Tech Note No. 2

by Pete Stark

As I mentioned last time, when I bought my "as-is" Theatre Organ, it was totally unusable because of noise. I'm happy to report excellent progress so far.

I have so far reworked only three of the pc boards -- the mixer compressor, preamp/vibrato, and the manual voicing (filter) board -- but the noise is already down to a very acceptable level. My approach was to replace all electrolytic capacitors (since I found a few bad ones and suspected -- quite rightly -- that there were others), most resistors (because I temporarily became a fanatic), and most transistors (because modern transistors are a lot quieter than old ones.)

A note on electrolytic capacitors

We discussed electrolytics last time, but I may have left you with the wrong impression. While it is true that in most places you can substitute a slightly different value, there are a few places where this should *not* be done. One place is in the percussion keyers, where the capacitor value determines a note's decay time.

Resistor replacement

Back in the days of vacuum tubes, noise in resistors was a big problem, and hi-fi manufacturers used special low-noise resistors to avoid it. But transistor circuits generally carry much less current and their resistors tend to have smaller values, so resistor noise is not as much of a problem today as it was then. I went crazy replacing resistors, but I don't think it was at all necessary.

Transistor replacement

Replacing transistors made the big difference in my organ. Since I've seen several notes in Fred Henn's newsletter about transistor replacement, let's look at the subject.

The first transistors were made of germanium; today, germanium has been almost totally replaced by silicon. In fact, no manufacturer today is making small-signal germanium transistors, so finding recent-production exact replacements for Schober transistors is impossible. You can use 20-year-old replacements, but silicon transistors are so much better that this is not worthwhile. You just have to be a bit careful when substituting.

Transistors come in two basic flavors -- field-effect transistors (FETs), and bipolar transistors. Let's forget FETs since Schober didn't use them, and concentrate on bipolar transistors. These come in two types -- PNP and NPN. In general, PNP transistors require a negative power supply, while NPN transistors require a positive power supply. There's an exception to this rule -- you can connect a transistor "upside down" and then use it on the opposite supply. For example, Schober used this trick on the PTR-5 preamp/vibrato board and the TTG-4A tone generator boards in the theatre organ, which use silicon NPN transistors on a negative supply. But this requires a bit of extra care, and is not too common.

When Schober started designing their organs, germanium transistors were cheapest, while silicon transistors were still new and very expensive. For technical reasons, PNP germanium transistors are easy to make whereas NPN germanium were much more difficult (and expensive) to make, so Schober used the 046127 PNP germanium transistor almost everywhere. The number 046127 is a "house number"; we don't know who actually made these or where they came from, but they were very inconsistent and very noisy. So Schober had to test them and select ones that would work well. Thus some were painted red, and some were white, depending on where they would be used.

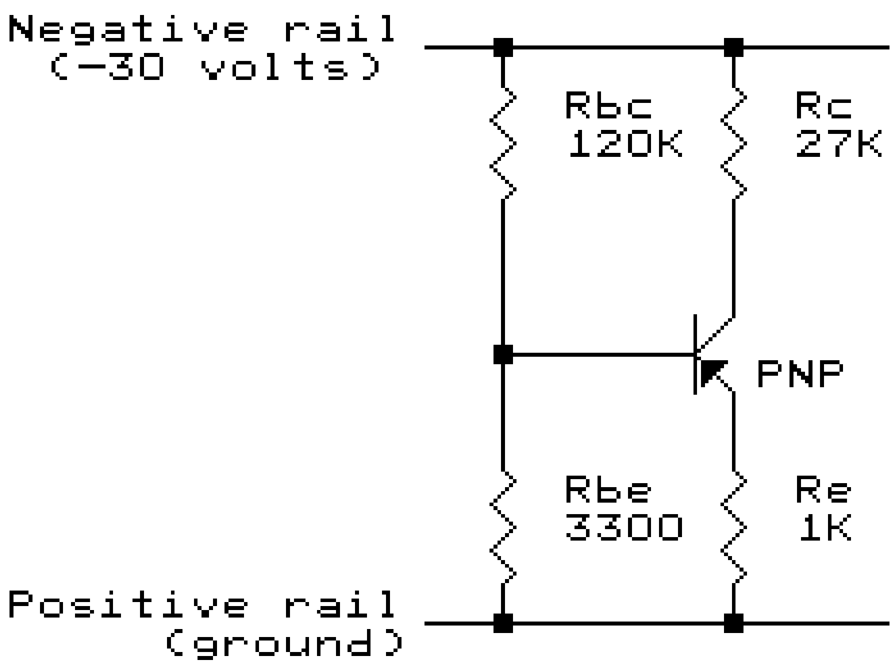
Some time in the early 1970's, Schober started to switch to silicon transistors. But the situation here is the opposite of germanium -- silicon NPN transistors are easier to make than PNP. Since Schober owners could build their organs in stages, Schober had to stay compatible with earlier boards and negative power supplies. PNP silicon transistors were so very expensive at the beginning that Schober redesigned the circuitry to use silicon NPN wherever possible. Of course, this required the transistor to be connected "upside down", but the savings in money was worth it.

Thus newer Schober boards used the 045500 NPN silicon transistor wherever possible, with just a few 045000 PNP silicon transistors here and there if necessary. (There are also a few high-power transistors, but these do not usually carry audio, so I did not bother to replace them.)

What shall we replace with? My own favorites (cheap, plentiful, and quiet) are the 2N4401 NPN silicon, and the 2N4403 PNP silicon transistor. Mine came from ALL Electronics (1-800-826-5432), and cost 13 cents in lots of 100; other vendors carry them at comparable prices. The 2N4401 is a direct replacement for the 045500; the 2N4403 is a direct replacement for the 045000. The 2N4403 can also be used to replace the 046127 transistor, but sometimes minor circuit changes are required. Let's see why.

Transistor biasing

The MTC-1 Mixer-Compressor in the theatre organ makes a good example (but I will try to make the discussion general so it applies to other organs as well). This board has eight 046127 transistors, all of which can be replaced by the 2N4403. Only one of the transistors, number 55, requires some minor resistor changes to adapt to the new transistor. Fig. 1 shows the circuit, called a *common-emitter* amplifier. Let's go through the calculations to determine what the various voltages in the circuit are.



Resistors Rbc and Rbe set the bias for the transistor; they determine the basic operating point of the stage. (To make the formulas a bit more universal, I am using the following symbols: Rbc is the resistor that goes from the base up in the direction of the collector; Rbe is the base resistor that goes down toward the emitter; Re will be the *total* resistance in series with the emitter (which sometimes consists of two resistors in series with one of them bypassed by a capacitor); and Rc will be the collector resistance.) The approximate formula for the base voltage Vb is then

$$Vb = -30 \frac{Rbe}{Rbe + Rbc} = -30 \frac{3300}{3300 + 120{,}000} = -0.8 \text{ volt}$$

Note that the -30 is the supply voltage. In Figure 1, the horizontal negative wire at the top, which goes to the -30-volt supply, is called the *negative rail*, and the bottom wire, which just happens to be grounded, is called the *positive rail*. (When Schober uses an NPN transistor with a negative supply, then the top wire becomes the positive rail and the bottom becomes the negative rail; more on this later.)

For the original PNP germanium transistor, the approximate emitter voltage Ve is found from

```
   Ve  =  Vb  - Vbe
```

where Vbe, the base-to-emitter voltage, depends on the transistor. Vbe is approximately -0.2 for a PNP germanium transistor, approximately -0.6 for a PNP silicon transistor, and approximately +0.6 for an NPN silicon transistor. We use -0.2, so the emitter voltage is

```
     Ve = Vb - ( - 0.2 ) = - 0.8 + 0.2 = -0.6 volt
```

The emitter current is then found from Ohm's law as

```
         Ve           -0.6
  Ie = --------  =  --------  =  -0.0006 ampere
         Re           1000
```

You have to watch the minus signs when you use a negative power supply. In general, the collector current Ic is almost exactly equal to Ie. The collector voltage is then the -30-volt power supply minus whatever is lost in the collector resistor Rc, which works out to

```
      Vc  =  -30 - Ie Rc

          =  -30 - (-0.0006)(27,000) = -30 + 16.2 = -13.8 volts
```

As before, you have to be very careful with the minus signs. Since "minus a minus" is a plus, the "-(-" in the equation works out to be an addition.

Let's see how these theoretical values compare with the voltages Schober gave in their service manual:

Voltage	Our value	Schober's value
Base	-0.8 volt	-0.9 volt
Emitter	-0.6 volt	-0.8 volt
Collector	-13.8 volts	-14 volts

Our values assume perfect components, whereas Schober's values were probably measured on a typical board, so we can't expect exact results, but this is pretty close.

The important value here is the -14 volts on the collector. For maximum signal-handling capability and minimum distortion at high volume, the collector voltage should be just slightly more than half of the supply voltage. -14 volts is OK, but -16 would have been a bit better.

Now, let's see what would happen if we replaced the 046127 germanium transistor with a silicon 2N4403 without any resistor changes. The base voltage Vb will still be about the same, but the emitter voltage Ve will now be -0.8 + 0.6, or about -0.2 volt, which is much less than the -0.06 volt we had with the germanium transistor. Let's carry through the remaining equations with this new value:

```
         Ve           -0.2
  Ie = --------  =  --------  =  -0.0002 ampere
         Re           1000

 Vc  =  -30 - Ie Rc
```

$$= -30 - (-0.0002)(27{,}000) = -30 + 5.4 = -24.6 \text{ volts}$$

The collector voltage should be a *bit* more than half of -30, but -24.6 is too much! All of this is caused by the emitter voltage being too small.

The correct way to change the emitter voltage is to change the base voltage. If the base voltage were -1.2 volts, then the emitter voltage would be -1.2 + 0.6, or back to the original -0.6 volts, and everything would be back to normal. So we have to juggle the two base resistors to make the base voltage a bit bigger. Look at the equation for Vb:

$$Vb = -30 \frac{Rbe}{Rbe + Rbc}$$

We can make Vb slightly larger by either making the numerator of the fraction bigger, making the denominator smaller, or a little bit of each. Let's try the next larger standard resistor size for Rbe (3900 ohms instead of 3300), and the next smaller standard size for Rbc (100K instead of 120K). This then gives us

$$Vb = -30 \frac{Rbe}{Rbe + Rbc} = -30 \frac{3900}{3900 + 100{,}000} = -1.13 \text{ volt}$$

$$Ve = Vb - (- 0.6) = - 1.13 + 0.6 = -0.53 \text{ volt}$$

$$Ie = \frac{Ve}{Re} = \frac{-0.53}{1000} = -0.00053 \text{ ampere}$$

$$Vc = -30 - Ie\ Rc$$

$$= -30 - (-0.00053)(27{,}000) = -30 + 14.3 = -15.7 \text{ volts}$$

which is almost perfect. This is the change I made; let's see how these numbers compare with the actual measurements from the modified mixer-compressor board on my own organ:

Voltage	Theoretical value	Measured value
Base	-1.13 volt	-1.08 volt
Emitter	-0.53 volt	-0.5 volt
Collector	-15.7 volts	-15.4 volts

The reason why we had to change resistors in this particular circuit, but not the others, is that Schober designed this circuit with an Rc that is 27 times larger than Re. Normally, this would be considered a bad design, because it makes the actual operating voltages too dependent on the transistor characteristics. Had they designed the circuit so these two resistors were closer in value, we could have replaced the germanium by a silicon transistor without any changes. But Schober had a reason for doing it this way -- there are two input signals into this transistor, one to the base, the other to the emitter. To make the resistors more equal in size, they would have had to change the circuit a bit, and then it would be difficult to input a signal into the emitter circuit. So here's a hint - if Rc and Re are similar in size (off by a factor of up to five, say) then usually no resistor changes are needed to change from a germanium to a silicon transistor. If Rc is much bigger than Re, on the other hand, then resistors must be modified to properly bias the transistors, using an approach similar to the above. This discussion, by the way, only applies to small transistors, not to power transistors.

Finally, a few loose ends. The wires labelled positive rail and negative rail in Figure 1 are simply the power supply connections. With a -30-volt power supply, the positive rail (which connects to the positive side of the power supply) is ground, and the negative rail is -30 volts. But NPN transistors require a positive voltage on the collector, so on those boards which use NPN transistors, the grounded positive rail would appear at the top of Figure 1, while the negative rail would appear at the bottom. You would use +30 volts in the calculations, but since measurements are usually taken with one lead of the meter at ground, you would subtract 30 volts from anything you get. That's confusing, so I've prepared a computer program which does the calculations for you. Here it is:

```
10 PRINT "This program does dc biasing calculations for transistors."
20 PRINT "Copyright (C) 1993 by Peter A. Stark"
30 'get input parameters
40 PRINT
50 PRINT "What kind of a transistor do you have? Enter"
60 PRINT " 1 for PNP germanium"
70 PRINT " 2 for NPN germanium"
80 PRINT " 3 for PNP silicon"
90 PRINT " 4 for NPN silicon: ";
100 INPUT "", QTYPE
110 IF QTYPE<>1 AND QTYPE<>2 AND QTYPE<>3 AND QTYPE<>4 THEN GOTO 50
120 IF QTYPE=1 THEN VCCSIGN=-1 : GOTO 160
130 IF QTYPE=2 THEN VCCSIGN=+1 : GOTO 160
140 IF QTYPE=3 THEN VCCSIGN=-1 : GOTO 160
150 IF QTYPE=4 THEN VCCSIGN=+1 : GOTO 160
160 INPUT "Enter the power supply voltage "; VCC
170 IF ABS(VCC)<1 THEN GOTO 160
180 VCCPOL = VCC / ABS(VCC)
190 VCC=ABS(VCC)
200 IF VCCPOL>0 AND (QTYPE=2 OR QTYPE=4) THEN GOTO 260
210 IF VCCPOL<0 AND (QTYPE=1 OR QTYPE=3) THEN GOTO 260
220 IF VCCPOL<0 THEN PRINT "Are you sure the voltage is negative? ";
230 IF VCCPOL>0 THEN PRINT "Are you sure the voltage is positive? ";
240 INPUT "", ANSWER$
250 IF LEFT$(ANSWER$,1)<>"Y" AND LEFT$(ANSWER$,1)<>"y" THEN GOTO 160
260 INPUT "Enter Rbc, the base resistor that goes toward the collector"; RBC
270 INPUT "Enter Rbe, the base resistor that goes toward the emitter"; RBE
280 INPUT "Enter Re, the total resistance in the emitter"; RE
290 INPUT "Enter Rc, the collector resistor"; RC
300 VB=(VCC * RBE / (RBC + RBE)) * VCCSIGN
310 IF QTYPE<2.5 THEN VBE=.2 ELSE VBE=.6
320 VBE= VCCSIGN * VBE
330 VE = VB - VBE
340 IE = VE / RE
350 VC = VCCSIGN*VCC - IE * RC
360 R$="(to ground)"
370 IF VCCSIGN>0 AND VCCPOL<0 THEN R$="(to the negative rail)"
380 IF VCCSIGN<0 AND VCCPOL>0 THEN R$="(to the positive rail)"
390 PRINT
400 PRINT "The base voltage "; R$; " is "; VB; " volts"
410 PRINT "The emitter voltage "; R$; " is "; VE; " volts"
420 PRINT "The collector voltage "; R$; " is "; VC; " volts"
430 IF R$="(to ground)" THEN STOP
440 PRINT
450 PRINT "The base voltage (to ground) is "; VCC * VCCPOL + VB; " volts"
460 PRINT "The emitter voltage (to ground) is "; VCC * VCCPOL + VE; " volts"
470 PRINT "The collector voltage (to ground) is "; VCC * VCCPOL + VC; " volts"
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