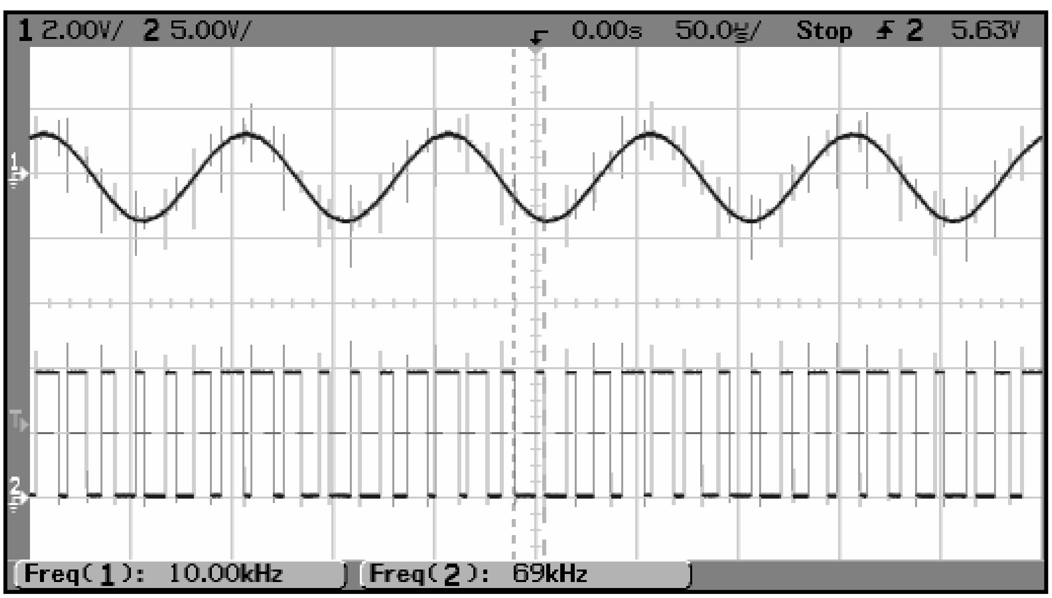


Figure 15 – PWM Output with 10 kHz Input Signal

Figure 15 on page 15 aligns the audio input signal with the output of the inverter. The duty cycle of the PWM waveform increases during the top portions of the sine wave and decreases during the bottom portions. Current flows in one direction through the load during the top portion of the PWM signal, and in the other direction during the bottom portion.

The changing current through the power transistors in the H-bridge creates a magnetic field. This magnetic field induces currents in other wires in the vicinity of the H-bridge. This is shown in the noise spikes in Figure 15 on page 15 and Figure 9 on page 11. The noise spikes on the audio signal appear every time the transistors in the H-bridge switch. The effect of the noise spikes is minimal because the speaker rejects these high frequency components.

4 Back End

4.1 H-Bridge Circuit

The availability of the LMD18201 and inclusion of the built in gate drive circuitry make it a natural choice for the H-bridge in this class D audio power amplifier. The LMD18201 can handle 3A and 55 V, which meets our power requirement. It also can be used directly with locked anti-phase pulse width modulation signals, which is a large advantage over using discrete MOSFETs. A schematic of the LMD18201 is shown below in Figure 16.

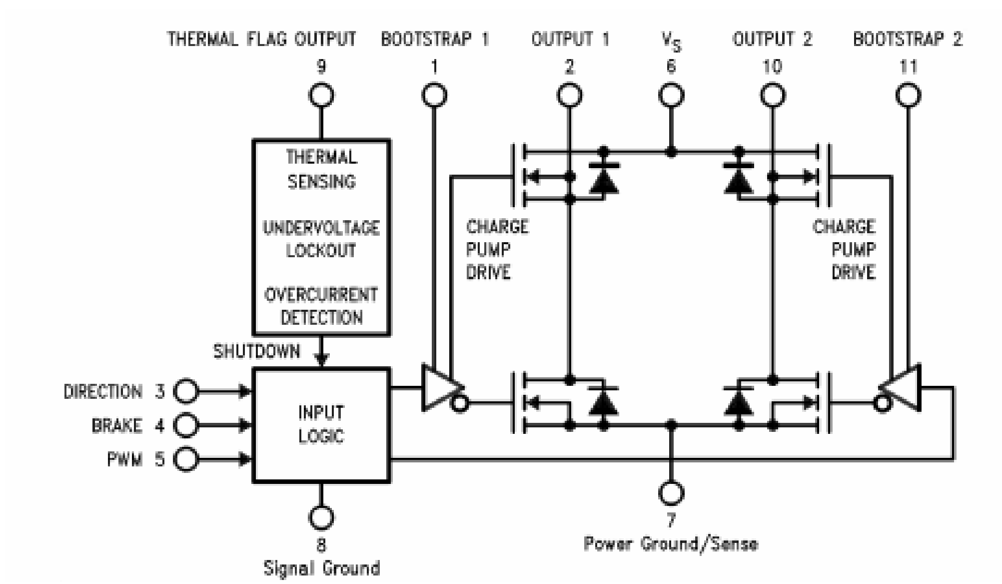


Figure 16 – LMD18201 Schematic

In order to use the locked anti-phase PWM scheme, the DIRECTION input is connected to the output of our inverter and the PWM input is tied to logic high (V_{cc}). The BRAKE input is tied to ground, indicating that we are not using a feature often applied in motor control applications. The H-bridge circuit we used is shown in Figure 17 on page 18.

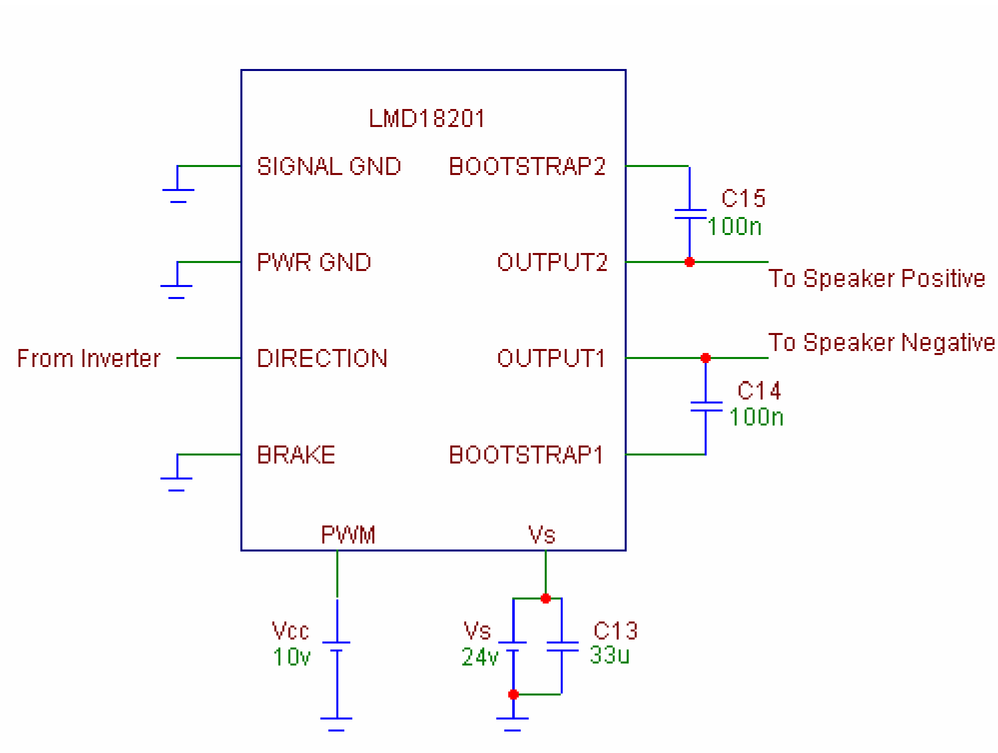


Figure 17 – LMD18201 Circuit

As shown in Figure 17 above, the V_S pin is connected to the 24 V high-current power supply. V_S is also in parallel with C13, a 33 μF tantalum capacitor which ensures there will be adequate current supplied to the H-bridge as V_S is switched across the load. C13 is soldered directly to the pin on the H-Bridge.

The mounting tab on the T0-220 package of the LMD18201 is internally connected to power ground. The LMD18201 is attached to a heat sink making the entire heat sink power ground. Signal ground and power ground are both tied to common ground through the heat sink with short, thick wires to minimize noise at the ground level.

C14 and C15, 100 nF bootstrap capacitors, help charge the parasitic gate input capacitance. Charging the parasitic gate input capacitances allows the H-bridge to switch at much higher frequencies than without the bootstrap capacitors ($\approx 500\,\text{kHz}$).

The H-bridge switches V_S across the speaker at a fast frequency (the period of switching is $1/f_o$ from section 3.1). The speaker acts as a low-pass filter to reject signal energy at frequencies above the audible range, so signal energy at the switching frequency is rejected (see Appendix C on page 28).

The duty cycle of the PWM signal is varied so that the average voltage across the speaker is directly related to the voltage level of the input signal. For a 0 V_{DC} input (no audio input), a 50% duty cycle PWM signal drives the H-bridge. The integration of the load voltage over one period is zero, and no sound is heard. An example of this appears below in Figure 18.

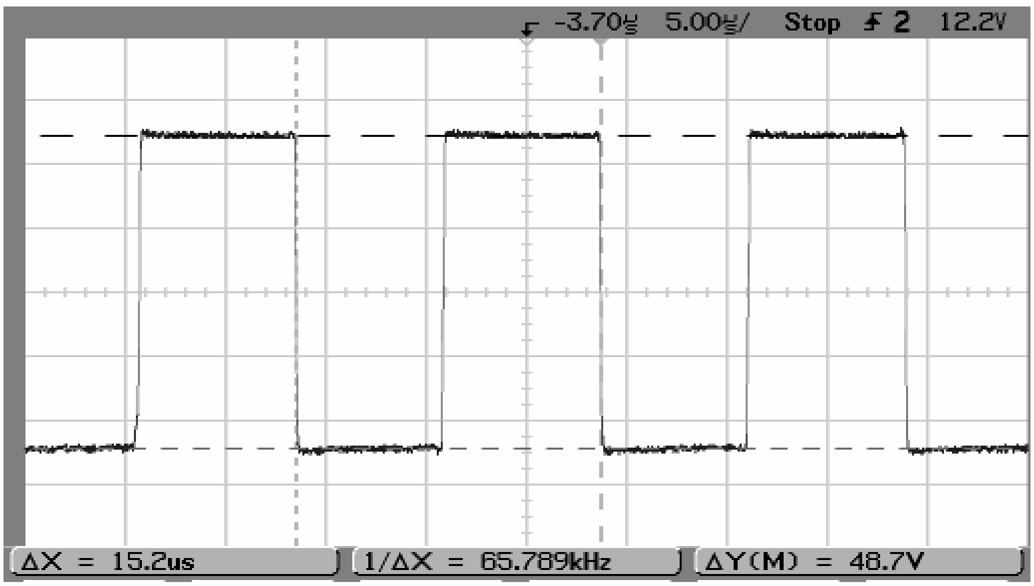


Figure 18 – Differential Voltage at Output of H-bridge

Figure 18 above shows an extremely clean PWM waveform which is essential to keep distortion minimal in the amplifier. The switching frequency of the transistors is 65.8 kHz, which is the exact frequency of the PWM waveform that drives the H-bridge. Also, the range of the new amplified PWM signal is 48.7 V, and it can supply enormous amounts of current compared to the front end. Lastly, and extremely important for a low distortion amplifier, the rise and fall times of the PWM signal are minimized, and the "high" and "low" bands are flat.

5 Power Supply Design

5.1 +/- 10 V Supplies

The low power, front end integrated circuits run off ± 10 V_{DC} supplies (V_{cc} and $-V_{cc}$). The schematic of both the positive and negative power supplies appears below in Figure 19.

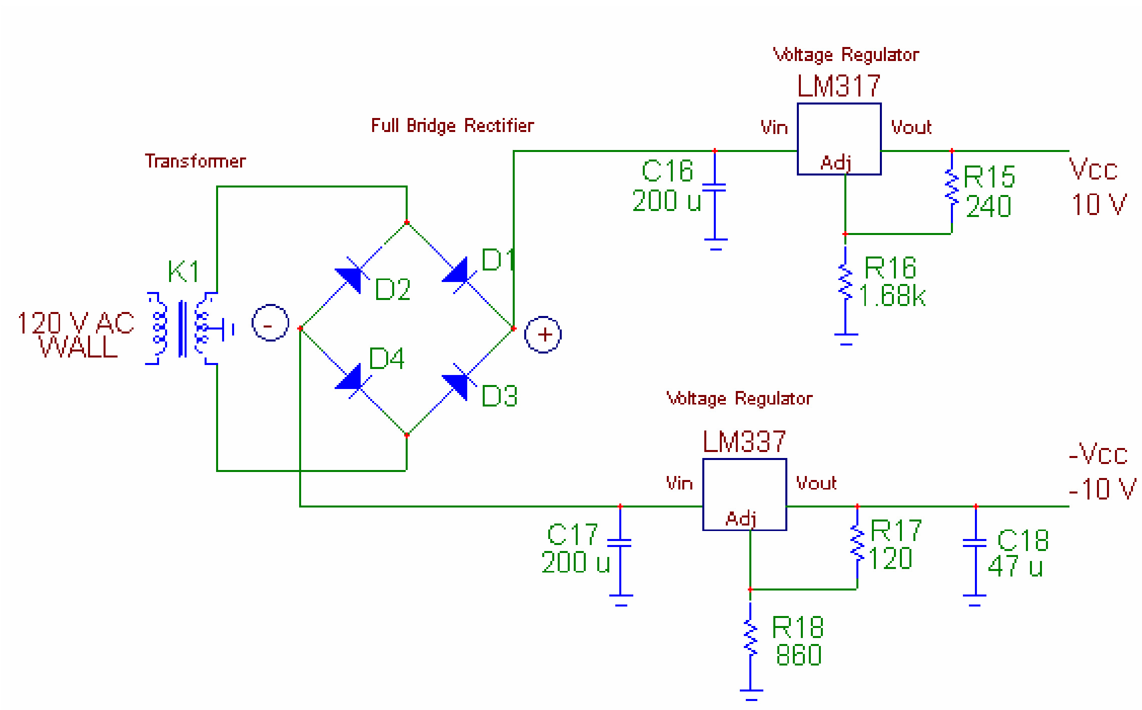


Figure 19 – ± 10 V Power Supply Circuit

A 12.6 V_{RMS} center tapped transformer shown as K1 in Figure 19 down-converts the 120 V_{AC} from the wall outlet. When testing our complete circuit design with the Agilent E3630A Triple Output DC Power Supply at ± 10 V, we found that the current drawn from each voltage supply was .02 A. Each supply is designed to be able to deliver 0.1 A to easily meet the current demand.

The LM317 regulates the +10 V rail, and the LM337 regulates the -10 V rail. R15, R16, R17, and R18 set the bias current in these regulators. C18 was added at the output of the -10 V rail to smooth the DC rail voltage.

5.2 24 V Supply

The schematic for our high-current, high-voltage power supply can be seen below in Figure 20.

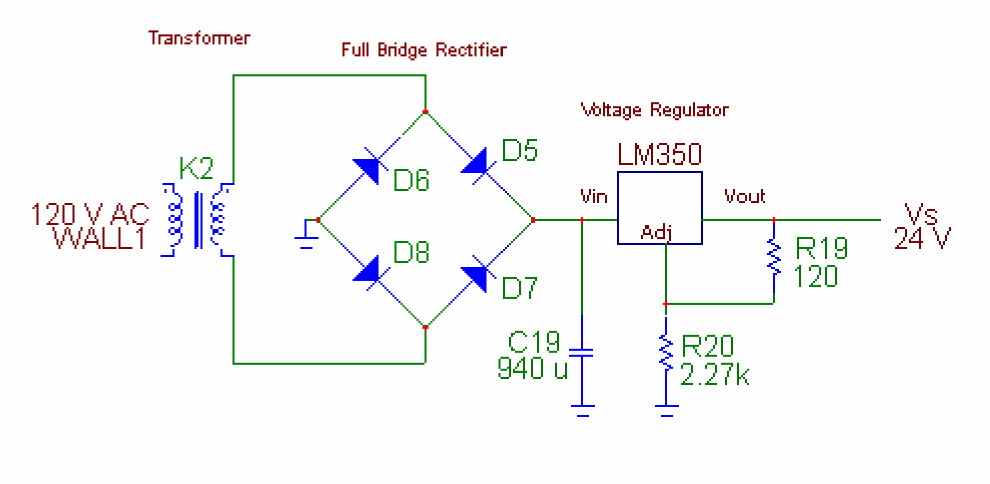


Figure 20 – 24 V, 3 A Power Supply

The current limit on the H-bridge is 3 A; therefore, Ohm's law dictates that the approximately 8 Ω load (speaker) cannot have more than 24 V across it. Figure 20 above shows a 32 V_{RMS} transformer, full wave rectifier, and voltage regulator which provide a relatively constant 24 V_{DC}, 3 A power supply.

The only time current is not demanded from the supply is during the very short transition times of the PWM signal. Therefore, most of the time current is flowing through the voltage regulator and being delivered to the load. This large current coupled with a significant voltage drop across the voltage regulator causes the regulator to dissipate a sizeable amount of heat. The regulator is mounted on a heat sink, which cools it to an appropriate temperature for proper functionality.

6 Results and Conclusions

6.1 Test Results

Our senior design project achieved all of the specifications that we proposed. Furthermore, the frequency operation was increased to the entire audio band, the output power was increased to 71.25 W for a single channel 9 Ω purely resistive load, and our efficiency was measured to be 86.9%. We also designed and built our own power supplies which went beyond our proposed project.

One problem we encountered when trying to test the amplifier was measuring total harmonic distortion (THD). We were unable to determine the THD of the amplifier because we did not have the proper equipment. The output voltage of the amplifier exceeded allowable levels on the spectrum analyzer. We also were unable to determine how to use the spectrum analyzer with a differential signal. This prevented us from finding the frequency response. Recently it has come to our attention that an audio transformer would allow us to examine the frequency response using the spectrum analyzer in the electronics lab. We plan to do this in the future.

6.2 Future Improvements

The output of the H-bridge can be directly applied to the speaker under the condition that the speaker is inductive and will reject the switching frequency. A low-pass filter could be used to pass only the audible frequency range ensuring the rejection of the switching frequency. Including a low-pass filter would protect the speaker by dissipating the power at the switching frequency in the filter and not the speaker.

A smaller encasement would allow the amplifier to be more portable. The current encasement has empty space, and keeping the components close together reduces the need for long wires.

Stereo output would also be a large improvement over the current design. Including left and right channels would provide the user with a richer sound.

Appendix A – Entire Class D Audio Power Amplifier Schematic

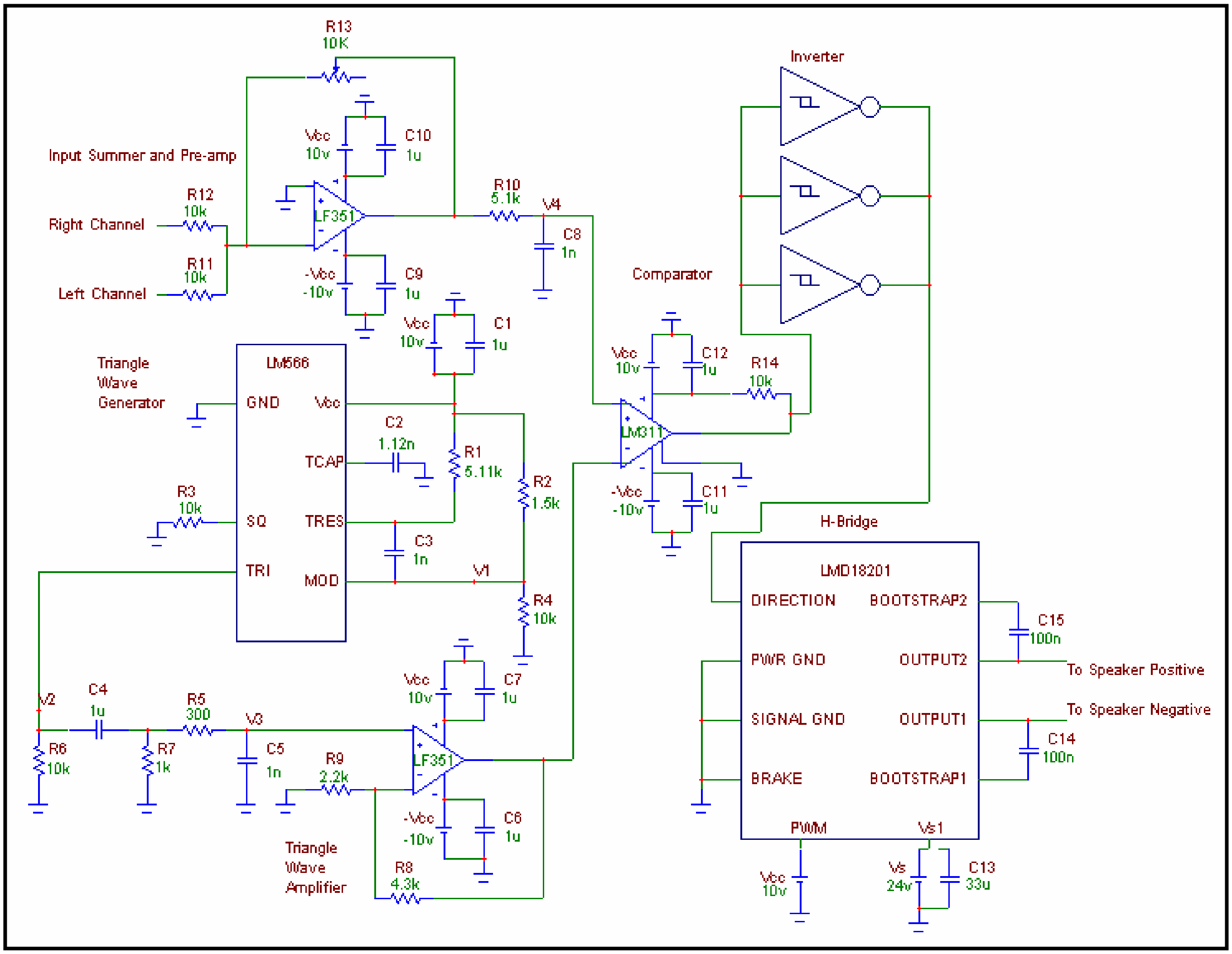


Figure 21 – Overview of Amplifier Schematic

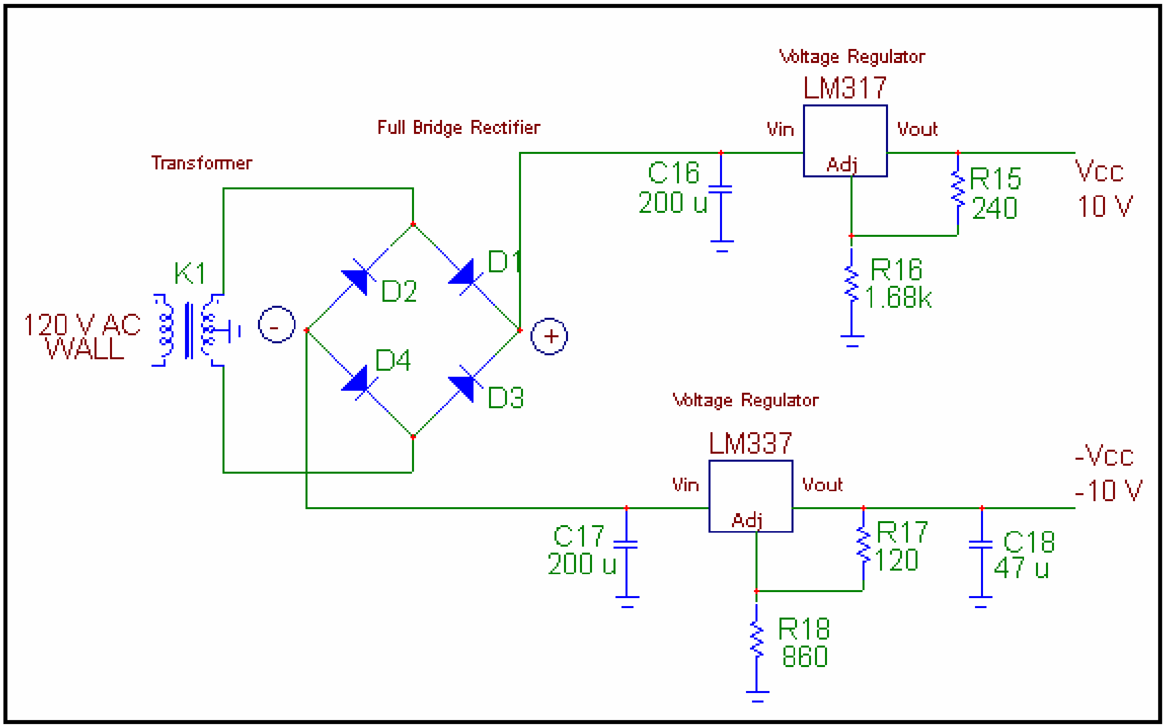


Figure 22 – Overview of ± 10 V_{DC} Power Supplies

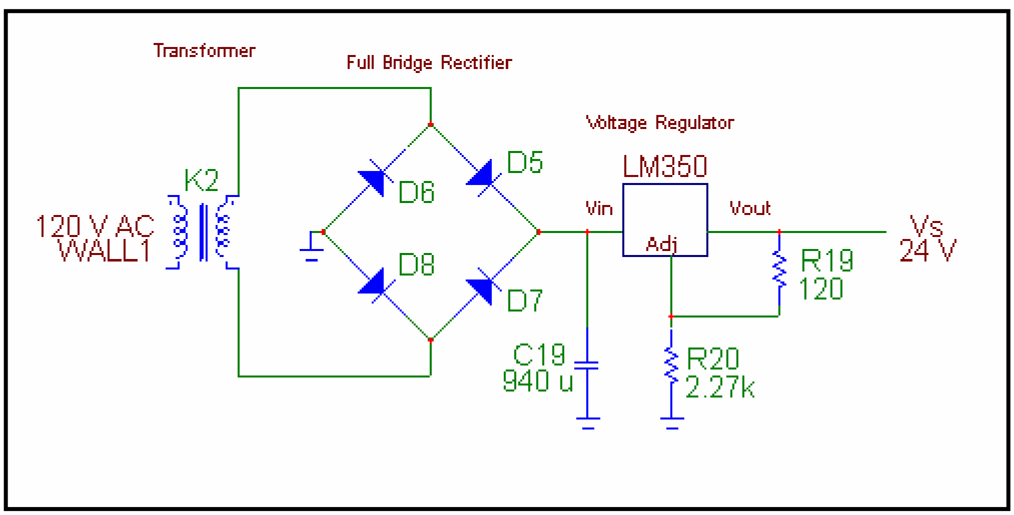


Figure 23 – Overview of 24 V_{DC} Power Supply

Appendix B – Parts List

*Note: All resistors are 0.25 Watts unless otherwise specified.

Triangle Wave Oscillator Circuit (Figure 4, page 6)

Component Name	Component Value	Comments
LM566		Voltage Controlled Oscillator
R1	5.11k	
R2	1.5k	
R3	10k	
R4	10k	
R5	300	
R6	10k	
R7	1k	
C1	1u	Tantalum
C2	1.12n	
C3	1n	
C4	1u	
C5	1n	

Oscillator Amplifier (Figure 6, page 8)

Component Name	Component Value	Comments
LF351		Op-Amp
R8	4.3k	
R9	2.2k	
C6	1u	Tantalum
C7	1u	Tantalum

Audio Signal Summer and Preamplifier Circuit (Figure 8, page 10)

Component Name	Component Value	Comments
LF351		Op-Amp
R10	5.1k	
R11	10k	
R12	10k	
R13		Logarithmic Potentiometer
C8	1n	
C9	1u	Tantalum
C10	1u	Tantalum

Voltage Comparator (Figure 10, page 12)

Component Name	Component Value	Comments
LM311		Voltage Comparator
R14	10k	
C11	1u	Tantalum
C12	1u	Tantalum

Inverter with Shmitt Trigger (Figure 13, page 14)

Component Name	Comments
MM74HC14	Hex Inverting Schmitt Trigger WE STRONGLY RECOMMEND SUBSTITUTING WITH THE MM74C14

H-Bridge (Figure 17, page 18)

Component Name	Component Value	Comments
LMD18201		H-Bridge
C13	33u	Tantalum
C14	100n	Tantalum
C15	100n	Tantalum

± 10 V Power Supplies (Figure 19, page 20)

Component Name	Component Value	Comments
± 12 VRMS Transformer		
Full Bridge Rectifier		
LM317		Positive Adjustable Voltage Regulator
LM337		Negative Adjustable Voltage Regulator
R15	240	
R16	1.68k	
R17	120	
R18	860	
C16	200u	
C17	200u	
C18	47u	

24 V, 3 A Power Supply (Figure 20, page 21)

Component Name	Component Value	Comments
30 VRMS Transformer		
Full Bridge Rectifier		
LM350		3 A Adjustable Output Positive Voltage Regulator
R19	120	
R20	2.27k	
C19	940u	

Appendix C – Speaker Characteristics

Typically, a speaker can be thought of as a resistor and inductor in series. This can be seen below in Figure 24.

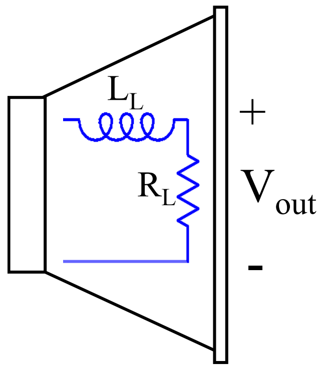


Figure 24 – Speaker Equivalent Circuit

The series configuration seen in Figure 24 above forms a low pass filter. We use this characteristic to our advantage to reject the high frequency switching component (65.8 kHz) while retaining the entire audio band. The significant signal power present at high frequencies must be rejected to achieve a high efficiency. The transfer function of Figure 24 above is given below in Equation 2.

$$H(\omega) = \frac{1}{1 + j \cdot \omega \cdot \frac{L_L}{R_L}}$$

Equation 2

At high frequencies, the magnitude of Equation 2 above approaches zero. It is also important to note that the inductance (L_L) and resistance (R_L) of the speaker will vary over the audio band.

Appendix D – Original Project Proposal

Class D Audio Power Amplifier

Jason Cookson, EE and Janelle Tonti, EE

Description

We propose to design and build a class D power audio amplifier. It will receive an input audio signal and amplify it to be played on an output device such as a speaker.

Inputs

DC Power

Audio signal

Output

Amplified output signal

Specifications

Frequency Operation: 200 Hz - 10 kHz

Output Power: 10 W (single channel)

Efficiency: >50%

Name: ________________________ Date: _____________

Jason Cookson, EE

Name: ________________________ Date: _____________

Janelle Tonti, EE

Advisor: ________________________ Date: _____________

Dr. Hummels

Appendix E – LM566 Datasheet

National Semiconductor

February 1995

LM566C Voltage Controlled Oscillator

LM566C Voltage Controlled Oscillator

General Description

The LM566CN is a general purpose voltage controlled oscillator which may be used to generate square and triangular waves, the frequency of which is a very linear function of a control voltage. The frequency is also a function of an external resistor and capacitor.

The LM566CN is specified for operation over the 0°C to +70°C temperature range.

Features

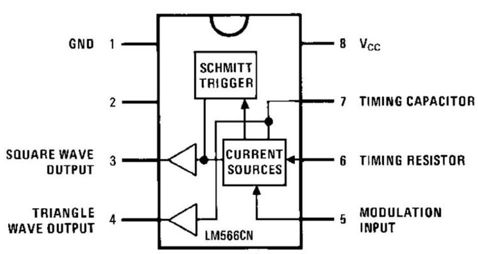
- Wide supply voltage range: 10V to 24V
- Very linear modulation characteristics
- High temperature stability
- Excellent supply voltage rejection
- 10 to 1 frequency range with fixed capacitor
- Frequency programmable by means of current, voltage, resistor or capacitor

Applications

- FM modulation
- Signal generation
- Function generation
- Frequency shift keying
- Tone generation

Connection Diagram

Dual-In-Line Package

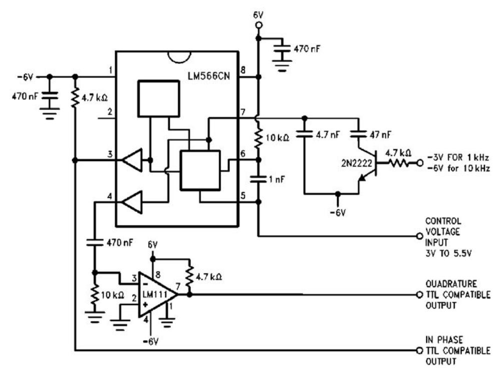


TL/H/7854–2

Order Number LM566CN
See NS Package Number N08E

Typical Application

1 kHz and 10 kHz TTL Compatible Voltage Controlled Oscillator



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Absolute Maximum Ratings

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/Distributors for availability and specifications.

Power Supply Voltage	26V
Power Dissipation (Note 1)	1000 mW
Operating Temperature Range, LM566CN	0°C to +70°C
Lead Temperature (Soldering, 10 sec.)	+260°C

Electrical Characteristics V_{CC} = 12V, T_A = 25°C, AC Test Circuit

Parameter	Conditions	LM566C			Units
		Min	Typ	Max	
Maximum Operating Frequency	R0 = 2k C0 = 2.7 pF	0.5	1		MHz
VCO Free-Running Frequency	C_O = 1.5 nF R_O = 20k f_O = 10 kHz	−30	0	+30	%
Input Voltage Range Pin 5		¾ V_{CC}		V_{CC}	
Average Temperature Coefficient of Operating Frequency			200		ppm/°C
Supply Voltage Rejection	10–20V		0.1	2	%/V
Input Impedance Pin 5		0.5	1		MΩ
VCO Sensitivity	For Pin 5, From 8–10V, f_O = 10 kHz	6.0	6.6	7.2	kHz/V
FM Distortion	±10% Deviation		0.2	1.5	%
Maximum Sweep Rate			1		MHz
Sweep Range			10:1		
Output Impedance Pin 3			50		Ω
Pin 4			50		Ω
Square Wave Output Level	R_{L1} = 10k	5.0	5.4		Vp-p
Triangle Wave Output Level	R_{L2} = 10k	2.0	2.4		Vp-p
Square Wave Duty Cycle		40	50	60	%
Square Wave Rise Time			20		ns
Square Wave Fall Time			50		ns
Triangle Wave Linearity	+1V Segment at ½ V_{CC}		0.5		%

Note 1: The maximum junction temperature of the LM566CN is 150°C. For operation at elevated junction temperatures, maximum power dissipation must be derated based on a thermal resistance of 115°C/W, junction to ambient.

Applications Information

The LM566CN may be operated from either a single supply as shown in this test circuit, or from a split (±) power supply. When operating from a split supply, the square wave output (pin 3) is TTL compatible (2 mA current sink) with the addition of a 4.7 kΩ resistor from pin 3 to ground.

A 0.001 µF capacitor is connected between pins 5 and 6 to prevent parasitic oscillations that may occur during VCO switching.

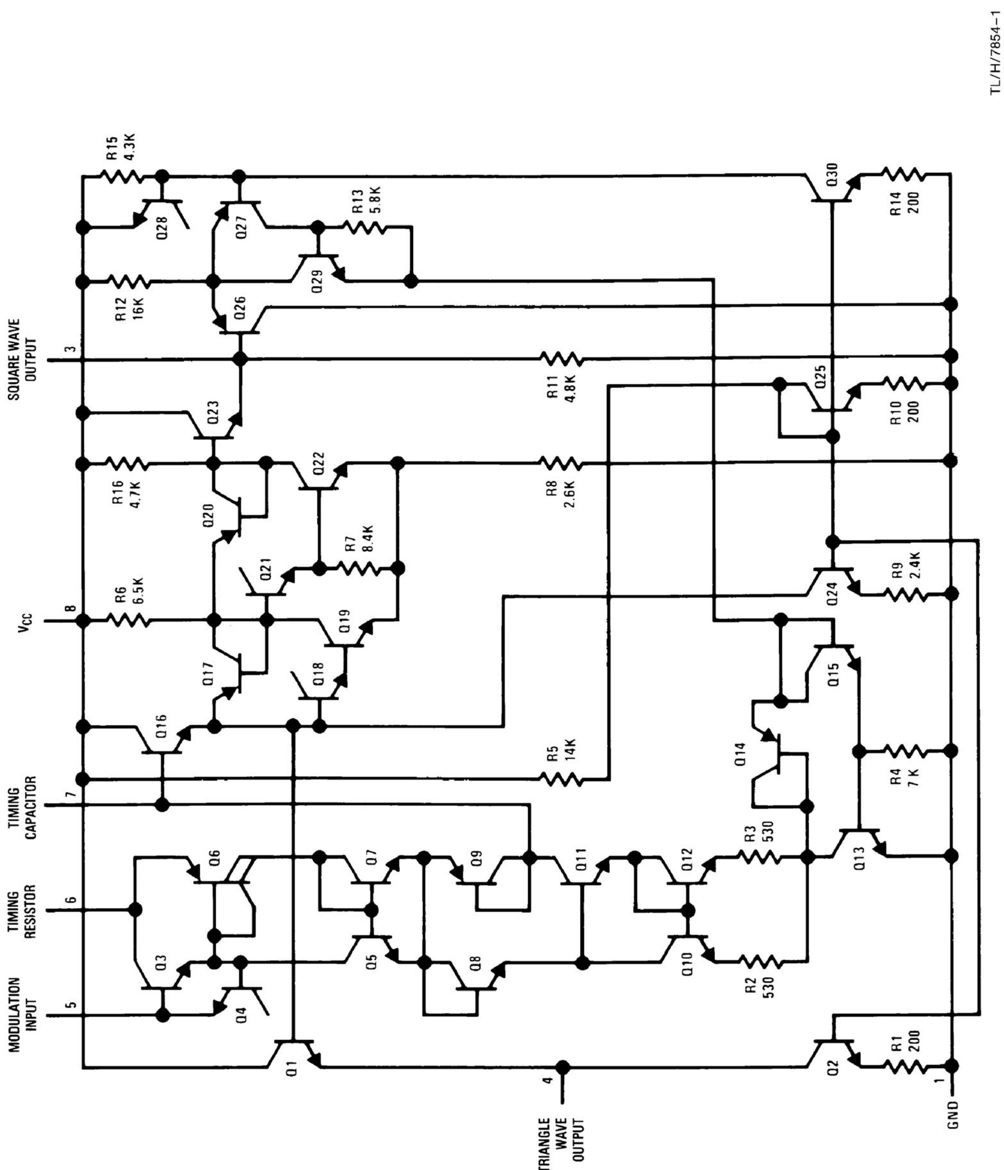
$$f_O = \frac{2.4(V^+ - V_5)}{R_O\, C_O\, V^+}$$

where

$2K < R_O < 20K$

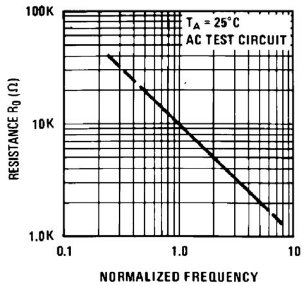
and V_5 is voltage between pin 5 and pin 1.

Schematic Diagram

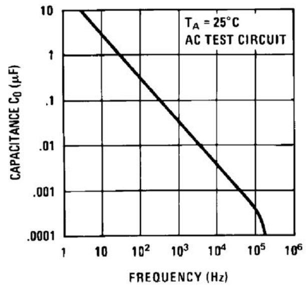


Typical Performance Characteristics

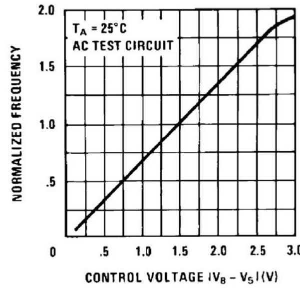
Operating Frequency as a Function of Timing Resistor



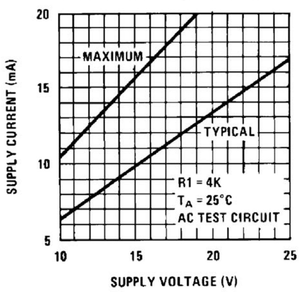
Operating Frequency as a Function of Timing Capacitor



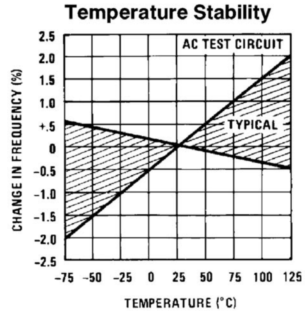
Normalized Frequency as a Function of Control Voltage



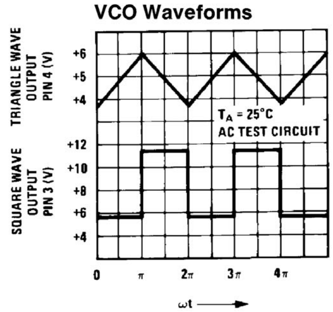
Power Supply Current



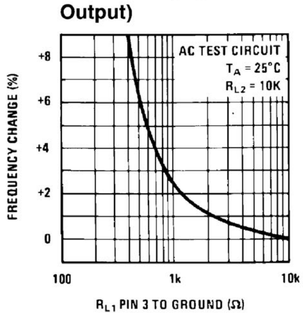
Temperature Stability



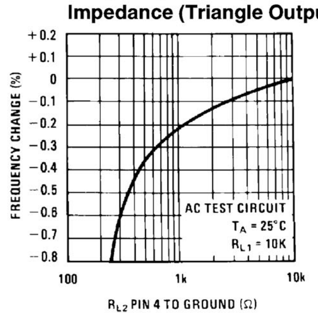
VCO Waveforms



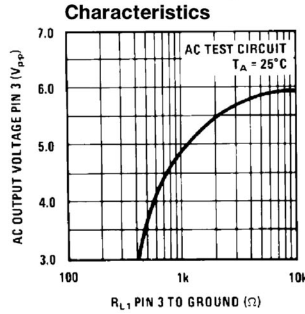
Frequency Stability vs Load Resistance (Square Wave Output)



Frequency Stability vs Load Impedance (Triangle Output)



Square Wave Output Characteristics



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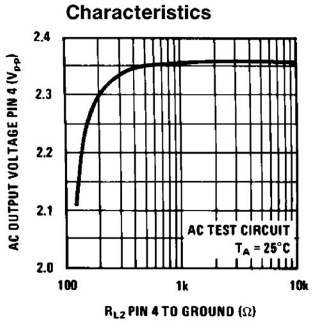
Triangle Wave Output Characteristics



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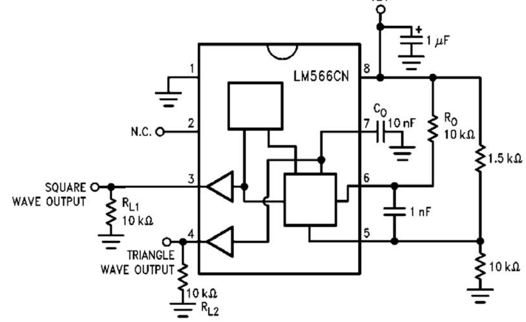
AC Test Circuit



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