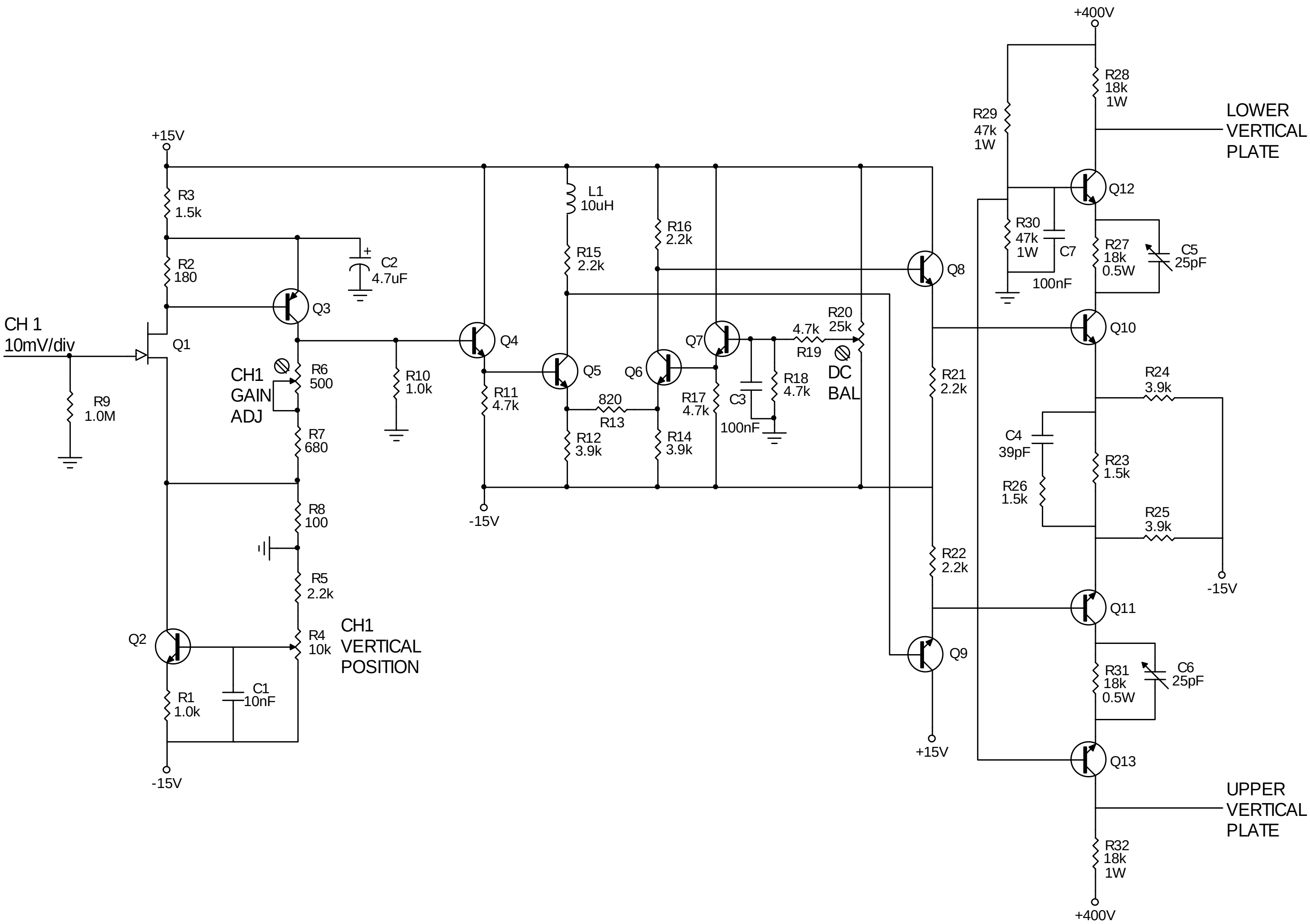
Design Faults Of An Oscilloscope Amplifier

by Dennis L Feucht

Last time, the following oscilloscope vertical amplifier was presented as a challenge in identifying its design faults. You need not be an oscilloscope design expert to engage in this exercise, for the given design was from my less sophisticated teen years. The circuit works, but could be improved in various ways. Here is my list of design faults and improvements.



A List Of Deficiencies And Some Improvements

I have not pushed this list to its limit by including BJT model refinements (beyond the basic incremental T model -- no compensation for Gummel-Poon intricacies), nor did I add a delay line to allow the horizontal system to start the sweep before the triggering event appears at the vertical deflection plates. (This was a slow 'scope, after all, though faster than the 200 kHz bandwidth DuMont 208-B from the 1920s that I was intending to replace with it.) What follows are some of the more obvious design deficiencies.

Input Stage

By adjusting the vertical position by varying the static current of Q1 of the feedback amplifier causes the JFET biasing and TCs to vary with it. Ideally, static design is optimized to minimize temperature drift and thermals and is fixed. Secondly, I_D(Q1) is within the feedback loop, and any output change will be due to the inadequacy of the feedback to null it out -- not a good way to adjust position! In other words, the open-loop gain of the amplifier will affect the sensitivity of the position control and, as it drifts around, so will the vertical trace position on the screen.

A more thorough static analysis than that given above shows that the static state of both Q1 and Q3 (which interact due to feedback) are variable with both Q2 current and input voltage -- not a good way to design.

A better scheme for positioning is to introduce the voltage offset by a suitable network between the output of the stage and input of Q4. Another scheme is for the positioning offset to appear later in the amplifier, across a differential stage, so that any drift in positioning would be amplified less. That is, the sensitivity of the trace position to position control drift would be reduced. However, as this is typically implemented, it would take a dual position pot, one for each side of the diff-amp.

Second, because the operating point varies so much, the thermal distortion will vary too. R3 helps to set the V_{DS}(Q1) for maximum power dissipation and consequently minimum variation in power with input voltage change.

Third, C2 introduces low-frequency dynamic effects, namely a pole-zero pair in the loop gain. They will probably interact with thermal effects, and maybe even compensate partially for them. (Though not fully; thermals are not exponential and can only be approximately compensated by multiple poles or zeros.)

Fourth, the input dynamic range varies with input voltage because of varying static current through R3, causing V_{D1} to vary.

This stage benefits due to feedback, but it has too many disadvantages and should probably be replaced by a differential FET buffer stage instead. By not making the amplifier differential from the input onward, CMRR is reduced by the reduced gain of second and third stages.

Buffered Diff-Amp Stage

Q4 – Q7 will be taken as a unit. First, the emitter-followers, Q4, Q7, are not thermally compensated with collector resistors. Their input resistances are not equal and differences in base bias current between them can cause diff-amp offset, though if it remains constant, can be compensated by R20. Besides a lack of high-frequency (hf) compensation for Q4, Q7, which could leave them near instability in the hf region (between f_β and f_T – see technote "Why Circuits Oscillate – BJTs" http://www.analogZONE.com/col_1017.htm for explanation), the diff-amp stage of Q5, Q6 needs a capacitor across emitter resistor R13, to frequency-compensate the divider that R13 forms with the emitter of Q6.

For faster response, the collectors of both Q5 and Q6 could use some bandwidth extension. The shunt inductive peaking of Q5 is a start, but series inductive or even T-coil peaking would further extend bandwidth. For a Knight-Kit 'scope CRT, however, maybe this amplifier is fast enough. To remove the Miller effect slow-down of this stage, Q5 and Q6 should be followed by common-base stages, like the output stage, Q10 – Q13.

Output Stage

Emitter-followers Q8, Q9 lack thermal compensation. The final diff-amp driver stage at least has frequency compensation (R26, C4) across R23, but this series RC will more likely compensate thermals than the R23 divider effect due to C_{bc} of Q10, Q11. Thermal compensation of Q10, Q11 is provided by R27, R31, and because these values are high, to avoid the Miller effect, they are shunted by adjustable capacitors, C5, C6. These are adjusted to compensate them for the input C_{bc} of the CB stages that follow: Q12, Q13.

The worst mistake of this stage is the load resistors, made intentionally low in value to increase bandwidth, but large in power dissipation to achieve it. A more elegant approach would have been to add inductive frequency compensation, especially with the CRT plate capacitance as the load.

Closure

This amplifier worked and was useable, but lacked refinement. I hope that these comments either corroborate your own conclusions or else provide some new considerations for amplifier design. A good place to hone such design skills is by studying the schematic diagrams of vertical amplifiers found in Tektronix oscilloscope Instruction Manuals from the 1960s and 1970s. (After that, they become too integrated and the circuits become hidden from the user.) Some recommended manuals for beginners, which can be readily found in the electronics surplus market, are for the following ‘scopes: 310, 316, 504, and T921/T922. The first three use vacuum tubes; the T900 series do not. For intermediate study: 535 and 545B, which have tubes, and the 454B, and 2236 (service manual), which do not. These circuit diagrams contain additional components for compensation, which can only lead to further considerations for optimal amplifier design.

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