Practical Application of Op-Amps

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Introduction

This paper is based on years of practical experience with op-amps. It contains practical advice on using operational amplifiers and how to prevent some common problems. A lot of the information comes from the many articles, application notes, and books that I have read over the years as well as the experience of myself and some of my associates. The reader is encouraged to study all application notes written by the many manufactures of op-amps for more information. Some of the problems that I describe here may not be understood until you have had personal experience with them. Knowledge is one good thing that comes from bad experience.

The mathematical models typically used to analyze and design op-amp circuits would seem to indicate that op-amps are easy to apply and no problems should be expected. Unfortunately, the models do not consider many parasitic circuit effects that can ruin the otherwise good performance of op-amps. Although these problems are difficult to analyze in general because parasitic effects are hard to quantify, there are methods for swamping the effects of most problems.

Figure 1 (At the end of this document) shows a typical op-amp circuit with many of the solutions discussed below.

Physical layout

The worst problems usually occur in circuits intended for low-frequency operation. Since parasitic effects are usually completely nil at low-frequencies, little thought may be given to the physical layout of the op-amp circuit. Unfortunately, the op-amp is too stupid to know that it only needs to operate at low frequencies. If a high frequency resonance exists within the bandwidth of the op-amp and a parasitic path provides sufficient positive feedback, the op-amp will do what it "thinks" you wanted -- oscillate. Thus, the first rule for preventing oscillations in op-amps is, **"Always design the physical layout of the circuit to minimize the parasitic effects up to the unity-gain frequency of the op-amp."** The second rule is, **"Always assume that parasitic inductance and capacitance form a resonance with Q high enough (i.e. underdamped) to be a problem unless resistance is added to limit the Q."** Most things in the world have an underdamped response.

Power supplies

Although most op-amps are operated with +- 15 Volt symmetrical power supplies, this is not a requirement. All that is required is that there be enough voltage difference between the Vcc and Vee terminals and that there not be too much. Many op-amps will work with a total power supply voltage as low as 10 Volts. Some of the newer parts will work on 3 Volts or less. The typical maximum total power supply voltage is around 36 Volts. Some special types can work on lower or higher voltages.

The following Vcc and Vee voltages will operate typical op-amps. Always consult the manufacture's data sheet for specific limits. The power supplies do not have to be highly regulated due to the very high power supply rejection of most op-amps although do not get too sloppy. Many other combinations are possible. Generally, when using very non-symmetrical supplies, some extra biasing circuits have to be added. See manufacture's examples. Note that the output voltage swing will typically be from Vee +2 to Vcc -2 Volts.

Vcc	Vee	Comments
+15	-15	The most common situation.
+14.3	-15.1	Typical situation. The op-amp does not care at all
+12	-12	Common for analog I/O electronics in computers.
+5	-5	A proposed new standard for analog electronics.
+28 (+- 4)	0	Typical in military power electronics.
+20	-5	Odd, but the op-amp does not care.
0	-12	Ditto.
+130	+100	Sometimes this is the only way. Make sure that input voltages stay between these limits. Also, make sure that output current is limited. This and higher voltages up to a point will work but any accident and some power on/off transient effects can destroy the op-amp. Special protection circuits are needed.

Some designers insist on using +-15.000 Volt power supplies and will spare no expense achieving this. The op-amps could not care less. The designer has probably used the power supplies as reference for circuit operation -- a clear violation of the rule, **"Never use a power supply as a voltage reference."** If you need a reference voltage, use a temperature compensated voltage reference that is under your control. Never depend on the quality of power supplies that are under the control of someone else. The only exception to the rule is a situation where it is important for some signal to be relative to a power supply voltage.

Power supply decoupling

Op-amps like to see a zero (or at least very low) power supply impedance at their Vcc and Vee terminals. Otherwise, positive internal feedback paths will exist that can cause the op-amp to oscillate. It must be realized that the wires connecting to the voltage sources have both resistance and inductance. The resistance is generally of no consequence in op-amp circuits but the inductance can form a resonance with the bypass capacitors typically placed across the voltage sources. At the resonant frequency, the power supply impedance is then much larger than the DC resistance. If this resonance is within the bandwidth of the op-amp, oscillation may result.

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To eliminate power supply resonances, place a 10 to 100 Ohm resistor in series with the Vcc and Vee connections. The resistance has negligible voltage drop but serves to de-Q the resonance. The resistors should be physically close as possible to the op-amp. Also, the Vcc and Vee terminals should be bypassed with a ceramic capacitor (typically 0.01 to 0.1 uF) with minimum path length to ground. Sometimes, an electrolytic capacitor of 1 to 100 uF is also used. Electrolytic capacitors are only useful for bypass at low frequencies due to the relatively large internal inductance. Ceramic capacitors are used for high frequency (where the oscillations are most likely to occur) bypassing. Always consult manufacture's data and application notes.

The resistors also serve to limit the power supply current during a fault condition (i.e. output shorted to ground). The op-amp may be spared from destruction. The resistors may end up as fuses.

Load resonance damping

The output stage of an op-amp is typically a push-pull emitter follower. An odd characteristic of emitter followers is that capacitance at the emitter transforms to a negative resistance in series with the base. If this negative resistance becomes greater than the positive resistance in the base circuit, the op-amp will probably oscillate (typically from several hundred kHz to several MHz).

Also, oscillations can occur at the resonant frequency of a long wire and real or parasitic capacitance to ground on the output of an op-amp. Examples of this situation are: (1) a DC voltmeter or an X1 oscilloscope probe connected to the output for testing purposes, (2) a long cable to connect the output to some remote electronics.

The solution is to place a resistor (about 50 to 1000 Ohms) is series with the output of the op-amp. The resistor should be physically close to the op-amp. This resistor de-Qs any LC resonance and isolates any capacitance from the output of the op-amp. This resistor does affect the high frequency operation of the circuit and this must be taken into account. Most op-amp circuits deal with very low frequencies, though.

Input resonance damping

Some op-amps in the non-inverting connection have a tendency to oscillate when the input is connected to a source through a long wire or cable. The oscillation is caused by internal parasitic capacitive feedback to the input which is at a maximum at the resonant frequency of the input connection (i.e. source impedance at resonance looks very high). The solution is to insert a resistor (as large a value as possible without upsetting performance) in series with the non-inverting input. This resistor isolates the resonance from the feedback reactance, hopefully preventing a necessary phase shift required for oscillation. When possible, a better approach is to terminate the cable at the input to the op-amp so that the source impedance looks low for all frequencies.

Ferrite beads

Ferrite beads are often used to prevent high-frequency oscillations. They are typically placed right on the output lead and sometimes the input leads of a wide-band op-amp. A common misconception is that the beads add inductance to the circuit forming what is historically known as an RF-choke. A ferrite bead forms an extremely lossy inductor having much more series resistance than inductive reactance. A ferrite bead is a frequency dependent resistor whose resistance increases with frequency. Depending on composition and size, a single bead may achieve 10 to 50 Ohms at 20 MHz. The advantage of the beads is that at low frequencies, the effective resistance is just that of the wire they are placed around.

One final note – although it is usually impossible to tell them apart by appearance, there are high-frequency ferrite materials intended for building low-loss, high-frequency inductors.

Choice of resistor values

The output stage of most op-amps can drive a -10 to +10 Volt signal into 2000 Ohms when operated from +-15 Volt supplies. To minimize bias current problems and parasitic capacitance problems (high frequency response is either greater or lower than predicted), use the lowest resistor values possible for the feedback circuits. Make sure that the total load on the output of the op-amp is larger than 2000 Ohms.

Compensation of input capacitance

Each input terminal of an op-amp will have typically several picofarrads of capacitance to ground. This capacitance will cause additional phase lags in the feedback circuit which in turn leads to a rising response with frequency. Sometimes, the phase lag is sufficient to cause oscillation.

The solution is to use AC divider theory on the feedback (i.e. set all time constants equal). With the proper capacitance placed across the feedback resistance the input capacitance is compensated for and the frequency response of the feedback network is flat. The ratio of capacitive reactances (real and parasitic) is the same as the resistor ratio. Thus, the high frequency AC attenuation is the same as the DC attenuation.

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Offset adjustments

A simple method for producing small offset voltages to be applied to an op-amp is shown in Figure 2A. This method has the serious disadvantage of very high coupling of power supply variations into the amplifier. This method completely ruins the power supply rejection of op-amps. I have too often seen this method used.

Better methods are shown in Figure 2B. Some op-amps have extra pins for compensating the input offset voltage. The proper method for using these pins to null the offset with little or no sensitivity to Vcc or Vee varies with device construction -- consult the manufacture's application notes.

Manufacture's Application Notes

Although most application notes are excellent sources for information on how to succeed with op-amps, be careful. I have seen some bad mistakes in some notes. Also, some examples are over-simplified and depend on the reader knowing the missing details. The inexperienced reader may be disappointed if he/she copies the circuit without understanding. Beware of "el-cheapo" examples – they usually depend on an unusual characteristic of a particular part and are not suitable for any serious design.

Testing an op-amp circuit design

A poorly designed circuit may work very well under ideal laboratory conditions. Laboratory power supplies, signal generators, and other equipment usually have very idealized characteristics. The temperature and humidity in the laboratory are usually well controlled. In the real world, your circuit may have to work with poorly regulated power supplies, wide changes in temperature and humidity, as well as other situations. The circuit that worked so well in the laboratory may be useless in the real world. The purpose of laboratory testing is not to find out how well something will work but rather, how bad!

The following tests should be applied to all circuits that must operate in the real world. These tests simulate some common real world conditions and will reveal a poorly designed circuit. Apply these tests after the circuit is working well under ideal conditions. Use the idealized performance as the reference point.

(1) Vary the Vcc and Vee voltages plus and minus at least a Volt independent of each other. The output of the circuit should not change more than a few millivolts if that much. If you have a method for introducing noise or other signals on the power supply outputs, verify that the circuit does not respond.

(2) Using a hair-drier or heat gun, gently and uniformly heat the circuit until the components are about as hot as can be touched. This is a poor man's temperature test.

A controlled oven is far superior because thermal gradients are avoided. Thermal gradients or non-uniform heating can produce larger than normal operation errors. Note any sensitivity to temperature.

(3) The poor-man's low temperature test is usually performed by spraying the circuit with component cooler. The boiling point of the Freon is less than -40° C. The components cool as the Freon boils. This test is best used for indicating the temperature sensitivity of a specific component as it is difficult to uniformly cool the entire circuit. Contrary to popular belief, it is not necessary to blast the circuit with "tons" of Freon. Not only is it wasteful, but the circuit will not be cooled as much either. Best results are obtained with a very slow stream of about a drop every one or two seconds on a particular component. The component will quickly turn white with frost. Do realize that the frost on the circuit provides conductive paths that do not normally exist. The circuit may be more upset by these new current paths than by the low temperature. Note that this test is not applicable to circuits that rely on components whose values will track with temperature because this test introduces non-real world thermal gradients.

(4) Apply much larger than normal amplitudes to the circuit inputs but not so large as to do damage. Note any unusual output phenomena. If the circuit is to be used as part of a closed-loop servo, make sure that the output phase does not invert or have long recovery times in response to excessive inputs as these aberration will cause a limit cycle oscillation that will not stop. Perform frequency response testing; apply square waves; apply transients or other undesired inputs that the circuit may have to respond to in the real world. In general, apply tests that simulate as much as possible the environment that the circuit must perform in.

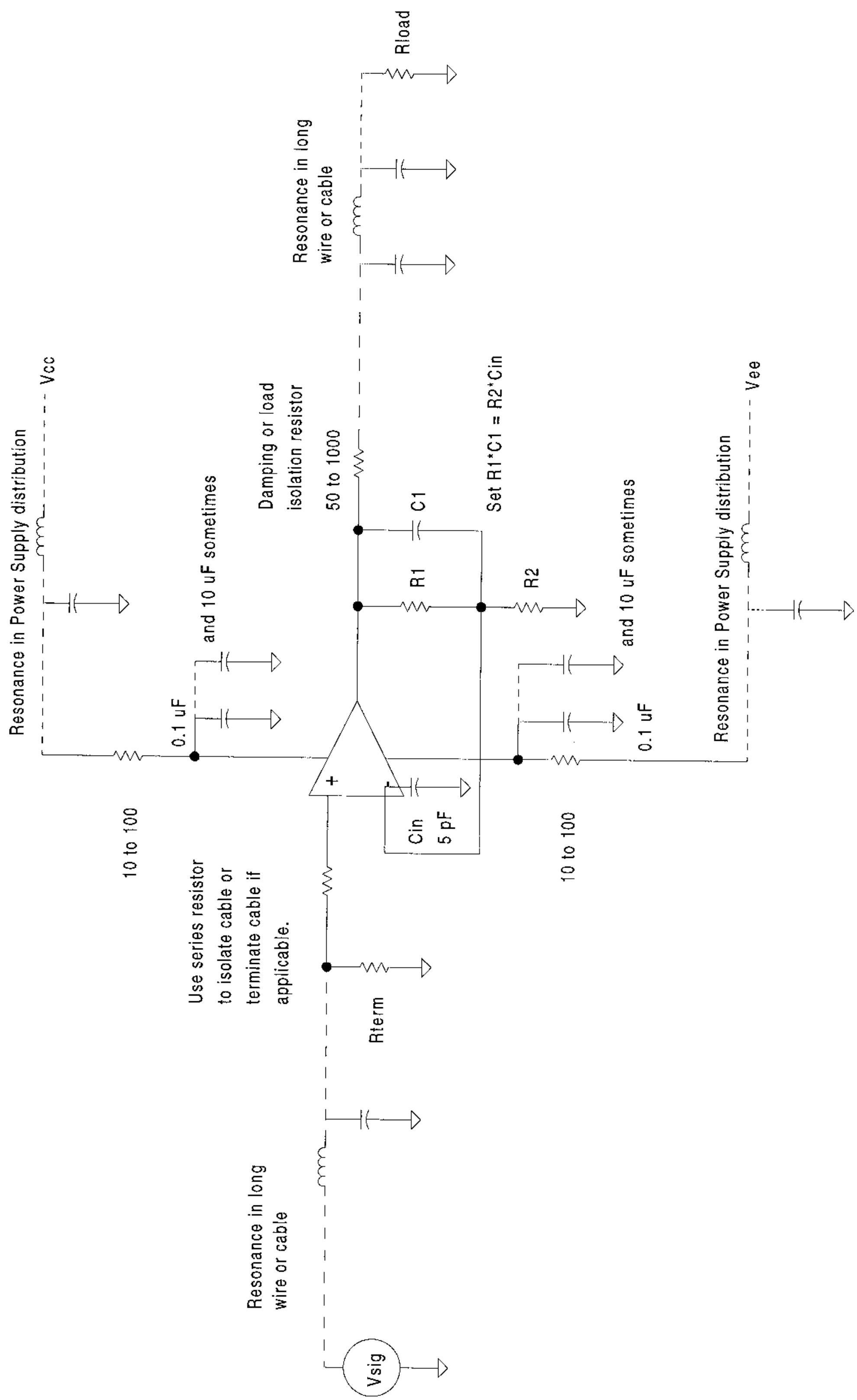

Figure 1: Oscillation causes and cures

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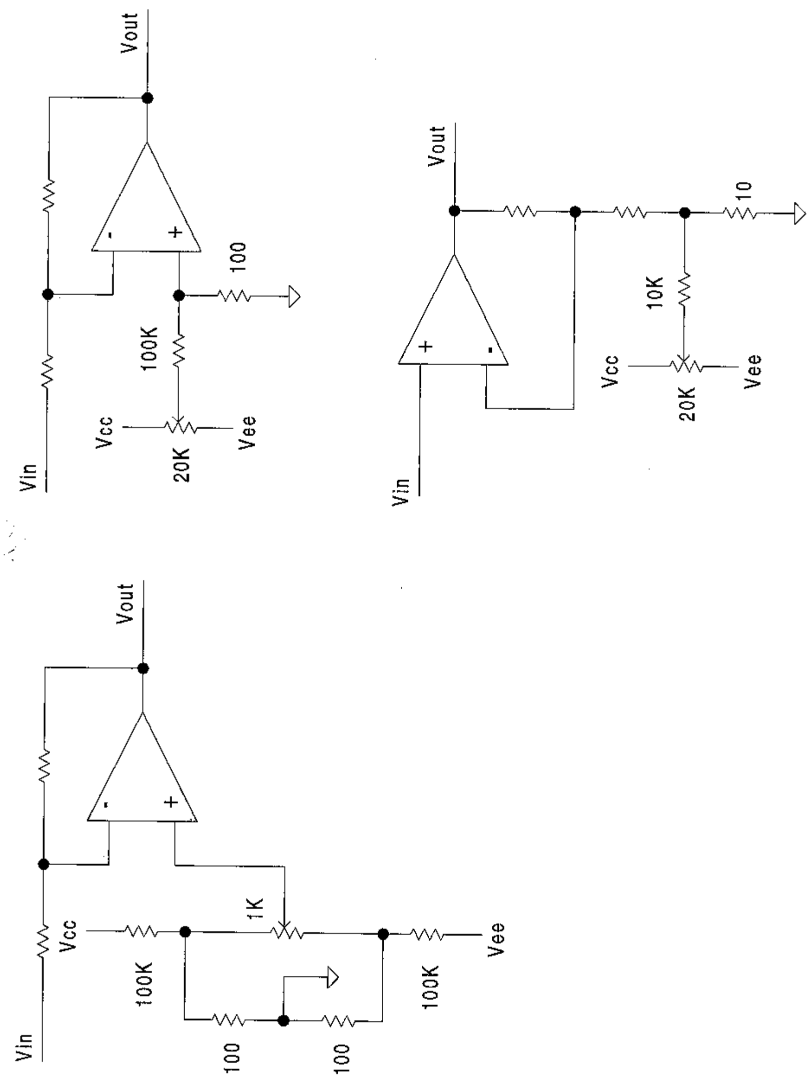
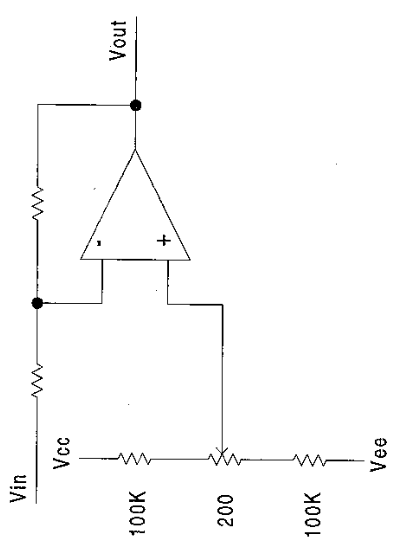


Acceptable methods for adjusting offset voltage.
These circuits do not show input bias current compensation.
It is better to use voltage references rather than Vcc and Vee for offset adjustment.

Figure 2B



A very poor method for adjusting offset voltage. Circuit is extremely sensitive to changes in Vcc and Vee.

Figure 2A