本电路中的放大器必须满足单位增益稳定的要求，R6 和 R7 的作用是降低输入偏置电流引起的误差。

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注释 1：（NE5532 注）

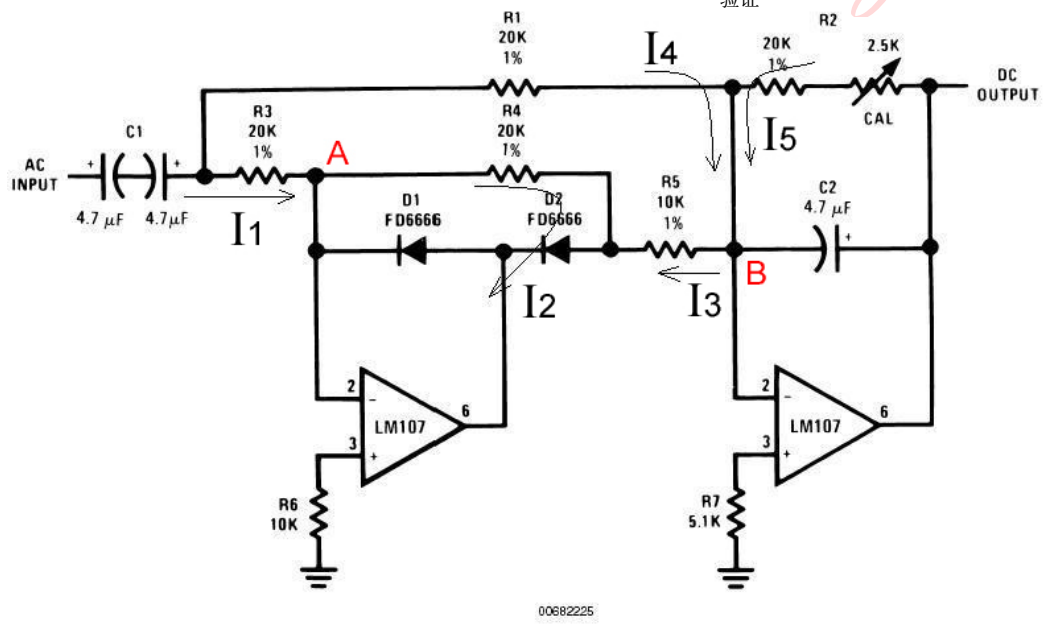


FIGURE 25. Full-Wave Rectifier and Averaging Filter

如上图，由 OP 的虚断特性，对 A 点做 KCL 方程，有：

$$I_1 = I_2$$

再由 OP 的虚短特性，A 点电位为 0V，则输出电压方程为：

$$U_o + U_D + R_4 I_2 = 0$$

其中U_D为二极管 D2 的前向降压，方程整理后为：

$$U_o + U_D + \frac{R_4 U_i}{R_3} = 0$$

由上可见U_D对输出电压的精度有影响。

注释 2：（NE5532 注）

首先，对节点处的电流讨论是没有意义的，流入节点的电流一定等于流出节点的电流，再者，I3 与 I4 不是等大反相的关系，分析如下：

由于此时 OPA1 处于反相放大状态，其输出电压$U_{o1} = -Ui$（忽略二极管带来的电压误差）

按照设计思路，此时 A2 的输出应该等于U_{o1}，则电流方向如上图。

$$I_5 = \frac{U_i}{R_1} = I_4 = \frac{U_{o2}}{R_2}$$

对 B 点运用 KCL 方程，则有：

$$I_3 = 2I_4$$

即得到：$R_5 = \frac{R_1}{2}$

17. Sine Wave Oscillator

正弦波振荡器：

An amplitude-stabilized sine-wave oscillator is shown in Figure 26. This circuit provides high purity sine-wave output down to low frequencies with minimum circuit complexity. An important advantage of this circuit is that the traditional tungsten filament lamp amplitude regulator is eliminated along with its time constant and linearity problems.

In addition, the reliability problems associated with a lamp are eliminated.

The Wien Bridge oscillator is widely used and takes advantage of the fact that the phase of the voltage across the parallel branch of a series and a parallel RC network connected in series, is the same as the phase of the applied voltage across the two networks at one particular frequency and that the phase lags with increasing frequency and leads with decreasing frequency. When this network—the Wien Bridge—is used as a positive feedback element around an amplifier, oscillation occurs at the frequency at which the phase shift is zero. Additional negative feedback is provided to set loop gain to unity at the oscillation frequency, to stabilize the frequency of oscillation, and to reduce harmonic distortion.

The circuit presented here differs from the classic usage only in the form of the negative feedback stabilization scheme. Circuit operation is as follows: negative peaks in excess of -8.25V cause D1 and D2 to conduct, charging C4. The charge stored in C4 provides bias to Q1, which determines amplifier gain. C3 is a low frequency roll-off capacitor in the feedback network and prevents offset voltage and offset current errors from being multiplied by amplifier gain.

Distortion is determined by amplifier open-loop gain and by the response time of the negative feedback loop filter, R5 and C4. A trade-off is necessary in determining amplitude stabilization time constant and oscillator distortion. R4 is chosen to adjust the negative feedback loop so that the FET is operated at a small negative gate bias. The circuit shown provides optimum values for a general purpose oscillator.

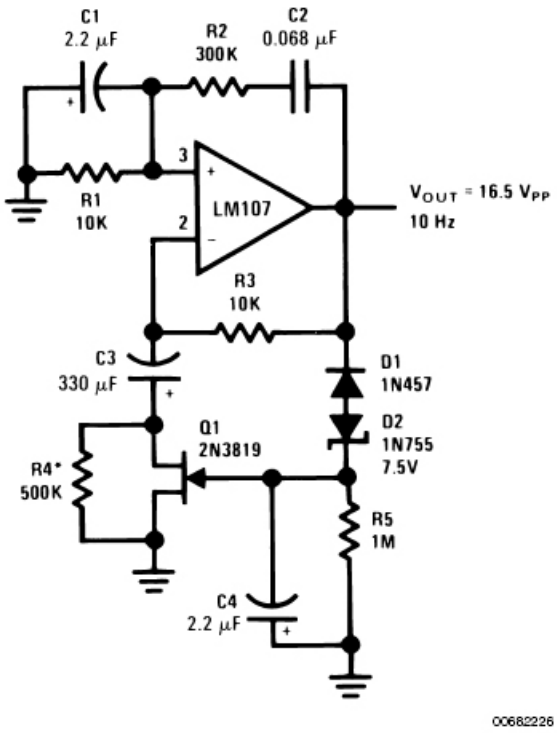


FIGURE 26. Wien Bridge Sine Wave Oscillator

图 26 给出了一个带稳幅功能的正弦波振荡器。这个电路以最简洁的结构实现了高纯净度正弦波输出，而且在较低的频率上也是如此。这个电路的主要优点之一是克服了传统钨丝灯幅值调节电路所带来的时间常数以及线性度方面的问题。

此外，灯泡的可靠性问题也无需再考虑了。

文氏桥振荡器一直都被广泛地应用着，该电路的原理是——如果将一个串联 RC 网络和一个并联 RC 网络串接起来，那么在某个特定频率下，电路输出电压的相位将与输入电压的相位相等，而当频率升高时，输出电压相位滞后，当频率降低时，输出电压相位超前。这个电路就是“文氏桥”，如果以文氏桥作为放大器的正反馈路径，那么当相移等于 0 的时候，就会出现振荡。为了使振荡频率稳定并降低谐波失真，需要加入一个在震荡频率处能够提供单位增益的负反馈路径。

本电路与经典电路的唯一区别在于负反馈稳定部分。电路原理如下：超出-8.25V 的负电平使 D1 和 D2 导通，给 C4 充电，C4 储存的电荷为 Q1 提供偏置，从而控制放大器的增益。C3 在反馈电路中起低通滤波的作用，防止失调电压和失调电流引起的误差被放大到输出端。

失真是开环增益和负反馈路径中滤波器的时间常数 R5C4 造成的。设计者需要在稳幅时间常数和振荡器的失真度之间进行权衡。R4 用来调整负反馈路径，使 FET 工作在微小的门极反相偏置电压下。对于一般性应用，*图 26* 电路中的参数可以提供最佳性能。

18. Triangle-Wave Generator

三角波发生器：

A constant amplitude triangular-wave generator is shown in Figure 27. This circuit provides a variable frequency triangular wave whose amplitude is independent of frequency.

The generator embodies an integrator as a ramp generator and a threshold detector with hysterisis as a reset circuit. The integrator has been described in a previous section and requires no further explanation. The threshold detector is similar to a Schmitt Trigger in that it is a latch circuit with a large dead zone. This function is implemented by using positive feedback around an operational amplifier. When the amplifier output is in either the positive or negative saturated state, the positive feedback network provides a voltage at the non-inverting input which is determined by the attenuation of the feedback loop and the saturation voltage of the amplifier. To cause the amplifier to change states, the voltage at the input of the amplifier must be caused to change polarity by an amount in excess of the amplifier input offset voltage. When this is done the amplifier saturates in the opposite direction and remains in that state until the voltage at its input again reverses. The complete circuit operation may be understood by examining the operation with the output of the threshold detector in the positive state. The detector positive saturation voltage is applied to the integrator summing junction through the combination R3 and R4 causing a current I+ to flow.

The integrator then generates a negative-going ramp with a rate of I+/C1 volts per second until its output equals the negative trip point of the threshold detector. The threshold detector then changes to the negative output state and supplies a negative current, I-, at the integrator summing point. The integrator now generates a positive-going ramp with a rate of I-/C1 volts per second until its output equals the positive trip point of the threshold detector where the detector again changes output state and the cycle repeats. Triangular-wave frequency is determined by R3, R4 and C1 and the positive and negative saturation voltages of the amplifier A1. Amplitude is determined by the ratio of R5 to the combination of R1 and R2 and the threshold detector saturation voltages. Positive and negative ramp rates are equal and positive and negative peaks are equal if the detector has equal positive and negative saturation voltages. The output waveform may be offset with respect to ground if the inverting input of the threshold detector, A1, is offset with respect to ground.

The generator may be made independent of temperature and supply voltage if the detector is clamped with matched zener diodes as shown in Figure 28.

The integrator should be compensated for unity-gain and the detector may be compensated if power supply impedance causes oscillation during its transition time. The current into the integrator should be large with respect to I_{bias} for maximum symmetry, and offset voltage should be small with respect to V_{OUT} peak.

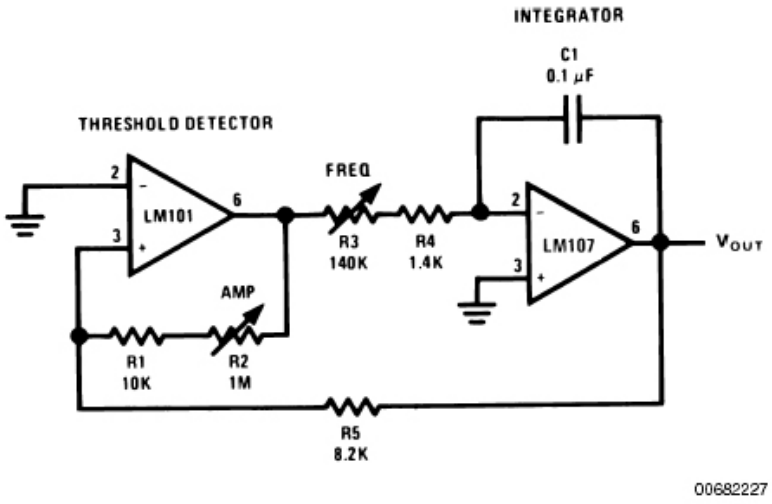


FIGURE 27. Triangular-Wave Generator

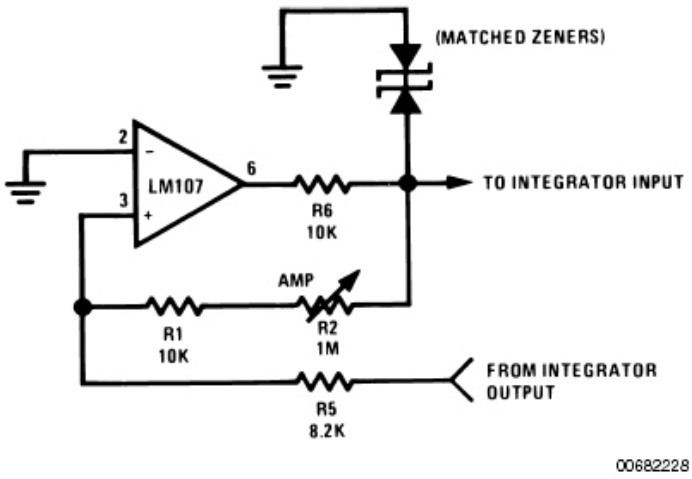


FIGURE 28. Threshold Detector with Regulated Output

图 27 所示电路是一个幅值固定不变的三角波发生器。该电路产生频率可变的三角波信号，但其幅值与频率无关。

此电路用积分器产生斜坡信号，用阈值检测器作为复位电路。积分器前文已详细介绍过，这里不再赘述。阈值检测器就是一种回差范围较大的锁存电路，与施密特触发器相似。电路的功能是通过 OP 的正反馈路径实现的。不论放大器输出是正是负，只要 OP 达到输出饱和

状态，OP 正反馈路径就会在 OP 同相输入端加上一个电压，该电压的大小由 OP 正反馈路径的衰减和 OP 输出饱和时的电压共同决定。为了使放大器的状态发生改变，OP 输入端的电压必须改变极性，并且改变量必须大于 OP 输入失调电压，接着放大器的输出就会改变极性并达到饱和，直到输入端的电压再次反相，再重复这个过程。掌握阈值检测器在正值输出时的工作过程就可以了解整个电路的原理。检测器的正的饱和输出电压通过 R3 和 R4 加在积分器的求和节点上，电流为 I+。

积分器随即产生由正到负的斜坡信号，斜率为 I+/C1（伏/秒）。当这个输出信号达到阈值检测器的低电压门限时，阈值检测器的输出变成负值，加在积分器求和节点的电流反向，变成 I-。积分器的输出变成由负到正的斜坡信号，斜率为 I-/C1（伏/秒）。当这个输出信号达到阈值检测器的高电压门限时，阈值检测器的输出再次变成正值，至此开始循环。三角波的频率是由 R3、R4、C1 以及 OPA1 的饱和输出电压的大小决定的。幅值则等于 R5 与 R1、R2（之和）的比值乘以阈值检测器的饱和输出电压。三角波信号两个斜边的斜率绝对值相等，如果阈值检测器正向饱和电压和反向饱和电压的大小相等，那么三角波信号的正向峰值和反向峰值也相等。如果阈值检测器 A1 的反相输入端对地有一个偏置电压，那么输出波形也将带有一个对地的偏置。

只要按***图 28*** 那样在阈值检测器中使用性能匹配的稳压二极管，那么这个信号发生器电路就可以做到与温度变化和电源电压变化无关。

图中积分器所用 OP 应该是单位增益稳定的，如果电源阻抗导致阈值检测器在输出转换期间发生振荡，那么阈值检测器也需要进行补偿。流入积分器的电流应该大于 I_{bias}，以求得最佳的对称性，失调电压也应小于 V_{OUT} 的峰值。

19. Tracking Regulated Power Supply

自动跟踪对称电源：

A tracking regulated power supply is shown in Figure 29. This supply is very suitable for powering an operational amplifier system since positive and negative voltages track, eliminating common mode signals originating in the supply voltage. In addition, only one voltage reference and a minimum number of passive components are required.

Power supply operation may be understood by considering first the positive regulator. The positive regulator compares the voltage at the wiper of R4 to the voltage reference, D2. The difference between these two voltages is the input voltage for the amplifier and since R3, R4, and R5 form a negative feedback loop, the amplifier output voltage changes in such a way as to minimize this difference. The voltage reference current is supplied from the amplifier output to increase power supply line regulation. This allows the regulator to operate from supplies with large ripple voltages. Regulating the reference current in this way requires a separate source of current for supply start-up. Resistor R1 and diode D1 provide this start-up current. D1 decouples the reference string from the amplifier output during start-up and R1 supplies the start-up current from the unregulated positive supply. After start-up, the low amplifier output impedance reduces reference current variations due to the current through R1.

The negative regulator is simply a unity-gain inverter withinput resistor, R6, and feedback resistor, R7.

The amplifiers must be compensated for unity-gain operation. The power supply may be modulated by injecting current into the wiper of R4. In this case, the output voltage variations will be equal and opposite at the positive and negative outputs.

The power supply voltage may be controlled by replacing D1, D2, R1 and R2 with a variable voltage reference.