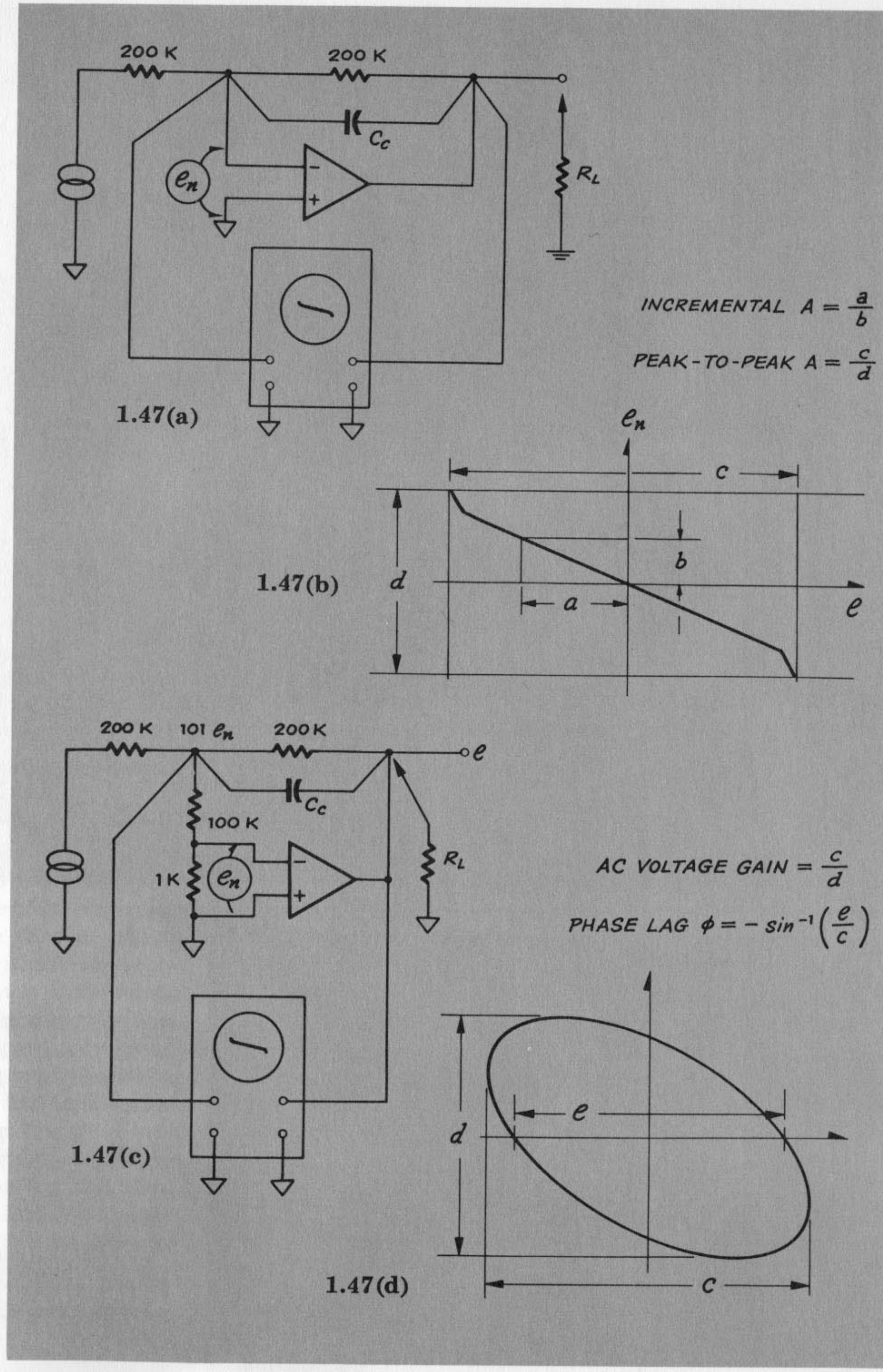
I.47
I.17
II.1
II.3

**I.47 MEASURING OPEN-LOOP GAIN.** In this and the four modules that follow, we shall be discussing means of measuring the performance of an Operational Amplifier—not necessarily *in situ*, but sometimes in special test circuits designed to render such tests practical and accurate, and hence easy and meaningful. Such a special test circuit, designed to measure the open-loop gain and phase characteristics of an amplifier over a range of frequencies, is shown to the right in figure (a). It will be recognized as a simple unity-gain inverter, with the stabilizing capacitor, $C_c$, that we have now learned to add almost automatically to such circuits. Having established the standardized operating conditions—power supply voltage, temperature, etc., we are now prepared to feed a signal into the inverter and examine the Lissajous pattern produced by feeding the summing-point signal into the vertical channel of an oscilloscope and feeding the output voltage into the horizontal channel. An external load resistor may be connected or not, as desired.

We can write the expression for the gain of the amplifier as:

$$\text{gain} = A = \left|\frac{e}{e_n}\right| \tag{1-24}$$

so that either the incremental or the peak gain can be read from the oscilloscope as shown in figure (b). If amplifier gain is exceptionally high, or if an oscilloscope with adequate vertical sensitivity is not available, the amplifier can be used to "preamplify its own voltage error," as shown in (c), in which the vertical sensitivity of the oscilloscope is made effectively 101 times as great as its nominal value. Since this high gain applies to dc signals as well as ac, the voltage offset adjustment should be made carefully, to avoid saturation of the CRO. So long as the input impedance of the amplifier is much higher than 1 kΩ, this technique is valid; at high frequencies, however, circuit (c) is neither necessary nor recommended, and circuit (a) should be used. As frequency is increased beyond very low frequencies, the oscilloscope display will gradually become elliptical because of amplifier phase shift (see I.41). The AC voltage gain magnitude and phase for any particular frequency can be read from the oscilloscope as shown in figure (d). At very high frequencies, rate limiting will show up as distortion (see I.17) and the output-signal test amplitude must be reduced in order to make meaningful measurements of small-signal (linear) response. The input capacitances of the oscilloscope, and the feedback capacitance, $C_c$, will not affect the accuracy of the measurements, but the high frequency amplitude response and the relative phase shifts of the oscilloscope amplifiers over the entire frequency range should be verified as acceptable.



1.47(a)

1.47(b)

1.47(c)

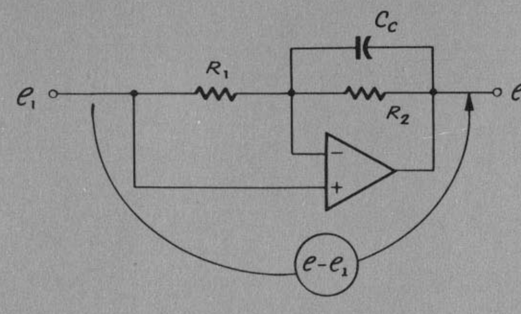
1.47(d)

I.48
I.16

**I.48 MEASURING COMMON-MODE REJECTION.** In this circuit it is best to make the ratio $R_2/R_1$ some simple integral value, about one tenth to one hundredth of the *CMRR* one expects to find, using moderately low resistances to set up the ratio. The value $(e - e_1)$ is best measured on an instrument with a true differential input, such as a differential DVM, a floating CRO, or a VOM. The *CMRR* is defined as inversely proportional to the magnitude of $(e - e_1)$, for a fixed common-mode swing. This circuit is especially well suited to amplifiers having very high no-load voltage gain . . . much higher than the expected *CMRR*. (See I.47 for measurement of *A*.)

$$(e - e_1) = \left(\frac{R_2}{R_1} + 1\right)\left(\frac{e_1}{CMRR} + \frac{e}{A}\right) \qquad (1\text{-}25)$$

$$CMRR \cong \left(\frac{e_1}{e - e_1}\right)\left(\frac{R_2}{R_1} + 1\right) \qquad (1\text{-}26)$$

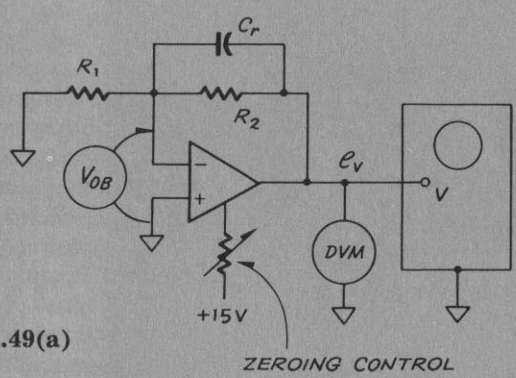



1.48

I.49
I.7
I.8
I.11
I.12
I.14
I.15
I.18
to
I.23

**I.49 MEASURING "DC" OFFSETS.** Circuit (a) may be used to determine the voltage offset of an amplifier. For good sensitivity it is preferable to make $R_2$ at least 100 times as high as $R_1$ so that the oscilloscope or digital voltmeter used to read the output will be able to operate on a convenient range. On the other hand, the greater the circuit-gain, the lower the loop-gain, which may introduce a (definitely second order) finite gain error factor. $C_r$ is used to limit the bandwidth to low frequencies, so as to prevent the masking of voltage offset by noise. The procedure is simple: obtain the best zero adjustment possible, if one is present, and read the output voltage. The equation shown may then be solved to relate $e_V$ to $V_{OB}$. $R_1$ and $R_2$ should be kept at the lowest feasible values, to prevent current offset from superimposing its effect on the voltage offset measurements. 100 Ω and 10 kΩ or 100 kΩ are suitable values, for example.

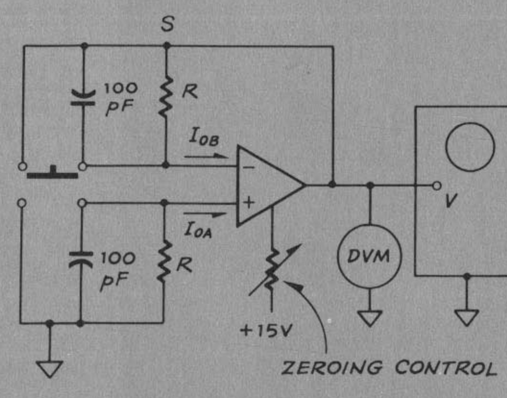
Circuit (b) provides a means of measuring the input current to each terminal, independently. If the voltage offset measurement has just been made, the zeroing control should be left in that position, unless it is intended that the voltage offset be adjusted to compensate for current offset. Output measurements are then made for both positions of the switch, and the two results translated into equivalent currents, as shown on the diagram. Note that it is possible to obtain increased sensitivity for this measurement, if necessary, when low currents are being measured by attenuating the feedback to points in the same manner as was done in (a). Note also that if the switch can simultaneously close both circuits, the amplifier's voltage offset can be zeroed. If both circuits are simultaneously opened, the difference of the input currents can be measured.




1.49(a)

VOLTAGE OFFSET

$$V_{OB} = \frac{e_V}{1 + \frac{R_2}{R_1}}$$




1.49(b)

INPUT CURRENT

$$I_{OB} = \frac{e_V}{R}$$

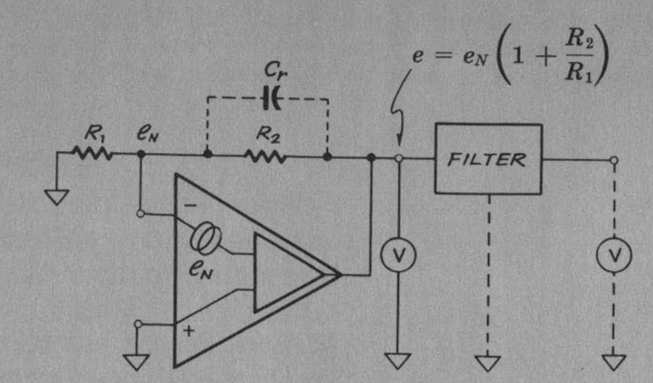
$$-I_{OA} = \frac{e_V}{R}$$

$$10^6 < R < 10^8$$

| MEASURE | SWITCH |
|---|---|
| $I_{OA}$ | UP |
| $I_{OB}$ | DOWN |

## I.50 MEASURING VOLTAGE NOISE AND FLICKER.

This circuit may be used to measure the noise and flicker of an amplifier, provided that the following conditions are imposed upon its use: (1) That $R_1$ be sufficiently low so that current noise components of the amplifier and thermal noise generated in it may be neglected; (2) That some means (like $C_r$) be employed to limit the measurement bandwidth to that over which the amplifier will ultimately be used . . . or to that for which the noise rating that is being checked is specified; (3) That the measuring instrument ($V$) whatever it be—from an RMS voltmeter to a peak-to-peak device, such as a CRO—have adequate (but not too great) bandwidth to perform the measurement, and; (4) That every possible precaution be taken to insure good grounding and shielding, and minimum stray coupling of any kind. If several noise bandwidths are to be examined, or if it is desired to limit the noise bandwidth in a more exact fashion than by the gradual roll-off effect of $C_r$ it is probably better to interpose the filter shown on the drawing between the output of the amplifier and the measured instrument. This filter may be of the adjustable low-pass/band-pass/high-pass design commonly used in noise and vibration analysis (and it can of course be an active one assembled with operational amplifiers.) (See III.22–28.)




1.50

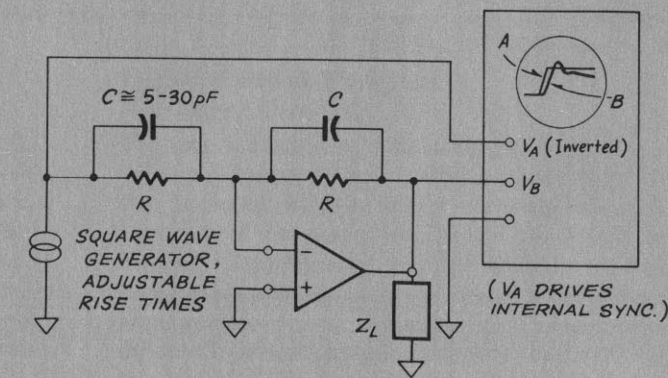
I.50
I.7
I.9
I.10
II.22
to
II.28

## I.51 MEASURING TRANSIENT RESPONSE.

There is no single circuit that will test the transient response of an amplifier under all possible ultimate-use conditions. (It may well be possible to set up the ultimate-use circuit, however, and run a test of the type we are about to describe, and this possibility should not be over-looked.) The circuit shown here will, however, provide enough information to permit a meaningful prediction of the transient behavior of the amplifier in most circuit configurations. The amplifier is connected as an inverter, and is driven from a pulse or square wave generator having adjustable rise and fall times, and a good, distortion-free output attenuator. $R$ is set to a value comparable to the net input circuit resistance that is anticipated, and the amplifier is loaded with an impedance as close to the ultimate-use circuit as possible. A dual-channel CRO having much greater bandwidth than the amplifier under test is used to monitor both the input and the output signals.

Let us refresh our understanding of the open-loop gain-versus-frequency characteristics of the amplifier by referring back to I.17. If non-linearities do not exist, the transient response of an amplifier may be predicted exactly from the gain and phase characteristics. The relationship between the fastest rise time that the amplifier will pass without distortion and the high frequency break-point in the gain characteristics is simple and easily calculated. Unfortunately, there *are* both propagation and magnitude non-linearities in any Operational Amplifier, so that the large-signal response characteristics may bear very little relationship to those predicted by the small-signal curves. In particular, the inability of the circuit to "slew" at a rate demanded by large-signal, fast output transients causes what is known as "rate-limiting."

The test procedure is as follows: (1) Starting with the smallest signal that may be conveniently viewed on the $V_B$ channel of the CRO, superimpose the starting points of both $V_B$ and $V_A$ (with $V_A$ "inverted" by the CRO controls) and determine the fastest rise time at which they may be made to coincide within reasonable limits. This rise time is a measure of the small signal transient response; (2) Increase the amplitude of the input, decreasing the sensitivity of both channels of the CRO proportionately, until rate limiting is evident. A further increase in amplitude should cause even further divergence; (3) If the maximum output amplitude is known, one may set it up on $V_A$ and then increase the rise time until $V_A$ and $V_B$ appear to be identical. That rise time is a measure of the maximum slewing rate of the amplifier for that amplitude of output signal.




1.51

I.51
I.17
I.18
I.40
to
I.44