HEWLETT hp PACKARD

APPLICATION NOTE 60

WHICH AC VOLTMETER?

Hewlett-Packard AC voltmeters are manufactured in each of the three basic kinds, rms-responding, peak-responding, and average-responding. Illustrated is one example of each: Model 3400A rms-responding (left), Model 410C peak-responding (center), and Model 403B average-responding (right).

Electronic ac voltmeters are classified into three broad categories: rms-responding, peak-responding, and average-responding. The majority of ac voltmeters, however, are either the average-responding or peak-responding types with the meter scale calibrated to read the rms value of a sine wave. Only a small minority of instruments in actual use are true rms-responding instruments. This is in spite of the fact that most measurements are concerned with rms values. The discussion which follows considers the reasons for the existence of the three types, all three being manufactured by Hewlett-Packard, and reviews the advantages and limitations of each.

BASIC CONSIDERATIONS

Electronic ac voltmeters are ac-to-dc converters which *derive a dc current proportional to the ac input being measured* and use this current for meter deflection. Conversion to dc eliminates the serious errors which otherwise would result from a meter movement's sensitivity to frequency. The differences among the three types of electronic meters lie in their interpretation of the value of the input signal.

RMS INDICATIONS

The rms (root-mean-square) value of a waveform usually is the quantity of interest in ac voltage measurements. The rms value long ago was established as equivalent to a dc voltage which generates the same amount of heat in a resistive load that the ac does. For this reason, rms voltage is synonymous with effective voltage.

The rms voltage is defined, rather imposingly, as the square root of the average of the squares of the quantities being measured (this concept is explored more fully in Appendix I). Theoretically, this can be done by measuring the voltage point by point along the waveform for one cycle, squaring the numerical value of the voltage at each point, finding the average value of all the squared terms, and then taking the square root of the average value. Regardless of the shape of the waveform, this procedure leads to the rms or effective value. As is well known, *the rms value of a sine wave is 0.707 times the peak or maximum value of the voltage waveform.*

AVERAGE VALUES

The average value of an ac voltage is simply the average of the voltage values measured point by point along the waveform. This procedure, by omitting the squaring and root extraction needed to obtain the rms value, results in a different numerical value.

The average value of a sine wave really is zero because the waveform has equal positive and negative values when averaged for one whole cycle. Since the equivalent dc or energy content in the waveform usually is the quantity of interest, the average value of a sine wave is taken to mean the average rectified value. The average value of one half cycle of a sine wave is 0.636 times the peak value.

Actually, there are not many measurement situations where the average value of a waveform is the desired quantity. An average-responding ac voltmeter, however, can be constructed *more simply and at less cost than a true rms-responding* voltmeter, as shall be described later. For this reason, average-responding voltmeters are widely-used, although the fact that they are average-responding often receives little consideration.

The use of average-responding rather than rms-responding voltmeters is a consequence of the wide use of sine waves in electronic measurements. In calibrating an average-responding meter, a pure sine wave with an rms amplitude of 1 volt can be applied to the meter and the resulting pointer deflection marked on the scale as 1 volt. Actually, the average value of this sine wave is 0.91 volts but since pointer deflection is linearly proportional to the input voltage, an average-responding meter calibrated in rms volts provides reliable indications of rms voltage as if the input is a sine wave. As a matter of fact, this indication is not affected more than 3% by as much as 10% harmonic content in the input waveform and useful indications are obtained on waveforms with even more distortion. For this reason, average-reading voltmeters are widely accepted as low-cost substitutes for true rms-responding voltmeters.

PEAK-RESPONDING INDICATIONS

There are situations where the peak amplitude of an ac signal is significant, such as the monitoring of a transmitter modulating signal, or in studies of vibration components, or in other situations where peak energy must be known. The dominant reason for the use of peak-responding ac voltmeters, however, lies in the nature of their circuitry. Peak-responding circuits allow a voltmeter to serve as a multi-function meter and, what is more important, enables it to be used at much higher frequencies. For example, the Hewlett-Packard 410 series of peak-responding instruments retain accuracy to hundreds of megacycles.

Here again, since the majority of measurement situations *involve sine waves, peak-responding meters usually are* calibrated in rms volts. A calibrating sine wave of 1 volt rms amplitude actually causes a pointer deflection equivalent to 1.414 volts, but this point can be marked as 1 volt rms on the scale. As long as the input waveform is a sine wave, the peak-responding indication is proportional to the rms value. The peak-responding meter, though, is much more sensitive to distortion in the waveform than the average-responding meter is. This factor will be discussed in more detail later on.

PRINCIPLES OF OPERATION

AVERAGE-RESPONDING METERS

A simplified version of the circuit used in the -hp- 400 series average-responding ac voltmeters is shown in Fig. 1. Circuit operation is as follows.

The test signal is applied to the attenuator through a cathode-follower, insuring a high-impedance input unaffected by range switching in the attenuator. The ac amplifier has a large amount of negative feedback thus assuring gain-stability for measurement accuracy, as well as broadening the frequency range of the instrument. Inclusion of the meter circuit in the feedback path minimizes the effects of diode non-linearities and meter coil inductance on circuit performance.

A large feedback factor (typically 60 db) suppresses the *effects of variations in tube or transistor parameters so* that accuracy depends primarily on the passive components. Accuracy is readily obtained with high quality resistors. Despite the large feedback factor, the amplifiers have sufficient gain to obtain high sensitivity also.

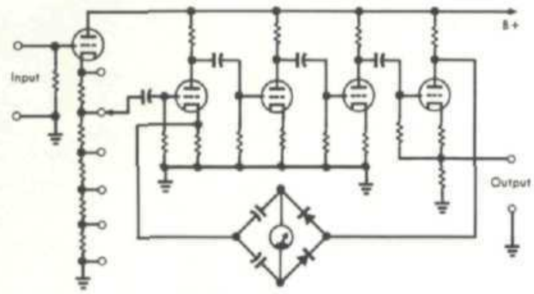

FIG. 1–Basic circuit arrangement of typical average-responding voltmeter. (-hp-400D).

It should be noted that the capacitors in the meter circuit do not serve as storage or filter capacitors for the rectifier diodes. Rather, they are coupling capacitors for the feedback signal, functioning as two capacitors in parallel. The diodes act as switches to maintain a unidirectional meter current despite changes in the instantaneous polarity of the input voltage (Fig. 2).

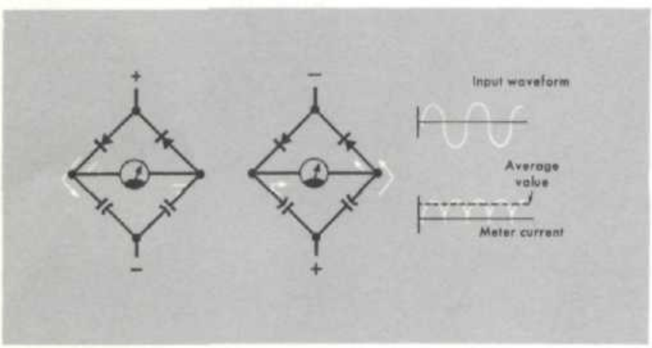

FIG. 2–Arrows show current flow during positive portion of input waveform (a) and during negative portion (b). Current through meter is a train of unidirectional half-sinusoids.

The mechanical inertia of the meter movement prevents the pointer from responding to the individual current pulses. As a result, the pointer deflection corresponds to the average value of the current pulses, rather than to the peak value.

THE PEAK-RESPONDING METER

The fundamental difference between the peak-responding voltmeter and the average-responding voltmeter concerns the use of a storage capacitor with the rectifying diode. The capacitor charges through the diode to the peak value of the applied voltage, and the meter circuit then responds to the capacitor voltage.

Practically speaking, there are other differences. The diode and capacitor can be placed ahead of the amplifier, as shown in Fig. 3. The capacitor can discharge but slowly through the high-impedance input of the amplifier so that a negligibly small amount of current supplied by the circuit under test keeps the capacitor charged to the ac peak voltage.

Since the capacitor charges to the total peak voltage above ground reference, the meter reading will be affected by the presence of dc with the ac voltage, unlike the average-responding meter which has ac-coupled circuits. Furthermore, if the measured waveform is unsymmetrical, a different reading may be obtained if the voltmeter leads are reversed, thereby charging the storage capacitor to the negative peak (the so-called turn-over effect).

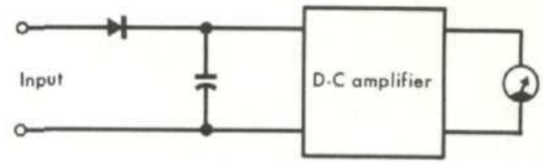

FIG. 3–Peak-responding meter circuit.

A dc amplifier is used in the peak-responding meter to develop the necessary meter current. The amplifier and meter may then also be used for making dc voltage measurements. For this reason, most peak-responding ac voltmeters also serve as dc voltmeters and, by the addition of shunt resistors and dc voltage sources, as milliammeters and ohmmeters. The majority of the inexpensive, multi-purpose instruments so widely used in repair shops and laboratories use this circuit arrangement.

The primary advantage of the peak-responding voltmeter, however, is that the rectifying diode and storage capacitor may be taken out of the instrument and placed in the probe, as in the -hp- series 410 voltmeters (Fig. 4). The measured ac signal then travels no further than the diode. Rectifier diodes designed especially for the -hp- 410 voltmeters (Fig. 5) reduce this distance to a practical minimum so that the series inductance of the signal path is as short as possible and so that the capacitance added to the test circuit by the probe is as low as 1.5 pf.

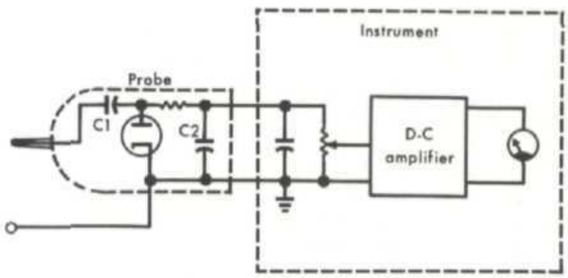

FIG. 4–Another form of peak-responding voltmeter. C1 is charged to peak voltage through diode while C2 is merely part of low-pass filter.

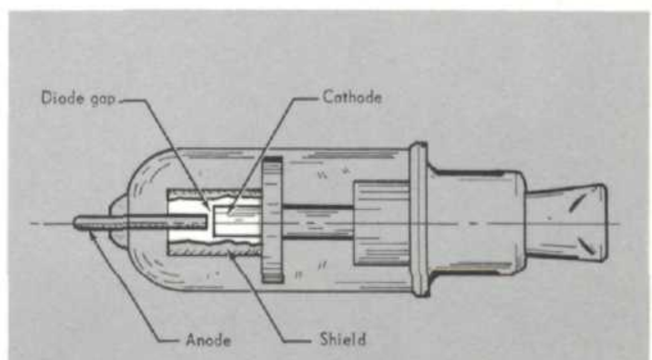

FIG. 5–Diode especially designed for -hp-410 series UHF-voltmeter probe has small, plane surfaces in diode gap for minimum capacitance. Gap is only 0.01 inch to shorten transit time.

The peak-responding voltmeter, with rectifying diode in the probe, therefore is able to measure frequencies up to hundreds of megacycles with a minimum of circuit loading. Average-responding meters, on the other hand, must pass the ac signal through test leads into the instrument and then through an amplifier before rectification. The attenuator limits frequency response and the capacitance of the test leads and input circuit loads the test circuit.

The question then comes to mind: Why not use a peak-*responding meter for all measurements?* One reason is the susceptibility of the peak-reading meter to errors caused by harmonic distortion in the input waveform. Another reason concerns the maximum sensitivity of the instrument, which is limited by diode characteristics. Diodes, whether semiconductor or thermionic, have highly non-linear ampere/volt characteristics below 1 volt. This non-linearity sometimes is compensated for by a separate non-linear meter scale on the most sensitive range, but accuracy is difficult to achieve since similar diodes do not necessarily have similar ampere/volt characteristics. For this reason, careful design is required to achieve even 1/2 volt FSD sensitivity on the lowest range of a peak-responding voltmeter.

THE RF MILLIVOLTMETER

Diode non-linearities as a limit on sensitivity have been eliminated in the -hp- Model 411A RF Millivoltmeter. This instrument uses a balanced circuit, as shown in Fig. 6, with one input receiving the peak value of the voltage being measured. The balanced differential amplifier, acting as a null detector, controls the amplitude of an internally-generated ac signal which is fed to a second diode in the probe. The peak voltage (dc) from this diode serves as the other amplifier input. The null circuitry insures that the signal at the second diode has the same amplitude as the input signal.

The internally-generated ac has a constant frequency (100 kc) and is easily measured. It serves as the indication of the unknown input. All that is required is that the two signals be identical in amplitude, so that diode non-linearities do not enter into the measurement. The most sensitive range on this instrument is 0.010 volt (10 millivolts).

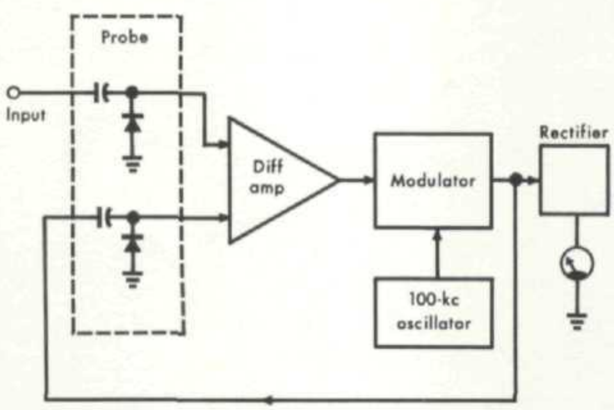

FIG. 6—RF Millivoltmeter.

THE RMS VOLTMETER

In past years, rms-responding electronic voltmeters have not been used widely because of the difficulties in designing a rugged, easily-operated instrument of reasonable cost. Recently, however, these difficulties have largely been overcome. A prime example is the Hewlett-Packard 3400A. It provides an attractive alternative now, wherever measurements are to be made in the range from 10 cycles to 10 megacycles of voltages whose waveform is, or may be, substantially non-sinusoidal.

The rms-responding voltmeter presents special circuit design problems compared to the straightforward techniques used in the average- and peak-responding voltmeters. This is because the input voltage must be squared, and then the square root of the average of the squared quantity taken.

One approach has been to take advantage of the non-linear characteristics of diodes which, in the region below 1 volt, have an ampere/volt characteristic which approximates the curve $y = x^2$. The square-law detector widely used for RF power measurements is an example of this approach. By calibrating the meter scale so that it indicates the square root of the driving voltage, the meter indicates the rms value. Precise calibration is difficult, however, because the diode characteristics do not always conform precisely to a square-law curve and, furthermore, this characteristic is not uniform from diode to diode. This problem is reduced by amplifying the signal, and using the much larger voltage to drive the meter through a more predictable non-linear network made up of several diodes and resistors.

Another approach is to use a thermocouple. The signal to be measured is applied to a fine heater wire, and a thermocouple attached to the heater wire generates a dc proportional to the temperature of the wire. This measurement is based on the original concept of the rms value as the equivalent of the heating power in a waveform.

The accuracy of this arrangement has been difficult to control because of the non-linear behavior of thermocouples, which complicates meter calibration, and also because of the thermal problems involved. Thermal effects are reduced by installing the heater and thermocouple in an evacuated glass bulb and by using fine wires of low thermal conductivity. Other problems with thermocouples have been concerned with sluggish response and susceptibility to burn-out.

These difficulties have been overcome in the -hp- Model 3400A RMS Voltmeter by application of the null balance technique used in the -hp- 411A RF Millivoltmeter. Here, two thermocouples are mounted in the same thermal environment. Non-linear effects in the measuring thermocouple are cancelled by similar non-linear operation of the second thermocouple.

As shown in the block diagram of Fig. 7, the amplified input signal is applied to the measuring thermocouple while a dc feedback current is fed to the heater of the balancing thermocouple. The dc current is derived from the voltage output difference between the thermocouples. The circuitry may be regarded as a feedback control system which matches the heating power of the dc feedback voltage to the input waveform's heating power. Meter deflection is proportional to the feedback dc, which in turn is equivalent to the rms value of the input signal. The meter indication, therefore, is linear and not subject to the non-linearities of the thermocouples.

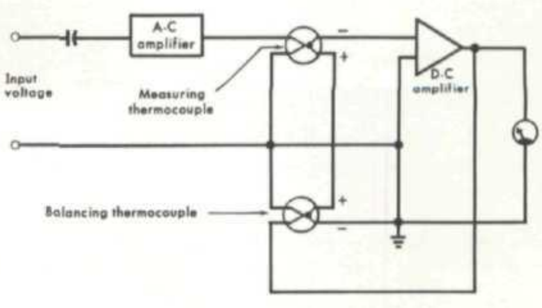

FIG. 7—Block diagram of -hp-3400A rms voltmeter using thermocouples in null-balance configuration.

One note of caution about rms voltmeters concerns the crest factor. The maximum crest factor is defined as the maximum ratio of the waveform peak-to-rms value that can be accommodated. The crest factor is limited primarily by the amplifiers, and the maximum represents the level beyond which the input waveform drives the amplifiers into non-linear operation. The -hp- 3400A RMS Voltmeter maintains full scale accuracy with crest factors as high as 10:1. At 10% of full scale deflection, waveforms with crest factors as high as 100:1 are accommodated. The meaning of a crest factor of this magnitude is perhaps not immediately apparent. When dealing with pulse waveforms there is a natural tendency to consider that crest factor is about the same as peak-to-average ratio, or the inverse of the duty factor. Actually, the crest factor is nearly equivalent to the inverse of the square root of the duty factor. Thus a pulse waveform of 1% duty cycle, or 100:1 peak-to-average power, turns out to require of the rms-responding voltmeter a crest factor around 10. An rms voltmeter which meets this specification must first have an amplifier dynamic range sufficiently wide to pass pulses ten times the amplitude of the full-scale rms value, and, furthermore to anticipate the measurement of pulse trains with both positive and negative pulses, must have double that dynamic range. In the design, however, wide dynamic range is not the only consideration. To prevent thermocouple burnout, the amplifier design must have some sort of power limiting. Straightforward amplitude limiting, as can be seen, is not the answer, since this would limit the crest factor. The amplifier therefore must be designed with a limit on the voltage-time product, to prevent thermocouple burnout, while yet allowing a wide dynamic range. Crest factor may then be taken as a figure of merit for rms-responding voltmeters.

WHICH VOLTMETER TO PICK?

The basic facts about ac voltmeters discussed so far can be summarized as follows:

(1) For measurements involving sine waves with only modest amounts of distortion (<10%), the average-responding voltmeter provides the best accuracy and most sensitivity per dollar.

(2) For high-frequency measurements (>>1 Mc), the peak-responding voltmeter with diode-probe input is the most economical choice. Peak-responding circuits are acceptable as part of an AC-DC voltohmmeter if the inaccuracies caused by distortion in the input waveform can be tolerated.

(3) For measurements where it is important to determine the effective power of waveforms that depart significantly from a true sinusoidal form, the true rms-responding voltmeter is the appropriate choice.

Instrument	Primary Uses	Frequency Range	Voltage or Current Range	Input Impedance
AC Measurements				
400D*	Wide range ac measurements, high sensitivity	10 cps to 4 mc	0.001 to 300 v full scale, 12 ranges	10 meg, 15, 25 pf shunt
400H*	High accuracy wide range ac measurements	10 cps to 4 mc	0.001 to 300 v full scale, 12 ranges	10 meg, 15, 25 pf shunt
400L*	Log voltages, linear db measurements	10 cps to 4 mc	0.001 to 300 v full scale, 12 ranges	10 meg, 15, 25 pf shunt
403A*	Battery-operated portable; fast, accurate, hum-free ac measurements	1 cps to 1 mc	0.001 to 300 v full scale, 12 ranges	2 megohms, 40, 20 pf shunt
403B*	AC voltage measurements in lab or field; ac line or battery operation	5 cps to 2 mc	1 mv to 300 v full scale	2 megohms
3400A‡	True rms readings of complex ac waveforms	10 cps to 10 mc	0.001 to 300 v full scale	10 megohms, 25 pf shunt
411A**	Millivolt, db readings to gigacycle range	500 kc to 1 gc	10 mv to 10 v full scale, 7 ranges	Typically 200 K at 1 mc, 1 v
AC–DC–OHMS				
410B**	Audio, rf, vhf measurements; dc voltages; resistances	dc; ac—20 cps to 700 mc	dc, 1 to 1000 v full scale ac, 1 to 300 v full scale	dc, 122 megohms ac, 10 megohms/1.5 pf
410C**	DC voltage; resistance, current; audio, rf, vhf measurements, with ac probe	dc; ac—20 cps to 700 mc	dc v, 14 mv to 1500 v full scale; dc amps, 1.5 μa to 150 ma full scale; ac v, 0.5 to 300 v full scale	dc v 100 megohms ac, 10 megohms/1.5 pf

*Average-responding **Peak-responding ‡RMS-responding

Data subject to change without notice

TABLE 1—Hewlett-Packard AC Voltmeters.

DISTORTION EFFECTS

How much distortion in the measured signal can be tolerated by average- or peak-responding meters? No firm answer can be given to this question since so many factors are involved.

Table 2 lists the inaccuracies resulting from distortion. The table shows that a given amount of harmonic distortion may result in a wide range of possible inaccuracies, a consequence of the fact that the phase as well as the amplitude of a harmonic component affects the readings. This is illustrated by Fig. 8, which shows two waveforms both with identical amounts of fundamental frequency and added 3rd harmonic. In the diagram at left, the fundamental crosses the zero baseline in phase with the harmonic waveform and in the diagram at right they are out of phase.

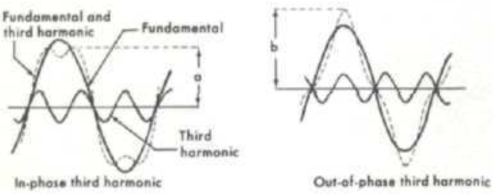

FIG. 8–Phase of harmonics in waveform affect shape and thus peak value of complex wave.

The peak responding meter would show a range of readings between "a" and "b", depending upon the phase of the harmonic. The range of amplitudes that would be shown by the average responding meter is more difficult to diagnose, but note that in the left diagram, two half-cycles of the third harmonic add to the fundamental while one half-cycle subtracts whereas in the right diagram, only one-half cycle adds while two half-cycles subtract. The waveform in the right diagram therefore has a lower average value than the left waveform. A detailed analysis of the effects of waveform on voltmeter readings is presented in Appendix II.

To repeat, the desired accuracy in the measurement determines the amount of distortion (meaning departure from true sine wave) that can be tolerated in the measured waveform. The rms voltmeter is unaffected by waveform shapes excepting, of course, those cases when harmonic components lie outside the passband of the voltmeter circuits. The rms-responding meter is especially useful, for example, in the monitoring of the line power fed to a resistive load, where the line regulator distorts the waveform; another case in point is measurement of the frequency response of a communication system, where modulation and demodulation processes may be non-linear to an unknown degree. Again, the average-responding meter tolerates relatively large amounts of distortion, while the peak-responding meter is most sensitive to waveform.

Harmonic Content	True rms value	Average - responding meter	Peak-responding meter
0	100	100	100
10 percent 2nd	100.5	100	90 to 110
20 percent 2nd	102	100-102	80 to 120
50 percent 2nd	112	100-110	75 to 150
10 percent 3rd	100.5	96-104	90 to 110
20 percent 3rd	102	94-108	88 to 120
50 percent 3rd	112	90-116	108 to 150

TABLE 2–Measurement errors from harmonic voltages.

VOLTMETERS AND NOISE

An oscillogram showing typical circuit noise is shown in Fig. 9. A peak-responding meter responds to the highest peak of such a waveform during the period of measurement, but the meter indication seldom reaches this peak value because of several complicating factors. These include the charging and discharging time constants of the voltmeter input circuit and the impedance of the test circuit at the point of measurement. In general, the peak-responding meter reads noise 3 to 5 times higher than the actual rms value. Although peak-responding voltmeters can be used for noise measurements, extreme care is required when interpreting the readings.

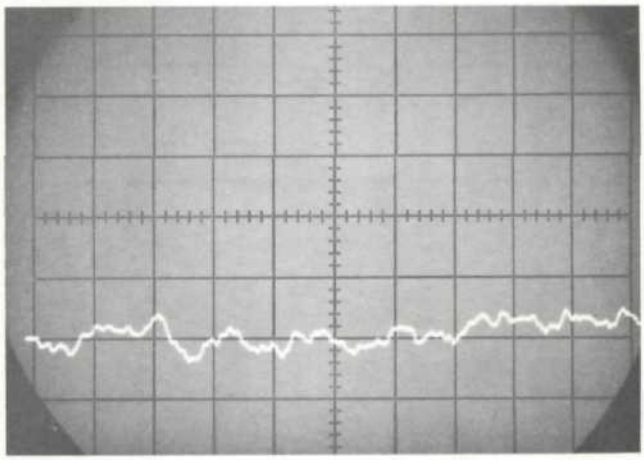

FIG. 9–Oscillogram of noise voltage illustrates variable peak values.

The average-responding meter does much better with noise voltages since it does read the average value, which ordinarily is constant. Probability analysis shows that the average value of noise (rectified) is 0.8862 times the rms value (the rms value of random or gaussian noise is the same as σ, the standard deviation). This correction factor should be applied with care, however, since any alteration of the character of the noise, which is most likely to happen in electronic circuits because of non-linearities, alters the correction factor. The average-responding meter is well-suited, though, for relative measurements of noise levels.

The rms-responding meter, of course, provides the most reliable measurements of noise or signals with noise. Indeed, the widest present use of rms-responding meters is found in measurements involving noise. In this service, the readings of both average-responding and peak-responding meters must be interpreted with care and often with questionable assumptions. Correction factors for peak-reading instruments, for example, rely on the assumption that energy distribution is gaussian out to the tips of the distribution (See Appendix II). So long as its crest factor and frequency range are adequate to the purpose, the rms-responding instrument may be taken as giving accurate representations of effective power even where the signal may have been subjected to unknown variations due to non-linearities or frequency discrimination in the circuitry under investigation.

SIGNALS PLUS NOISE

Many measurements are concerned with sine wave signals corrupted by noise. To find the true value of the sine wave, the usual procedure is to measure the noise voltage without the signal present, and then measure signal and noise together. Subtraction of the noise voltage from the total yields the signal voltage.

As discussed previously, the rms-responding meter provides the most reliable indication while the peak-responding meter is unsatisfactory to a degree which depends on the amplitude of the noise. The average-responding meter handles signals plus noise fairly reliably. The response of rectifier diodes to noise is not linear, however, so care should be exercised. As a practical matter, though, if the signal-to-noise ratio is greater than 5, the error in the readings is no greater than other voltmeter errors.

A NOTE ON METER SCALES

Most ac voltmeters have three scales printed on the meter face, as shown in Fig. 10. Two voltage scales are provided to accommodate the 1-3-10 range switching sequence commonly used. This allows the lowest one-third portion of one range to be expanded to full scale by switching to the next lowest range. Meter readings therefore may always be taken in the upper two-thirds of the scale for highest accuracy. The -hp- Model 410C uses a 5-15-50 range sequence so that the commonly found 115 volts will lie in the upper portion of the scale (150 volt range).

The ratio between the two voltage scales was chosen to correspond to a 10-db difference between scales so that only one decibel scale is necessary. The decibel scale, however, corresponds to power and it provides a valid reading only when the meter reads the voltage across the appropriate impedance. For the convenience of communications personnel, where db readings are widely used, the 0 db mark commonly is set to 0 dbm, equivalent to the voltage developed across a 600 ohm resistor when dissipating 1 milliwatt (0.775 v). The -hp- 411A RF Voltmeter, on the other hand, establishes the 0 db level at 1 milliwatt across 50 ohms for convenience in working with RF systems.

Logarithmic scales commonly are achieved with a meter movement having pole pieces shaped so that deflection sensitivity becomes progressively less as deflection increases. The lower parts of the voltage scales are thus expanded so that percentage accuracy is constant across the whole scale, rather than being a fixed percentage of full scale deflection. At the same time, the decibel scale becomes linear. Since this type of meter is most widely used in communications, the db scale is placed on the outermost circumference.

The attainable accuracy of a high-quality electronic voltmeter is determined primarily by the accuracy of the meter calibration. High accuracy meters, such as the Hewlett-Packard Model 400H, use individually-calibrated meters. To improve reading resolution when this accuracy is available, a larger meter face is used and a mirror-scale is included to minimize parallax errors in reading.

Based on material appearing in EDN--November 1963 Test Instrument Issue, "Which AC Voltmeter?" by Howard L. Roberts

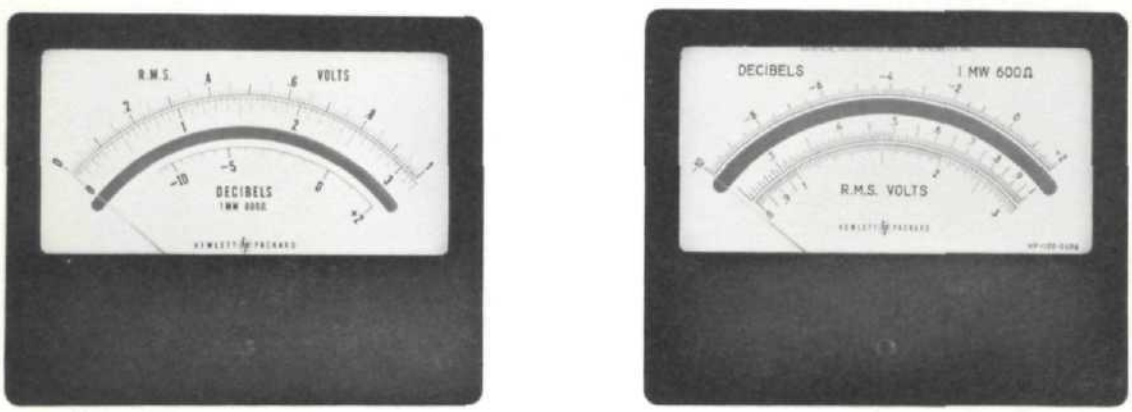

FIG. 10—Meter face of typical average-responding meter with 1 - 3 - 10 range sequence (left). Meter at right has logarithmic response with scales expanded towards low end of range.

APPENDIX I

If there were "n" discrete values in a series of measurements, the rms value is found by squaring the value of each measurement, adding the squared values, dividing by the number of discrete values to find the average and taking the square root of the average. Mathematically, this is expressed as:

$$y_{rms} = \sqrt{\frac{1}{n} \sum_{p=1}^{n} y_p^2}$$

If the quantity being measured were a continuous function, such as a voltage waveform, the summation process is replaced by integration. Then the rms value is expressed as:

$$y_{rms} = \sqrt{\frac{1}{t} \int_0^t y^2 \, dt}$$

where the measurement is carried out through the interval 0 to t.

From this, the rms value of one half-cycle of a sine wave is found:

$$E_{rms} = \sqrt{\frac{1}{\pi} \int_0^\pi (E_{max} \sin \theta)^2 d\theta}$$

$$= \sqrt{\frac{1}{2} (E_{max})^2}$$

$$= 0.707 \; E_{max}$$

The average value of a quantity is simply the algebraic average of values taken throughout the period of interest. If there were "n" discrete values within this period, this would be described simply as:

$$y_{avg} = \frac{1}{n} \sum_{\mu=1}^{n} y_\mu$$

If the quantity varies continuously, the average value is defined mathematically as:

$$y_{avg} = \frac{1}{t} \int_0^t y dt$$

Note that the inertia of the meter movement of an average-reading voltmeter performs this integration.

The average value of one half-cycle of a sine wave then is:

$$E_{avg} = \frac{1}{\pi} \int_0^\pi E_{max} \sin \theta \, d\theta$$

$$= \frac{2}{\pi} E_{max}$$

$$= 0.636 \; E_{max}$$

APPENDIX II

Reprint of material appearing in H-P Journals - - Vol 6 No's 8, 9 & 10 Apr, May & June 1955, "Some Effects of Waveform on VTVM Readings" by B.M. Oliver

Some Effects of Waveform on VTVM Readings

WHEN using a vacuum-tube voltmeter calibrated in rms values, how is the peak-to-peak value of a square wave obtained from the voltmeter reading? Or what is the effect on the reading of the presence of 10% third harmonic? In practice, numerous questions such as these occur as to how waveforms other than pure sine waves influence the voltmeter reading. Before questions of this nature can be answered, however, it is necessary to know the operating principle of the voltmeter being used.

-hp- voltmeters are of two types: those in which the meter deflection is proportional to the average value of a rectified cycle of the applied waveform and those in which the deflection is proportional to the positive peak value. Equivalent circuits of these types are shown in Fig. 1. In the *-hp-* average-reading type the applied waveform is amplified to a convenient high level. It is then rectified and the resultant current pulses applied to a d-c milliammeter calibrated in terms of the input voltage. The ballistic characteristics of the meter integrate the moments of force in the meter movement to produce a steady deflection of the meter pointer. Any d-c component in the applied voltage is excluded from the measurement because of the input blocking capacitor.

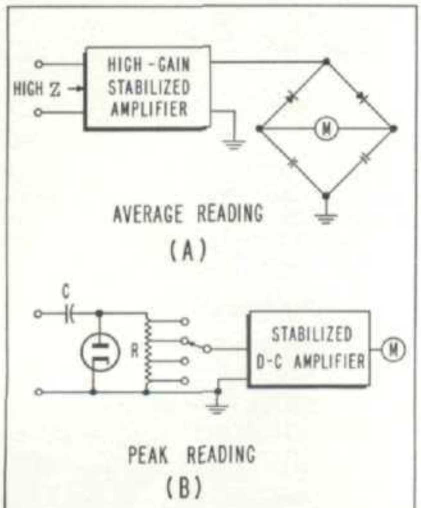

Fig. 1. *(a) Average-reading type circuit used in -hp- 400 series voltmeters to obtain relative freedom from waveform effects as discussed in accompanying article. (b) Peak-reading type circuit used in -hp- 410 voltmeters. Although this circuit has greater sensitivity to waveform effects, it is possible, through suitable design to operate the circuit up to hundreds of megacycles as in the -hp- 410B 700-megacycle voltmeter.*

In the *-hp-* peak-reading type circuit (Fig. 1[b]) the positive peak of the applied waveform charges a capacitor through a diode. The resulting d-c voltage, or a known fraction of it, is then applied to a stabilized d-c amplifier. A voltage-calibrated meter monitors the amplifier output. Again, any d-c component is excluded.

Both of these circuits are calibrated so that they indicate the rms value of an applied pure sine wave. That is, the average-reading type reads 1.11 times the average value of a rectified cycle of any applied wave; the peak-reading type reads 0.707 times the positive peak. The rms calibration of (or scale used with) both meters applies as long as the input is a pure sine wave. But when the meters are used to measure complex waves, the readings must be correctly interpreted because the ratios of rms to average and rms to peak are usually not the same in a complex wave as in a sine wave. In general the average-reading meter gives readings on complex waves which are closer to the true rms values than does the peak reading meter.

EXTREMES OF ERROR, AVERAGE-READING METERS

In a square wave the unique relation exists that the average, rms, and peak values are all the same.

(a)

-hp- Model 400D 10 cps - 4 megacycle voltmeter uses average-reading type circuit.

(b)

-hp- Model 410B 700-megacycle voltmeter uses peak-reading type circuit.

Fig. 2

Since an average-reading meter indicates 1.11 times the average value, it will indicate 11% high for the rms value of a square wave. Further, a square wave has the lowest ratio of rms value to absolute average value of any wave. It follows, then, that an average-reading meter will never read more than 11% high.

At the other extreme consider a series of short duty cycle pulses having a given rms value. As the duty cycle approaches zero, the pulse amplitude need only increase as

$1/\sqrt{\text{duty cycle}}$ to keep the rms value constant. Thus, the absolute average value of the wave approaches zero. It is conceivable, then, that an average-reading meter would indicate as much as 100% low. Excluding short duty cycle pulse waveforms, however, an average-reading meter seldom reads more than 20% low on complex waves.

SECOND HARMONIC WITH AVERAGE-READING METERS

The accuracy with which an average-reading meter will indicate the rms value of a wave with harmonic content depends not only on the amplitude of the harmonic but on its phase and order as well. In the case of a wave with second harmonic content, the difference between the true rms value of the wave and the reading indicated by an average-reading voltmeter will be small for most waves encountered in practice.

Fig. 3 shows the calculated range of absolute average values of a wave consisting of a fundamental with various amounts of second harmonic. The upper and lower limits of the shaded area are determined by the phase of the harmonic with respect to the fundamental. Consider, for example, a wave consisting of a fundamental combined with an "in-phase" second harmonic, i.e., a second harmonic whose zero-axis intercepts coincide with the corresponding fundamental intercepts as shown in Fig. 4(a). In each half cycle of the fundamental, the second harmonic contributes a positive component and a negative component which are equal in area and so do not alter the average value of the rectified wave. An in-phase second harmonic will thus cause no change in the meter reading until the harmonic reaches a value such that its initial slope (slope at 0, 2π, 4π, etc., radians) exceeds the slope of the fundamental. For such higher slopes the complex wave acquires additional crossings of the zero axis. When this happens, the harmonic adds area to the rectified wave and the average value begins to increase. Since the initial slope of a second harmonic does not exceed the slope of the fundamental until the harmonic reaches a value of 50%, the average value of the wave will remain constant until an in-phase second harmonic reaches this value. The lower boundary of the shaded area in Fig. 3 shows this case.

The condition for which a second harmonic will cause the average value of the complex wave to follow most closely the rms sum of the components is where the harmonic has a "quadrature" relation to the fundamental, i.e., the peaks of the harmonic occur at the time the fundamental intercepts the zero axis, as illustrated in Fig. 4(b). This is also the condition usually encountered in practice. A square law term in a transfer characteristic, for example, produces a quadrature relation for the second harmonic.

The calculated average values for a wave consisting of a fundamental with various amounts of a quadrature second harmonic are plotted in Fig. 3 as the upper boundary for the shaded area.

The calculated data in Fig. 3 were verified experimentally by establishing a "fundamental" and a "second harmonic" and adjusting these so that they caused a slow beat on an *-hp-* 400D average-reading type meter. The limits of the beat were then observed. The data obtained in this manner are plotted as small circles on the curve. The close agreement is apparent.

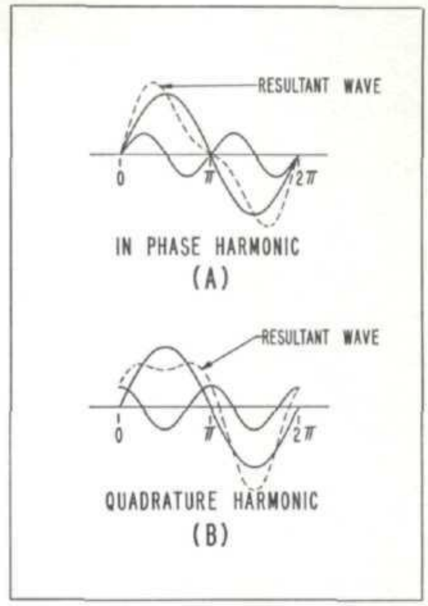

Fig. 4. *(a) In-phase harmonic causes lowest readings on average-reading voltmeter. (b) Quadrature harmonic causes average-reading voltmeter to follow rms value most closely. Quadrature relation is case usually encountered in practice.*

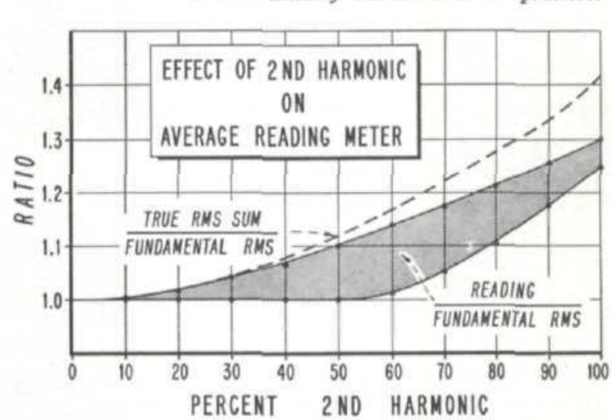

Fig. 3. *Calculated limits (shaded area) of absolute average value of wave consisting of fundamental and various amounts of second harmonic. Small circles show experimental verification of calculated data. Dashed line shows true rms value.*

In examining Fig. 3 it will be seen that for second harmonics of typical magnitudes the average-reading type meter will give readings quite close to the true rms sum. For a second harmonic of 25% magnitude, for example, the error of the average-reading meter is but 3% and this applies in the case of an in-phase harmonic. With a 10% second harmonic, the error is less than 1%.

THIRD HARMONIC WITH AVERAGE-READING METERS

A wave consisting of a fundamental and the third harmonic causes considerably greater variations in the reading of an average-reading type voltmeter than does a wave with second harmonic content. This is shown in Fig. 5. Whereas the reading of the meter on a wave containing second harmonic is always lower than the rms value, the reading with a wave containing third harmonic can be either high or low for harmonic contents up to amounts as high as 75%.

In the case of a wave having third harmonic, the maximum area under the complex envelope and thus the maximum meter reading occur when the harmonic contributes the area of an extra half-cycle (Fig. 6[a]) of the harmonic to the total waveform. This situation determines the values of the upper boundary of the shaded area in Fig. 5. The minimum average area occurs when the harmonic subtracts the area of one-half cycle of its waveform from the fundamental. This determines the lower boundary for the shaded area for harmonic content up to 33⅓%.

For more than 33⅓% third harmonic slope reversals occur as before and the extra added area causes the lower limit to begin to rise.

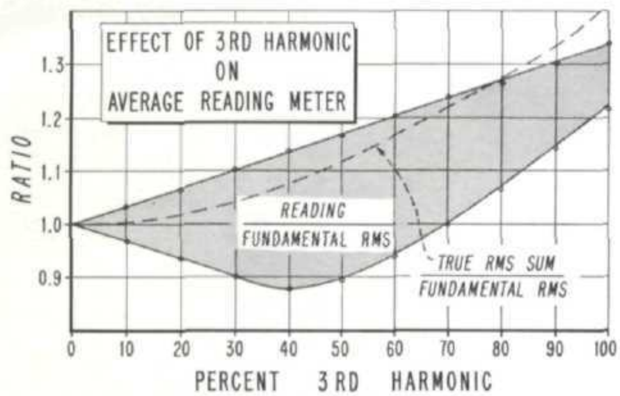

Fig. 5. *Calculated limits of absolute average values of wave consisting of fundamental with various amounts of third harmonic. Small circles show experimental verification of calculated data.*

The calculated data in Fig. 5 were verified experimentally in a manner similar to the verification for Fig. 3. The results are plotted in Fig. 5.

Not only does the third harmonic cause greater variations in the meter reading than the second harmonic, but, it will cause greater variations than any other harmonic. The extremes of error with "small amounts" of odd harmonics are given by the percentage of the harmonic divided by the order of the harmonic. "Small amounts" of harmonic in this case can be defined as percentages less than 100/n where n is the order of the odd harmonic.

It should be noted that, for typical amounts of this worst harmonic, the third, the accuracy of an average-reading meter is still good. Third harmonics up to 10%, for example, can cause errors of up to only 3.3%.

COMBINED HARMONICS WITH AVERAGE METERS

When more than one harmonic is present in the applied wave, the mathematics of each case becomes more complicated and the number of cases is increased tremendously. As a result no analytic study of the situation has been made.

Some experimental data have been compiled, however, for the case of combined second and third harmonics with various amounts of fundamental. This case is of interest in distortion measurements made by the fundamental rejection method.

The data are shown in the second, third, and fourth curves of Fig. 7 for waves containing second and third harmonics in various ratios of fundamental from infinite fundamental (i.e., zero harmonics) to zero fundamental (i.e., infinite harmonics).

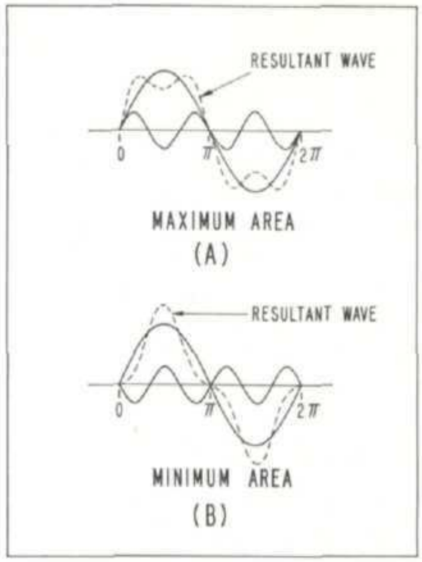

Fig. 6. *In-phase (a) and out-of-phase (b) third harmonic. In phase relation gives more accurate readings.*

The shaded areas represent the extremes of readings (as per cent of true total rms) obtained as the phase of the fundamental varied with respect to the harmonics. For these curves the second and third "harmonics" were adjusted to be off frequency with a slow beat of approximately 1 cps. Then the fundamental frequency was adjusted to beat at 0.1 cps with respect to this combination. The extremes of deflection were then noted during the course of many complete cycles of the lowest beat frequency. The data obtained are plotted as the limits of the shaded areas. The shaded areas thus give the extreme errors for all relative phases of the fundamental and second and third harmonics.

These curves show the tendency of an average-reading meter to read low on complex waves. When the input consists of many inharmonically related sinusoids, the error approaches that for gaussian noise, which is about 11% low as will be shown later.

EXTREMES OF ERROR, PEAK-READING METERS

With peak-reading type meters, the limits of error can theoretically range from 100% low to infinitely high. Consider, for example, the pulse waveform shown in Fig. 8.

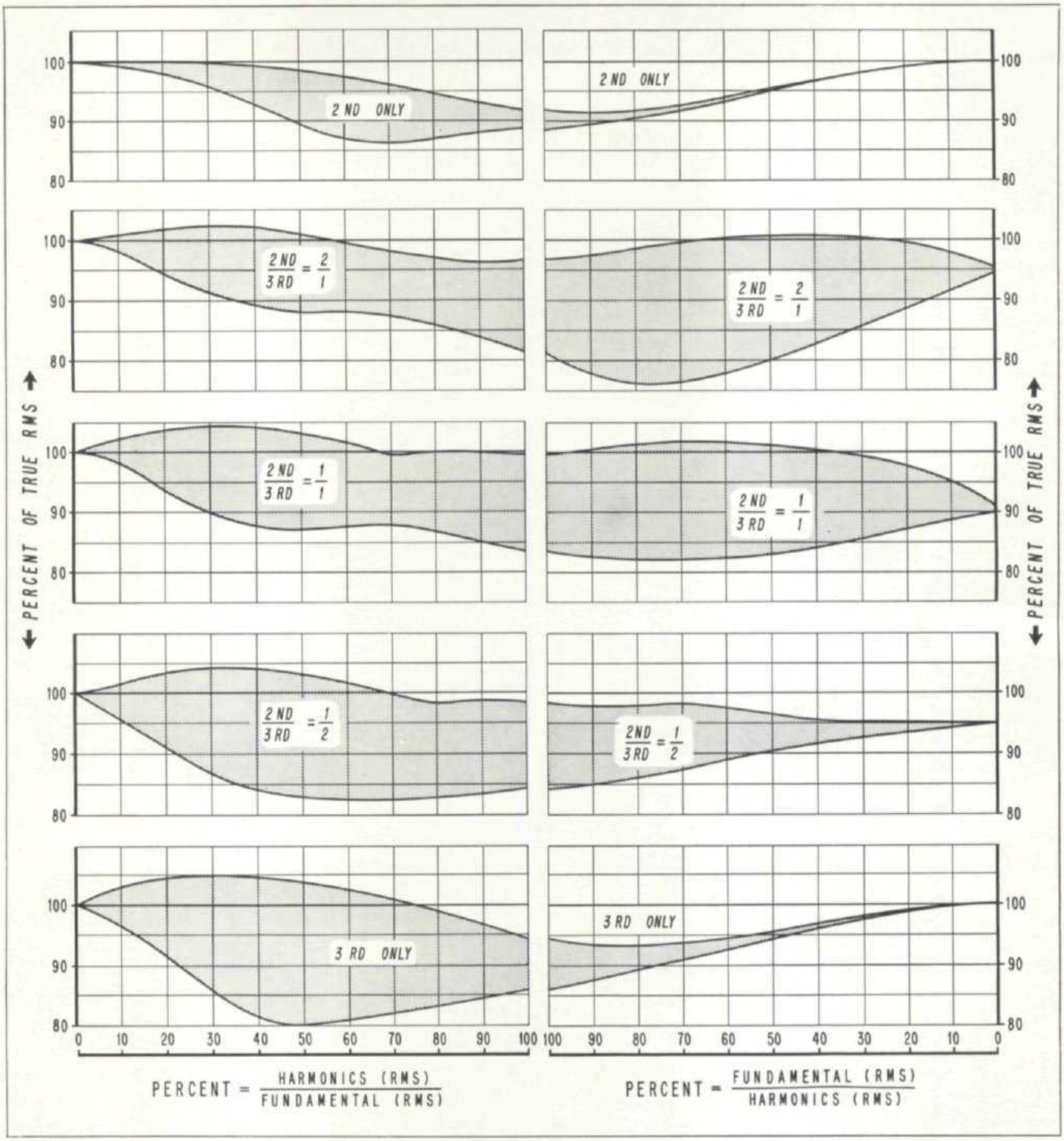

Fig. 7. *Data showing effects of harmonics in various amounts and combinations on average-reading type voltmeter. Curves for* 2nd only *and* 3rd only *on both halves of figure are calculated and experimentally confirmed as explained in text. Note change of scale in right half of figure.*

This waveform can be shown to have an rms value

$$E_{rms} = E\sqrt{\delta(1-\delta)}$$

where δ is the duty cycle t/τ. Since the actual meter deflection is proportional to the peak value of the waveform, the ratio of E_{peak} to E_{rms} will show the operation of the meter

$$\frac{E_{peak}}{E_{rms}} = \frac{E(1-\delta)}{E\sqrt{\delta(1-\delta)}} = \sqrt{\frac{1-\delta}{\delta}}$$

Thus, if the waveform has a low value for δ, the duty cycle, the meter reading will, in the limit, be infinitely high. If the duty cycle has a relatively large value approaching unity (i.e., the pulses will become

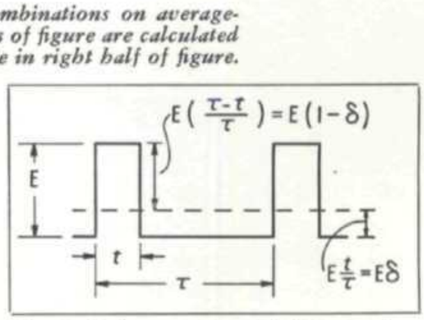

Fig. 8. *Pulse waveform defining values used in text.*

what are usually considered to be negative pulses), the meter reading will approach zero or be 100% low.

HARMONICS WITH PEAK-READING METERS

Since the deflection of a peak-reading meter is proportional to the peak of the applied waveform, the maximum reading will be obtained on such a meter when the relative phases of the wave components are such that a peak of the harmonic coincides with the peak of the fundamental. The maximum reading for a given magnitude of harmonic will thus be the same regardless of the order of the harmonic. The ratio of this maximum to the fundamental is plotted as the upper curve in Fig. 9.

The minimum value that the peak can have will be obtained when a peak of the harmonic is in phase opposition to the peak of the fundamental. The lowest minimum peak values will be obtained with low order harmonics. As the order of the harmonic is increased, the minimum peak value will increase until it approaches as a limit the maximum peak value, i.e., when the fundamental and harmonic peaks coincide. The reason that the minimum reading finally increases as the amount of the harmonic is increased *is that the harmonic ultimately* causes neighboring peaks to be formed (see Fig. 6[a]). These are what the meter then responds to, and their amplitude increases with increased harmonic. The higher this order, n, of the harmonic, the smaller is the percentage $\left(\frac{100}{n^2}\right)$ at which these peaks first form.

The two lower curves in Fig. 9 show the error possible when the phases of the second or third harmonics are such as to cause the minimum possible reading of the meter. Higher harmonics will give minimum reading curves that progressively approach the curve for the maximum possible reading.

If the error in Fig. 9 for a peak-reading meter is compared with that in Figs. 3 and 5 for an average-reading meter, the superiority of the average-reading meter in approximating the true rms value of the waveform will at once be apparent.

AVERAGE AND PEAK METERS WITH A-M WAVES

If an average meter is being used to measure an amplitude-modulated wave, the meter will, if the modulation is linear, read the rms of the average or unmodulated carrier.

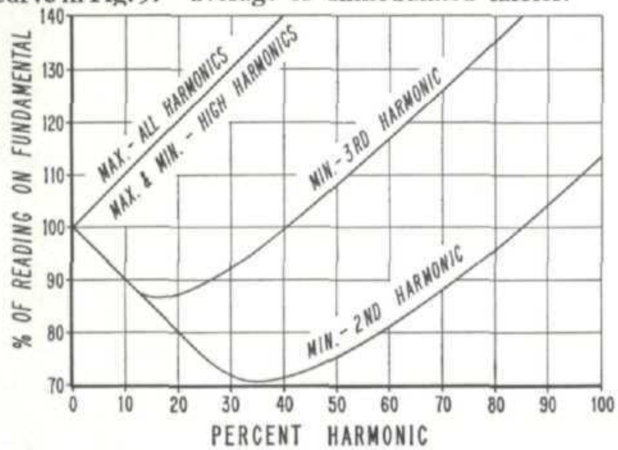

Fig. 9. *Curves showing maximum and minimum readings possible on peak-reading meter when applied wave consists of fundamental with various amounts of harmonic content.*

A peak meter will read the rms value of the peak r-f amplitude.

The two meters can thus be combined to make readings of the percentage modulation of the modulated wave, because percent modulation is equal to 100 $[(E_{peak}/E_{average})-1]$.

AVERAGE AND PEAK METERS WITH HUM

It often happens that a small amount of hum is combined with the voltage to be measured. When the frequency to be measured is relatively high with respect to the hum frequency, a small amount of hum such as 10% will increase the reading of an average type meter by about one-half as much as it would increase the reading of a true rms meter. (Thus, 10% hum will give a reading which is 1.0025 times the reading without hum, i.e., an increase of only $\frac{1}{4}$%.)

A peak-reading meter, on the other hand, will add the hum voltage linearly to the desired voltage. The meter reading will thus be high by an amount approximately equal to the hum amplitude (10% hum will result in a meter reading of 110%).

AVERAGE METERS WITH GAUSSIAN NOISE

The voltage of thermal noise is characterized by a probability distribution which is of gaussian shape. Shot noise will also have a gaussian probability distribution if the average number of shots per second is much greater than the bandwidth in cycles per second. Impulse noise behaves as shot noise only if the impulses are totally independent and occur at random times. Rectified gaussian noise as obtained from an envelope detector does not have a gaussian distribution.

The indication of an average-reading meter on noise can be calculated as follows. The rectified d-c voltage V_o from noise will be

$$V_o = \int_{-\infty}^{\infty} Vp(V)dV = 2\int_{0}^{\infty} Vp(V)dV$$

where the second integral follows from the first if p(V) is symmetrical about zero.

If the noise is gaussian, the probability p(V)dV that the instantaneous voltage lies between V and V + dV is:

$$p(V)dV = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{V^2}{2\sigma^2}} dV$$

where σ is the rms noise voltage. Substituting this into the expression for V_o gives

$$V_o = \frac{2}{\sigma\sqrt{2\pi}}\int_{0}^{\infty} Ve^{-\frac{V^2}{2\sigma^2}} dV$$

$$= \frac{2\sigma}{\sqrt{2\pi}}$$

Since the meter is calibrated to read the rms value of a sine wave, the indicated voltage $V_i = 1.11$ (i.e., $\frac{\pi}{2\sqrt{2}}$) times V_o, where V_o is the average or rectified value. Thus,

$$\frac{V_i}{\sigma} = \frac{\sqrt{\pi}}{2}$$
$$= 0.886 \text{ or } -1.05 \text{ db}$$

Average-reading meters thus read 1 db low on gaussian noise provided that no overload occurs on the peaks.

PEAK METERS WITH GAUSSIAN NOISE

The reading of a peak meter on gaussian noise depends on the efficiency of rectification, i.e., on the ratio of the resistance through which the input capacitor is charged to that through which it is discharged. If the noise is extremely wide band compared with the reciprocal of the charge and discharge time constants of the meter, the reading will be steady and found as follows:

$$\dot{i}_{discharge} = \dot{i}_{charge}$$

$$\frac{V_0}{R_d} \cong \frac{1}{R_c}\int_{V_0}^{\infty} Vp(V)dV$$

where R_d = discharging resistance
R_c = charging resistance
V_o = rectified d-c value of noise

For gaussian noise this becomes

$$\frac{R_c}{R_d} = \frac{1}{\sigma V_0\sqrt{2\pi}}\int_{V_0}^{\infty} Ve^{-\frac{V^2}{2\sigma^2}}dV$$

$$= \frac{1}{\sqrt{2\pi}}\frac{\sigma}{V_0}e^{-\frac{V_0^2}{2\sigma^2}}$$

$\frac{V_o}{\sigma}$ is the ratio of rectified d-c to the true rms of the noise. If the meter is calibrated to read rms on a sine wave, then $V_o = \sqrt{2}\,V_i$ where V_i is the indicated rms. Hence

$$\frac{R_c}{R_d} = \frac{1}{2\sqrt{\pi}}\frac{\sigma}{V_i}e^{-\left(\frac{V_i}{\sigma}\right)^2}$$

or
$$\frac{R_d}{R_c} = 2\sqrt{\pi}\,Ke^{K^2}$$

where
$$K = \frac{\text{indicated rms}}{\text{true rms}}$$

The factor K is plotted as a function of R_d/R_c in Fig. 10. This curve allows one to estimate the correction factor to be applied to the reading of a peak meter to get the rms of a gaussian noise input. The approximate region of the curve applicable to the *-hp-* 410B is marked.

Although the curve is useful since it is quite flat in the region of interest, several considerations dictate that it should be used only for rough estimating. For one thing the charging resistance is rather uncertain in most cases since it depends on diode perveance and current. Further, with very high R_d/R_c the current drawn

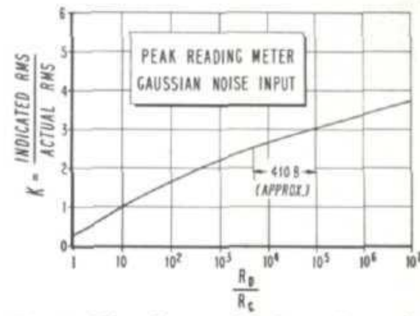

Fig. 10. *Plot of correction factor for peak-reading meters when used to measure rms value of gaussian noise. Portion of curve applicable to -hp- Model 410 is marked. Curve should be used only for rough estimating.*

by the diode is infrequent and large so that loading on the circuit by the meter tends to suppress the high peaks and decrease K. Finally, the curve is predicated on the probability distribution being gaussian out to the tips of the distribution. Any amplifier non-linearity will change the distribution.

—B. M. Oliver

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