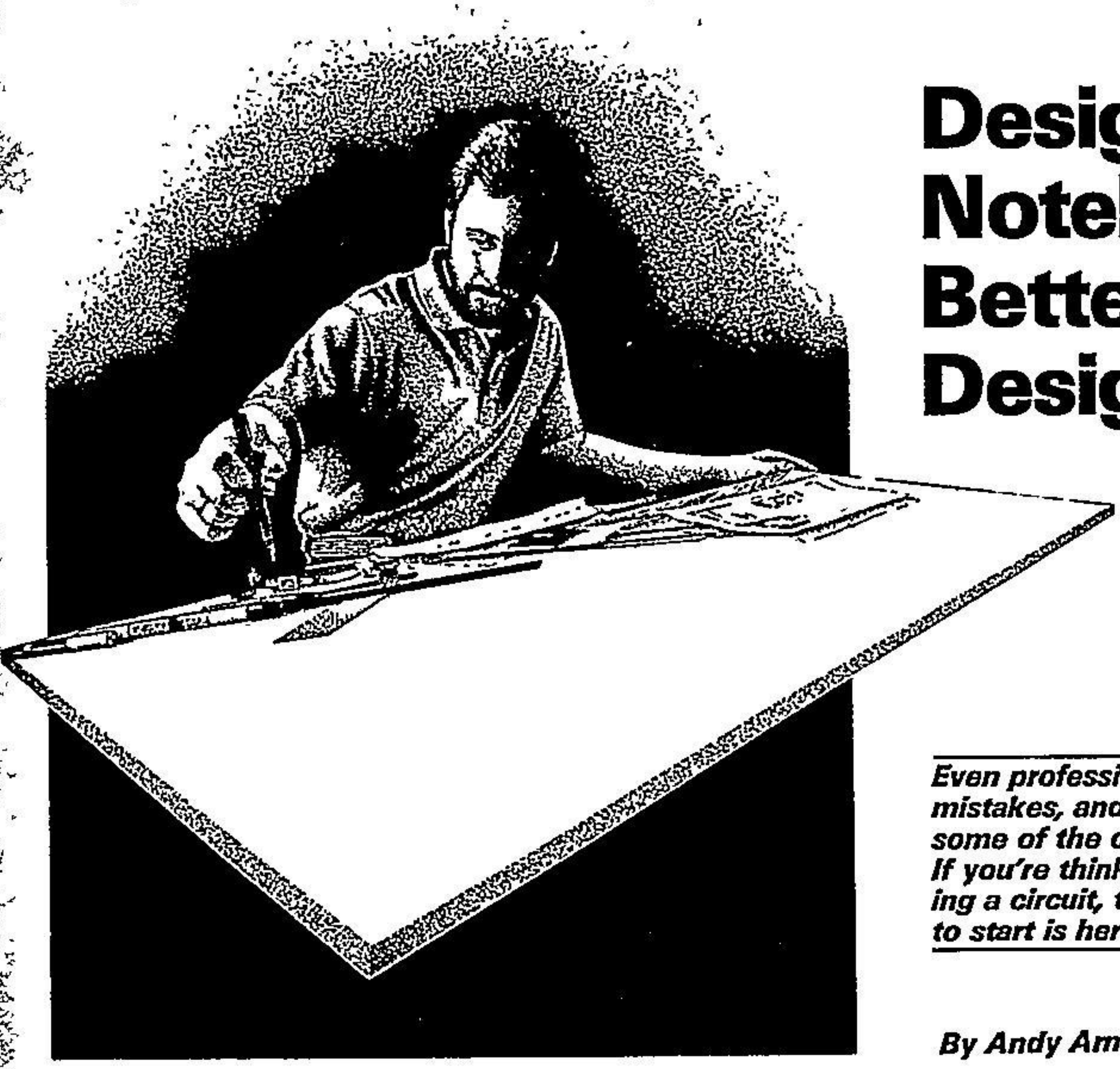

Designer' Notebook: Better By Design

Even professionals make mistakes, and here are some of the common ones. If you're thinking of designing a circuit, the best place to start is here.

By Andy Armstrong

AFTER inspecting many designs at the draft stage, it is clear that there are some misunderstandings and design errors which crop up again and again. Some aspects of circuit design, for reasons unknown, seem to be ignored or glossed over by even the most seasoned practitioners.

Most of the problems fall into the category of "things which will work most of the time or work with certain samples of the components used".

A typical example was faced by a friend of mine in a vacation job after his second year at college, and involved unijunction transistors. Someone had designed (by dint of sheer building) a control unit, incorporating a unijunction, for an electric arc welder. The first production batch of welders worked very well, but none in the second batch worked at all.

It turned out that the circuit had been optimized by trial and error to work with a batch of unijunctions which were at the edge of the specification. The next batch purchased had more typical characteristics, and the circuit could not cope. The configuration of the circuit was not designed to take account of the tolerances of unijunctions, but a change of component values centred the circuit on the typical operating parameters. Subsequently only one component value had to be changed if a batch of unijunctions was too far from typical.

Design Posts

Nobody expects magazine projects to be designed to industrial standards. This would be uneconomic because of the very large amount of time required to design even a simple circuit to production standard, and because of the need to make more than one prototype to double check a design. These limitations notwithstanding, a project design needs to be as close in standard to an industrial design as possible, and should, in particular, avoid problems connected with variations in the electrical and mechanical characteristics of components.

Of course, there are differences in emphasis. For example, a circuit may rely on a particular component characteristic, perhaps requiring that two diodes have a similar voltage drop at a certain current. The home constructor could happily select the components, but in an industrial design, the cost of paying someone to grade components would mean that the real price of a 5 cent diode would be a lot more than 5 cents.

On the other hand, if too much decision-making on the part of the constructor is necessary to make a project work, then some of the people who build it will simply never succeed.

Family Characteristics

Many of the marginal designs encountered have used CMOS, so this is the place to start.

The 4000 series of CMOS is designed to work over a wide range of power supply voltages. Different manufacturers specify slightly different operating characteristics at different voltages, but here I shall refer to the Mullard/Signetics HEF4000B range. Some of the family specifications are reproduced here for reference.

A number of circuits use a CMOS gate output to switch a transistor, which is used to control a relay, lamp, etc. Normally, a small signal transistor is used to drive the load and in order to work well, the transistor must be switched on hard. This requires adequate base current; a rule of thumb is to use a base current of 0.1 times the required collector load current. This can exceed the current which the gate is guaranteed to supply, though in fact most gates manage well over the minimum specified current.

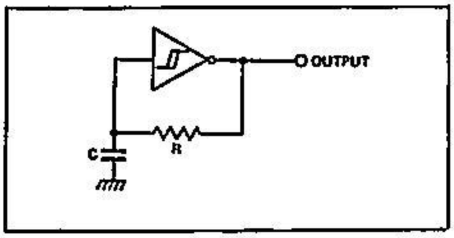

Fig. 1. Simple schmitt oscillator.

It is not a good idea to rely on your good fortune in selecting a gate Back on the industrial front, I recently had to investigate a rash of mysterious board failures, and discovered that one of the CMOS gates was being asked to deliver about twice its guaranteed output current. After a while, most gates from one batch failed, though the design had been produced without problems for several years beforehand. Presumably this batch of gates was unable to exceed its specification without damage.

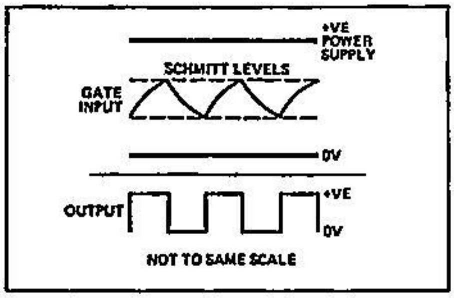

Fig. 2. Waveform diagram.

To avoid this sort of problem in home projects, a CMOS gate sourcing current should have a load resistance of at least 1kohm per volt of power supply. If this means that the transistor it is feeding receives insufficient base drive to switch properly, then the answer is to use a Darlington transistor, or two transistors connected as a Darlington pair.

Alternatively, you could use a power FET suitable for the desired load current. A power FET capable of switching several amps may be driven directly by a CMOS gate. The switching speed may be low, because of the limited rate at which the CMOS output can charge or discharge the FET gate capacitance. The heavy load presented to the CMOS gate output by this capacitance is of short enough duration not to risk damaging the CMOS chip unless a high frequency switching signal is used.

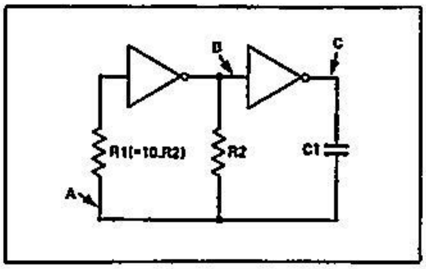

Fig. 3 Clock oscillator.

There is one exception to these stern warnings about overloading CMOS outputs. When powered from a 5V supply, most CMOS chips are designed to be short circuit proof. The practice of driving an LED from the output of a CMOS gate should not be harmful at this supply voltage, though the output will not provide a proper logic level when used in this manner. My recommendation is that this practice be confined to novelty circuits.

Clock Oscillators

Many projects incorporate some sort of oscillator, which may be needed to clock a counter, or to generate an audible tone. Figure 1 illustrates a simple oscillator circuit, using a Schmitt trigger IC. As shown in the waveform diagram, Fig. 2, the capacitor charges through the feedback resistor until the voltage on it reaches the positive threshold of the Schmitt trigger gate. The output of the gate then switches to logic 0 and the capacitor starts to discharge until it reaches the lower Schmitt threshold.

There are two drawbacks to this circuit. The Schmitt levels may vary widely from batch to batch of the chip, and the output frequency of the circuit is directly dependent on these levels. Also, the threshold levels are not symmetrical with respect to the power supply (the characteristic of Schmitts known as hysteresis), so the mark-to-space ratio of the output wave is not unity. If the mark-to-space ratio is not important, the circuit may be made more acceptable by the addition of a potentiometer to fine tune the frequency.

A more consistent circuit is shown in Fig. 3, and its waveform diagram in Fig. 4. The junction point of R2 and C1 alternately takes up voltages outside the power supply rails, and then charges or discharges to approximately half the power supply voltage. Because the voltage range over which the capacitor works is large, small differences in switching level between different samples of chip do not have much effect on the frequency or the mark-to-space ratio. The frequency is approximately $1/(2.2 \times R2 \times C1)$.]

Many project designers omit the resistor R1. If this component is omitted, then the junction of R2 and C1 is prevented from taking up a voltage outside the supply rails by the input protection diodes of the CMOS gate. The frequency is approximately three times the frequency given if R1 is included (and if R1 is, as specified, ten times R2). Variations in switching levels or gain between samples of chip now have a more significant effect, so the net effect is to decrease the predictability of the circuit's performance.

If very high value resistors are used in the circuit, then high frequency noise pickup on the input connected to R1 may be a problem. In this case, rather than lower R1 and make the operation less predictable, a capacitor of a few hundred picofarads may be added in parallel with R1. Practice has shown that this always solves the problem without any detectable effect on the correct operation of the circuit.

In some project designs, NOR or NAND gates are used instead of inverters. The "spare" inputs may be used to gate the oscillator and turn it on or off in response to a logic signal. A logic 0 signal will stop a NAND gate oscillator, while logic 1 will stop a NOR gate oscillator. If it is necessary to start to clock a counter immediately the oscillator is started, then the rest of the oscillator should be considered. For example, if the signal is generated by pressing a switch, the response should be immediate or the user may begin to wonder if it is working.

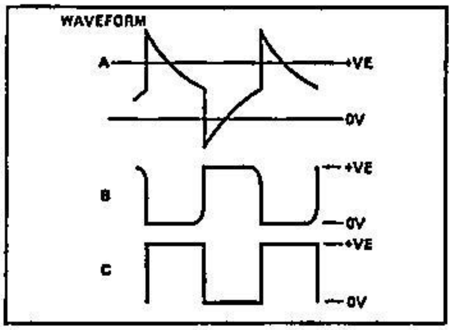

Fig. 4 Waveform for the clock oscillator.

The circuit shown in Fig. 5 will generate a positive edge on its output immediately a logic 0 is applied to its control input. By its nature, the circuit in its inhibited state will always charge its capacitor in such a way that it is ready to switch as soon as it is allowed to do so.

Op Amps

The correct use of op amps is another area which seems to be difficult for some project designers. There are several aspects which cause problems.

First of all, some designers simply fail to take account of the input bias and offset current. If a bipolar op amp is used, the bias resistors should be of a low enough value that the voltage drop in them is small. I recall seeing a reader's circuit in one electronics magazine, showing a 741 connected with all the bias current for the negative input flowing through a 4M7 resistor.

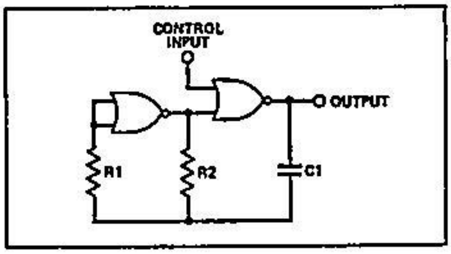

Fig. 5. An instant turn-on.

A good rule is to make the bias resistors as low as the rest of the circuit design allows, and to make the total DC resistance connected to each input the same. In this way, the difference in voltage between the two inputs (the offset) is determined by the difference in bias current between the two inputs (the input offset current) rather than the total bias current. If the offset is still too large, then a FET input amplifier should be used.

The open loop gain of an op amp also seems to confuse some people. The text of the reader's circuit mentioned above stated, "the maximum gain of a 741 is quoted as 20,000, but in this circuit it is wired to provide a gain of 47,000". This mistake arises from a misunderstanding about the way the op amp's gain is determined. The gain is determined by the ratio of the two feedback resistors in the circuit. You can use any ratio you please, but you cannot make the op amp give more than its maximum open loop gain.

A typical op amp frequency response is shown in Fig. 6. There are two relevant and related factors, the open loop gain and the gain-bandwidth product. The open loop gain defines the maximum low frequency gain the op amp can produce under any circumstances, and the gain-bandwidth product indicates the increase in gain with decreasing frequency.

An op amp having a gain-bandwidth product of 1MHz, for example, will have an open loop gain of unity at a frequency of 1 MHz. As the frequency is decreased, this gain will rise until the maximum open loop gain is reached, often at a frequency of about 10Hz, unless the internal stability capacitor is set to start rolling it off sooner.

Totally Slewed

The effects of output slew rate limiting and of power supply variations on op amp characteristics are clearly illustrated by a mistake of mine, made when 741s were the normal choice of op amp for any task. In a car project, I used a 741 to clock a CMOS counter. According to the data books, the slew rate of the output of a 741 is inadequate to clock the CMOS counter reliably, but still the circuit seemed to work, at least some of the time. After a little experimenting, I found that the car battery voltage affected the circuit. It all worked well when the engine was running and the lights were turned off, but couldn't be relied on when the battery was being drained and its voltage dipped.

It seems that the op amp's slew rate was slightly higher when the voltage was higher. This was just enough to make the counter clock on.

The moral of this is that the slew rate of the op amp can be crucial, and that you should not assume that a characteristic which is specified to be just good enough with, say, +/-15V power supplies will still be all right at lower voltages. This is true even though the op amp may be specified to work at much lower voltages. Data books never claim that a circuit will work precisely as well under all circumstances.

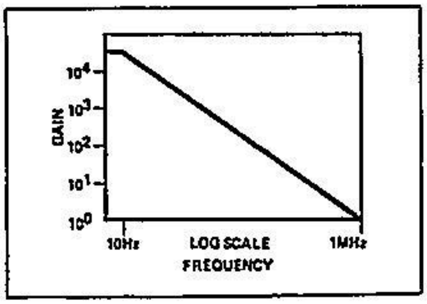

Fig. 6. Typical frequency response of an op-amp.

Passive Components

There are two common areas of misunderstanding which I have noticed in the use of passive components. The problem with resistors is very simple: ordinary quarter-watt resistors have a low voltage rating that you have to watch when connecting to voltages above 300V, say. Resistors rated 1/2 watt and greater have a higher voltage rating and are therefore generally okay to use in higher voltage circuits. Check the manufacturer's specs before assuming that resistance and dissipation are the only things to worry about. The voltage rating of a resistor can limit the maximum power that can be fed into it to less than its nominal wattage rating.

The other point of misunderstanding is in the use of non-polarized capacitors on AC, specifically when connected to the AC power line. Most people realize that a capacitor to be used on AC should have a DC rating equal to the peak of the AC waveform, but the problem does not stop there.

At any significant frequency, above a few Hertz, the voltage which the capacitor can withstand is reduced, because the chemical bonds in the dielectric material are stressed first one way then the other by an AC waveform, and in this process power is dissipated. Weak spots in the dielectric can become hot spots if subjected to AC waveforms, and can subsequently break down. Dielectric materials with higher levels of AC power dissipation suffer from this problem more severely. Generally, polypropylene capacitors are much better than polyester, while ceramics come in widely varying qualities.

One type of polyester capacitor, for example, is rated at 400VDC or 150VAC. A high quality polypropylene capacitor in the same catalogue is rated at 1000VDC, 350VAC at up to 5KHz. Some mica capacitors are rated to handle substantial RF signals. ■