# Power op amps solve deflection-yoke drive problems

*Power op amps provide the ability to position beams in any desired position as well as the ability to retain a steady-state position. Putting both the power and signal stages in one compact package affords space/weight savings, and the lower parts count contributes to reliability.*

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When compared with open-loop systems, closed-loop power op-amp circuits offer distinct advantages in current control for driving deflection yokes. By configuring a power op amp in a conventional voltage/current conversion circuit, you can use negative feedback to force the coil current to stay exactly proportional to the control voltage. The resulting higher accuracy makes many new applications, such as E-beam lithography, heads-up displays (which require random beam positioning), and other complex data displays, feasible.

By placing the nonlinear impedance of the deflection yoke inside the feedback loop of a power op amp, you can readily realize steady-state positioning, which is difficult, if not impossible, to achieve with open-loop circuits. In addition, using power op amps you can easily design sweep systems with substantially improved linearity. Finally, the op amps' versatility helps speed the design process and reduce development costs. The end result is a higher-accuracy display that uses fewer parts and has better reliability.

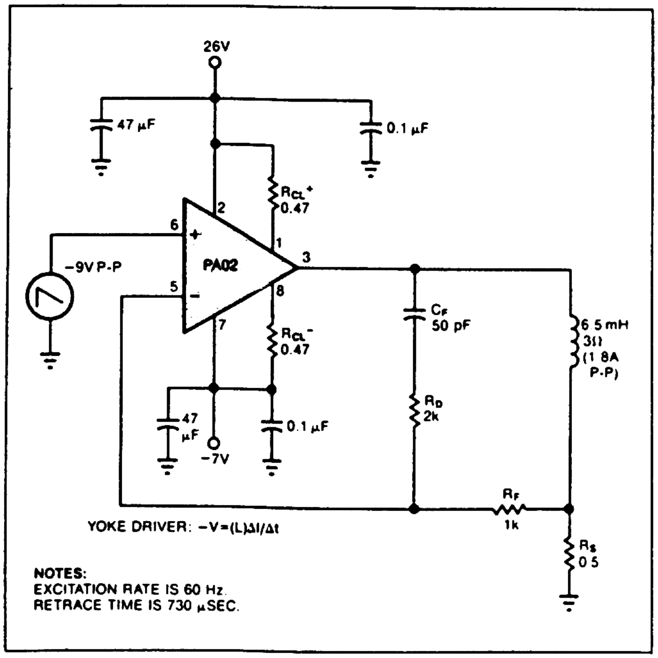


***Fig 1—Specifically designed to drive an RCA Cody II tube,** this circuit provides high accuracy, a high slew rate, a fast settling time, low crossover distortion, and low internal losses.*

The vertical-deflection circuit of **Fig 1** is specifically designed to drive a high-efficiency RCA Cody II tube.

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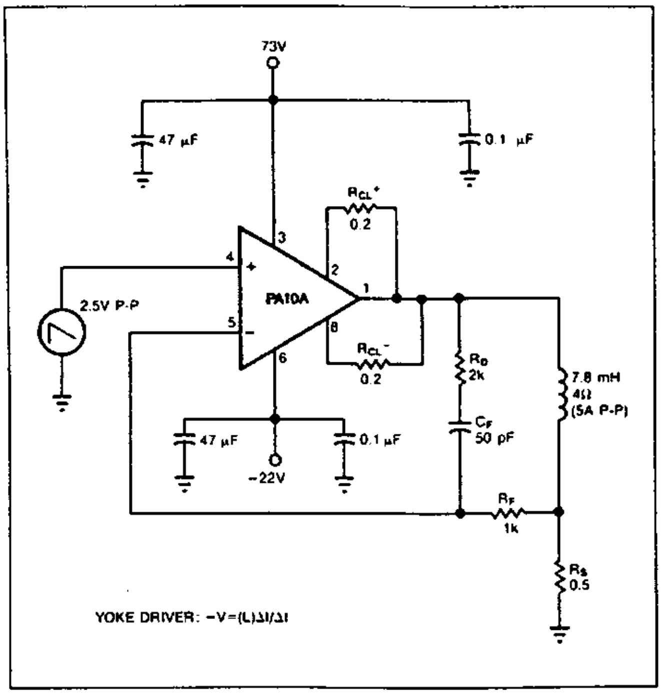


***Fig 2—By using the PA10A power op amp** in place of **Fig 1's PA02**, you can drive a 7.8-mH/4Ω coil at 5A p-p without changing timing requirements.*

The PA02 is well-suited to this application: It has very good linearity, a high slew rate, a fast settling time, low crossover distortion, and low internal losses—characteristics that are critical for a high-resolution display.

Sense resistor $R_S$, which converts the yoke current to a voltage for op-amp feedback, is the key component in this circuit. With the feedback applied to the inverting input, and the position-control voltage applied to the noninverting input, the summing junction's virtual-ground characteristic ensures that the voltage across $R_S$ is equal to the input voltage. As a result, the highly linear control of the voltage across $R_S$ ensures accurate beam positioning.

The value of $R_S$ has a significant impact on the performance of this circuit. All op-amp errors—voltage offset, imperfect common-mode rejection, offset drift, etc—will appear across the sense resistor. To minimize these errors when they're translated into current, you must set the value of $R_S$ as high as possible. If you choose a very large value for $R_S$, you can, in fact, reduce these errors to the point where they are insignificant. Unfortunately, choosing a large value for $R_S$ will diminish drive capability and increase circuit power dissipation because the total coil current flows through the sense resistor.

To optimize the value of $R_S$ for a given application, you must make some error-vs-efficiency tradeoffs, and so the inductance, transition times, and current level will define the necessary voltage drive requirements. The Cody II display is designed to operate at 50 or 60 Hz, with retrace times of 730 μsec and coil currents of 2.25A p-p.

To change the current in an inductor, the drive voltage ($V_{DRIVE}$) is proportional to both current change and inductance, but inversely proportional to transition time:

$$V_{DRIVE}=Ldi/dt$$
$$V_{DRIVE}=(6.5\ mH)(2.25A/15\ mSEC) \quad \text{sweep}$$
$$V_{DRIVE}=(6.5\ mH)(2.25A/730\ \mu SEC) \quad \text{retrace.}$$

To determine the required supply-voltage levels, add the supply-to-output differential rating of the power op amp (listed on the data sheet) and the voltage dropped across the combined values of the sense resistor plus the coil resistance to these drive requirements:

$$V_{DROP}=I_P\ (R_S+R_L)$$
$$V_{DROP}=1.125A(0.5+3)=3.94V$$
$$V_S=V_{DRIVE}+V_{S-O}+V_{DROP}$$
$$V_S=0.98+2+3.94=6.92V \quad \text{sweep}$$
$$V_S=20.03+2+3.94=25.97V \quad \text{retrace.}$$

You must exercise some caution when you use nonsymmetrical power supplies because, under abnormal conditions, the inductive load has the potential to store energy from the higher-valued supply. For example, if the high-output voltage remains on the yoke longer than the normal retrace time, the collapsing magnetic field will discharge the stored energy into the lower voltage supply via the power op amp's inductive-kickback protection diodes. This collapse will generate a voltage transient on the supply rail; the transient's amplitude will be a function of the stored energy and the transient impedance of the power supply. If the transient- and supply-voltage combination exceeds the rail-to-rail voltage rating of the amplifier, you'll destroy the amplifier. A zener clamp on the amplifier output will minimize the possibility of this problem occurring.

## Delve into stability concerns

Because the current-control capabilities of this circuit rely on feedback from the current/voltage-conversion sense resistor, the inductance of the yoke will introduce some phase shift into the feedback signal. Although the phase shift on a perfect inductor theoretically approaches 90°, the phase margin of an op amp is always less than 90°, so you must add some circuitry to prevent oscillation.

In **Fig 1**, the network consisting of $R_D$, $R_F$, and $C_F$ shifts the feedback from current mode (via $R_S$) to direct-voltage mode at the higher frequencies. This scheme bypasses the extra phase shift introduced by the inductor. As far as component values for this network are concerned, first of all $R_F$ must be much larger than $R_S$ but must not be greater than 1 kΩ because the op amp's input capacitance would otherwise add phase shift. You then select $R_D$ to properly dampen the circuit at the unity-gain frequency. $R_D$'s value is usually a multiple of $R_F$; a safe starting value is $2R_F$. Finally, select $C_F$ to establish the 3-dB corner frequency at one-third the unity-gain bandwidth of the amplifier. For the PA02's 4.5-MHz bandwidth, $C_F$ should be 50 pF.

To develop an even more powerful deflection circuit, substitute the PA10A power op amp (**Fig 2**). With this op amp, you can drive a 7.8-mH/4Ω coil at 5A p-p without changing timing requirements. Calculations for this design are

$$V_{DRIVE}=(5A)(7.8\text{ mH}/15\text{ mSEC})=2.6V \quad \text{sweep} \quad \textbf{(1)}$$

$$V_{DRIVE}=(5A)(7.8\text{ mH}/730\ \mu\text{SEC})=53.43V \quad \text{retrace} \quad \textbf{(2)}$$

$$V_{DROP}=(2.5A)(0.5+40)=11.25V \quad \textbf{(3)}$$

$$V_S=2.6V+8V+11.25V=21.85V \quad \text{sweep}$$

$$V_S=53.43V+8V+11.25V=72.68V \quad \text{retrace.}$$

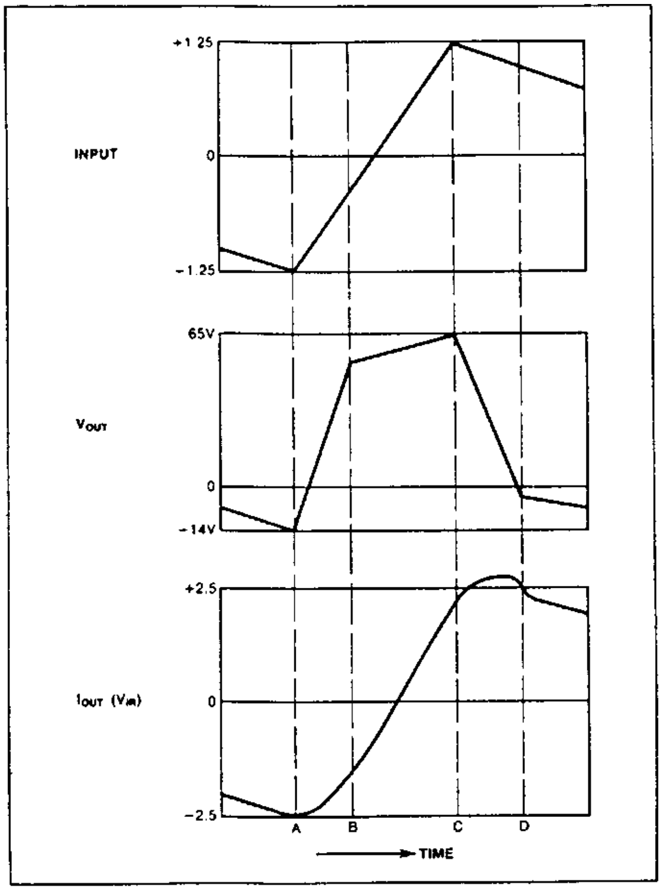


*Fig 3—The op amp must generate these output voltage waveforms to develop the desired retrace current step for the circuit of Fig 2. The trace preceding point A is the end of the sweep waveform.*

The circuits of **Fig 1** and **Fig 2** each have a 730-µsec retrace-time requirement. In both cases, the op amps easily meet this requirement because they have slew rates and settling times that are significantly faster than the retrace time.

To better understand the deflection application (as well as other applications), refer to **Fig 3**. You can see the output voltage waveforms the op amp must generate to develop the desired retrace current step for **Fig 2**. The trace preceding point A is the end of the sweep waveform and has a relatively slow current rate of change. The peak output voltage at point A equals the sum of **Eq 1** and **Eq 3**.

Retracing begins at time A, where **Eq 2** dictates the drive voltage required to achieve the retrace di/dt. From time A to time B, the amplifier is running at its slew-rate limit. The current in the yoke starts to track the input voltages at time B. From time B to time C, the op amp's output voltage is the sum of **Eq 2** and the value of instantaneous IR drops. **Eq 3** indicates the final value.

The abrupt slope change of the input waveform at point C again puts the amplifier in a slew-rate-limit mode until the output current is proportional to the input voltage (**Eq 1** plus IR drops). At point D, **Eq 1** is satisfied, and the amplifier will maintain the required current for the sweep portion of the waveform.

**Fig 3** uses time expansion, which better illustrates the slew-rate and voltage-swing requirements for the amplifier. During the retrace section of the waveform, the amplifier has to sum the drive voltage (**Eq** 1 and **Eq** 2) twice. In the **Fig 2** circuit, this drive voltage amounts to 112V. With the PA10A's typical slew rate of 5V/µsec, the slew time is only 22.5 µsec—an insignificant portion of the total retrace time. Once you understand the voltage-swing requirements, however, it's easy to see that slew rate becomes important as the scan rates increase.

*Once you understand voltage-swing requirements, it's obvious that slew rate becomes important as scan rates increase.*

In both **Fig 1** and **Fig 2**, having the nonlinear inductive element inside the op-amp feedback loop improves accuracy levels. In addition, the op amp's high gain and the use of negative feedback improves linearity.

Heads-up displays require swift transitions between any two points on the screen. The waveforms in **Fig 4a** illustrate the yoke's input-drive-voltage and current requirements for achieving a single full-scale step in beam position for **Fig 4b**'s circuit. The 3V levels sustain the steady-state current through the coil resistance and sense resistors; the 29V level corresponds to the peak output voltage required for a position change.

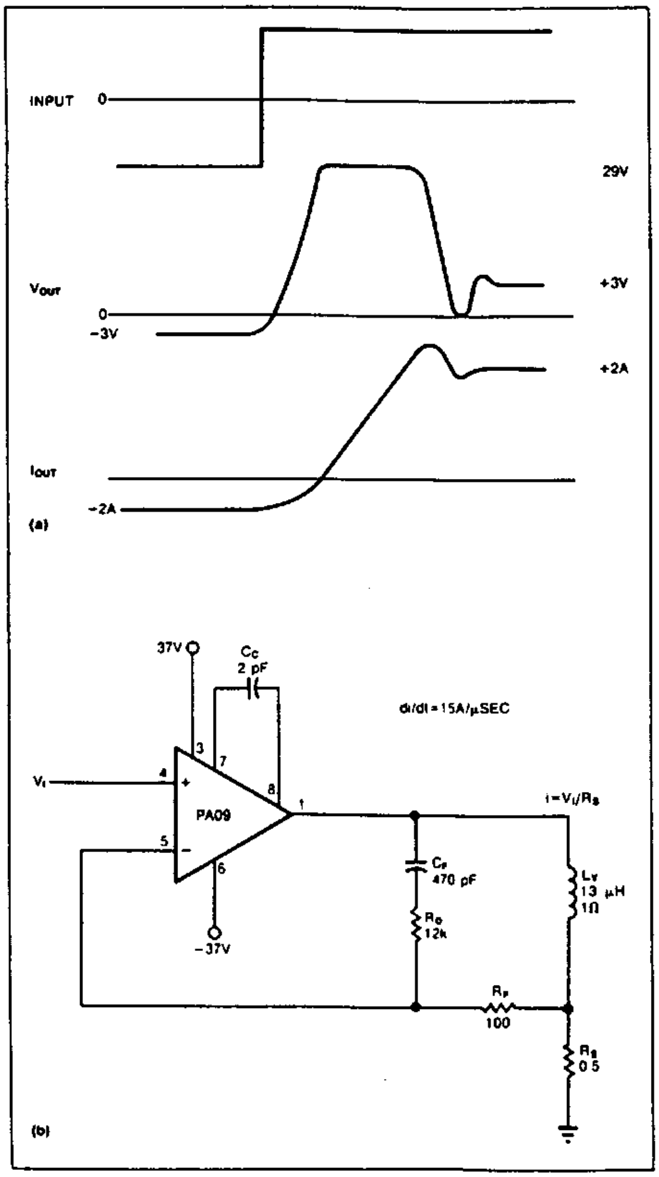


*Fig 4—Heads-up displays demand swift transitions between any two points on the screen. The waveforms in a illustrate what the circuit in b must generate to satisfy the yoke's input-voltage and current-drive requirements.*

You can use slew-rate and settling-time figures from the amplifier's data sheet to determine what percentage of the total transition time will be required for slewing and settling. As a starting point, it's reasonable to allow 50% of the total transition time.

The circuit in **Fig 4b** is designed to make a maximum transition in 4 µsec when delivering 2A to the 13-µH coil. Although the fundamentals of **Fig 4b**'s circuit are identical to those of the previous two circuit examples, the high speed involved does introduce some differences. To achieve rapid transitions, you must optimize amplifier slew rates, something you can accomplish quite easily with the PA09, a video power op amp with external phase compensation. Nonetheless, you'll have to examine the poles and zeros in the feedback loop because reactive feedback elements force the amplifier to operate over a very wide gain range—very high gain during transitions, but unity gain at steady state.

The network of $C_F$, $R_D$, and $R_F$ sets high-frequency gain at approximately 100. At this gain, you can phase-compensate the amplifier and still maintain fast slew rates. Next, you must plot the feedback zero of the yoke-inductance and sense-resistor combination (**Fig 5a**). Then, you draw in the high-frequency feedback level of the RC network (which is approximately 40 dB) and select $C_F$ to produce a pole approximately one decade below the intersection point. **Fig 5b** shows the PA09's open-loop Bode plot as well as modifications due to feedback effects—that is, a slope increase below 500 kHz and a shallow slope at the unity-gain crossing point to ensure stability.

With 50% of the total transition time set aside for slewing and settling, 2 µsec remains to change the yoke current with full voltage applied to the coil. You can calculate voltage requirements as follows:

$$V = L\ di/dt$$
$$V = (13\ \mu H)(4A/2\ \mu SEC) = 26V$$
$$V_{DROP} = (2A)(0.5+1) = 3V$$
$$V_{DRIVE} = 26V + 3V = 29V$$
$$V_S = 29V + 8V = 37V.$$

You also have to calculate the value of the phase-compensation capacitor per the requirements of the PA09. The amplifier's data sheet recommends component values as a function of circuit gain ($R_D/R_F$). With

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the recommended compensation capacitor, the PA09's data sheet indicates that amplifier slew rate will be 400V/μsec. For a 58V swing, this slew rate equates to a voltage slewing time of 145 nsec. Adding the settling time (1.2 μsec to 0.01%), the total is comfortably below the 50% allotment of 2 μsec.

Of course, you can modify component values during circuit testing to improve performance. In this particular case, the value of $R_D$ had a considerable effect on circuit damping, which is predictable because $R_D$ affects the corner frequency where the roll-off slope flattens near the unity-gain point. The value of $C_F$, on the other hand, wasn't particularly critical. Nevertheless, a 2-pF compensation capacitor, as opposed to the 5-pF value recommended on the data sheet, helped increase the slew rate without significantly affecting stability.

**Some circuit-layout tips will help**

Because of the PA09's high speed, you must take certain precautions to avoid any degradation in circuit stability and accuracy. To help prevent unwanted feedback, for example, use single-point grounding for the entire network or use a solid ground plane.

To ensure adequate decoupling at high frequencies, bypass each power supply with a tantalum capacitor of at least 10 μF and parallel it with a 0.47-μF ceramic capacitor. You should connect the ceramic capacitors directly between each of the two amplifier supply pins and the ground plane, and you should locate the tantalum capacitors as close to the amplifier as possible.

Use short input leads to minimize trace capacitance at the input pins. Input impedance of 500Ω max, combined with the PA09's input capacitance of approximately 6 pF, will maintain low phase shift and promote stability and accuracy.

You should also keep the output leads as short as possible. In the video frequency range, even a few inches of wire can have significant inductance, which will raise the interconnection impedance and limit the output slew rate. In addition, the skin effect increases the resistance of heavy-gauge wires at high frequencies. To minimize losses, it's best to use multistrand Litz wire to carry large video currents.

Finally, you must connect the amplifier case to an ac ground (signal common) even though it's isolated. In the video frequency range, the case can act as an antenna and cause errors or even oscillation.

The circuit in **Fig 6** drives the deflection yoke of a precision X-Y display from a ±15V supply. This transimpedance bridge is the only configuration that can provide the necessary high voltage drive from such supply levels. The circuit allows you to double the

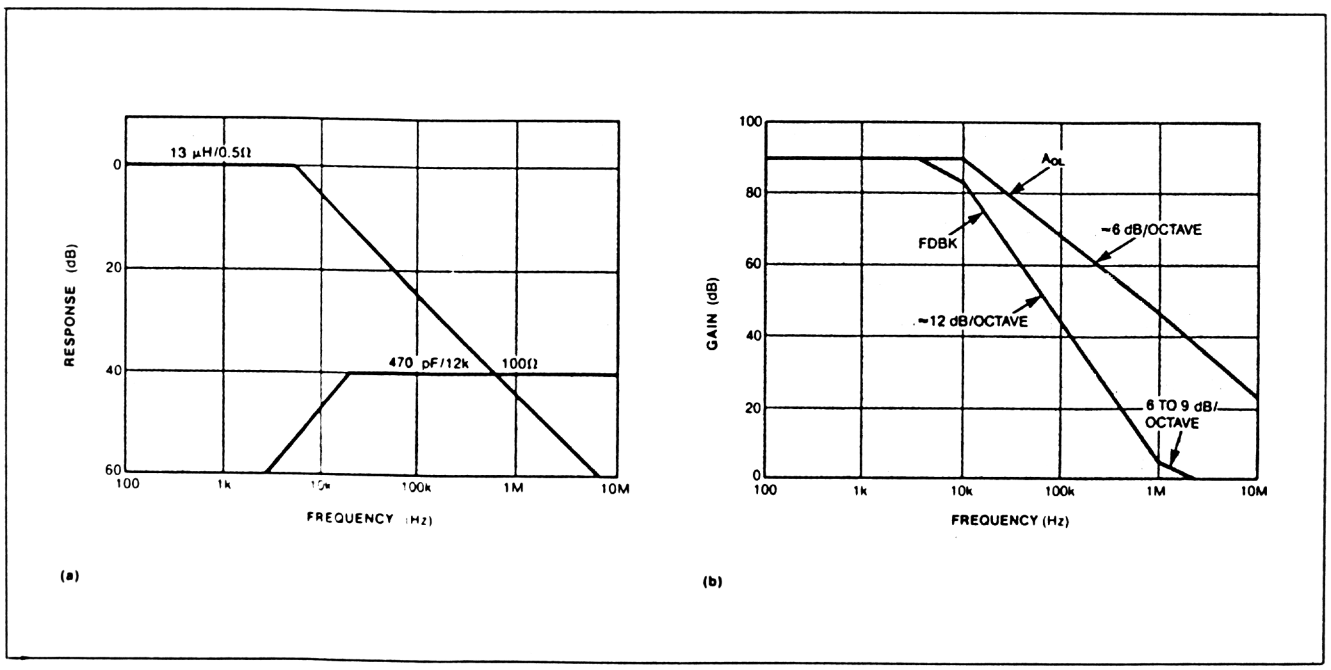


*Fig 5—You must examine the poles and zeroes in the feedback loop closely to achieve rapid transitions. First plot the feedback zero of the yoke inductance and sense resistor, and then draw in the high-frequency feedback level of the RC network (a). A look at the PA09's open-loop Bode plot (b) shows the modifications due to feedback effects.*

*With a transimpedance-bridge configuration, you don't have to use separate supplies for CRT deflection.*

amplifier's rated output voltage capability and thus eliminate the need to use separate power supplies for CRT deflection.

In **Fig 6**, sense resistor $R_8$ combines with $IC_1$ to implement a differential voltage-controlled current source. $IC_2$ functions as an inverter to provide an equal, opposite-phase voltage drive to the load. The feedback path of $R_{1A}$ through $R_{1D}$ performs the single-ended-to-differential conversion by making the output voltage a common-mode signal for $IC_1$. In this manner, the amplifier's common-mode rejection and the resistive-divider ratios maintain the transimpedance function (differential feedback from $R_8$ only).

Because $R_{1A}/R_{1B}$ and $R_{1C}/R_{1D}$ must divide the output voltage equally for both amplifier inputs, you'll have to use a matched or precision resistor network. In addition to initial matching, the network's temperature-tracking ratios are also critical. The series RC network, in parallel with the inductive load, reduces the load's phase shift at high frequencies and effectively eliminates the possibility of oscillation.

For a display with a 0.3-mH yoke inductance, a ±3.75A full-scale current requirement, and 0.4Ω dc coil resistance, the maximum transition time between any

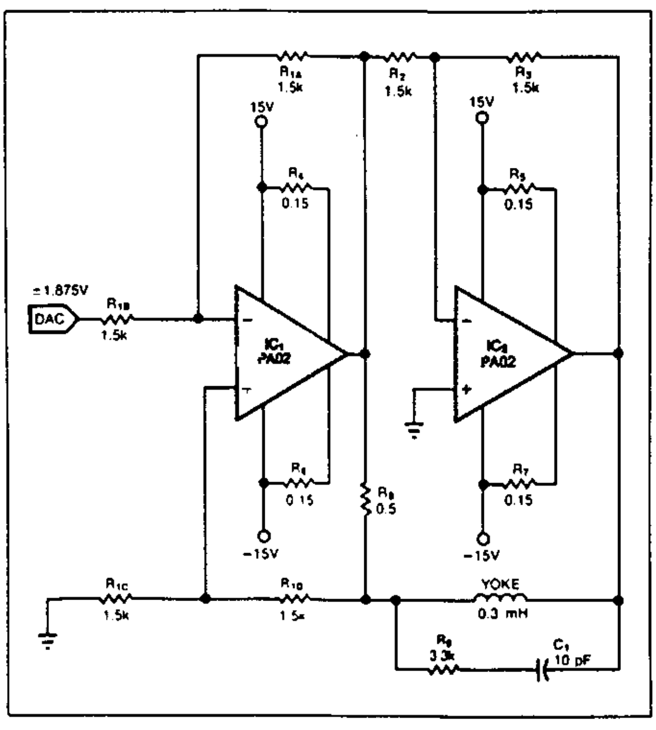


*Fig 6—The transimpedance bridge is the only configuration that can satisfy a deflection yoke's high-voltage drive requirements from a ±15V supply.*

two points is 100 μsec. The calculations similar to those required for the previous examples are

$$V = L\,di/dt$$
$$V = (3\text{ mH})(7.5\text{A}/100\ \mu\text{SEC}) = 22.5\text{V}$$
$$V_{DROP} = 3.75\text{A}(0.5+0.4) = 3.375\text{V}$$
$$V_{DRIVE} = 22.5\text{V} + 3.375\text{V} = 25.875\text{V}.$$

Each amplifier in the bridge provides one-half the required drive level: approximately 13V. The PA02 is well-suited to this application because of its high 20V/μsec slew rate and its ability to drive the load close to the supply rail. During the beam transition time, the average output voltage swing of the circuit will be greater than 26V.

Because of the inductive load, the current flow will change direction only after the transition is 50% complete. This restriction allows both amplifiers to swing to their no-load saturation levels (less than 1V from the supply rail) for this time period. In addition, IR drops during this time period generate voltages that add to the amplifier drive. During the second half of the transition, the current direction changes and the amplifier output swing decreases. Even at 75% completion, however, each amplifier will still swing in excess of 13V because the current magnitude hasn't reached the 2A level. **EDN**

## Author's biography


*Granger Scofield is vice president of marketing at Apex Microtechnology Corp (Tucson, AZ). In addition to product planning and seminar presentations, he provides technical assistance via an applications hot line and generates application notes and data sheets. Granger spends his leisure time riding motorcycles (on and off road) and tinkering with model trains.*


Article Interest Quotient (Circle One)
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