An Applications Guide for OP Amps

National Semiconductor Corporation

运算放大器使用指南

美国国家半导体公司

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1. Introduction

概述：

The general utility of the operational amplifier is derived from the fact that it is intended for use in a feedback loop whose feedback properties determine the feed-forward characteristics of the amplifier and loop combination. To suit it for this usage, the ideal operational amplifier would have infinite input impedance, zero output impedance, infinite gain and an open-loop 3 dB point at infinite frequency rolling off at 6dB per octave. Unfortunately, the unit cost–in quantity-–would also be infinite.

Intensive development of the operational amplifier, particularly in integrated form, has yielded circuits which are quite good engineering approximations of the ideal for finite cost. Quantity prices for the best contemporary integrated amplifiers are low compared with transistor prices of five years ago. The low cost and high quality of these amplifiers allows the implementation of equipment and systems functions impractical with discrete components. An example is the low frequency function generator which may use 15 to 20 operational amplifiers in generation, wave shaping, triggering and phase-locking.

The availability of the low-cost integrated amplifier makes it mandatory that systems and equipments engineers be familiar with operational amplifier applications. This paper will present amplifier usages ranging from the simple unity-gain buffer to relatively complex generator and wave shaping circuits. The general theory of operational amplifiers is not within the scope of this paper and many excellent references are available in the literature.1,2,3,4 The approach will be shaded toward the practical, amplifier parameters will be discussed as they affect circuit performance, and application restrictions will be outlined.

The applications discussed will be arranged in order of increasing complexity in five categories: simple amplifiers, operational circuits, transducer amplifiers, wave shapers and generators, and power supplies. The integrated amplifiers shown in the figures are for the most part internally compensated so frequency stabilization components are not shown; however, other amplifiers may be used to achieve greater operating speed in many circuits as will be shown in the text. Amplifier parameter definitions are contained in Appendix I.

我们知道，通用 OP 工作在这样的情况下：在接入负反馈环路后，OP 和反馈环路的特性仅由反馈环路来决定。为了得到这样的特性，理想 OP 应该有无限大的输入阻抗，0 输出内阻抗，无限大的增益，无限大的开环增益带宽（3dB 带宽），以及其 6dB/每 2 倍频程的频率滚降。不幸的是，要想实现这样的电路，其成本也将是无限的。

OP 技术上的发展，特别是在整合周边电路方面的进步，使得我们能够用有限的成本，在工程上实现近似于理想状态的 OP。在计入数量因素后，使用同时期的高性能集成 OP 的成本已经比 5 年前使用分立元件的成本大大下降。正是有了 OP 这种高性能，低成本的产品，才使得一些原来为分立元件系统成本和技术所限制的电路得以实现。一个很好的例子就是低频函数发生器，它可以由 15 到 20 片 OP 完成，包括波形整形，触发和相位锁定电路。

使用OP可以降低生产的成本，这使得系统和设备设计工程师们有必要熟悉OP的特性。本文将讲述OP的使用方法，从简单的缓冲器到复杂的信号发生器和波形整形电路。本文不讨论OP的基本理论，请参阅附注里的参考文献1，2，3，4。本文仅讨论OP的实际应用，OP参数的选择对电路的影响，并给出应用限制条件的概述。

我们按照从简到繁，分 5 个阶段来讨论 OP 的运用：简单放大器，运算电路，信号变送电路，整形电路和信号发生电路，电源电路。我们所例举的集成 OP，一般包含了内部频率补偿电路，所以外部频率补偿电路没有给出。当然，我们也可以选择其他的 OP 以达到更高的工作频率。OP 的参数说明在附件 I 里。

2. The Inverting Amplifier

反相放大器：

The basic operational amplifier circuit is shown in Figure 1. This circuit gives closed-loop gain of R2/R1 when this ratio is small compared with the amplifier open-loop gain and, as the name implies, is an inverting circuit. The input impedance is equal to R1. The closed-loop bandwidth is equal to the unity-gain frequency divided by one plus the closed-loop gain.

The only cautions to be observed are that R3 should be chosen to be equal to the parallel combination of R1 and R2 to minimize the offset voltage error due to bias current and that there will be an offset voltage at the amplifier output equal to closed-loop gain times the offset voltage at the amplifier input.

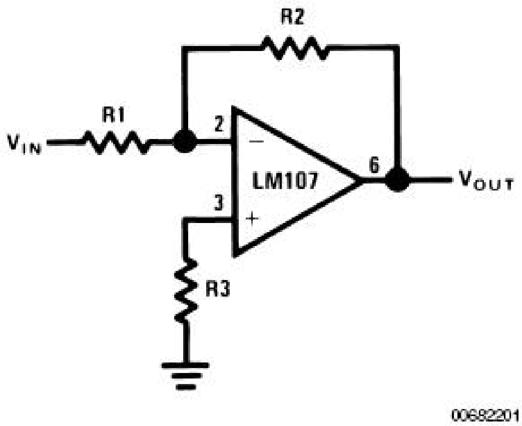
Offset voltage at the input of an operational amplifier is comprised of two components, these components are identified in specifying the amplifier as input offset voltage and input bias current. The input offset voltage is fixed for a particular amplifier, however the contribution due to input bias current is dependent on the circuit configuration used. For minimum offset voltage at the amplifier input without circuit adjustment the source resistance for both inputs should be equal. In this case the maximum offset voltage would be the algebraic sum of amplifier offset voltage and the voltage drop across the source resistance due to offset current. Amplifier offset voltage is the predominant error term for low source resistances and offset current causes the main error for high source resistances.

In high source resistance applications, offset voltage at the amplifier output may be adjusted by adjusting the value of R3 and using the variation in voltage drop across it as an input offset voltage trim.

Offset voltage at the amplifier output is not as important in AC coupled applications. Here the only consideration is that any offset voltage at the output reduces the peak to peak linear output swing of the amplifier.

The gain-frequency characteristic of the amplifier and its feedback network must be such that oscillation does not occur. To meet this condition, the phase shift through amplifier and feedback network must never exceed 180° for any frequency where the gain of the amplifier and its feedback network is greater than unity. In practical applications, the phase shift should not approach 180° since this is the situation of conditional stability. Obviously the most critical case occurs when the attenuation of the feedback network is zero. Amplifiers which are not internally compensated may be used to achieve increased performance in circuits where feedback network attenuation is high. As an example, the LM101 may be operated at unity gain in the inverting amplifier circuit with a 15 pF compensating capacitor, since the feedback network has an attenuation of 6 dB, while it requires 30 pF in the non-inverting unity gain connection where the feedback network has zero attenuation. Since amplifier slew rate is dependent on compensation, the LM101 slew rate in the inverting unity gain connection will be twice that for the non-inverting connection and the inverting gain of ten connection will yield eleven times the slew rate of the non-inverting unity gain connection. The compensation trade-off for a particular connection is stability versus bandwidth, larger values of compensation capacitor yield greater stability and lower bandwidth and vice versa.

The preceding discussion of offset voltage, bias current and stability is applicable to most amplifier applications and will be referenced in later sections. A more complete treatment is contained in Reference 4.



$$V_{OUT} = \frac{R2}{R1} V_{IN}$$

$$R3 = R1 \parallel R2$$

For minimum error due to input bias current

FIGURE 1. Inverting Amplifier

基本的反相放大器电路示于图 1。顾名思义，在 R2/R1 的数值远小于 OP 开环增益时，这个数值就是反相放大器的增益。输入阻抗就是 R1 的阻值，闭环增益带宽=单位增益带宽/（1+闭环增益）

在设计中需要注意的是：R3 的阻值应该等于 R1 和 R2 的并联电阻，以减小输入偏置电流所带来的失调电压。输出失调电压=输入失调电压*闭环增益

OP 输入端的失调电压有两个主要的来源，输入偏置电流（Input bias current）和输入失

调电压（Input offset voltage）。对于一个给定的 OP，输入失调电压就已经确定了，但是由输入失调电流所带来的失调电压与所采用的电路结构有关系，为了在不使用调整电路的情况下减小输入偏置电流所带来的失调电压，应该使得同、反相输入端对地的直流电阻相等，使得由于偏置电流在输入电阻上压降所带来的失调电压相互抵消。在对低内阻信号源的放大器中，OP 的输入失调电压将成为失调电压误差的主要来源，而对于高内阻信号源的放大器，OP 的输入偏置电流在信号源内阻上的压降将成为上述误差的主要来源。

在高输入阻抗的情况下，失调电压可以采用 R3 的阻值来调整，利用输入偏置电流在其上的压降来对输入失调电压作出补偿（既用这个的得到的压降来抵消输入失调电压）。

在交流耦合的时候，失调电压并不显得很重要，这时的主要问题是：失调电压减小了输出电压峰—峰值（P-P）的线性动态范围。

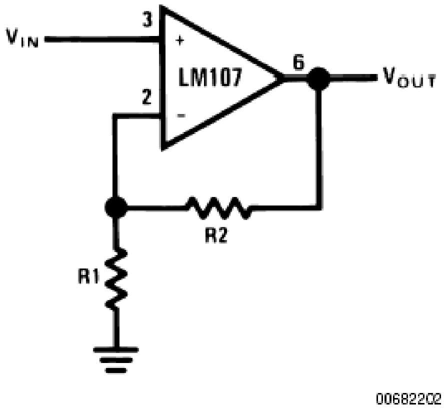
工作在闭环状态下的 OP 和其反馈网络的增益——频率特性，必须保证不会产生震荡。为了实现稳定，OP 和反馈环路对任何频率的信号，在环路增益大于 1 时的环路相移角度绝对不能超过 180°。在实践上，为了达到稳定条件，相移角度不应该接近 180°。显然，最为临界的状态发生在反馈网络的衰减为 0 的时候（既跟随器状态）。没有做内部补偿的 OP 可以被用在深度反馈电路中以取得更好的频率特性。举一个例子：LM101 在反相单位增益电路中，由于反馈网络 6dB 的衰减，仅需要 15pF 的补偿电容；但在同相单位增益电路中，由于反馈环路没有衰减，就需要 30pF 的补偿电容。由于 OP 的转换速度（SR）取决于补偿电容的大小， LM101 的 SR 在反相单位增益电路里可以做到同相单位增益电路的 2 倍。反相电路在同等 SR 的条件下可以做到跟随器电路的 110%。对于一个给定的 OP 放大器电路，在进行补偿时需要在稳定性和带宽之间进行进行权衡。加大补偿电容可以提高稳定性，但是牺牲了放大器的增益带宽，反之亦然。

上面对失调电压、输入偏置电流的讨论可以适用于绝大多数放大器，在后面的讨论中也会再次涉及，更深入的介绍请参见***参考文献 4***。

3. The Non-Inverting Amplifier

同相放大器：

Figure 2 shows a high input impedance non-inverting circuit. This circuit gives a closed-loop gain equal to the ratio of the sum of R1 and R2 to R1 and a closed-loop 3 dB bandwidth equal to the amplifier unity-gain frequency divided by the closed-loop gain. The primary differences between this connection and the inverting circuit are that the output is not inverted and that the input impedance is very high and is equal to the differential input impedance multiplied by loop gain. (Open loop gain/Closed loop gain.) In DC coupled applications, input impedance is not as important as input current and its voltage drop across the source resistance. Applications cautions are the same for this amplifier as for the inverting amplifier with one exception. The amplifier output will go into saturation if the input is allowed to float. This may be important if the amplifier must be switched from source to source. The compensation trade off discussed for he inverting amplifier is also valid for this connection.



$$V_{OUT} = \frac{R1 + R2}{R1} V_{IN}$$

$R1 \parallel R2 = R_{SOURCE}$

For minimum error due to input bias current

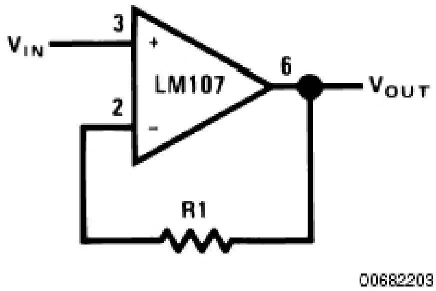
FIGURE 2. Non-Inverting Amplifier

图2 给出了一个高输入阻抗，同相放大器电路的电路。其闭环放大倍数为（R1+R2）/R1，其闭环 3dB 带宽为其单位增益带宽除以其闭环增益。和反相电路相比，其最大的不同点在于，其输出信号和输入信号是同相的，其输入阻抗也是相当高的，为 OP 差模输入阻抗与环路增益的乘积（环路增益为：开环增益/闭环增益）。在直流耦合情况下，输入阻抗对于 OP 电路的影响作用比起输入电流，主要是由于其在信号源内阻上所带来的压降来说，是在次要地位的。对于本电路的应用注意事项，除了一点之外均和反相放大器相同：在输入端悬浮的状态下，本电路的输出可能饱和。这点在要求 OP 输出电压范围能够达到电源电压范围的时候很重要。对补偿的讨论和反相放大器相同。

4. The Unity-Gain Buffer

单位增益缓冲器：

The unity-gain buffer is shown in Figure 3. The circuit gives the highest input impedance of any operational amplifier circuit. Input impedance is equal to the differential input impedance multiplied by the open-loop gain, in parallel with common mode input impedance. The gain error of this circuit is equal to the reciprocal of the amplifier open-loop gain or to the common mode rejection, whichever is less. Input impedance is a misleading concept in a DC coupled unity-gain buffer. Bias current for the amplifier will be supplied by the source resistance and will cause an error at the amplifier input due to its voltage drop across the source resistance. Since this is the case, a low bias current amplifier such as the LH1026 should be chosen as a unity-gain buffer when working from high source resistances. Bias current compensation techniques are discussed in Reference 5. The cautions to be observed in applying this circuit are three: the amplifier must be compensated for unity gain operation, the output swing of the amplifier may be limited by the amplifier common mode range, and some amplifiers exhibit a latch-up mode when the amplifier common mode range is exceeded. The LM107 may be used in this circuit with none of these problems; or, for faster operation, the LM102 may be chosen.



$V_{OUT} = V_{IN}$

$R1 = R_{SOURCE}$

For minimum error due to input bias current

FIGURE 3. Unity Gain Buffer

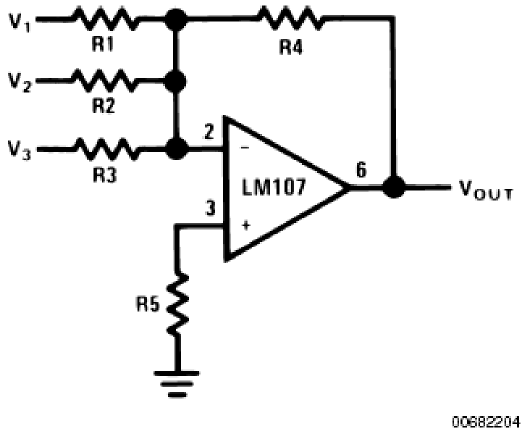
*图3*给出了单位增益放大器（缓冲器、跟随器——译者）的电路。这个电路在所有的放大器组态电路中具有最高的输入阻抗。其输入阻抗值为，开环增益与差模输入阻抗之积和共模输入阻抗相并联。其增益误差等于开环增益的倒数、CMRR值中较小者。在这种直流耦合，单位增益组态下，输入电阻是一个不合适的电路概念。由于输入偏置电流由信号源提供，这样就会在信号源的内阻上造成压降，成为输入信号电压的误差来源。在这种情况下，可以选用例如LH1026之类的低偏置电流的OP，以便减小在对高内阻信号源放大的情况下的误差。偏置电流补偿技术请*参考文献5*。本电路的设计注意事项有3个：必须对OP在单位增益状态下作补偿。输出电压的摆幅可能会被OP的共模范围所限制。在输入超过起共模范围时，有

的OP可能会进入阻塞状态。LM107可以避免上述问题，另外也可以选用高速OP，LM102。

5. Summing Amplifier

加法器：

The summing amplifier, a special case of the inverting amplifier, is shown in Figure 4. The circuit gives an inverted output which is equal to the weighted algebraic sum of all three inputs. The gain of any input of this circuit is equal to the ratio of the appropriate input resistor to the feedback resistor, R4. Amplifier bandwidth may be calculated as in the inverting amplifier shown in Figure 1 by assuming the input resistor to be the parallel combination of R1, R2, and R3. Application cautions are the same as for the inverting amplifier. If an uncompensated amplifier is used, compensation is calculated on the basis of this bandwidth as is discussed in the section describing the simple inverting amplifier. The advantage of this circuit is that there is no interaction between inputs and operations such as summing and weighted averaging are implemented very easily.



$$V_{OUT} = -R4\left(\frac{V_1}{R1} + \frac{V_2}{R2} + \frac{V_3}{R3}\right)$$

R5 = R1 ‖ R2 ‖ R3 ‖ R4

For minimum offset error due to input bias current

FIGURE 4. Summing Amplifier

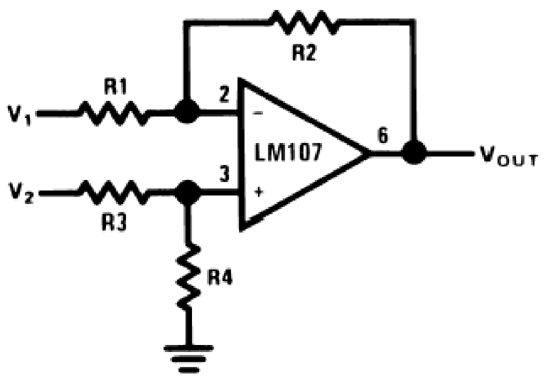
求和电路是反相放大器的一种特殊形式。如*图4*。其输出电压为3个输入电压加权代数和取反（因为其为反相电路，其每路的增益为负值——译者）。每路输入电压的增益等于其反馈电阻和输入电阻之比（取反——译者）。增益带宽的计算方式和反相放大电路相同，参见例1，将其输入电阻替换为R1、R2、R3的并联电阻值。应用上的注意事项和反相放大电路相同。如果使用了没有内部补偿功能的OP，应该在简单反相器的带宽的基础上计算补偿量。这个电路的特点在于：各个输入之间相互不影响，求和或者取平均的功能很容易就可以实现。

6. The Difference Amplifier

差分放大器：

The difference amplifier is the complement of the summing amplifier and allows the subtraction of two voltages or, as a special case, the cancellation of a signal common to the two inputs. This circuit is shown in Figure 5 and is useful as a computational amplifier, in making a differential to single-ended conversion or in rejecting a common mode signal.

Circuit bandwidth may be calculated in the same manner as for the inverting amplifier, but input impedance is somewhat more complicated. Input impedance for the two inputs is not necessarily equal; inverting input impedance is the same as for the inverting amplifier of Figure 1 and the non-inverting input impedance is the sum of R3 and R4. Gain for either input is the ratio of R1 to R2 for the special case of a differential input single-ended output where R1 = R3 and R2 = R4. The general expression for gain is given in the figure. Compensation should be chosen on the basis of amplifier bandwidth. Care must be exercised in applying this circuit since input impedances are not equal for minimum bias current error.



$$V_{OUT} = \left(\frac{R1 + R2}{R3 + R4}\right)\frac{R4}{R1}V_2 - \frac{R2}{R1}V_1$$

For R1 = R3 and R2 = R4

$$V_{OUT} = \frac{R2}{R1}(V_2 - V_1)$$

R1 || R2 = R3 || R4

For minimum offset error due to input bias current

FIGURE 5. Difference Amplifier

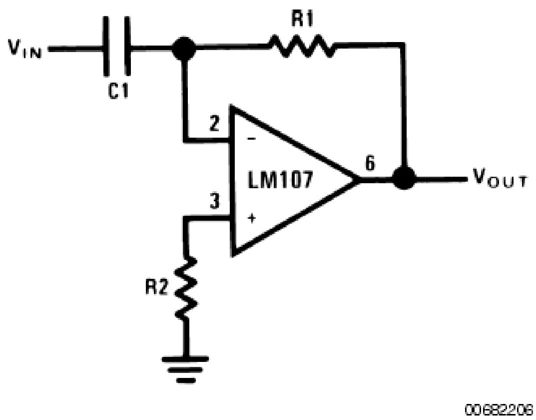
差分放大器是对求和电路的发展，这种电路可以减小甚至去处两个输入信号中的共模成分。电路见***图5***，这种电路在运算电路中相当有用，比如差分对单端的转换，抑制共模信号。

电路带宽的计算方式和反相电路相同。输入阻抗的计算方式相对复杂。两个输入端的输入阻抗没有必要相等；反相放大部分的输入阻抗和反相放大器的计算方法相同。同相放大部分的输入阻抗为R3、R4之和。在R1=R3，R2=R4，差分输入，单端输出的特殊情况下，两个输入的增益都是R2/R1。一般情况下增益的计算方法见图中说明。补偿可以按照放大器的具体带宽进行。在应用中应该注意一点：两端的输入阻抗是不相等的，要注意输入偏置电流的引起的误差。

7. Differentiator

微分器：

The differentiator is shown in Figure 6 and, as the name implies, is used to perform the mathematical operation of differentiation. The form shown is not the practical form, it is a true differentiator and is extremely susceptible to high frequency noise since AC gain increases at the rate of 6 dB per octave. In addition, the feedback network of the differentiator, R1C1, is an RC low pass filter which contributes 90° phase shift to the loop and may cause stability problems even with an amplifier which is compensated for unity gain.



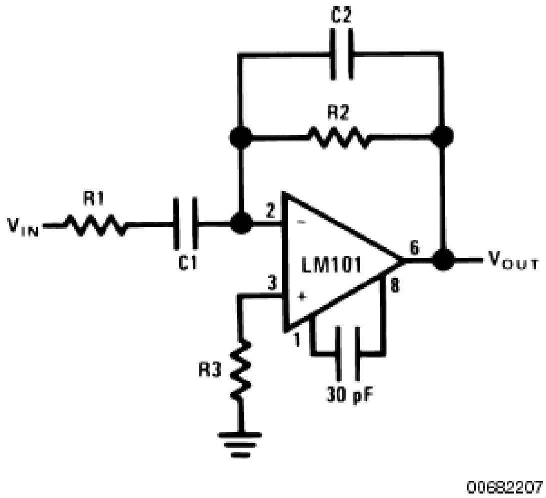
$$V_{OUT} = -R1C1\frac{d}{dt}(V_{IN})$$

R1 = R2

For minimum offset error due to input bias current

FIGURE 6. Differentiator

A practical differentiator is shown in Figure 7. Here both the stability and noise problems are corrected by addition of two additional components, R1 and C2. R2 and C2 form a 6 dB per octave high frequency roll-off in the feedback network and R1C1 form a 6 dB per octave roll-off network in the input network for a total high frequency roll-off of 12 dB per octave to reduce the effect of high frequency input and amplifier noise. In addition R1C1 and R2C2 form lead networks in the feedback loop which, if placed below the amplifier unity gain frequency, provide 90° phase lead to compensate the 90° phase lag of R2C1 and prevent loop instability. A gain frequency plot is shown in Figure 8 for clarity.



$$f_c = \frac{1}{2\pi R2C1}$$

$$f_h = \frac{1}{2\pi R1C1} = \frac{1}{2\pi R2C2}$$

$$f_c \ll f_h \ll f_{unity\ gain}$$

FIGURE 7. Practical Differentiator

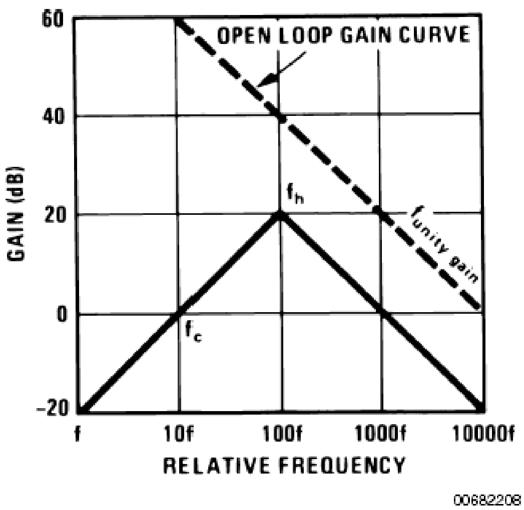


FIGURE 8. Differentiator Frequency Response

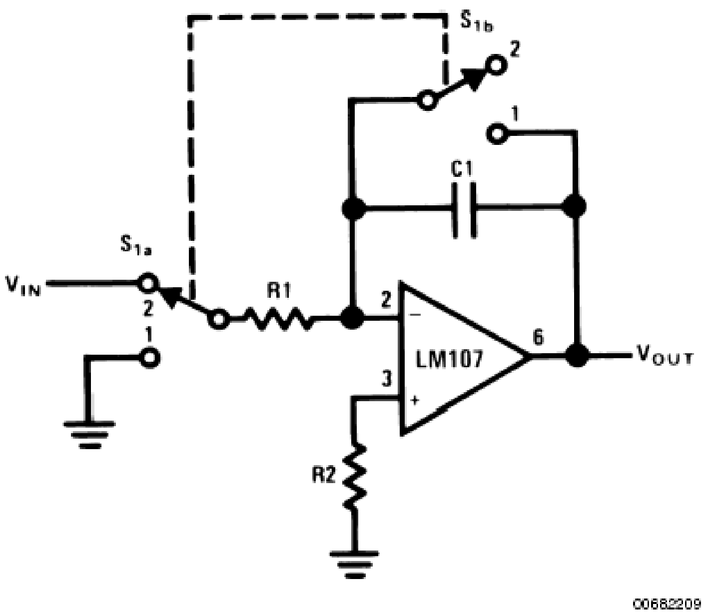
微分器的电路如*图6*，其用于实现数学上的微分运算。这里给出的电路形式不是实际的应用形式。由于其6dB/2倍频程的交流增益特性，其对高频噪声将相当敏感。反馈环路中，R1C1组成了一个等效的低通滤波器，由于其在反馈环中90°的相移，即使对单位增益采取了补偿措施，在这里也可能出现稳定性问题。

*图7*为微分器的实际应用电路。这个电路考虑了稳定性因素和噪声因素，增加了R1和C2。R2-C2在反馈环路上构成了一个6dB/2倍频程的高频衰减网络，R1-C1在输入上构成了一个6dB/2倍频程衰减网络，这样，整个频率特性呈现为12dB/2倍频程的高频衰减，抑制了由于高频信号输入OP所带来的噪声。R1C1、R2C2一同在反馈环路上构成了一个网络，如果将其频点设置在OP的单位增益带宽之内，其将提供90°前向相移，以补偿由R2-C1带来的90°相位滞后，提高环路的稳定性。波特图如*图8*所示。

8. Integrator

积分器：

The integrator is shown in Figure 9 and performs the mathematical operation of integration. This circuit is essentially a low-pass filter with a frequency response decreasing at 6 dB per octave. An amplitude-frequency plot is shown in Figure 10. The circuit must be provided with an external method of establishing initial conditions. This is shown in the figure as S1. When S 1 is in position 1, the amplifier is connected in unity-gain and capacitor C1 is discharged, setting an initial condition of zero volts. When S1 is in position 2, the amplifier is connected as an integrator and its output will change in accordance with a constant times the time integral of the input voltage. The cautions to be observed with this circuit are two: the amplifier used should generally be stabilized for unity-gain operation and R2 must equal R1 for minimum error due to bias current.



$$V_{OUT} = \frac{1}{R1C1}\int_{t_1}^{t_2} V_{IN}\,dt$$

$$f_c = \frac{1}{2\pi R1C1}$$

$$R1 = R2$$

For minimum offset error due to input bias current

FIGURE 9. Integrator

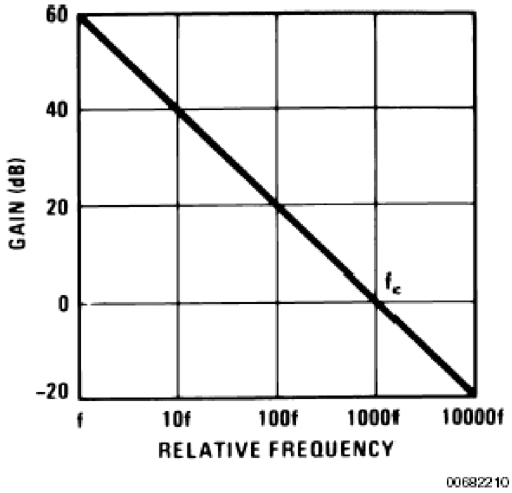


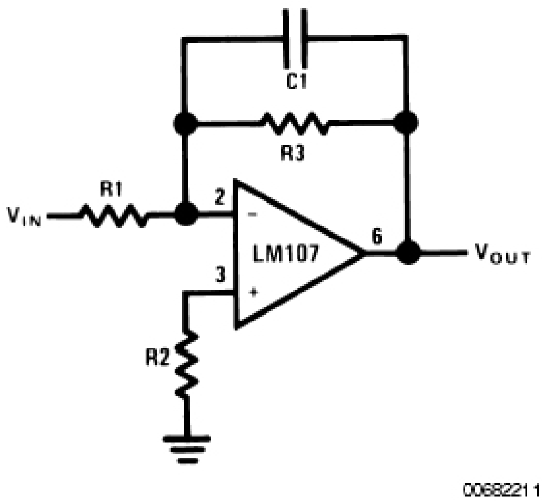
FIGURE 10. Integrator Frequency Response

积分器用于实现数学上的积分运算，如*图9*所示。在本质上，积分器可以看成是一个呈6dB/2倍频程频率特性的LPF，波特图见*图10*。积分器必须加入初始化电路，以给电路创造积分的初始化条件。图中S1的目的就在于此，当S1在1位置时，OP工作在单位增益（跟随器）状态。电容C1上的电荷被释放掉，使得积分初始值为0；当S1在2位置时，OP工作在积分器状态，其输出将为输入信号电压幅度对时间的积分与一个常数之积。在使用本电路时注意两点：OP在单位增益状态下应能稳定，R1和R2的阻值必须相等，以减小输入偏置电流所带来的误差。

9. Simple Low-pass Filter

简单低通滤波器：

The simple low-pass filter is shown in Figure 11. This circuit has a 6 dB per octave roll-off after a closed-loop 3 dB point defined by fc. Gain below this corner frequency is defined by the ratio of R3 to R1. The circuit may be considered as an AC integrator at frequencies well above fc; however, the time domain response is that of a single RC rather than an integral. R2 should be chosen equal to the parallel combination of R1 and R3 to minimize errors due to bias current. The amplifier should be compensated for unity-gain or an internally compensated amplifier can be used. A gain frequency plot of circuit response is shown in Figure 12 to illustrate the difference between this circuit and the true integrator.



$$f_L = \frac{1}{2\pi R1C1}$$

$$f_C = \frac{1}{2\pi R3C1}$$

$$A_L = \frac{R3}{R1}$$

FIGURE 11. Simple Low Pass Filter

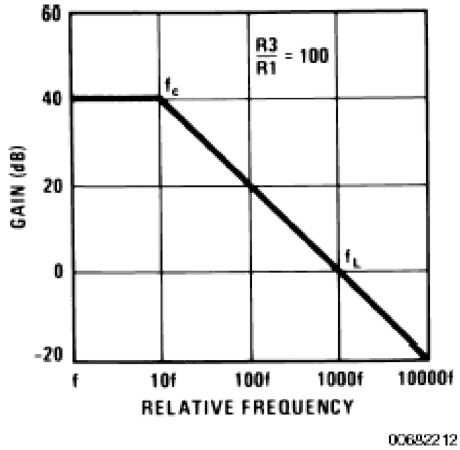


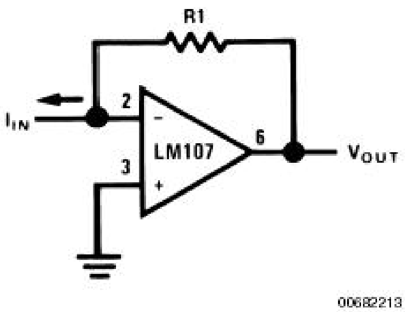
FIGURE 12. Low Pass Filter Response

简单低通滤波器的电路如*图11*。本电路在闭环3dB转折点为fc，对高于fc的信号有6dB/2倍频程的衰减。低于fc频率的信号的增益由R3/R1决定，在输入信号频率远大于fc的情况下，电路可以看成是对交流信号的积分器；可以认为，在此时，从时域响应上看，比起积分来说，RC（的时间延迟特性）更明显。R2的阻值应选为R1和R3的并联阻值，以减小输入偏置电流带来的误差。在这里可以选择带内部频率补偿的OP或者在外部对单位增益的频率特性进行补偿。电路的增益波特图见*图12*，本图说明了LPF和真正的积分器之间在频率特性上的区别。

10. The Current-to-Voltage Converter

电流—电压转换电路：

Current may be measured in two ways with an operational amplifier. The current may be converted into a voltage with a resistor and then amplified or the current may be injected directly into a summing node. Converting into voltage is undesirable for two reasons: first, an impedance is inserted into the measuring line causing an error; second, amplifier offset voltage is also amplified with a subsequent loss of accuracy. The use of a current-to-voltage transducer avoids both of these problems. The current-to-voltage transducer is shown in Figure 13. The input current is fed directly into the summing node and the amplifier output voltage changes to extract the same current from the summing node through R1. The scale factor of this circuit is R1 volts per amp. The only conversion error in this circuit is I_{bias} which is summed algebraically with I_{IN}. This basic circuit is useful for many applications other than current measurement. It is shown as a photocell amplifier in the following section. The only design constraints are that scale factors must be chosen to minimize errors due to bias current and since voltage gain and source impedance are often indeterminate (as with photocells) the amplifier must be compensated for unity-gain operation. Valuable techniques for bias current compensation are contained in Reference 5.



$V_{OUT} = I_{IN}\,R1$

FIGURE 13. Current to Voltage Converter

利用OP进行电流测量，有两种方法。利用电流在电阻上的压降，再进行电压放大，或者直接将电流注入OP的求和点。这样的电路，转换得到的电压信号可以直接加在OP放大的输入端上。这种转换方式有两个不妥的地方：首先电阻的加入将会破坏电路原来的状态，带来测量上的误差。其次OP的失调电压也会被OP自己放大，并加到测量的输出结果中去。使用电流——电压转换电路可以避免上面两点不足。电路结构如*图13*。输入电流直接接入OP的求和点（反相输入端），由KCL定理可知，OP输出端将通过R1向这个点（求和点）提供同样大小的电流以达到平衡，电路的增益（这里叫跨导似乎更好——译者）由R1决定。本电路唯一的误差来源于输入偏置电流I_{bias}，该电流作为误差，和输入电流I_{IN}做了代数叠加。

电流——电压转换电路的用途不限于电流的测量上，还可以用在例如后面的光电池放大电路中。在设计中唯一需要注意的是电路的增益的选择，增益的选择要做到使得偏置电流所带来的误差达到最小。由于信号源的电压和内阻通常是不恒定的，OP必须对单位增益做补偿。偏置电流的补偿方法可以参考***文献5***。

11. Photocell Amplifiers

光电放大器：

Amplifiers for photoconductive, photodiode and photovoltaic cells are shown in Figures 14, 15, 16 respectively. All photogenerators display some voltage dependence of both speed and linearity. It is obvious that the current through a photoconductive cell will not display strict proportionality to incident light if the cell terminal voltage is allowed to vary with cell conductance. Somewhat less obvious is the fact that photodiode leakage and photovoltaic cell internal losses are also functions of terminal voltage.

The current-to-voltage converter neatly sidesteps gross linearity problems by fixing a constant terminal voltage, zero in the case of photovoltaic cells and a fixed bias voltage in the case of photoconductors or photodiodes.

Photodetector speed is optimized by operating into a fixed low load impedance. Currently available photovoltaic detectors show response times in the microsecond range at zero load impedance and photoconductors, even though slow, are materially faster at low load resistances. The feedback resistance, R1, is dependent on cell sensitivity and should be chosen for either maximum dynamic range or for a desired scale factor. R2 is elective: in the case of photovoltaic cells or of photodiodes, it is not required in the case of photoconductive cells, it should be chosen to minimize bias current error over the operating range.

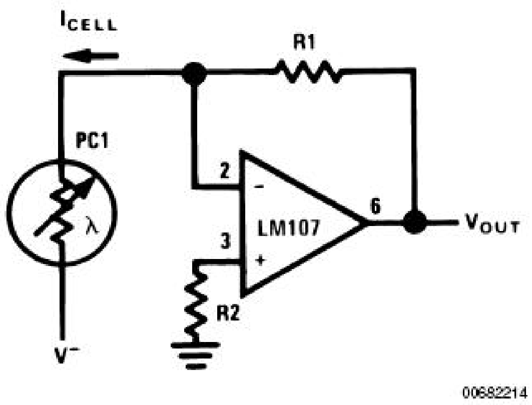
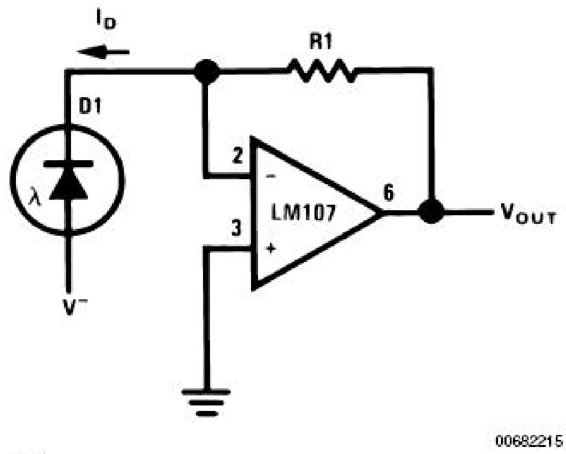
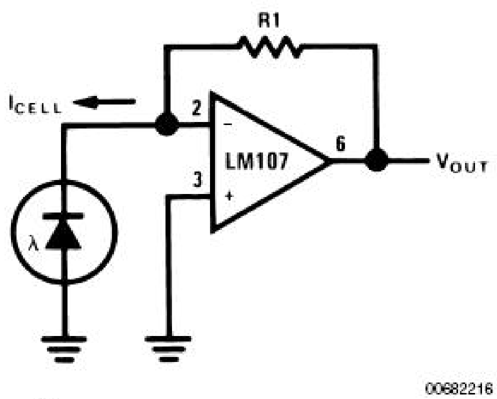


FIGURE 14. Amplifier for Photoconductive Cell



$V_{OUT} = R1\ I_D$

FIGURE 15. Photodiode Amplifier



$V_{OUT} = I_{CELL}\ R1$

FIGURE 16. Photovoltaic Cell Amplifier

光电放大器用于放大由光电导、光电二极管和光电池所得到的光强度信号，如*图* ***14***、***15***、***16***。这些光电传感器的输出电压与线性度和（响应）速度有关。显然，如果任由光电导电池的端电压随其电导变化而变化，那么其输出电流与入射光强度之间就不会遵循严格的比例关系。此外，光电二极管的漏电流和光电池的内部损耗也是其端电压的函数。

电流——电压转换电路利用在光电检测器的输出端加上一个恒定的电压来巧妙地解决了整体上的线性度问题。对于光电池来说，这个电压为 0V；对于光电导或光电二极管来说，是一个偏置电压。

光电检测器件，在负载为适当的低阻抗时，其信号转换速度将得到优化。现行的光电检测器在 0 负载的情况下，响应速度可以达到毫秒数量级，半导体光电器件稍慢，但是在低阻抗负载的情况下，其速度也会得到质的提高。反馈电阻 R1 的取值由电池的灵敏度和要求的最大动态范围，或者需要的电流——电压转换比例决定。R2 分情况选取：在光电池和光电二极管时不需要这个电阻，在光电导的时候，电阻的阻值应该能使在工作范围内，由 OP 输入偏置电流所带来的误差最小。

12. Precision Current Source

精密电流源：

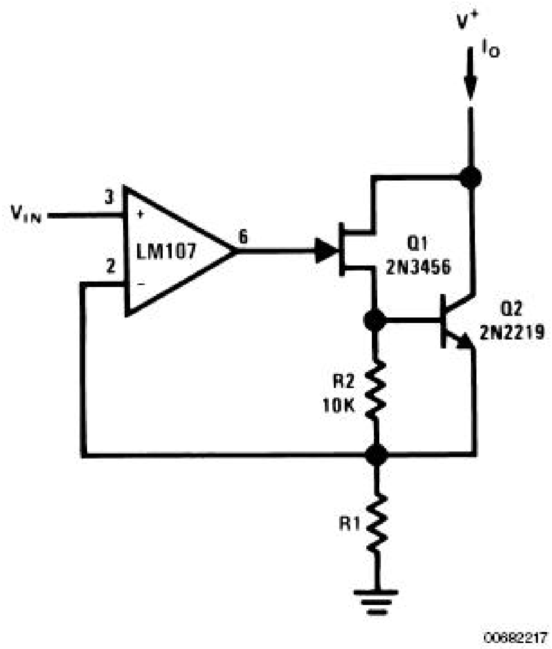
The precision current source is shown in Figures 17, 18. The configurations shown will sink or source conventional current respectively.

Caution must be exercised in applying these circuits. The voltage compliance of the source extends from BV_{CER} of the external transistor to approximately 1 volt more negative than V_{IN}. The compliance of the current sink is the same in the positive direction.

The impedance of these current generators is essentially infinite for small currents and they are accurate so long as V_{IN} is much greater than V_{OS} and I_O is much greater than I_{bias}.

The source and sink illustrated in Figures 17, 18 use an FET to drive a bipolar output transistor. It is possible to use a Darlington connection in place of the FET-bipolar combination in cases where the output current is high and the base current of the Darlington input would not cause a significant error.

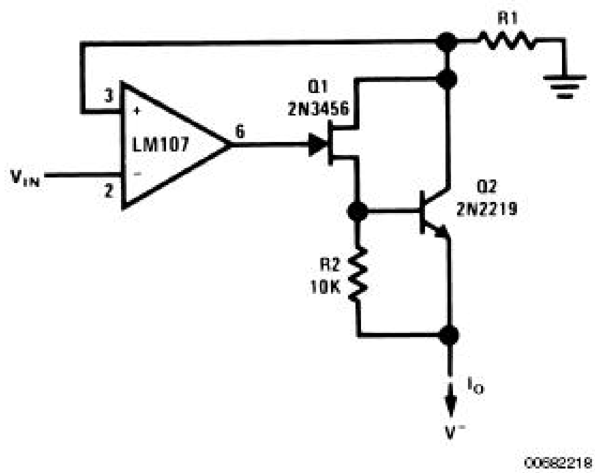
The amplifiers used must be compensated for unity-gain and additional compensation may be required depending on load reactance and external transistor parameters.



$$I_O = \frac{V_{IN}}{R1}$$

$V_{IN} \geq 0V$

FIGURE 17. Precision Current Sink



$$I_O = \frac{V_{IN}}{R1}$$

$V_{IN} \leq 0V$

FIGURE 18. Precision Current Source

图 17、*18* 分别给出了精密电流源电路在吸入和输出电流两种情况下的电路结构。

在实际应用本电路的时候必须注意，（OP 输出端的）电压范围为外部晶体管的 BV_{CER} 到比输入电压 V_{IN} 低约 1V（多）。

从原则上说，电流源电路在小电流状态下内阻是无穷大的。在 V_{IN} 大于 V_{OS}，并且 I_O 比 OP 的偏置电流大得多的情况下，可以认为输出电流是精确的。

图 17、*18* 中使用了一个 FET 来驱动输出级的 BJT。当需要大的输出电流的时候，可以选用达林顿来取代这个输出电路。并且其（栅极）输入电流不会对电路带来显著的误差。

本电路使用的 OP 必须对单位增益进行补偿。并且根据负载特性和输出级电路的特性可能需要额外的补偿。

13. Adjustable Voltage References

可调参考电压源：

Adjustable voltage reference circuits are shown in Figures 19, 20, 21, 22. The two circuits shown have different areas of applicability. The basic difference between the two is that Figures 19, 20 illustrate a voltage source which provides a voltage greater than the reference diode while Figures 21, 22 illustrates a voltage source which provides a voltage lower than the reference diode. The figures show both positive and negative voltage sources.

High precision extended temperature applications of the circuit of Figures 19, 20 require that the range of adjustment of V_{OUT} be restricted. When this is done, R1 may be chosen to provide optimum zener current for minimum zener T.C. Since I_Z is not a function of V+, reference T.C. will be independent of V+.

The circuit of Figures 21, 22 are suited for high precision extended temperature service if V+ is reasonably constant since I_Z is dependent on V+. R1, R2, R3, and R4 are chosen to provide the proper I_Z for minimum T.C. and to minimize errors due to I_{bias}.

The circuits shown should both be compensated for unity-gain operation or, if large capacitive loads are expected, should be overcompensated. Output noise may be reduced in both circuits by bypassing the amplifier input.

The circuits shown employ a single power supply, this requires that common mode range be considered in choosing an amplifier for these applications. If the common mode range requirements are in excess of the capability of the amplifier, two power supplies may be used. The LH101 may be used with a single power supply since the common mode range is from V+ to within approximately 2 volts of V-.

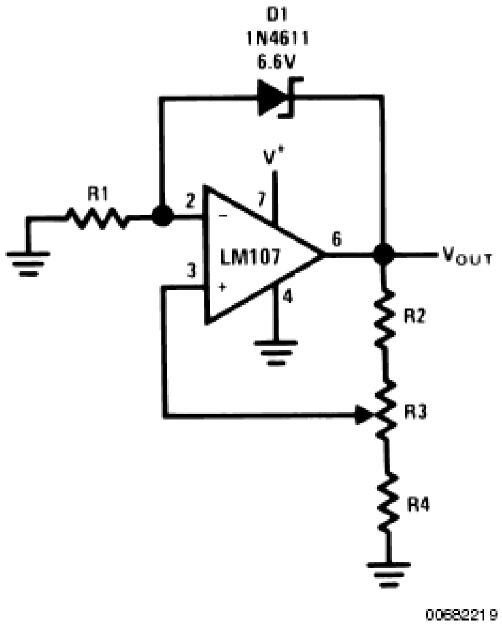


FIGURE 19. Positive Voltage Reference

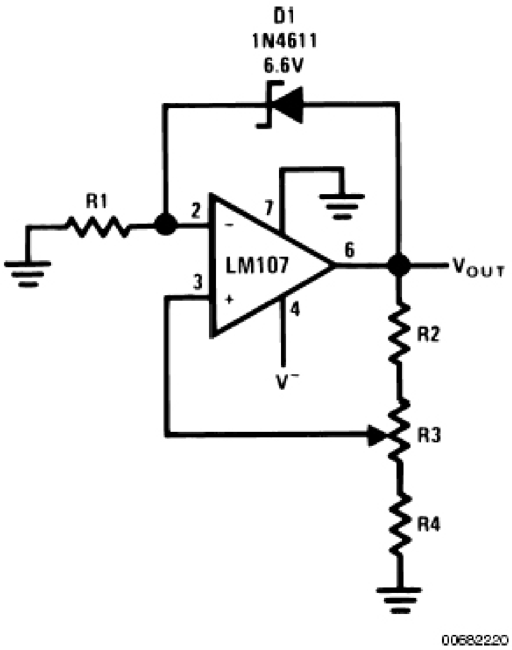


FIGURE 20. Negative Voltage Reference

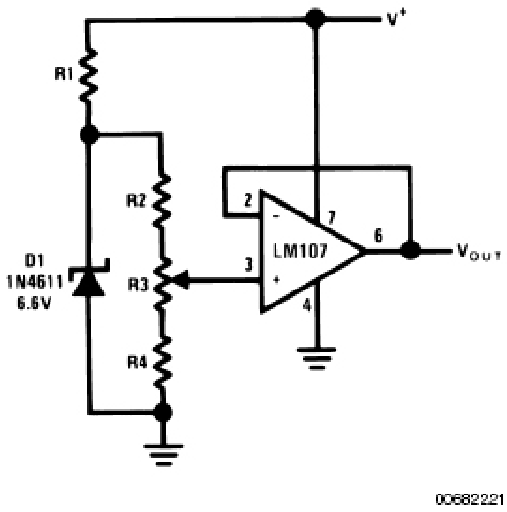


FIGURE 21. Positive Voltage Reference

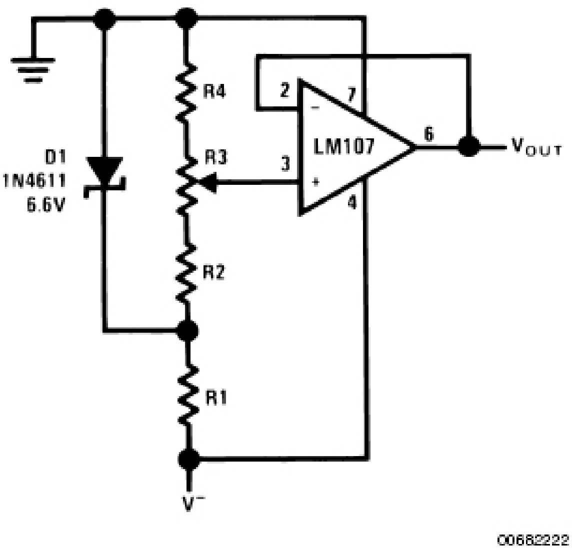


FIGURE 22. Negative Voltage Reference

可调电压参考源的电路示于*图 19*、*20*、*21*、*22* 中。图中的两种电路形式有着不同的应用范围，最基本的区别在于，*图 19* 和 *20* 所示的电路可以提供大于电路中所使用的稳压二极管稳定电压的输出电压，而*图 21* 和 *22* 中的电路的输出电压小于稳压管的稳定电压。在每种形式的电路中，又分别给出了正电压和负电压输出的应用电路。

由于温度因素会影响精度，*图 19*、*20* 中电路的输出电压范围不能太宽。另外，由于 Iz（流过稳压管的电流）与 V+无关（仅取决于 R1）， R1 的取值应该尽量使得稳压管的击穿电流大小合适，借此来减小其温度特性的影响。

图 21、*22* 中的电路适合于要求在宽温度范围内取得较好精度的情况下使用，由于 Iz 和 V+有关，这种电路要求 V+相对稳定。R1、2、3、4 应该适当选择，以给稳压管提供适当的击穿电流和减小其温度特性的影响。

以上电路中的 OP 必须对单位增益做频率补偿，如果负载呈较大的容性，则可能需要做过补偿。如果想减小输出噪声，可以在上述电路的输入端采取旁路措施。

图中的电源采用单电源供电，这就对 OP 的共模输入范围的选择提出了要求，如果所要求的输入电压范围超过共模输入范围，则应该使用双电源供电。LH101 的共模电压范围达 V+到 V-之上 2V，可以在单电源的情况下使用。

14. The Reset Stabilized Amplifier

复位稳定放大器：

The reset stabilized amplifier is a form of chopper-stabilized amplifier and is shown in Figure 23. As shown, the amplifier is operated closed-loop with a gain of one.

The connection is useful in eliminating errors due to offset voltage and bias current. The output of this circuit is a pulse whose amplitude is equal to V_{IN}. Operation may be understood by considering the two conditions corresponding to the position of S1. When S 1 is in position 2, the amplifier is connected in the unity gain connection and the voltage at the output will be equal to the sum of the input offset voltage and the drop across R2 due to input bias current. The voltage at the inverting input will be equal to input offset voltage. Capacitor C1 will charge to the sum of input offset voltage and V_{IN} through R1. When C1 is charged, no current flows through the source resistance and R1 so there is no error due to input resistance. S1 is then changed to position 1. The voltage stored on C1 is inserted between the output and inverting input of the amplifier and the output of the amplifier changes by V_{IN} to maintain the amplifier input at the input offset voltage. The output then changes from (V_{OS} + I_{bias}R2) to (V_{IN} + I_{bias}R2) as S1 is changed from position 2 to position 1. Amplifier bias current is supplied through R2 from the output of the amplifier or from C2 when S1 is in position 2 and position 1 respectively. R3 serves to reduce the offset at the amplifier output if the amplifier must have maximum linear range or if it is desired to DC couple the amplifier.

An additional advantage of this connection is that input resistance approaches infinity as the capacitor C1 approaches full charge, eliminating errors due to loading of the source resistance. The time spent in position 2 should be long with respect to the charging time of C1 for maximum accuracy.

The amplifier used must be compensated for unity gain operation and it may be necessary to overcompensate because of the phase shift across R2 due to C1 and the amplifier input capacity. Since this connection is usually used at very low switching speeds, slew rate is not normally a practical consideration and overcompensation does not reduce accuracy.

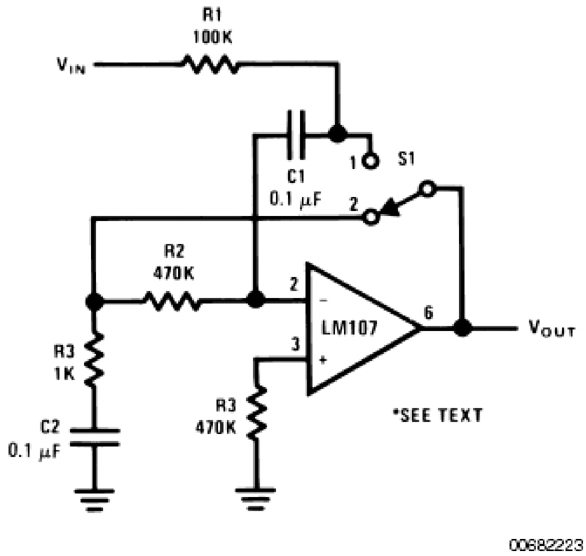


FIGURE 23. Reset Stabilized Amplifier

复位稳定放大器是斩波稳定放大器的一种，其电路如*图 23* 所示。在图中的状态为，放大器工作于闭环增益为 1 的情况。

这种电路可有效消除因失调电压和偏置电流引起的误差。该电路的输出是一个幅值等于 V_{IN} 的脉冲。为了理解其工作原理，需要分析一下将开关 S1 拨向不同的位置时，电路结构如何改变。先将 S1 拨到位置 2，此时放大器为单位增益接法——输出端电压等于输入失调电压加上 R2 与输入偏置电流产生的电压，反相端的电压等于输入失调电压，电容 C1 持续充电直到其端电压等于输入失调电压与 V_{IN} 的代数和。C1 充电完毕时，流经信号源内阻及 R1 的电流为零，因此信号源内阻不会造成误差。接着 S1 拨到位置 1，使 C1 的电压加在放大器的输出端和反相输入端之间，（由于电容端电压不能突变，所以）输出端的电压将产生大小等于 V_{IN} 的变化，使放大器输入端维持输入失调电压，即当开关 S1 从位置 2 拨到位置 1 时，输出端电压将从(V_{OS} + IbiasR2)变为(V_{IN} + IbiasR2)。S1 处于位置 2 时，放大器的偏置电流是由输出端经电阻 R2 提供的，当 S1 转向位置 1 时则由 C2 提供。R3 的作用是降低输出失调电压，如果要求放大器具有最大的线性范围，或者采用直流耦合，就应该使用该电容。

上面这个电路的另一个优点在于，当电容 C1 充电完毕后，输入电阻将趋于无穷大，因此可以消除因信号源内阻产生的误差。开关接通位置 2 的持续时间要足够长，以保证电容 C1 完成充电，这样才能获得最佳的精度。

此电路必须使用单位增益稳定的 OP，因为 R2—C1 产生的相移，所以还可能需要一定的过补偿。鉴于本电路常用于切换频率很低的场合，转换速率（SR）一般不是关键指标，因此过补偿不会降低精度。

15. The Analog Multiplier

模拟乘法器：

A simple embodiment of the analog multiplier is shown in Figure 24. This circuit circumvents many of the problems associated with the log-antilog circuit and provides three quadrant analog multiplication which is relatively temperature insensitive and which is not subject to the bias current errors which plague most multipliers.

Circuit operation may be understood by considering A2 as a controlled gain amplifier, amplifying V2, whose gain is dependent on the ratio of the resistance of PC2 to R5 and by considering A1 as a control amplifier which establishes the resistance of PC2 as a function of V 1. In this way it is seen that VOUT is a function of both V1 and V2.

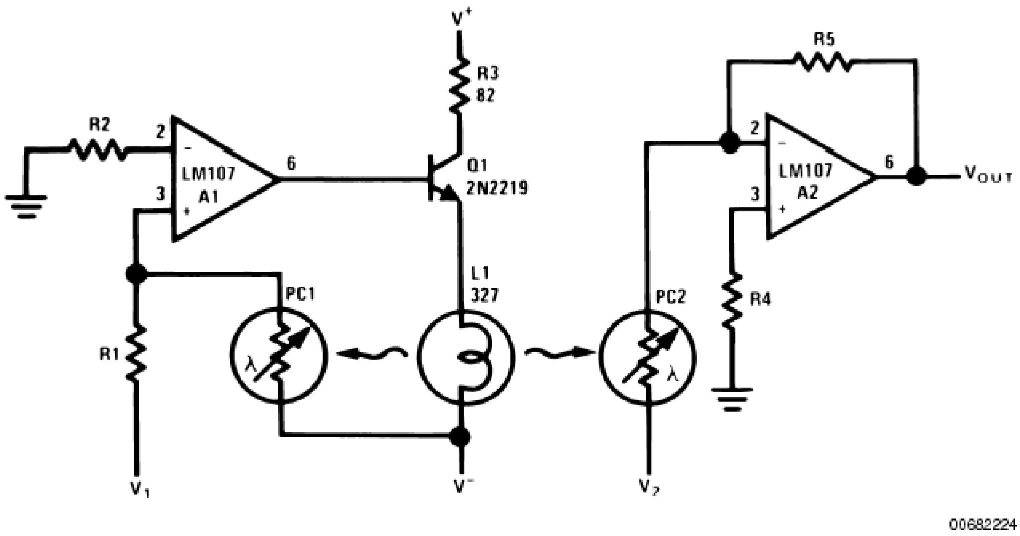
A1, the control amplifier, provides drive for the lamp, L1. When an input voltage, V1, is present, L1 is driven by A1 until the current to the summing junction from the negative supply through PC1 is equal to the current to the summing junction from V1 through R1. Since the negative supply voltage is fixed, this forces the resistance of PC1 to a value proportional to R1 and to the ratio of V1 to V -. L1 also illuminates PC2 and, if the photoconductors are matched, causes PC2 to have a resistance equal to PC1.

A2, the controlled gain amplifier, acts as an inverting amplifier whose gain is equal to the ratio of the resistance of PC2 to R5. If R5 is chosen equal to the product of R1 and V-, then VOUT becomes simply the product of V1 and V2. R5 may be scaled in powers of ten to provide any required output scale factor.

PC1 and PC2 should be matched for best tracking over temperature since the T.C. of resistance is related to resistance match for cells of the same geometry. Small mismatches may be compensated by varying the value of R5 as a scale factor adjustment. The photoconductive cells should receive equal illumination from L1, a convenient method is to mount the cells in holes in an aluminum block and to mount the lamp midway between them. This mounting method provides controlled spacing and also provides a thermal bridge between the two cells to reduce differences in cell temperature. This technique may be extended to the use of FET's or other devices to meet special resistance or environment requirements.

The circuit as shown gives an inverting output whose magnitude is equal to one-tenth the product of the two analog inputs. Input V 1 is restricted to positive values, but V2 may assume both positive and negative values. This circuit is restricted to low frequency operation by the lamp time constant.

R2 and R4 are chosen to minimize errors due to input offset current as outlined in the section describing the photocell amplifier. R3 is included to reduce in-rush current when first turning on the lamp, L1.



$$R5 = R1\left(\frac{V-}{10}\right)$$

$$V_1 > 0$$

$$V_{OUT} = \frac{V_1 V_2}{10}$$

FIGURE 24. Analog Multiplier

图 24 给出了一个简单的模拟乘法器电路。这个电路不但克服了对数-反对数方式实现乘法的缺陷，而且可以实现不受温度变化影响的 3 象限乘法运算。绝大多数的乘法器都存在偏置电流误差的困扰，本电路解决了这个问题。

为便于理解本电路的原理，可以将 A2 视为一个增益受 A1 控制的放大器，A1 在 PC2 的阻值与 V1 之间建立起函数关系，A2 对 V2 进行放大，其增益由 PC2 和 R5 的阻值之比决定。因此，VOUT 是 V1 和 V2 的函数。

控制方放大器 A1，驱动灯泡 L1。输入电压 V1 时，A1 输出升高，使 L1 逐渐变亮。当求和节点上，经 PC1 流回负电源的电流与 V1 经 R1 流入求和节点的电流相等时，L1 亮度不再变化。因为负电源电压恒定，所以 PC1 的电阻等于-R1V-/V1。L1 发出的光同时照射 PC2，如果两个光敏电阻参数匹配，那么 PC2 的阻值就会等于 PC1。

受控方放大器 A2 相当于一个增益受控制的反相放大器，其增益为-R5/PC2。如果让 R5 的阻值等于 R1V-，那么 VOUT 就等于 V1V2。R5 的阻值是乘法运算的比例系数，可以任意设定以实现任意大小的输出，比如设置为 10 的幂。

PC1 和 PC2 的温度特性应该匹配，这就要求其具有相同的几何尺寸，以保证其 T.C.特性。在失配程度比较小时，可以通过改变 R5 的大小进行补偿。L1 照射到两个光敏电阻上的光强度应该相等，有一个简便的方法可以实现这个要求，将两个光敏电阻固定在同一个铝块上的两个小孔内，灯泡则固定在两个光敏电阻的中间。采用这个方法，光敏电阻与灯泡的间距是可调的，另外，铝块在两个光敏电阻之间起了平衡温度的作用，使得其温度差减小。这个方法也可以推广到 FET 对管或者其他需要性能匹配的场合，满足电阻或者环境方面的特殊要求。

图示电路的输出等于两个输入电压的乘积除以 10，相位相反。输入电压 V1 必须大于零，V2 既可以为正也可以为负。受灯泡的时间常数限制，本电路只能低频工作。

R2 和 R4 用来降低因输入失调电流产生的误差，其原理与前文光电二极管放大器所述一致。R3 用于抑制灯泡 L1 初次通电时的浪涌电流。

16. The Full-Wave Rectifier and Averaging Filter

全波整流器和平均值滤波器：

The circuit shown in Figure 25 is the heart of an average reading, rms calibrated AC voltmeter. As shown, it is a rectifier and averaging filter. Deletion of C2 removes the averaging function and provides a precision full-wave rectifier, and deletion of C1 provides an absolute value generator.

Circuit operation may be understood by following the signal path for negative and then for positive inputs. For negative signals, the output of amplifier A1 is clamped to +0.7V by D1 and disconnected from the summing point of A2 by D2. A2 then functions as a simple unity-gain inverter with input resistor, R1, and feedback resistor, R2, giving a positive going output.

For positive inputs, A1 operates as a normal amplifier connected to the A2 summing point through resistor, R5. Amplifier A1 then acts as a simple unity-gain inverter with input resistor, R3, and feedback resistor, R5. A1 gain accuracy is not affected by D2 since it is inside the feedback loop. Positive current enters the A2 summing point through resistor, R1, and negative current is drawn from the A2 summing point through resistor, R5. Since the voltages across R1 and R5 are equal and opposite, and R5 is one-half the value of R1, the net input current at the A2 summing point is equal to and opposite from the current through R1 and amplifier A2 operates as a summing inverter with unity gain, again giving a positive output.

The circuit becomes an averaging filter when C2 is connected across R2. Operation of A2 then is similar to the Simple Low Pass Filter previously described. The time constant R2C2 should be chosen to be much larger than the maximum period of the input voltage which is to be averaged.

Capacitor C1 may be deleted if the circuit is to be used as an absolute value generator. When this is done, the circuit output will be the positive absolute value of the input voltage.

The amplifiers chosen must be compensated for unity-gain operation and R6 and R7 must be chosen to minimize output errors due to input offset current.

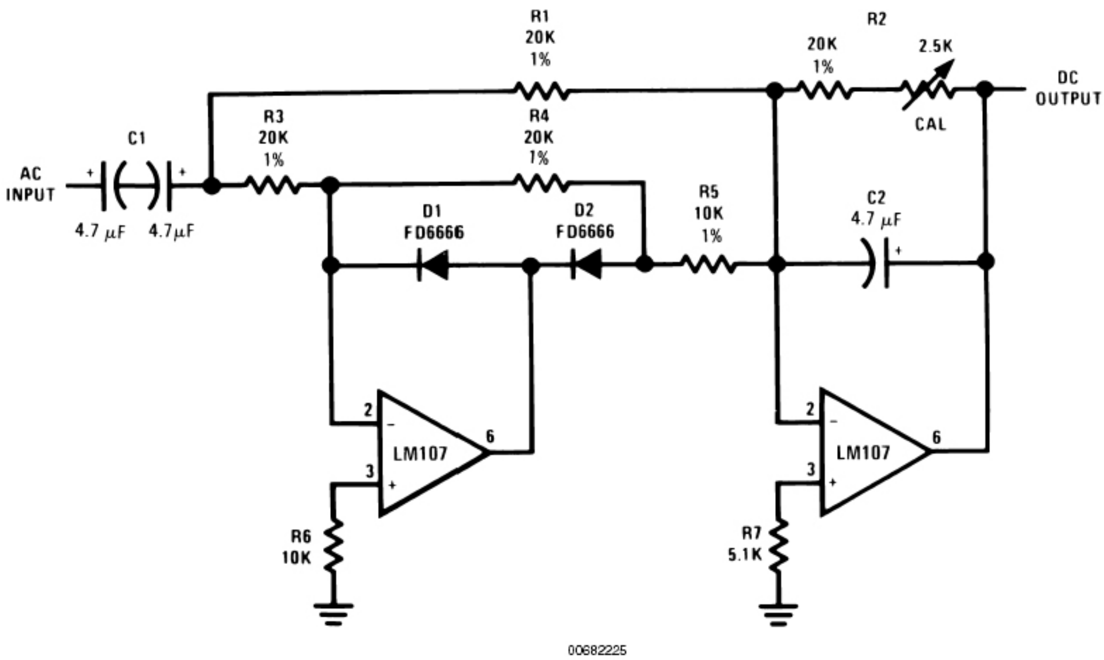


FIGURE 25. Full-Wave Rectifier and Averaging Filter

图 25 是一个平均值输出，有效值刻度的交流电压表头放大电路。它由一个整流器和一个平均值滤波器构成。如果去掉 C2，电路就不再具有平均值滤波功能，只是一个精密全波整流器，如果去掉 C1，电路就变成求绝对值的电路。

为了理解电路原理，下面将从信号路径入手，先分析输入电压小于零的情况，再分析输入电压大于零的情况。对于小于零的输入电压信号，放大器 A1 的输出被二极管 D1 箝位至 +0.7V，二极管 D2 将其与放大器 A2 的求和节点（反相端）隔离开。此时 A2 相当于一个简单的单位增益反相器，输入电阻是 R1，反馈电阻是 R2，输出电压大于零。

输入大于零时，A1 起放大作用，输出经电阻 R5 连到 A2 的求和节点。放大器 A1 接成一个简单的单位增益反相器，输入电阻是 R3，反馈电阻是 R5（此处反馈电阻应该为 R4，疑原文笔误——译者）。由于 D2 位于反馈环路之内，所以它不会影响 A1 的增益精度（译者认为有误，见*注释 1*）。正向电流经 R1 流入 A2 的求和节点，反向电流经电阻 R5 流出 A2 的求和节点。由于 R1 和 R5 上的电压大小相等方向相反，而且 R5 的阻值是 R1 的 1/2，所以 A2 的求和节点处的电流与 R1 上的电流大小相等流向相反，（译者认为有误，见*注释 2*）此时 A2 构成一个单位增益反相加法器，输出仍然为正值。

在 R2 上跨接电容 C2，构成了一个平均值滤波器。此时 A2 的作用与前文所述的“简单低通滤波器”相似。R2C2 的时间常数必须仔细选取，使其远远大于输入电压的最长平均周期。

如果去掉电容 C1，本电路就会变成一个计算绝对值的电路，即电路输出将等于输入电压的绝对值。

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。

注释 1：（NE5532 注）

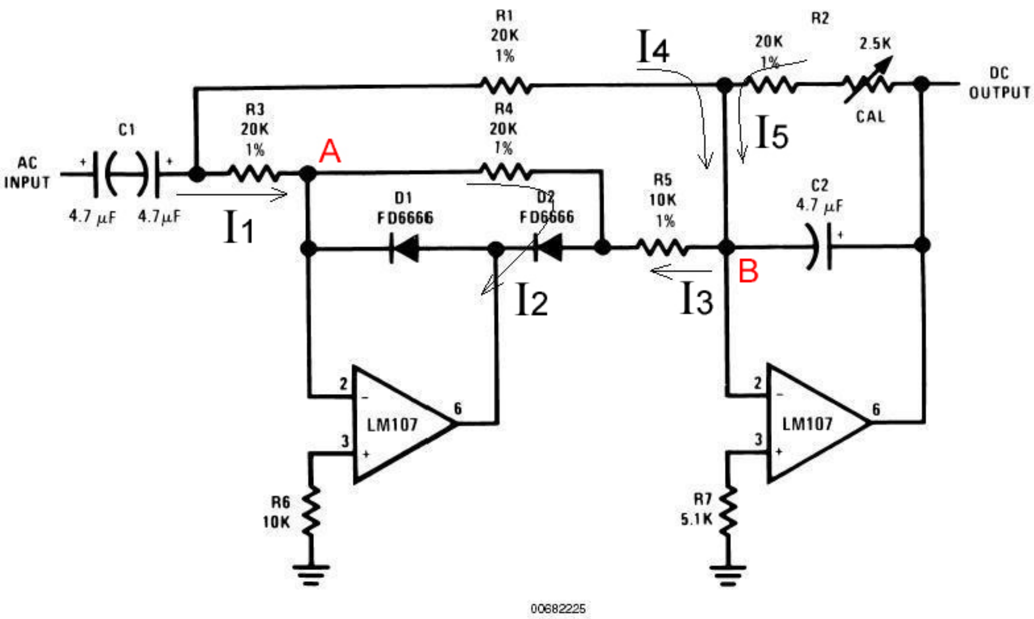


FIGURE 25. Full-Wave Rectifier and Averaging Filter

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：$R_5 = \dfrac{R_1}{2}$

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.

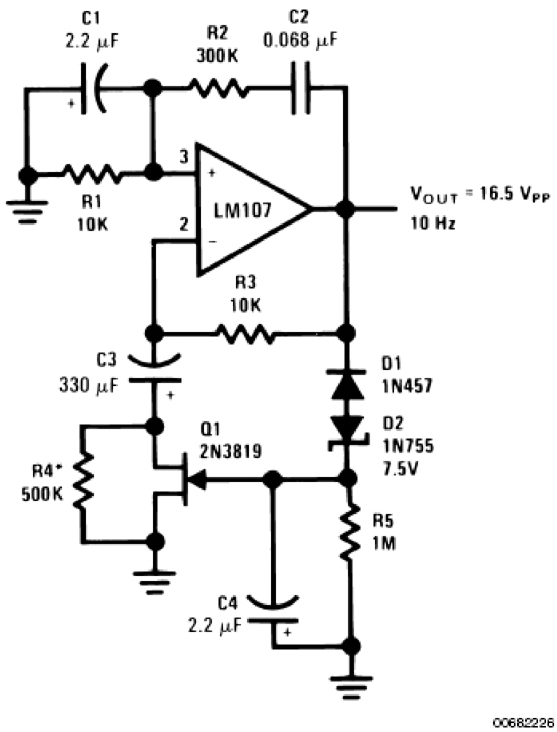


FIGURE 26. Wien Bridge Sine Wave Oscillator

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.

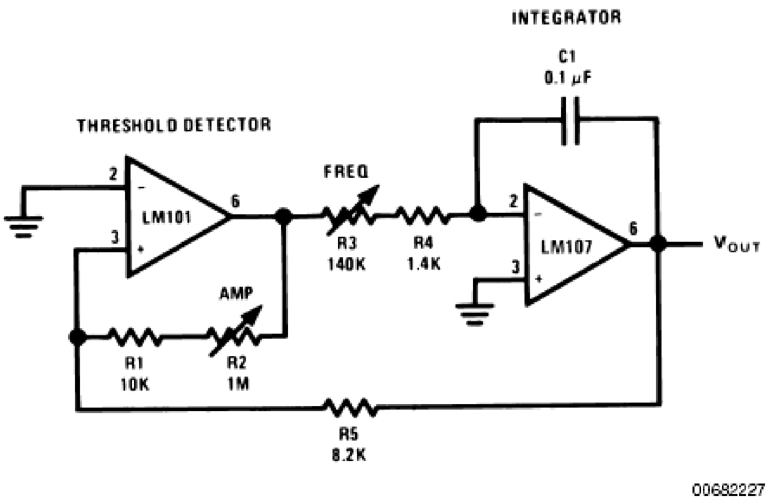


FIGURE 27. Triangular-Wave Generator

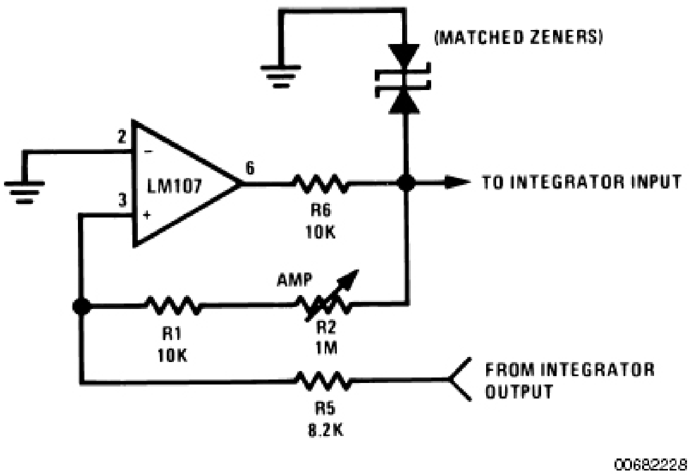


FIGURE 28. Threshold Detector with Regulated Output

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：

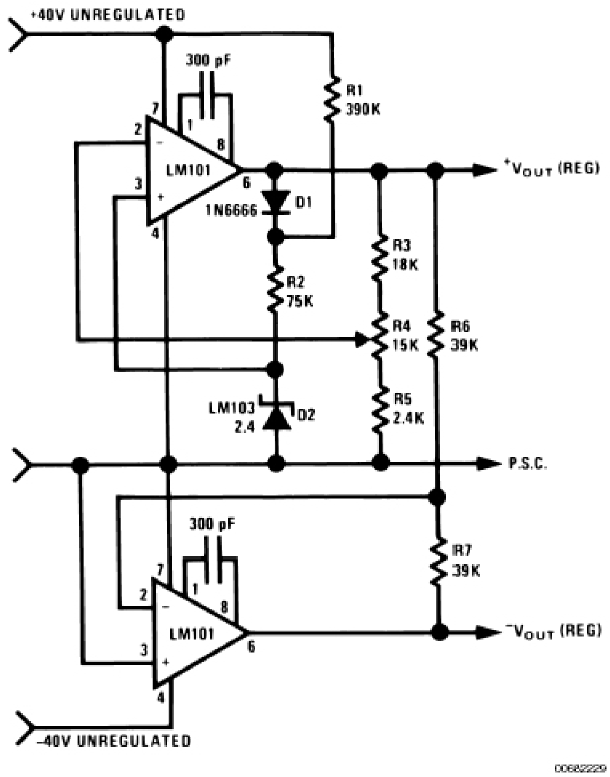
A tracking regulated power supply is shown in Figure 29. This supply is very suitable for powering an operational amplifier system since positive and negative voltages track, eliminating common mode signals originating in the supply voltage. In addition, only one voltage reference and a minimum number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



Output voltage is variable from ±5V to ±35V.
Negative output tracks positive output to within the ratio of R6 to R7.

FIGURE 29. Tracking Power Supply

图 29 的电路是一个输出对称的稳压电源，它非常适合给 OP 供电，这是因为其正负电源电压是对称的，所以电源的共模干扰可以被抑制掉。此外，这个电路比较简洁，仅使用了一个基准电压源和很少的无源器件。

下面从正电源整流部分入手来介绍本电路的原理。正电源整流部分的 OP 对从电位器 R4 取出的电压和稳压管 D2 给出的参考电压进行比较，这两个电压的差值构成 OP 的输入电压；R3、R4、R5 构成了 OP 的负反馈路径，因此 OP 的输出变化趋势会使得输入的差值尽量减小；基准电压源的电流由放大器的输出端提供，这样可以提高对电源的线性范围，使本电路可以适应纹波较大的供电电源。这样一种调节基准电压源的电流的方法需要一个单独的电流源来提供初始启动电流，电阻 R1 和二极管 D1 就起到这个作用：D1 用于在启动时将启动电路和 OP 的输出端隔离开，而输入电源会经 R1 为 D1 提供启动电流。完成启动后，放大器很低的输出阻抗将会降低因流经 R1 的电流不足以影响稳压管上的电压稳定性。

负电源整流部分就是一个简单的单位增益反相器，输入电阻是 R6，反馈电阻是 R7。

图中所用 OP 必须进行单位增益稳定的补偿。如果在电位器 R4 的抽头处注入外接信号，就可以实现供电电源调制。这时，输出正负电压始终对称，变化量相等。

将 D1、D2、R1 和 R2 换成一个可变参考电压源，本电路就变成了一个可控电源。

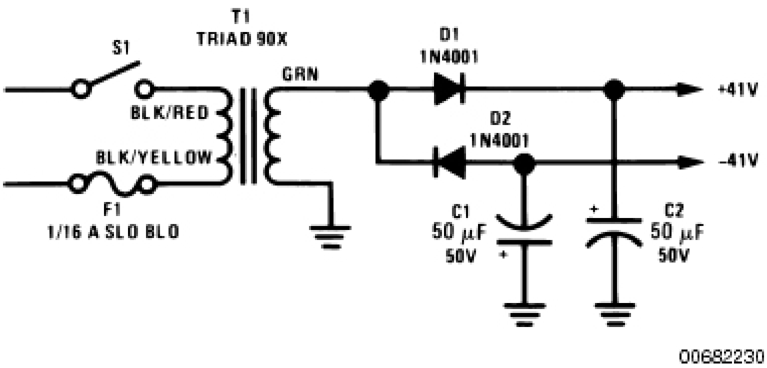
20. Programmable Bench Power Supply

可调的实验电源：

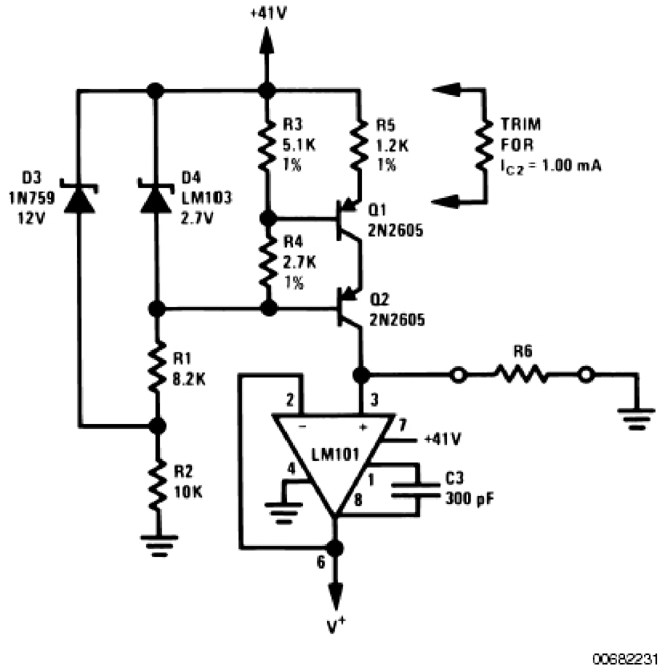
The complete power supply shown in Figure 30 is a programmable positive and negative power supply. The regulator section of the supply comprises two voltage followers whose input is provided by the voltage drop across a reference resistor of a precision current source. Output voltage is variable from ±5V to ±35V. Negative output tracks positive output to within the ratio of R6 to R7.

Programming sensitivity of the positive and negative supply is 1V/1000 Ω of resistors R6 and R12 respectively. The output voltage of the positive regulator may be varied from approximately +2V to +38V with respect to ground and the negative regulator output voltage may be varied from - 38V to 0V with respect to ground. Since LM107 amplifiers are used, the supplies are inherently short circuit proof. This current limiting feature also serves to protect a test circuit if this supply is used in integrated circuit testing.

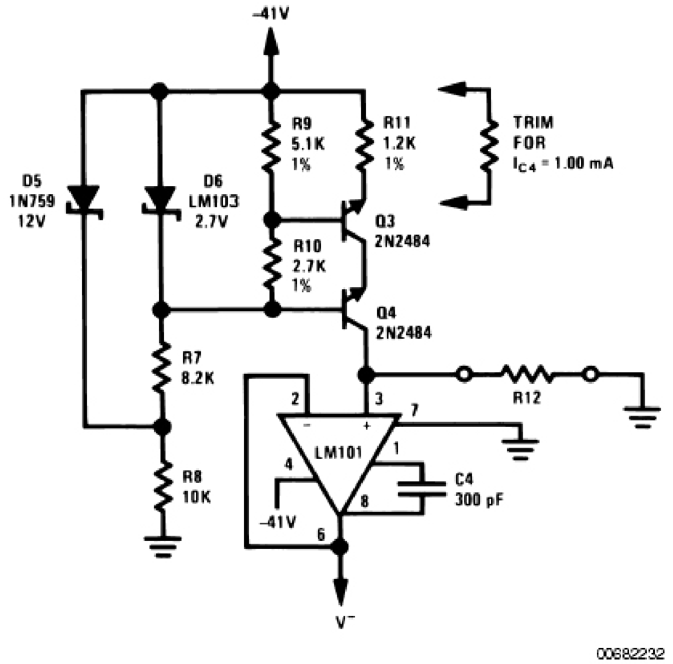
Internally compensated amplifiers may be used in this application if the expected capacitive loading is small. If large capacitive loads are expected, an externally compensated amplifier should be used and the amplifier should be overcompensated for additional stability. Power supply noise may be reduced by bypassing the amplifier inputs to ground with capacitors in the 0.1 to 1.0 μ F range.



a.



b.



c.

FIGURE 30. Low-Power Supply for Integrated Circuit Testing

图 30 给出了一个正负输出均可调的电源电路。基准电压源由两个电压跟随器组成，跟随器的输入是精密恒流源的电流在参考电阻上的压降。本电源的输出电压从±5V 至±35V 可调，负电压跟随正电压一起变化，R6/R12（原文中为 R6/R7，疑为作者笔误——译者）决定了二者绝对值之比。

正负电源分别由电阻 R6 和 R12 调整，调整率都是 1V/1000Ω。正电压参考源对地的输出电压为+2V 至+38V，负电压整流器对地的输出电压为-38V 至 0V。由于使用了放大器 LM107（原图中为 LM101，不知是否为作者笔误——译者），此电路具有了短路保护能力。当用这个电源测试集成电路时，这种限流能力可以为被测电路提供保护。

此电路配接较低的容性负载时，可选用内部补偿型运放。如果需要接较大的容性负载，就要选用外部补偿型运放，并且为了提高稳定性还需要进行过补偿。在运放的输入端与地之间加接 0.1μF 至 1.0μF 大小的去耦电容可以降低电源的噪声。

21. Conclusions

结论：

The foregoing circuits are illustrative of the versatility of the integrated operational amplifier and provide a guide to a number of useful applications. The cautions noted in each section will show the more common pitfalls encountered in amplifier usage.

本文述及的电路展示了集成运放放大器的多种运用，给出了 OP 的多种实际应用电路。每个章节中的注意事项列举了很多在应用运放时常见的错误。

22. 附录 I Definition of Terms

术语表：

Input Offset Voltage: That voltage which must be applied between the input terminals through two equal resistances to obtain zero output voltage.	输入失调电压：为了使OP静态输出电压为零，运放的两个输入端对地之间必须有相等的直流电阻。
Input Offset Current: The difference in the currents into the two input terminals when the output is at zero.	输入失调电流：输出电压为零时，流入运放两个输入端的电流的差值。
Input Bias Current: The average of the two input currents.	输入偏置电流：运放静态下两个输入端电流的平均值。
Input Voltage Range: The range of voltages on the input terminals for which the amplifier operates within specifications.	输入电压范围：在保证放大器性能的前提下，输入端允许的电压范围。
Common Mode Rejection Ratio: The ratio of the input voltage range to the peak-to-peak change in input offset voltage over this range.	共模抑制比：输入电压变化对由其引发的输入失调电压峰-峰值变化之比。
Input Resistance: The ratio of the change in input voltage to the change in input current on either input with the other grounded.	输入电阻：当运放的一个输入端接地时，另一个输入端上的输入电压变化量与输入电流变化量之比。
Supply Current: The current required from the power supply to operate the amplifier with no load and the output at zero.	供电电流，在空载及零输出的条件下，OP的工作电流。
Output Voltage Swing: The peak output voltage swing, referred to zero, that can be obtained without clipping.	输出电压摆幅：在不出现削峰的情况下，输出端对地的最大输出电压。
Large-Signal Voltage Gain: The ratio of the output voltage swing to the change in input voltage required to drive the output from zero to this voltage.	大信号电压增益：输出电压摆幅与为了获得该输出摆幅而施加的输入电压变化量之比。
Power Supply Rejection: The ratio of the change in input offset voltage to change in power supply voltage producing it.	电源抑制比：输入失调电压变化量与引起该变化的电源电压变化量之比。
Slew Rate: The internally-limited rate of change in output voltage with a large-amplitude step function applied to the input.	摆速：由OP内部结构所限制的，在OP的输入端加大幅值的阶跃信号，输出端电压的变化速率。

23. References

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