Customize Your Instruments

Here's how to design engine and other instruments in your homebuilt aircraft.

BY JIM WEIR

Oshkosh '87 was my 15th year at the Oshkosh forums podium. The subject the first eight years was the installation of hidden antennas in composite aircraft, and the last seven years have been spent trying to show how to construct and install simple and inexpensive electronic devices in your homebuilt or factory-built aircraft.

Last summer's forum was an explanation of the engine instrumentation that I supplied the *Voyager* aircraft for its around-the-world flight and how the principles of this instrumentation can be used to design engine electronics for any aircraft.

Here are some general comments about the problem.

When Jeana Yeager and Dick Rutan flew around the world in *Voyager*, they needed lightweight, inexpensive, reliable engine instrumentation that would work in a very hostile environment—such as an airplane running nonstop for a week and bouncing around in thunderbumpers. We tried newfangled computer chips, microprocessors and the latest in digital technology. What we wound up with were old-fashioned linear amplifiers and moving-coil meters. Without going into a long song and dance about the problems encountered and solved, suffice it to say that humans like to see moving-pointer *meter* presentation of data backed up with digital "idiot light" alarms for out-of-limit data.

We finally settled on a single analog meter, very similar to a Cessna gas gauge, with a single switch that would allow Dick or Jeana to monitor half a dozen pressures and temperatures. Along with the meter were half a dozen green lights that said that all was well and half a dozen orange lights that said "something is wrong here." When the oil pressure went goofy over Africa, a single orange light labeled "rear engine oil pressure" illuminated, telling the crew where the problem was. When Dick switched the meter to the *rear oil pressure* position, he measured the pressure and then analyzed and solved the problem. No great difficulty—the rear engine had just run out of oil!

Designing the engine instrumentation sensor system

Voyager was blessed with a large number of companies that reached into their corporate back pockets and supplied parts at no cost to the program. Among these was the Honeywell Corporation, which supplied us with $500 pressure and temperature sensors as though they were water. Unless you have a sugar daddy like Honeywell, you will have to buy sensors with your own spending money, and $500 sensors are a little out of my price range.

What *is* within my price range is a line of automobile pressure and temperature senders made by several manufacturers. While there are a number of domestic and foreign sources for these little jewels, this article will use the Echlin (NAPA) sensors because NAPA parts houses are everywhere. If you have a particularly reasonable and convenient sensor source that you would like to use, go ahead, as the equations and calculations that follow lend themselves to universal design. I will caution you to follow good aviation design practice, especially regarding oil pressure sensors. Remember that if the sensor diaphragm ruptures, the car can pull over to the side of the road. Aircraft installation should include a flow restrictor fitting.

Regardless of the manufacturer of the sensor, the basic theory is that a change in *quantity* to be measured causes a linear change in *resistance* of the sensor. The change in resistance is inversely proportional to the change in quantity. Thus, if the oil pressure increases, the resistance of the sensor decreases; if the water temperature decreases, the resistance of the sensor goes up.

We can convert that change in resistance to a change in voltage by a simple bias resistor connected to both the sensor and a source of regulated voltage. Our chosen oil pressure sensor (Echlin p/n OP 6091, Photo 1) is biased with a 470-ohm resistor connected to a 10-volt DC regulated supply. Neither the 10 VDC

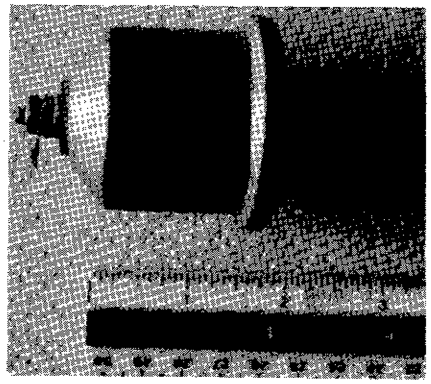


Photo 1. This Echlin automotive pressure sender can be used as a sensor in this aircraft annunciator/ metering system.

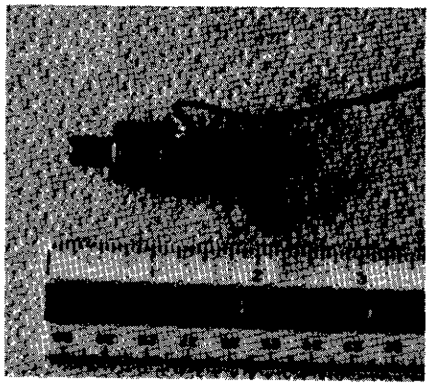


Photo 2. The temperature sender is also an Echlin automotive unit.

Photos: Dave Martin

supply nor the 470-ohm resistor value is necessarily sacred. I chose them because (1) I want to run the rest of the electronics from 10 VDC and, (2) 470 ohms gave a nice straight graph with reasonable voltage values. Feel free to play around with either of these values.

What we got when we connected the biased pressure sender to a source of regulated pressure (a Sears air compressor) and ran the pressure regulator up and down was the graph shown in Figure 1. Note that it is almost a straight line between the 10 psi lower limit and the 80 psi upper limit.

Similarly, the temperature sensor (Echlin TS 6628, Photo 2) curve of output voltage versus temperature is shown as Figure 2. How do you calibrate the sensor? Well, if you have ice cubes, an aluminum sauce pot, a stove and a good thermometer, I'll bet you can find a way. (Hint: two of the calibration marks are at 32 and 212° F.)

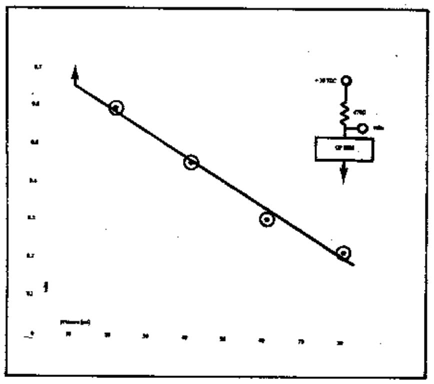
The secret of the design: normalizing the sensor output

Look closely at the two sensor calibration curves and you will note that they are widely dissimilar in their voltage output ranges. The pressure curve goes from about 0.2 to 0.6 volts and the temperature curve starts at half a volt or so (0.5 volts) and winds up at about 5 volts. While we could monkey around with bias resistor values and possibly make the curves somewhat similar, we would play hob with linearity, thermal heating and all those nasty things that large values of bias resistors resolve for us. On the other hand, if the voltage-quantity curves do *not* coincide, we will be playing around with op-amp and meter multiplier resistor values for hours trying to get the thing to play.

The answer is an electronic circuit called a *normalization amplifier* between the sensor and the rest of the electronics. This amplifier is nothing more than a simple op-amp with its resistor values chosen so that the *output* of the op-amp is the same voltage range no matter what sensor is chosen. And, arbitrarily, I am going to make the output of the op-amp such that 1.0 volt out is the low redline and 8.0 volts is the high redline. I could have just as easily made 2 volts the low and 6 the high, or 5 the low and 7 the high, but 1 and 8 make it easy from the standpoint of marking and calibrating the meter.

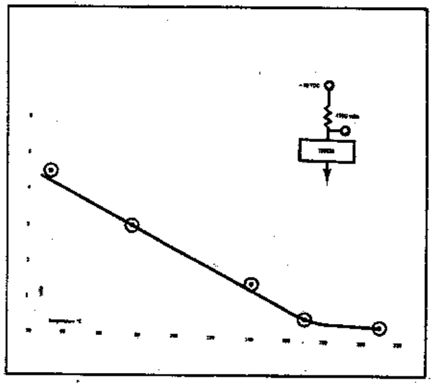
Now for the first time you will have to make a choice. What limits do you set on your engine for oil pressure? In my case, I like to know when the pressure drops below 20 psi and climbs above 60 psi. You may set your own limits anywhere on the oil pressure-versus-output voltage curve (Figure 1). Once the limits are set, you can read your voltage limit values from the curve. In my case, 20 psi corresponds to 0.6 volts and 60 psi corresponds to 0.35 volts.

Figure 1. Pressure sender.



Illustrations: Jim Weir

Figure 2. Temperature sender.



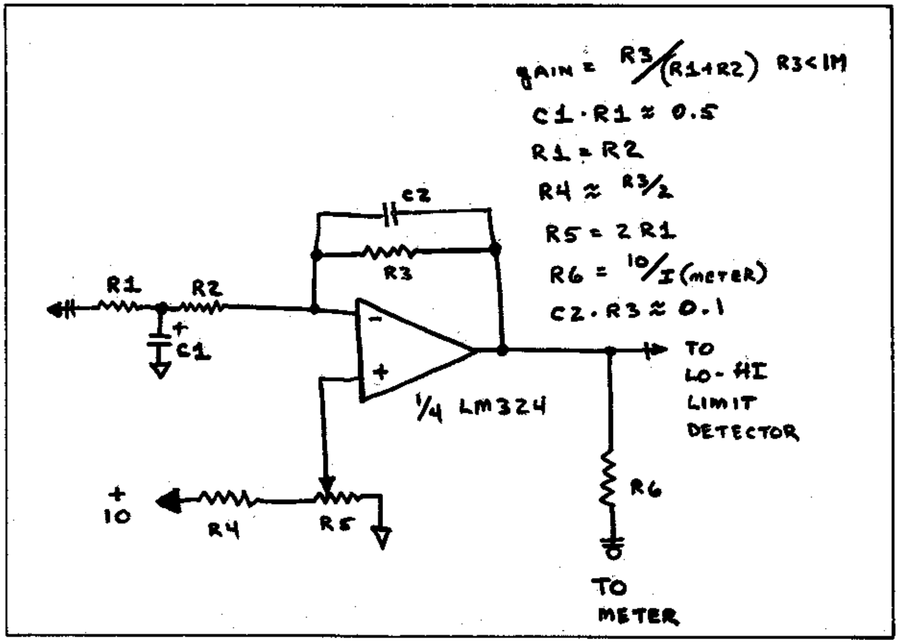


Figure 3. Basic gain stage.

Now we can calculate the gain of the normalization amplifier. If I want the amplifier to go from 1 volt to 8 volts with an input of 0.35 to 0.60 volts, the gain must be (8-1)/(0.6-0.35) which is 7/0.25, which is 28. My amplifier, then, must have a gain of 28. This is duck soup for a garden-variety op-amp, which has programmable gains from 0 to a million.

Similarly, the design for the oil temperature sensor amplifier says that if I choose 100° as my low temperature and 160° as my high temperature, then my amplifier must have a gain of 7/(2.5-0.8) which is 7/1.7 which is a gain of 4.11.

The normalization problem now resolves itself in the design of the amplifiers. Figure 3 shows a general basic gain stage using an op-amp called an LM324. This integrated circuit op-amp comes four to a 14-pin package and can be had at Radio Shack stores, four for $1.29 (p/n 276-1711).

We get to make one arbitrary decision about the resistor values of this circuit, and then all other values must correspond to this initial decision. Before we make that decision, let's consider some facts:

a. Op-amps do not like resistor values much in excess of 1 megohm (one million ohms, written 1M). Input current, offset voltage and all those other baddies go to hell in a handbasket with high resistor values.

b. Variable resistors (R5 in our schematic) do not come in a lot of different values. Standard values are 1K, 10K, 100K and 1M.

c. For capacitors C2 and C1 to be reasonable in size and value, the resistor values should be as large as possible.

With these restrictions in mind, let's begin by selecting R5 to be 10K ohms. This forces R1 to be half that value. We will choose the nearest standard value, 4.7K. This in turn forces R2 to be equal to R1, or 4.7K. To get a gain of 28 forces R3 to be 28 times (R1 + R2) or 270K. R4 is thus forced to 150K. This concudes the resistor calculations.

To select the capacitors, note that the product of C1 (in farads) times R1 (in ohms) should be about 0.5, which forces C1 to be 100 microfarads. Similarly, C2 calculates to be 0.1 μF. Just for grins, you should note that the only thing the capacitors do is "damp" the circuit to keep noise out. If you like twitchy meters, reduce the capacitor values by a factor of 10. If you like rather sluggish but rock-steady meters, use capacitors 10 times the calculated values. What I am saying is that the capacitors do not affect the calibration or accuracy of the circuit; they only affect the way the lights and meter respond to a rapidly changing input.

One last resistor value remains to be calculated, and the design of the normalization amplifier is complete. To select this resistor, though, you have to choose your meter (see parts sources at the end of this article), and while every other part in this design can be bought at Radio Shack, the meter will have to be ordered elsewhere. The good news is that the other parts sources have every conceivable shape, size and value of meter you might want.

For my purposes, I gave *Voyager* a garden-variety 0-to-1-milliampere meter that my company uses by the hundreds. It's not that Dick Rutan is a hamhanded with electronics devices, mind you. It is just that I wanted a few hundred spares on the shelf—just in case! To calculate the value of R6, take the maximum supply voltage of the circuit (10 volts—see below) and divide by the current rating of the meter (0.001 ampere—one milliampere) to get a value for R6 of 10K ohms. You can then mark the redlines on your meter at the 0.1- and 0.8-milliampere points, which will be 1 volt and 8 volts out from the op-amp respectively. (You will recognize 1 volt and 8 volts as your previously chosen redline voltages, yes?)

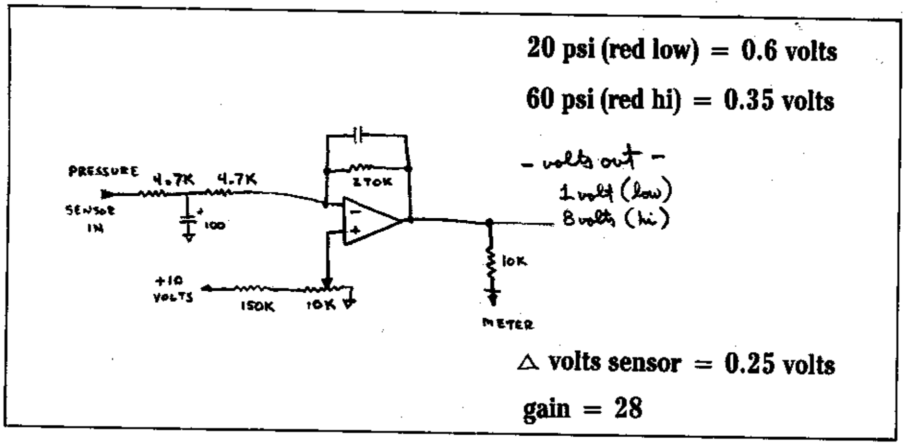


Figure 4. Pressure amplifier.

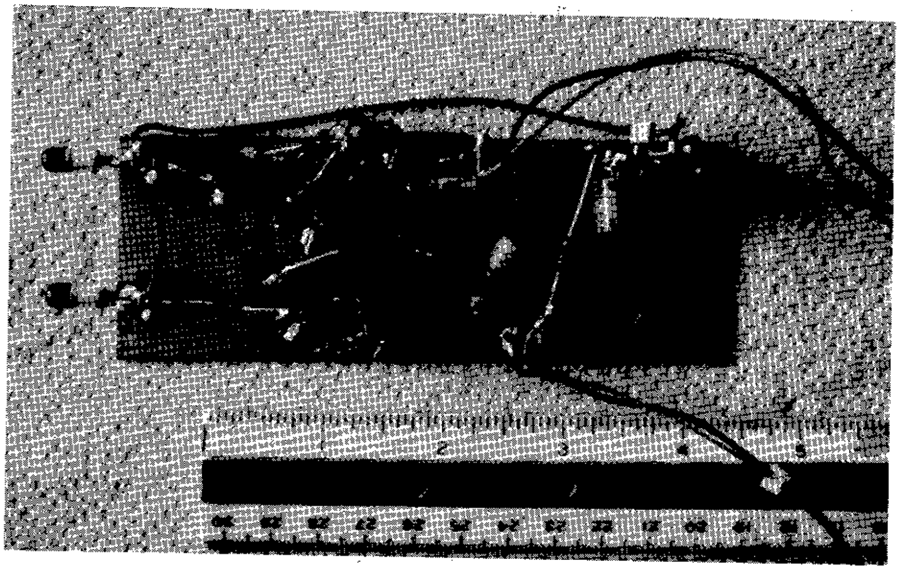
In a similar manner, you then calculate the resistor values for the temperature sensor. Note here that you may, if you like, choose R5 to be 100K ohms and thus make the capacitors smaller in value and size. Figures 4 and 5 show the final design of the pressure and temperature amplifiers respectively.

The design of a double-ended limit detector

What we have designed up to this point is a circuit that will take any sensor curve and normalize that sensor so that it puts out the same voltage/quantity curve as any other dissimilar sensor. We can drive a meter with this voltage, and the top and bottom redlines will be at the same point on the meter for any sensor. What we need to do now is to light a lamp for the high and low limits for any sensor.

Since the LM324 has four op-amps per package, and since we have only used one of them for the normalization amplifier, we can use two more to form a double-ended limit detector. What we want to do is to light a single lamp no matter whether the sensor we are measuring goes too high or too low. Such a circuit is shown in Figure 6. The two 10 Megohm resistors shown on the circuit form what is called a "1% twitch-preventer." The 8-volt line will actually have to go to 8.08 volts before the lamp will light and will thereafter have to go back below 7.92 volts before it will go out. This prevents the circuit from sitting on the ragged edge of redline and oscillating.

Photo 3. Author Jim Weir's "dead bug" (ICs mounted with "legs" up) circuit board is not pretty, but it is simple and works well.



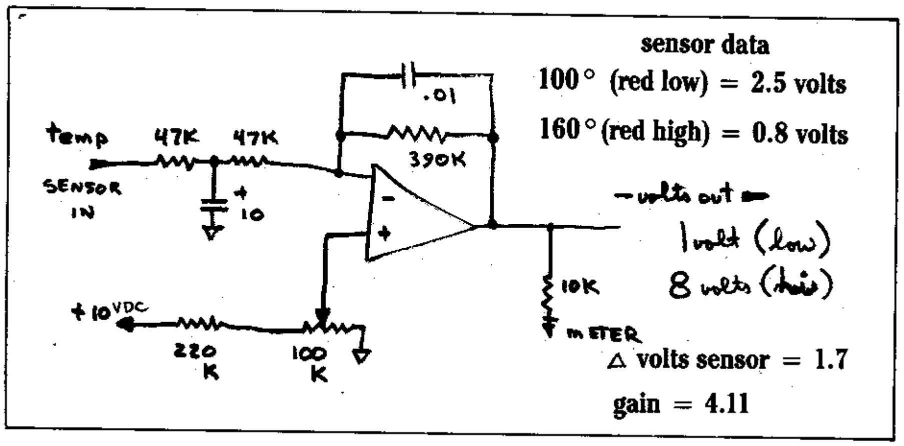


Figure 5. Temperature amplifier.

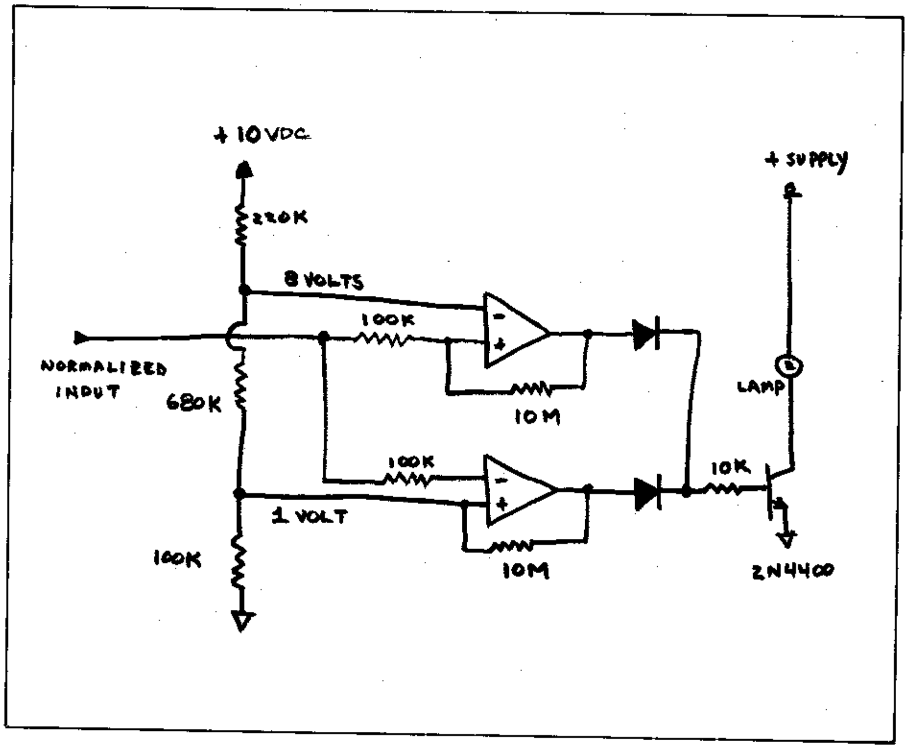
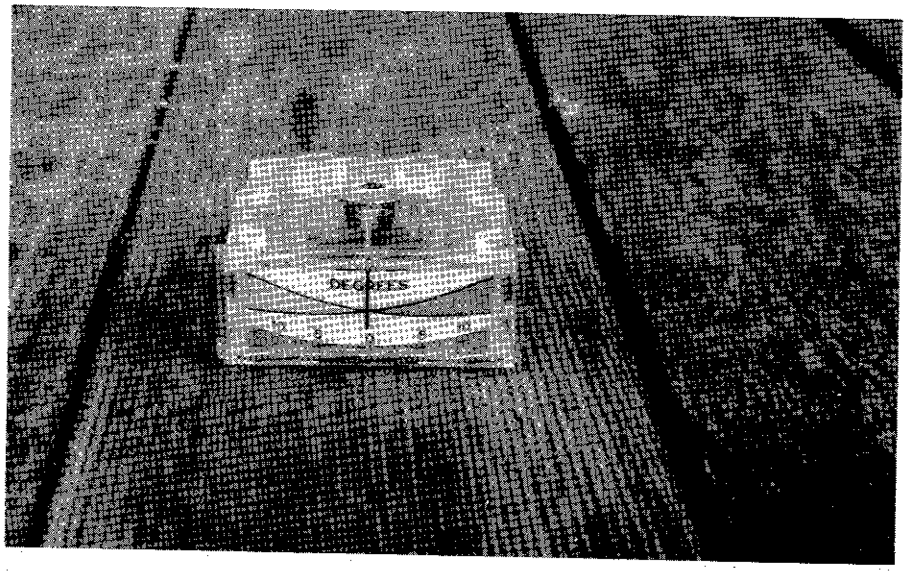


Figure 6. Double-ended limit detector.



The light is either full on or full off.

The two diodes can be any general-purpose silicon switching or power diode—absolutely non-critical. If you want two lights, one for high limit and one for low limit (as we used in *Voyager*), delete the diodes and hook the 10K base drive resistor directly to one of the op-amp outputs. Provide another 10K ohm resistor to the output of the other op-amp, another 2N4400 switching transistor and another light to the + voltage supply. In the configuration shown, the lamps should draw less than 100 mA. You can cheat and run the 10K base drive resistor down to 1K or so if you want to drive 250 mA loads, but the 2N4400 will get pretty warm.

The final design

The power supply for this beast is a 78L05 integrated circuit regulator with a 5-volt zener boost diode in the ground leg (See Figure 7). This little rascal will keep a regulated +10 volts at its output for +12 to +28 volt systems. The only problem is that it is only good to about 100 mA (0.1 amps) of output. A little calculation shows that if we get more than five sensors on line, this rating will be exceeded. If you plan on a multiple (six-plus) sensor system, then use the slightly larger 7805 IC. Also, I have shown the lamps as 12-volt bulbs. If you have a (yech!) 28-volt system, just use 28-volt bulbs.

Figure 7 also summarizes the design of both the pressure and temperature channels. Figure 8 is a general representation of how the transducer, gain amplifier and double-ended limit detector are connected.

Some general comments

R5 in each channel is adjusted so that the meter reads exactly as it should at center scale. This has the effect of making the top-scale and bottom-scale errors equal. If you want, you can calibrate the meter *exactly* at any point you wish with R5 and accept any minor errors this causes.

You have your choice of providing a separate meter for each channel or one meter that can be switch-selected

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Photo 4. A 0-1 mA meter like this can be marked to reflect the input from numerous sensors. A wafer switch selects the function to be monitored

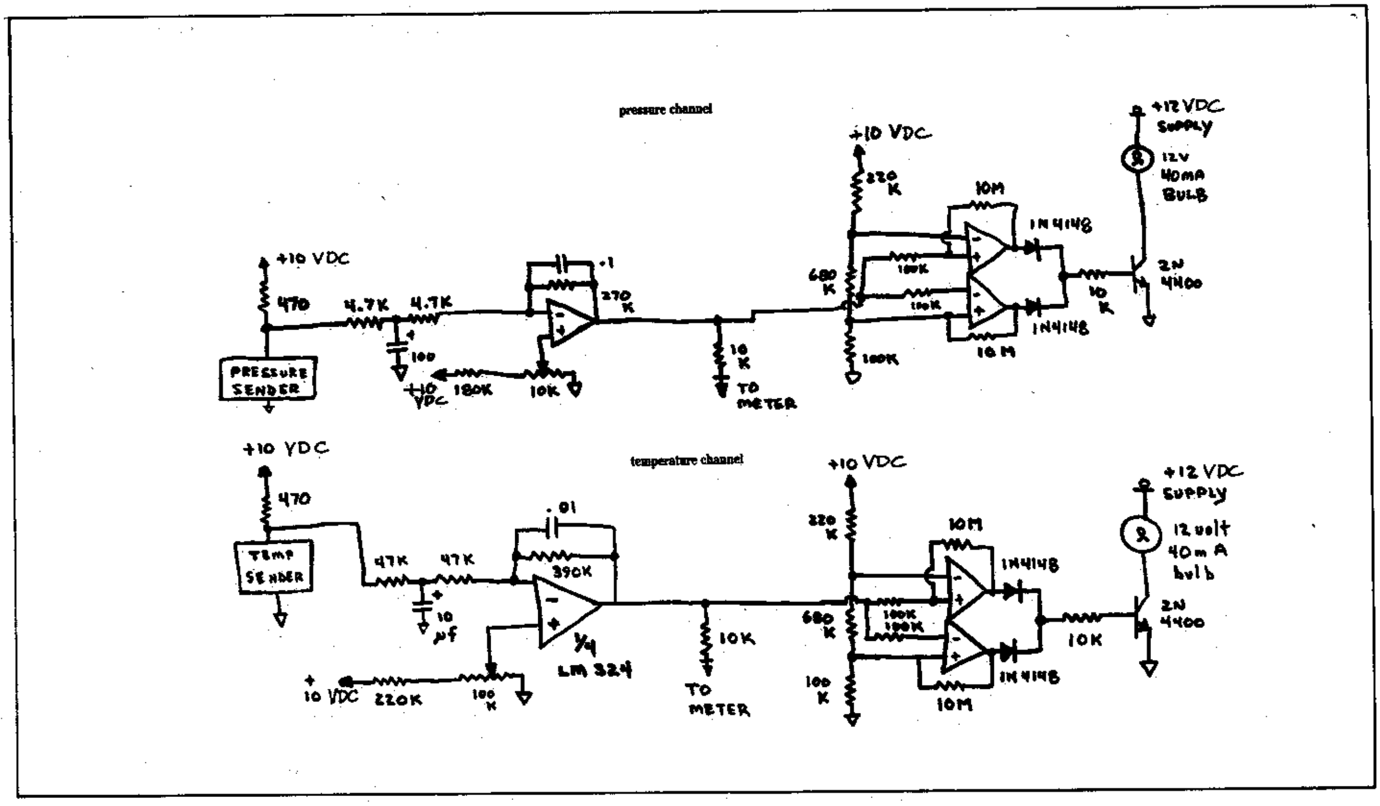

Figure 7b. Pressure and temperature channels.

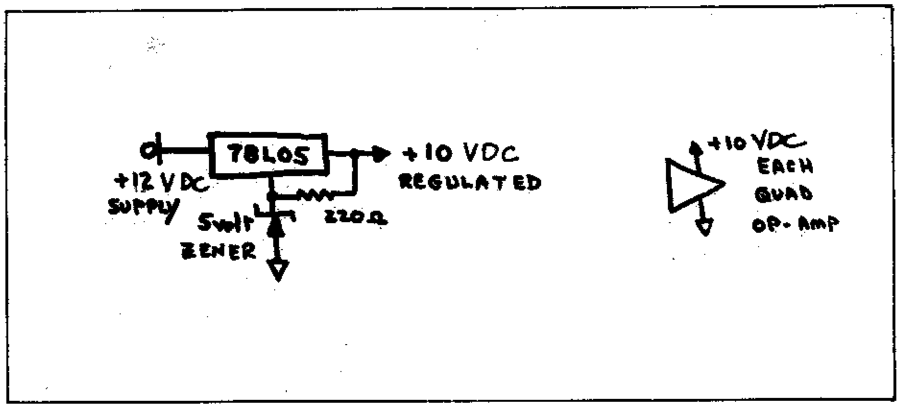

Figure 7a. Power supply.

INSTRUMENTS

continued

between all channels. There are advantages to either approach. Separate meters for each channel allows you to look down a row of centered meters and assure yourself that nothing is creeping up toward redline. Using one meter and switch-selecting allows a larger meter that can be easily read. I have no particular preference. Of course, the lily-gilders out there could provide *two* resistors (R6 × 2) from the normalization op-amp—one resistor to a tiny one-for-each-channel meter and the other resistor switch-selected to a large meter.

Again, for the lily-gilders: you will notice that I have used only three sections of the four-section op-amp for each channel. Any good op-amp textbook will show you how to make an audio oscillator from a single section of an op-amp. It is also trivially simple to turn this oscillator on and off with a voltage—like the output voltage of the double-ended limit detector. Run this oscillator to your headphone audio amplifier and you can have an audio as well as a visual alarm. Make the frequency of the oscillator different for each sensor channel and you can tell from the tone of the alarm what went out of limits.

Please don't limit yourself to oil pressure and oil temperature. Fuel pressure, carb throat temperature, airspeed (pitot pressure), outside air temp—the possibilities are constrained only by the limits of your mind. Nor limit yourself to pressure and temperature. Any quantity that causes a voltage or resistance change can be measured and used by this system. Let your imagination wander—fuel quantity, gross weight (using load cells), altitude, battery bus voltage and current, vacuum . . . and the like can all result in a sensor input to this system.

Parts sources

These sources are chosen because they all have catalogs and will sell by mail order. They are *not* aviation supply houses and *cannot* give you technical advice. Please do not foul it up for the rest of us by bugging them for advice.

Mouser Electronics, 11433 Woodside Ave., Santee, CA 92071; (619) 449-2222

Calrad, 819 N. Highland, Los Angeles, CA 90038; 213/465-2131

Jameco, 1355 Shoreway Rd., Belmont, CA 94002; 415/592-8121 ☐

FOR MORE INFORMATION on low-cost aircraft electronics, mostly in kit form, contact Jim Weir's company, RST, 13281 Grass Valley Ave., Grass Valley, CA 95945; phone 916/272-2203. A free catalog is available.