

TAME DEFLECTION CIRCUITS WITH POWER BOOSTERS

BUILD A MAGNETIC OR
ELECTROSTATIC
DEFLECTION AMPLIFIER
FROM HIGH-VOLTAGE
HYBRIDS WITH 160-KHZ
FULL-POWER
BANDWIDTHS.

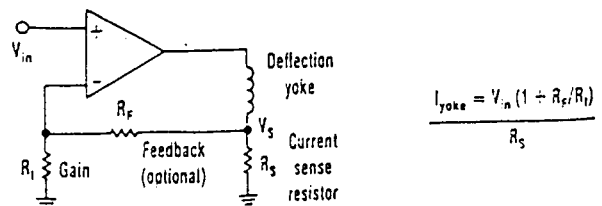
Even if you build magnetic deflection amplifiers everyday, they aren't the easiest circuits to design. Moreover, if you're a novice, they can represent a horrendous task. Not only must they accurately reproduce fast, complex waveforms, but they must handle high voltages and currents reliably and without excess dissipation. And they must drive inductive loads within a feedback loop, which can be tricky. Here's a way to simplify your job with a family of power op amps.

The term, "deflection amplifier," generally describes circuits used to deflect an electron or ion beam either directly (electrostatic) or via an inductor (magnetic). While most commonly associated with CRTs, deflection amplifiers are used in various applications, including scanning electron microscopes, small cyclotrons, and beam-deposition systems.

The two methods used for deflection—magnetic and electrostatic—require completely different amplifier designs. In general, magnetic deflection requires high power (current) at relatively low voltages, while electrostatic deflection requires high voltages but negligible current. Moreover, you can optimize the quality of the deflection, especially its linearity, by choosing the proper amplifier configuration. In particular, magnetic-deflection amplifier design requires careful consideration of power dissipation, bandwidth, and dynamic stability (they must not ring or oscillate). These requirements are typically in conflict with each other.

A circuit component recently introduced by Apex, the PB50 power booster-with-gain amplifier, is well suited for use in magnetic-deflection amplifiers (see "A look inside the PB50"). This hybrid's output voltage swings up to ± 90 V and ± 2 A, while slewing at 50 V/ μ s. The booster is designed to be driven by a small-signal op amp with a feedback loop closed around both devices. This configuration is called a composite amplifier. Designers may shy away from such a combination because of concerns over stabilizing the composite amplifier—particularly when the power booster has gain, as with the PB50. Furthermore, the typically employed, current feedback magnetic deflection circuit is inherently unstable.

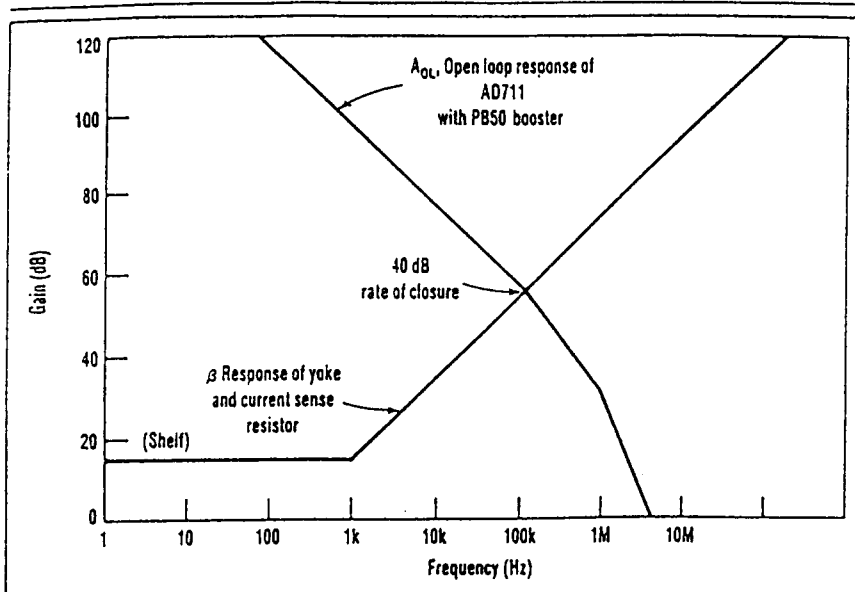
Using the PB50 booster in a magnetic-deflection amplifier application shows you how to solve these stability problems and illustrates the ease with which the booster can be designed into even difficult applications. A circuit for a companion part to the PB50, the PB58, operates



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1. THE VOLTAGE ACROSS the current-sense resistor is a function of V_{in} and the current through the op amp. Thus, the deflection yoke's current is a function of V_{in} .

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2. AN INDUCTANCE within the closed feedback loop of an op amp produces an inherently unstable, 40 dB/decade rate-of-closure.

from ± 150 V.

Beam position in magnetic deflection applications is a function of deflection yoke current. Consequently, among modern op-amp topologies, the basic current-control configuration, in its simplest noninverting form, becomes the circuit of choice (Fig. 1). A voltage V_{in} applied to the noninverting (+) input forces the amplifier output to reach the value necessary to make the voltage on the inverting input equal to V_{in} . The output voltage feedback V_s (in this circuit) is developed across a low-value resistor R_s in series with the deflection yoke. Because V_s is a function of the yoke current, the circuit supplies a yoke current directly proportional to the input voltage.

In addition, this current feedback linearizes the input voltage-to-output current relationship. For example, in sawtooth-scan applications, the circuit can be driven from an easily obtained sawtooth input voltage. Yet under dynamic conditions, the amplifier insures that the current in the yoke conforms to the sawtooth input while developing exponential voltage waveforms at its output (the amplifier's output). In fact, such current feedback circuits eliminate the need for a vertical-linearity control in TV and other CRT applications.

While the basic circuit and concept are really quite simple, there's problems in real-world applications. An analysis of the feedback loop frequency response, plotted against the amplifier open-loop gain, reveals inherent instability because of a 40 dB/decade rate-of-closure of the response. Your job is to come up with a stable design—without limiting the circuit's speed.

First, you must choose the right amplifier to supply the high level of performance required for deflection amplifiers—especially at the high sweep rates required for horizontal deflection in the latest raster-scan graphics systems. A typical application might need an amplifier with the following specifications:

Output voltage swing: ± 30 V

Current: ± 2 A

Slew rate: 50 V/ μ s

Gain-bandwidth: 10 MHz

The op amp parameters associated with dc accuracy—such as offset, offset drift, and bias current—are of less importance (in these applications) and values offered by general purpose devices are usually adequate for any op-amp based approach. However, the high output voltage and current requirements may steer you toward a power op-amp solution, which is often used for

magnetic deflection applications. Such power op amps as the Apex PA09 and PA19 work well for magnetic deflection because they put out up to 4 A at up to 3 MHz.

However, the cost requirements of a system often preclude the use of the power op amp. And the need to "flex" the power supply rails to minimize power dissipation (that is, to dynamically change the supply voltages in sync with the drive signal) could complicate the use of a power op amp. Previously, the only alternative was a discrete design made with discrete power transistors.

At first glance a discrete design may look good—not simple, but possible. It consists of a small signal op amp, such as an AD711, driving a power output stage. The driver op amp can operate with constant supply rails, allowing it to maintain full control of the output, while the supply rails of the output stage are "flexed" to minimize dissipation.

At a minimum, the approach requires a lengthy design effort to address all the reliability and performance requirements. For example, Class A/B biasing is required because low crossover distortion is critical. If the amplifier is needed to operate over a wide ambient temperature range, then just optimizing the output-stage biasing circuitry is complex. In addition, the amplifier's internal stability must be addressed—along with the added stability of the yoke-filled feedback network. A tough egg to crack. Moreover, what has become a high-component-count circuit results in tradeoffs of reliability and economy.

The typical discrete approach might consist of cascaded, complementary, common-emitter stages taking the output from the second set of collectors. It provides both high efficiency and bandwidth. But stabilization of the common-emitter output stage, with local gain connected in a feedback loop around an op amp, can be difficult. The PB50 booster essentially packs all the circuitry of such a discrete amplifier into an 8-pin TO-3. Moreover, it cuts valuable board area and also simplifies the job of stabilizing the com-

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plete composite amplifier loop—yoke and all.

The goal of this magnetic deflection amplifier design, including its compensation, is to obtain the fastest response possible while remaining free of excessive ringing or overshoot. As noted, the current feedback deflection circuit is inherently unstable (Fig. 2). The open loop response A_{OL} is the response of the composite amplifier—the AD711 driver plus the PB58 booster with its 22-pF compensation capacitor between pins 1 and 8 (Fig. 3a).

Superimposed on the amplifier response is the response of the yoke and sense-resistor feedback network. The network has a pole occurring at the frequency set by the 200- μ H yoke inductance and the 0.5- Ω sense resistor. The horizontal section of the curve, or shelf, at frequencies below 1 kHz represents the effect of the closed loop gain-setting feedback and input resistors, R_F and R_I . The effect, if any, of yoke dc resistance will appear in this region, too. The intersection of the feedback-loop response and the open-loop response exhibits a 40 dB/decade rate of closure. However, optimum stability demands a rate-of-closure less than 20 dB/decade.

Note also that at 100 kHz, the amplifier response curve encounters another pole that increases the amplifier slope to greater than 20 dB/decade, though it doesn't reach 40 dB/decade until about 1 MHz. The region above 100 kHz and at closed

loop gains below 55 dB will be marginal for stability, while the region above 1 MHz is definitely unstable for gains less than 30 dB. It will be necessary to overcome the effects of the rate of closure caused by yoke feedback, without causing the amplifier to operate in any unstable areas.

You could simply connect a damping resistor in parallel with the yoke, which would provide stability, but your intent is to create an amplifier that's a true current source. By definition, the true current source can't have pure resistance in parallel with its load, unless that resistance is an intended part of the load. This parallel resistor technique offers less than optimum performance for the magnetic deflection amplifier—especially for rapid transitions.

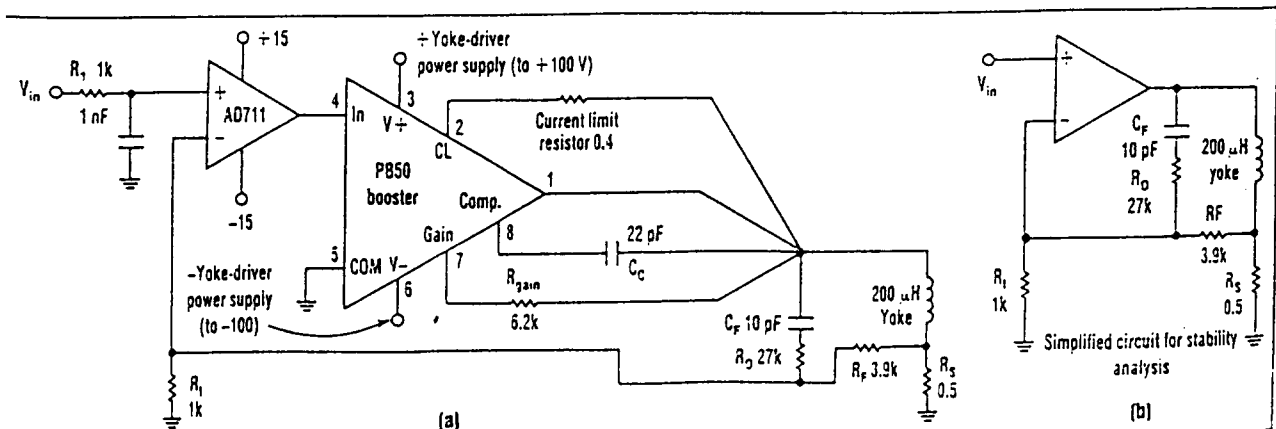
To supply maximum stability and speed, select a circuit that combines a dominant high-frequency feedback path with ideal phase and gain relationships (Fig. 3b). The circuit illustrates the use of the auxiliary feedback components R_F , C_F , and R_D , and gain setting resistor R_I . Here, R_I was selected to supply an overall gain of five to enhance stability.

The easiest way to select component values for the auxiliary stabilizing feedback is by plotting gain and feedback relationships graphically (Fig. 4). This method takes advantage of information on any amplifier data sheet. You can then see the amplifier response, superimposed on booster response, plus yoke-resistor feedback response.

To arrive at values for the stabilizing feedback, select a ratio for R_D/R_F (in parallel with R_I) greater than the open-loop gain at the point where the composite amplifier response begins to exceed 20 dB/decade. This gain level insures that the feedback isn't excessive when the phase response from the amplifiers themselves has gone past the point that's acceptable for stability. At the same time, the ratio must be at least 20 dB lower in amplitude response than the yoke feedback at the intersection of yoke feedback and A_{OL} so that the auxiliary feedback dominates at this critical point.

In the amplifier used here another approach was chosen to best realize high-speed performance. R_D was selected for a high-frequency shelf above the point where the amplifier A_{OL} response reaches 40 dB/decade at 1 MHz. Typically, this might seem potentially unstable because the high-frequency closed-loop gain intersects the A_{OL} curve where A_{OL} is still decreasing at something over 20 dB/decade. But proper capacitor selection overcomes the phase shifts present at this point.

The capacitor would usually be selected to supply an upward break in the auxiliary feedback response at a frequency an order of magnitude less than the intersection of the yoke response and A_{OL} curve. To increase response speed, the capacitor can be decreased with the limit occurring where the upward break intersects the A_{OL} curve. In this example,



3. THE PB58 BOOSTER amplifier driven by an op amp (the AD711) forms a high-speed current source for driving a CRT magnetic deflection yoke (a). The circuit is stabilized by the RC network across the yoke. Stability analysis is easier with the simplified circuit (b).

The DMOSFET output devices are the key in the architecture of the PB50 and 58, which gives the performance needed of these deflection-amplifier applications. These power transistors make possible the full-power bandwidth of the PB series over 160 kHz. The architecture resembles an op amp with a single-ended input stage. A bipolar transistor is used on the

input because FETs offer no real benefit as the device will be driven by an op amp. This transistor drives a MOSFET, which supplies the gain and high-voltage for the output stage.

The output stage consists of a V_{gs} multiplier and complementary pair of MOSFET followers with bipolar transistor between each gate and source implementing the hybrid's current-limit function. A

few other bipolar transistors serve as the current sources dedicated to biasing the amplifier.

The PB series has a built-in overall feedback loop when pin 7 is connected to the output. While this loop sets a gain of three, it can be raised with an external resistor in series with the loop. The PB series is compensated with capacitor C_C in parallel with the feedback resistance.

though, the capacitor was selected to supply an upward break in response that nearly intersects the A_{OL} curve. This causes a phase lead to occur in the feedback loop, which moderates the effect of the greater than 20 dB/decade amplifier roll-off experienced at this point. The actual circuit proved to be unconditionally stable and free from ringing.

Power dissipation in deflection amplifiers can be directly affected by the amplifier's speed requirements. The drive voltage required at the yoke is a function of how rapidly current must be changed in the yoke. Higher voltages mean higher speeds. But most deflection circuits are required to operate over a range

of speeds. Vector scan systems may operate at any rate and sawtooth raster scan systems, by their very nature, operate with at least two speeds: one for scan, one for retrace.

One approach you can take is to set power-supply voltages high enough to accommodate the highest speed required. However, this is inefficient and can produce unnecessary amplifier heating as a result of internal power dissipation.

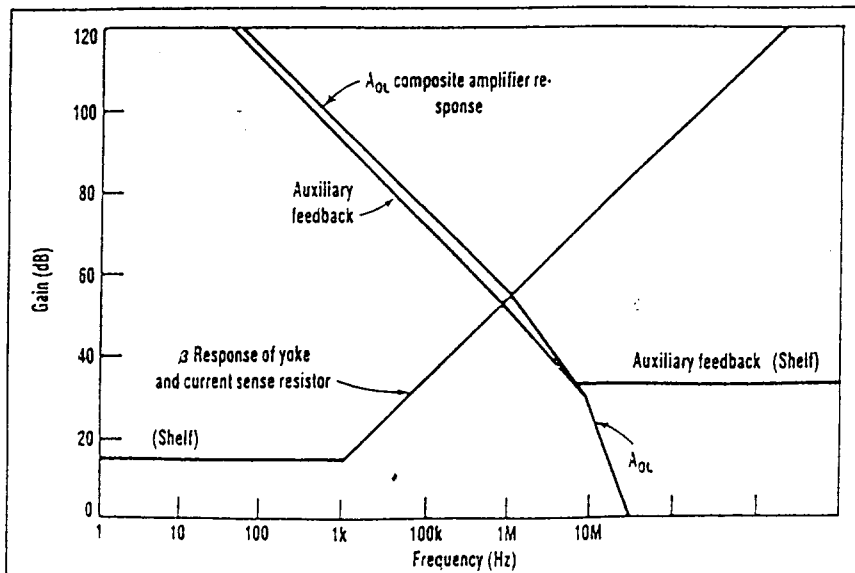
In a sawtooth raster scan application, designed to operate at a set sweep speed and amplitude, it's possible just to use nonsymmetrical supply voltages to solve the efficiency problem. In vector scan systems, or systems where widely varying

speeds are required, the power-supply voltages can be varied to suit the immediate requirements.

Generally, two discrete sets of power-supply voltages are used for the power amplifier, and its supply pins are switched between them in synch with the drive signal (Fig. 5). The lower voltages are obtained via the diodes ("ultra-fast" recovery devices rated for at least 1 A and 200 V) between the driver's ± 15 V supply, which can power the other analog circuits, and the booster's supply pins. Switching on Q_1 turns on the pnp Darlington and applies a positive high voltage to the PB50 booster (a maximum of 100 V), and its output can swing positive. Similarly, turning on Q_3 applies a negative high voltage to the booster (via the npn Darlington) making it possible for its output to swing negative. In either case, the diodes disconnect the low-voltage supplies from the booster (the Darlington should be rated at a minimum of 5 A and 200 V).

In the discrete approach (described earlier), the driving op amp and all but the output power transistors can be supplied from constant low-voltage power supplies. Only the output-stage supply rails need be switched. Because the driver op amp isn't disturbed by supply voltage fluctuations, it maintains accurate control of overall amplifier behavior, greatly simplifying the complications that might arise from flexing.

By comparison, a single-power op amp has an input and power output stage with their supply lines tied together internally. Because they



4. INSURING THAT THE AUXILIARY FEEDBACK (the RC network across the yoke) response dominates the circuit, at the point where the composite amplifier response begins to exceed 20 dB/decade, creates a stable design for driving deflection yokes.

aren't designed for the massive changes in supply voltage brought about by flexing, severe problems may arise from lack of sufficient power-supply rejection. The transition times of the square wave switching the amplifier's power pins contain considerable high-frequency energy, and the power-supply rejection of any op amp degrades with frequency. With the single power op amp approach, switching spikes are likely at the output when the device's supply rail is flexed.

By using an op amp and a separate booster, you get the best of all worlds. The driver op amp is supplied from constant rails while the lines to the booster amplifier are flexed (*Fig. 5, again*). Supplying power-supply transition times during flexing, which are compatible with the deflection amplifier's slew rate, ensures the best results.

With power dissipation and stability considerations addressed, the final deflection amplifier may still exhibit performance deficiencies. Ringing and overshoots, after rapid transitions such as retrace, are the most common nagging problems that remain after arriving at a suitable deflection-amplifier design.

Choosing the proper stabilizing feedback is certainly the most important item in controlling settling behavior. But the effect of "slew-rate

overload" is an area commonly overlooked. This occurs when the input signal to an amplifier is changing at a rate greater than the amplifier's slew rate. The output can't keep up with the input. Consequently, neither can the feedback. The amplifier is out of control—it's skidding. During this interval, the op amp's input is subjected to an inordinately large differential signal, which overloads or saturates the stage. A lengthy and unstable recovery results causing much of the ringing in deflection-amplifier applications.

The solution may be obvious: Control the drive signal's slew rate, simply making sure that it doesn't exceed the amplifier's slew rate. Will this slow the circuit down? No, just the opposite. In fact, settling characteristics will improve. And if such problems occurred, consider that the amplifier was actually overdriven to begin with.

Input slew-rate control can take many forms. For instance, if the drive comes from a digital-to-analog converter, perhaps reprogramming the d-a converter's drive will implement such control. Or slow down the retrace time of the oscillator generating the sawtooth drive.

A simple, universal method, consists of just a one-pole low-pass R-C filter at the amplifier input. Initially, this might seem undesirable because

of effects on frequency response. But the response of a network adequate to control slew overload won't usually impact the amplifier's usable bandwidth.

While some manufactures offer information on slew-rate limiting, it's not commonly available on amplifier data sheets. The equation given here simply limits the maximum possible rate-of-change of a step-function input signal to less than the slew rate on the data sheet.

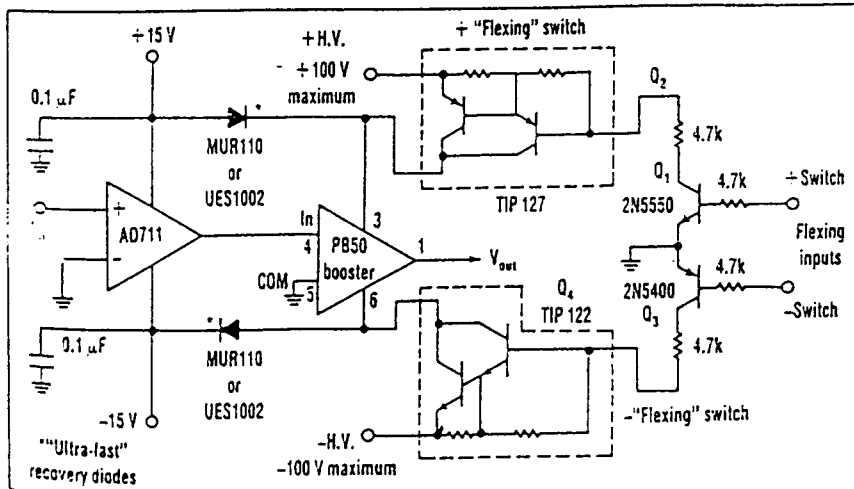
Selection of component values for the input low-pass filter is based on the equivalent closed loop gain of the circuit at its highest frequencies; the gain of the high frequency "shelf" of the overall feedback response. The RC product of the resistor and capacitor are determined from the following equation:

$RC = (V_{pk-pk} \text{ in} \times A_V) / S_R$, where S_R is the output slew rate of the amplifier in Volts/s and A_V is the closed loop gain of the composite amplifier.

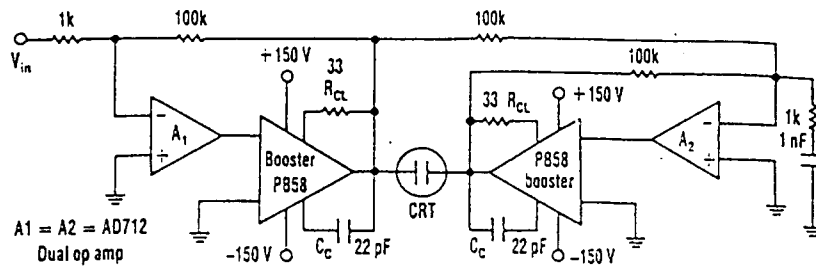
(Note: This equation is generic. It can be used to prevent slew-rate limiting for any amplifier.)

In the amplifier shown (peak yoke current = 1 A, open loop gain = 5), input voltage will swing 0.2 V_{pk-pk}. The shelf's effective gain is about 35 dB. Slew rate of the PB50 booster is 50 V/μs, resulting in an RC product that lets a 1000-Ω resistor and 120-pF capacitor supply slew-rate control. The pole frequency of such a filter is 1.3 MHz, showing that this filter will have no detrimental effect on amplifier bandwidth. The final magnetic-deflection amplifier design offers a full-scale transition time, from -1 A to +1 A (and vice versa) of under 5 μs, corresponding to a 200-kHz sweep frequency for a CRT.

In contrast to the magnetic-deflection amplifier's need for high currents, electrostatic-deflection amplifiers require the use of high voltages and low currents. With its ±150-V swing capability, or up to 300 V rail-to-rail, a PB58 power op amp is the preferred choice for electrostatic deflection. The PB58 is the most economical wideband solution available at up to 300 V. With its current capability of 1.5 A, the PB58 is also useful



5. POWER DISSIPATION in the booster is minimized by "flexing" its power supply voltage—applying a high voltage to the positive rail when the output must swing positive; a negative high voltage to the negative rail when the output must swing negative. The Darlington's are the power switches.



6. TO MINIMIZE DEFOCUSING and trace distortion, electrostatic deflection amplifiers for CRTs should have balanced (push-pull) outputs, like the circuit shown, built with composite amplifiers.

in magnetic deflection amplifiers.

Electrostatic deflection CRTs supply the sharpest displays when driven by a balanced (differential or push-pull) output-deflection amplifier. The balanced drive results in a constant average voltage between the deflection plates, for minimal defocusing and trace distortion.

A pair of PB58 boosters, along with two driver amplifiers (each half of an AD712) build just such a circuit with only a few added parts (Fig. 6). The circuit is conventional in all respects except care is taken to ensure high frequency performance. With 2.8-V input, it supplies output swings of up to 288 Vpk. Power bandwidth is 160 kHz and slew rate 200 V/ μ s.

The input amplifier, A_1 , operates at a gain of 100, while its companion on the other side of the bridge, A_2 , is a unity gain inverter. The RC network across the inputs of A_2 represents a technique often referred to as "noise gain compensation." With the added compensation—the combination of A_1 's feedback resistor and the network resistor and capacitor—the unity gain inverter is supplied with a "noise" gain of 100 just at high frequencies by reducing the negative feedback.

In this example, the noise-gain compensation ups the stability of the driver amplifier-PB58 combo (because the high-frequency negative feedback is reduced). It also reduces required phase compensation. Identical phase compensation can now be used for the high-gain input amplifier and the unity-gain inverter, leading to the frequency response match between both circuits needed for op-

timum high-speed performance.

In themselves, the CRT's deflection plates represent an easily driven load for any high-voltage op-amp circuit. Complications arise when the plates are located some distance from the amplifier so they must be driven via coaxial cables. At the useful frequencies of the amplifier (shown), the cable's capacitance will be more relevant than any transmission line effects and can be treated as a purely capacitive load. Problems can be minimized by using the lowest capacitance cable possible.

Capacitive loading will have two detrimental effects: Negative effects on bandwidth and potential stability problems. Compensating for capacitive-load-related stability problems also complicates the bandwidth problems because it requires either a resistor or inductor in series with the amplifier output to isolate the capacitive loading. To eliminate these problems, the amplifier should be physically positioned close to the CRT whenever possible. □

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