X-Y RECORDER NOTES

NUMBER 4

High-Sensitivity X-Y Recorder Has Few Input Restrictions

To match its high sensitivity, this new recorder provides 130 dB of common-mode rejection for virtually any input configuration. No external "guard" connection is needed unless the common-mode voltage exceeds ten volts peak.

The following article was written by Donald Huff, Daniel Johnson, and John Wade and appeared in the "Hewlett-Packard Journal."

THE NEW MODEL 7047A RECORDER is the fastest, most sensitive X-Y recorder ever built by Hewlett-Packard. This rugged, reliable, one-pen laboratory recorder (Fig. 1) has maximum input sensitivity of 0.02 millivolts per centimetre on both axes. It is capable of slewing at more than 76 cm/s and of accelerating at rates exceeding 5080 and 7620 cm/s on the X and Y axes, respectively.

Making the high sensitivity usable is a special common driver amplifier circuit that, acting as an internally driven guard, provides 130 dB common-mode rejection with virtually any input configuration. This is a significant difference from other recorders, which require that the LO input terminal always be connected to the low side of the source if high common-mode rejection is needed. No external "guard" connection is required by the 7047A unless the common-mode voltage exceeds ten volts peak.

Standard features of the 7047A Recorder are twelve calibrated dc input ranges on each axis, a time base that provides six sweep speeds from 0.1 s/cm to 50 s/cm, calibrated zero offset with zero control, switchable input filters, polarity reversal switches, and remote control of many functions by TTL signals or contact closures. The servo-motors are continuous-duty aluminum-framed dc motors that do not wear when the pen is driven off scale. Chart paper up to 11 by 17 inches or DIN size A3 is held in place electrostatically. Pens are disposable, and four colors of ink are available.

Options include metric or English calibration and an event marker.

7047A Design

The 7047A Recorder is a member of the 7040 Series and shares many parts with other members of that series. The basic aluminum mainframe casting is the same in all members of the series. The mechanics, motors, and servo electronics of the 7047A are the same as those of other high-performance members of the series.

The principal differences between the 7047A and other members of the 7040 Series are in the preamplifiers that condition the input signals and drive the servo electronics. The dc amplifier used in other members of the series does not have the very low

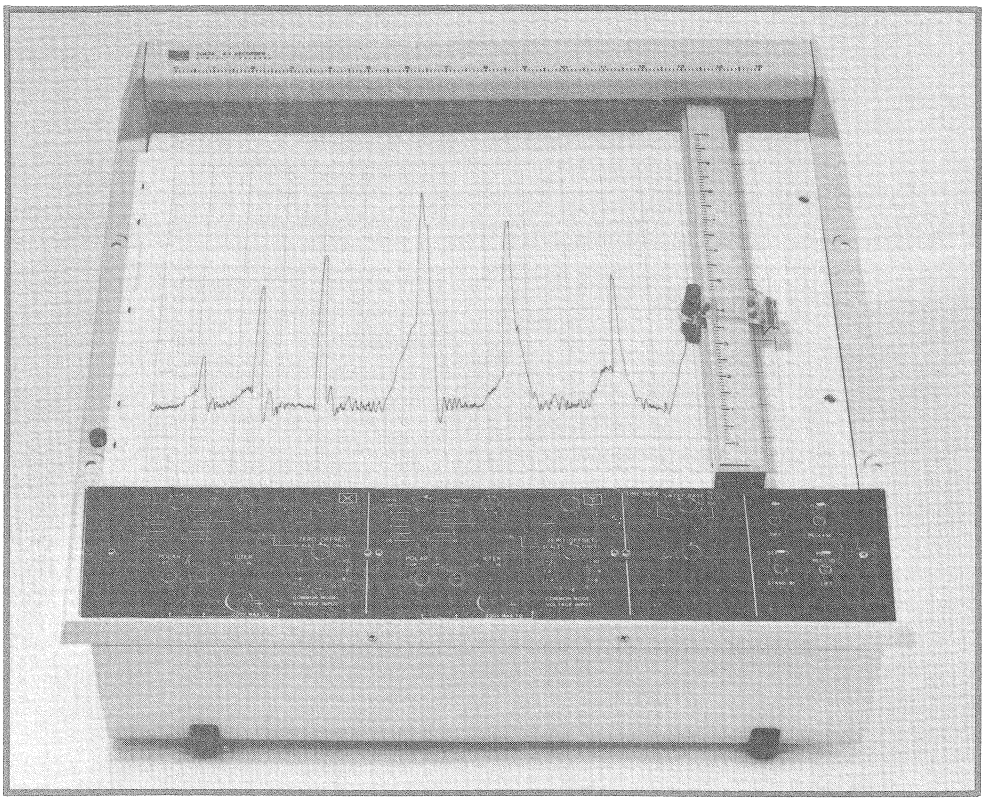


Fig. 1. *Model 7047A X-Y Recorder has maximum input sensitivity of 0.02 mV/cm (or 0.05 mV/in with English scaling) on both axes. Common-mode rejection is greater than 130 dB with 1-kΩ impedance in series with either input terminal (or both). Six sweep speeds, calibrated zero offset, polarity switches, and input filters are standard features.*

noise and drift required in a high-sensitivity recorder. Therefore a new amplifier was designed, using a chopper configuration (Fig. 2). It provides the necessary gain (1200 on the most sensitive range) without any significant noise or drift problems.

Also because of the new recorder's high sensitivity, greater common-mode rejection was required for the 7047A than for other 7040-Series recorders. Its specified common-mode rejection ratio (CMRR) of 130 dB is not only 20 dB greater than that of others in the ser-

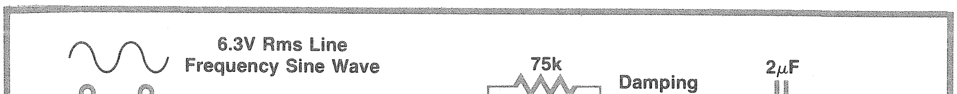


Fig. 2. *High sensitivity of the 7047A Recorder comes from its chopper stabilized input preamplifier. Shown here are a simplified schematic of the preamp and an equivalent circuit (inset) for the most sensitive range. The preamp acts as a dc operational amplifier, A_1.*

ies, but guaranteed as well for a 1-kΩ impedance in either the HI or the LO input lead. The input configuration is virtually unlimited, as shown in Fig. 3. Most recorders cannot operate on their most sensitive ranges with the HI terminal grounded and a 1-kΩ impedance at the LO terminal (Fig. 3b), because a noticeable line-frequency buzz appears at the pen tip. This problem is caused by the unbalance capacitance to ground at the secondary of the power transformer, which creates a noise voltage and causes a current to flow out of the common input or LO terminal, through the unbalance and/or source resistance and then to ground. The resulting voltage drop across the resistance appears as an input signal to the recorder. The high CMRR requirement plus the need to eliminate this noise pump-out current from the LO terminal led to the adoption of the "common driver" scheme. This circuit, which is described in detail later in this article, represents the biggest single contribution to the 7047A's ability to make the wide variety of measurements it does make.

The packaging that houses the somewhat sophisticated front-end electronics of the 7047A (input terminals, zero-check switch, filter switch, range switch, chopper preamp, and common driver) as well as various other functions (polarity switch, calibrated zero offset switch, zero potentiometer and vernier potentiometer) consists of two shielded, totally enclosed, virtually identical boxes, one for each axis (Fig. 4). A protruding cable with multipin connector connects each preamplifier to the appropriate servo electronics inside the mainframe.

The casting used to mount the boxes, the time-base switches, and power controls is the same as that used to mount the input terminals, various switches, and power controls for the older 7046A X-Y Recorder. Hence, no new castings were required for the 7047A, and except for that associated with the input boxes, no new tooling was required. Thus the development cost was kept relatively low, and most of the engineering effort could be directed toward the design of the chopper amplifier and the common driver circuit.

CMR and Noise Problems

Recorder amplifier circuits usually have a common input terminal, LO, and a high input terminal, HI. The input signal V_i and source resistances R_H and R_L are connected in series between these terminals, while a common-mode voltage V_{CM} is applied to both. See Fig. 5.

The secondary winding of the transformer in the power supply of the instrument usually has an unbalance capacitance to ground, C_{UB}. This creates a noise voltage V_N and causes a current I_N to flow out of the common input terminal, through the source resistance R_L and then to ground. The resulting voltage drop, $I_N R_L$, across the source resistance appears as an input signal to the circuit. Hence the true input signal is distorted.

Another problem arises when a common-mode voltage is applied as shown in Fig. 5. The common-mode voltage causes a current I_{CM} to flow through the leakage impedance* $R_{CG}||C_{CG}$ to ground and back to the common mode voltage source. This again causes a voltage drop across the source resistance R_L, which appears as an input to the circuit and distorts the true input.

Several methods have been used to reduce the ex-

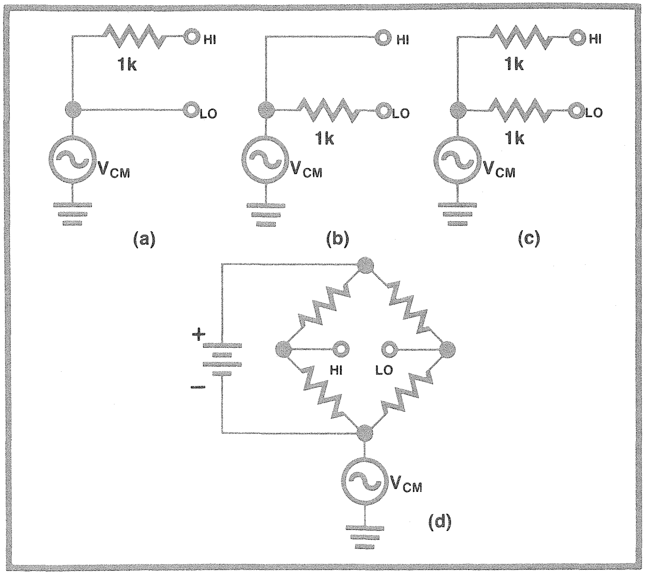


Fig. 3. *7047A meets its CMR specifications with any of these input configurations.*

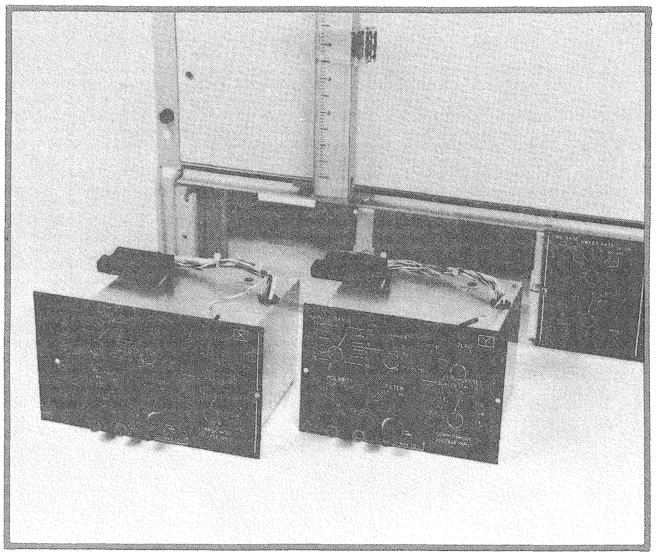


Fig. 4. *Two shielded boxes house the sophisticated 7047A front-end electronics. The boxes are removable for servicing.*

---

*C_{UB} is neglected here because $C_{UB} << C_{CG}$.

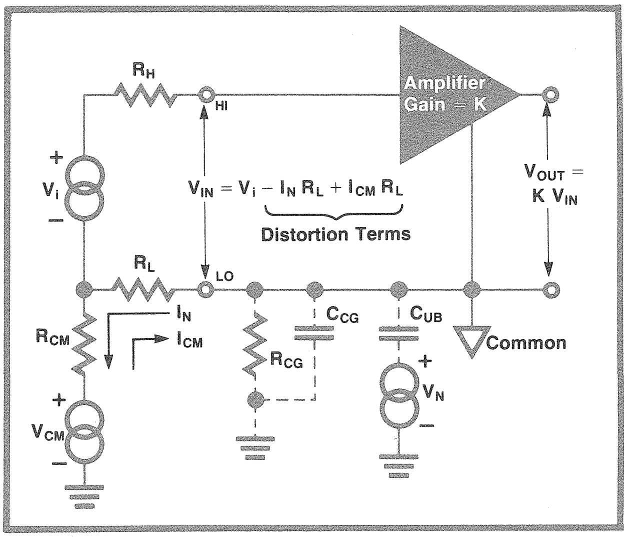


Fig. 5. *Conventional input amplifiers have problems because of pump-out and common-mode currents flowing through the source resistance, R_L.*

traneous currents superimposed on the input signal. One method is to enclose the secondary windings of the power transformer in a box shield. This eliminates most of the stray capacitance to ground. However, since there must be an opening for the transformer wires, the capacitance shield is not complete. This method can reduce the stray capacitance by an order of magnitude, but is very expensive.

Another possible solution is to prohibit any input resistance between ground and the common input terminal. This is unsatisfactory because in many measurement applications a source resistance cannot be avoided. Fig. 3d shows one such situation.

A third method applies when only one side of the input signal has a source resistance. It provides a polarity switch that reverses the polarity of the preamplifier output for the same polarity of input signal. By reversing the leads to the input terminals and using this polarity switch, the source resistance can always be placed in series with the HI input terminal. This removes the input resistance from the extraneous current path and greatly reduces the distortion of the input signal. This solution, however, is inadequate when there is an impedance in both input terminals simultaneously (e.g., bridge measurements), or when an impedance in series with one terminal has to be switched from one terminal to the other without adjustments.

Another method uses separate amplifiers for each input terminal followed by a differential amplifier to drive the output. The high impedance of the input amplifiers prevents any currents from flowing out of the input terminals. However, resistor matching problems limit the expected common-mode rejection to about 80 dB, far below the 130 dB desired for the 7047A. Another problem with this configuration is that the voltage drift of the two input amplifiers has an additive effect on the output voltage. Therefore, to achieve a given stability both amplifiers must have no more than half the drift of the original single preamplifier. Also, the total noise voltage is approximately 40% more than the original noise voltage.

A widely used method is guarding, or placing an electrical shield called a guard around the circuit to isolate the circuit from ground. This achieves two things. First, the internally generated noise current flowing out of the input terminals is greatly reduced. Second, high common-mode rejection, especially at line frequency, can be realized by driving the guard terminal at the common-mode voltage. This diverts the common-mode current around the source impedance in the LO terminal. Guarding has some drawbacks, such as additional cost, and the burden of driving a guard terminal properly.[1]

The Common Driver Amplifier

The common driver amplifier used in the 7047A permits measurements to be made with better than 130 dB common-mode rejection at dc and line frequency with a 1-kΩ resistance in either the HI or the LO input lead or both. This holds over the full Hewlett-Packard Class B environmental range (0° to 55°C, up to 95% relative humidity at 40°C). The effects of unbalance capacitance from the power transformers are virtually eliminated and a "guard" terminal does not have to be driven provided the common-mode voltage is less than the output voltage range of an operational amplifier in the circuit. Since roughly 90% of all measurements and recordings taken involve less than 10V, this voltage was chosen as a reasonable limiting value. When this voltage is exceeded, an auxiliary input terminal (COMMON MODE VOLTAGE INPUT) may be driven to circumvent the saturation limitation of the amplifier. The only shielding required is to isolate the HI and LO input terminals from chassis ground. This shield is connected to circuit common, which is now an inaccessible point inside the recorder.

How It Works

Fig. 6 is a simplified schematic diagram of the complete 7047A preamplifier, including the common driver amplifier. The noise generator V_N and unbalance capacitor C_{UB} represent the current source from the power transformer. The leakage impedance ($R_{CG} || C_{CG}$) is due to many factors; for example, the preamplifier shield, the servo amplifier, and the servo motor, all referenced to circuit common, are in close proximity to chassis ground. The input signal to be amplified is V_i and the source resistances in the

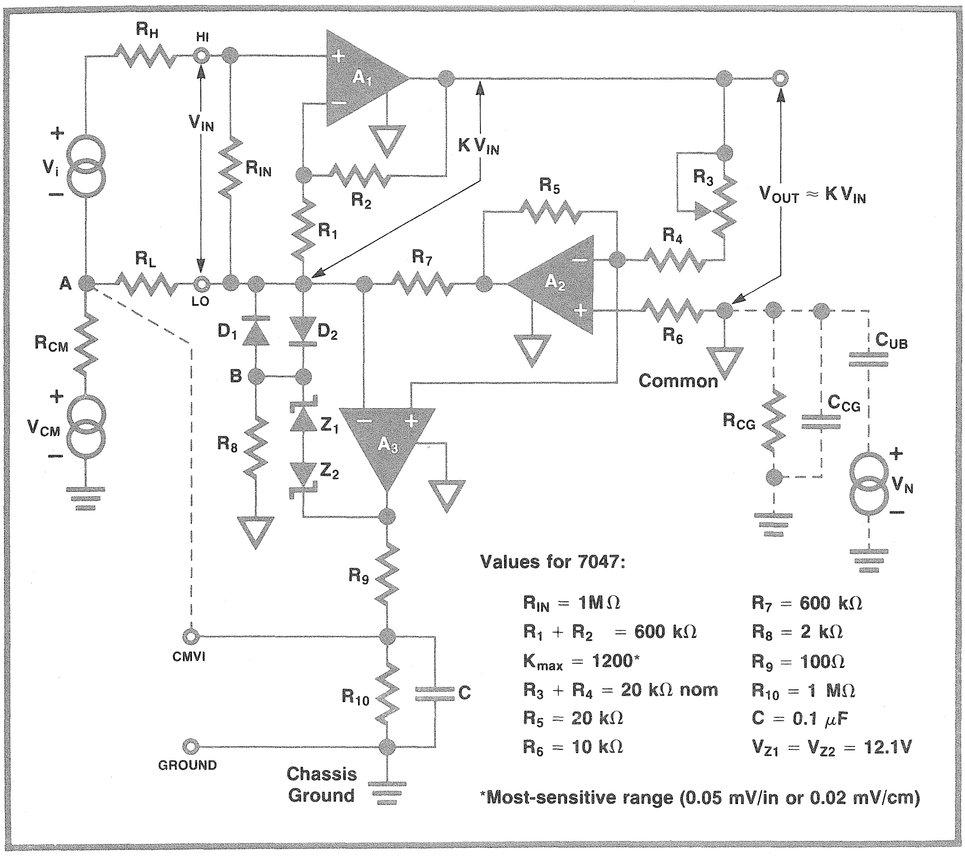


Fig. 6. *Simplified schematic of the 7047A input circuit. A_1 is the equivalent of the input preamplifier and A_3 is the common driver amplifier. The* COMMON MODE VOLTAGE INPUT (CMVI) *does not have to be connected unless the common-mode voltage exceeds ±10 V.*

HI and LO terminal leads are shown as R_H and R_L, respectively. The common-mode source V_{CM} is shown in series with its source resistance R_{CM}.

The main preamplifier is shown in Fig. 6 as operational amplifier A_1. Although it actually consists of a chopper, an ac amplifier, a demodulator, and an integrator, its overall effect is that of a dc operational amplifier. A_1 provides a non-inverting gain of

$$K = 1 + R_2/R_1$$

for the voltage V_{IN}, which appears across the input HI and LO terminals.

The operational amplifier A_2 inverts the output voltage V_{OUT} so that, ideally, all of the current flowing through R_2 and R_1 because of V_{OUT} has a return path through R_7 and into the output of A_2. The potentiometer R_3 allows a precise adjustment of this current sinking so virtually no current flows out of the LO terminal.

The operational amplifier A_3, the common driver amplifier, has its negative terminal connected to the LO input terminal. It serves to drive the circuit common to the same voltage as the voltage applied to the LO input terminal. (Note that all three operational amplifiers A_1, A_2, and A_3 have their power supplies, and hence their outputs, referenced to circuit common.)

Resistors R_9 and R_{10} and capacitor C are connected in a series-parallel combination between the output of A_3 and chassis ground to provide a shunting path to ground for the transformer noise coupled into the circuit common from the power supply. Thus chassis ground forms part of a negative feedback path for amplifier A_3 through the elements R_9, R_{10}, and C, the common mode voltage source V_{CM} and R_{CM}, and the impedance R_L.

The output of A_3 is also connected to its negative input terminal through an alternative feedback path consisting of the zener diodes Z_1 and Z_2, and the diodes D_1 and D_2. The point B is connected through resistor R_8 to circuit common. This diode-resistor network activates the alternative feedback path before amplifier A_3 reaches the saturation point. The auxiliary common-mode voltage input terminal (CMVI) is connected to the output of A_3 through resistor R_9 to provide an alternate reference voltage (instead of chassis ground) for the output of A_3 when the common-mode voltage exceeds the range of A_3.

In normal operation, the common-mode voltage is less than the voltage range of A_3 and the CMVI terminal is not externally connected. The voltage V_{IN} is amplified by A_1 and its feedback resistors R_1 and R_2. The voltage V_{OUT} at the output of A_1, which is referenced to circuit common, drives the unity-gain amplifier A_2, which inverts this voltage. Because R_7 equals

R_1+R_2, virtually all of the current through R_1 and R_2 is drawn through resistor R_7, and not out of the LO terminal.

Amplifier A_3 serves as a voltage follower and keeps the voltage potential on circuit common equal to the voltage on the LO input terminal. The result of this is that the currents through R_L resulting from V_{CM} and V_N are greatly reduced compared to the case shown in Fig. 5. Consequently, the CMRR with a resistance in the LO terminal is greatly improved and the pump-out noise current is virtually eliminated (see Appendix I).

The current through R_H because of V_{CM} is also considerably reduced because circuit common is moving with respect to ground along with this common-mode voltage. Therefore the CMRR with a resistance unbalance in the HI terminal is improved significantly (for the 7047A, at least an order of magnitude over the earlier 7045A, which is conventionally floated).

The main limitations on CMRR are imperfect shielding between the HI and LO terminals and chassis ground, and finite gain in amplifier A_3. The input imperfections in the operational amplifiers (offset voltages and bias and offset currents) are not serious with appropriate design and component selection (see Appendix II).

When V_{CM} exceeds the range of A_3 the alternative diode-resistor feedback path will be activated, unless a voltage within ±10V of V_{CM} is applied at the auxiliary CMVI terminal. For the straightforward situation of Fig. 6, the best connection is shown by the dashed line to point A. In this case A_3 need only supply the voltage difference between the common-mode voltage applied through the LO input terminal and the voltage applied to the CMVI terminal.

If no signal is applied to the CMVI terminal under the above conditions and the alternative feedback path is activated, the circuit still functions but it loses its ability to shunt to ground the current generated by the noise voltage V_N, and this flows out of the LO input terminal as in Fig. 5. Also, the CMRR is reduced, especially for the case of the 1-kΩ resistance in series with the LO terminal.

The alternative feedback path for A_3 is especially necessary to keep it from saturating when the signal source V_i is floating (e.g., a battery) and there is no common-mode voltage source. The absence of V_{CM} (with $R_{CM} = \infty$) disrupts the normal feedback path through chassis ground. Without a negative feedback path amplifier A_3 would become an open-loop amplifier and would lose its ability to reduce the voltage difference between the LO terminal and circuit common to near zero. However, before A_3 reaches its saturation point, its output voltage reaches the turn-on voltage of zener diodes Z_1 and Z_2. The output current of A_3 produces a voltage difference across R_8, which in turn produces a voltage difference across the signal diodes D_1 and D_2 sufficient to forward bias one of them, depending on the polarity of the biasing voltage. Thus the alternative negative feedback path is activated to keep amplifier A_3 from saturating.

Other 7047A Features

The front-panel POLARITY switches, one for each axis, determine whether positive signals drive the recorder right-to-left or left-to-right on the X-axis, and down-to-up or up-to-down on the Y-axis. Thus the user can drive the recorder in a predetermined direction regardless of the polarity of the input signal and without having to exchange input leads. If he cannot drive the CMVI terminal with a common-mode voltage exceeding 10V, he can use the POLARITY switch along with exchanging the input leads to maximize CMR, provided there is no resistance in series with the LO terminal. The CMR performance will then approximate that of the 7045A Recorder (i.e., 110 dB at dc and 90 dB at line frequency for a 1-kΩ resistance in series with the HI terminal).

The front-panel FILTER switches, one for each axis, provide more than 20 dB additional normal-mode rejection at line frequency when the filter is IN. Some degradation of rise time occurs.

Reference

1. "Floating Measurements and Guarding," Application Note 123, Hewlett-Packard Co., 1970.

APPENDIX I

Analytical Expressions For Common-Mode Rejection Ratio and Noise Pump-Out Current

The common driver amplifier, A_3 in Fig. 6, is shown in the diagram below with gain A. Also shown are the sources of the unwanted current I_L, the common-mode voltage V_{CM}, and V'_N, which is the Thévenin equivalent of the noise source V_N in Fig. 6, that is,

$$V'_N = \frac{j\omega C_{UB} Z_{CG}}{1 + j\omega C_{UB} Z_{CG}} V_N \tag{1}$$

where

$$Z_{CG} = \frac{R_{CG}}{1 + j\omega C_{CG} R_{CG}} \tag{2}$$

also from Fig. 6. The Thévenin equivalent impedance is

$$Z'_{CG} = \frac{R_{CG}}{1 + j\omega C'_{CG} R_{CG}} \tag{3}$$

where

$$C'_{CG} = C_{CG} + C_{UB} \tag{4}$$

The output impedance Z_o is the parallel combination of R_o and C_o, which are, respectively, R_{10} and C in Fig. 6. The input resistance R_i is equivalent to the series combination of R_1 and R_2 in parallel with R_7. All components obviously insignificant to the analysis are omitted.

We can now write the loop equations

$$V_{CM} + A(V_C - V_L) - I_L(R_{CM} + R_i + Z_o) - I_N Z_o = 0 \tag{5}$$

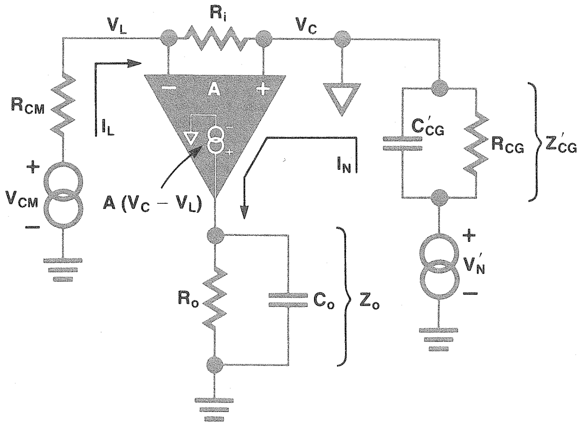
and

$$V'_N - I_N(Z'_{CG} + Z_o) + A(V_C - V_L) - I_L Z_o = 0 \tag{6}$$

Since

$$V_C - V_L = -I_L R_i \tag{7}$$

equations (5) and (6) become



$$V_{CM} - I_L[R_{CM} + (1 + A)R_i + Z_o] - I_N Z_o = 0 \tag{8}$$

and

$$V'_N - I_N(Z'_{CG} + Z_o) - I_L(Z_o + AR_i) = 0 \tag{9}$$

Solving for I_N in equation (9) we have

$$I_N = \frac{V'_N - I_L(Z_o + AR_i)}{Z'_{CG} + Z_o} \tag{10}$$

Substituting (10) into (8) we obtain

$$I_L = \frac{V_{CM} - V'_N \dfrac{Z_o}{Z'_{CG} + Z_o}}{R_{CM} + Z_o + (1 + A)R_i - \dfrac{Z_o(Z_o + AR_i)}{Z'_{CG} + Z_o}} \tag{11}$$

Under all normal operating conditions it can be assumed that

$$|Z'_{CG}| >> |Z_o| \tag{12}$$

$$|A| >> 1 \tag{13}$$

$$|AR_i| >> |R_{CM} + Z_o| \tag{14}$$

Hence

$$I_L \approx \frac{V_{CM}}{AR_i} - \frac{V'_N Z_o}{AR_i\, Z'_{CG}} \tag{15}$$

Since from (1), (2), (3), and (4)

$$\frac{V'_N}{Z'_{CG}} = j\omega C_{UB} V_N \tag{16}$$

we have

$$I_L \approx \frac{V_{CM}}{AR_i} - j\omega C_{UB} V_N \frac{Z_o}{AR_i} \tag{17}$$

The first term in equation (17) represents the current resulting from the common-mode voltage V_{CM}. Therefore, for a resistance R_L in series with the LO terminal,

$$\text{CMRR} \approx \frac{V_{CM}}{\dfrac{V_{CM} R_L}{|A| R_i}} = \frac{|A| R_i}{R_L} \tag{18}$$

For $R_L = 1$ kΩ and $R_i = 300$ kΩ,

$$\text{CMRR} \approx 300|A| \tag{19}$$

Using design values from the 7047A we get the following approximate values for CMRR:

2.0×10^9 or 186 dB, dc nominal
1.6×10^8 or 164 dB, dc minimum
6.0×10^7 or 155 dB, 60 Hz nominal
4.7×10^6 or 133 dB, 60 Hz minimum.

These values agree closely with measured values for the 7047A.

The second term in equation (17) represents the current resulting from the power transformer noise current. This is reduced by a factor of AR_i/Z_o, which for the 7047A is nominally 2×10^6, absolute value. With a 10-kΩ source resistance and the HI terminal connected to ground, this source of pump-out current was not measurable on the 7047A.

APPENDIX II
Effects of Amplifier Offsets

The common driver amplifier A_3 from Fig. 6 is shown in the diagram below with its associated resistors and an external source resistance of R_L. The HI terminal is grounded, since this represents a more significant case than when the LO terminal is grounded. The offset voltage of A_3 is shown as a variable battery v_{03} (an internal potentiometer is used to adjust its equivalent value). The bias and offset currents of A_3 may be neglected because a low-leakage dual-input FET is used. The sum of the offset voltage and the product of offset current and drift compensation resistance R_6 for amplifier A_2 in Fig. 6 is shown as the fixed battery v_{02}. v_{01} is the equivalent offset referred to the input of the chopper amplifier A_1. V_0 is the sum of the series batteries v_{02} and v_{03}, and $-V_0$ is the voltage with respect to circuit common at the negative input of A_3. V_1 and V_2 are the voltages with respect to circuit common at the outputs of A_1 and A_2, respectively (see Fig. 6). Since a dc analysis is being done, all capacitors are ignored.

Assuming A_3 to now be an ideal operational amplifier (i.e., infinite gain, infinite input impedance, and zero offset), we can use superposition to write

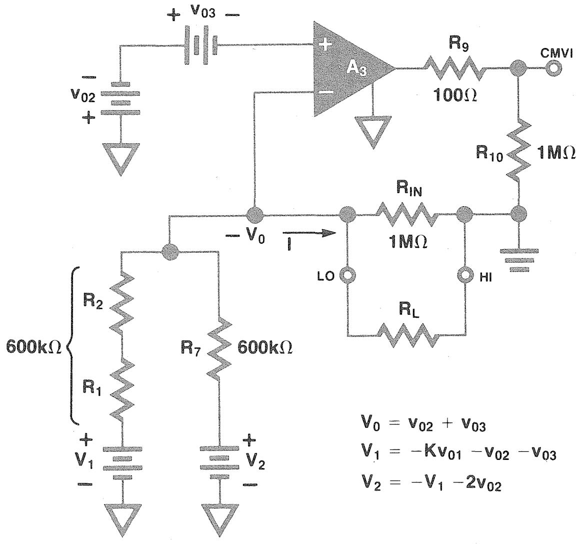
$$\begin{aligned} I &= V_0/300k\Omega + V_1/600k\Omega + V_2/600k\Omega \\ &= V_0/300k\Omega + V_1/600k\Omega - V_1/600k\Omega - v_{02}/300k\Omega \\ &= V_0/300k\Omega - v_{02}/300k\Omega \\ &= (v_{02} + v_{03})/300k\Omega - v_{02}/300k\Omega \\ &= v_{03}/300k\Omega \end{aligned}$$

Hence, by adjusting only the offset voltage v_{03} of the common driver amplifier A_3 to zero, the pump-out current I due to offsets can be eliminated. The effect of drift in amplifier A_2 on pump-out current I is eliminated by the algebraic cancellation of the terms containing v_{02}. This is the result of connecting the + terminal of amplifier A_3 to the − terminal of amplifier A_2 (see Fig. 6), a connection whose advantages are not obvious at first glance.

The offset voltage at the output of the preamplifier is given by

$$V_1 = -Kv_{01} - v_{02} - v_{03}$$

For the 7047A design the Kv_{01} term is only significant on the most sensitive ranges when K is large. Hence, only $v_{02} + v_{03}$ is compensated by adding a series equivalent low-impedance fixed voltage on a less-sensitive range. Kv_{01}, which comes into play only on the most sensitive ranges, is tolerated, and typically is on the order of a few millivolts or an offset of about 0.1 cm at the pen tip on the 0.02 mV/cm range (the sensitivity at the output of the preamplifier is 24 mV/cm on all ranges).



HEWLETT PACKARD

5952-2861
APPLICATION NOTE 214-4

JULY 1977

PRINTED IN U.S.A.