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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AKAER NE5532

2004-5

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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.

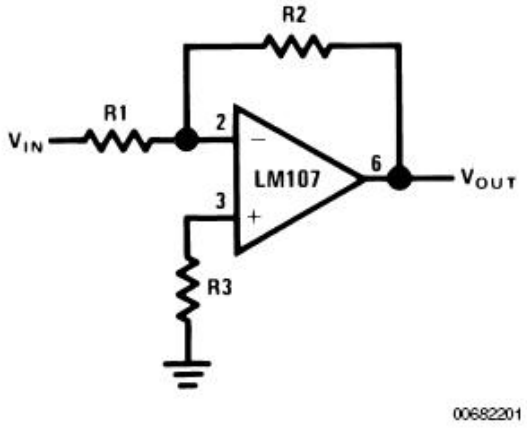
In high source resistance applications, offset voltage at the amplifier output may be adjusted by adjusting the value of R3 and using the variation in voltage drop across it as an input offset voltage trim.

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。

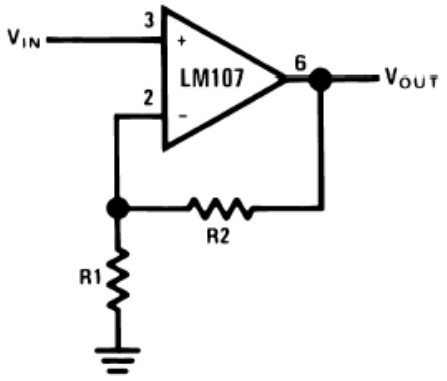
工作在闭环状态下的 OP 和其反馈网络的增益——频率特性，必须保证不会产生震荡。为了实现稳定，OP 和反馈环路对任何频率的信号，在环路增益大于 1 时的环路相移角度绝对不能超过 180°。在实践上，为了达到稳定条件，相移角度不应该接近 180°。显然，最为临界的状态发生在反馈网络的衰减为 0 的时候（既跟随器状态）。没有做内部补偿的 OP 可以被用在深度反馈电路中以取得更好的频率特性。举一个例子：LM101 在反相单位增益电路中，由于反馈网络 6dB 的衰减，仅需要 15pF 的补偿电容；但在同相单位增益电路中，由于反馈环路没有衰减，就需要 30pF 的补偿电容。由于 OP 的转换速度（SR）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

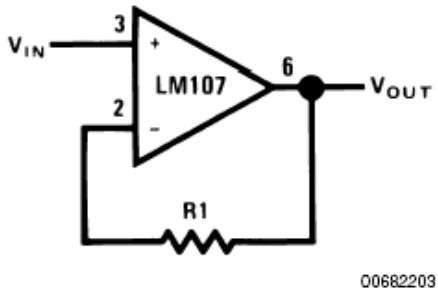
FIGURE 2. Non-Inverting Amplifier

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