

Precision Magnetic Deflection

INTRODUCTION

Closed loop power op amp circuits offer distinct advantages in current control over open loop systems. Using a power op amp in the conventional voltage to current conversion circuit, the negative feedback forces the coil current to stay exactly proportional to the control voltage. The resulting accuracy makes many new applications feasible. For example, by placing the non-linear impedance of the deflection yoke inside the feedback loop, steady state positioning, which is difficult, if not impossible, to achieve with open loop circuits, can easily be implemented with a power op amp. In addition, sweep systems with substantially improved linearity can be designed using power op amps.

Typical applications include: heads-up displays, which require random beam positioning or E-beam lithography; and other complex data displays which can achieve the needed accuracy with a power op amp. Moreover, the versatility and ease of use of power op amps will help speed up the design process while at the same time reducing development cost. The final result will be a more accurate and reliable display using fewer parts.

HIGH RESOLUTION AND HIGH EFFICIENCY

The vertical deflection circuit of Figure 1 was designed to drive a high efficiency RCA CODY II tube. The PA02 was selected for this configuration because of its exceptional linearity and other advantages such as high slew rate, fast settling time, low crossover distortion, and low internal losses. All of these advantages contribute to a superior resolution display.

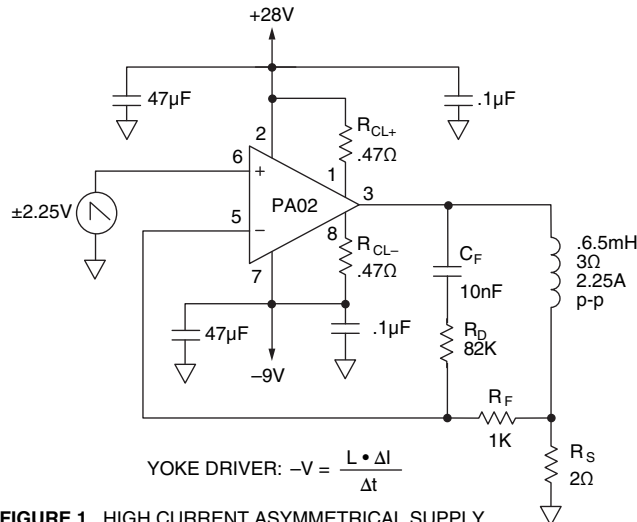


FIGURE 1. HIGH CURRENT ASYMMETRICAL SUPPLY

The key to this circuit is the sense resistor (R_s) which converts the yoke current to a voltage for op amp feedback. With the feedback applied to the inverting input and the position control voltage applied to the non-inverting input, the summing junction's virtual ground characteristic assures the voltage across R_s is equal to the input voltage. Thus, the highly linear control of the voltage across R_s insures accurate beam positioning.

The value assigned to R_s has significant impact on the circuit performance. All op amp input errors such as voltage offset,

imperfect common mode rejection, offset drift, etc., will appear across the sense resistor, producing current errors. While it is easy to see large sense resistors minimize DC errors, it takes a little more study to realize they help dynamic response also. The R_s value is a major player in setting the loop gain of the circuit. Larger feedback voltages will result in noticeable improvements in power bandwidth and settling time. The limiting factors on raising R_s values are brought on by the fact that load current flows through them; voltage drive capability decreases; and power dissipation in this resistor increases.

Weighing these trade-offs between errors, bandwidth, and efficiency in the selection of R_s value will produce the optimum choice for each application. The voltage drive requirements will then be defined by inductance, transition times and current. This display must operate at 50Hz or 60Hz with retrace times of 730μs and coil currents of 2.25A_{p-p}.

The drive voltage required to change the current in an inductor is proportional to both current change and inductance, but inversely proportional to transition time.

$$V_{DRIVE} = \Delta I * L / \Delta t \quad (1)$$

$$V_{DRIVE} = 2.25A_{p-p} * 6.5mH / 15.93ms = .918V \quad (2)$$

$$V_{DRIVE} = 2.25A_{p-p} * 6.5mH / 730\mu s = 20.03V \quad (3)$$

To determine the power supply levels, add the supply-to-output differential rating of the power op amp (from the Amplifier Data Sheet) and the voltage dropped across the combined values of the sense resistor plus the coil resistance, to these drive requirements to arrive at +28V and -9V as follows:

$$V_{DROP} = I_{PK} * (R_s + R_L) \quad (4)$$

$$V_{DROP} = 1.125A_{PK} * (2\Omega + 3\Omega) = 5.625V \quad (5)$$

$$V_s = V_{DRIVE} + (V_s - V_o) + V_{DROP} \quad (6)$$

$$V_s = .918V + 2V + 5.625V \cong 8.6V \quad (\text{sweep}) \quad (7)$$

$$V_s = 20.03V + 2V + 5.625V \cong 27.7V \quad (\text{retrace}) \quad (8)$$

Caution should be exercised when using asymmetric power supplies, because the inductive load has the potential to store energy from the higher supply. This could be initiated by an abnormal condition causing the high output voltage to remain on the yoke longer than the normal retrace time. After such an occurrence, the collapsing magnetic field would discharge the stored energy into the lower voltage supply via the inductive kickback protection diodes in the power op amp. This will produce a voltage transient on the supply rail with its amplitude a function of stored energy and the transient impedance of the power supply. If this transient added to the supply voltage exceeds the rail-to-rail voltage rating of the amplifier, the result will be destructive. In such cases, a zener clamp on the amplifier output should be used.

A note of caution when using modular construction. Instruction manuals always specify, "power down first, then remove the module." However, because this doesn't always happen, protective action should be taken. The mechanical break of the connection to any inductance, coil or wire, causes high voltage flyback pulses. The stored energy must be absorbed somewhere. It's much better to use the zener clamp than to risk the op amp.

STABILITY CONCERNS

Since the current control capabilities of this circuit rely on feedback from the current-to-voltage conversion sense resistor, phase shift due to the inductance of the yoke will be evident in the feedback signal. Because the phase shift approaches 90° on a perfect inductor and the phase margin of an op amp is always less than 90°, design adaptations are required to prevent oscillation.

The network consisting of R_D , R_F and C_F serves to shift from a current feedback via R_S to a direct voltage feedback at the upper frequencies. This bypasses the extra phase shift caused by the inductor. In selecting component values for this network, R_F should be much larger than R_S , but should not exceed 1KΩ for the PA02, because the input capacitance of the op amp would otherwise add phase shift. In selecting values of R_D and C_F start with values prescribed by the Apex Precision Power Design tool which will yield a stable circuit. Spice analysis and bench measurements will usually allow impedance of both these components to increase and speed up the circuit.

For an even more powerful version of this circuit, the PA10 power op amp can be used, as shown in Figure 2. With this device, a 7.8mH 4Ω coil can be driven at 5A_{p,p} with the same timing requirements. Calculations for this design are:

$$V_{DRIVE} = 5A_{p,p} * 7.8mH / 15.93ms = 2.45V \quad (9)$$

$$V_{DRIVE} = 5A_{p,p} * 7.8mH / 730\mu s = 53.43V \quad (10)$$

$$V_{DROP} = 2.5APK * (1\Omega + 4\Omega) = 12.5V \quad (11)$$

$$V_S = 2.45V + 6.5V + 12.5V \cong 21.5V \quad (\text{sweep}) \quad (12)$$

$$V_S = 53.43V + 6.5V + 12.5V \cong 72.5V \quad (\text{retrace}) \quad (13)$$

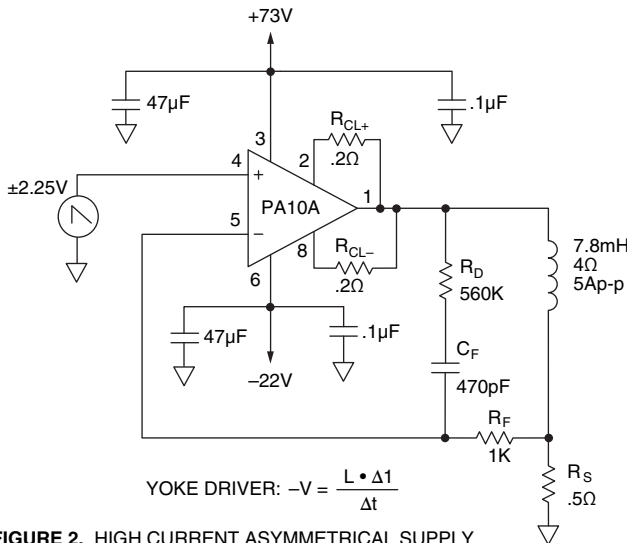


FIGURE 2. HIGH CURRENT ASYMMETRICAL SUPPLY

Both of the circuits illustrated have a 730μs retrace time requirement, met easily by the op amp's slew rate and settling time which is substantially faster.

To better understand this and other applications, Figure 3 illustrates input and output waveforms. Traces prior to time A, are the end of the sweep portion where current is changing at a relatively slow rate. The peak output voltage at time A is roughly the sum of equations 9 and 11.

Retracing begins at time A; the electron beam is turned off; and the amplifier starts running open loop because output current is not keeping up with the input command. Circuit slew rate is displayed between time A and time B where the output saturates. This slew rate is usually somewhat less than

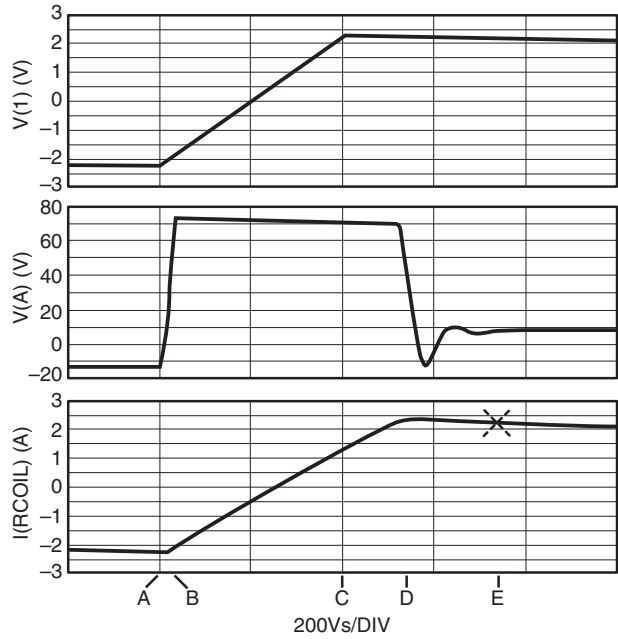


FIGURE 3. RETRACE WAVEFORMS

the amplifier rating because overdrive is small and the R_D/C_F network is a feedback path at the equivalent high frequency signal. At time C, the output current has caught up with the command signal, so the op amp begins closing the loop and settling. Time D is the end of the allotted retrace time and the electron beam is turned back on. Note the non-linearity of the current waveform between times C and D will not cause problems because of this timing.

Note that we calculated a supply voltage requirement of about 73V to change current 5A in 730μs, but most of this change takes place in about 550μs. The first thing making this possible is shown in the amplifier output voltage trace of Figure 3, where saturation voltage of the amplifier is much better than the 6.5V level of the calculations. At time B, current is still flowing through the negative side output transistor, NOT the positive side. The stored energy in the inductor is actually helping the op amp swing closer to the rail. A second factor helping reduce current slew time is again related to stored energy. From time B until current reaches zero, voltage developed across the sense resistor adds to the op amp voltage rather than subtracting from it. Spice analysis indicates peak voltage across the coil at time B is 74.6V.

If a circuit does not include offset and amplitude adjustment capability, the positive peak of the input signal needs to be increased by an amount equal to the normal current change between the actual input peak and time D. From Figure 3 this would be about $5A / 15.93ms * .32ms \cong 0.1A$, or $2.35_{V_{PK}}$ input.

When evaluating slew rates of potential amplifiers for these circuits, note that the amplifier is required to swing nearly twice the peak-to-peak output in a small fraction of the total retrace time. In this example, voltage slewing time was about 10% of the retrace time.

Both the PA02 used in Figure 1, and the PA10 used in Figure 2, have raised accuracy levels by placing the non-linear inductive element inside the op amp feedback loop. The very high gain of the op amp and the use of negative feedback produces superior linearity.

RAPID TRANSITION FOR HEADS-UP DISPLAY

Heads-up displays demand swift transition between any two points on the screen. The waveforms of Figure 4 depict the input drive voltage and required current to the yoke to achieve a single full-scale step in beam position for the circuit in Figure 5. The 3V levels sustain the steady state current through the coil resistance and the sense resistors. The 29V level corresponds to the peak output voltage required for a position change.

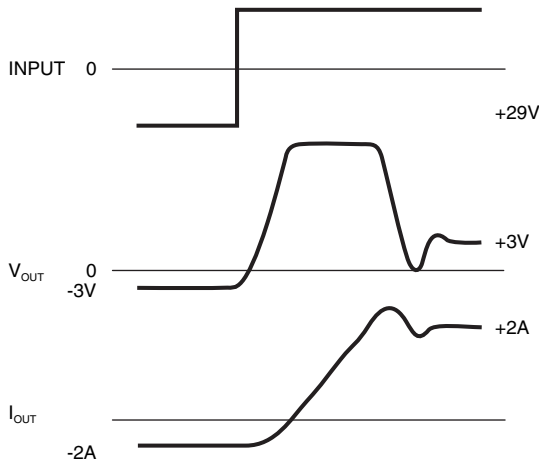


FIGURE 4. FULL SCALE STEP FUNCTION WAVEFORMS

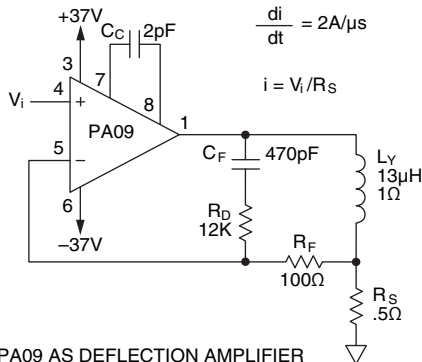


FIGURE 5. PA09 AS DEFLECTION AMPLIFIER

Starting with amplifier slew rates and settling times from the data sheet, it is determined what percentage of the total transition time will be required for slewing and settling. A reasonable starting point would be to allow 50% of the total transition time.

This circuit was designed for a maximum transition time of 4μs when delivering 2A_{pk} currents to the 13μH coil. While the fundamentals of this circuit are the same as previously detailed, there are differences due to the higher speed. To achieve rapid transitions, amplifier slew rates must be optimized. As a rule of thumb, compensation for this type circuit should not be lighter than that specified for a gain of 100. Again, the Power Design tool will help selecting values for R_D and C_F. With high speed circuits, it is even more important to analyze performance on the bench to insure parasitics don't spoil the circuit.

If 50% of the total transition time is allowed for slewing and settling, 2μs will remain to change the yoke current with full voltage applied to the coil. Voltage requirements are calculated as follows:

$$V = di \cdot L/dt \tag{14}$$

$$V = 4A \cdot 13\mu H / 2\mu s = 26V \tag{15}$$

$$V_{DROD} = 2A \cdot (.5\Omega + 1\Omega) = 3V \tag{16}$$

$$V_{DRIVE} = 26V + 3V = 29V \tag{17}$$

$$V_S = 29V + 8V = 37V \tag{18}$$

With the external compensation selected, the PA09 Data Sheet indicates the amplifier slew rate will be 400V per micro-second. For a calculated swing of 58V, the required voltage slewing time is 145 nanoseconds. Adding the settling time to 0.01% of 1.2μs, the total is comfortably below the 50% allotment of 2 microseconds.

When the circuit was tested, values were further optimized for best performance. The value of R_D had a considerable effect on damping of the circuit. This could be predicted because R_D affects the corner frequency where the roll off slope must be flattened near the unity gain point. The value of C_F was not critical; however, a compensation capacitor of 2pF, as opposed to the data sheet recommendation of 5pF, helped to increase the slew rate without significant affect on stability.

Due to the high speed of PA09, specific precautions are recommended to insure that optimum stability and accuracy are maintained:

1. To help prevent current feedback, use single point grounding for the entire circuit or utilize a solid ground plane.
2. To insure adequate decoupling at high frequency, bypass each power supply with a tantalum capacitor of at least 10μF per ampere of load current, plus a .47μF ceramic capacitor connected in parallel. The ceramic capacitors should be connected directly between each of the two amplifier supply pins and the ground plane. The larger capacitors should be situated as close as possible.
3. Use short leads to minimize trace capacitance at the input pins. Input impedances of 500Ω or less combined with the PA09 input capacitance of approximately 6pF will maintain low phase shift and promote stability and accuracy.
4. The output leads should also be kept as short as possible. In the video frequency range, even a few inches of wire have significant inductance, thereby raising the interconnection impedance and limiting the output slew rate. Also, the skin effect increases the resistance of heavy wires at high frequencies. Multistrand Litz Wire is recommended to carry large video currents with low losses.
5. The amplifier case must be connected to an AC ground (signal common). Even though it is isolated, it can act as an antenna in the video frequency range and cause errors or even oscillation.

TRANSIMPEDANCE BRIDGE FOR HIGHER DRIVE VOLTAGE

The circuit illustrated in Figure 6 drives the deflection yoke of a precision x-y display from an available ±15V supply. Only the bridge configuration can provide the high voltage drive levels required with the power supplies available. This enables the system to drive double the single amplifier output voltage. Consequently, the need for separate power supplies solely for CRT deflection is eliminated.

A1 in Figure 6 (next page) is configured as a Howland Current Pump. Voltage on the bottom of the sense resistor is applied directly to the load; voltage at the top is the applied voltage plus a voltage proportional to load current. With both these points for feedback, the amplifier sees a common

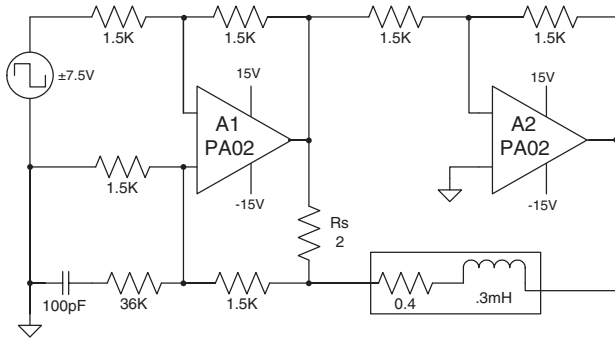


FIGURE 6. CURRENT-OUT BRIDGE DRIVE
 function of load voltage on both inputs which it can reject (CMR), but sees a function of load current differentially. In this arrangement, A1 drives the load anywhere required (with in saturation limits) to achieve load current commanded by the input signal. As ratio match between the two feedback paths around A1 is critical, these four resistors are often implemented with a resistor network to achieve both precision match and tracking over temperature. A2 provides a gain of -1 to drive the opposite terminal of the coil. Gain setting resistors for A2 are not nearly as critical, a mismatch here simply means one amplifier works a little harder than the other. The PA02 brings a unique combination of high slew rate and low saturation voltage to this circuit. Starting values for the R-C compensation network come from Power Design and are fine tuned with bench measurements.

At first glance, it might appear the choice of 2Ω for the sense resistor is quite large because the peak voltage drop across it is 7.5V, or half the supply voltage.

Voltage across the inductor required to move the beam is given by:

$$V_L = 300\mu\text{H} * 7.5\text{A} / 100\mu\text{s} = 22.5\text{V} \quad (19)$$

If one were to add to this the peak voltage drop across the coil resistance (1.5V) and the sense resistor (7.5V), it would be easy to assume a total swing of 31.5V or greater than 15V at 3.75A would be required of each amplifier.

Salvation for this problem lies in analyzing current flow direction.

In the middle graph of Figure 7, we find the large sense resistor does not destroy the circuit drive capability. The main portion of the transition is complete in about 80μs and settles nicely.

In the top graph, we find a surprise; both amplifiers are actually swinging OUTSIDE their supply rails. The "upside down" topology of the output transistors in the PA02 allows energy stored in the inductor to fly back, turning on the internal protection diodes. The result is peak voltages in the first portion of the transition greater than total supply.

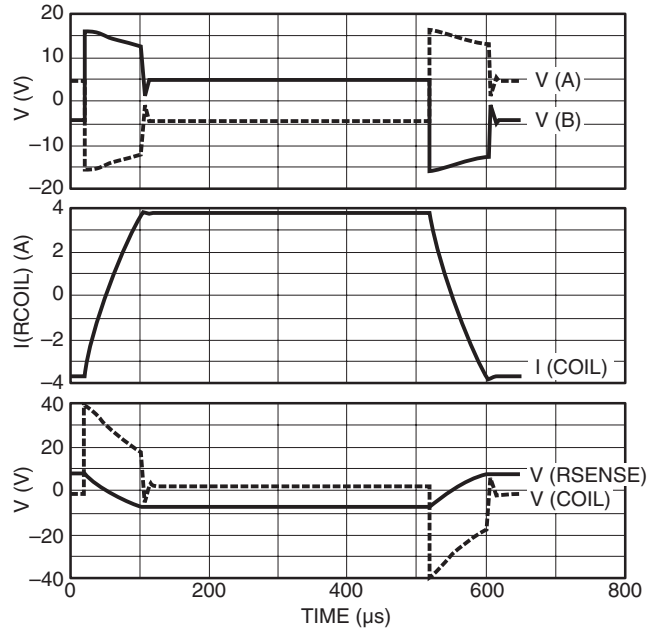


FIGURE 7. BRIDGE DRIVE CURRENTS AND VOLTAGES

In the bottom graph, we find stored energy in the inductor develops voltage across the sense resistor, which ADDS to the op amp voltage until current crosses zero. In this manner, peak voltage across the coil is nearly 40V!

The seemingly large value of sense resistor did not kill us on voltage drive requirements and gives two benefits: First, internal power dissipation is lower than with a smaller resistor. Secondly, with larger feedback signal levels, the amplifier closed loop gain is lower; loop gain is larger; fidelity of the current output is better; and voltage offset contributes a lower current offset error.

CONCLUSION

The capabilities of the power op amp provide higher accuracy levels, the ability to position beams in any desired position and to retain a steady state position. Having both the power and signals stage in one compact package offers space/weight advantages. The lower parts count increase reliability.

Power op amps are comparatively inexpensive and easy to use. They represent the most efficient solution to reducing development costs and decreasing design time.

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