SECTION X
UNUSUAL APPLICATIONS FOR OP AMPS

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SECTION X

Unusual Op Amp Applications

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Perverting the Monolithic Op Amp

Derek F. Bowers

Introduction

The background behind this section started out fairly innocently. I have childhood memories of using small screwdrivers as brad awls and micrometers as glue clamps. I also remember converting the sledge (that had been carefully built by my father) in conjunction with some ladders and the garden shed into my first and only venture into roller coaster design.

By the time my career in electronics was underway, I had devised a veritable cornucopia of dubious practices. I showed my colleagues how to strip enamelled wire with a Bunsen burner and a jar of methanol, to purloin (somebody else's) nail-clippers for trimming coaxial braid, and employ an electric toaster as a test load for audio power amplifiers. Obviously, the designers of such artifacts had failed to elucidate the endless possibilities for their misuse.

Inevitably, I suppose, the operational amplifier was bound to fall victim to my natural predisposition to explore all possibilities, no matter how unconventional they might be. What surprises me, however, is how much material I have found from other sources. Apparently, I am by no means alone.

I think I can show that the op-amp, in being such a general element, is rarely used in the exact manner for which it was designed. I also firmly believe that regarding an op-amp in its purely conventional role is missing out on a lot of potential applications.

This section explores the unusual possibilities of present-day op-amps, while pointing out some of the pitfalls in designing with this universal component.

Where Do Op Amps Come From?

I will not attempt to provide any form of history of negative feedback theory here, but suffice it to say that the first recognizable op-amp topologies seem to have evolved from work done by Lovell and Parkinson in the design of the Western Electric Nark-9 Gun Director during World War II. The actual term *operational amplifier* was not coined until 1947, however, in a paper by Ragazzini and colleagues [1].

Ragazzini described a vacuum-tube design producing a high gain amplifier capable of driving a feedback network to force a virtual earth. Such an amplifier is capable of realizing the 'classical' operations such as inversion, differentiation and integration; the major operations of an analog computer.

The next step in the evolution of the op-amp comes from the realization that the virtual earth can actually be an extra (non-inverting) input, an advance generally attributed to Carl S. den Brinker. Now we start to see the basis of the familiar modern op-amp concept, though I pleasurably note that we are already starting to bend the rules.

WHAT REALLY IS AN OP AMP?

Using an op-amp is a little like buying a car. One specifies the color, seat material, make of sound equipment etc., but never that the vehicle must have four wheels and an engine. This is taken for granted.

Similarly, op-amps have pages of specifications such as offset voltage, gain, slew rate and so on, but it is almost always presumed to behave as a basically functional amplifier. Such an assumption is only guaranteed by the design (of course) but also by the test methodology involved.

Suffice it to say that the modern day op-amp should behave as a gain element presenting extremely high differential gain, very low common mode gain, and stability when some amount of feedback (often 100%) is applied from the output to the inverting gain terminal.

The validity of such a simplistic model is questionable, and given more space, I would explore this point further. However, for present purposes, I propose that the monolithic op-amp be regarded as an almost ideal voltage amplifier; a reasonable viewpoint in the light of all the possible permutations for its use; particularly those described in the following discourse.

BASIC ASSUMPTIONS ABOUT OP AMPS

The vast majority of monolithic op-amps are tested (and therefore specified) by a series of tests within an externally compensated test loop, which I believe originated at Tektronix, Incorporated. While making all the usual DC measurements possible, such a test loop in no way simulates the way an actual op-amp will be used. Many manufacturers (including Analog Devices) have implemented additional tests to measure noise, stability, slew rate et cetera, but the fact remains that without knowing the precise feedback circuitry around the device, the final performance can never be completely guaranteed. But experience shows that these tests are more-or-less adequate for the vast majority of applications. The "vast majority" of applications includes areas where the op-amp is used with some sort of passive feedback to form voltage amplification, inversion, or with reactive feedback to provide the function of active filters, integrators or differentiators. Most op-amp "cookbooks" also dabble in areas such as logarithmic amplifiers, where nonlinear gain is introduced inside the feedback loop. Alas, when an op-amp is employed in such a manner many of the manufacturer's tests (and data sheet curves) are rendered invalid.

But all this is fairly standard for analog components. Attempting to test a transistor, for example, to guarantee performance under every conceivable operating condition is clearly ludicrous. But good analog engineers understand transistors, and don't need a fifty page manual in order to use them. Similarly, a good understanding of op-amps is necessary for their successful inclusion in all but the simplest of systems. Proceeding one step further yields some circuits which are clearly beyond the boundaries of normal op-amp applications, but which perform highly useful functions with a minimum of complexity.

GAIN IN THE FEEDBACK LOOP

Perhaps the first departure from the classical op-amp usage is when some form of gain or nonlinearity is added into the feedback loop. Frequency compensation is a major issue here, partly because the feedback components introduce additional phase shift, but also because there is a possibility of the overall feedback becoming greater than 100%. This can cause problems for even the most "unity-gain stable" op-amp. Another caveat involves input voltage range; remember early op-amps such as the 709? This device had an output voltage swing greater than its input voltage range. Even worse, the device suffered phase reversal when this range was exceeded. The result was that it had a strong tendency to latch-up in unity gain applications. Most modern op-amps are designed to avoid this, but all bets are off if active devices in the feedback loop are used. Techniques to avoid this are similar to those needed when shunt-mode operation is employed, and will be dealt with in due course.

Dealing with the frequency compensation issue can be somewhat tricky also. Figure 10.1 shows a fast logarithmic amplifier which I designed as an application for the MAT-02 ultra-matched NPN dual transistor. The circuit details are covered in the MAT-02 data sheet, but essentially revolves around non-linear (potentially high-gain) feedback for both of the op-amps. The basic trick for ensuring stability is to provide a capacitor from the output to the inverting input for both amplifiers (Cl & C2), assuming them to be unity-gain stable (which in this case they are). This capacitor bypasses the non-linear feedback at frequencies critical to the amplifier's stability. At the higher input currents, however, The dynamic emitter impedance of Ql appears in parallel with C2, reducing its effectiveness. The obvious solution of increasing C2 would lead to slow performance at lower currents. The addition of R4 circumvents this problem by swamping the dynamic resistance term, thus allowing a smaller value of C2. It is desirable that R4 be made as large as possible, but its upper limit is set by the output swing capability of Al.

COMPOSITE AMPLIFIERS

Another purpose of adding gain inside the feedback loop is to improve the op-amp's input characteristics. Figure 10.2 is an ultra-low noise op-amp, created by adding an additional gain stage to an OP-27 [2]. The three parallel MAT-02 transistor pairs, running at 1mA per transistor, yield a voltage noise spectral density of only 500pV/√Hz. The 6mA tail current is generated by Q4, which is biased by a red LED. The LED has about one volt more forward voltage drop than the transistor, but about the same temperature coefficient, generating a stable voltage across R12 (yes, I know that LED's aren't designed to do this, but micrometers aren't intended to be glue clamps either). Resistors R1-R3 ensure equal splitting among the devices.

10

FAST LOG AMP CIRCUIT

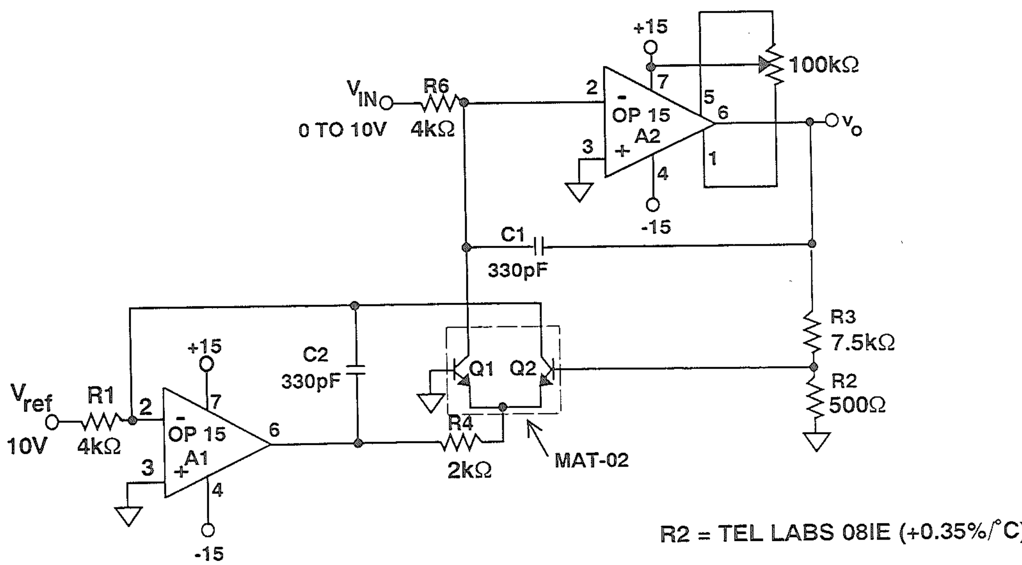


Figure 10.1

ULTRA LOW-NOISE COMPOSITE OP AMP USING ADDITIONAL GAIN STAGE

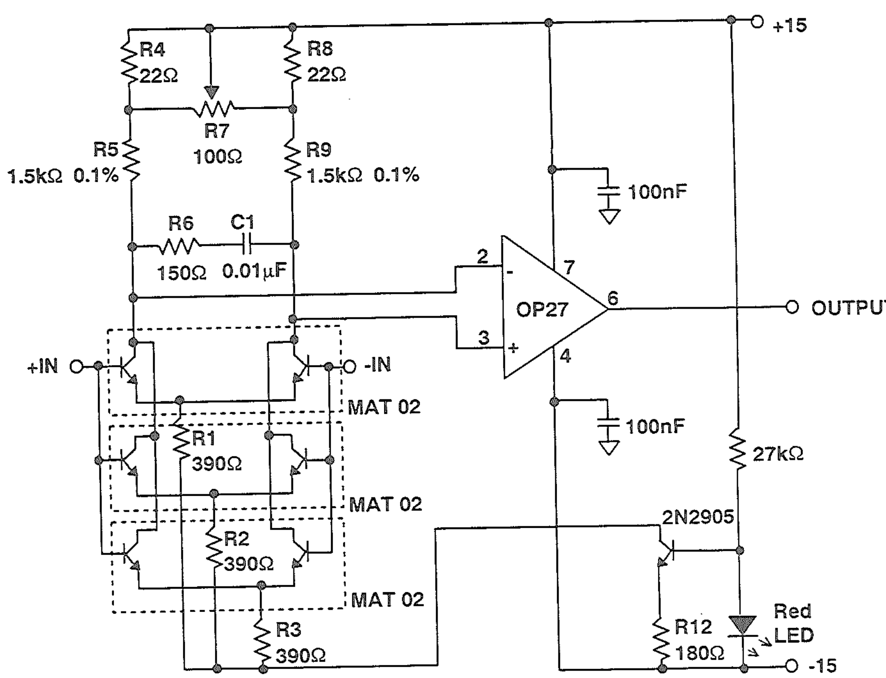


Figure 10.2

Frequency compensation is provided by R6 and Cl. The Idea here is to create a dominant pole with Cl and add a zero to accommodate the natural frequency compensation of the OP-27. The overall amplifier is compensated for gains of ten and above, since we couldn't really see why anybody would use such a low-noise amplifier at lower gains.

While such frequency compensation does work, it is difficult to optimize for a wide range of gains, and of course, yields amplifiers which are slower than those with less gain stages. Figure 10.3 shows a way around this [3].

The input stage of the SSM-2134 op-amp can be by-passed by feeding signals to its null pins. Furthermore, the internal input stage can be shut off by connecting pins 2 & 3 to the negative supply. Two drain resistors (Rd) parallel the internal SSM-2134 collector resistors, and the input stage (in this case a dual JFET) is biased by tail resistor Rs. Adding some extra components produces an extremely high performance JFET input op-amp as shown in Figure 10.4.

Here, a FET cascode pair reduces input bias current (<2pA), and a constant current source replaces the tail resistor for improved CMRR. For best circuit performance, the drain current is adjusted to produce a 2.5V drop across the drain load resistors. Next, the CMRR trim is adjusted to optimize this parameter. Finally, the input offset can be trimmed out. The overall amplifier has a 2nV/√Hz input noise voltage and a 50V/µs slew-rate without compensation. compensation capacitor Cc (on the order of a few tens of picofarads) can be added if capacitive loads need to be driven.

USING OFFSET NULL PINS TO CREATE JFET INPUT COMPOSITE

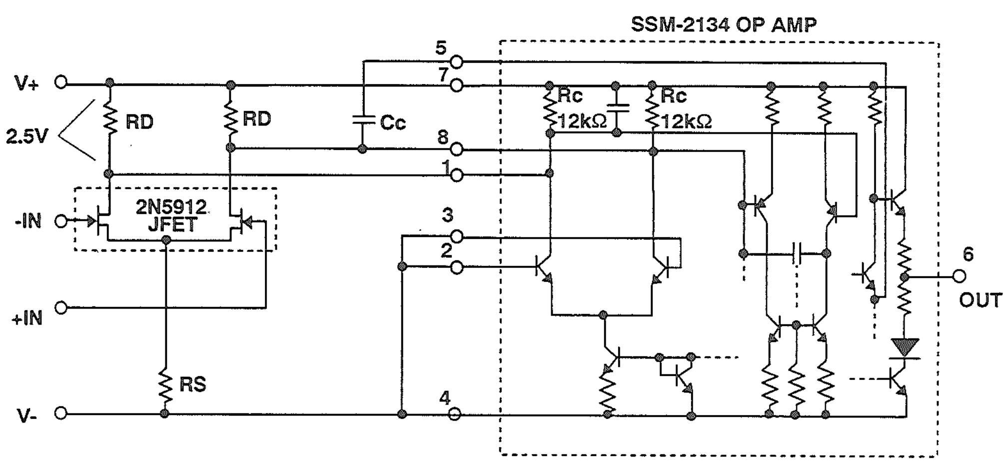


Figure 10.3

Another technique for producing composite amplifiers is shown in Figure 10.5. Here, a fast JFET input op-amp is corrected for DC errors by a slow but accurate superbeta input amplifier. The OP-97 continuously monitors the offset voltage of the OP-42 and forces it to near zero via the null pins of the latter amplifier. The external resistors are chosen to give realistic voltage swings at the output of the OP-97, and the factor of two difference yields an approximately symmetric correction range. Such amplifiers feature the full bandwidth and slew rate of the main amplifier, coupled with the DC precision of the correction amplifier. Settling time, however, is usually degraded because transient errors cannot be corrected quickly by the slower op-amp.

HIGH PERFORMANCE JFET INPUT COMPOSITE OP AMP

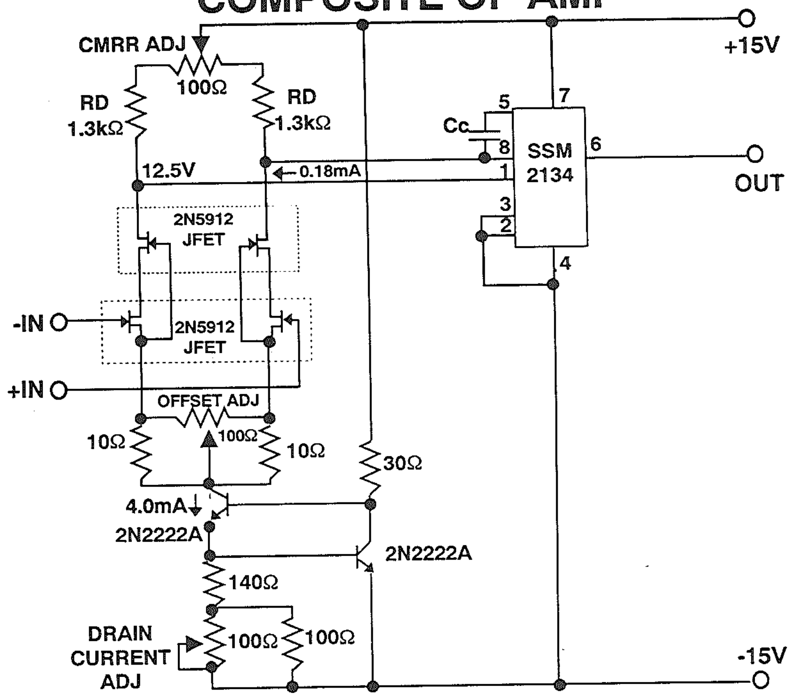


Figure 10.4

COMPOSITE AMPLIFIER USING FAST JFET INPUT OP AMP AND PRECISION SUPERBETA INPUT OP AMP

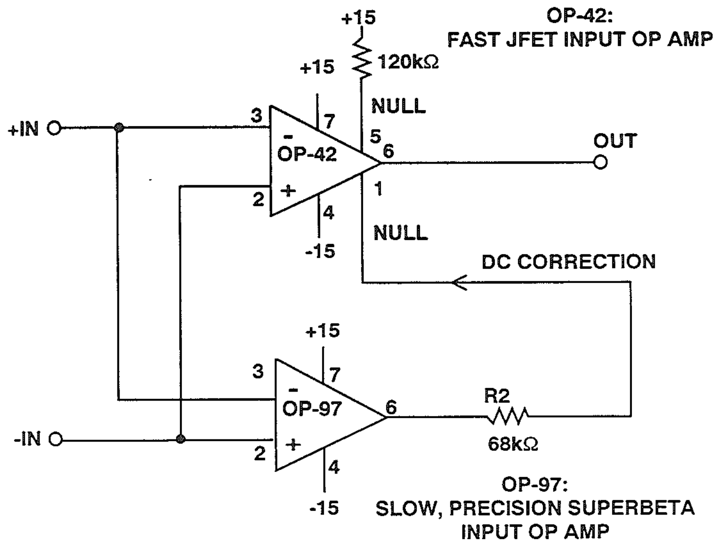


Figure 10.5

FURTHER ABUSES OF THE NULL PINS

The circuits of Figure 10.3 & Figure 10.4 rely on the fact that the null pins of an SSM-2134 give direct access to the internal load resistors. This is not generally true for op-amps, though these pins do provide a possible extra pair of inputs (or feedback points) for the op-amp (the popular 741 amplifier actually has higher gain at its null pins than at the inputs). There is a caveat here, however. Most op-amps have a nulling arrangement equivalent to that shown in Figure 10.6a, where nulling is intended to the negative supply. Some however, have the nulling at the positive supply. Usually, pins 1 & 5 are used for negative supply nulling, and pins 1 & 8 are used for positive supply nulling, but there are exceptions; the OP-160 and AD847 for example. Occasionally, a scheme such as that in Figure 10.6b is used, and in general op amps using such a topology are best avoided for applications such as that of Figure 10.5.

It is dangerous to generalize the function of null pins, but the 741-type of nulling scheme offers an inverting function at pin 5 and a non-inverting one at pin 1, level shifted (of course) down to the negative supply rail. This is the convention we tend to follow at the PMI division of Analog Devices. This, for example means that overcompensation of an op-amp can be achieved with a capacitor from the output to pin 5. Figure 10.7 is another way to use these pins [4], a rather unusual approach to a single-supply instrumentation amplifier, with an input and output range which includes ground.

DIFFERENT OP AMPS USE DIFFERENT NULLING SCHEMES, THEREFORE DO NOT GENERALIZE ON FUNCTION OF NULL PINS

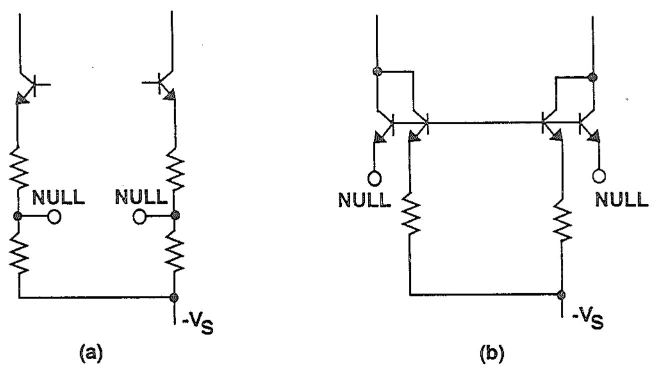


Figure 10.6

SINGLE-SUPPLY INSTRUMENTATION AMPLIFIER USING NULL PIN FOR FEEDBACK CONNECTION

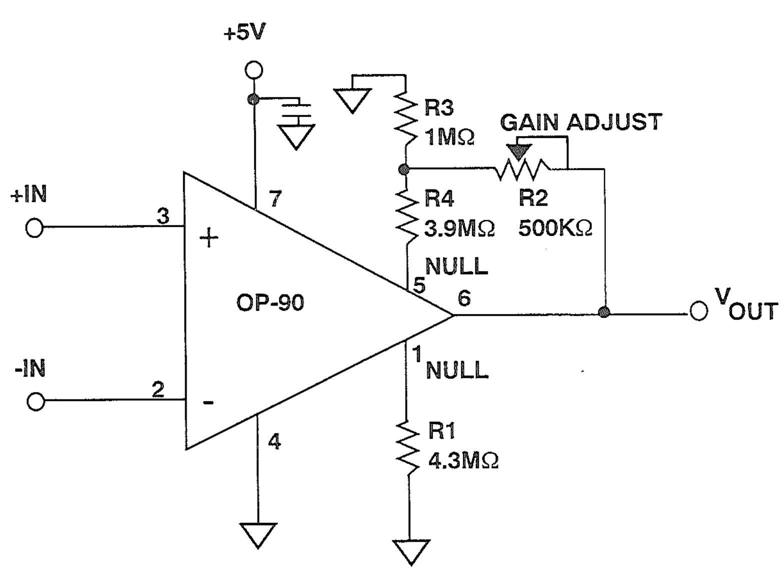


Figure 10.7

Feedback is provided via pin 5 of the OP-90, which frees up both the inputs for differential signal handling. Distortion is that of a differential pair; so this type of amplifier is only suitable for high gain applications. At a gain of 1000, linearity measures about 0.05% over a 2.5V output range. A gain trim is always necessary with this type of configuration because of internal tolerances associated with the internal nulling circuitry, but the values shown are designed for a gain of 1000. The OP-90, incidentally, has temperature compensated input stage transconductance, and in this application gain drift is only 50ppm/K.

The very low power bandgap reference of Figure 10.8 is another example of constructive abuse of the null pins (OP-90 data sheet for an official reference, but yet another of my strange creations). The overall circuit generates a low temperature coefficient 1.23 volt output with supplies from 2.5V to 36V, with only 17μA of supply current. When adjusted, the output drift is about 20ppm/K, but lower drift can be achieved by optimizing the output voltage; a 1% change produces a predictable 33ppm/K temperature drift. A significant problem with this type of circuit is ensuring reliable start-up. When no current is flowing through R1 & R2, the op-amp is beyond its positive input-range limit and has an undefined output state. To prevent this, one of the null pins (pin 5) is shorted to ground, forcing the output to a high state at power-up. This does introduce a few millivolts of offset at the amplifier's inputs, but this is not important in this application, since the offset is proportional to temperature, and therefore trims out when the output adjust is performed.

LOW-POWER BANDGAP VOLTAGE REFERENCE

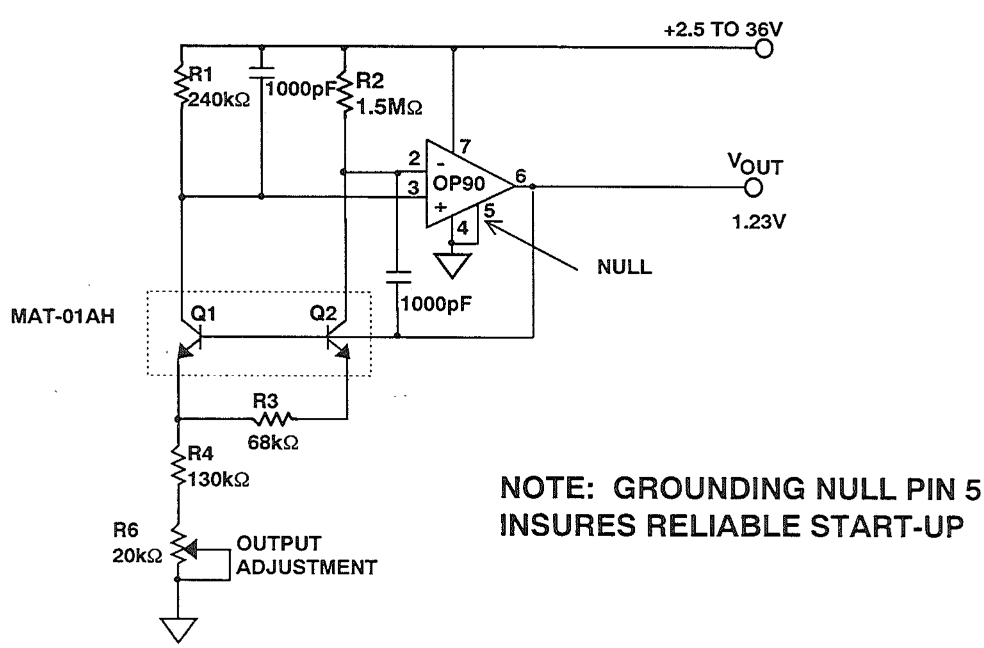


Figure 10.8

OP AMPS WITHOUT FEEDBACK

With the availability of the plethora of monolithic comparators available, at first glance it seems pointless to attempt to warp an op-amp into this function. But no available comparators have the precision performance of high-grade op-amps, and precision op-amps without internal compensation (such as the OP-06) can be surprisingly fast where low overdrive response is needed [5]. The circuit of Figure 10.9 delivers a TTL compatible output with a response time of about 1μs for 5mV overdrive, and 2.5μs for a 500μV overdrive.

Some op-amps feature a compensation pin which closely tracks the output voltage. This enables the output to be clamped at TTL levels with a zener diode (Figure 10.10), making comparator design quite painless.

COMPARATOR MADE FROM UN-COMPENSATED PRECISION OP AMP

OVERDRIVE	PROP DELAY
500μV	2.5μs
5mV	1μs

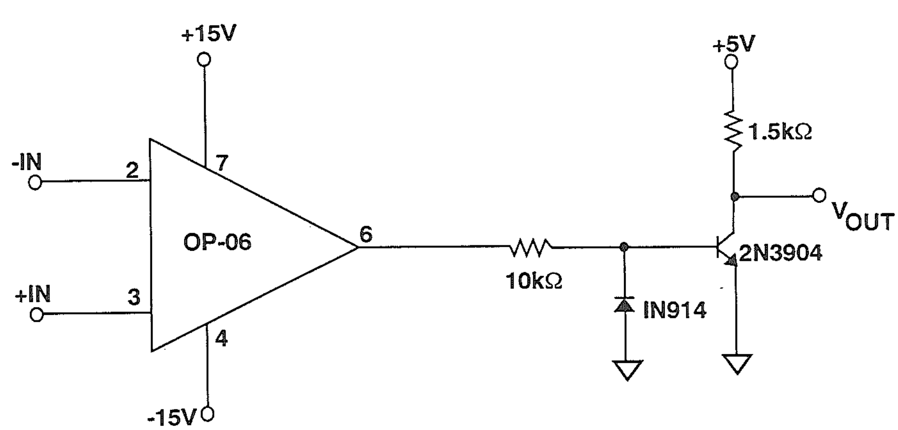


Figure 10.9

USING COMPENSATION PIN TO CLAMP OP AMP OUTPUT TO TTL LEVELS

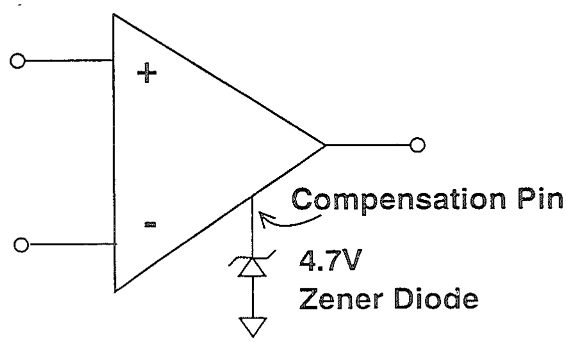


Figure 10.10

One possible problem when using op-amps without feedback is that large differential input voltage may be permanently present. Older NPN input op-amps could break down (with a subsequent degradation in input precision) under these conditions, but most are protected by clamp diodes these days. Even so, a substantial input current will flow when these are turned on, and this should be taken into consideration.

Even when feedback is employed, some circuits rely on correct operation when the feedback loop is broken. One example is the series-mode precision rectifier of Figure 10.11, which can also be used as a peak detector if R1 is replaced by a capacitor. This circuit requires a high input impedance under all conditions. Amplifiers with FET or lateral PNP inputs are good for this type of application.

SERIES-MODE PRECISION RECTIFIER

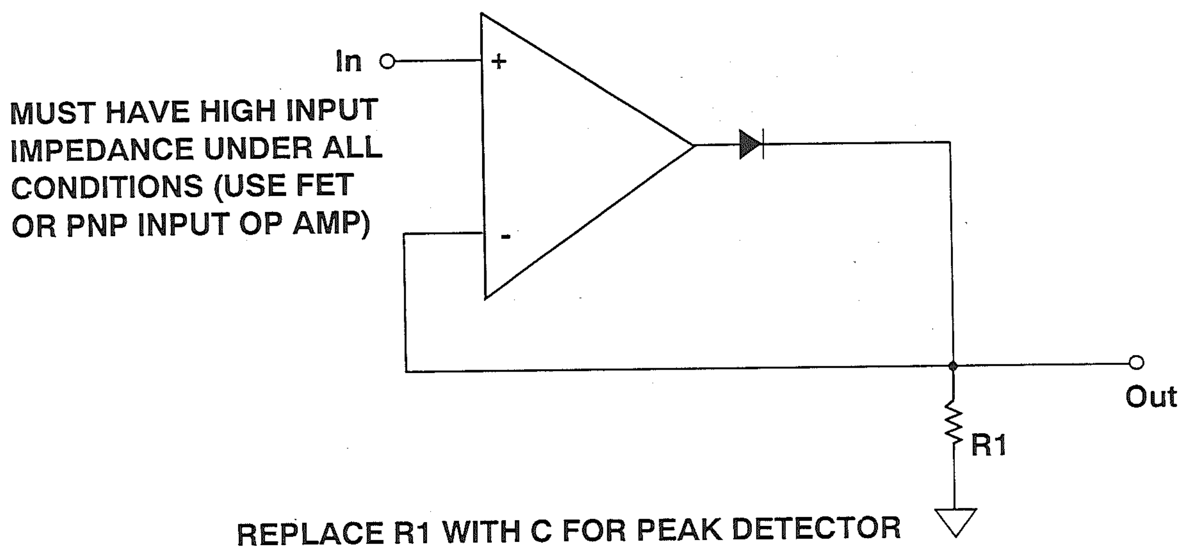


Figure 10.11

MORE MALTREATMENT OF THE COMPENSATION PINS

As mentioned earlier, some op-amps have a compensation pin which closely tracks the output. This can be used as a general purpose clipping function [6]. Referring to Figure 10.12, bias voltages for two back to back diode clamps are provided by a resistor string. Such a circuit is useful for preventing gross overdrive of analog switches, A/D converters etc.

There are also some quite ingenious ways of compensating op amps. Figure 10.13 is full-wave precision rectifier of the usual two op-amp type. Al is a type usually compensated by a capacitor from the output to pin 8. In this case however, two capacitors are used, connected to the output side of the feedback diodes [7]. This effectively disconnects the compensation when the diodes turn off, removing much of the usual 'dead-band' as the input swings through zero. I have done all sorts of other things with compensation pins, including using them to parallel op-amps. But these days even I have my limits.

USING OP AMP COMPENSATION PIN FOR CLIPPING

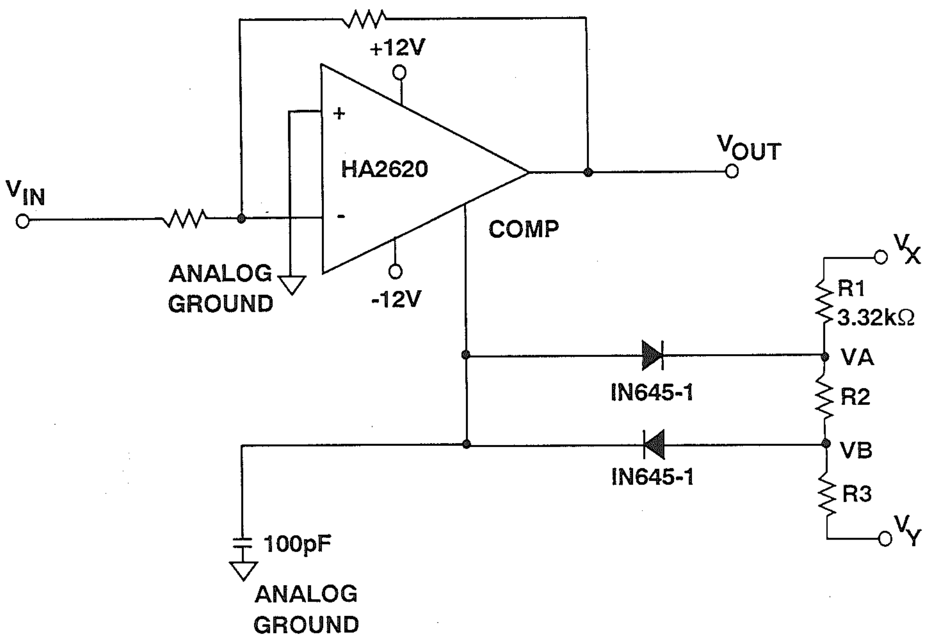


Figure 10.12

PRECISION FULL-WAVE RECTIFIER MINIMIZES ZERO-VOLT "DEADBAND"

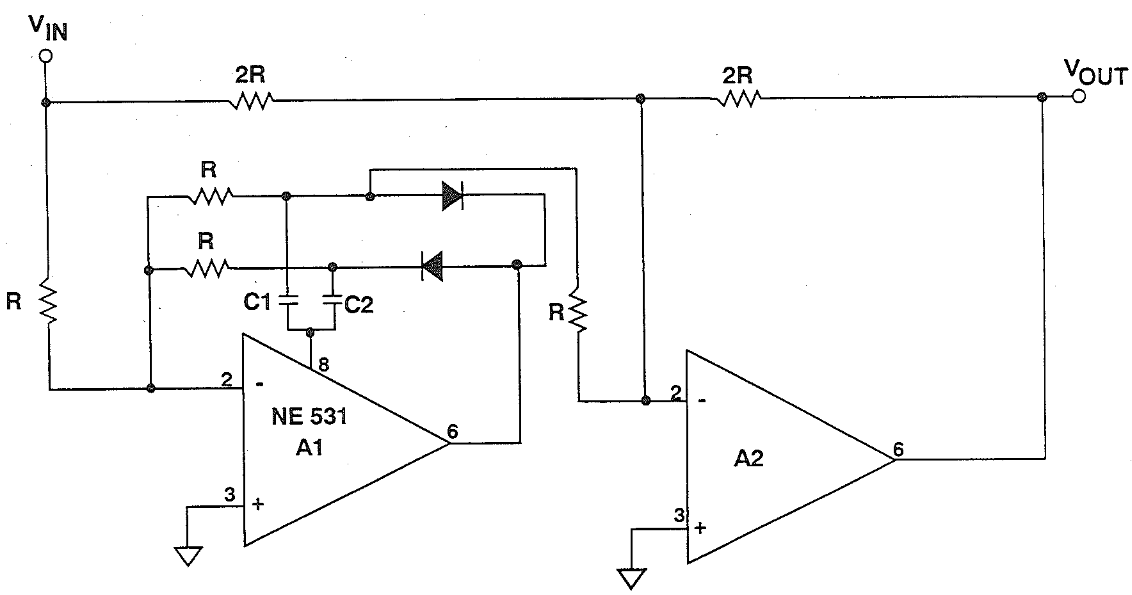


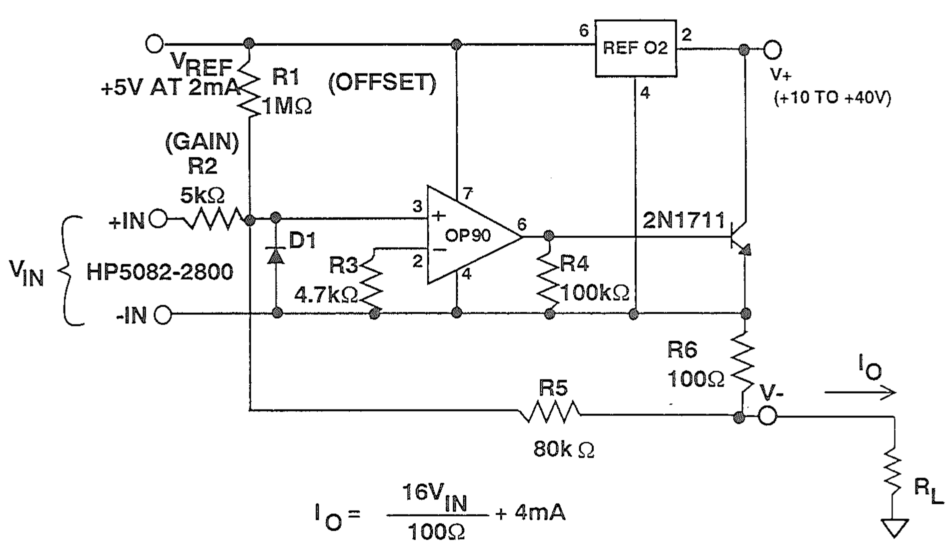
Figure 10.13

SHUNT-MODE OPERATION

Op-amps which can operate with the output at one of the supplies can be used in the shunt-mode. Positive shunt-mode operation would involve strapping the output to the negative supply pin, and vice versa for negative operation. To illustrate the concept, Figure 10.14 shows a fully floating 4-20mA industrial control loop transmitter [4]. The idea of shunt-mode operation is to force the supply current of the OP-90 to flow through the sense resistor, R6, thus removing it as an error source. Note that the OP-90 alone cannot directly source 20mA, so an external transistor has been added. The REF-02 provides the 4mA offset and also supplies up to 2mA for transducer excitation. If necessary, R1 can provide an offset trim, and R2 a gain trim. The trims do not interact, because the non-inverting input of the op-amp is at virtual ground. The Schottky diode, D1, is not necessary for circuit operation, but it prevents glitches from pulling the non-inverting input more than 300mV below ground. Without this protection, such glitches could cause phase reversal in the OP-90, possibly causing latch-up of the transmitter. The circuit's linearity is about 0.002%, and its line rejection is 0.002%/V.

Shunt mode operation has also been used to yield output voltages (notably in regulator applications) beyond the voltage rating of the operational amplifier.

FLOATING 4-TO-20mA TRANSMITTER ILLUSTRATES SHUNT-MODE OPERATION



$$I_O = \frac{16V_{IN}}{100\Omega} + 4mA$$

FOR VALUES SHOWN

Figure 10.14

SUPPLY SENSING

Just as the inputs are not the only way to get signals into an op-amp, the output is not the only way to get them out either. Figure 10.15 is a voltage to current converter based on the idea of supply sensing [8].

The basic idea is to invert the supply currents of the amplifier with transistor current "mirrors" and subtract them at I_{out}. With no input, these currents will be symmetric (except for the input bias currents of the op amp), and result in no net output current. Any input voltage will be impressed across R1, unbalancing the supply currents by an amount exactly equal to the input voltage divided by R1. This imbalance appears at I_{out} as a high-impedance current output. Op-amp voltage swings can be minimized using this approach, and because there is no feedback from the output such circuits can be made very fast. The main design problem lies in designing accurate current mirrors.

These can be formed from monolithic duals (such as MAT-02 & MAT-03), or monolithic quad packages (Analog Devices manufacturers a quad NPN, the MAT-04, and PNP quads are available from other manufacturers). Emitter degeneration resistors in series with the upper and lower emitter pairs can also improve accuracy, remembering that without them a 250μV V_{be} mismatch will create 1% of error.

Figure 10.16 shows an instrumentation amplifier based on the supply sensing technique. Here, an extra op-amp is added to provide a differential high impedance drive to R1. Again the supply currents of Al are subtracted and fed to R2 (the

FAST VOLTAGE-TO-CURRENT CONVERTER USING POWER SUPPLY SENSING

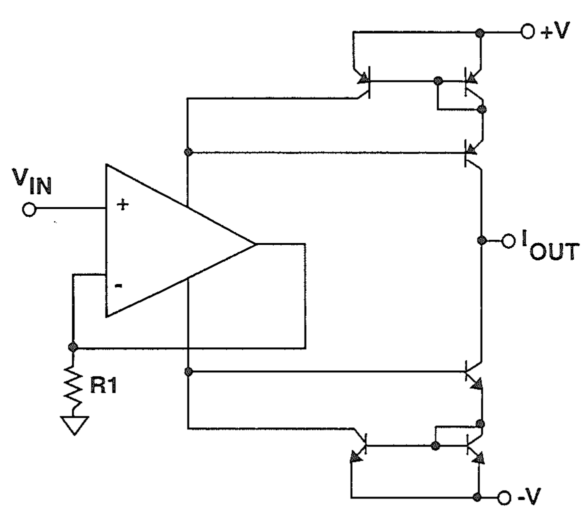


Figure 10.15

output buffer may not be necessary in some applications). The gain is simply set by the ratio of R2 to R1, and no trims are necessary to achieve high common-mode rejection. Note that the usual trick of using a dual op-amp for the input amplifiers is not practical here, because no dual of which I am aware brings out independent supplies for both amplifiers.

Figure 10.17 shows a (differential input) full-wave rectifier based on supply sensing. Here only the negative supply currents are used, and they are added instead of subtracted. Unfortunately, this leads to an output offset equal to both quiescent supply currents and this must be removed by adjustment of Rp. Figure 10.18 shows a comparison between this circuit (a)and the more conventional two op-amp configuration (b). Identical op-amps were used in both cases. For the record, the vertical scale is 1V/division, horizontal is 10µs/division and the op-amps were OP-41's, though faster amplifiers can be used of course.

It is possible to provide overall feedback around a supply sensing amplifier, and this actually results in a current feedback op-amp. This technique has been used to produce a very high performance audio amplifier [9].

INSTRUMENTATION AMPLIFIER USING POWER SUPPLY SENSING TECHNIQUE

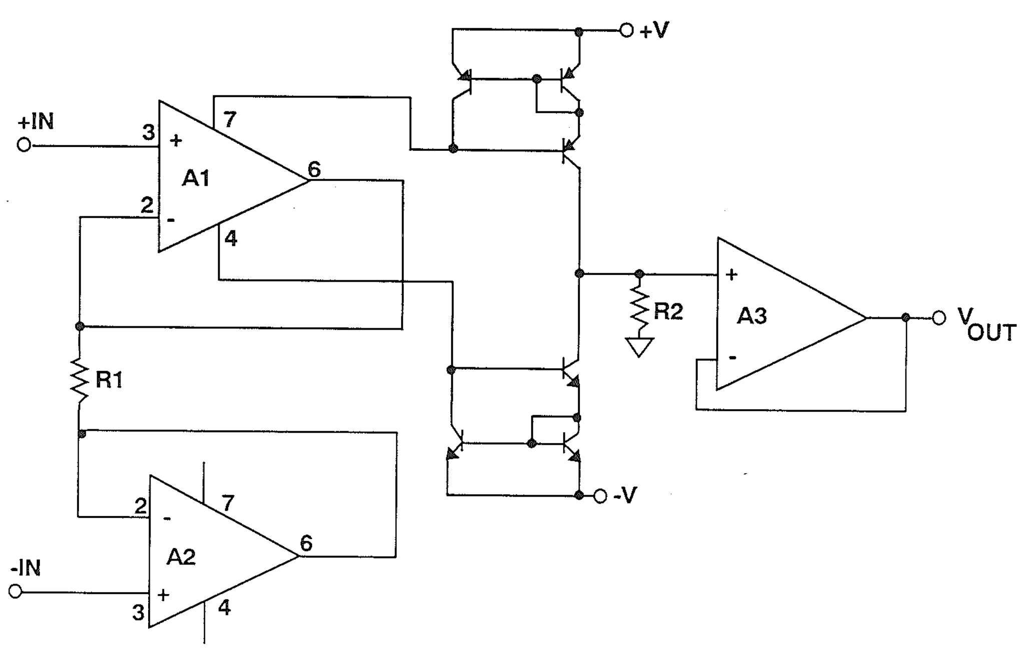


Figure 10.16

DIFFERENTIAL INPUT FULL-WAVE RECTIFIER USING POWER SUPPLY SENSING

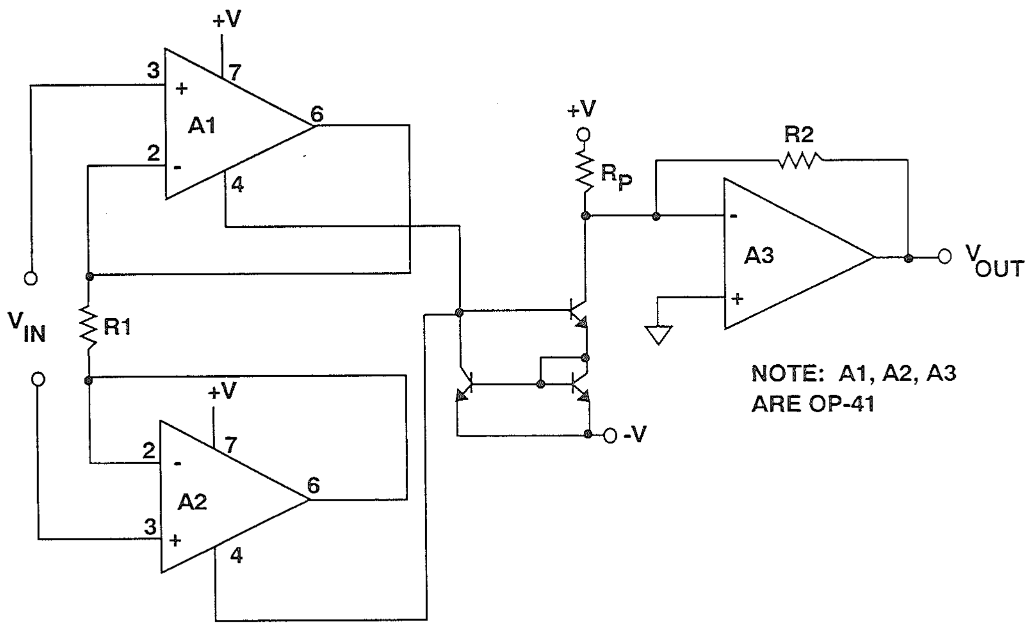
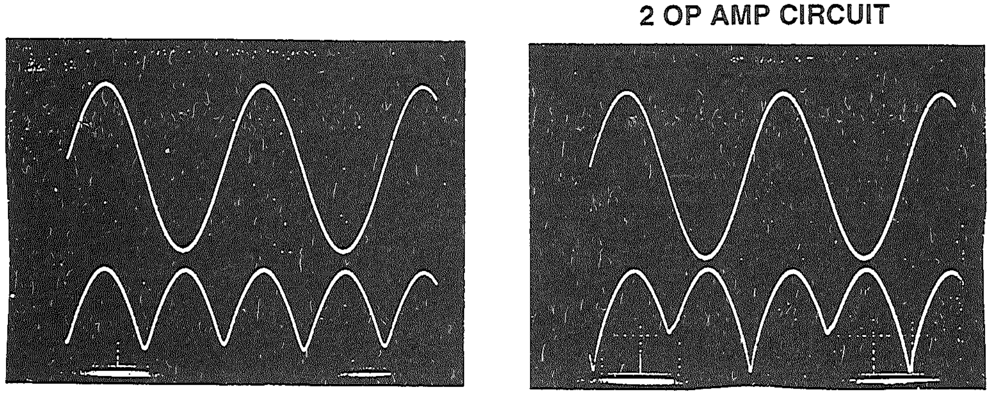


Figure 10.17

COMPARISON BETWEEN FULL-WAVE RECTIFIER USING POWER SUPPLY SENSING AND CONVENTIONAL 2 OP-AMP CIRCUIT

SUPPLY SENSING CIRCUIT

CONVENTIONAL
2 OP AMP CIRCUIT



VERTICAL SCALE: 1V/DIV.
HORIZONTAL SCALE: 10µs/DIV.

Figure 10.18

SOME NOTES ON COMPUTER SIMULATION

Many system designers are now using computer simulation techniques to at least verify the basic soundness of a design. However, the op-amp macromodels supplied by semiconductor vendors are definitely not aimed at applications such as those presented here. Most do not include the null or compensation pins, and many do not even model the power supply currents correctly [10]. The Analog Devices models not only get the supply currents right [11] but can also be used to simulate applications such as supply sensing. Some very advanced models are coming from companies such as ANALOGY incorporated, and these may be more generally useful in oddball applications. But in general, the circuits I have described are in a class which really should be verified at the breadboard level, with the exact type of amplifier being finally used.

CONCLUSION

I hate writing conclusions. I have merely scratched the surface of the subject matter here, so I regard this text as an overture rather than an opera. If I have provided an eyeopener for the almost limitless ways of using op amps, then I feel I have accomplished what I set out to do.

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USING OP AMPS AS COMPARATORS

JAMES M. BRYANT

INTRODUCTION

A comparator is a device with two input terminals and a logic output which indicates which of the two inputs is at the higher potential. An operational amplifier is an amplifier with differential inputs, a single-ended output, and extremely high gain. Its output generally swings close to its supply rails. There is therefore a temptation to use op-amps as comparators. When faced with this temptation it is well to remember Mr. Punch's advice to those about to marry - DON'T!

Comparators are designed to work open-loop, they are designed to drive logic from their outputs, and they are designed to work at high speed with minimal instability. Op-amps are not designed for use as comparators, they may saturate if over-driven and recover comparatively slowly, many have input stages which behave in unexpected ways when used with large differential voltages, and their outputs are rarely compatible with logic.

COMPARATORS VERSUS OP AMPS

- A COMPARATOR GIVES A LOGIC OUTPUT INDICATING THE RELATIVE POTENTIALS ON ITS TWO INPUTS
- AN OPERATIONAL AMPLIFIER AMPLIFIES THE DIFFERENTIAL VOLTAGE APPLIED TO ITS TWO INPUTS

Figure 10.19

WHEN CONSIDERING USING OP-AMPS AS COMPARATORS

REMEMBER

MR. PUNCH'S ADVICE TO THOSE ABOUT TO MARRY

DON'T!

Figure 10.20

Nevertheless it is often tempting to use an op-amp as a comparator since comparators are, in general, designed for speed at the expense of some other parameters, and a suitable op-amp may have lower V_{OS}, I_b and price (especially if it is one op-amp of a chip containing four) than a comparable comparator. But it will also be much slower - an op-amp should never be used as a comparator if high speed is important to the application.

This section of the Seminar considers some of the issues to be considered when, for whatever reason, an op-amp is to be used as a comparator. Not all of them can be resolved by reference to the op-amp data sheet, since op-amps are not intended for use as comparators and are rarely specified for such an application.

The most common issues are speed (as we have already mentioned), the effects of input structures (protection diodes, phase inversion in FET amplifiers, and many others), output structures which are not intended to drive logic, hysteresis and stability, and common-mode effects.

HOWEVER

- OP-AMPS CAN HAVE LOWER:

    OFFSET VOLTAGE
    BIAS CURRENT
    PRICE

- THEY WILL DEFINITELY HAVE LOWER SPEED!

Figure 10.21

ISSUES TO BE CONSIDERED WHEN USING OP-AMPS AS COMPARATORS

- *ALWAYS* SPEED
- OUTPUT LEVELS
- HYSTERESIS & STABILITY
- EFFECTS OF INPUT STRUCTURES
    - Protection Diodes
    - Phase-Inversion in BIFET Amplifiers
    - Common-Mode Range

Figure 10.22

Speed

Most comparators are quite fast and some are very fast indeed - but so are some op-amps. Why must we expect low speed when using an op-amp as a comparator?

A comparator is designed to be used with large differential input voltages, whereas op-amps normally operate with their differential input voltage minimized by negative feedback. When an op-amp is over-driven, sometimes by only a few millivolts, some of its stages may saturate. If this occurs the device will take a comparatively long time to come out of saturation and will therefore be much slower than if it always remained unsaturated.

The desaturation time of an overdriven op-amp is likely to be considerably longer than the normal group delay of the amplifier, and will often depend on the amount of overdrive. Since few op-amps have their desaturation time specified for various amounts of overdrive it will generally be necessary to determine, by experiment, the behavior of the amplifier under the conditions of overdrive to be expected in a particular application.

WHY IS AN OP-AMP SLOWER THAN A COMPARATOR?

- **An Op-Amp Saturates when Over-driven Takes Time to Recover From Saturation (De-saturation Time)**
- **A Comparator is Designed NOT to Saturate**

Figure 10.23

SATURATION MAKES AN OP AMP USED AS A COMPARATOR SLOWER THAN THE SAME AMPLIFIER USED WITH NEGATIVE FEEDBACK

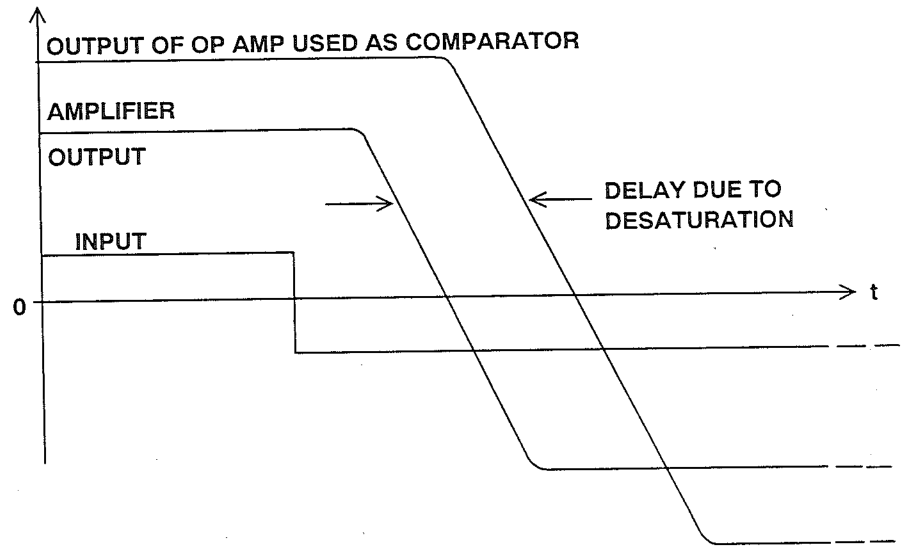


Figure 10.24

DESATURATION TIMES

- FOR VARIOUS LEVELS OF OVERDRIVE ARE RARELY SPECIFIED FOR OP-AMPS
- IT WILL BE NECESSARY TO DETERMINE THEM BY EXPERIMENT UNDER THE CONDITIONS OF THE PARTICULAR APPLICATION
- Remember that since this parameter is not specified or guaranteed it may vary quite widely from device. Test several devices from several batches and NEVER regard any set of results as typical.

Figure 10.25

The results of such experiments should be regarded with suspicion and the values of propagation delay through the op-amp comparator which is chosen for worst-case design calculations should be at least twice the worst value seen in any experiment.

OUTPUT CONSIDERATIONS

The output of a purpose-built comparator will be designed to drive a particular logic family or families, while the output of an op-amp is designed to swing from supply rail to supply rail. Frequently the logic being driven by the op-amp comparator will not share the op-amp's supplies and the op-amp rail to rail swing may go outside the logic supply rails - this will probably destroy the logic circuitry, and the resulting short-circuit may destroy the op-amp as well.

OP-AMP OUTPUTS AND LOGIC INPUTS

- **ARE GENERALLY INCOMPATIBLE (CMOS sharing the op-amp supply is an exception.)**
- **SOME INTERFACE CIRCUITRY IS USUALLY NECESSARY**

Figure 10.26

Of course some circuits will actually require rail-output swings from their comparator(s) and no addition interfacing is necessary. These include circuits which are not using IC logic but using the output of the comparator to switch discrete diodes and transistors, and circuits where the logic is CMOS powered from the same positive and negative supplies as the op-amp. (BEWARE: CMOS powered from the positive op-amp supply and the [center] ground rail is not included in this category - the op-amp output MUST be within the CMOS supply rails at all times.)

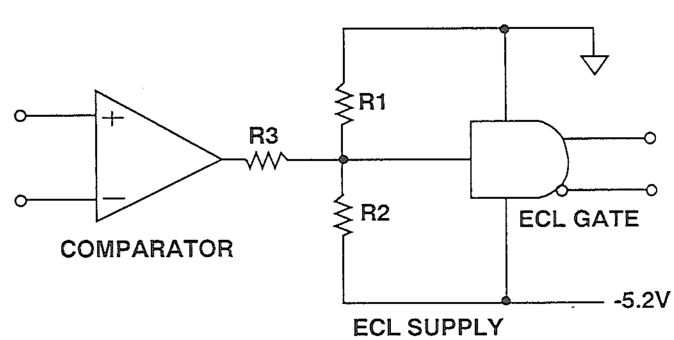
There are three types of logic which we must consider: ECL, TTL and CMOS.

ECL is a very fast current steering logic family. It is unlikely that an op-amp would be used as a comparator in applications where ECL's highest speed is involved, for reasons given above, so we shall usually be concerned only to drive ECL logic levels from an op-amp's signal swing and some additional loss of speed due to stray capacities will be unimportant. To do this we need only three resistors, as shown in Figure 10.27.

R1, R2 and R3 are chosen so that when the op-amp output is positive the level at the gate is -0.8V, and when it is low it is -1.6V. ECL is occasionally used with positive, rather than negative, supplies (i.e. the other rail is connected to ground), the same basic interface circuit may be used but the values must be recalculated.

Although CMOS and TTL input structures, logic levels, and current flows are quite different (although some CMOS is specified to work with TTL input levels) the same interface circuitry will work perfectly well with both types of logic, since they both work for logic 0 near to 0 V and logic 1 near to 5 V.

INTERFACE WITH ECL GATE



■ **LOW RESISTOR VALUES WILL MINIMIZE THE EFFECT OF STRAY CAPACITANCE BUT INCREASE POWER CONSUMPTION**

Figure 10.27

SIMPLE INTERFACES WITH CMOS AND TTL GATES

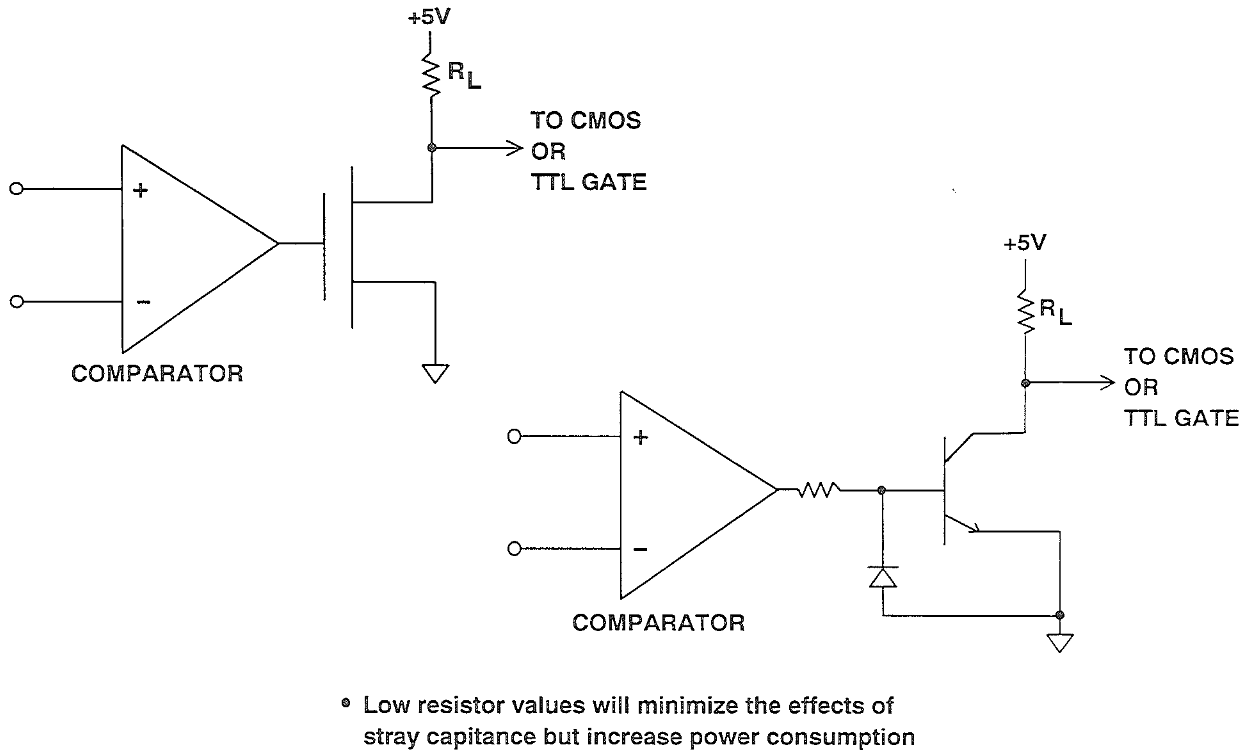


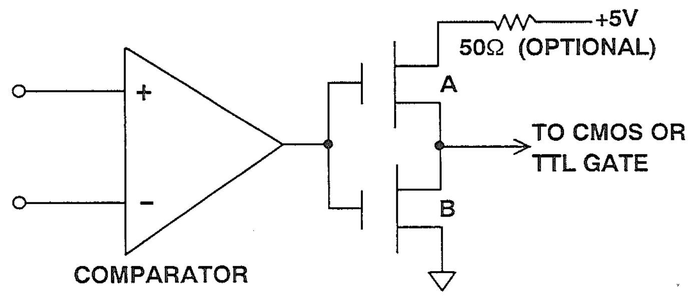
Figure 10.28

The simplest interface uses a single N-channel VMOS transistor and a pull-up resistor, R_L. A similar circuit may be made with an NPN transistor, R_L, and an additional resistor and diode. These circuits are simple, inexpensive and reliable, and may be connected with several transistors in parallel and a single R_L to give a "wired-or" function, but the speed of the 0-1 transition depends on the value of R_L and the stray capacity of the output node. The lower the value of R_L the faster, but the higher the power consumption.

By using two VMOS devices, one P-channel and one N-channel, it is possible to make a CMOS/TTL interface using only two components which has no quiescent power consumption in either state. Furthermore, it may be made inverting or non-inverting by simple positioning of components. It does, however, have a large current surge during switching, when both devices are on at once, and unless VMOS devices with high channel resistance are used a current limiting resistor may be necessary to reduce this effect. It is also important, in this application and the one in Figure 10.28, to use VMOS devices with gate-source breakdown voltages, V_{bgs}, greater than the output voltages of the comparator *in either direction*. A value of $V_{bgs} > \pm 25$ V is common in VMOS devices and is usually adequate, but some VMOS devices contain gate protection diodes which reduce the value - these should not be used.

Some op-amps have a terminal which may be used to clamp the output to within certain limits by connecting the terminal to reference voltages by diodes. Where such terminals exist they may be used to limit the op-amp output to values suitable for the logic being used but the circuitry is more complex than the simple interface circuitry given above and it is rarely worthwhile to do so.

LOW POWER INTERFACE WITH CMOS AND TTL GATES



- Can be inverting or non-inverting, depending on placing of VMOS devices.

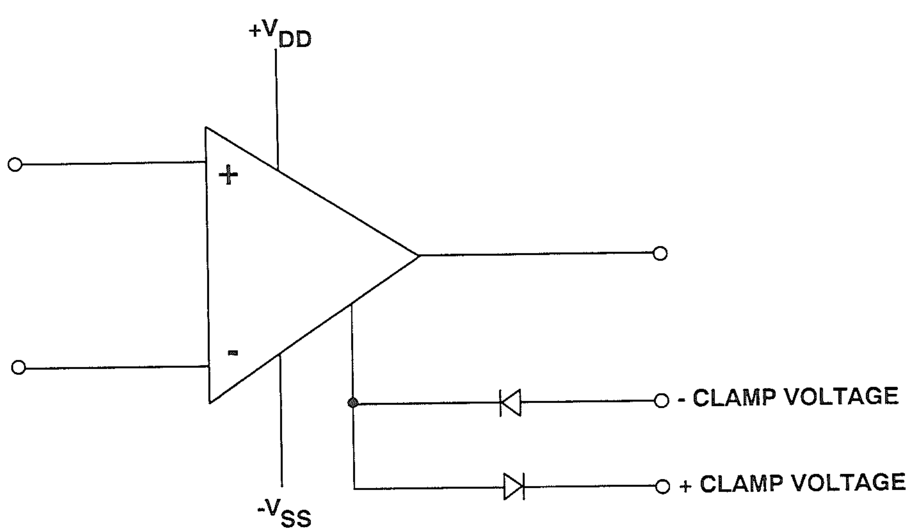
Inverting: A = P-channel/B = N-channel

Non-inverting: A = N-channel/B = P-channel

(V_{bgs} >±25 V for both devices)

Figure 10.29

OP AMPS WITH CLAMP CIRCUITRY MAY USE THIS TO LIMIT OUTPUT LEVELS TO LOGIC LEVELS



- But the circuitry shown in previous diagrams may be easier to use

Figure 10.30

INPUT CIRCUITRY

There are a number of effects which must be considered regarding the inputs of op-amps used as comparators. The first-level assumption engineers make about all op-amps and comparators is that they have infinite input impedance and can be regarded as open circuits - this is a reasonable starting position (except for current feedback (transimpedance) op-amps, which have a high impedance on their non-inverting input but a low impedance of a few tens of Ω on their inverting input, which is internally buffered to the same potential as the inverting input) but it must not be held indefinitely.

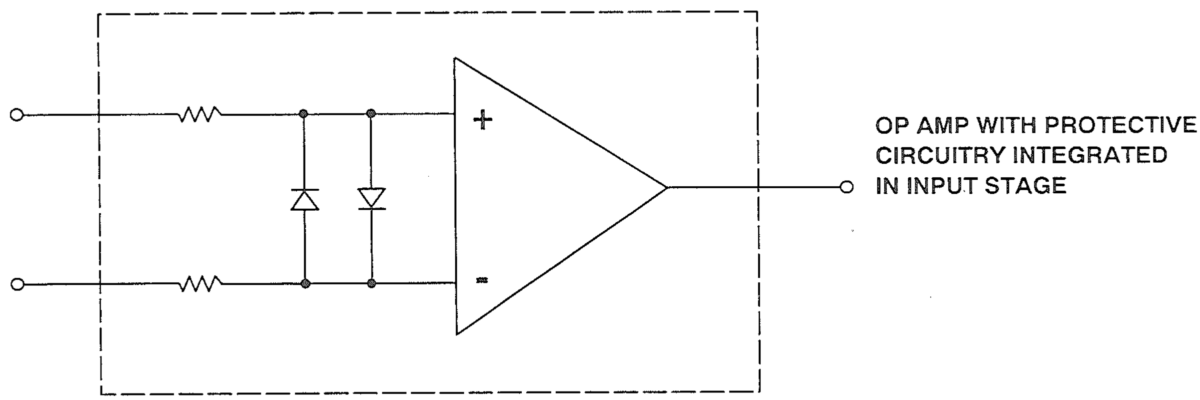
If an op-amp has a simple long-tailed pair as its input structure (whether using bipolar transistors or FETs) then its input impedance will remain high if a large differential voltage is applied to it. But many op-amps (especially bias-compensated ones such as the OP-07 and its many descendants) contain protective circuitry to prevent large voltages damaging input devices.

OP-AMP INPUT IMPEDANCE

- **INPUT IMPEDANCE IS NOT INFINITE (ESPECIALLY WHEN LARGE DIFFERENTIAL VOLTAGE IS APPLIED)**

Figure 10.31

MANY OP-AMPS HAVE CIRCUITRY TO PROTECT THEIR INPUT DEVICES



- This greatly reduces their input impedance when differential input voltages of more than ±700 mV are present

Figure 10.32

Others contain more complex input circuitry, which only has high impedance when the differential voltage applied to it is less than a few tens of mV, or which may actually be damaged by differential voltages of more than a few volts. It is therefore necessary, when using an op-amp as a comparator, to study the data sheet to determine how the input circuitry behaves when large differential voltages are applied to it. (It is always necessary to study the data sheet when using an integrated circuit to ensure that its non-ideal behavior (and every integrated circuit ever made has some non-ideal behavior) is compatible with the proposed application - it is just more important than usual in the present case.)

Of course some comparator applications never involve large differential voltages - or if they do the comparator input impedance when large differential voltages are present is comparatively unimportant. In such cases it may be appropriate to use as a comparator an op-amp whose input circuitry behaves non-linearly - but the issues involved must be considered, not just ignored.

As mentioned elsewhere in this seminar, nearly all BIFET op-amps exhibit anomalous behavior when their inputs are close to one of their supplies (usually the negative supply). Their inverting and non-inverting inputs may become interchanged. If this should occur when the op-amp is being used as a comparator the phase of the system involved will be inverted, which could well be inconvenient. The solution is, again, careful reading of the data sheet to determine just what common-mode range is acceptable.

READ THE DATA SHEET

- DETERMINE IF NON-LINEARITIES IN YOUR OP-AMP'S INPUT WILL AFFECT ITS OPERATION AS A COMPARATOR

- LOOK FOR:-

  Low values of Absolute Max Differential Input Voltage

  Graphs of Bias Current or Input Current vs Differential or Common-Mode Input Voltage

  Any other input specification which may indicate non-linearities

- WILL YOUR PROPOSED APPLICATION WORK WITH A COMPARATOR WHICH BEHAVES IN THIS WAY??

Figure 10.33

PHASE INVERSION

- BIFET AND PNP INPUT AMPLIFIERS OFTEN SUFFER PHASE- INVERSION WHEN THEIR COMMON-MODE VOLTAGE IS CLOSE TO THEIR SUPPLIES

- Verify your common-mode range when using BIFET and PNP input op-amps.

Figure 10.34

HYSTERESIS & STABILITY

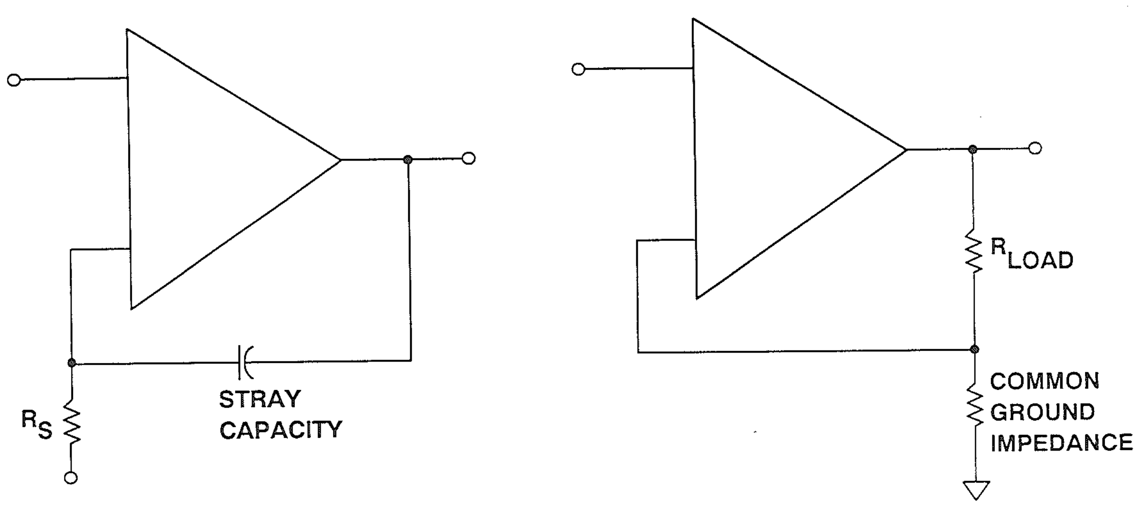
When an op-amp is functioning as a comparator there is no negative feedback present so, during transitions, its full open-loop gain is present and very small amounts of positive feedback can start oscillation.

This instability can result from capacitive feedback from the output to an input (usually the non-inverting input), or from coupling due to output currents flowing in ground impedances which are common to the input circuitry. The cure for the first is to minimize stray feedback capacity by proper layout, and to ensure that the impedance seen by the non-inverting input is as low as possible, ensuring that any remaining capacitively fed-back signal is attenuated to insignificance.

Ground current feedback is controlled by intelligent design of the ground circuit layout, as discussed in the relevant section of this Seminar.

Sometimes it is not possible to prevent instability by these measures. The only remaining possibility is to use positive feedback to introduce a small amount of hysteresis so that once a transition has started the input must undergo significant reversal before the reverse transition can occur.

OPEN-LOOP OP-AMPS USED AS COMPARATORS MAY SUFFER INSTABILITY OR LATCH-UP DUE TO FEEDBACK FROM STRAY CAPACITY OR COMMON GROUND IMPEDANCES.



- The Problem may be eased by minimizing stray capacitance, source impedances, and common ground impedances.

Figure 10.35

HYSTERESIS

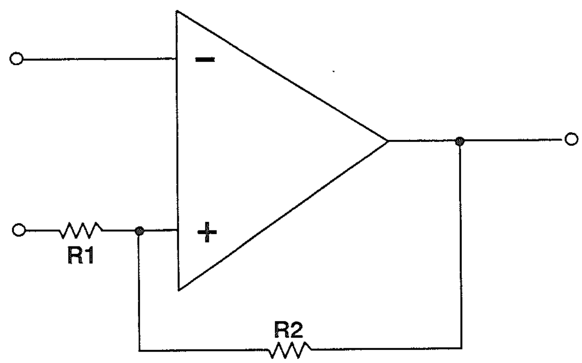
- **CAN CURE COMPARATOR OSCILLATION BY INTRODUCING A CONTROLLED "LATCH-UP"**
- **The amount of Hysteresis is predictable and is controlled by the ratio of the positive feedback resistors.**

Figure 10.36

This can be done with two resistors, and the amount of hysteresis is proportional to their ratio. The signal input to the comparator may be applied to either the inverting or the non-inverting input, but if it is applied to the inverting input its source impedance must be low enough to have insignificant effect on R1 (of course if the source impedance is sufficiently predictable it may be used as R1).

If the reference voltage is midway between the two comparator output voltages (as is the case with a symmetrical power supply and a ground reference) then the introduction of hysteresis will move the positive and negative thresholds equal distances from the reference, but if the reference is nearer to one output than to the other the thresholds will be asymmetrically placed about the reference voltage.

POSITIVE FEEDBACK ADDS HYSTERESIS TO A COMPARATOR



OUTPUT SWING: V_S

HYSTERESIS = $\dfrac{V_S\,(R1+R2)}{R1}$

- Input signal may be applied to either input
  but its source impedance must be low if it is applied to R1

Figure 10.37

CALCULATION OF THRESHOLDS WHEN THE REFERENCE IS NOT MIDWAY BETWEEN THE OUTPUTS

- Comparator output voltages are V_p & V_n
- Reference voltage is V_r
- Negative threshold is $\dfrac{(R1 + R2)V_r - R1V_p}{R2}$
- Positive threshold is $\dfrac{(R1 + R2)V_r - R1V_n}{R2}$

Figure 10.38

Conclusion

Operational amplifiers are not designed to be used as comparators, so this section has been, intentionally, a little discouraging. Nevertheless there are many applications where the use of an op-amp as a comparator is a correct engineering decision - what is important is to make it a *considered* decision, and ensure that the op-amp chosen will perform as expected. To do this it is necessary to read the data sheet carefully, to consider the effects of non-ideal op-amp performance, and to calculate the effects of op-amp parameters on the application. Since the op-amp is being used in a non-standard manner some experiment may also be necessary - since the amplifier used for the experiment will not necessarily be typical the results of experiments should always be interpreted somewhat pessimistically.

CONCLUSION

- **OP-AMPS MAY BE USED AS COMPARATORS BUT BE CAREFUL!**
- **Read the Data Sheet**
- **Calculate the effects of non-ideal parameters**
- **Experiment**
- **Always interpret your results a little pessimistically**

Figure 10.39