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A New Clip-On Oscilloscope/Voltmeter Probe For 25∿ - 20 MC Current Measurements

TWO years ago -hp- introduced a dc milliammeter* that used a clip-on probe to couple to the conductor that carried the current to be measured. Because it merely clipped around the conductor and thus avoided the need for breaking the circuit, this probe changed the measurement of current from an inconvenient and sometimes difficult measurement to an easy measurement. Later, this dc instrument was followed by another clip-on probe type instrument** which measured ac current in combination with the -hp- wide-band oscilloscope.

The popularity of these clip-on probes for current measurements has now led to the development of a new and even more flexible clip-on probe—one that measures ac current in combination with any of a number of -hp- oscilloscopes and voltmeters. This new probe measures current over the full range of the frequencies most commonly used in typical work—25∿ to 20 megacycles—and over an amplitude range from below ½ milliampere up to 1 ampere rms. It can be used equally well with pulse and other complex waveforms as with sine waves. Further, because it has the outstanding property of reflecting virtually no loading into the circuit being measured, the probe enables current to be measured with ease in cases that previously would have been considered impractically difficult. Such cases include measuring the current in circuits at resonance, in ground buses, in solid-state rectifiers at turn-on, etc.

The probe operates with an accompanying small amplifier (Fig. 3) to convert the ac current being measured to a proportional voltage. This voltage can then be measured with a suitable oscilloscope or voltmeter. The current-to-voltage conversion factor is 1 millivolt/milliampere so that a 1:1 correspondence will exist between the current measured and the volt-

*Arndt Bergh, Charles O. Forge, and George S. Kan, "A Clip-On DC Milliammeter for Measuring Tube and Transistor Circuit Currents," Hewlett-Packard Journal, Volume 9, No. 10-11, June-July, 1958.

**Robert R. Wilke, "A Clip-On Oscilloscope Probe for Measuring and Viewing Current Waveforms," Hewlett-Packard Journal, Volume 10, No. 9-10, May-June, 1959.

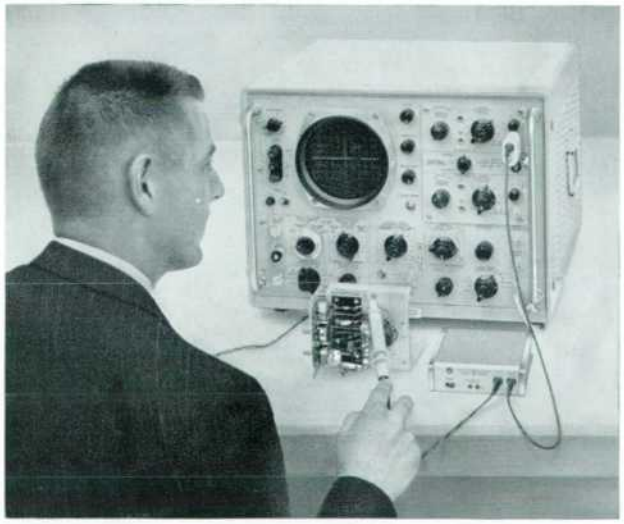

Fig. 1. *New -hp- 456A AC Current Probe (in foreground) can be used with oscilloscopes and voltmeters to measure ac currents over a wide amplitude and frequency range. Probe enables current to be measured in formerly-difficult circuits such as in ground wires.*

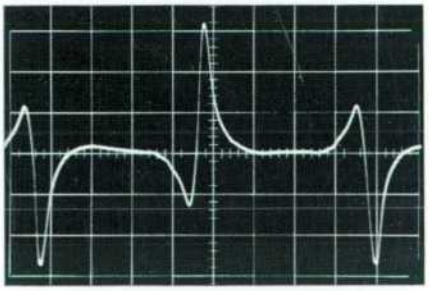

Fig. 2. *Oscillogram made using new probe to measure hum current in ground wire interconnecting two equipments in a typical test bench setup like that in Fig. 5. Vertical sensitivity is 20 ma/cm. Such large ground-wire currents can apply large undesired hum voltages across input of driven equipments.*

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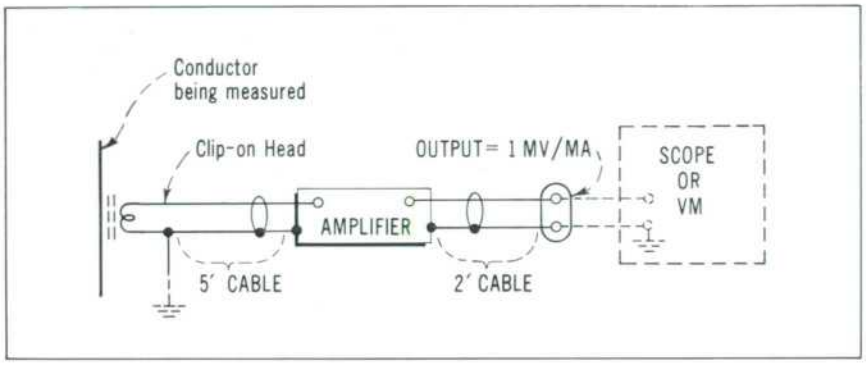

Fig. 3. *New current probe consists of clip-on head and transistorized amplifier which can be used with oscilloscope or ac voltmeter.*

age applied to the oscilloscope or voltmeter. Current readings can thus be taken directly from the voltage calibrations on the oscilloscope or voltmeter. Table I presents a list of -*hp*- instruments with which the probe can be used.

LOW CIRCUIT LOADING

Electrically, the probe consists of the secondary winding of a wide-range current transformer for which the conductor being measured becomes a single-turn primary. To accommodate the clip-on action, the secondary is wound on a split core which opens and closes with the probe jaws. The whole assembly is magnetically and electrostatically shielded from external fields and electrostatically shielded from the primary conductor.

An extremely valuable feature of such a probe is that it can be designed to reflect very little impedance into the circuit being measured. For the new probe the loading reflected into the measured circuit is less than 50 milliohms in series with 0.05 microhenry. Because this loading is so small, currents can be measured in the formerly-difficult cases noted earlier such as in ground buses.

The measurement of ground-wire currents, in fact, is probably considerably more valuable than is generally realized. At power line frequencies currents of surprising magnitude can flow in the leads that interconnect the chassis of several equipments. This is true not only of unshielded ground wires where stray magnetic fields may induce the currents, but can also occur from a number of other causes. Fig. 5, for example, illustrates how the use of 3-prong type power cable plugs will transfer a significant portion of a voltage drop in a ground bus to the input terminals of an equipment. The current measured in a setup like that in Fig. 5 is shown in Fig. 2 (front page). This current, with a peak amplitude of more than 50 ma, could easily cause a hum signal of 0.1 millivolt to be impressed at the input terminals of an equipment connected in the setup of Fig. 5.

The source of currents like that in Fig. 2 can often be traced to other equipments and devices connected to the power line. Where such equipments have capacity, or sometimes leakage, to their frame or chassis and where the frame or chassis is grounded to the bus to which the third prong on a power cable connects, these large and troublesome currents may be encountered.

TABLE I

-*hp*- INSTRUMENTS FOR USE WITH 456A AC CURRENT PROBE

-*hp*- Voltmeters	-*hp*- Oscilloscopes
400D	120A
400H	122A
400L	130B
403A	150A
	160B
Wave Analyzer 302A	170A

Fig. 4. *Probe head clip-on jaws are operated by flanges on probe body.*

PROBE FREQUENCY RESPONSE

The probe has a wide and constant frequency response (Fig. 6) that permits it to be used with a variety of voltmeters and oscilloscopes. With most of these instruments, the probe response is sufficient that current can be measured up to the high-frequency limit of the companion instrument without consideration of the probe's frequency characteristics. This is the case, for example, for all of the instruments listed in Table 1 except the 170A 30-mc oscilloscope. It should also be noted that with most of these instruments the overall low frequency response of the combination will be primarily that of the probe.

In the general case the high-frequency response is somewhat affected by the load capacity into which the probe amplifier is operated. Since the widest frequency-range instrument with which the probe is likely to be used is the wide band type of oscilloscope, the probe amplifier has been designed to achieve widest frequency response when operated into the load capacity typical of this type of oscilloscope (approx. 25 mmf). This arrangement automatically gives the probe and amplifier the optimum bandwidth for the companion instru-

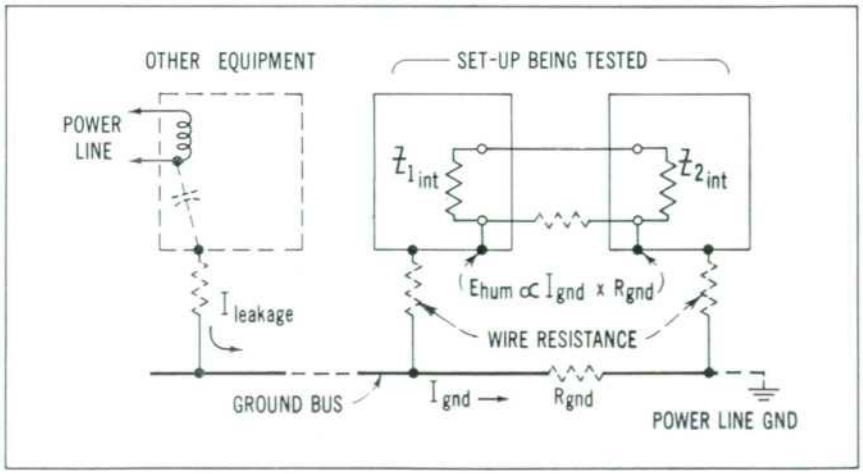

Fig. 5. *Diagram illustrating how capacity from power circuit to chassis in equipment connected to power line ground bus produces hum at terminals of other equipments grounded to same bus. Oscillogram on front page is of hum current in ground lead between units being tested in set-up like this as measured with new probe.*

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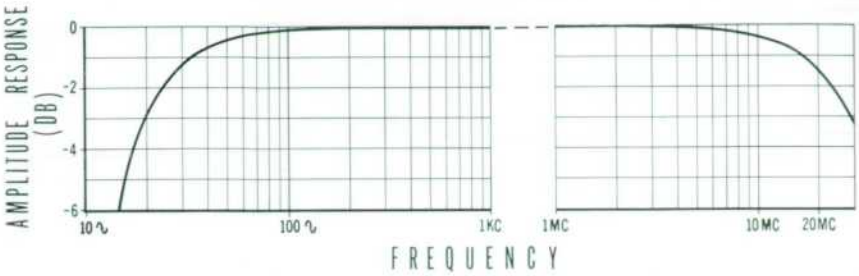


Fig. 6. *Typical frequency response of -hp- Model 456A Current Probe when operated into rated load.*

ment with which it is used. For cases where the probe is to be used with other equipment, the curve of Fig. 7 can be used to determine the resulting high frequency response.

Figs. 6 and 7 both assume that the resistive portion of the load into which the probe amplifier is operated is 100 or more kilohms. Smaller load resistances can be used, however, with some loss in accuracy.

Amplitude-wise, the probe calibration is adjusted at 1 kc to be accurate within ±1%. The frequency response is then sufficiently constant that overall accuracy remains within an additional ±1% from a few hundred cycles to above a megacycle.

FAST PULSE RESPONSE

The wide bandwidth of the probe head and its amplifier gives the overall instrument a fast rise time of approximately 20 millimicroseconds and an otherwise accurate fast pulse response, as demonstrated by the oscillogram of Fig. 8. The rise time illustrated in Fig. 8 approximates that of the faster wide band oscilloscopes and thus makes the probe very valuable in fast circuit applications. This value applies not only to the measurement of current but in some cases to the investigation of voltage, as discussed below.

Where speed or rise time of the measuring equipment is a factor, it is interesting to note that the probe may give faster response time when used with a fast oscilloscope than is obtained when the oscilloscope is used in the usual way for voltage measurements. One common situation where this is true is where a measurement is to be made of the voltage rise time across a plate load resistor of some hundreds or more ohms. In such a case the capacity of some 10 to 30 mmf added by the oscilloscope when making a voltage measurement will increase the time constant of the resultant RC combination and slow the speed of measurement. A plate load resistor of 1,000 ohms, for example, when shunted by 20 mmf has a 10-90% rise time of 44 millimicroseconds.

The new current probe, on the other hand, can be used in this same situation by clipping to the "cold" end of a plate load resistor where the probe adds no effective capacity. In this case the probe rise time of 20 millimicroseconds, although it may be modified somewhat by the rise time of the oscilloscope used, may still be significantly faster than the rise time obtained in a voltage measurement.

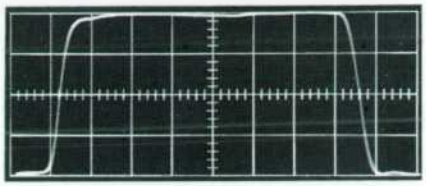
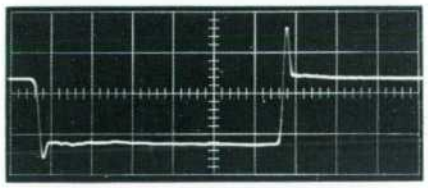


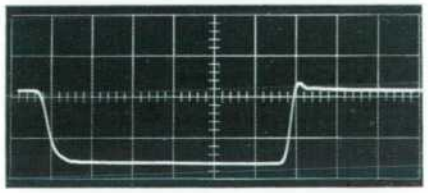
Fig. 8. *Fast pulse response of current probe as displayed by -hp- 170A wide-band oscilloscope. Sweep time is 0.05 μsec/cm, showing probe 10-90% rise time of 0.02 μsec.*

Another case where the probe often proves superior to the voltage-across-resistance method of measuring current is demonstrated by the oscillograms in Fig. 9. These oscillograms show measurements made of the current in the emitter circuit of a pulsed transistor. The upper oscillogram was made by inserting a 1-ohm resistance in the emitter circuit and measuring the resulting voltage drop with the oscilloscope. The second oscillogram was made with the 1-ohm resistance removed from the circuit and with the probe connected to give the current reading directly. In both cases the current scale is the same.

If these two oscillograms are compared, it will be seen that the voltage-derived measurement shows considerably more overshoot as well as a current value about 10% lower than in the case where the current value was measured with the probe. The overshoot arises from the voltage drop occurring across the inductance of about ¾" of lead on the resistor. The 10% change in current occurs from the effect of the 1-ohm resistor in the emitter circuit.



(a)



(b)

Fig. 9. *Oscillograms contrasting pulse waveforms obtained in grounded-emitter transistor using two measurement techniques. Upper trace shows voltage waveform across 1-ohm resistor with large overshoot produced by lead inductance. Lower trace shows more accurate current waveform obtained using new probe.*

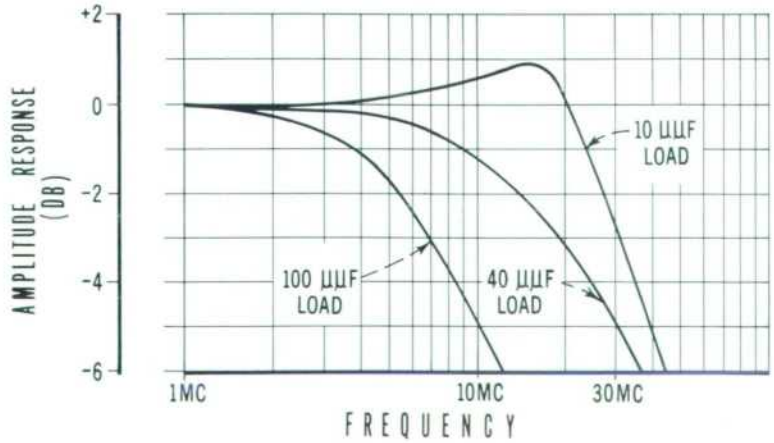


Fig. 7. *Typical high frequency response of probe when used with various load capacities. Probe has been designed so that optimum frequency response occurs with 25 mmf capacities typical of wide-band oscilloscopes.*

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Fig. 10. *Close-up view of -hp- 456A AC Current Probe.*

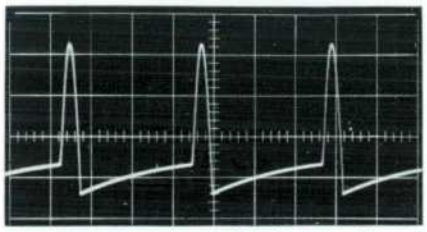

Fig. 11. *Current pulses in one leg of bridge type power rectifier circuit as measured with new probe.*

LOW FREQUENCY RESPONSE

The low frequency amplitude response, as indicated in Fig. 6, is such that the probe can be used to measure currents down to virtually the lowest audio frequencies, since the lower 3-db point is rated at 25 cps. This extended low frequency response has the additional value that it enables the probe to measure relatively long pulses with little resultant sag. In measuring rectifier currents at power line frequencies, however, there will be a moderate waveform distortion due to phase shift at 60 or 120 cps. This distortion, though, does not prevent determination of the peak current or conduction angle. Fig. 11 illustrates this point by showing the waveform obtained when a measurement was made with the probe of the current in one rectifier of a bridge rectifier circuit using solid-state rectifiers. This is an otherwise-difficult measurement that could scarcely be made without the probe.

In determining the peak value of a waveform such as that shown in Fig. 11, it is convenient to position the waveform vertically on the oscilloscope so that the lower corners of the pulse are equally-spaced about one of the horizontal graticule lines as shown. The peak pulse current can then be read from this line to the pulse peak.

MEASURING DISTORTION IN CURRENT WAVEFORMS

When working with audio frequencies it is often desirable to obtain information concerning the harmonic distortion in current waveforms. Frequently, this information can be obtained by measuring the distortion in a voltage waveform related to the current in question. In other cases, however, the current flows through a non-linear impedance so that the resulting voltage waveform is not suitable for a distortion measurement. One such situation occurs when a signal current flows into the non-linear emitter circuit of a transistor. Here, the voltage waveform will not produce the needed distortion information, since the transistor operation is related to input current.

For such instances the new current probe can be used with the -hp- Model 302A Wave Analyzer* to obtain an analysis of the current waveform. The Model 302A measures components up to 50 kc and has a narrow bandwidth which in transistor applications is beneficial in reducing the effect of transistor noise on the measurement. Harmonic components 30 db or more below 1 milliampere can ordinarily be measured with this arrangement. Distortion measurements can be made with negligible contribution from the probe itself, a typical value for this contribution being 70 db below 10 milliamperes at 1 kc. Similarly, dc currents of the magnitudes typically encountered in circuit work have little effect on the probe distortion.

*J. R. Petrak, "A New 20 CPS—50 KC Wave Analyzer with High Selectivity and Simplified Tuning," Hewlett-Packard Journal, Volume 11, No. 1-2, Sept.-Oct., 1959.

MICROAMPERE-RANGE CURRENTS

The combination of the new probe and the Model 302A Harmonic Wave Analyzer can also be used for measuring very small alternating currents in the frequency range from 20 cps to 50 kc. On its most sensitive range the Model 302A measures voltages of 30 microvolts full scale so that this range, when combined with the 1 mv/ma conversion factor of the probe, permits currents below 30 microamperes to be measured. The method thus offers a means of measuring such small currents as the base current in transistors. Even though such currents are below the nominal noise level of the probe (50 μa), the measurement can still be made because of the filtering effect of the wave analyzer's selectivity characteristic.

The measurement of small currents with the wave analyzer can also be facilitated by the fact that the analyzer makes available for external use a signal (BFO output) which is the same in frequency as the frequency to which the analyzer input is tuned. Use of this signal to drive a circuit under test often eliminates the need for an external signal source and can greatly assist in measuring a signal current in the presence of noise.

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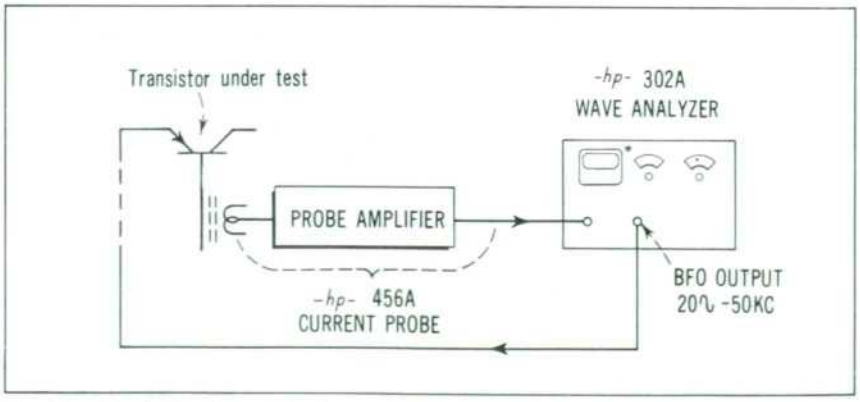

Fig. 12. *Probe can be used with -hp- 302A Wave Analyzer to measure distortion in current waveforms or to measure small audio currents, as described in text.*

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THE VALUE OF AC CURRENT MEASUREMENTS

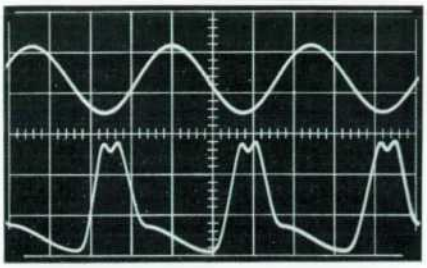

Fig. 1. *Oscillogram of plate voltage (upper trace) and plate current (lower trace) of Class C-pentode measured using -hp- 456A current probe with dual-channel oscilloscope. Note sine-wave current component along base line of lower trace.*

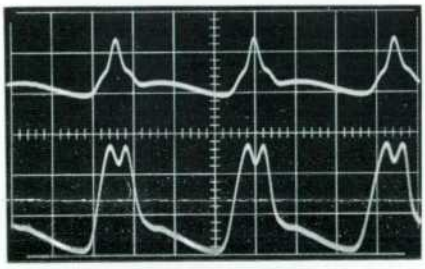

Fig. 2. *Oscillogram showing screen current (upper trace) and plate current (lower trace) of same tube as in Fig. 1 measured using two 456A current probes with dual-channel oscilloscope. Upper trace has twice the sensitivity of lower trace.*

Experience with the -hp- clip-on current probes has frequently and consistently shown that the convenience with which these probes enable current to be measured leads to information that would not otherwise be obtained. A case in point is demonstrated by the accompanying oscillograms. The upper waveform in the first oscillogram shows the plate voltage waveform on a pentode operating in a class C stage. From all appearances this waveform is conventional and does not indicate much about the operating conditions of the tube. Immediately below the plate voltage waveform in Fig. 1, however, is the plate current waveform as measured with the new Model 456A Current Probe and displayed by an -hp- Model 160B dual-trace oscilloscope. This plate current waveform shows at once that the plate is being driven below the knee of the plate current-plate voltage characteristic. At the current peaks the plate current is notched, indicating that the plate is bottoming and thus losing current to the screen. It is also interesting to note that the current base line, instead of showing zero current, shows a sine-wave current component which is the current that flows mainly through the plate capacitance of the tube.

In Fig. 2 the upper trace shows the screen-grid current, while the lower trace again shows the plate current for the same tube as in Fig. 1. The oscillogram was made by using two of the current probes simultaneously. For convenience the screen current is shown at twice the sensitivity of the plate current. It is readily apparent that the lost pulses of plate current are drawn by the screen. The screen also shows a sine-wave component of capacitive current.

CURRENT SUMMING AND EQUALIZING

Since the probe is effectively a current transformer, it has the property that it will algebraically sum the instantaneous value of the currents in two or more conductors it may be clipped around. This property makes the probe a valuable and easily-applied tool in applications in which it is desired to equalize or balance ac currents. In the case involving the class C stage described above, for example, it is possible to use this summing property to examine the plate current pulses exclusive of the current component flowing through the capacity of the tube. This would then easily permit the angle of plate current flow to be measured. Fig. 3 shows the result when this is done. In Fig. 3 the same plate current pulses as in Fig. 2 are shown, except at twice the display sensitivity. In Fig. 2 the capacitive component is present, while in Fig. 3 this component has been bucked out. The method used to obtain the bucking current is indicated in Fig. 4. The probe was clipped around the plate lead of the tube, but at the same time a lead from an external variable capacitor was connected to the plate lead and passed through the probe as shown. By suitably adjusting the variable capacitor, a capacitive current equal but opposite to the capacitive current flowing at the plate can be applied to the probe. For display purposes the tube's electron current is thus separated from the capacitive current.

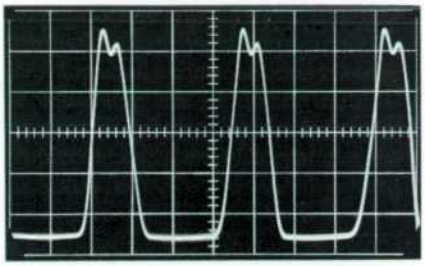

Fig. 3. *Same plate current as in Fig. 2 but with capacitive component bucked out using technique indicated in Fig. 4 and described in text.*

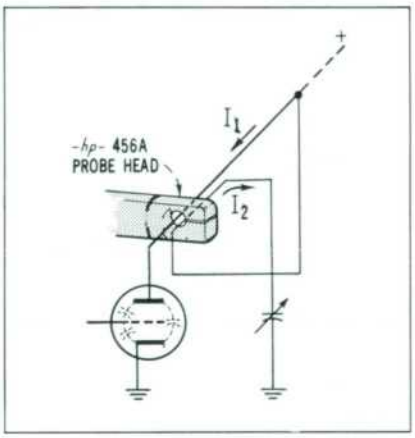

Fig. 4. *Arrangement used to buck out capacitive component of plate current.*

It is also interesting to note that the arrangement shown in Fig. 4 provides a dynamic measure of the output capacity of the tube. This occurs because the final setting of the variable capacitor should be equal to the tube output capacity.

The probe is valuable in a number of other current-equalizing applications. Especially common among these are equalizing the input and output currents in push-pull and balanced circuits in both transistor and tube applications.

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Fig. 13. *-hp- Model 456A Current probe as used with -hp- Model 400D VTVM.*

HIGHER SENSITIVITIES

Under some if not many circumstances, the basic 1 mv/ma sensitivity of the probe can be increased two or more times by looping additional turns of the conductor being measured through the probe head. Looping turns in this way will increase the probe sensitivity in proportion to the number of times the conductor passes through the head and will do so without increasing the nominal noise level of the probe. The main considerations involved in this method of increasing sensitivity are the additional self-inductance that the looping causes in the primary conductor and the effect of this self-inductance in combination with the loop-to-loop capacitance of the conductor. This combination can result in a resonance in the low megacycle region. Where this resonance is not a factor, however, and where physical factors permit, as many as 10 turns can be used in this way.

INSULATION CONSIDERATIONS

The exterior surfaces of the probe head are molded from an electrically-insulating plastic so as to preclude the possibility of shock when the probe is clipped on a conductor that is at an ac and/or dc voltage. However, the interior surfaces of the aperture that receives the conductor to be measured necessarily consist of metallic parts to achieve the desired electrostatic and magnetic shielding for the probe head. These parts are electrically connected to the low terminal of the plug that interconnects the probe to its companion instrument. Since insulating these shield parts would seriously diminish the electrical and mechanical usefulness of the probe, it has been deemed more advantageous to the user to arrange the probe to rely on the insulation of the conductor being measured to electrically isolate the probe from any voltage on the conductor. Hence the probe should be used only with adequately insulated conductors when a voltage exists on the conductor. Normally, this requirement imposes no serious inconvenience, since conductors with significant voltage will often already be insulated. Where bare conductors off ground are encountered, it is usually adequate to insulate a portion of the conductor by a turn or two of electrical insulating tape. It is also often convenient merely to clip the probe around a small insulated composition resistor where one is in the circuit.

In addition to the conductor insulation consideration, the low side of the double plug on the output of the probe amplifier should for personnel safety be connected only to the equipment terminal that is solidly grounded to a power line system ground.

GROUND LEAD

The probe head is provided with a detachable ground lead (Fig. 10) which is occasionally useful in fast circuit work. If the oscilloscope used with the probe has significant response at 15 mc and higher and the circuit under measurement has energy at these frequencies, it is desirable to use the ground lead to connect the probe head to the chassis under test. This will short stray capacities and minimize undesired spurious responses that may be formed with such capacities. At these frequencies solid grounding between the oscilloscope, probe amplifier chassis, and chassis under test are also generally necessary.

BATTERY OR POWER LINE OPERATION

The amplifier for the probe has been designed as a transistorized amplifier to achieve the advantages of long life, small size, and light weight. Transistorization has also made it practical to arrange the amplifier to be battery-operated, thereby achieving portability as well as a lower selling price, although the amplifier is also available in an ac-operated version. The two versions are identical in size and appearance.

Battery operation also has performance advantages because the residual noise level of the amplifier is somewhat lower in the battery-operated version.

GENERAL

The probe has several other conveniences which are worthy of mention. As a convenience in pulse work, the head is marked with an arrow to relate the direction of conventional current flow in the conductor being measured to the resulting positive voltage at the probe output terminals. The probe aperture is large enough (5/32″ diameter) to accept most conductors usually found in electronics work. Head shielding from external magnetic fields is such that these are seldom troublesome, but in any case a check can be made merely by holding the probe with closed jaws in the region of interest to see if a reading occurs.

Electrically, the probe has a capacity of only about 4 mmf to the conductor measured and consequently only a slight conductor voltage effect of 0.03 ma/volt-megacycle. In most cases this is too small to be noticed. Similarly, the effect of dc in the measured conductor is normally insignificant, since half an ampere of dc at the lowest audio frequencies or several amperes at higher frequencies are required before an effect is noticeable.

ACKNOWLEDGMENT

The design group for the new probe was headed by George S. Kan and included Hudson F. Grotzinger, who performed the mechanical design, in addition to the undersigned.

—Charles O. Forge

SPECIFICATIONS
-hp- MODEL 456A
AC CURRENT PROBE

Sensitivity: 1 mv/ma ± 1% at 1 kc.

Frequency Response: ± 2%, 100 cps to 3 mc.
± 5%, 60 cps to 4 mc.
-3 db, 25 cps to 20 mc.

Pulse Response: Rise time is less than 20 nanoseconds; sag is less than 16% per millisecond.

Maximum Input: 1 amp rms; 1.5 amp peak. 100 ma above 5 mc.

Effect of DC Current: No appreciable effect on sensitivity and distortion from dc current up to 0.5 amp.

Input Impedance: (Impedance added in series with measured wire by probe). Less than 50 milliohms in series with .05 μh. (This is approximately the inductance of 1½ in. of hookup wire).

Probe Shunt Capacity: Approximately 4 pf added from wire to ground.

Distortion at 1 KC: For ½ amp input at least 50 db down. For 10 ma input at least 70 db down.

Equivalent Input Noise: Less than 50 μa rms (100 μa when ac powered).

Output Impedance: 220 ohms at 1 kc. Approximately + 1 v dc component. Should work into load of not less than 100,000 ohms shunted by approximately 25 pf.

Power: Battery-operated with mercury-cell type batteries furnished; battery life is approximately 400 hours. Ac power supply optional at extra cost, 115/230 v ± 10%, 50 to 1000 cps; approx. 1 watt.

Weight: Net 3 lbs.

Dimensions: 5 in. wide, 6 in. deep, 1½ in. high. Probe cable is 5 ft. long; output cable is 2 ft. long and terminated with a dual banana plug.

Price: -hp- Model 456A with batteries, $190.00. -hp- Model 456A with ac supply (456A-95A) installed in lieu of batteries, $210.00.

Prices f.o.b. Palo Alto, California
Data Subject to change without notice

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