SECTION 2

BASIC MEASUREMENTS

2-1 GENERAL

Basic electronic measurements involve the fundamental electrical quantities, voltage and current, and the circuit characteristics, resistance, capacitance, and inductance. The voltage and current in a circuit are dependent on the resistance, capacitance, and inductance. Therefore, voltage and current measurements are used to determine circuit conditions.

2-2 VOLTAGE MEASUREMENT

Voltage measurements, when compared with available voltage charts, provide a valuable aid in locating trouble quickly and easily. However, if the sensitivity of the test voltmeter differs from that of the voltmeter used in preparing the chart, the voltage measurements must be evaluated before the true circuit conditions can be determined. It must be kept in mind that in certain cases a voltmeter, particularly one of low sensitivity used on a low range, may disturb some circuits to such a degree as to render them inoperative or the voltmeter will provide a false indication.

2-2.1 DC VOLTAGE MEASUREMENT

Direct current voltage may be either steady or pulsating, and may be superimposed on ac. The average value of a dc waveform depends on symmetry and waveshape, and may vary from 63.6 percent of peak value for a rectified full sine wave to 50 percent of peak value for a triangular wave, and to 0 for a superimposed sine wave. Regardless of whether the dc is steady or pulsating, or whether ac is superimposed on the dc, a rectifier form of measuring device will indicate average value. All voltages are measured by placing the meter in parallel with the component, circuit, or equipment to be measured. Therefore, the voltmeter should theoretically have an infinite internal resistance so that it will absorb no energy from the circuit under test and will measure the true voltage. The accuracy of the voltage indication depends on the total meter resistance in comparison with the parallel resistance across which the voltage is being measured. As the value of the load decreases, the percentage of error is reduced; ordinarily, when the voltmeter resistance is ten times greater than the resistance across which the voltage is being measured, the error can be tolerated. If this error cannot be tolerated, a high input impedance voltmeter should be used. This can usually be accomplished with a vacuum tube voltmeter (VTVM). Using two voltmeters in series increases the voltage range and in many cases provides a more accurate measurement of voltage across the load (because of the increase in voltmeter resistance). If the voltage to be measured is sufficiently high, several similar voltmeters can be connected in series across the load to provide greater accuracy; the total voltage drop is the sum of the individual meter indications.

2-2.1.1 Oscilloscope Method

A dc voltage measurement can be made with an oscilloscope having a direct-coupled deflection amplifier or terminals for connection directly to the deflection plates of the cathode-ray tube. A dc voltage can also be measured by an oscilloscope having only an ac vertical deflection amplifier input if an electrical chopper is used in conjunction with the oscilloscope. This is a vibrator type of device which periodically interrupts the voltage applied to the oscilloscope input to form a rectangular waveshape. The resultant signal can then be coupled to the ac deflection amplifier, and the peak-to-peak voltage will be the same as the value of the original dc voltage. Normally, the measurement of the dc voltage with an oscilloscope is convenient only when other measurements are being made on the same equipment with the oscilloscope, or when a vacuum tube voltmeter is not available and a high impedance voltmeter is required.

2-2.1.2 Electronic Voltmeter Method — DC

The vacuum tube voltmeter is a highly versatile and broadly used piece of electronic test equipment. It can be used to measure ac voltages, both positive and negative dc voltages, and resistance. Most VTVM's will have the following characteristics: high input impedance (10 megohms), several ohmmeter scales, wide frequency response, peak-to-peak voltage scales, meter protection against burnout, and a feature to zero the meter. When the VTVM is used for measuring dc voltages it is usually because of its high input impedance. This high input impedance allows the technician to measure circuits where no loading can be tolerated, such as automatic gain control (AGC) or automatic frequency control (AFC) circuits.

2-2.1.3 Digital Voltmeter Method

The most common voltmeters used Navy-wide today have an accuracy generally around ± 2% of full scale reading. The digital voltmeter in most cases provides an accuracy of ± 5 percent in the less expensive models. The DVM displays the reading numerically, reducing human error and tedium, and increases reading speed. Automatic range and polarity-changing features also reduce human error. Data in a digital form can also be processed by a computer. Many DVM's have outputs to record measurements on printers, tape and card punches, and magnetic tape equipment. Most DVM's have a high input impedance and are not as likely to disturb the circuit being tested.

2-2.2 AC VOLTAGE MEASUREMENT

For ac voltage measurements, the input impedance of the meter will determine the amount of energy removed from the circuit under test. The sensitivity of the meter will determine the lowest voltage that can be measured. The shunt capacitance of the meter input will determine the upper frequency limit of the meter. If the ac meter is placed across a high impedance circuit, the meter will load the high impedance circuit, disturbing circuit conditions possibly to the point where the circuit ceases to function. Furthermore, if the circuit being measured is a relatively high frequency circuit, the internal capacitance of the ordinary voltmeter rectifier can produce circuit disturbance by detuning the circuit. For sensitive voltage measurements, an electron tube voltmeter or an oscilloscope should be used to obtain a high shunting resistance across the circuit under test. A dc electronic voltmeter in conjunction with a rectifying probe uses or extracts only small amounts of energy from the circuit under test. Another advantage of an electronic voltmeter over the ordinary voltmeter is that voltages of lower magnitudes can be measured.

2-2.2.1 Oscilloscope Method

An oscilloscope may be used as a high impedance voltmeter. In standard oscilloscopes, the vertical amplifier input impedance is generally greater than 1 megohm, making it possible to measure voltages in high impedance circuits. If the signal is applied directly to the plates, rather than at the vertical amplifier input, the input impedance is increased considerably. A major advantage of using an oscilloscope for voltage and current measurements is that the waveform can be observed; consequently, errors in measuring complex peak voltages are minimized. Voltage measurements are easiest to make when the deflection of the trace extends across the major portion of the scope screen. If the amplitude of the measured voltage is very low, the trace dimensions may be small; however, whenever possible, the trace should extend across at least 60 percent of the screen diameter. If a large voltage to be measured cannot be attenuated to a usable value by circuits within the oscilloscope, an external resistive or capacitive voltage divider can be used. Such voltage dividers are often furnished with oscilloscope test sets, and are called voltage multiplier probes. When the voltage of pulses or other complex waveforms is being measured, the divider must be so designed as not to distort the measured signal. The oscilloscope can be calibrated for voltage measurement by applying a known voltage to the vertical horizontal input and observing the number of graticule units the trace is deflected. For ac voltage measurements, it is advisable to use the ac deflection amplifier circuits to eliminate any dc portion of the waveform. This will simplify measurements, especially if identification of the positive and negative portions of a signal is desired. The zero reference line can be established by decreasing the vertical amplifier gain to zero and positioning the horizontal trace along one of the lines of the graticule. The peak-to-peak voltage of the applied signal can be calculated by counting the number of graticule units from the positive to the negative peaks and multiplying the voltage value per unit, which was determined during the calibration of the oscilloscope. The value of the positive or negative portion of the waveform can be calculated by counting the number of graticule units from the zero reference line to the peak to be measured. If the oscilloscope has been calibrated to indicate peak voltage and it is necessary to determine the rms voltage of a sinusoidal signal, divide the graticule units from the positive to the negative peaks by half and multiply this value by 0.707. When utilizing the oscilloscope for ac voltage measurements, care should be taken to ensure the upper frequency range of the oscilloscope is not exceeded, otherwise inaccurate values will be displayed.

2-2.2.2 Electronic Voltmeter Method — AC

The vacuum tube voltmeter is a highly versatile and broadly used piece of electronic test equipment. It can be used to measure ac voltages, both positive and negative dc voltages, and resistance. Most VTVM's will have the following characteristics: high input impedance (10 megohms), several ohmmeter scales, wide frequency response peak-to-peak voltage scales, meter protection against burnout, and a feature to zero the meter. When the VTVM is used for measuring ac voltages it's usually because of its high input impedance and wide frequency response. This high input impedance allows the technician to measure circuits where no loading can be tolerated such as on the base of a transistor. The technician can expect most VTVM's used Navy-wide to be accurate from dc to 400 megahertz (UHF).

2-2.2.3 Digital Voltmeter Method — AC

Same as dc digital voltmeter method. See digital voltmeter method - Paragraph 2-2.1.3.

2-3 CURRENT MEASUREMENTS

Unless an ammeter is already an integral part of the circuit under test, current measurements are rarely taken. Usually, current measurements can be taken only if the ammeter is placed in series with the circuit under test, and this requires that a circuit connection be unsoldered or otherwise opened to inject the meter. An easier method to obtain a current measurement would be to take a voltage measurement and calculate the current with Ohm's law. In addition, a high resistance circuit will contain such a small amount of current that it cannot be measured accurately with ordinary field test equipment. The accuracy of measured current depends on the relative magnitude of the series meter's internal resistance as compared with the resistance of the external circuit. If the total circuit current is decreased by increasing the load, R_L, then the percentage of error will decrease. Therefore, greater accuracy is obtained if the meter resistance is much less than the load resistance. A method of obtaining greater accuracy of current measurement is to decrease the total internal meter resistance with respect to load resistance. This is accomplished by connecting two ammeters in parallel with each other, and in series with the circuit in which the current is being measured. Additional ammeters may be connected in parallel in the same manner for additional accuracy. The arithmetical sum of all the parallel meters represents the total current flow in the circuit.

2-3.1 AC CURRENT MEASUREMENT

Current can be measured with an oscilloscope by shunting the signal input terminals with a low-value resistor. The oscilloscope input terminals and resistor are then connected in series in the circuit to be tested. The value of the resistor must be small so as not to interfere with the operation of the circuit under test, but it also must be large enough that the voltage developed will cause adequate deflection of the oscilloscope trace. For example, if an oscilloscope having a vertical deflection sensitivity of 0.1 volt rms per inch is used in conjunction with a 10-ohm shunt resistor to measure a 25-mA current, the vertical trace will be deflected 2.5 inches.

$$E = IR$$

$$E = 0.025 \times 10 = 0.25 \text{ volts}$$

$$\text{Deflection} = \frac{\text{voltage}}{\text{sensitivity}} = \frac{0.25}{0.1} = 2.5 \text{ inches}$$

For current measurements the oscilloscope can be calibrated by connecting an ammeter in series with the input terminals and the calibration signal source. An alternate method is to determine the value of the shunt resistor, and measure the calibration signal developed across it with an accurate voltmeter. The calibration signal current can then be calculated by means of Ohm's law. Since the oscilloscope merely indicates the voltage developed across the shunt resistor, the measurements for alternating or direct current will be similar to voltage measurements using an oscilloscope.

2-3.2 CURRENT PROBES

Although not used very often by Navy technicians, current probes are available. The primary advantage in using a current probe is that it does not need to be in series with the current being measured. The unsoldering of wires or connection to terminals is not necessary. These probes can be broken into three basic classifications of passive, active and Hall effect. Each type has advantages and disadvantages peculiar to its method of operation. Prior to using a current probe it is recommended that the technician thoroughly understands the application instructions.

2-4 RESISTANCE MEASUREMENTS

Point-to-point resistance charts referenced to accessible points within the equipment are contained in many maintenance publications. Without these equipment resistance charts, resistance measurements within a complicated circuit would be difficult. Most circuits contain other circuit elements, such as a coil or resistor, in parallel with the resistance being measured. Thus, to eliminate this possible source of error, disconnect or unsolder one side of the resistor or group of resistors under test. It is best to be acquainted with the calibration of ohmmeter scales, especially on the higher ranges, because it is often not possible to obtain accuracy on the maximum scale range of the meter. An ohmmeter used in field testing should be portable, convenient, and simple to operate; these factors are generally more important than extreme accuracy. With the exception of bridge circuits, voltage dividers, and balanced circuits, a meter may provide only approximate resistance readings, but these readings are adequate, considering the wide tolerances of resistors themselves. When an ohmmeter is used, completely de-energize the circuit under test and remove any tubes, meters, or other current-sensitive elements before the resistance measurement is performed. Because of the excessive battery or source voltage drain and possible component damage, low values of resistance should not be measured with an ohmmeter. Low resistances requiring precision measurement should be measured with a bridge type of instrument. An ohmmeter consists of a galvanometer, batteries, and resistors of known value connected in such a way that unknown resistors to be measured are compared with standards. Figure 2-1 illustrates some basic ohmmeter circuits.

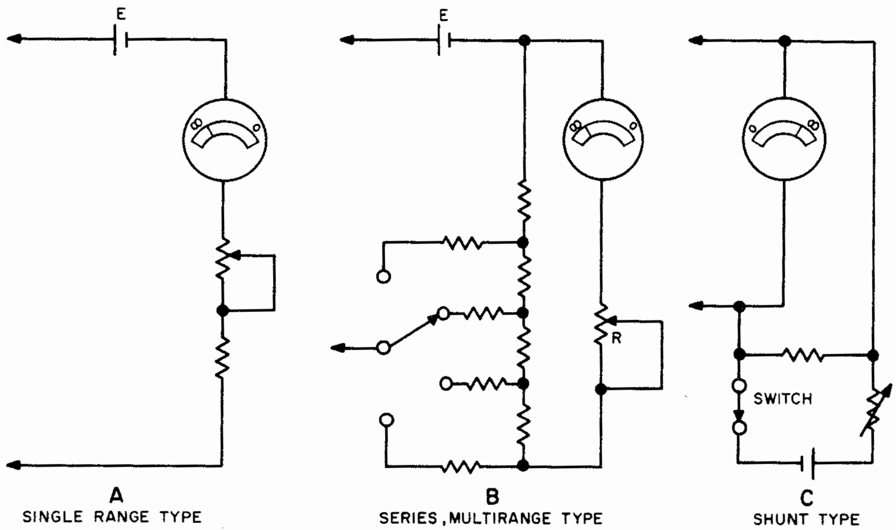


Figure 2-1. Basic Ohmmeter Circuits

When the test leads of the meter are shorted, the series resistor is adjusted for full-scale deflection. The scale markings are spaced closer together toward the infinity point on the meter. Therefore, more accurate readings are obtained on the lower portion of the scale. Ohmmeter applications include resistance measurements, continuity checks, and inductor, capacitor, and transformer checks. A transformer may be tested by checking whether there is an open or short, low insulation resistance to ground, or improper continuity within the transformer windings. A capacitor may be tested to determine whether it is open or shorted. When the ohmmeter is placed in series with the capacitor, the ballistic kick of the meter, due to the changing current, is proportional to the capacitance. The deflection obtained is compared with the deflection from a capacitor of known value. An external series battery will increase the sensitivity of the instrument. Megger-type meters are used to measure resistances as high as 10,000 megohms, because they are capable of providing large voltages to produce readable indications. The unknown resistance is connected between the megger terminals, and the hand generator part of the meter is cranked. A low resistance will cause the pointer to be pulled off the scale toward zero, so only high-resistance values can be measured.

2-4.1 DIGITAL MULTIMETERS

The digital multimeter, when measuring resistance, has the same operator advantages as the DVM in Paragraph 2-2.1.3. When measuring below 10,000 ohms, be sure to zero the meter. Resistance accuracy is given at the meter input terminals and does not take into account lead resistance.

2-5 CAPACITOR MEASUREMENTS

Capacitance is that property of a circuit which produces an electrostatic field when two conducting bodies separated by a dielectric material have a potential applied to them. Capacitors are made by compressing an insulating material, the dielectric, between two conductors, the plates. The farad, which is the basic measurement of a capacitor, is dependent upon the area of the plates, the distance between the plates, and the type of dielectric used. Electrically, it is a measure of one coulomb of potential charged by one volt. Since a coulomb, the amount of current flow maintained at one ampere that passes a given point of a circuit in one second, is such a large charge a one-farad capacitor would be enormous. Therefore, most capacitors are measured in millionths of a farad (microfarad) expressed as μF or in one millionths of a microfarad (picofarad) expressed as pF. Capacitors incur various losses as a result of such factors as resistance in the conductors (plates) or leads, current leakage, and dielectric absorption, all of which contribute to the power factor of the capacitor. Theoretically, the power factor of an ideal capacitor should be zero; however, the losses listed above cause the power factors of practical capacitors to range from near zero to a possible 100 percent. The average power factor for good capacitors, excluding electrolytics, is 2 to 3 percent. Current leakage, which is an inverse function of frequency, is important only at the lower frequencies, and becomes negligible as the higher frequencies are reached. Dielectric absorption (sometimes referred to as dielectric viscosity) results in losses that produce heat, and has the same effect as resistance in series with the capacitor. It should be noted that some capacitors can retain a charge long after the voltage has been removed. The electrical charge retained by capacitors in electronic circuits when de-energized is, in many cases, sufficient to cause a lethal shock. This hazard shall be considered before performing any type of maintenance on any electric or electronic circuit, or before making connections to a seemingly dead circuit. Be safe — discharge and ground all high-voltage capacitors and expose high-voltage terminals leads, and the like by using only an authorized shorting probe. Repeat discharge operations several times to make sure that all high voltage terminations are completely discharged. Extreme caution shall be used prior to working on or near de-energized circuits which employ large capacitors. Short-circuit the terminals to ground, using only an authorized safety shorting probe or built-in grounding bar for this purpose. It is of the utmost importance that technical and maintenance personnel engaged in repairs of circuits which employ large capacitors, use only an authorized safety shorting probe to discharge the circuits before performing any work on them. The only authorized general-purpose safety shorting probe for naval service application may be requisitioned, using National Stock Number (NSN) 1H-5920-01-029-4176. Certain electronic equipments are provided with built-in special-purpose safety shorting probes. These probes are not considered "general-purpose", and are to be used only with the equipment with which they are provided, and only in a manner as directed by the technical manuals for the equipment. THEY SHALL NOT BE REMOVED AND USED ELSEWHERE. When using the general-purpose safety shorting probe, always be sure first to connect the grounding clip to a good ground connection (if necessary, scrape the paint of the grounding metal to make a good contact). Then, while holding the safety shorting probe by the handle behind the protective shield, touch the end of metal rod to the point to be shorted-out. Touch each point to be shorted-out several times to make sure that the circuit is completely discharged. Always be extremely careful and make absolutely sure that you do not touch any of the metal parts of the safety shorting probe while touching the probe to the exposed "hot" terminal. It pays to be safe; use the safety shorting probe with care. Large capacitors, dormant in storage, can also develop a large static charge. This charge is caused by environmental conditions such as a close proximity to an RF field. An easy way to avoid this condition is to short the stored capacitor's terminals with a piece of wire. Remember to remove the wire before installing the capacitor. If you receive a large capacitor which is not shorted, short the terminals together. Remember, charged capacitors can kill.

2-5.1 TYPES OF CAPACITORS

In the manufacture of capacitors, a number of materials can be used as dielectric. The following is a brief discussion of some of the commonly used dielectrics.

2-5.1.1 Paper Capacitors

Paper dielectric capacitors consist of two thin sheets of foil wound together around a layer of impregnated paper. This paper is treated from forest floor to capacitor manufacture. It is impregnated with mineral oil or a synthetic for increased dielectric constant. Normally, the capacitors are then either hermetically sealed or wrapped in a waxed film of paper to seal out moisture. This type of construction can produce an inductance factor. Inherent inductance can be reduced to almost zero by straddling the sheets of foil and capping the ends, thus shorting out the inductance. Another disadvantage to paper dielectric capacitors is their material's natural imperfection. Minute holes may exist in the paper, shorting out the capacitors. To lessen this effect, multiple layers of paper are used. This also increases the voltage rating. A new type of paper capacitor is the metallized paper type. They are made by applying a thin vapor of metal on the paper and then rolling it with other layers of paper. This gives access to increased capacitance capabilities due to the better bond between the plates and the dielectric. A higher voltage rating is also achieved because any internal arcing will burn away the film in the area of the arc. This self-healing effect is a disadvantage when used in RC logic networks. The internal arcing can alter desired signals. Paper capacitors are designed to operate in low ambient temperature ranges of between 0^{o}-85^{o}C, and normally range between .001 µf and 15 µf, although some may range as high as 75µf. From the circuit usage standpoint, the capacitance tolerance for paper capacitors used for coupling and by-passing is rather wide, and compares with the tolerance for electrolytic filter capacitors. Contrary to the wide-spread impression among many technicians, metal-encased capacitors are not necessarily manufactured to close tolerances for paper tubular capacitors. Table 2-1 shows the standard capacitor tolerances for paper tubular capacitors.

2-5.1.2 Plastic Film Capacitors

A very new approach to making capacitors is the plastic film type. Plastic film capacitors are very dense, and they exhibit a relatively high dielectric constant with good insulation resistance. In addition, the plastic film can be manufactured into very thin strips with good physical strength. Plastic film capacitors are

TABLE 2-1. TOLERANCES FOR PAPER TUBULAR CAPACITORS

CAPACITOR LETTER CODE	CAPACITOR TOLERANCE (PERCENT) PLUS	MINUS
K	10	10
L	15	15
V	20	10
M	20	20
W	25	0
X	40	15
Y	60	25

probably the best replacement for paper capacitors because of their ease of construction once the film is made. The construction is similar to that of paper capacitors. The best known types of plastic film capacitors are made of polyester film. However, other materials, such as polystyrene, cellulose triacetrate, polyparaxylene, polytetrafluoroethylene (better known as Teflon) and others are also used in the making of plastic film capacitors. Some have higher temperature ranges, while others may provide better stability over a longer period of time but, because the production cost of polyester is far less than that of most other plastic materials, polyester is more commonly used in military applications.

2-5.1.3 Mica Capacitors

Mica capacitors consist of two sets of metal-foil plates separated by thin sheets of mica. Mica is used in capacitors because of its excellent dielectric properties and high breakdown voltage resistance, and also because it can be split into sheets of definite thicknesses. Tabs are attached to each metal-foil plate for external connection. The unit is provided with lugs (or pigtail leads), and then molded in a bakelite cover. Another form of mica capacitor is the silver-fired type. This type provides a more precise contact between the dielectric and the plates. A silver coat is applied directly to the mica and the whole unit is fired in a furnace. Greater capacitance, with an increase in the mechanical resonant frequency, is achieved because the dielectric and plates are bonded as one. These silver mica capacitors are almost exclusively used in modern applications. The dipped capacitor is the most common application of the silver mica capacitor. Capacitors utilizing mica as a dielectric are characterized by low losses and long useful life. Practical values for mica capacitors range from 1 pF to 91,000 pF with voltage rating approaching 30,000 WVDC.

2-5.1.4 Glass Capacitors

Glass capacitors are constructed very similar to mica, but since glass does not have the natural imperfections of mica, aluminum foil is used instead of tin lead foil. Since aluminum has a higher melting point than tin lead, it can be fused with the glass dielectric. This makes for a more durable capacitor. Practical values are near those of mica from .5 pF to 10,000 pF.

2-5.1.5 Ceramic Capacitors

Capacitors using ceramic dielectrics on which a deposit of silver is plated to form the plates are similar in size to the mica type. However, a ceramic capacitor can be made considerably smaller than a mica capacitor for a given capacitance, because certain ceramics have dielectric constants that are much greater than that of mica. With higher dielectric constants, however, there is usually associated a high and nonlinear temperature coefficient and somewhat higher losses. In addition to their compactness, these capacitors can be designed to have either a positive or negative temperature coefficient, or they can be made so that they are essentially unaffected by temperature. Practical values for these capacitors range from 1 pF to 1 μF.

2-5.1.6 Electrolytic Capacitors

The dc electrolytic capacitor makes use of the fact that aluminum (and certain other materials), when placed in a suitable solution and made the positive electrode, forms a thin insulating surface film; this film withstands a considerable voltage, and at the same time has a high electrostatic capacitance per unit area of film. The thickness of the film depends upon the amplitude of the voltage used in its formation; higher voltages result in thicker films. The film gradually disintegrates if the impressed voltage is removed, but is again formed when the voltage is reapplied. The forming action is accompanied by a large leakage current, which soon drops to normal (approximately 200 microamperes per microfarad for 450 volts). Continuous operation over a period of several hours further drops the leakage current to a few microamperes per microfarad. Operation of this type of electrolytic capacitor for a considerable period of time at a voltage lower than the forming voltage causes the thickness of the film to decrease, and as a result the capacitance increases. To maintain the oxide film intact, a positive potential must be applied to the anode; hence, the use of these capacitors is restricted to direct current only. (Electrolytic capacitors are also designed for ac applications by placing two positive electrodes in one container. When connected to an ac source, the electrodes produce a rectifying effect; hence, they are not polarized. An example of this type of capacitor is the ac motor-starting capacitor.) Voltages in excess of the working voltages may puncture the film; however, if the applied voltage is reduced, the healing action of the electrolytic capacitor will sometimes restore the film. Because large losses accompany the use of electrolytic capacitors, they are used principally in filter circuits, where the losses can be tolerated. Of the previous types of capacitors mentioned, it is relatively easy to ascertain if they are shorted or open. An electrolytic capacitor does not fall into either one of these categories. If an electrolytic capacitor is replaced with one having a high leakage current, the new capacitor will either fail in a very short time, cause poor overall operation, or cause damage to other circuitry of the equipment concerned. The direct-current leakage of an electrolytic capacitor, when measured with an acceptable capacitor analyzer, should not exceed the current value which can be calculated from the information listed in Table 2-2.

TABLE 2-2. ELECTROLYTIC CAPACITOR LEAKAGE CURRENT CHART

RATED WORKING VOLTAGE (VOLTS)	ALLOWABLE LEAKAGE CURRENT (mA/μF)
15 to 100	0.1
101 to 299	0.2
300 to more	0.5

For example, if a 16 μF capacitor rated at 450 volts (working voltage) is to be tested, multiply the value of the capacitor (16 μF) by the allowable leakage current for that voltage category (0.5 mA). The total allowable leakage current, therefore, is 9 milliamperes. The information listed in Table 2-2 applies to both wet and dry electrolytic capacitors. If the direct-current leakage exceeds the calculated allowable leakage, the capacitor should be discarded. Capacitors in spares (especially wet electrolytics) should be tested periodically to ensure that the leakage current remains within the prescribed limits. Sometimes it is necessary to reform capacitors that have been idle for a while. There are several means of accomplishing this. One would be to apply a low voltage of approximately 10% of rated value to the capacitor, increasing it to rated value over a period of one minute. Tantalum electrolytic capacitors are finding more and more uses in military applications because of their excellent stability at varying temperatures. They are most commonly found in miniature electronic circuits, especially computer circuits because they do not arc internally. In addition, more capacitance per size than with the aluminum electrolytics can be realized. Also, tantalum capacitors can be operated over a wider temperature range, 80°C to +200°C, and they have an almost indefinite storage life without reforming. Practical values for electrolytic capacitors are from 5 μF to 2000 μF for aluminum, and from .25 to 2200 μF for tantalum.

2-5.1.7 Air Capacitors

Variable capacitors employing an air dielectric are used to adjust the resonant frequency of tuned circuits whenever a variable capacitor having small losses is required. Some of these small losses, which contribute to an increase in the power factor, are due to a charging current in the plates and leakage associated with the insulators that isolate the stator from the rotor. Other losses are incurred by the coupling shaft which connects the stationary plates of the variable air capacitor. Practical values for these capacitors range from 5 pF to 600 pF for the maximum capacitance setting.

2-5.2 CAPACITANCE-MEASURING EQUIPMENT

Capacitance measurements are usually accomplished by either a bridge-type or a reactance-type capacitance meter. For accuracy, the former equipment is comparable to the resistance bridge, and the latter instrument is comparable to the ohmmeter. Capacitance tolerances vary even more widely than resistance tolerances, being dependent upon the type of capacitor, the value of the capacitance, and the voltage rating. The results of capacitance tests must be evaluated to determine whether a particular capacitor will fulfill the requirements of the circuit in which it is used. The power factor of a capacitor is important because it is an indication of the various losses attributable to the dielectric, such as current leakage and dielectric absorption. Current leakage is of considerable importance, especially in electrolytic capacitors. Capacitor tests involving quality and value must be made in the course of electronic servicing; however, the technician must make the important decision of whether to reject or continue to use a certain capacitor after it has been tested. The following basic types of test equipment circuitry are used for capacitance measurement: the reactance type, which is often an associated test circuit incorporated into another test equipment to increase its usefulness and the Q-meter, which makes use of the resonance technique.

2-5.2.1 Bridge Type

To facilitate the discussion concerning the bridge-type capacitance analyzer, the ZM-11/U Bridge will be used as a representative test equipment. Although the ZM-11/U Bridge measures, among other tests, inductance and resistance as well as capacitance, the discussion that follows covers only the measurement of capacitance. The capacitance measurement portion of the test equipment is shown in Figure 2-2.

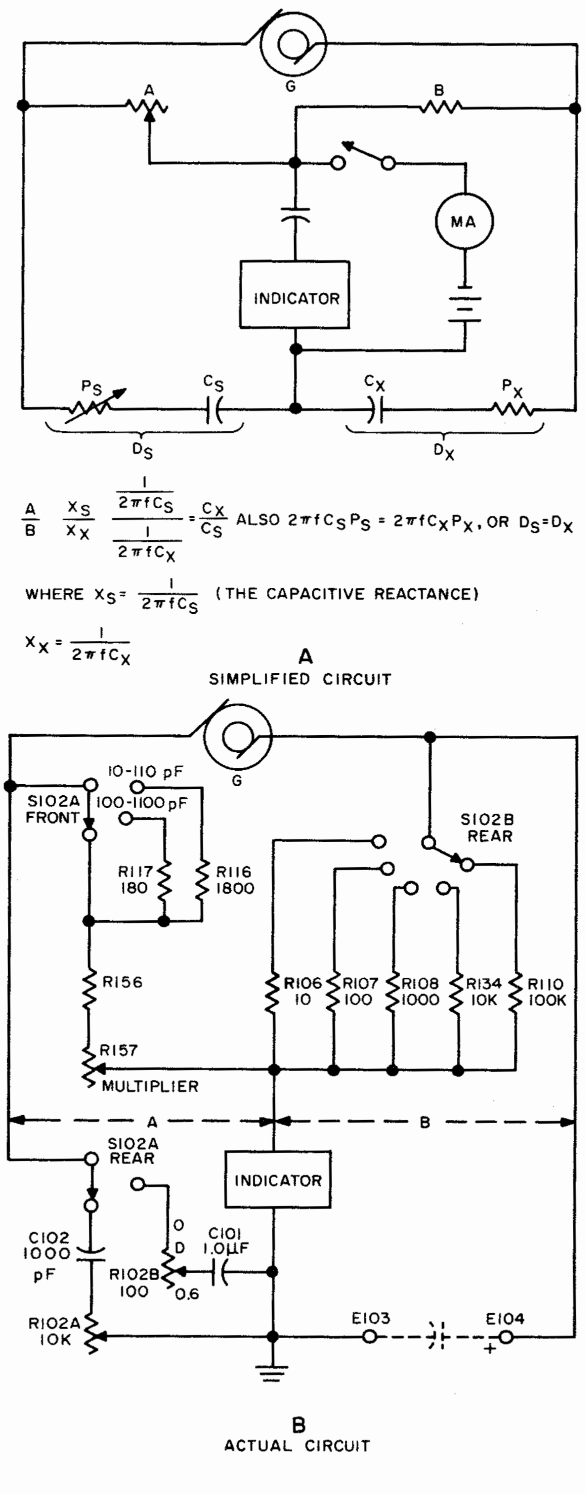


Figure 2-2. Capacitor Bridge Measuring Circuit

The measurement of capacitance is made by a suitable bridge circuit, which will be described in Paragraph 2-7.1. Incidental to the measurement of capacitance, the dissipation factor (analogous to power factor) of the capacitor under test is determined; this reading may be applied to circuit problems, with due regard, however, to the frequency of the alternating current (1000 Hz) used for testing. A dc polarizing voltage is provided for application to electrolytic capacitors while measuring their capacitance value and dissipation factor. The capacitor leakage current may be determined either with or without taking the capacitance or dissipation readings. Part (A) of Figure 2-2 shows a simplified bridge circuit which will be used to explain the measurement of capacitance. As can be seen from the balance equation, shown in the same figure, it is actually the capacitive reactance, rather than the capacitance, which is balanced. In addition to its reactive property, the capacitance under test always exhibits some loss. This loss may have the characteristics of either a shunt or a series resistance, or it may be a combination of both. Regardless of its true nature, the loss can always be represented by a simple series resistance, which is shown as P_X in part (A) of the figure. This loss can be balanced by the calibrated series resistance, P_S, shown in the standard arm side. Rather than calibrate this control in terms of resistance, it is an operational convenience to calibrate it in terms of the dissipation factor, D, as indicated in Part (A) of Figure 2-2. The control then provides the means for completing the capacitance balance, and its dial reading indicates a loss figure for the capacitor under test. Part (B) of Figure 2-2 shows the actual circuit arrangement used for the measurement of capacitance. Two capacitance standards are used, and progressive capacitance ranges are provided. Because two values of standard capacitance are used, two values of the dissipation factor must also be provided. These controls are ganged on one shaft, to which is attached the D (dissipation) panel dial. The 1000-pF standard is used through the first four capacitance ranges, 10 pF to 0.11 µF. Capacitors tested in this ranges are usually constructed with mica or paper as the dielectric, and cannot have a very high dissipation factor before their condition is suspected. For this reason, with the 1000-pF standard, the dissipation factor, D, was limited to a maximum value of 0.06. This provides the best readability in the region of usual interest. The remaining capacitance ranges cover capacitor values from 0.1 µF to 1000 µF. In the higher portion of this range, the capacitor under test is likely to be of electrolytic construction, and a wider range of the dissipation factor is required to balance acceptable capacitors. Therefore, for the latter four ranges, the dissipation factor covers from 0 to 0.6. The stray capacitance between the panel connections, together with that of the connecting wiring and switch contacts, amounts to about 17 or 18 pF. This is compensated for in the following manner. It is to be noted that in part (B) of Figure 2-2, for the 10 to 110 pF range the resistance of the "A" arm is 100 ohms per pF and that for this range, an 1800-ohm resistor inserted in the "A" arm has the effect of subtracting 17 pF from the reading of the multiplier dial. Similarly, on the 100 to 1100-pF range, insertion of 180 ohms has the same effect. The above resistors are inserted automatically by suitable contacts on the FUNCTION and RANGE switches. The effect of the residual capacitance on the higher ranges is negligible, and, consequently, is not compensated for. Direct current electrolytic capacitors often require the application of a dc voltage in order to exhibit the same capacitance value and dissipation factor that they would in actual circuit operation. If the capacitor is in good condition, the first application of a dc voltage that is equal to or less than the working voltage causes a sudden rush of current, which falls back to a smaller steady value after 3 or 4 minutes. The steady current flow is known as the leakage current. When a stable value of current is reached, the capacitor is said to be polarized. For the testing of electrolytic capacitors under simulated circuit conditions, a hypothetical battery and meter are shown in part (A) of Figure 2-2. The series capacitor blocks the battery from the indicator, and the dc flow is through the "B" arm and the capacitor under test, C_X (and P_X). The dc leakage current may be read on the meter. In the typical bridge-type analyzer, the battery function is replaced by a power supply of the RF type. The panel meter is normally connected as a 0 to 500-volt voltmeter, so that the technician can measure the potential applied to the capacitor under test. When the meter switch is turned to the mA settings, current ranges of 25, 5 and 1 milliampere are selected, in turn, to obtain a measurement of the leakage current through the electrolytic capacitor. Note that the dc power supply and meter circuits are so connected that there is no interference with the normal operation of the capacitance-measuring bridge circuit, and also that the dissipation factor of the capacitor may be obtained while the capacitor is polarized.

2-5.2.2 Reactance Type

The reactance type of capacitance measuring equipment makes use of the following principle: if an ac voltage (usually 6.3 volts) of fixed frequency is applied across a capacitor and resistor in series, the voltage drop produced across the reactance of the capacitor by the resulting current flow is inversely proportional to the capacitance. The voltage drop is used to actuate a meter which is calibrated in capacitance values. This test equipment gives approximate values only, and, like the ohmmeter, is used mostly when portability and speed are more important than precision. The accuracy of the reading is less for capacitors that have a high power factor. In such a capacitor, the losses incurred effectively place a certain amount of resistance in series with the capacitive reactance. The effect of this resistance, when the capacitor is measured, is to cause a greater voltage drop across the capacitor. This drop is due, not to the reactance above, but to the impedance, which is comprised of both the reactance and the resistance. Therefore, it can be seen that the capacitance indicated by the analyzer will be lower than the actual value. Figure 2-3 shows a simplified schematic diagram of the capacitance-measuring section of a typical reactance-type electronic volt-ohm-capacitance-millameter. A 6.3 ac voltage is taken from the filament-designated value of the capacitor. Because of a particular use or circuit application, some capacitors are permitted an even wider variation of capacitance value than is indicated by their rated tolerances.

2-5.2.3 The Octopus

A quick in-circuit check to determine the go/no go condition of a capacitor can be accomplsihed with the aid of an octopus. (The use of the octopus is discussed fully in Paragraph 2-10). Basically, an ac signal is applied across the capacitor and a resultant pattern is displayed on an oscilloscope. If the pattern is as it should be, the capacitor is usually good. This is only a quick check, and in no way establishes the overall quality of an in-circuit capacitor. Power factors cannot be determined with an octopus.

2-6 INDUCTANCE MEASUREMENT

A current flowing through a conductor produces a magnetic field around that conductor. If the conductor is formed into a coil, a stronger magnetic field is set up. The relationship between the strength of the field and the intensity of the current causing it is expressed by the inductance of the coil (or conductor). When the current producing the magnetic field ceases, the energy of the magnetic field is returned in part to the circuit source in the form of a reverse current. Inductance, then, is the ability of a coil to function as a storehouse of energy in magnetic form, and is determined by the shape and dimensions of the coil. Inductance is measured in henries, millihenries (0.001 henry), or microhenries (0.000001 henry).

2-6.1 INDUCTORS

Inductors can be described generally as circuit elements used to introduce inductive reactance into ac circuits. An inductor is essentially a coil of wire wound around a form utilizing a core of air, magnetic metal, or nonmagnetic metal. A core of magnetic

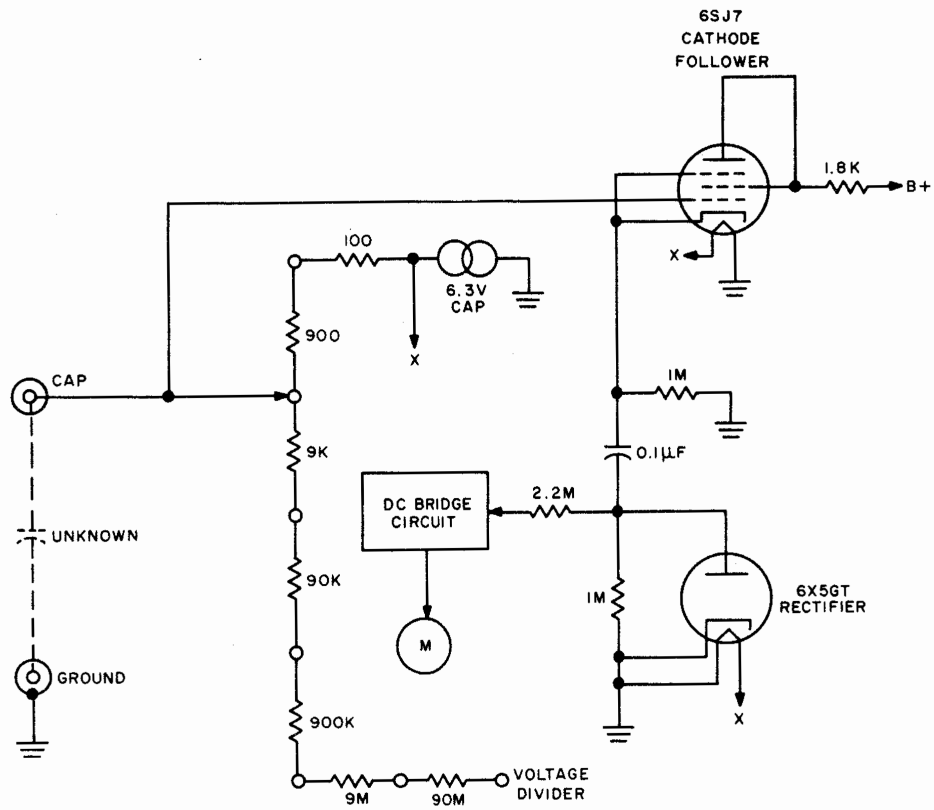


Figure 2-3. Capacitance-Measuring Section Taken from a Typical Reactance Type Electronic Volt-Ohm-Capacitance Milliammeter

metal produces greater inductance (for a coil of given size and number of turns) than does an air core; a core on nonmagnetic metal produces less. At frequencies in the HF and higher regions of the spectrum, coils of small size and high Q are generally required. These are usually single-layer solenoids with air or metallic cores. Since comparatively low values of inductance are required, this type of coil is very compact, and relatively high values of Q are obtained. At frequencies in the LF and MF regions of the spectrum, single-layer solenoid, universal, spiral, and other types of windings are used. When size is a factor, the more compact windings are preferred to the solenoid type of coil. At frequencies below 500 kHz, the single-layer solenoid is too large for practical use, therefore the more compact types are used exclusively. The inherent resistance of the conductor with which an inductor is wound is the most important factor contributing to the losses of the inductor. Losses due to this resistance increase with increased frequency, because skin effect results in concentration of the current near the outer surface of the wire. Skin effect, which is negligible at low frequencies, can be an important factor at high frequencies. Other contributing factors to inductor losses are: (1) eddy-currents set up in the core and surrounding objects (if they are conductors); (2) the dielectric properties of the form used for the coil and surrounding objects; and (3) hysteresis in the core and surrounding objects, if they are magnetic metals. Losses occur as a result of the dielectric properties of the coil form because of the distributed capacitance of the inductor, for example, between turns, between the terminals and leads, etc. To some extent the core (and surrounding objects) serves as a dielectric of the distributed capacitance, and the resulting dielectric losses contribute to the overall losses of the inductor.

2-6.2 SHIELDING

At radio frequencies, shields of aluminum or other highly conductive materials are placed around inductors. These shields have eddy-currents generated in them thus providing the shield. This will reduce magnetic coupling but lower the coil's final inductance increasing its losses over that of an unshielded coil. When low frequencies are involved, occasionally an inductor must be shielded with a material having a very high permeability such as Mumetal.

2-6.3 STORAGE FACTOR (Q)

As we discussed earlier, an inductor has the ability to act as a storehouse of magnetic energy. However, because of the various loss factors described above, all of the energy stored in the magnetic field is not returned to the source as the applied voltage decreases to zero. The losses of an inductor may be represented by an equivalent series resistance, having such a value that it would dissipate an amount of energy equal to the total amount dissipated by the inductor. The losses of an inductor may be expressed in terms of the ratio of its inductive reactance to its equivalent series resistance. This ratio is referred to as the Q of the inductor, and is stated in equation form as $Q = X_L/R$.

2-6.4 METALLIC CORES

At the relatively higher frequencies (HF and above), eddy-current losses preclude the use of solid or laminated metal cores. Instead, finely ground iron (or allo) particles are mixed with a bakelite filler and an insulating varnish binder, and pressed into the form of a cylindrical slug. This construction insulates the iron particles from one another, and thus reduces eddy-current losses. Coils utilizing powdered-iron cores are compact, and have high values of Q. Variation of the inductance is accomplished by mounting the iron slug so that it can be moved in and out of the coil along the coil axis.

2-6.5 FILTER CHOKES

Choke coils used in filters for elimination of power-line hum are always of the iron-core type. They are manufactured in inductance values of about 5 to 30 henries. Iron-core chokes are often used in circuits carrying both direct current and alternating current. To prevent saturation of the core (in this condition, an increase in current does not produce a corresponding increase in flux density), one or more air gaps are always built into the core. The total gap must be wide enough to prevent magnetic saturation but must not be so wide as to reduce the inductance below that required as a minimum.

2-6.6 INDUCTANCE MEASUREMENTS

Inductance measurements are seldom required in the course of trouble-shooting. However, in some cases inductance measurements are useful, and instruments are available for making this test. Many capacitance test sets can be used to measure inductance. Most manufacturers of capacitance test sets furnish inductance conversion charts if the test equipment scale is not calibrated to read the value of inductance directly. For the measurement of inductance, the following basic types of test equipment circuitry are used: (1) the bridge circuit type, which is the most accurate; and (2) the reactance type, which is often an additional test circuit incorporated into another test equipment to increase its utility. The measurement of capacitance was discussed, using ZM-11B/U Bridge (capacitance-inductance-resistance instrument) as a typical test equipment. Since the measurement of capacitance and inductance are interrelated, the existing capacitance standards and loss controls of this test equipment are utilized whenever possible. A wider range of dissipation must be provided to accommodate the practical value of inductors. In order to accommodate the extensive range in inductor loss factors, two basic bridge circuits are utilized: the Hay bridge; and the Maxwell bridge.

2-6.6.1 Hay Bridge

The Hay bridge measures inductance by comparing it with a capacitance; it differs from the Maxwell bridge in that the resistance associated with the capacitance is a series instead of a shunt resistance. The inductance balance depends upon the losses (Q) of the inductance. The Hay bridge is employed for inductors having low losses (low D dial reading or high Q) at 1000 Hz. This circuit is in effect when the FUNCTION switch is turned to the L(D) position, and its basic balance equations are shown in part (A) of Figure 2-4. The equations numbered (3) and (4) assume that D^2 may be neglected with respect to 1.0 under certain conditions. For a D dial reading up to 0.05, the error resulting from the above assumption is 0.25 percent. Above this point the error increases rapidly and appreciably affects the basic accuracy of the test equipment. This limitation is expressed on the front panel of the test equipment as follows: IF $D_L > 0.05$ ON L(D): REBALANCE ON L(Q). In other words, if the dissipation (D_L) of an inductor, as read on the D dial when using the Hay bridge (FUNCTION switch set to L(D) position) exceeds 0.05, then a change must be made to the Maxwell bridge (FUNCTION switch set to L(Q) position), which is discussed in the following paragraph. The loss factor of the inductor under test is then balanced in terms of the Q of the inductor.

2-6.6.2 Maxwell Bridge

The Maxwell bridge, shown in part (B) of Figure 2-4, measures inductance by comparing it with a capacitance and (effectively) two resistances. This bridge circuit is employed for measuring the inductance of inductors having greater losses than is expressed by a D dial reading of 0.05. For such inductors it is necessary to introduce, in place of the series control (D dial), a new loss control (Q dial), which shunts the standard capacitor. This control, which becomes effec-

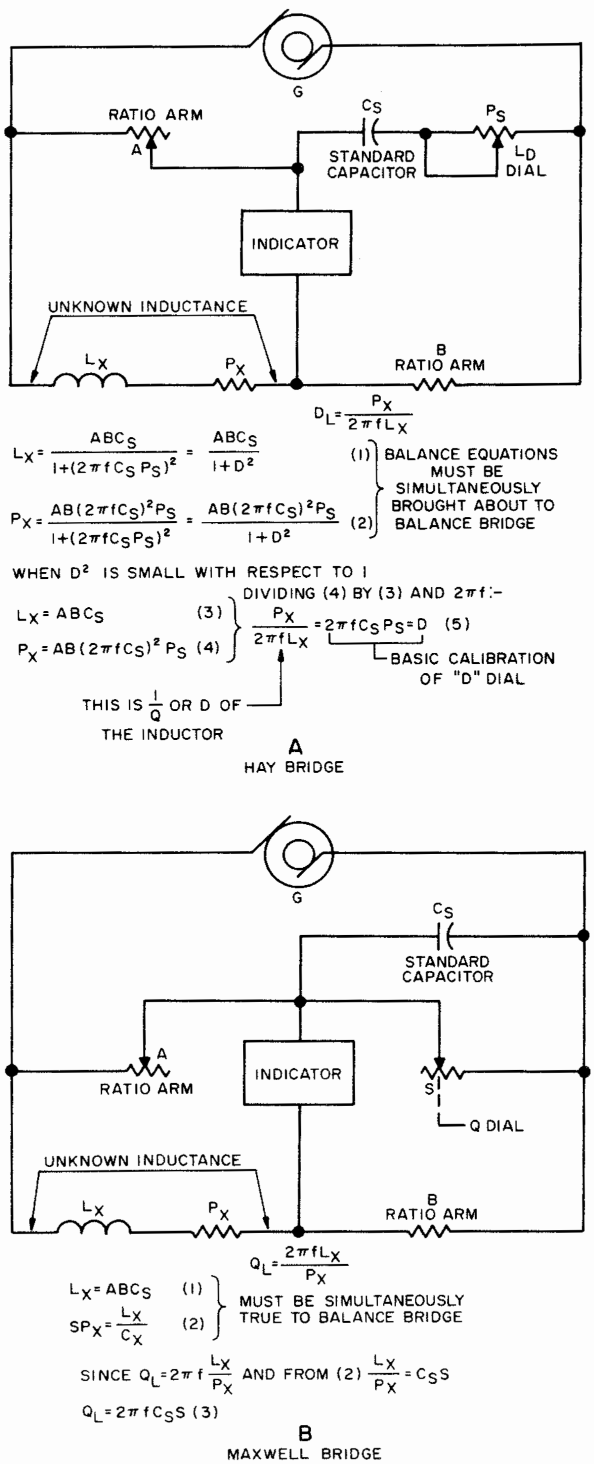


Figure 2-4. Basic Bridge Circuits Used for Inductance Measurements

tive when the FUNCTION switch is turned to the L(Q) position, is conveniently calibrated in values of Q, the storage factor of the inductor under measurement. Comparison of equation (3), shown in part (A) of Figure 2-4, with equation (1) of part (B) of the same figure shows that the balance for inductance is the same for either bridge circuit. This permits the use of the same markings on the RANGE switch for both the L(D) and L(Q) positions of the FUNCTION switch.

2-6.7 MEASUREMENT PROCEDURE

To measure inductance with the ZM-11B/U proceed as follows. Connect the inductor under test to the posts marked L (second and fourth from left). Turn the FUNCTION switch to the L(D) or L(Q) position, depending on the probable loss factor of the inductor under test. As a rule, inductors with powdered-iron cores (designed for operation in the af range) fall within the loss range of the L(D) position of the FUNCTION switch, and RF and AF inductors fall within the loss range of the L(Q) position. If you are unable to decide between the L(D) and L(Q) positions, you should attempt a balance on the L(Q) position first. Turn the RANGE switch to a reasonable setting with the L range, and attempt a balance by rotating the MULTIPLY BY dial. If any indication of balance is attained, try to complete it by simultaneous adjustment of the Q dial. If the condition of balance is approached at either end of the MULTIPLY BY dial, try the next higher or lower position of the RANGE switch and complete the bridge balance. If the condition is reached where a partial balance is attained on the MULTIPLY BY dial but lack of range on the Q dial does not permit completion of the balance, the inductor under test probably has a Q factor greater than 20. In this case, change the FUNCTION switch to the L(D) position. Using the D dial, balance should now be attained. (Mechanical interlocks between the D and Q dials make it necessary to return either one of the dials to its initial position before the other can be operated.) After bridge balance has been reached, as shown on the indicator tube, read the position of the RANGE switch on the L range and multiply this reading by the indication of the MULTIPLY BY dial. The product, then, is the inductance of the inductor under test. Note the indication of the D or Q dial at which balance was attained. If the apparent value of dissipation D, as measured on the L(D) position of the FUNCTION switch, is greater than 0.05, the balance point may have been missed on the L(Q) function. The operator should repeat the test on that function for greatest accuracy of inductance determination. The equivalent series resistance (at 1000 Hz) of the inductor can be determined by substituting the measured values in one of the following formulas, the selection of the formula depending upon whether Q or D is measured: $R = 2\pi fL/Q$, or $R = 2\pi fLD$ (where L is in henries).

2-6.8 REACTANCE MEASURING EQUIPMENT

The reactance type of inductance measuring equipment makes use of the following principle: if an ac voltage of fixed frequency is applied across an inductor (and a resistor in series), the voltage drop produced across the reactance of the inductor by the resulting current flow is directly proportional to the value of the inductance. It is readily seen that inductance measurement utilizing the reactance method is identical to capacitance measurements using the same method, except that current flow is directly proportional to the value of inductance, rather than inversely proportional as in the case of capacitance. It follows then that if a reactance-type capacitance measuring equipment is provided with a chart which converts the capacitance readings to equivalent inductance values, and a proper range multiplying factor, the same test setup can be used to measure both capacitance and inductance. In practice, test equipments using the reactance method for capacitance determination usually provide an inductance conversion chart. Because the current flowing through the inductance under test is directly proportional to the value of inductance, the reciprocals of the capacitance range multipliers must be used; for example, a multiplier of 0.1 becomes 1/0.1, or 10, and a multiplier of 100 becomes 1/100, or 0.01. The reactance-type equipment gives approximate values only, and, like the ohmmeter, is used only when portability and speed are more important than precision. If the ohmic resistance of the inductor is low, the inductance value obtained from the conversion chart can be used directly. If the ohmic value (as measured with an ohmmeter) is appreciable, a more accurate value of inductance can be obtained by use of the following formula: $L = \sqrt{Z_L^2 - R_L^2}/2\pi f$ (where L is the inductance, ZL is the impedance of the inductance under test, f is the frequency, and RL is the ohmic resistance).

2-6.9 MEASUREMENT OF INDUCTANCE USING THE VTVM

If using the ZM-11B/U is inconvenient or it is not available, inductance can be found by using a VTVM and a decade resistance box as shown in Figure 2-5. In the following example the inductance of an

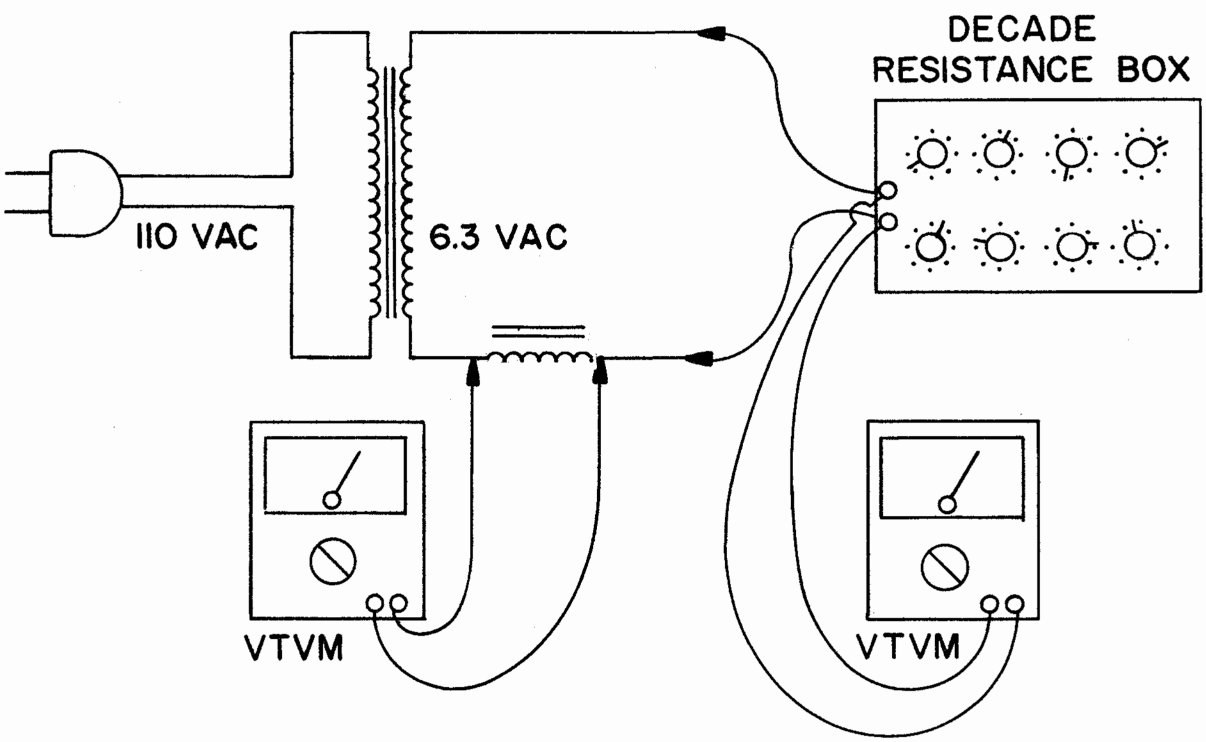


Figure 2-5. Determining Inductance with a VTVM and Decade Resistance Box

unknown coil in the secondary winding of a 6.3 filament transformer will be determined with a VTVM and decade resistance box. The unknown coil must be connected in series with the decade resistance box. The voltage across the decade box and across the coil must be monitored as the decade box is adjusted. When equal voltages are reached, read the resistance of the decade box. Since the voltage across the inductor equals the voltage across the decade box, the XL (inductive reactance) of the coil must be equal to the resistance read on the decade box. For an example, assume that the resistance reading on the decade box is 4000 ohms. This must mean that the XL (inductive reactance) of the coil is also equal to 4000 ohms. The inductance formula $L = \frac{XL}{2\pi f}$ can now be used to find the inductance of the coil in henries.

$$XL = 4000 \qquad L = \frac{4000}{(6.28)(60)}$$

$$2\pi = 6.28$$

$$f = 60 \qquad L = \frac{4000}{376.8}$$

$$L = 10.62 \text{ henries}$$

2-7 IMPEDANCE MEASUREMENTS

Impedance measurements are often employed during routine test procedures for locating difficult parameter defects. It effectively totals the inductive and capacitive reactance together with the resistance in a circuit, to provide a measure of the impedance offered to the flow of alternating current or voltage. In addition, impedance measurements are useful in the testing and analysis of antennas and transmission lines, and for determining the figure of merit (Q) of electrical parts and resonant circuits. Impedance-measuring equipment, such as impedance bridges, are used mainly for determining the capacitance and inductance of electrical parts. However, the values of lumped circuit constants may be obtained and used in direct calculations of impedance. "Q" meters are impedance-measuring instruments that determine the ratio of reactance to resistance of capacitors or inductors, or of circuits containing capacitors, inductors, and resistors. Details of (Q) meters and impedance bridges as well as a number of other methods of measuring circuit impedance are described in the following paragraphs. Also discussed are methods of measuring impedance of antennas and transmission lines.

2-7.1 BRIDGE METHODS

Bridges are one of the most accurate types of measuring devices used in the measurement of impedance. In addition, they are also used to measure dc resistance, capacitance, and inductance. Certain kinds of bridges are more suitable for the measurement of a specific characteristic, such as capacitance or inductance. The general schematics for the various bridge circuits are shown in Figure 2-6, together with a listing of their most prevalent use. The bridge circuits shown in Figure 2-6 are characteristic in that they usually contain two branches in the measuring circuit, two branches in the comparing circuit, a detector circuit, and a power circuit; see Figure 2-7. The bridge shown in Figure 2-7 is actually the dc Wheatstone bridge; however, the general principle of circuit operation for ac remains the same. The comparing circuit contains branches A and B, and provisions for changing the ratios of these branches with respect to each other. In this way, various measuring ranges can be obtained. Comparison of Figures 2-6 and 2-7 shows that either or both branches of the comparing circuit do not necessarily contain resistors alone. Branch B of the Hay bridge, containing C_B and R_B in series connection, provides a striking contrast with the parallel connection of C_B and R_B of the Maxwell bridge. The measuring circuit (referring again to Figure 2-7) also contains two branches. The resistance, capacitance, or inductance to be measured is connected to branch X of the bridge measuring circuit. The subscript "X" is also used in Figure 2-6 to designate the circuit parameters involved in computing the values of various electronic parts. Branch S contains the variable control used to bring the bridge into a balanced condition. A potentiometer is used for this purpose in most bridge equipment because it offers a wide range of smoothly variable current changes within the measuring circuit. The third arm of the bridge is the detector circuit. The detector circuit may use a galvanometer for sensitive measurements requiring high accuracy. In the case of bridges using alternating current as the power source, the galvanometer must be adapted for use in an ac circuit. In many practical bridge circuits using alternating current to operate the bridge, an electron ray tube is used to indicate the balanced condition by opening and closing the shadow area of the tube. Headsets are often used for audible balance detection, but this method reduces the accuracy obtainable with the bridge. Switches are used in bridge circuits, one to control the application of operating power to the bridge; and one to complete the detector circuit. Frequently, the two switching functions are combined into a single key,

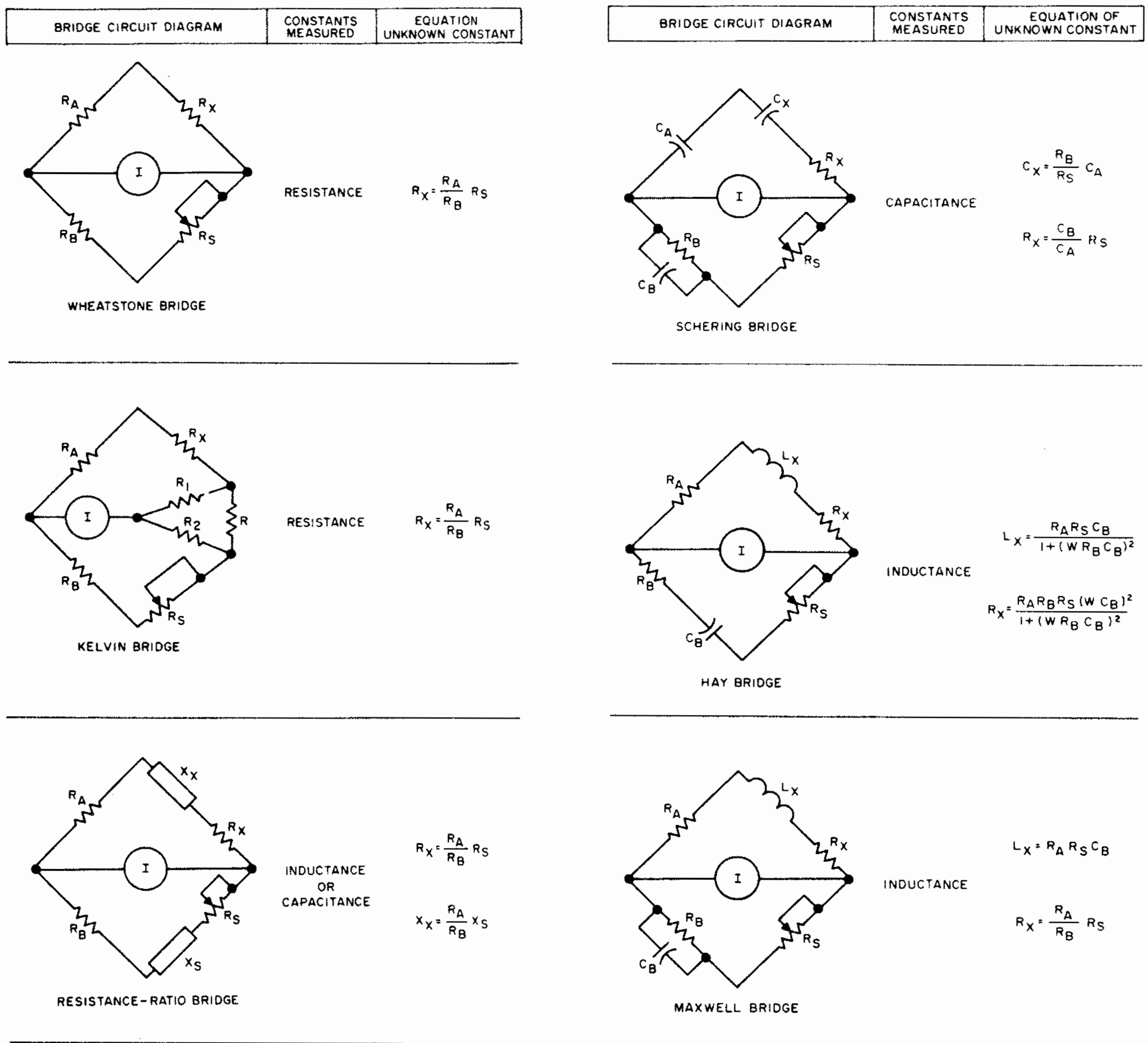


Figure 2-6. Basic Bridge Circuits

called a bridge key, so that the operating power is applied to the bridge prior to the detector circuit. This type of operational sequence reduces inductive and capacitive effects during the process of measurement. The most unfavorable condition for making a measurement occurs when the resistance, capacitance, or inductance to be measured is completely unknown, so that the galvanometer cannot be protected by setting the bridge arms for approximate balance. In order to reduce the possibility of damage to the galvanometer, it is necessary to employ an adjustable shunt circuit across the meter terminals. As the bridge is brought closer to the balanced condition, the resistance of the shunt can be increased; so that when the bridge is in balance, the meter shunt can be removed completely to obtain maximum detector sensitivity. Bridges designed specifically for, or that include, capacitance measurement as a function available as part of the bridge instrument provide a direct current source of potential for electrolytic capacitors. The electrolytic capacitors often require the application of direct current polarizing voltages in order for them to exhibit the same capacitance values and dissipation factors that would be obtained in actual circuit operation. The dc power supply and meter circuits used for this purpose are connected so that there is no interference with the normal operation of the capacitance-measuring bridge circuit, and so that the dissipation factor of the capacitor may be obtained while the capacitor is polarized. In Figure 2-7, the signal voltage in the A and B branches of the bridge will be divided in proportion to the resistance ratios of its component members, R_a and R_b, for the range of

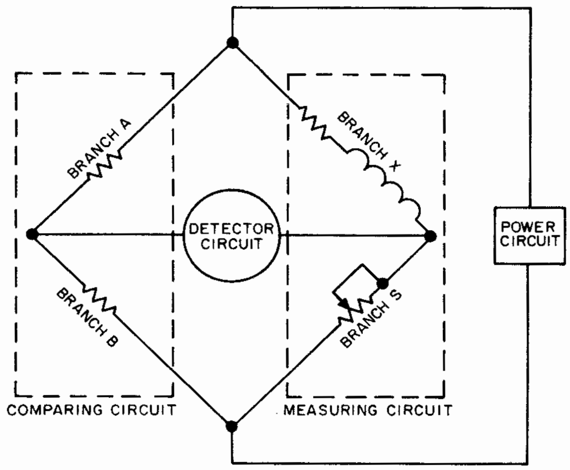


Figure 2-7. General Bridge Circuit Configuration

values selected. This same signal voltage is impressed across the branches S and X of the bridge. The variable control, R_s, is rotated to change the current flowing through the S and X branches of the bridge. When the point is reached where the voltage drop across branch S is equal to the voltage drop across branch A, the voltage drop across branch X is equal to the voltage drop across branch B. At this time the potentials across the detector circuit are the same, resulting in a cessation of current flow through the detector circuit, to give an indication of zero current flow. The bridge is balanced at these settings of its operating controls, and they cannot be placed at any other setting and still maintain this balanced condition. It should be apparent that the ability of the bridge circuit to detect a balanced condition is not impaired by the length of the leads connecting the bridge to the electronic part to be measured. However, the accuracy of the measurement is not always acceptable because the connecting leads exhibit capacitive and inductive effects which must be subtracting from the total measurement. Hence, the most serious errors affecting the accuracy of a measurement are due to the connecting leads. Stray wiring capacitances and inductance, called residuals, existing between the branches of the bridge are another cause of errors. The Resistance Ratio Bridge, for example, is redrawn in Figure 2-8 to show the interfering residuals that must be eliminated or taken into consideration. Fortunately, these residuals can be reduced to negligible proportions by shielding and grounding. A method of shielding and grounding a

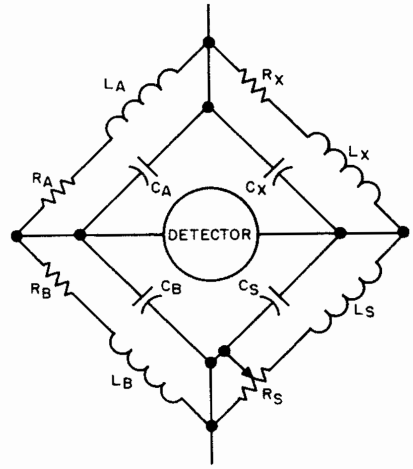


Figure 2-8. Resistance-Ratio Bridge Residual Elements

bridge circuit to reduce the effects of interfering residuals is through the use of a Wagner ground; refer to Figure 2-9.

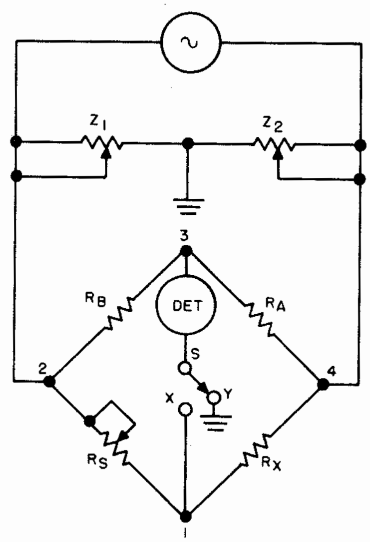


Figure 2-9. Wagner Ground

Observe that with switch S in position Y, the balanced condition can be obtained by the adjustment of Z_1, and Z_2. With switch S in position X, the normal method of balancing the bridge applies. Alternately balancing the bridge, using Z_1, Z_2 when the switch is at position Y and R_s when the switch is at position X, will show that a point will be reached where there is no deflection of the meter movement for either switch position. Under these conditions, point 1 is at ground potential and the residuals at points 2, 3, and 4 are effectively eliminated from the bridge. The main disadvantage of the Wagner ground is that two balances must be made for each measurement. One is to balance the bridge, while the other is to balance the Wagner ground. Both balancing operations are interacting because R_a R_b is a common impedance. Many bridge instruments provide terminals for external excitation potentials. Do not use a voltage in excess of that needed to obtain reliable indicator deflection. The resistivity of electronic parts varies with heat, which is a function of the power applied.

2-7.1.1 Wheatstone Bridge

The Wheatstone bridge (shown in Figure 2-6) is one of the most widely used bridge instruments for the measurement of resistance. The instrument is portable because it requires only a small, direct current source of energy to drive the bridge; sufficient energy is easily obtained from flashlight battery cells. In those cases where an external supply voltage is desirable for the operation of the bridge, use the minimum voltage that will give a reliable indication by the galvanometer. Increasing the supply voltage decreases bridge accuracy because of uncompensated thermal variations. If greater bridge sensitivity is required, use a galvanometer with greater sensitivity. A number of considerations are involved in the choice of a galvanometer. For example, the galvanometer should not be subject to false or erratic indications due to external magnetic fields. This requirement dictates the choice of a shielded meter mechanism. It is also desirable to use a critically damped meter mechanism to ensure a decisive movement of the meter pointer during conditions of bridge unbalance. Thermal agitation sometimes produces voltages that interfere with the balancing of the bridge. For this reason, the Wheatstone bridge usually includes a polarity reversing switch in the detector circuit. When a measurement is required, note the reading for both positive and negative indications, and then obtain an average of both readings. The accuracy of measurements made with the Wheatstone bridge is independent of the value of the supply voltages. The units used in the calibration of the galvanometer are unimportant to the accuracy of the bridge, since a zero indication is desired at the balanced condition. Resistance values ranging from 1 ohm to 1 megohm can be measured with an accuracy of approximately 0.1 percent. Difficulties are encountered when very high and very low resistances are measured. This type of bridge generally has a lower measuring limit of 0.1 ohm and an upper limit of about 0.1 megohm. Resistance less than 0.1 ohm are difficult to measure accurately, because of uncertainty arising from the contact resistance present between the resistor to be measured and the binding posts of the bridge. Measurement of resistances greater than 100,000 ohms becomes difficult because of two factors: first, the ratio of standard resistances R_a and R_b involve a ratio on the order of 1000:1; second, the voltage applied to the bridge must be substantially increased to obtain definite galvanometer action. The result is that an increase in the supply voltage increases the power dissipation (heat) of the bridge resistors. The change in resistance R_b, due to the heat, is sufficient to produce an appreciable error. A Kelvin bridge is recommended for measuring resistances lower than 0.1 ohm, while the electronic multimeter is recommended for the indicating device in bridges used for the measurement of very high resistances. One of the most elementary precautions concerning the use of a bridge, when measuring low resistances, is to tighten the binding posts securely so that the contact resistance between the binding posts and the resistance to be measured is a minimum. Leakage paths between the resistor leads along the outside surface of the resistor body must be avoided when resistances greater than 0.1 megohm are measured. Search for defective solder joints or broken strands in stranded wire leads, because these defects can cause erratic galvanometer indications. In those cases where wire leads must be used to reach from the resistance under test to the bridge terminals, measure the ohmic value of those leads prior to further measurements.

2-7.1.2 Kelvin Bridge

It is often necessary to make rapid measurements of low resistances, such as samples of wire or low values of meter shunt resistors. A frequently employed instrument which is capable of good precision is the Kelvin bridge, shown in Figure 2-6. Note the similarity between this and the Wheatstone bridge. Two additional resistances, R_1 and R_2, are connected in series and shunted across resistance R, which is the circuit resistance existing between the standard and unknown resistances, R_s and R_x, respectively. In performing the adjustment for balance, it is necessary to make the ratio R_1/R_2 equal to the ratio R_a/R_b. When this is done, the unknown resistance can be computed in the same manner as for the Wheatstone bridge, because resistance R is effectively eliminated. In using a Kelvin bridge, it is necessary to follow precautions similar to those given for the Wheatstone bridge. A rheostat is usually placed in series with the battery so that bridge current can be conveniently limited to the maximum current allowable. This value of current, which affects the sensitivity of the bridge, is determined by the largest amount of heat which can be sustained by the bridge resistances without causing a change in their values. All connections must be firm and electrically perfect, so that contact resistances are held to a minimum. The use of point and knife-edge clamps is recommended. Commercially manufactured Kelvin bridges have accuracies on the order of 2 percent for resistance ranges from 0.001 to 25 ohms.

2-7.1.3 Resistance-Ratio Bridge

The resistance-ratio bridge may be used to measure capacitance, inductance, or resistance, as long as the electronic part to be measured is compared with a similar standard. The measurement of the value of a capacitor must be made in terms of another capacitor of known characteristics, termed the standard capacitor. The same holds true for an inductance measurement. The standard of comparison is designated as X_x in Figure 2-6, and the losses of the standard are represented as X_r. If difficulty is experienced in obtaining a balanced bridge condition, it is advisable to insert additional resistance in series with branch S of the bridge. This adjustment becomes necessary because the Q of the unknown capacitor or inductor in branch X is higher than the comparable Q of the standard in branch S.

2-7.1.4 Schering Bridge

The Schering bridge, shown in Figure 2-6, is about the most commonly used type of bridge for the measurement of capacitor and dielectric losses. The Q of a capacitor is defined as the reciprocal of a dissipation factor. Accordingly, capacitor Q is determined by the frequency used to conduct the measurement, and the value of the capacitor, C_b, required to obtain bridge balance. The accuracy of this type of bridge is excellent, about 2 percent for dissipation factors ranging from 0.00002 to 0.6. Typical accuracies for capacitive reactances in the range of 100 picofarads to 1 microfarad are 0.2 percent. Although the Schering bridge is basically a capacitance bridge, low-Q inductances can be measured at high frequencies in terms of a negative capacitance.

2-7.1.5 Hay Bridge

The Hay bridge, shown in Figure 2-6, is used for the measurement of inductance and the Q of the inductor. It is interesting to note that this type of bridge measures inductance by comparing it with a standard capacitor of known characteristics. This arrangement provides the advantage of a wide measurement range with the minimum use of electronic parts as comparison standards. A typical range of values that can be measured with the Hay bridge is from 1 microhenry to 100 henries. The accuracy of the measurements made with this bridge is about 2 percent. Inspection of Figure 2-6 shows that the frequency used in conducting the inductance measurement must be taken into account because of the series reactance of capacitor C_b. The loss factor of the inductor under test is balanced in terms of the Q of the inductor. The Hay bridge, then, is used for measurement of inductances having a Q greater than 10. For instance, a Q of 10 gives a calibration error of 1 percent, whereas a Q of 30 gives a calibration error of 0.1 percent.

2-7.1.6 Maxwell Bridge

The Maxwell bridge is used for the measurement of inductance and inductive Q; refer to Figure 2-6. This bridge is similar to the Hay bridge because it also measures inductance by comparison with a standard capacitor of known characteristics. Notice, in particular, that capacitor C_b is connected in parallel with resistor R_b. In connection with this difference, the requirement of an accurately known frequency is removed. This bridge circuit is employed for measuring the inductance of inductors having large losses, i.e., low Q. The range of this type of instrument is much greater than that of the Hay bridge; values ranging from 1 microhenry to 1000 henries are measurable, with an error of only 2 percent.

2-7.2 SUBSTITUTION TECHNIQUES IN BRIDGE MEASUREMENT

The schematic of a substitution bridge circuit is shown in Figure 2-10. In this type of circuit, nominal accuracies of one percent are obtainable for frequencies between 20 and 20,000 hertz, with imped-

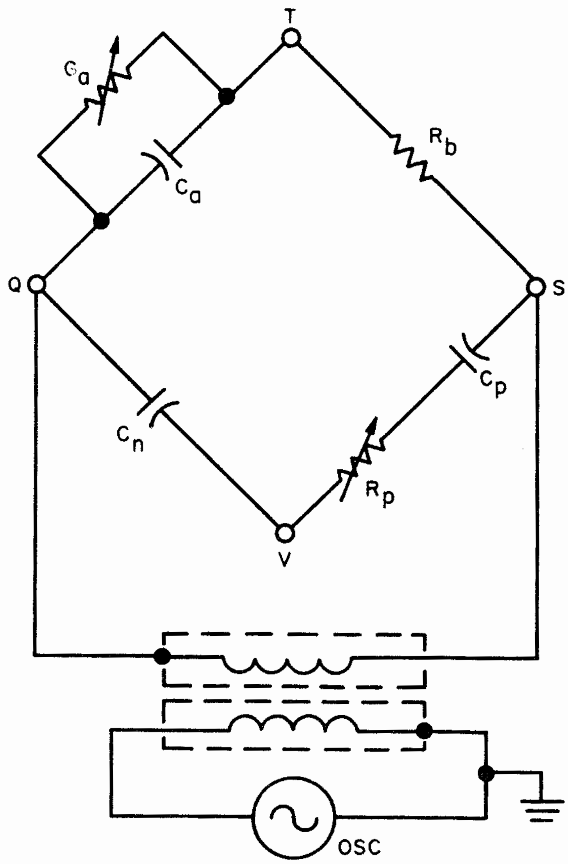


Figure 2-10. Substitution Bridge Schematic

ances ranging from a short circuit to an open circuit. When the unknown impedance is inserted between resistor Rp and terminal V, it is considered a series substitution device. When connected between terminals Q and T, it is considered as parallel substitution. Different formulas are used to calculate the actual value.

2-7.3 TWIN-T BRIDGED-T BRIDGES

Consideration of the generalized four-terminal circuit, shown in Figure 2-11, leads to the

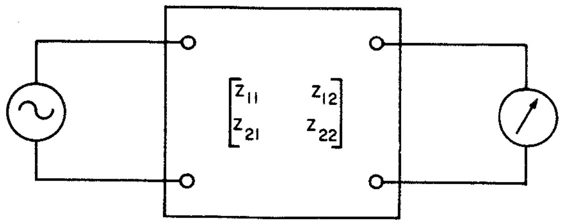


Figure 2-11. Generalized Four Terminal Network

realization that if a requirement of zero transmission is imposed on the circuit, the Wheatstone bridge is but one of the circuit configurations that will satisfy the imposed conditions. Another bridge arrangement which is successfully utilized is the Twin-T circuit, illustrated in Figure 2-12. The particular advantage inherent in this

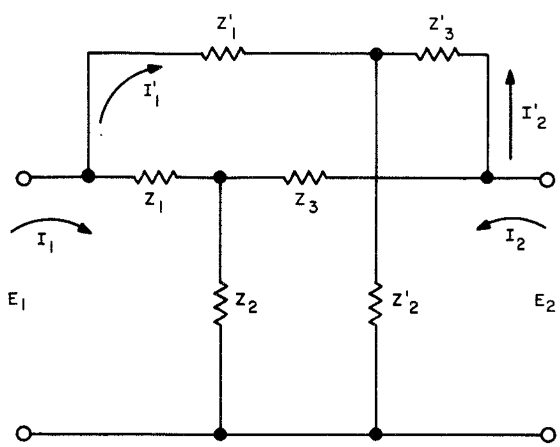


Figure 2-12. Twin-T Circuit

arrangement is that no shielded transformer is required since the generator and detector are brought to a common ground point. Balancing the network to zero transmission implies that the output currents I_2 and I'_2 are equal in magnitude and 180° out of phase. Since the output impedance cannot affect the balance condition, the output terminals can be short-circuited and I_2 and I'_2 calculated. By equating their sum to zero the null conditions of the network are determined. This technique is, in effect, the equivalent of calculating the transfer of impedance Z_{12} of the generalized network of Figure 2-11, where $Z_{12} = E_1/I_2$ with the output short-circuited. Under conditions of short circuit I_2 can be shown to be

$$I_2 = \frac{E_1}{Z_1+\frac{Z_2Z_3}{Z_2+Z_3}} \cdot \frac{Z_2}{Z_2+Z_3} = \frac{E_1Z_2}{Z_1Z_2+Z_1Z_3+Z_2Z_3}.$$

Similarly,

$$I'_2 = \frac{E_1Z'_2}{Z'_1Z'_2+Z'_1Z'_3+Z'_2Z'_3}$$

Now

$$Z_{12}+Z'_{12}=E_1\left(\frac{1}{I_2}+\frac{1}{I'_2}\right)=\frac{E_1}{I_2I'_2}(I'_2+I_2)$$

Therefore,

if $I_2+I'_2=0$, then $Z_{12}+Z'_{12}=0$.

But from the preceding equations

$$Z_{12}=Z_1+Z_2+\frac{Z_1Z_3}{Z_2}$$

and

$$Z'_{12}=Z'_1+Z'_2+\frac{Z'_1Z'_3}{Z'_2}$$

Hence the general null condition is

$$Z_{12}+Z'_{12}=Z_1+Z_2+\frac{Z_1Z_3}{Z_2}+Z'_1+Z'_2+\frac{Z'_1Z'_3}{Z'_2}=0$$

If in Figure 2-12, impedance Z'_2 becomes infinite, Z'_1 and Z'_3 are combined to form a new impedance Z_4. The Twin-T network then degenerates into the Bridged-T of Figure 2-13. Hence the general null condition becomes

$$Z_{12}+Z'_{12}=Z_1+Z_3+Z_4+\frac{Z_1Z_3}{Z_2}=0$$

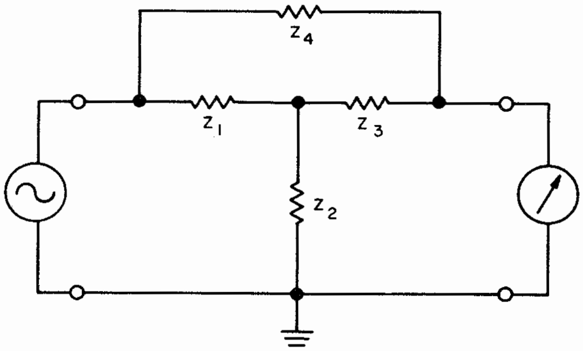


Figure 2-13. Bridged-T Bridge

Figure 2-14 is an example of a bridged-T circuit utilized in a null meter which measures inductive impedance.

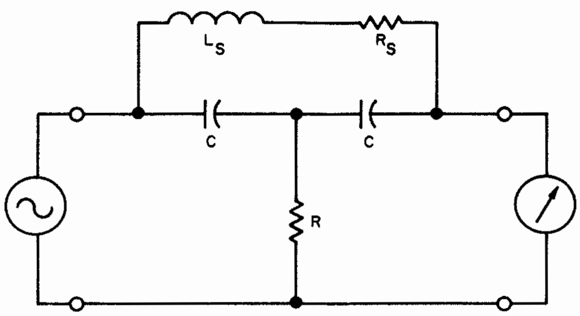


Figure 2-14. A Null Instrument Utilizing a Bridged-T

The Bridged-T circuit has several advantages. These are:

1. A twin capacitor can be calibrated directly in effective tuning capacitance.
2. Excluding coils of low Q, a variable resistor can be calibrated in terms of the parallel resistance of the unknown.
3. Capacitance-to-ground across the ends of the coil do not affect the null conditions.

The circuit is particularly suitable for measuring iron-cored coils carrying direct current while operating with alternating voltages. The input and output susceptances of the generalized Twin-T of Figure 2-12, at balance, can be calculated by alternately shorting the output and input terminals, producing the circuits shown in Figure 2-15.

2-7.4 VECTOR BRIDGES

The bridges described previously determined the resistive and reactive components of the unknown impedance, whereas the vector bridge indicates the magnitude and phase angle. Typically, vector bridges require two null readings. Consider the basic bridge circuit of Figure 2-16. To determine the magnitude of the unknown impedance (Z_x) the voltages across R and Z_x are applied through emitter followers Q_1 and Q_2, to the balanced rectifiers, CR-1 and CR-2. Resistors A and B are equal in value. For $R = Z_x$, voltages $E_{2\ 1}$ and $E_{4\ 1}$ are equal (in magnitude) and the VTVM will indicate zero volts. The absolute value of Z_x is determined from the dial calibration of R. With the amplitude balance left unaltered, the external circuits are reconnected as shown in Figure 2-17. It may be noted that $E_{1,\ 3}$ is being compared to a portion of $E_{2,1}$. Potentiometer, R, calibrated in degrees, is adjusted for a null indication on the VTVM and the phase angle read directly. The vector diagram of Figure 2-18 shows these voltage and phase relationships. $E_{2,4}$ represents the supply voltage, E. $E_{2,\ 3}$ and $E_{3,\ 4}$ are the voltages (E/2) across equal resistors, A and B. $E_{2,\ 1}$ is the voltage across R in phase with the current through R and Z_x. $E_{4,\ 1}$ is the voltage across Z_x, leading the current through Z_x by phase angle, θ_x (inductive reactance assumed). Since $E_{2,\ 1}$ and $E_{4,\ 1}$ have been made equal by the amplitude balance, angle 1, 2, 3 is equal to $\theta/2$. $E_{1,\ 3}$ is readily seen to be as depicted in Figure 2-18.

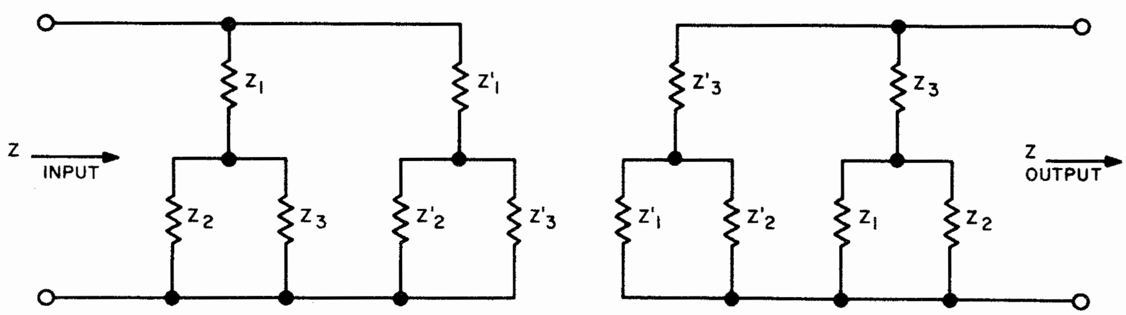


Figure 2-15. Input and Output Impedances of Twin-T at Balance

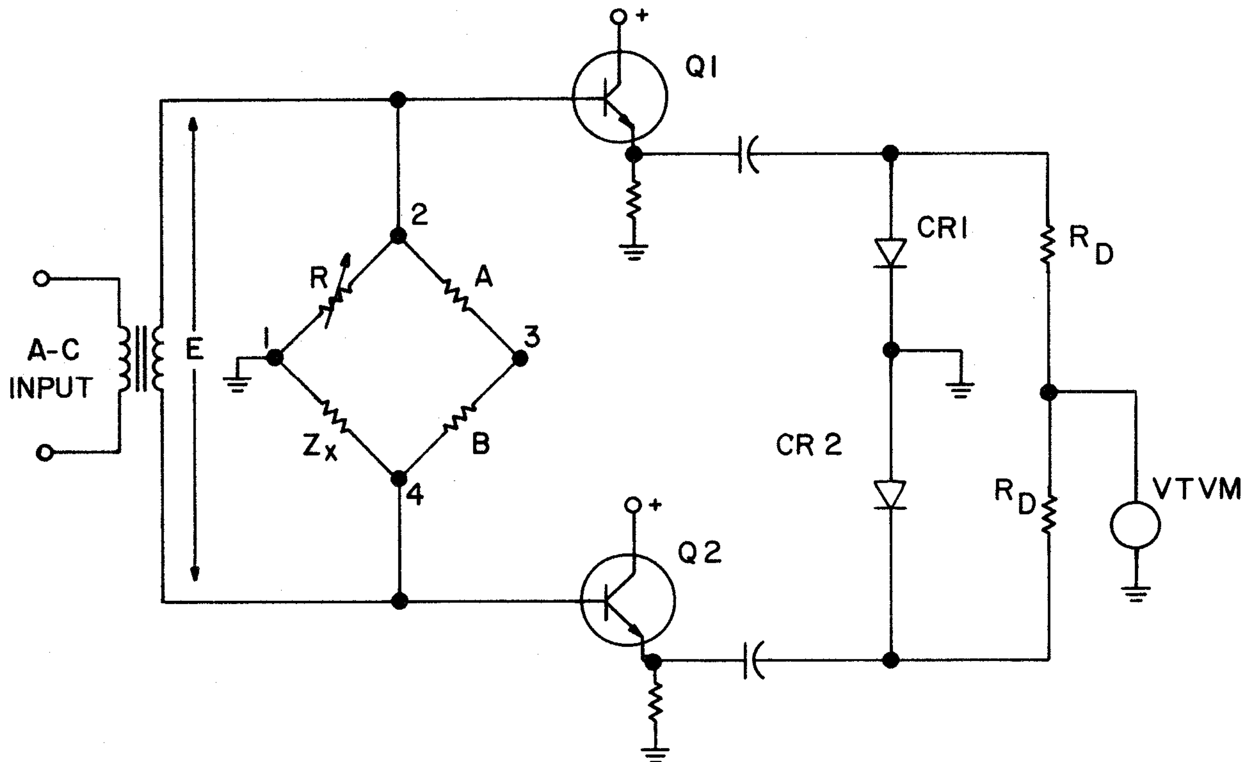


Figure 2-16. Vector Bridge

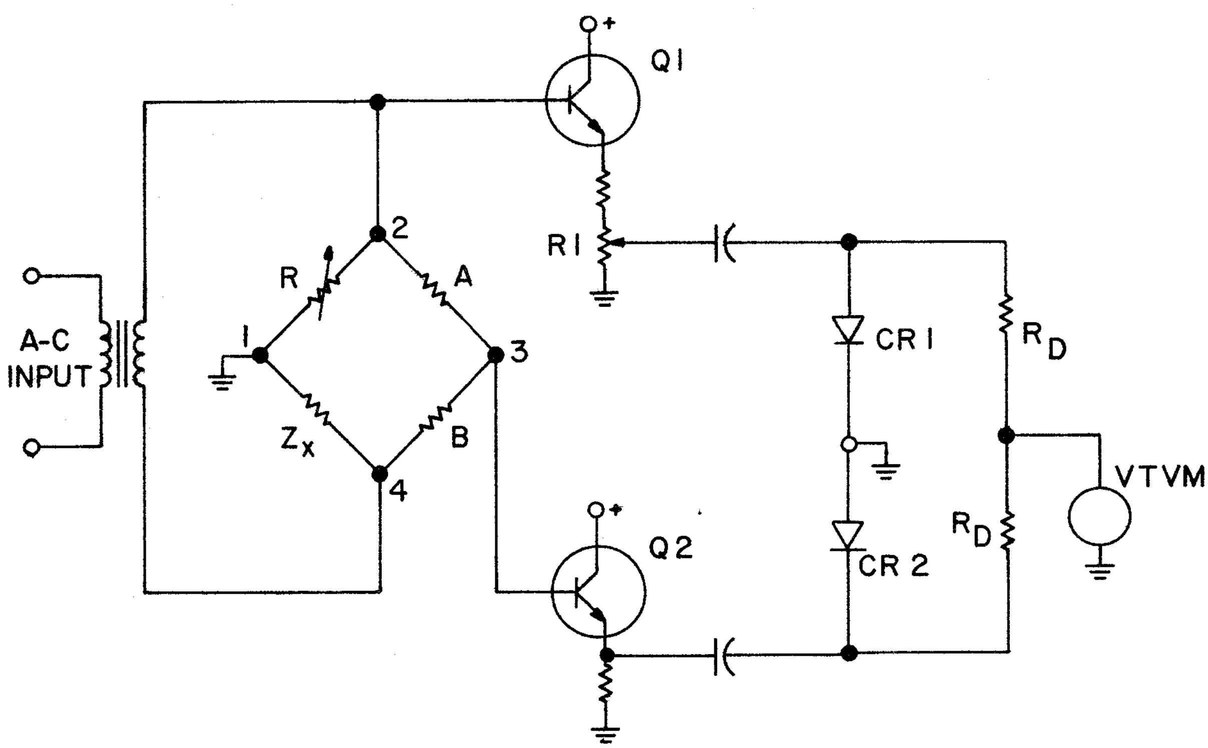


Figure 2-17. Vector Bridge Phase Angle Determination

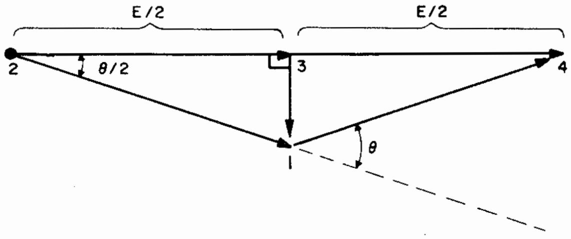


Figure 2-18. Vector Bridge Phasor Diagram

$$E_{1,3} = \frac{E}{2}\tan\frac{\theta}{2} = \frac{E}{2} \cdot \frac{\sin\frac{\theta}{2}}{\cos\frac{\theta}{2}}$$

$E_{2,1}$ is given by

$$E_{2,1} = \frac{E}{2\cos\frac{\theta}{2}}$$

Hence $E_{1,3} = E_{2,1} \sin\frac{\theta}{2}$

If Z_x is purely resistive, $E_{1,3}$ will be zero, hence the setting of R will be at zero volts. For Z_x reactive, the setting of R-1 will be at maximum voltage. For phase angles between 0 and 90 , the scale of R1 may be calibrated directly in degrees. The sign of the phase angle can be determined by changing the signal frequency slightly and observing the change in impedance. The presence of harmonics in the signal input will hamper the measurements severely. If a pure frequency source is not available, suitable low pass filters will have to be employed in the output leads from the bridge.

2-7.5 CONSTANT CURRENT IMPEDANCE MEASURING TECHNIQUE

This technique employs an audio oscillator and a VTVM, as shown in Figure 2-19. A large value

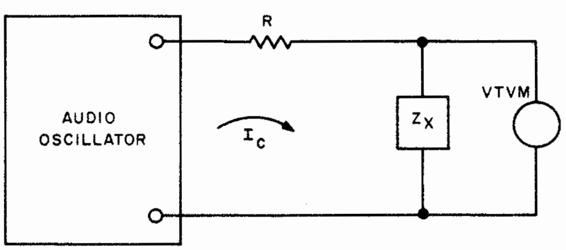


Figure 2-19. Constant-Current Impedance Measuring Method

of resistance, R, is selected so that I_c is virtually independent of the range of Z_x to be measured. Thus, I_cZ_x represents the value of voltage measured by the VTVM. Hence, if R is deliberately chosen so that the significant figures of the maximum value of I_cZ_x to be measured correspond to the full scale reading of the VTVM, a direct reading impedance meter is realized. For example, assume that the audio oscillator open-circuit voltage is 10 volts (rms) and that the full scale reading of the VTVM is 0.05 volt. If it is desired to measure Z_x for values ranging to a maximum of 5000 ohms, R may be chosen as 1 megohm. Hence, I=A, and for Z_x to be equal to 5000 ohms, the VTVM will deflect to 5, corresponding to 0.05 volt. Thus, the significant figure of the voltage and the impedance value are identical, thereby enabling the VTVM to be used as a direct-reading impedance meter. Similar techniques may be employed to make the VTVM direct reading in L or C. Note that an oscillator source free of harmonics should be employed.

2-7.6 IMPEDANCE ANGLE METER

Like vector bridges, impedance angle meters determine an unknown impedance in terms of magnitude and phase angle. A non-bridge technique is employed, however. The simplified circuit of a commercial instrument is shown in Figure 2-20. With switches S_1 and S_2 at the BAL position, the variable standard resistor, R, is adjusted until the balanced rectifier outputs of Q_1 and Q_2 are equal (indicated by a null in the deflection of the voltmeter connected across the emitter of Q_3 and Q_4.) The dial setting of R gives the value of Z_x. For phase angle determination, the circuit is switched to CAL and the input voltage adjusted for full scale voltmeter deflection. The circuit is then switched to PHASE, thus applying the parallelled outputs of Q_1 and Q_2 to rectify CR1 only. The base of Q_4 is fixed at ground. If Z is purely resistive, the outputs of Q_1 and Q_2 cancel and the voltmeter indicates zero deflection. For a complex impedance, the base of Q_3 will be unbalanced with respect to the base of Q_4 and the voltmeter deflection, calibrated in degrees, determines the phase angle of the unknown impedance. Typical commercial impedance angle meters, operating at 2MHz, are accurate to within 4% for impedances of from 10 to 500 ohms.

2-7.7 IMPEDANCE MEASUREMENTS BY SQUARE WAVE TESTING

The square wave technique provides a rapid and reasonably accurate method for impedance measurement. A block diagram of the necessary equipment is shown in Figure 2-21. The emitter follower is optional and is required only if the output impedance of

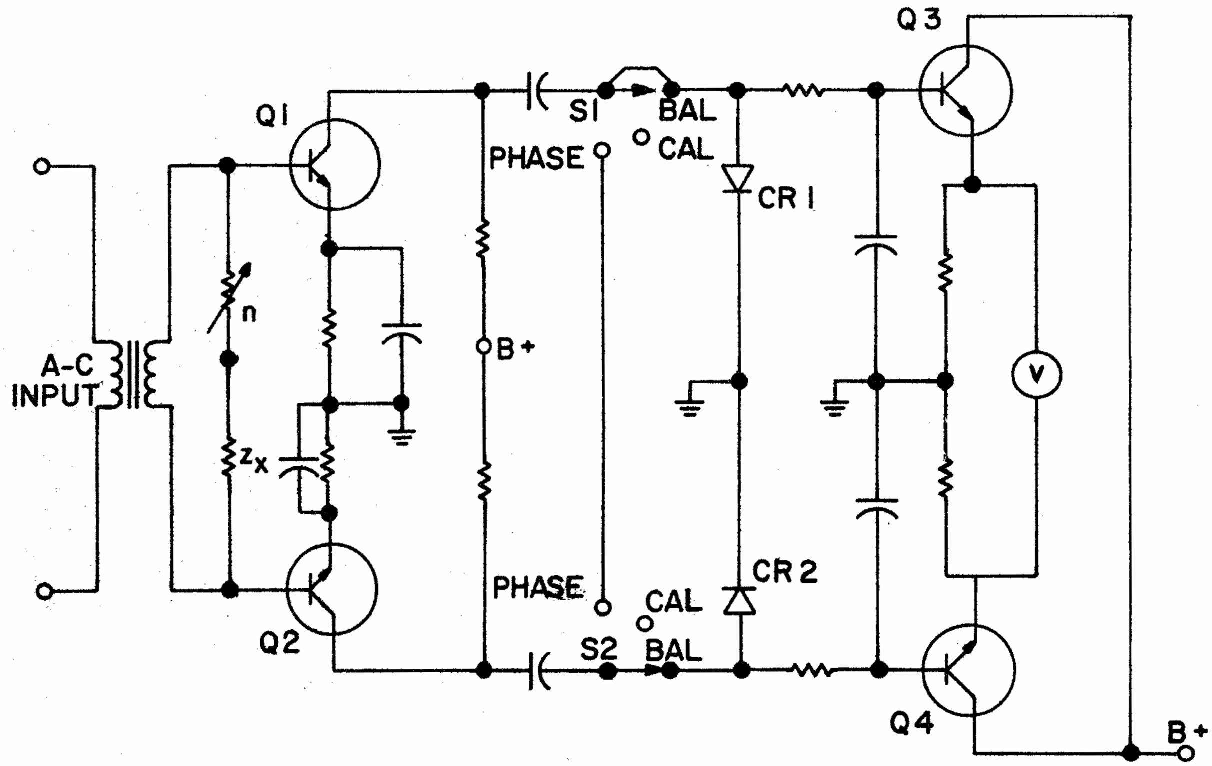


Figure 2-20. Impedance-Angle Meter

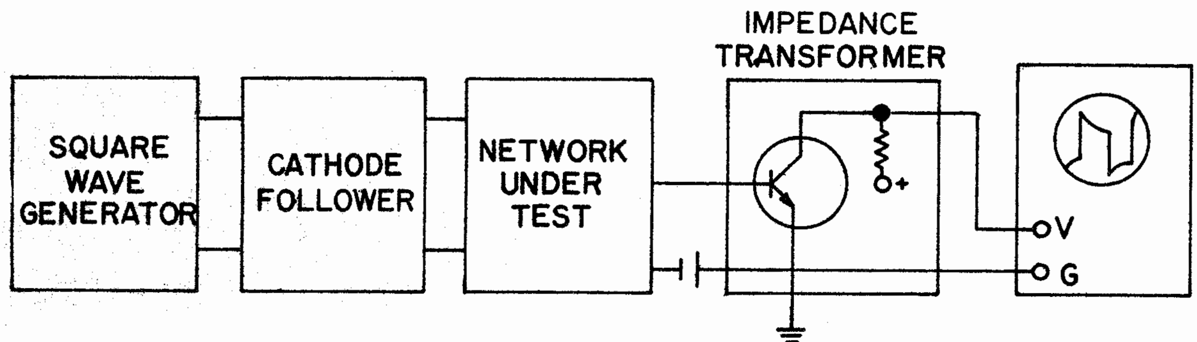


Figure 2-21. Square Wave Impedance Measurement Test Arrangement

the square wave generator is greater than 0.1 of the smallest impedance to be measured. The basis for the measurement technique illustrated in Figure 2-22 is as follows. The waveform of the voltage, E_R, across resistance R is shown in Figure 2-23. The expression for that portion of the waveform which is decreasing negatively is given by

$$E_R = (1e)\left(-\frac{t}{RC}\right)$$

If the source frequency, f_o, is equal to 1/2 RC, then the capacitor reactance is given by

$$X_c = \frac{1}{2\pi f_o C} = \frac{2\pi RC}{2\pi C} = R$$

At frequency f_o, the time duration of a half cycle is RC, whence E_R is

$$E_R = -1e^{-\pi} = -.043$$

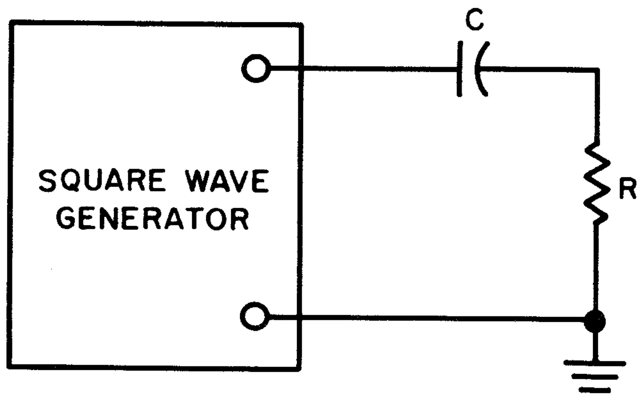


Figure 2-22. Square Wave Technique for R or C Measurement

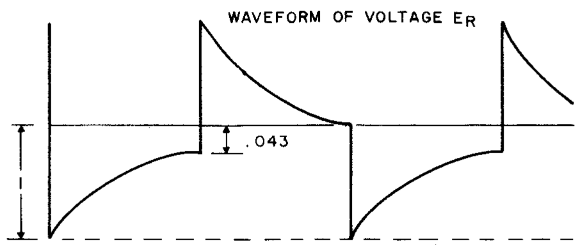


Figure 2-23. Waveform of Voltage, E_R

Thus, by adjusting R, a variable standard-resistor, to the value where at switchover E_R has fallen to 4.3% of its peak negative value, X_c can be determined. If R is to be measured, C is made the adjustable standard. If inductance is to be measured, the procedure is similar except that the voltage across the inductance is applied to the oscilloscope as shown in Figure 2-24. To avoid the shunting effects of the input impedance of the oscillo-

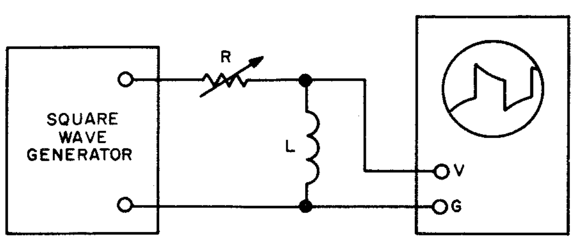


Figure 2-24. Square Wave Technique for L Measurement

scope, the resistance of Figure 2-22 and the inductance of Figure 2-24 provide a dc base return if inserted in the base emitter path of the impedance transformer of Figure 2-21. Consequently, the impedance shunting, L or R, will be merely the input capacity of the impedance transformer stage. One of the limiting factors in this technique is the oscilloscope, which must be capable of passing square wave signals employed with minimal distortion. Another, of course, is the accuracy with which the observer is able to establish the waveform of proper amplitude on the oscilloscope.

2-7.8 ONE-VOLTMETER METHOD OF IMPEDANCE MEASUREMENT

This technique requires a frequency source, a VTVM, and a calibrated adjustable (resistive or reactive) impedance. Figure 2-25A illustrates the circuit

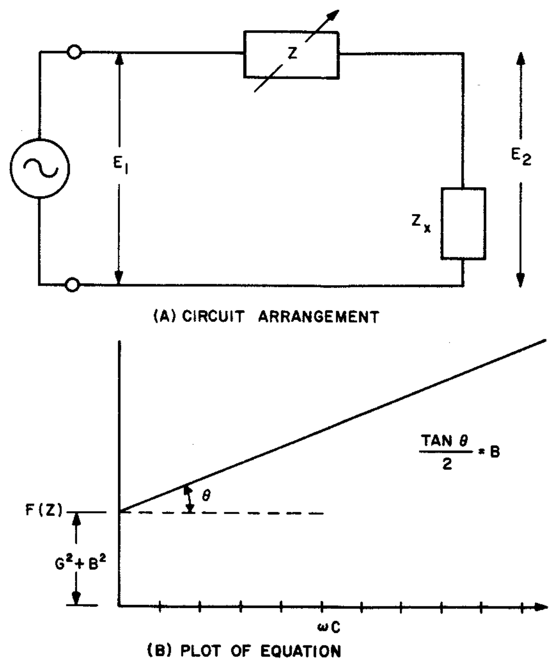


Figure 2-25. One-Voltmeter Method of Impedance Measurement

arrangement, where Z_x represents the unknown impedance. The method of measurement consists of tabulating voltages E_1 and E_2 for a range of values of the variable impedance, Z. The data are used to derive a straight line graph whence the real and quadrature components of the unknown impedance may be determined from the slope and intercept. The basis for the measurement may be illustrated by assuming the determination of an unknown impedance, using a calibrated variable capacitor.

Let

$$m = \frac{E_1}{E_2}, \quad Z = \frac{-j}{\omega C}$$

$$Z_x = R + jX = Y_x^{-1} = (G + jB)^{-1}$$

Now

$$m = \frac{E_1}{E_2} = 1 + ZY_x = \frac{1+B-jG}{\omega C} = \frac{1+B-jG}{\omega C}$$

Squaring both sides of this equation and rearranging terms yields

$$F(Z) = (m^2 - 1)^2 C^2 = (G^2 + B^2) + 2B(C)$$

If the equation is plotted, as in Figure 2-25B, with F(Z) as ordinate and ωC as abscissa, a straight line plot results, with a slope equal to 2B and with a vertical intercept equal to $G^2 + B^2$, whence Z_x is readily determined.

2-7.9 Q-METER METHOD

The Q-meter, shown in Figure 2-26, con-

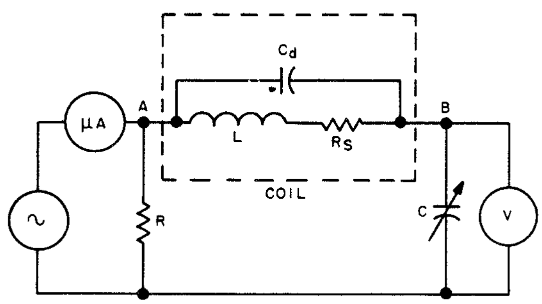


Figure 2-26. Simplified Q-Meter Circuit, Series

sists of a radio frequency oscillator and a measuring circuit. This type of equipment measures reactive electronic parts by resonating them with a capacitor of known characteristics. The capabilities of the Q-meter include measurements of inductive and capacitive reactances, their resistive losses, and tuned circuit impedances. A radio frequency oscillator, continuously variable between approximately 50 kHz and 75 MHz, supplies a calibrated output voltage to the measuring circuit. The coupling unit consists of a shielded transmission line terminated in a low-value non-inductive resistor, R, and a thermocouple type of ammeter or a vacuum tube voltmeter. The measuring or Q circuit consists of an accurately calibrated variable (vernier) capacitor, a voltmeter, and two terminal posts. An inductance must be connected to the terminal posts in order to conduct any kind of measurement with this type of equipment. A signal of known amplitude and frequency is injected into the measuring circuit from the radio frequency oscillator. The inductance connected across the input terminals presents inductive, capacitive, and resistive components at all frequencies except at the resonant frequency. When the circuit is tuned to resonance by means of the Q circuit vernier capacitor, C, or the oscillator frequency is adjusted to the resonant frequency of the circuit, the current is limited only by the series resistance of the coil, R_s, and the injection resistance, R. The voltage developed at resonance across this tuned circuit is a direct function of the injection voltage and the circuit Q. A vacuum tube voltmeter is used to monitor the voltage across the tuned circuit. Since the injection current is monitored by the µA meter, the radio frequency input signal can be maintained at a constant level; hence the Q vacuum tube voltmeter reading is directly related to circuit Q. There are two general methods of making measurements with the Q-meter. One method consists of connecting the unknown coil or impedance to the Q circuit in a series connection. The second method involves an extra resonating operation where the unknown circuit element or impedance is connected to the Q circuit in a parallel connection. The Q of the circuit element measured has the same value, whether or not the series or parallel method is used in conducting the measurement. However, the effective values of resistance and reactance may be quite different, depending on the choice of connection. The series connection of Figure 2-26 is generally useful for measuring low impedances, and the parallel connection of Figure 2-27 is preferred for measuring high impedances.

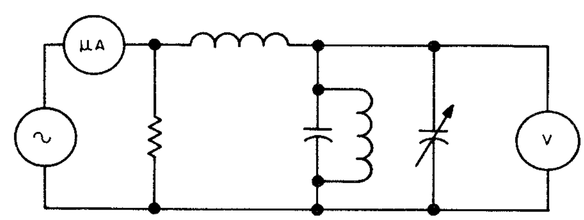


Figure 2-27. Simplified Q-Meter Circuit, Parallel

2-7.9.1 Q Measurements

At resonance, the reactances of the circuit elements balance out, and the current, neglecting the small current across R, will be $I = E/R_e$, where R_e is the effective resistance of the unknown impedance. The effective Q of the circuit, Q_e, will be the ratio of the voltage developed across the vernier capacitor to the small voltage injected by the oscillator, and is given by the relationships $Q_e = E_c/E$, $1/2\pi fCR_e$, or $2\pi fL_e/R_e$. The difference between the true Q and the effective Q depends upon the distributed capacitance of the coil, C_d. From the practical viewpoint, this difference is of very little importance, because in the design of tuned circuits, the minimum capacitance used to tune a coil is usually 10 to 20 times the distributed capacitance of the coil. The maximum difference between the effective and true Q will be 5 to 10 percent when measured with the minimum vernier tuning capacitance. In special cases, when high accuracy is necessary, a more accurate calculation must be made, using the relationship $Q = Q_e (1 + C_d/C)$.

2-7.9.2 Inductance Measurements

The Q-meter method of measurement gives the apparent or effective inductance of a coil. True inductance is less than the effective inductance by an amount which depends on the distributed capacitance of the coil having a high distributed capacitance, or a high capacitance between the leads may be obtained by measuring these residual capacitances as another operational step. The true inductance must then be calculated from

$$L = Le \left(\frac{C}{C + C_d} \right)$$

where L_e is the effective inductance, C is the vernier capacitance, and C_d is the distributed capacitance. When the coil being measured is unshielded, it should be mounted at a sufficient distance from the metallic top of the Q-meter so that the effect of the Q-meter on the resistance or inductance of the coil is negligible. However, the leads should not be longer than necessary to secure this result. When measuring shielded coils, the shield should be grounded to the low potential coil terminal. In no case should the shield be grounded to both the low potential coil terminal and the capacitor terminal because the series voltage in the Q circuit is inserted between these terminals. In measurements involving two coils within the Q-circuit, care should be taken to avoid coupling between the coils. At least one coil should be shielded.

2-7.9.3 Distributed Capacitance Measurements

There are two general methods of measuring the distributed capacitance across a coil. Generally speaking, the reason for the two methods involves the desired accuracy of measurement and the value of the capacitance to be measured. One method is to hold the vernier capacitor in the Q circuit constant while tuning to find the initial resonant frequency, then recording the setting of the vernier capacitor. The oscillator frequency is then set to one-half its previous value and the Q circuit brought into resonance, recording the new setting of the vernier capacitor. The distributed capacitance of the coil, C_d, can be calculated from the relationship $C_d = 1/3\ (C_2 - 4C_1)$, where C_1 and C_2 are the initial and final settings of the Q circuit vernier capacitor. The best accuracy to be expected with this method is approximately 2 picofarads for distributed capacitances exceeding about 10 picofarads. A second method depends upon the fact that at the resonant frequency of the coil, the impedance across its terminals is effectively a nonreactive resistance. The measurement consists of making a number of settings of the Q-meter frequency and resonating the Q circuit at each of these frequencies while alternately connecting and disconnecting the test coil across the Q circuit. A frequency will be found where the alternate connection and disconnection of the coil produces no change in the setting of capacitance of the coil, C_d. This can be calculated from the relationship $C_d = 1/3\ (C_2 - 4C_1)$, where C_1 and C_2 are the vernier capacitors in the Q circuit. The distributed capacitance, C_d, may then be calculated from the realtionship $C_d = (f_1/f_0)^2\ C_1$, where C_1 and f_1 are the initial Q circuit capacitor setting and oscillator frequency, and f_0 is the final oscillator frequency (resonant frequency of the coil). This method of calculating the distributed capacitance of a coil is used when higher accuracy is required or when the value of the distributed capacitance is less than 20 to 30 picofarads. Accuracy when using this method requires that the inductance of the coil remain unchanged at the two frequencies of measurement. While this method is reasonably accurate for commonly used coils, it may not be valid for coils having iron cores.

2-7.9.4 Small Capacitor Measurements

Measurements of the capacitance and the dissipation (power) factor of small capacitors can be made with the Q-meter if the test capacitor is within the tuning range of the vernier capacitor. This is done by connecting the capacitor to be tested in parallel with the vernier capacitor; see Figure 2-28. The value of

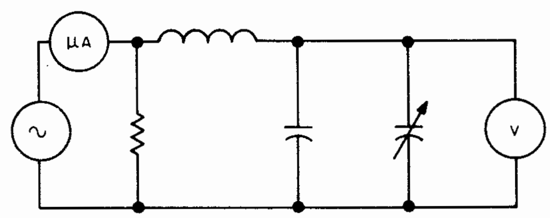


Figure 2-28. Simplified Q-Meter Connection for Measuring Small Capacitances

capacitance is calculated from $C_p = C_1 - C_2$, where C_p is the effective parallel capacitance of the test capacitor, and $C_1 - C_2$ is the change in the setting of the vernier capacitor. The difference between this value and the effective series capacitance is negligible for capacitors having a Q greater than 10, which will be the case for most small capacitors. When the Q of a capacitor is 10 or less, the effective series capacitance may be calculated from

$$C_p = \frac{1 + Q_x^2}{Q_x^2}$$

It is important, especially when measuring very small capacitances, that the measurement exclude the capacitance of the capacitor leads. This may be done by connecting suitable leads to the Q-meter before making the initial resonance setting of the Q circuit, and connecting the test capacitor at the end of the leads, taking care not to disturb the lead positions during the measurement.

2-7.9.5 Large Capacitor Measurements

Large capacitors, ranging from 0.1 to 0.2 microfarad, may be measured by connecting them in series with a standard coil, and then connecting this combination to the coil terminals of the Q-meter. The capacitor under test is to be connected to the low potential side of the coil. For this measurement it is necessary that the coil have an inductance which will resonate to the desired test frequency with the Q circuit vernier capacitor set to a high capacitance value. A resistor having a resistance not exceeding 10 megohms is also required; see Figure 2-29. This resistance must be connected across the test capacitor when it is in the Q circuit. This provides a direct current path for establishing the grid bias of the vacuum tube voltmeter. It is important when measuring large capacitors to observe the precaution of including as little inductance as possible in the capacitor leads during measurement. The internal inductance of the capacitor is usually quite small, and even an inch or two of capacitor lead may cause a serious error. When measuring the circuit without the capacitor, it is generally advisable to leave the capacitor in the circuit. Shorting the capacitor terminals together with a heavy copper jumper without causing lead position changes will reduce inductance errors to a minimum. The accuracy of the direct reading measurement of circuit Q is approximately 5 percent for all frequencies up to the region of 30 megahertz and decreases with increasing frequency. The accuracy of the measurement of capacitors, dielectrics, etc., is generally better than 10 percent. The vernier capacitor has a calibration generally better than 1 percent of 1 picofarad, whichever is greater. In all measurements, the Q circuit is adjusted to resonance, as indicated by a maximum deflection of the Q voltmeter. The dial readings and Q readings at resonance are the values to be used in the formulas in calculating quantities not directly indicated. The vernier capacitor is usually set to zero, or else its capacitance is to be added to the main vernier dial reading. The leads between the Q-meter and the electronic part being measured are to be heavy and as short as possible when conducting measurements at high frequencies. Owing to the method of voltage injection into the Q circuit, the low potential coil terminal is not at ground potential. Care must be taken to make sure that the components connected to the coil terminals are not grounded to the Q-meter cabinet or other ground, because this will prevent correct operation of the Q circuit. Electronic parts or circuits having a ground connection or large capacitance to ground cannot be measured when connected to the coil terminals. Such parts may, in some cases, be connected in parallel with the Q circuit (vernier capacitor terminals) for measurement. In measurements such as the Q or resistance of capacitors, in which the accuracy depends on the accuracy of the total vernier capacitance, the capacitance between any leads should be taken into account by disconnecting the capacitor at its terminals and measuring the effect of the leads. A check of the capacitance between leads is particularly important in determining the distributed capacitance of a coil.

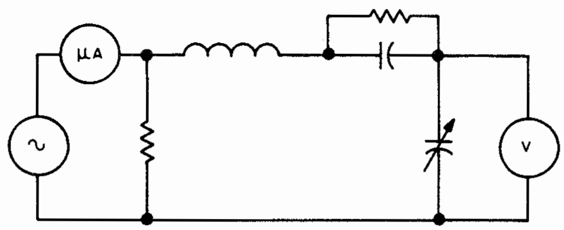


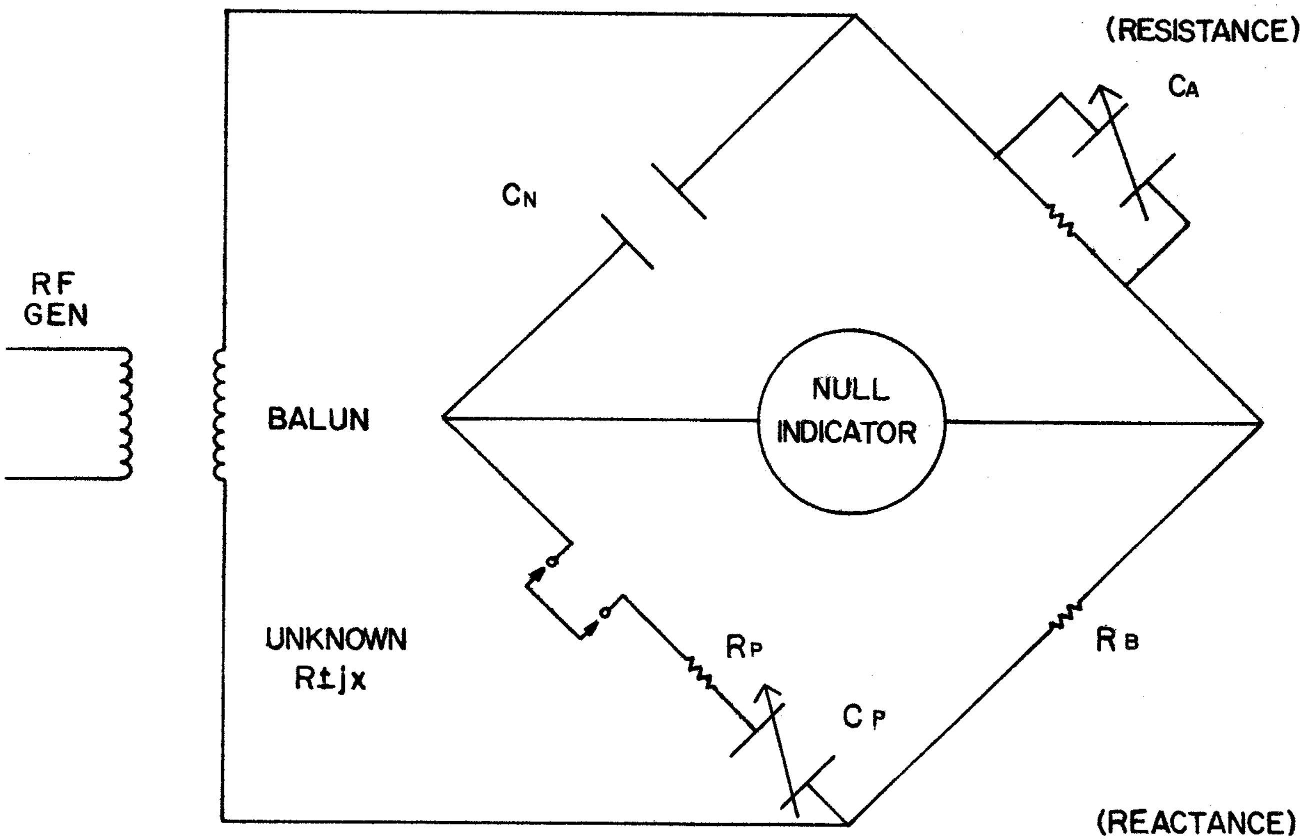
Figure 2-29. Simplified Q-Meter Connection for Measuring Large Capacitances

2-7.10 IMPEDANCE TESTING OF ANTENNAS AND TRANSMISSION LINES

The amount of current that flows in an antenna is one of the most important factors affecting the performance of transmitter equipment. Thus, in order to secure the maximum radiated power from a transmitter of a given power, as much of the radio-frequency energy generated as possible must be efficiently transferred to the antenna. Also, for optimum reception, the maximum transfer of energy from the antenna to the receiver must occur. Efficient transmission and reception conditions prevail whenever the transmitter (or receiver) is properly matched to the transmission line and the transmission line is properly matched to the antenna. Normally, the antenna equipment, and performance tests concerning impedance match consist primarily of taking standing-wave measurements. However, in certain instances, it will be found that an undesirably high standing-wave ratio will be obtained, caused by a change in antenna impedance. This could be the result of a new antenna installation, or the erection of a structure in the proximity of the antenna, so that the structure influences the antenna characteristics. In practice, the antenna matching network is generally varied to match the new antenna characteristics, since the transmission line is designed to match the equipment impedance. This can best be done by making a series of standing-wave-ratio checks and antenna matching adjustments until an acceptable standing-wave ratio is reached. It must be understood, however, that the antenna does have a specific impedance at a given frequency, and that, when necessary, this impedance may be determined by use of an RF impedance bridge.

2-7.10.1 RF Impedance Bridge

A typical RF impedence bridge is shown in Figure 2-30. Dial Ca is the resistive component and



$$R_X = R_B\left(\frac{C_{H2}-C_{A1}}{C_N}\right)$$

$$jx = \frac{1}{2\pi f}\left(\frac{1}{C_P{}^2} - \frac{1}{C_{P1}}\right)$$

Figure 2-30. Typical RF Bridge

dial Cp is the reactive component. This bridge is capable of resistance measurements of up to 1000 ohms with a reactive factor of ± 5000 ohms. Basically, the bridge is balanced with a known capacitance under short-circuit conditions. The unknown impedance is then inserted in lieu of the short buss, and the bridge is rebalanced. The difference between the known impedance, balance under short-circuit conditions, and the balance measurements obtained with the unknown impedance inserted in lieu of the short, is the value of the unknown impedance. This value can be computed, using the formula in Figure 2-30. An R-X meter utilizes a RF signal generator and detector, plus a calibrated RF bridge to determine transmission line impedance. It compares the parallel resistor-reacitve combination vice the series combination and can measure impedance over a frequency range of 500 kHz to 250 MHz. The resistance range is 15 to 0.1 ohm, and its reactive component ranges between 0.20pF. Inductive reactance is read as negative capacitance and ranges between 0-100pF. Most RF bridges are usable up to 60 MHz. In the UHF range, the detected output of a slotted line is used to determine transmission line impedance.

2-8 POWER MEASUREMENTS

It is often necessary to check the input and output signal power levels of electronic equipment. The determination of dc power is comparatively simple; the unit of power, the watt, is the product of the potential in volts and the current in amperes. Therefore, a few basic circuit measurements may be taken and the power computed by means of Ohm's law ($P = IE = I^2R = \frac{E^2}{R}$). However, the presence of a reactive component in ac circuits means that apparent power is being measured or calculated unless the rms voltage-current value is multiplied by a power factor to obtain true power. The measurement of ac power is further complicated by the frequency limitations of various power meters. If there is no phase difference, ac power may be computed in the same manner as dc power, by determining the average value of the product of the voltage and current. In practical ac circuits, the apparent power must be multiplied by the cosine of the phase angle between the voltage and current in order to compute true power. In the repeated measurement of audio-frequency power, you may use a normal power meter calibrated directly in watts. However, when reactive components of dissipative impedance introduce a phase angle, then the foregoing methods are no longer applicable. A device which is proportional to both the power factor and the apparent power must be used. Power-level measurements are concerned with decibel units, and a working knowledge of these units is required for proper interpretation of power tests. The decibel is used to determine the ratio of power changes or to indicate the power level in a circuit with respect to either zero or a standard reference level.

2-8.1 AF POWER

In the electrical transmission of speech or music where rapidly fluctuating amplitudes and frequencies are necessarily involved, the average power level measurement and its variation rate depend on the signal characteristics and time interval over which this average is taken. Power measurements for audio-frequency (AF) circuits are usually indicated in terms of decibels (dB), decibels referenced to one milliwatt (dBm), or volume units (vu). The power gain of an amplifier can be expressed in dB. The power level of a sinusoidal signal compared to a 1-milliwatt reference is indicated in dBm. The power level of a complex signal, such as voice, music, or multiplexed information, compared to a reference level of 1 milliwatt, is indicated in vu.

2-8.2 DECIBEL METERS

A dB meter is a form of ac electronic voltmeter calibrated in dBs. Such meters are useful for making measurements where direct indication in decibels is desired. However, it must be remembered that these are voltmeters, and that power measurements are not meaningful unless the circuit impedance is known. When the dB meter is calibrated, a reference point, based on a specific power, or value of voltage across a specified resistance, is selected to represent 0 dB. Many electronic voltmeters use a dB scale based on 1 milliwatt in a 600-ohm load to represent 0 dB. Based on this reference point, various voltage readings could be made on the low ac voltage scale. To provide a single calibrated dB scale for use on all dB ranges, numbers (+dB) corresponding to the voltage ratios existing between successive ranges and the low ac range are computed for each range. These numbers, shown on the front panel of the instrument, are added algebraically to each successive range reading to produce the correct value for the range. It should be clearly understood that the term decibel does not, in itself, indicate power. It does indicate a ratio or comparison between two power levels that permits you to calculate the power. Often, it is more desirable to express performance measurements in terms of decibels using a fixed power level as a reference. The original standard reference level was 6 milliwatts, but to simplify calculations a standard reference level of 1 milliwatt has been adopted.

2-8.3 VOLUME LEVEL METERS

The volume unit meter is used in audio equipment to indicate input power to a transmitter or to a transmission line. This type of meter has special characteristics, such as a standardized speed of pointer movement, speed of return, and calibration. The measurement of the average power level and its rate of variation with respect to time depends, not only on the signal characteristics, but also on the time interval over which the average is being taken. Accordingly, the speed of response of the instrument used to measure average power is of particular concern. Therefore, a standard power-level indicator incorporates a rectifier voltmeter having ballistic characteristics such that a sudden application of a single-frequency, constant-amplitude voltage giving a steady-state indication of zero vu will cause the instrument pointer to attain 99 percent of steady-state deflection in 0.3 second, with an overshoot of between 1 and 1.5 percent. The unit of measurement is the volume unit (vu), which is numerically equal to the number of dB above or below the reference level of 1 milliwatt into a 600-ohm load, provided the standard instrument was calibrated under constant-amplitude, sine-wave conditions. A change of one vu is the same as a change of one decibel. Therefore, it should be emphasized that the vu value obtained represents averages of the instantaneous power of speech or music obtained by an instrument having particular dynamic characteristics. The vu readings are equivalent to the power level in decibels only if the sinusoidal waveform is of constant amplitude. The standard instrument connected to a calibrating circuit is illustrated in Figure 2-31. A rectifier-voltmeter

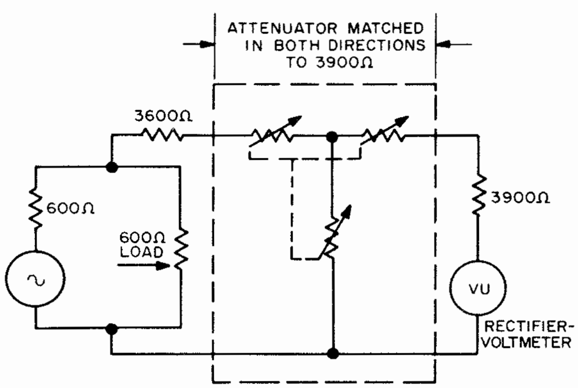


Figure 2-31 Schematic Circuit of a Volume-Level Indicator for Measuring Audio-Frequency Power in the Transmission of Speech and Music, Showing Connections to a Calibrating Circuit

whose impedance is 3900 ohms, is used in series with a 3600-ohm resistance. This combination is placed in parallel with the 600-ohm transmission line connecting the 600-ohm load to a 600-ohm generator. The calibration circuit impedance is 300 ohms with this arrangement. We can extend the measurement range by injecting a calibrated attenuator between the 3600-ohm resistor and the rectifier voltmeter. This attenuator must be matched to the 3900-ohm meter impedance, while the 7500-ohm total remains unchanged.

2-8.4 ELECTRODYNAMIC METERS

The electrodynamic wattmeter is used to measure power taken from alternating current or direct current power sources. (Refer to Figure 2-32.) The

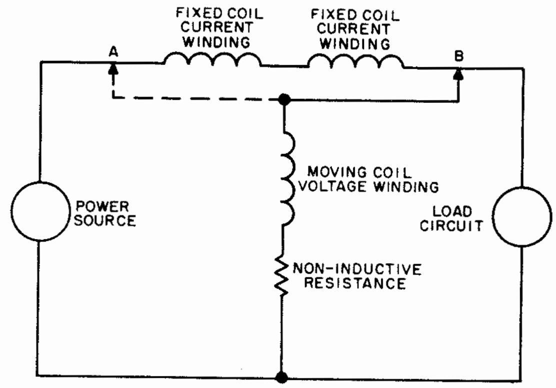


Figure 2-32. Electrical Equivalent of the Electrodynamic Wattmeter

electrodynamic wattmeter uses the reaction between the magnetic fields of two current-carrying coils (or sets of coils), one fixed and the other movable. When the current through the fixed-position field winding(s) is the same as current through the load, and the current through the moving coil is proportional to the load voltage, then the instantaneous pointer rotation is proportional to the instantaneous power. Since the moving pointer cannot follow the rapid variations in torque because of its longer natural period of vibration, it assumes a deflected position for which the average driving torque is equal to the restoring torque of the springs. Meter deflection is thus proportional to the average power. The dynamometer-type wattmeter automatically compensates for the power factor error of the circuit under test. It indicates only the instantaneous power resulting from in-phase values of current and voltage. With out-of-phase relationships, a current peak through the moving coil never occurs at the same instant as the voltage peak across the load, resulting in less pointer deflection than when the current and voltage are in phase. The simple meter shown in Figure 2-32 is not compensated. When the load is disconnected, this meter will still indicate that power is being consumed in the circuit. This difficulty can be eliminated by incorporating two compensating windings, mounted with the primary fixed coil current windings, as shown in Figure 2-33. These stationary windings are used to produce a

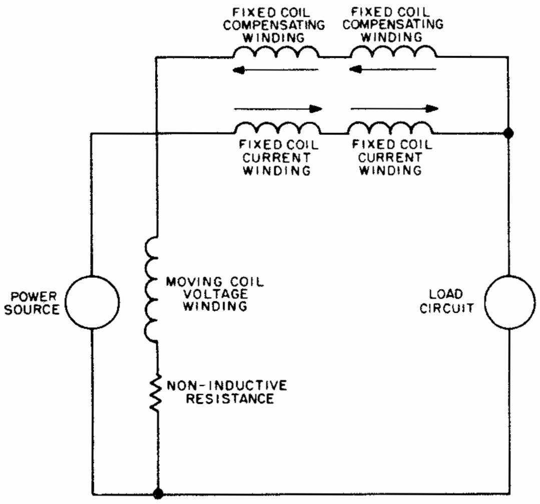


Figure 2-33. Electrical Equivalent of Compensated Electrodynamic Wattmeter

magnetic flux proportional to the current through the movable coil. As shown by the arrows in Figure 2-33, the currents through the primary movable coil and the compensating coil flow in opposite directions, producing a torque due to the opposing magnetic fields. These opposing fields cancel. Hence, with the load removed from the circuit, the meter will indicate zero power through the load. Electrodynamic wattmeters are subject to errors arising from various factors, such as temperature and frequency characteristics and vibration of the moving system. Aside from heat dissipation in the various coils, heat through the control mechanism will cause the springs to lengthen and lose tension, producing deflection errors. Figure 2-34 illustrates the mechanical equivalent of the electrodynamic wattmeter. Large currents within the circuit will also produce appreciable error. Therefore, the maximum current range of electrodynamic wattmeters is normally restricted to about 20

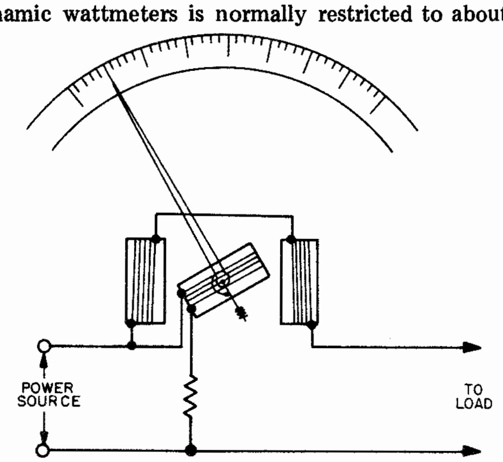


Figure 2-34. Mechanical Equivalent of the Electrodynamic Wattmeter

amperes. When larger load currents are involved, a current transformer of suitable range is used in conjunction with the wattmeter. However, a current transformer cannot be used if the ac circuit under test contains a dc component. The voltage range of wattmeters is generally limited to several hundred volts because of heat dissipation within the voltage circuit. However, the voltage range can be extended by using external voltage multipliers. Wattmeters used as laboratory standards have an accuracy of 0.1 percent, high-grade portable wattmeters an accuracy of 0.2 to 0.25 percent, and high-grade switchboard wattmeters an accuracy of 1 percent of full-scale value. Because electrodynamic wattmeter errors increase with frequency, only a rated accuracy of up to 800 hertz may be obtained for frequencies as high as 2500 hertz. Unshielded electrodynamic wattmeters should not be placed in the vicinity of stray magnetic fields. To prevent insulation breakdown and errors caused by electrostatic forces, an electrostatic tie-in is necessary between the voltage and current circuits and also between these circuits and ground. A wattmeter has current, voltage, and power ratings; therefore, damage may result when any of these ratings is exceeded. The electrodynamic wattmeter may be converted into an instrument for measuring reactive power by replacing the resistance normally in series with the voltage coil by a large inductance. A 90-degree current lag within the voltage coil provides a direct reading proportional to the reactive power in the circuit. Compensating networks must be used to cause the phase shift to be exactly 90 degrees.

2-8.5 TORSION-HEAD, IRON-CORED, AND COMPOSITE-COIL WATTMETERS

The torsion-head wattmeter is used to restore the movable coil to its original position after deflection, and to remove the mutual inductance error. Iron-cored wattmeters are primarily used as switchboard instruments, and employ the induction principle. Voltage and current coils are wound around a laminated iron core shaped to produce a mutually perpendicular magnetic field across an air gap. Eddy currents induced in a thin metal cylinder rotating in this air gap interact with the magnetic field to produce a torque proportional to the instantaneous power. This type of construction provides the advantages of increased operating torque, larger angles of rotation, ruggedness, compactness, and freedom from errors caused by stray fields. It has the disadvantage of a very narrow frequency range. The composite-coil wattmeter uses the upscale torque, produced by the ac power being measured, in opposition to the torque produced by an adjustable dc current in a set of windings intermingled or wound within the ac windings. Greater reading precision is obtained with this method than is possible with straightforward wattmeters, and errors due to elasticity of the spring suspension carrying the moving coil system are avoided.

2-8.6 VACUUM TUBE VOLTMETER

Electronic, or vacuum tube, wattmeters are used for direct small power measurements, or for power measurements at frequencies beyond the range of electrodynomometer-type instruments. A simplified electronic wattmeter circuit is shown in Figure 2-35.

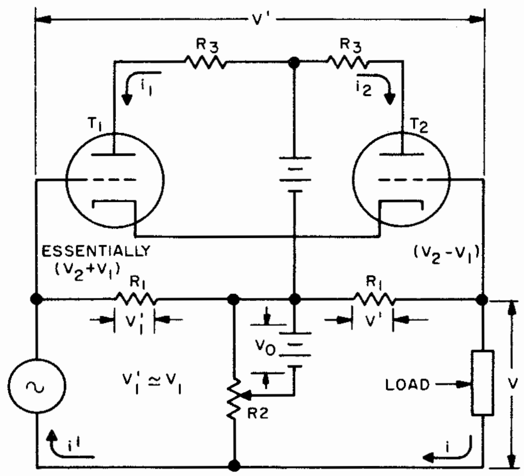


Figure 2-35. Simple Electronic Wattmeter Circuit

The matched triodes are operated in the square-law region, or nonlinear portion, of their characteristic grid-voltage, plate-current curves. The symmetrical resistive T-network between the generator and load will provide V_1 and V_2 voltages proportional to, and in phase with, the load current and voltage, respectively. A source of ac power is connected to the load through the series resistors, R_1. These two resistors are of equal value, and are made small to prevent the voltage drop across them from reducing the load voltage appreciably. R_2 is made large enough to have negligible power consumption. Therefore, the R_2 voltage is equal to the load voltage, and the voltage across either series resistor is proportional to the difference in the output currents of the tubes. The average value of the difference could be measured by a dc meter connected to read V_1. The preceding methods used to directly measure ac power are adequate only at a low frequency. As the frequency increases, the stray capacitances and inductances also increase. Therefore, the wattage reading error increases. Electronic multiplying circuits utilizing the characteristics of multigrid tubes are used as wattmeters. The operating conditions in a pentode are adjusted so that the plate current is proportional to the product of a linear function of plate voltage and an exponential function of grid voltage. Therefore, an accurate measurement of the average value of the product of two ac voltages, as required in a wattmeter application, is possible. Predictable performance over a frequency range of 20 hertz to 20 megahertz can be obtained.

2-8.7 ABSORPTION POWER METERS

Absorption power meters either absorb all or part of source power. They require a means of dissipating the absorbed power, a means of sensing the power thus dissipated, and a means of indicating the amount of power absorbed by the sensing network. Output power meters, thruline wattmeters, and meters employing bolometers are examples of absorption power meters used by the Navy.

2-8.7.1 Output Power Meters

Figure 2-36 depicts a common output power meter used in VHF-UHF applications. It has a 0 to 150 watt range covered in two steps: 0-50 watts; and 0-150 watts. Attenuator (in Figure 2-36) AT 1 provides a 50 ohm nominal resistive (dummy) load and employs metal film on glass construction. This dummy load is tapped to provide the proper operating voltage to the meter. Resistors R3 and R5 form a calibration network at 50 watts, and R7 and R8 form a calibration network at 150 watts. Accuracy, at approximately 23°C, is ± 5% for frequencies in the range of 30-600 MHz, ± 10% for frequencies between .6 and .8 GHz, and ± 20% for frequencies between 0.8 and 1.0 GHz. When RF power is applied to AT 1, this attenuator minimizes the effects of power factors generated by any reactive components. The RF energy is then detected and filtered by CR1 and C1, respectively. The resultant dc voltage, which is proportional to the input power, is applied to a sensitive microammeter via one of the calibration networks. This meter has a scale provided with two ranges: 0-50 watts; and 0-150 watts. To protect the meter, the higher range should always be tried first. If the value proves to be under 50 watts, a shift to the lower scale would provide enhanced accuracy.

2-8.7.2 In-Line Wattmeters

The basic in-line wattmeter (Figure 2-37) measures power applied to a 50 ohm impedance load and the power reflected from that load. The internal directional coupler is orientated such that it responds only to a wave traveling in one direction on the transmission line. The coupler can be rotated to accommodate either incidental or reflected power. The RF is then rectified, filtered, and applied to the meter, which is scaled in watts. Then RF power of 50-1000 watts can be measured between the frequencies of 2-30 MHz and 10-500 watts between the frequencies of 30-1000 MHz.

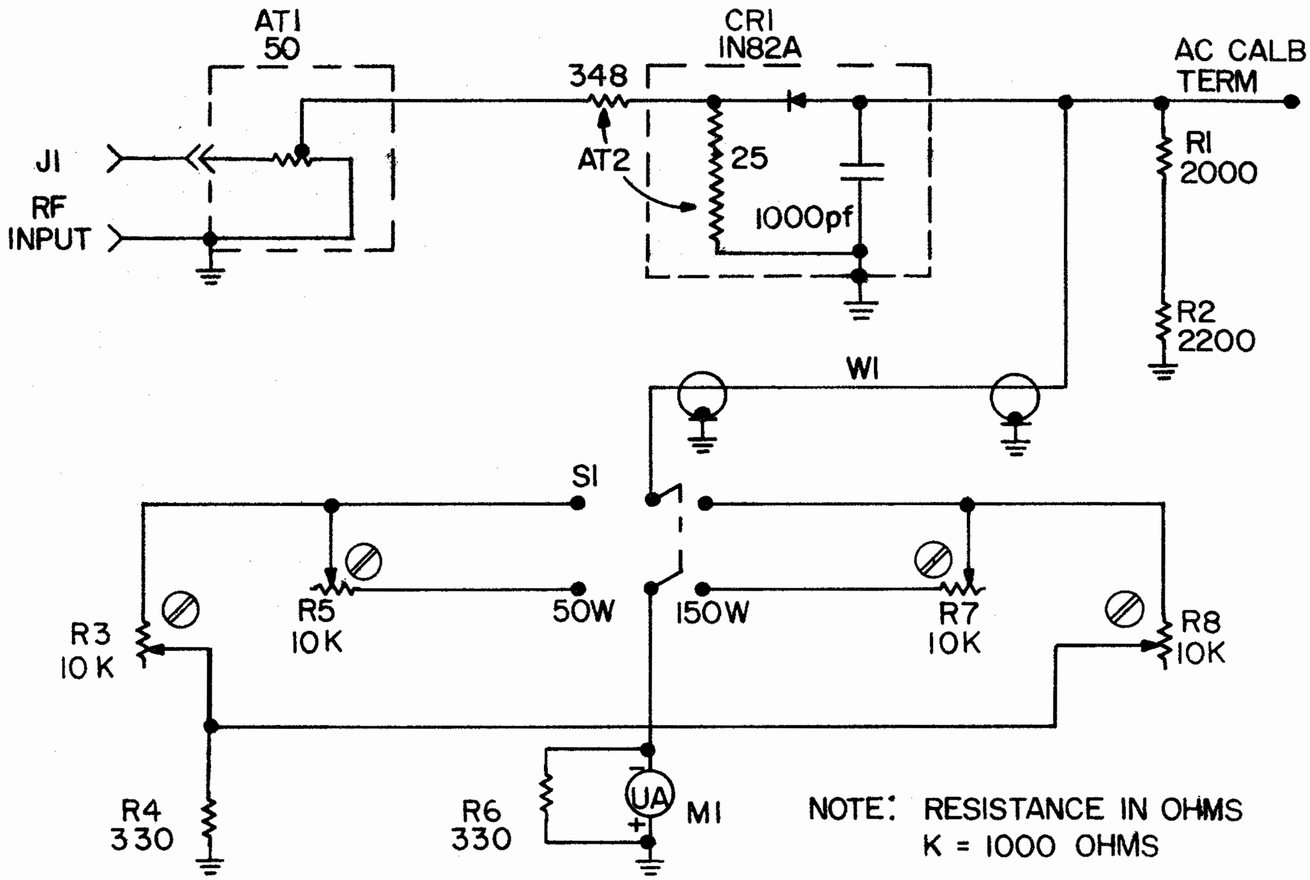


Figure 2-36. VHF-UHF Wattmeter

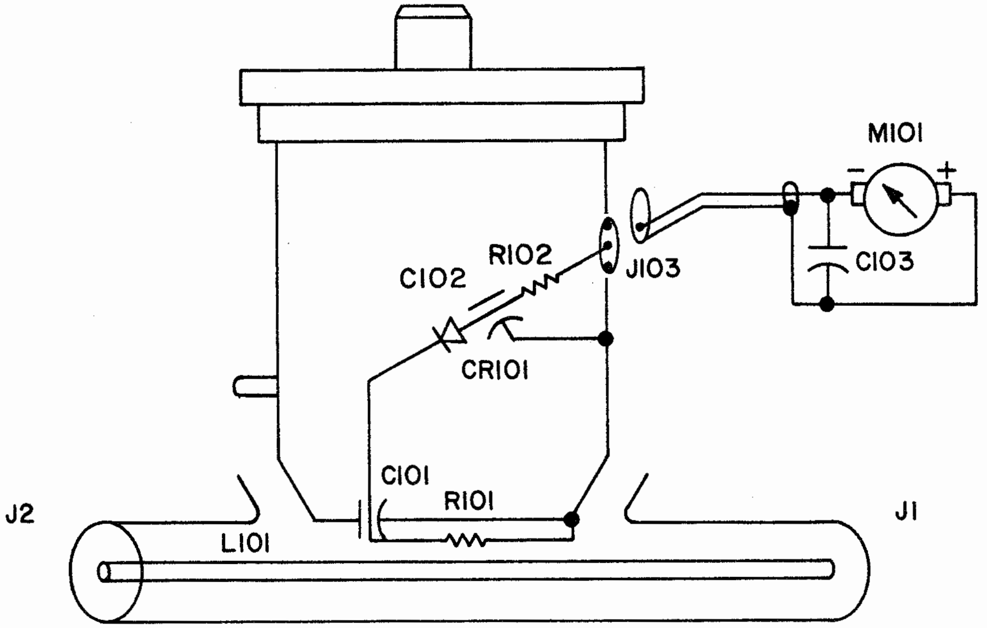


Figure 2-37. Typical In-Line Wattmeter

2-8.7.3 Bolometer

A bolometer features a specially constructed element of temperature-sensitive material. The active material is a semiconductor bead supported between two pigtail leads (called a thermistor). When RF power is applied to a bolometer element, the power absorption by the element heats the element and causes a change in its electrical resistance. Thus a bolometer can be used in a bridge circuit so that small resistance changes can be easily detected, and power measurement can be accomplished by the substitution method (that is, substitution of dc or low-frequency power to produce an equivalent heating effect). A D'Arsonval meter movement is usually employed as the null indicator. According to one principle of measurement (the principle used in the balanced bridge), the bridge is initially balanced with low-frequency bias power, RF power is then applied to the bolometer, and the bias power gradually removed until the bridge is again balanced. The actual RF power is then equal to the bias power removed. According to another principle of measurement (the principle used in the unbalanced bridge), the bridge is not rebalanced after the RF power is applied. Rather, the indicator reading is converted directly into power by calibration previously performed. Figure 2-38 illustrates the basic bolometer bridge circuit. The bolometer element

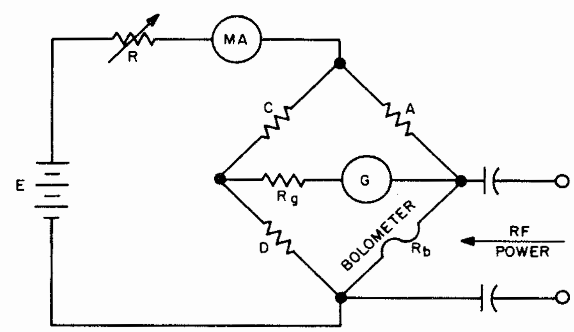


Figure 2-38. Basic Bolometer Bridge Circuit

must be physically small to be highly sensitive; it must be equally responsive to low-frequency and RF power; and it must be matched to the RF input power line. The cross-sectional dimension of the bolometer element is approximately equal to the skin depth of RF current penetration at the highest frequency of operation. This condition permits the dc and RF resistivities to be essentially equal, with the reactive component of the bolometer impedance at a minimum. Thermistors use semiconductor material shaped like a bead, with a thicker skin depth and shorter length to minimize standing-wave effects. These physical properties assure correspondence between lengthwise low-frequency and RF power distribution to provide the necessary inherent accuracy of the bolometer. An air-mounted bolometer provides a power sensitivity one hundred or more times that provided by static calorimetric devices. Additional sensitivity may be obtained by mounting the element within an evacuated envelope to eliminate convective heat loss. The small size of bolometer elements is associated with small thermal mass and short thermal time constants. The thermal time constant varies directly with the volume-to-area ratio of the element for a particular shape and composition. Typical time is up to 0.1 second for thermistor beads. The thermistor type of bolometer element is usually composed of a ceramic-like mixture of metallic oxides having a large negative temperature coefficient of resistance. Two fine platinum-alloy wires are embedded in the bead, after which the bead is sintered and coated with a glass film. Typical dimensions of a thermistor bead used for microwave measurements are 0.015-inch along its major axis and 0.010-inch along its minor axis. The thermistor bead may be operated at high temperatures; it is rugged, both electrically and mechanically it has high resistance-power sensitivity; and it has a good temperature-power sensitivity. In addition, it can endure large pulse energies; it has a sluggish thermal response; and it has negligible pulsed-power measurement errors. The more sensitive thermistor requires thermal shielding or heat compensation for best operation. Thermistors drop to very low resistances at large powers, and thus become mismatched. Figure 2-39 shows typical thermistor characteristics.

2-8.7.4 Balanced Bridges

The following subparagraphs describe

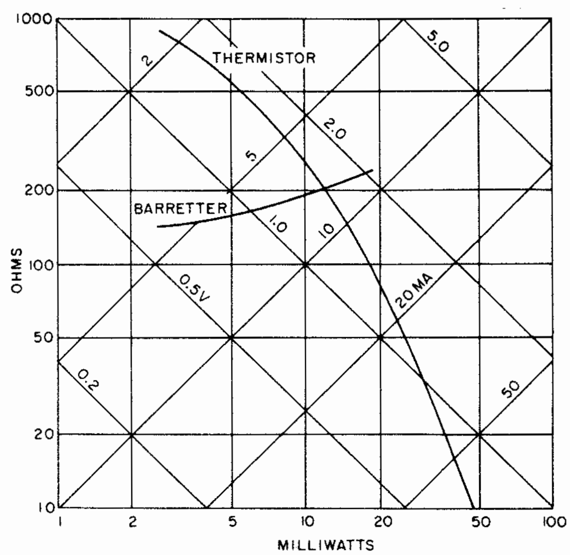


Figure 2-39. Typical Thermistor Characteristics

the various balanced bridges used in Navy electronic measurements.

2-8.7.4.1 Potentiometer Bridge

The potentiometer bridge is independent of bias supply drift. The bias change necessary to rebalance the bridge, following the application of RF power, is measured directly by a potentiometer method. Figure 2-40 illustrates the potentiometer bridge. The bridge is

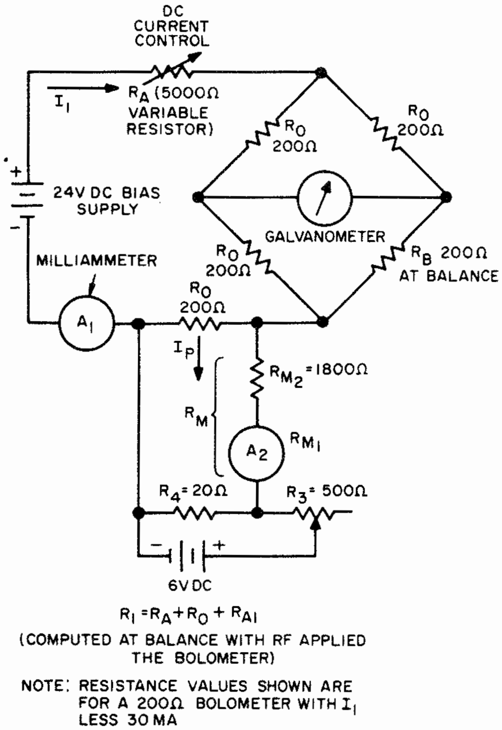


Figure 2-40. Potentiometer Bridge

balanced with bias power only, and the auxiliary circuit potentiometer, R_1, is adjusted so that ammeter A_2 indicates zero. The bridge is rebalanced by means of R_4 after RF power is applied, and the current through A_2 is then read. The RF power can be calculated from the meter readings of A_1 and A_2 at final bridge balance. The measurement accuracy is determined by the accuracy with which the meters are read.

2-8.7.4.2 Product Bridge

The product bridge utilizes the algebraic addition (product) of the simultaneous readings obtained from a voltmeter and ammeter combination. Figure 2-41 illustrates the meter connections within a product bridge. When the bridge is rebalanced with RF power in the bolometer, the voltmeter indication should be in direct proportion to the sum of both the initial and final currents within the bridge (I_1 + I_2), and the ammeter reading should be equal to the current difference (I_1 - I_2). The product of these two indications is proportional to the RF power. Upon the application of RF power to the bolometer, an L-pad attenuator of constant input resistance is connected into the circuit, and the rebalance of the bridge accomplished by adjusting this attenuator. The bias current taken from the bridge is diverted into shunt resistance R_1, and measured by the ammeter. Calibration and constant L-pad impedance affect the measurement accuracy. In addition, a drift-free bias supply and high internal resistance of the voltmeter are required.

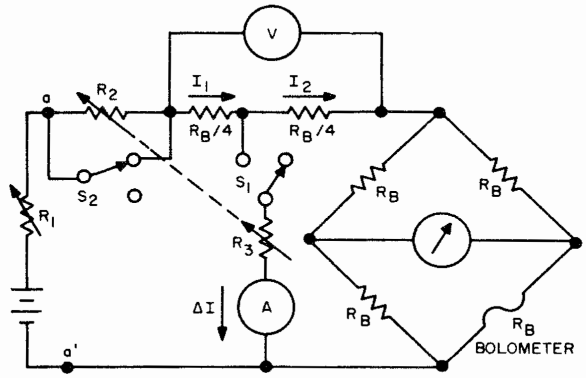


Figure 2-41. Product Bridge

2-8.7.4.3 Summation Bridge

The summation bridge is a direct reading all-dc bridge using a stable power supply, two ganged constant-input-impedance L-pad attenuators, and a meter summing circuit. The L-pad attenuators simultaneously control the bridge and meter circuit currents. The meter summing circuit provides a reading proportional to the RF power being measured. The bridge, which is of equal arm construction, uses two coils as summing elements in the double-coil ammeter illustrated in Figure 2-42. The adjustment calibration is accomplished by the variable shunt, R, across the meter circuit. This resistor provides an adjustable multiplier for the current, to permit calibration without affecting attenuator impedance when the multiplying factor is changed. The bridge accuracy is dependent on the closeness of meter tracking of the current reduction factor and the current attenuators.

2-8.7.5 Unbalanced Bridges

The following subparagraphs describe the operation of unbalanced bolometer bridges.

2-8.7.5.1 All-DC Compensated Bridge

This temperature-compensated unbalanced bridge circuit (Figure 2-43) employs one or two disk-type thermistors as ambient temperature compensating elements within a thermistor bridge. The disks (RT2 and RT3) are used as temperature-sensitive resis-

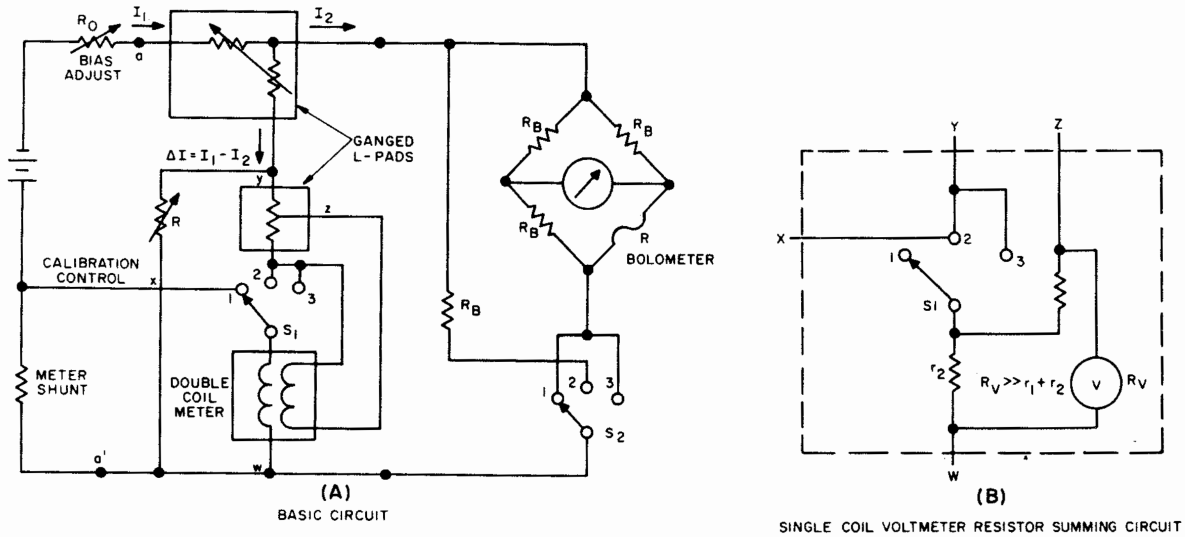


Figure 2-42. Summation Bridge

tors in the circuit, and are mounted to make good thermal contact with the waveguide. One disk, in the bridge meter circuit, compensates for the change in bridge sensitivity when the bridge is zeroed by readjustment of the bias current at different ambient temperatures. The second disk maintains the bridge bead thermistor at a constant resistance, regardless of ambient temperature changes, to prevent a temperature-induced drift of zero level during measurement. This method maintains the bridge sensitivity constant to within ± 1/2 dB over a 75-degree C ambient temperature range.

2-8.7.5.2 DC and Audio Power Compensated Bridge

The bolometer element in this type of bridge is raised to the proper operating temperature by two types of power. When the bridge is balanced, the dc power is fixed and is not adequate to balance the bridge

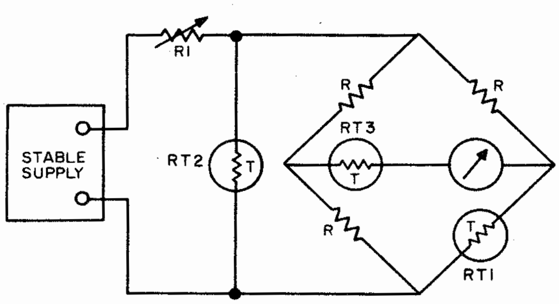


Figure 2-43. Simplified Diagram of a Two-Disk Thermistor Bridge

at the highest temperatures encountered in practice. Therefore, audio power supplied from a supplementary, adjustable source is used. The bridge sensitivity and calibration are constant, and independent of ambient temperature, because the null detector responds only to a constant value of power. Figure 2-44 illustrates this type of bridge (called a V bridge). As can be seen in the illustration, a disk thermistor permits bridge unbalance. This instrument has a measurement range of 0 to 2 mW. The measurement range can be extended with a shunt in the meter circuit; however, accuracy will be lost if a shunt is used.

2-8.7.6 Self-Balancing Bridge

A bridge which is automatically rebalanced when an unknown RF power is applied to the bolometer is termed a self-balancing bridge (Figure 2-45). The bolometer bridge may be used as the coupling network between the input and output of high-gain, frequency-selective audio amplifiers. Audio frequency oscillations of proper amplitude and phase are maintained by adequate feedback, causing the bolometer resistance to remain at a fixed value in order to balance the bridge. A multiplicity of power ranges may be obtained by using a multirange voltmeter. Self-balancing AF bridges are available for use with hot-wire, thermistor, or bolometer film elements. A normal bridge offers seven power ranges, (from 0.1 mW to 100 mW (full scale)), and is used with bolometers having resistances within ± 10 percent of selected values from 50 to 250 ohms. Since the sign of the bolometer element coefficient of resistance determines the feedback voltage phase, a switch is used on the instrument panel for reversing the amplifier input connections, permitting

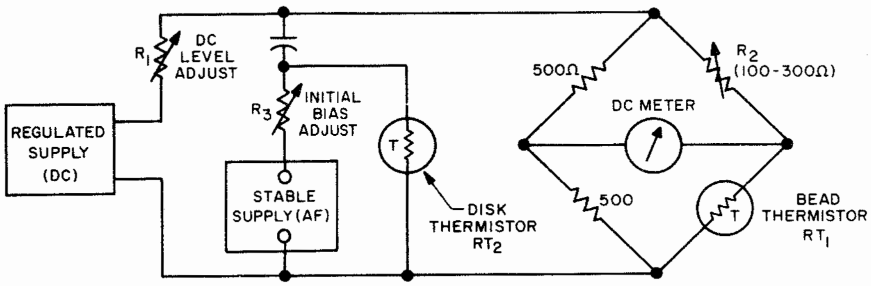


Figure 2-44. Simplified-Diagram of V Bridge

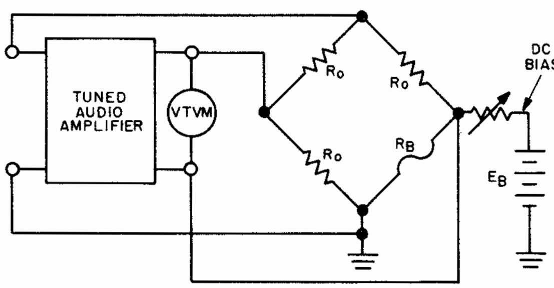


Figure 2-45. Self-Balancing Bridge Circuit

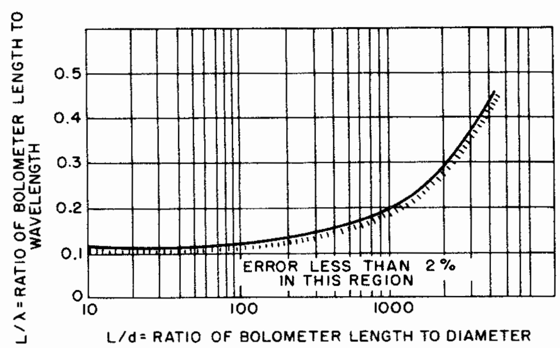


Figure 2-46. Relation Between Bolometer Wire Dimensions and Wavelength for Small Substitution Error

the bridge to be used with both positive and negative coefficient elements. Errors within this instrument are large if pulse-modulated RF power is being measured, especially when using hot-wire bolometer elements, which tend to follow the modulation envelope. As a result of normal dynamic bolometer behavior, audio voltages generated at the bridge detector terminals may cause spurious oscillations within the oscillator, which render any measurements meaningless. Sluggish thermistor elements have little of this type of error. The three main categories of error in bolometric measurements are instrumentation error, mounting inefficiency error, and equivalence (or substitution) error. Instrumentation error is as small as dc and low frequency techniques and bias power source stability permit. Compensation may be used to minimize the errors due to temperature changes. Equivalence error (lack of equivalence of heating effect produced by RF and substituted power) for thin-wire bolometers is a function of the ratio of wire length to operating wavelength. As shown in Figure 2-46, the region of small error for varying ratios of length-to-diameter and length-to-wavelength is due to an assumed standing wave along the bolometer, and may be determined by solving for the temperature distribution along the wire under dc and RF conditions. In the case of thermistor beads, the errors are small if the bead dimensions are small as compared with the RF wavelength.

Mounting inefficiency error is variable because the error is occasioned by stray losses in structures outside the bolometer element, such as contacts, leads, supports, and glass envelopes. In addition, the same mounting may exhibit varying errors due to the manner of inserting, positioning, or making contact with the bolometer element. The dynamic behavior of the bolometer during the measurement of pulsed or modulated power is an additional source of measurement error. This error is significant when short-time constant elements (such as Wollaston wires) are used. The bolometer resistance fluctuations cause periodic time variations in both temperature and resistance, as a result of the RF modulation envelope on the short-time constant elements. This type of bolometer error is due to variations of RF impedance during a pulse, or to nonlinear cooling of the bolometer between pulses. The error may be partially eliminated by coating the bolometer wire with a thin coat of low-loss dielectric such as silicone varnish. Thermistor elements and film bolometers under normal pulsed power exhibit negligible error.

2-8.7.7 Bolometer Power Meter

The standard power meter used in the Navy is an automatic self-balancing instrument employing dual-bridge circuits. It is designed to operate with temperature-compensated thermistor mounts that enable the technician to measure power in a 50 ohm coaxial system from 10 MHz to 18 GHz, and in a waveguide system from 2.6 GHz to 40 GHz. A seven-position switch allows full-scale power ranges of 10 microwatts to 10 milliwatts or from -20 dBm to +10 dBm. This system can be further extended with the aid of attenuators. The mount includes two thermistors, one of which (R_D) absorbs the microwave power to be measured, and other (R_C) supplies temperature compensation and converts the measured RF power to a meter indication. Basically, the power meter circuit (Figure 2-47) consists of two bridges, with each bridge including one of the thermistor elements as a bridge arm. The bridges are made self-balancing through the use of feedback loops. Positive or regenerative feedback is used in feedback loop 1; degenerative (negative) feedback is used in feedback loop 2. Both bridges are excited by a common 10 kHz source. The kHz amplifier-oscillator supplies power (I_{10} kHz) to bias thermistor R_D in feedback loop 1, to the resistance required to balance the RF bridge. An equal amount of 10 kHz power is supplied by the same oscillator to the second thermistor, R_C, in feedback loop 2, through two series-connected transformers (T1 and T2). The second feedback loop balances the metering bridge. When RF is applied to thermistor R_D (but not to R_C) an amount of 10 kHz power is present equal to the RF power being removed from R_D by the self-balancing action of the bridge. Transformers T1 and T2 are connected in series; therefore an equal amount of 10 kHz power is also removed from metering thermistor R_C. Since the RF power replaced the 10 kHz power, the RF bridge is in balance; however, the metering bridge must be balanced by its separate feedback loop. Sufficient dc power to equal the 10 kHz power lost by R_C is automatically replaced, balancing this loop. Hence the dc power applied to the metering bridge thermistor R_C is equal to the microwave power applied to R_D. The meter circuit senses the magnitude of the feedback current. The resultant meter current passes through a squaring circuit to the indicating meter. Since power is proportional to I^2, the squaring circuit provides a linear meter indication. The two thermistors are matched with respect to their temperature characteristics, therefore there is only a very small amount of drift of the zero point with ambient temperature changes. With a change in temperature, there is a change in the electrical power needed by

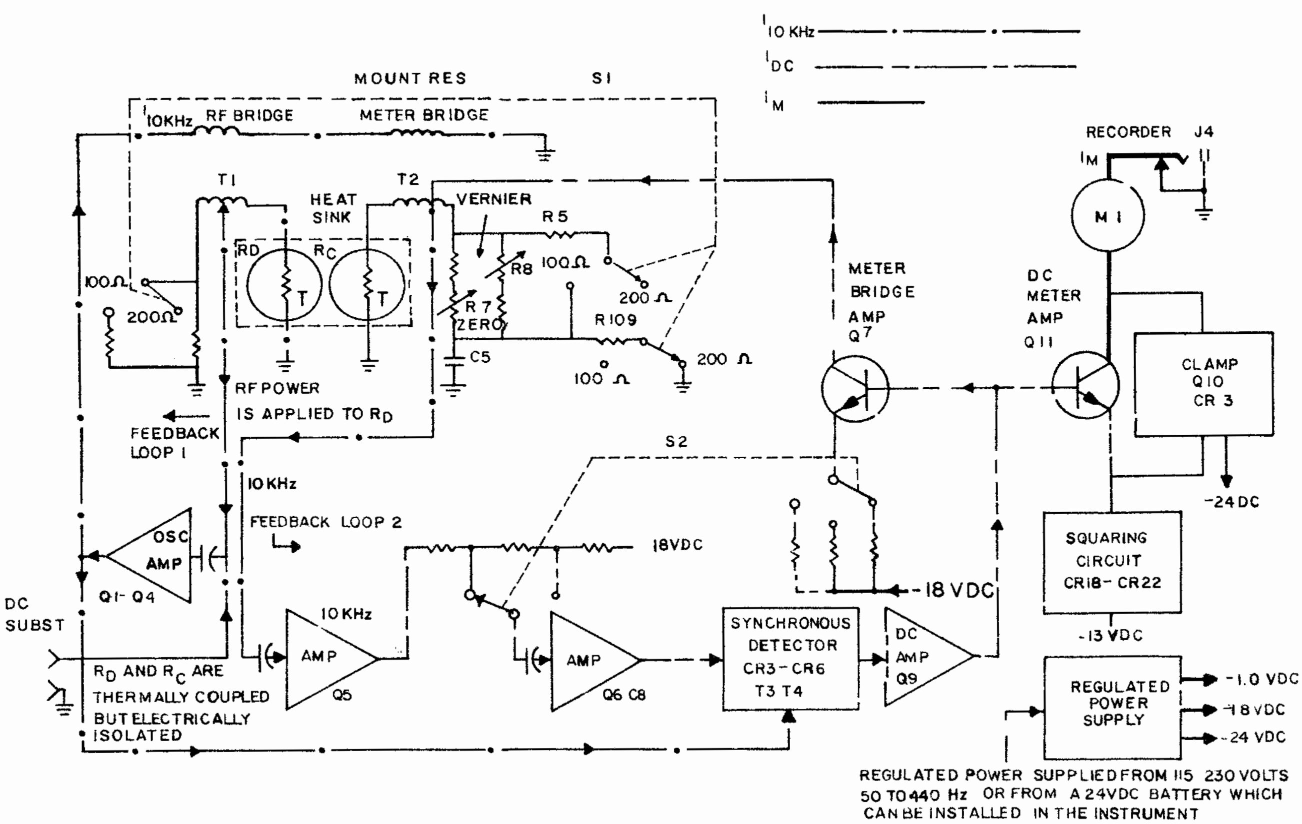


Figure 2-47. Power Meter Block Diagram

the thermistors to maintain constant operating resistances. This change is automatically performed by feedback loop 1 which changes the amount of 10 kHz power for both thermistors by the proper amount. The dc power in feedback loop 2 is not changed, and since it is this dc power that is metered, the temperature change has not affected the meter indication.

2-8.8 CALORIMETERS

The Calorimeters are the most accurate of all instruments for the measurement of high power. Average power determination is immaterial, and frequency or waveform considerations are minor with respect to the frequency range of application. Calorimeters depend on the complete conversion of the input electromagnetic energy into heat. Direct heating requires the measurement of the heating effect on the medium, or load, terminating the line. Indirect heating requires the measurement of the heating effect on a medium or body other than the original power-absorbing material. Power measurement with true calorimeter methods is based solely on temperature, mass, and time. Substitution methods use a known low-frequency power to produce the same physical effect as an unknown RF power being measured. Calorimeters are classified as static (non-flow) types and circulating (flow) types.

2-8.8.1 Static Calorimeters

The static calorimeter uses a thermally shielded body. Since an isolated body loses little heat to a surrounding medium, the temperature increase of the body is in direct proportion to the time of applied power. The product of the rate of temperature rise in the calorimetric body and its heat capacity equals applied power. Figure 2-48 illustrates a static type calorimeter.

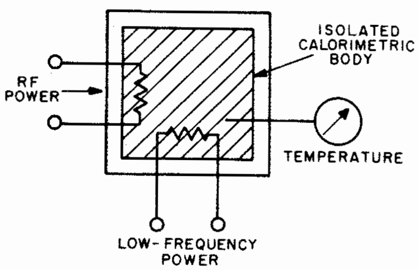


Figure 2-48. Generalized Static Calorimeter Using Low-Frequency Power Substitution

2-8.8.1.1 Adiabatic Calorimeter

In the adiabatic meter, power is applied directly to a thermally isolated body, and the rate of temperature rise is determined from a temperature change measurement during a sufficiently long known time interval. Figure 2-49 illustrates an adiabatic calorimeter using water as the body contained in a covered Dewar flask. A tapered-wall, open-ended waveguide contains a sealed inclined glass partition to create a wedge-shaped water load of low reflection coefficient. Thorough mixing of the water is accomplished with a stirrer, and a sensitive thermometer measures the temperature rise. A heating coil is wound around the waveguide inside the calorimeter, and is used for calibrating purposes when low-frequency power is applied. This type of meter can be used for accurate measurement of several hundred watts of average power, and can withstand 50 kilowatts of peak power.

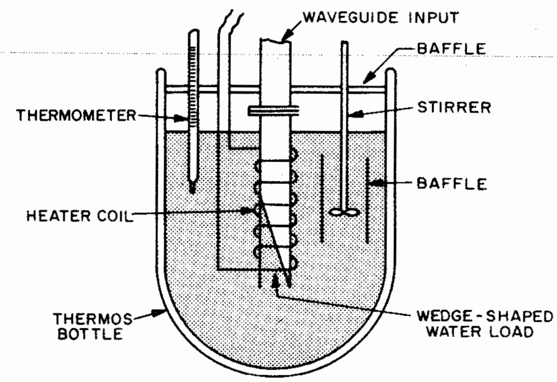


Figure 2-49. NBS Adiabatic Calorimeter

2-8.8.1.2 Nonadiabatic Calorimeter

The nonadiabatic calorimeter uses an RF termination with a resistive film strip or lossy dielectric materials (solid or liquid) as a load. Temperature indication can be accomplished with thermocouples, thermopiles, thermistors, thermometers, bimetallic strips, and manometers. Calibration is against a power standard or known low-frequency power. Based on the above principle, a coaxial calorimeter of good sensitivity with a short, 50-ohm resistive film on a lava (dielectric) center conductor, enclosed within a tapered, thin-walled outer conductor, is used for frequencies between 0 and 1200 megahertz. The RF termination is electrically connected to, but thermally isolated from, a massive mounting plate by a short section of silvered lava coaxial line with a high thermal resistance. The steady-state temperature rise of the outer casing of the load with respect to the mounting plate is indicated by a differential platinum resistance thermometer in a Wheatstone bridge. Low-frequency power applied to the termination will provide a method of calibration. Powers in the range of 0 to 2.5 watts may be measured. A 70-second time-constant and steady-state temperatures are attained in about six minutes. The small physical size of termination, (to keep convective and radiative heat losses low), provides high sensitivity. Calibration with lower-frequency power is extremely accurate because the termination is broadband and should exhibit the same power distribution from dc (zero) to 10,000 megahertz.

2-8.8.1.3 Twin Calorimeters

A Microwave Milliwatt Calorimeter, which provides a method of using two calorimetric bodies thermally shielded against ambient temperature variation, will provide enhanced sensitivity. Figure 2-50

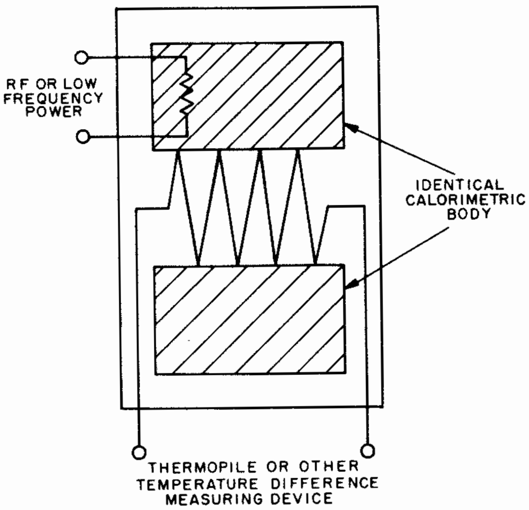


Figure 2-50. Twin Calorimetric System

illustrates this type of calorimeter device. The power to be measured is applied to one calorimeter-body, whereas the other acts as a temperature reference. The steady-state temperature difference between the two calorimeters is used as a measure of RF power. Calibration is performed with low-frequency power of equal heating effect as the RF power to obtain exceptionally good accuracy. A differential air-thermometer temperature difference indicator (Figure 2-51) is used with a twin calorimeter to measure microwave power in the 0.100 mW range. This instrument consists of two similar glass cells connected by a capillary tube containing a liquid pellet. Each glass cell contains a tapered carbon coated strip, and the entire assembly is mounted in a rectangular waveguide. Balancing dc power heats one strip; the other strip is heated by RF power. The liquid pellet indicates the differential expansion of the air within the two cells, and is viewed through an aperture in the waveguide wall, preferably with a microscope for highest sensitivity. Maximum accuracy is obtained if the RF power in the second cell, and the final measurement made by the substitution of a known dc power for the RF power in the same strip to maintain the original balance. This procedure permits a 2 percent accuracy at 10 mW.

2-8.8.2 Flow Calorimeters

Flow calorimeters are classified by the type of circulating method used (open or closed), the type of heating used (direct or indirect), and the type of measurement performed (true calorimetric or substitution). Water or other calorimetric fluid is used only once in an open system. An overflow system is used to maintain a constant rate of flow. Closed systems recirculate the fluid continuously be means of a pump, and a cooling system restores the fluid to ambient temperatures prior to its return to the calorimeter. Closed systems are more elaborate, but this self-contained method will permit the use of fluids other than water. Flow calori-

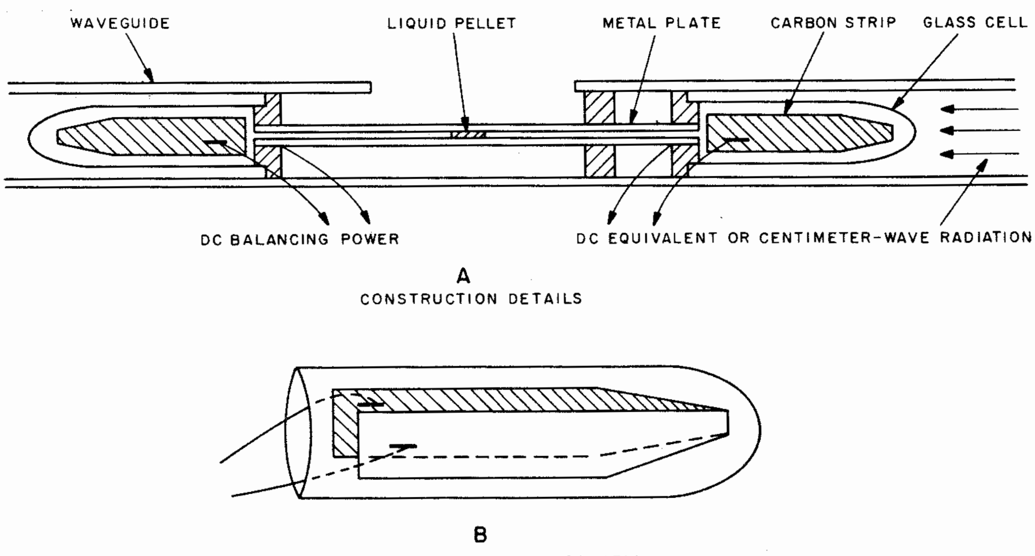


Figure 2-51. Differential Air Thermometer-Type Calorimeter

meters provide the primary standards for the measurement of high power levels, and, in conjunction with calibrated directional couplers, attenuators, power dividers, or other similar devices, serve to standardize medium and low-power measuring instruments. The measurement time depends on the required time for the entering fluid to reach the outlet, where the rise temperature is measured. The circulating fluid may serve in a dual capacity as the dissipative medium and coolant, using the direct heating method, or solely as a coolant, using the indirect heating method. Because of its excellent thermal properties and high dielectric loss at 1000 MHz or higher, water is normally used in both heating methods. Water is rarely used as the fluid at frequencies lower than 1000 MHz because of insufficient dielectric losses. The indirect heating method offers a wider frequency and power range coverage, and can be used in substitution-type measurements.

2-8.8.2.1 Substitution Flow Calorimeters

True calorimetric measurements contain appreciable error because of non-uniformity of flow rate, air bubbles, flow rate measurement inaccuracies, and temperature rise. Flow regulators, bubble traps, and good thermal insulation are required to eliminate the majority of these errors. Substitution methods do not involve direct heat dissipation measurement of moving fluid. Greater accuracy is obtained because known low-frequency power is substituted for unknown RF power, with all other measurement parameters remaining constant. The accuracy depends on the exactness of the low-frequency power determination and the degree that all factors remain fixed during the substitution of one type of power with another. Figure 2-52 illustrates a flow calorimeter using low-frequency power substitution. Two different measurement techniques are possible with this type of meter: the calibration technique and the balance technique. The calibration technique uses an adjustable known power to exactly reproduce the same

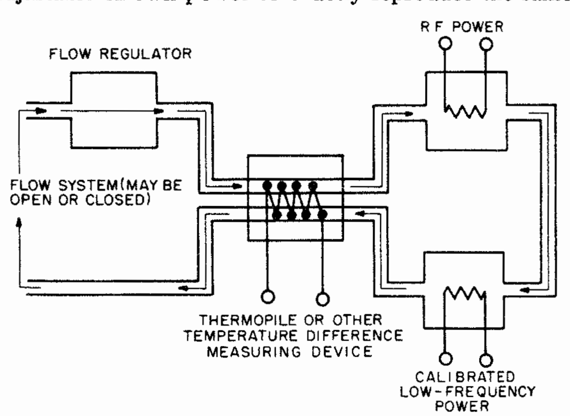


Figure 2-52. Generalized Flow Calorimetric System Using Substitution at Low-Frequency Power

temperature indication originally obtained by the unknown RF power measurement. The balance technique uses an initial low-frequency power (P_1) to provide a steady-state temperature rise in the calorimetric fluid. When unknown RF power is applied, the original power (P_1) is reduced to a new power (P_2) to maintain the same temperature indication. Therefore, the actual power equals P_1 - P_2. Figure 2-53 illustrates a widely used method of power measurement using a balanced

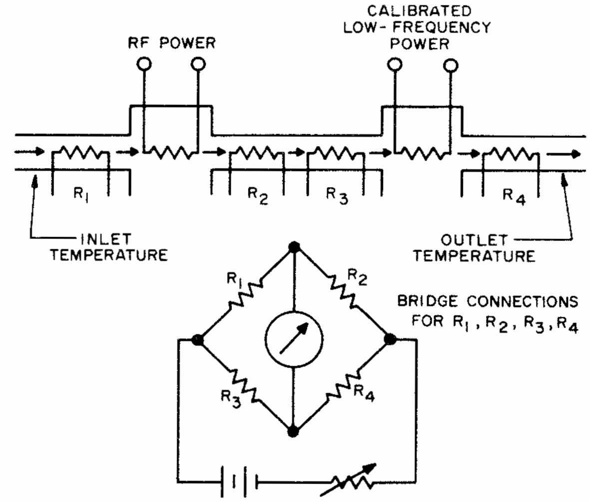


Figure 2-53. Generalized Balanced Flow Calorimeter

flow calorimeter. Temperature-sensitive resistors are bridge-connected as the thermometric elements, and are balanced at ambient temperature prior to the application of power. Low-frequency balancing power and the unknown RF power are applied to maintain the bridge at null. This occurs when the temperature rise due to the unknown RF power equals the temperature rise due to the known low-frequency power.

2-9 FREQUENCY MEASUREMENTS

Frequency measurements often form an essential part of preventive and corrective maintenance for communication and electronic equipment. Rotation frequencies of some mechanical devices must be determined. The output frequency of electric power generators is checked when the engine is started and during preventive maintenance routines. Carrier equipment which operates in the audio frequency range must be adjusted to operate at the correct frequencies. Radio transmitters must be accurately tuned to the assigned frequencies to provide reliable communications and to avoid interfering with radio circuits operating on other frequencies. Radar sets must be properly tuned to obtain satisfactory performance. The rotation frequency of record player turntables and teletypewriter motors can be measured by the use of a stroboscope. Stroboscopic methods compare the rate of one mechanical rotation or vibration with another or with the frequency of a fluctuating source of illumination. Tachometers can be used to measure the rotation frequency of armatures in electric motors, dynamotors, and engine-driven generators.

2-9.1 FREQUENCY MEASUREMENT METHODS

Frequency measuring equipment and devices, particularly those used to determine radio frequencies, constitute a distinct class of test equipment, because of the important and critical nature of such measurements. The requirement of precise calibration is extremely important in all frequency measuring work. To provide accurate measurements, every type of frequency measuring device must be calibrated against some frequency standard.

2-9.2 FREQUENCY STANDARDS

Of considerable importance in the measurements of frequency or wavelength are the standards against which frequency measuring devices are compared and calibrated. Frequency standards belong to two general categories: primary and secondary standards. The primary frequency standard maintained by the U.S. Bureau of Standards has long-term stability and an accuracy of one part in 10^{12}, utilizing an atomic clock. A secondary frequency standard is a highly stable and accurate standard that has been calibrated against the primary standard.

2-9.2.1 U.S. National Bureau of Standards

The National Bureau of Standards (Figure 2-54) provides time and frequency standards from sta-

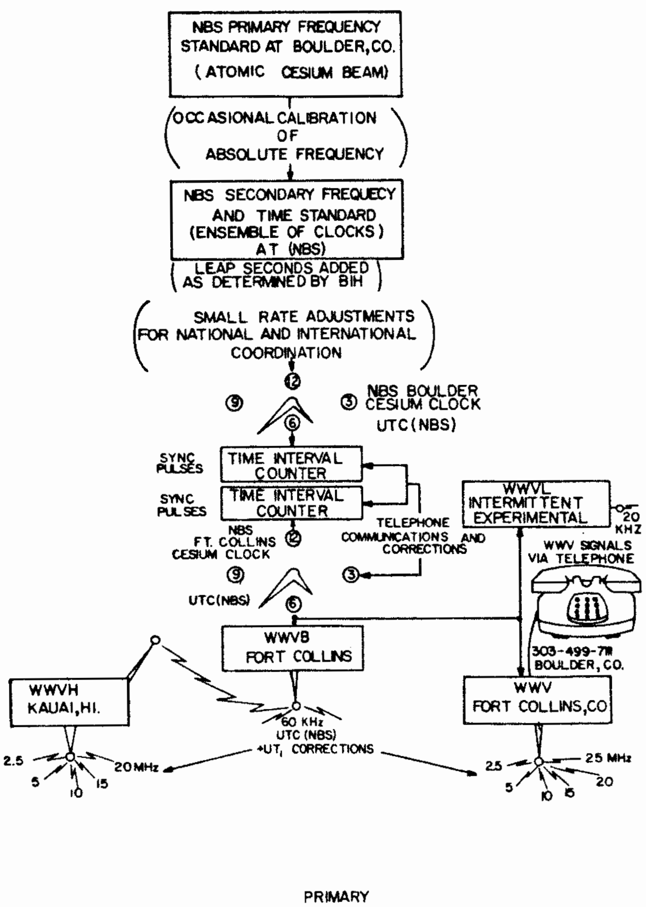


Figure 2-54. National Bureau of Standards Frequency and Time Facilities

tion WWV (N 40° 41', W 105° 02'), at Fort Collins, Colorado, and from station WWVH (N 21° 59', W 159° 46') at Kekaha, Kauai, Hawaii. The following technical radio services are given continuously by these stations:

- Standard radio frequencies
- Standard audio frequencies
- Standard time intervals
- Standard musical pitch
- Time signals
- Radio propagation notices (WWV only)
- Geophysical alerts
- Coordinated Universal Time (UTC) + UT_1 Corrections

The UTC scale uses the atomic second as a time interval. UT_1 is based on the earth's uniform rate of rotation. Since the earth's rotation is not precisely uniform, UT_1 is an adjustable interval.

2-9.2.2 Radio Frequencies

To ensure reliable coverage of the U.S.A. and extensive coverage of other parts of the world, radio stations WWV and WWVH provide the primary standard radio frequencies listed in Table 2-3. Figure 2-55 shows the broadcast format of stations WWV and WWVH.

2-9.2.3 Silent Periods

The transmissions of WWV and WWVH are interrupted for five minutes of each hour. The silent period begins at 15 minutes past the hour for station WWVH, and 45 minutes past the hour for station WWV. These silent periods are provided to eliminate errors due to interference.

2-9.2.4 Audio Frequencies and Musical Pitch

Two primary standard audio frequency tones (440Hz and 600Hz) are broadcast on all WWV and WWVH carrier frequencies. In the absence of a message, a 500Hz tone is broadcast during the message interval. The 440 Hz signal that denotes the one hour mark (Figure 2-55) is the standard musical pitch, A above middle C. The 600Hz tone provides a frequency standard for checking the 60Hz power line frequency.

2-9.2.5 Time Intervals and Signals

The standard time pulse marking interval of one second consists of five cycles of a 1000Hz tone at WWV and six cycles of a 1200Hz tone at WWVH. These marker pulses are heard as clock ticks. Intervals of one minute are marked by a 0.8 second, 1000Hz tone for WWV, and a 0.8 second, 1200Hz tone for WWVH. Each hour is marked by a 0.8 second, 1500Hz tone on both stations (Figure 2-55). Coordinated Universal Time (UTC) is announced on WWVH between the 45 and 52.5 seconds of each minute, and on WWV between the 52.5 and 60 seconds of each minute.

TABLE 2-3. NBS FREQUENCY STANDARDS AND TIME TRANSMISSION

TRANSMISSION	WWV	WWVH
RF Signal Frequency MHz	5, 10, and 15	5, 10, and 15
Frequency Stability	1 part in 10^{11}	1 part in 10^{11}
Frequency Deviation	1 part in 10^{12} per day	1 part in 10^{12} per day
Seconds Frequency and Duration	5 cycles of 1000Hz for .005 seconds	6 cycles of 1200Hz for .005 seconds
Audio Tones	600Hz and 500Hz with 440Hz to mark the hour	600Hz and 500Hz with 440Hz to mark the hour
Frequency Accuracy	1 part in 10^{12}	1 part in 10^{12}
Propagation Forecast	14 min. past the hour (in voice)	None

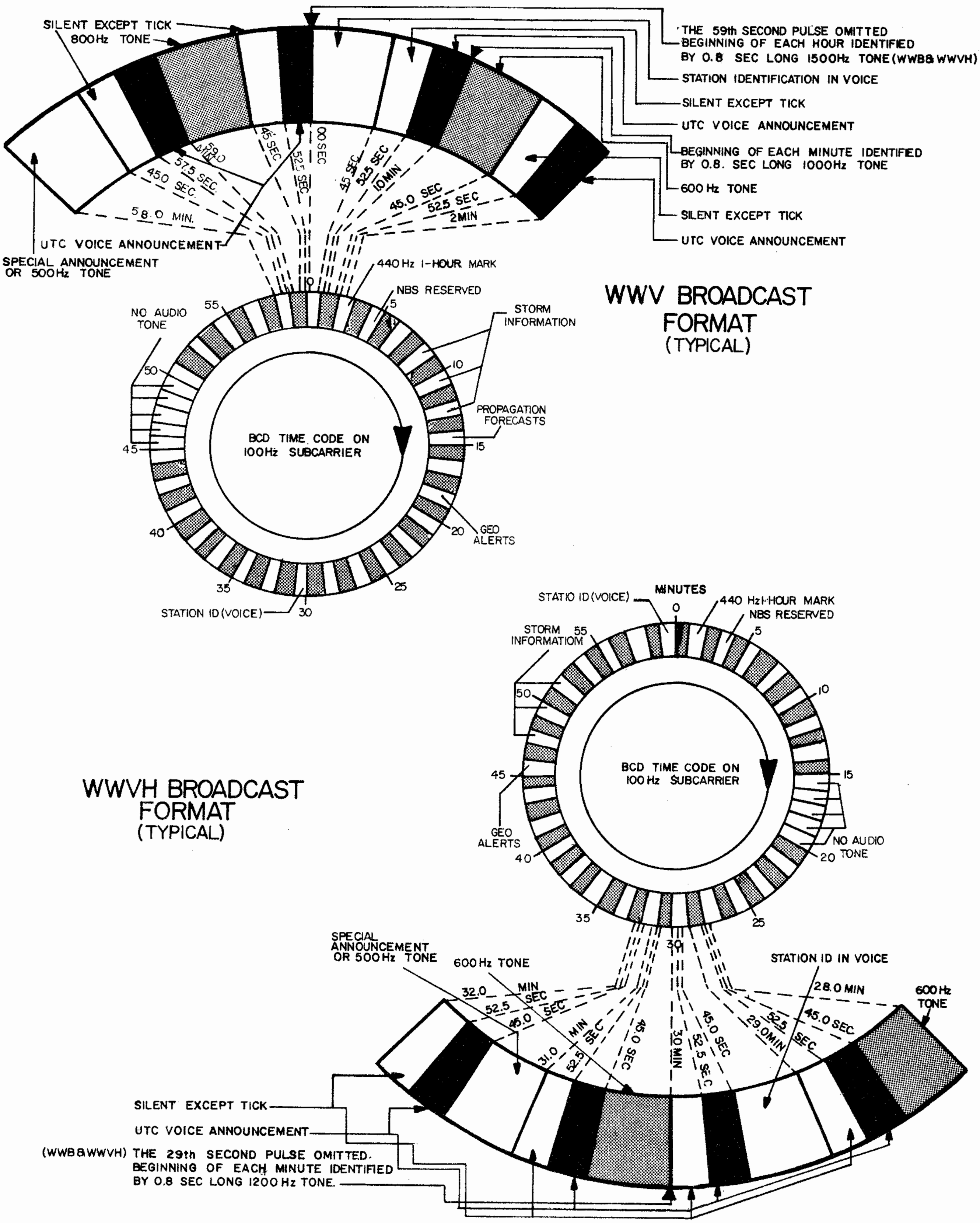


Figure 2-55. Schedules for WWV, WWVH

2-9.2.6 Radio Propagation Forecasts

An announcement of radio propagation conditions for the North Atlantic area is broadcast by station WWV in voice at 14 minutes after each hour. For example, these short-term announcements might state: "The radio propagation quality forecast at . . . . (time on the hour in UTC) is . . . . (excellent, very good, etc). Current geomagnetic activity is . . . . (normal, unsettled, disturbed)." The propagation format (refer to Table 2-4) is repeated phonetically and in numerical code to ensure clarity. The letter designations N, U, and W, signifying "normal", "unsettled", and "disturbed", respectively, classify the radio propagation conditions at the time of the broadcast. The digits from 1 to 9 indicate the expected radio propagation conditions during the next 6 hours; refer to Table 2-4 for code interpretations. The National Bureau of Standards forecasts are based on information obtained from a worldwide network of geophysical and solar observations.

TABLE 2-4. NBS RADIO PROPAGATION CODING

PHONETIC	PROPAGATION CONDITION
Whiskey	Disturbed
Uniform	Unsettled
November	Normal
NUMERAL	
1	Useless
2	Very poor
3	Poor
4	Poor to fair
5	Fair
6	Fair to good
7	Good
8	Very good
9	Excellent

2-9.2.7 Accuracy

The frequencies at the time of transmission from WWV have a relative stability on the order of 1 part in 10^{11}, with a frequency deviation of 1 part in 10^{12} per day. The frequencies at the time of transmission from station WWVH have a relative stability and frequency deviation on the same order as that of WWV. Time intervals from either station are derived from the same frequency standard that controls the radio stations carrier frequencies. The frequencies received at locations in the service range are generally as accurate as those transmitted. During ionospheric storms, transient conditions in the propagating medium may cause slight momentary frequency changes. These fluctuations may be as great as 1 part in 10^9. At times, these transient conditions in the ionosphere cause the received time pulses to scatter by several milliseconds. In addition to the high frequency transmission systems in use, two low frequency stations WWVB and WWVL are also provided at Fort Collins, Colorado. Station WWVB provides a standard frequency of 60kHz, and in addition provides time intervals, time signals, and UT_1 corrections. Station WWVL provides only a standard frequency of 20kHz. The effects of the propagating medium on the received frequencies are much less at low frequencies (LF) and at very low frequencies (VLF). Full transmitted accuracy may be duplicated by using appropriate receiving techniques. WWVB and WWVL frequencies are normally stable to better than 1 part in 10^{11}. Deviations from day to day are less than 1 part in 10^{12}. On December 31, 1971 at 2300 hours 59 minutes and 60.1076 seconds UTC, the NBS standard clock was retarded by .1076 seconds to place it precisely 10 seconds behind the International Atomic Time (TAI) scale as maintained by the French Bureau International dl'Heure (BIH). The UTC deviates from UTI at a negative rate of approximately one second per year. Corrections, as directed by BIH, are made in steps of precisely one second (termed a "leap" second). As a result, at any given instant, UTC differs from UT_1 by no more than ± 0.7 seconds. This high degree of accuracy is accomplished through the use of double second pulses. Doubling of the first seven pulses within a given second constitutes a "positive" correction. Doubling of the ninth through fifteenth pulse within the second denotes a "negative" correction. By counting the number of second pulses doubled, the amount of correction in 0.1 second increments can be determined by the receiving station.

2-9.2.8 Time Coded Subcarrier

A time code on a 100 Hz subcarrier is also transmitted by WWV and WWVH. The 100 Hz subcarrier is modulated at a rate of 1 pps. The leap second is inserted between the end of the 60th second of the last minute of the last day of an UTC month and before the next minute begins. The minute containing the correction involves either 59 or 61 seconds, depending on whether the correction is negative (subtractive) or positive (additive). Preferably, the change is made on December 31 or on June 30. Where ± 0.7 seconds is not sufficiently accurate for certain applications, a 0.1 accuracy coded correction format is also transmitted. The start of the time frame is the standard's point of reference. Time of year information is presented in minutes, hours and days, with the seconds obtained by counting the pulses. Each minute contains seven groups of code for minutes, hours, and days. This binary-coded decimal (BCD) format (Figure 2-56) is devised such that the minute (2 groups) precedes the hours (2 groups), followed by the days (3 groups). The leading edge of each pulse, which constitutes "on time", coincides with a positive-going zero axis crossing of the 100 Hz subcarrier frequency. The minute begins with a 1.03 second "hole" followed by eight binary zeros. This, in turn, is followed by the information format as shown in Figure 2-56. UT_1 corrections appear in the 56th, 57th, and 58th seconds of the format, with direction either positive or negative in the 50th second. Magnitude of the correction is in hundredths of a second up to 0.7 seconds with a binary one indicating positive, and a binary zero indicating negative. The 55th second signal denotes the difference between daylight time and standard time.

2-9.2.9 Secondary Standards

To use the frequency standard transmissions as a primary standard, compare the secondary or other standard to be calibrated against the received frequency. Adjust the secondary standard to a null indication when comparing with the transmitted primary frequency standards. This adjustment is to be made during the period when no audio tones are present. A secondary frequency standard usually includes an oscillator with one or more divider and/or multiplier stages, and suitable amplifiers. The oscillators should be very stable and have a high accuracy comparison capability and exceptional reliability. The accuracy of a secondary frequency standard is maintained only when periodic calibration checks are made against a primary standard, or against standard frequency transmissions of WWV or WWVH. These transmissions of WWV or WWVH are broadcast continuously, and are monitored for agreement with the National Primary Frequency Standard which is maintained by the Bureau of Standards, Time and Frequency Division, Boulder, Colorado.

2-9.3 MECHANICAL ROTATION/VIBRATION MEASUREMENTS

There are many instances when you are very much concerned with the question of rotational or vibratory speeds. Knowledge of rotational speeds is necessary where the output of a direct current generator has fallen below a minimum desired output, or where the speed of a motor (such as the motor in a teletypewriter or radar antenna) must be maintained at a constant value. There are many instruments that you can

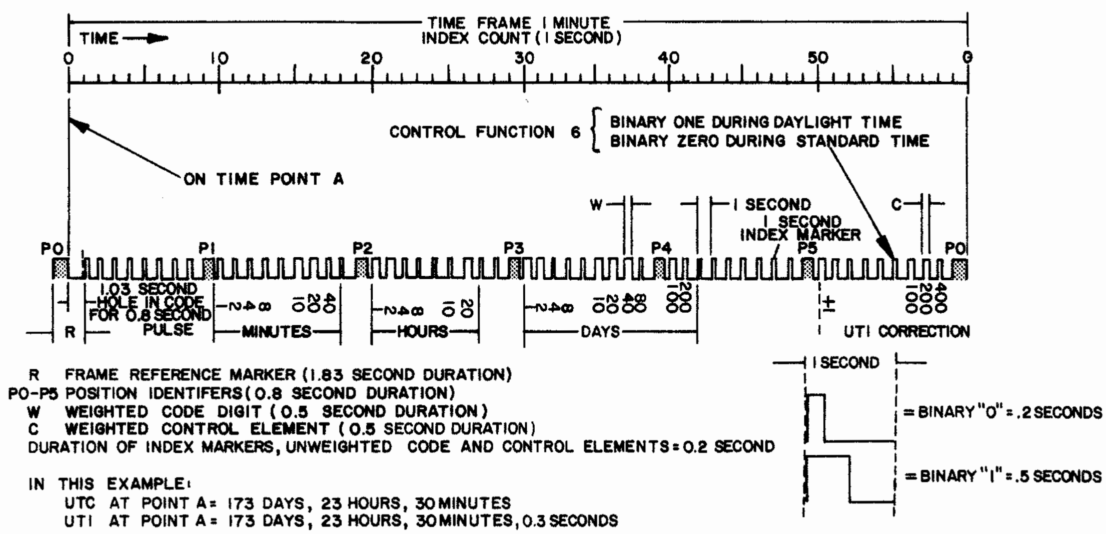


Figure 2-56. Time Code Format of WWV and WWVH

use for this purpose, such as tuning forks, stroboscopes, vibrating reed meters, and electromechanical counters. The oscilloscope and the frequency counter are some of the other devices which may be used, but their use may require the employment of accessory equipment.

2-9.3.1 Tuning Fork Methods

A tuning fork is generally used in conjunction with the measurement of the rotational speed of a teletypewriter or facsimile motor, but is not limited to this application. However, you must remember that the device can be used at only one frequency: the frequency of vibration for which it was manufactured. To use the tuning fork, a source of light is directed upon the point to be observed. In the case of a teletypewriter, a black-and-white segmented target is painted on the outer circumference of the motor governor. Radial spokes in a flywheel could be used equally well. Permit the motor to reach operational speed under normal load conditions; otherwise, the motor will slow down considerably when the normal load is applied. Strike the tuning fork against the side of the hand to set it into vibration. Then observe the target through the slots in the plates attached to the tines of the fork. The correct speed is obtained when the segments of the target appear to be stationary. If the segments seem to move backward, apparently against the known motor rotational direction, the speed is too low. If the segments seem to move forward, the speed is too high. There is also the possibility that the target segments will appear to jump back and forth, or to disappear suddenly. Such erratic action is often due to governor malfunctioning. A practicable speed adjustment is reached when the segments of the target appear to be just barely moving in the direction of rotation of the motor.

2-9.3.2 Stroboscope Methods

When using a stroboscope to measure the speed of rotating or reciprocating mechanisms, hold the instrument so that the light from the stroboscope lamp falls directly on the part to be observed. If the part is uniform, or symmetrical, place an identification mark with chalk or a grease pencil on the portion to be observed. This method provides a positive means of identification, because if only one reference mark is observed during measurement, you can be sure that either the fundamental synchronization or a submultiple thereof has been obtained. If the approximate speed of rotation is known, the stroboscope controls may be set to the appropriate positions prior to actual measurement. The main frequency control that determines the rate of the flashing light is then varied until the reference mark on the moving part appears to be standing still. The calibrated scale of the stroboscope will then show the speed directly, in revolutions per minute (rpm). If you have no idea of the speed of the moving part, it is best to start the measurement procedure at the highest frequency that the stroboscope can deliver. The flashing rate of the stroboscope can then be gradually reduced until a single stationary image of the reference mark is obtained. This is the point of fundamental synchronism that corresponds to the speed of the moving part. Do not continue to reduce the flashing rate of the instrument beyond this point without a valid reason for doing so. If you do continue the reduction, a stationary image will still be observed, but the stroboscope will indicate a submultiple of the true rotational speed, thus introducing a measurement error. Stroboscopes generally have a high and low range switch. The typical low range is from 600 to 3600 rpm and the upper range is from 3600 to 15,000 rpm; there is a slight overlap in ranges to insure reliable frequency coverage. In view of the limitations imposed by flasher tube life, the stroboscope should always be operated at a flashing rate which is as low as possible, consistent with the rotational speed of the observed part. If you should be required to operate this instrument over a long period of time, use a submultiple of the fundamental synchronous speed. The pattern will remain just as stationary, and the tube life will be greatly extended. In addition, the quality of the light is better at the lower ranges than at the upper end of the scale. If you are required to make a very precise measurement over a small range, or to measure deviations from a given standard speed, the scale can be calibrated by means of the trimmer controls and the vibrating reed calibration standard. To fit the required frequency between any two of the single stationary images provided by the vibrating reed standard, set the calibration scale to the higher value and adjust the "High" trimmer on the front panel. Then set the calibration scale to the lower value and adjust the "Low" trimmer on the front panel. For example, assume the shaft speed of the device to be measured is 1500 rpm. The calibrating reed images appear at 14,400, 7200, 3600, 2400, 1800, 1440, 1200, 900, 800, 720, and 600 rpm. The 1500-rpm shaft would fit between the calibrating reed images at 1800 and 1440 rpm. Therefore, set the calibration scale at exactly 1800, and adjust the "High" trimmer for a single stationary image of the calibration reed. Then set the calibration scale to exactly 1440, and adjust the "Low" trimmer for a single stationary image of the calibration reed. At this point, the stroboscope is calibrated and the maximum accuracy of the instrument can be obtained. Sometimes you will encounter a rotating or vibrating device that is moving faster (or slower) than the measuring range of the stroboscope will accommodate. Although such speeds can still be measured, you must use the multiple or submultiple synchronism points. There are two methods of measuring high speeds. The first method is to obtain a stationary single image of the rotating object at a subharmonic speed relationship, and record that value as "A". Then obtain a second stationary single image at the next lower subharmonic speed relationship, and record this value as "B". The unknown speed may then be computed from the formula:

$$\frac{AB}{A - B}$$

For example, assume reading "A" was 4000 rpm and reading "B" was 3500 rpm. Then the computation would be:

$$\frac{4000 \times 3500}{4000 - 3500} = \frac{14,000,000}{500} = 28,000 \text{ rpm}$$

The second method is used where the value of AB becomes progressively smaller. The "A" reading is obtained as in the previous example (for the sake of easier computation, suppose that the "A" reading is still 4000 rpm). Then obtain another submultiple reading for "B", keeping in mind the number of times a stationary single image was observed. If a stationary single image was observed 7 different times and the final "B" reading was 2000 rpm, the calculation would become:

$$Nx \frac{A \times B}{A - B} = 7x \frac{4000 \times 2000}{4000 - 2000} = 7x \frac{8000000}{2000}$$

At speeds lower than the lowest range of the stroboscope, multiple images will be observed. For example, assume a dial reading of 900 rpm was obtained when two stationary images were observed. Then dividing the rpm by the number of images will give the unknown shaft speed,

$$\text{or } \frac{900}{2} = 450 \text{ rpm}$$

Use caution in using a stroboscope
The illusion of stopped motion is
very convincing. Do not attempt to
touch the moving equipment.

2-9.3.3 Frequency Counter Methods

Various frequency counters have found application as an electronic tachometer to obtain accurate measurements of high-speed rotating machinery. A tachometer pickup may be used to produce signals which are fed directly to the frequency counter. If the tachometer pickup is designed to generate one signal per revolution, the counter will indicate directly in revolutions per second; but if the pickup is designed to produce 60 signals per revolution, the counter will indicate directly in revolutions per minute.

2-9.4 AUDIO FREQUENCY MEASUREMENTS

Audio frequencies can be measured with a variety of nonelectronic and electronic devices. An example of nonelectronic measuring devices is the vibrating reed meter. However, such instruments do not have a wide frequency range. The most common instruments available for the measurement of audio frequencies are the oscilloscope and the frequency counter. These are, of course, electronic devices.

2-9.4.1 Oscilloscope Methods

It has been stated that the ratio between the frequencies of two signals could be determined from Lissajous patterns. In addition to this method, there are various other oscilloscope techniques for comparing the frequency ratio of two signals. As a result, the oscilloscope is a valuable tool for the rapid determination of frequencies within the pass band of the instrument in use. When it is necessary to measure the phase relationship between two signals of the same frequency, a simple measurement can be performed with the oscilloscope. Since familiarity with these methods is advantageous, even if the need for them arises only occasionally, they are discussed under "Use of Lissajous Figures" in Paragraph 2-10.

2-9.4.2 Frequency Counter Method

While oscilloscopes can be used to compare rectangular waveforms for the purpose of measuring the frequency of a signal, frequency counters are much more useful for this purpose. The fundamental measurement of frequency is accomplished by totaling the number of cycles into the counter for a precise period of time. The result is then displayed as an exact digital readout. The audio frequency signal must be of sufficient amplitude to trigger the counter. The auto-manual switch provides two methods of frequency counter operation. One method is to initiate the count simultaneously with the initiation of the signal to be measured. With this method, the auto-manual switch should be set to the manual position. The other method assumes that the signal to be measured has been operating over some indefinite period of time, and that it will continue to do so after a measurement has been taken (hence only that segment of the signal required to make the frequency measurement is important). With this method, the auto-manual switch is to be set to the auto position.

2-9.4.3 Additional Methods

A direct comparison of phase is possible by the use of a dual trace oscilloscope. One signal is applied to the "A" vertical input and the other signal is applied to the "B" vertical input. The vertical selection switch is then set to the alternate position. To ascertain the phase difference of two sine waves, one sine wave must be displayed directly under the other, as illustrated in Figure 2-57. A phase difference between

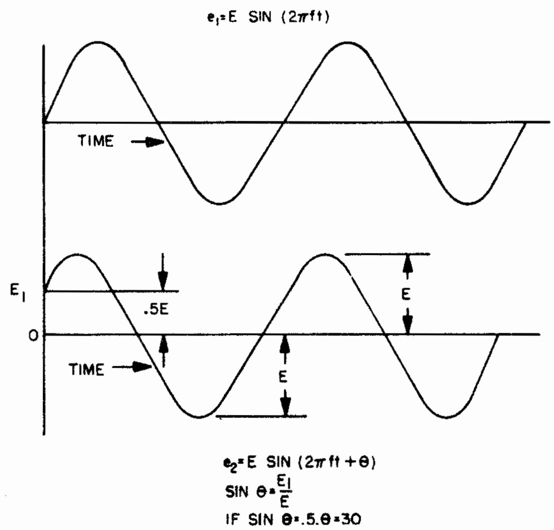


Figure 2-57. Direct Phase Comparison

the two signals can then be observed directly. If a measurement is required, the procedure to follow is simple. A convenient point on one of the waveforms is selected as a reference, such as the point where one of the sine waves is at its zero point and about to swing positive. At this point, the deflection of the other sine wave above the zero-voltage axis should be measured. The ratio of this distance to that of maximum amplitude is equal to the sine of the phase difference between the two signals.

2-9.5 RADIO FREQUENCY MEASUREMENTS

In this portion of the frequency spectrum, the methods as well as the frequency measuring equipment vary markedly from the methods and equipment used for audio frequency measurements, as described in preceding paragraphs, with the exception of the frequency counter. The radio frequency spectrum has been divided into specific bands by international agreement, as shown in Table 2-5.

2-9.5.1 Frequency Counter Methods

In the past, most frequency measurements above the audio range were made primarily with a frequency meter. This process involved heterodyning the frequency to be measured against the calibrated output of the frequency meter to obtain a zero beat from which the measured frequency was then read. This method proved inaccurate because of reading errors. In the early 1950's, the frequency counter was developed. This device could measure and indicate accurately frequencies up to 10 MHz. Present-day frequency counters can accurately read frequencies as high as 40 GHz if the proper plug-in extender assembly is used. In addition to direct frequency measurements indication, some types of frequency counters presently in use can measure the wave period, which is the inverse of frequency; ratio, which compares one frequency against another; time interval, the time between two events or the time between two functions of an event. In addition, frequency counters can totalize event indications. This is similar to measuring the frequency except that a manual or electronic start-stop gate controls the time over which the measurement is taken. Frequency counters can also provide scaling in the form of a digital output signal from the frequency counter that represents a frequency-related division of the input frequency. All of the above functions have definite applications. For timing a pulse, the period function is used; totalizing is employed in digital applications; and ratio is used in comparing harmonic-related signals. Scaling is used for triggering other test equipment which is used in conjunction with the frequency counter; and time interval capability is employed in measuring the interval between two pulses or between two sets of pulses. Because of the wide variety of frequency counters in use, the technical manual for a specific frequency counter should be consulted to determine the instrument's capabilities.

TABLE 2-5. RADIO FREQUENCY NOMENCLATURE

Frequency Range	Adjectival Designation
30 to 300 hertz	ELF Extremely low frequency
300 to 3000 hertz	VF Voice frequency
3 to 30 kilohertz	VLF Very-low frequency
30 to 300 kilohertz	LF Low frequency
300 to 3000 kilohertz	MF Medium frequency
3 to 30 megahertz	HF High frequency
30 to 300 megahertz	VHF Very-high frequency
300 to 3000 megahertz	UHF Ultra-high frequency
3 to 30 gigahertz	SHF Super-high frequency
30 to 300 gigahertz	EHF Extremely high frequency
300 to 3000 gigahertz or 3 terahertz	Unclassified

2-9.5.2 Frequency Counter Accuracy

All frequency counter measurements are measured with 1 part in 10^8 accuracy. However, frequency counters have provisions for input from external frequency standards. This extends the accuracy of the frequency to that of the standard. A frequency self-check capability is provided to determine if the counting and lighting circuits are operating properly.

2-10 WAVEFORM MEASUREMENTS

A waveform may be considered as a pictorial representation of a varying signal as related to time. An unknown waveform can be graphically plotted by using a system of coordinates where the amplitude of the unknown signal is plotted linearly against time. An analysis of the resultant waveform provides valuable information in determining the characteristics of many electronic (and some mechanical) devices. The waveform of a signal may indicate the presence of harmonics or parasitic oscillations, or it may indicate how closely a device is following a desired cycle of operation. Distortion of a waveform is the undesired change or deviation in the shape of the observed signal with respect to some reference waveform. As the parts in an amplifier begin to shift in value or deteriorate, waveform distortion usually occurs and indicates abnormal operation in a circuit, often in advance of complete breakdown. Malfunctioning of electrical or electronic circuits within an equipment can usually be traced, by waveform inspection, to a specific part or parts of the circuit responsible for the distorted signal. On the basis of these facts, it is apparent that there is an important need for a test equipment that can provide a pictorial presentation of a waveform at the instant of its occurrence in a circuit. The test equipment used for this purpose is the cathode-ray oscilloscope. The usefulness of an oscilloscope in any maintenance technique depends upon a knowledge of which controls to use to obtain various displays, where to connect the oscilloscope into the circuitry under observation, and how to interpret the resultant trace displayed on the screen.

2-10.1 PROCEDURES FOR WAVEFORM OBSERVATIONS

The term "distortion" or "distorted" is used by technicians and engineers alike in a very loose manner, generally signifying dissatisfaction with the shape of the wave processed by an amplifier. Classifying any waveform as a "distorted" wave without reference to the electronic circuitry involved is meaningless. A waveform which can be validly termed distorted with respect to a specific amplifier circuit may be the normal waveform to be expected from some other amplifier circuit. One of the most important steps in waveform analysis - the one which usually proves the most difficult for the maintenance man - is the interpretation of patterns viewed on the oscilloscope. Bear in mind that the unknown signal is always plotted as a function of a signal whose characteristics are known. If the characteristics of the signal on one axis are not known, then it will be almost impossible to identify or interpret the signal on the other axis. For this reason, it is common practice to use (on the horizontal axis) a sawtooth or sinusoidal waveform of known frequency, which is synchronized with the fundamental or some integral submultiple of the frequency under investigation. Since the sawtooth waveform gives horizontal deflection linearly proportional to time, it provides a plot of the waveshape of the unknown signal versus time. Whether the observed pattern is a true reproduction of the signal under observation is largely dependent on the limitations of the particular oscilloscope available for use. The basic oscilloscope is limited by the following circuit characteristics, which are inherent in the design of the test equipment's frequency response and sensitivity of both the vertical and horizontal amplifiers: phase distortion, input impedance, and the maximum permissible level of the input signal. The degree to which these circuit characteristics influence the reproduction of waveforms is determined, for the most part, by design considerations involving compromises between production costs and over-all test equipment utility. Use of the oscilloscope to observe waveshapes when tracing signals is especially indispensable when circuits contain more than one type of signal. This is the case when observing composite signals which contain synchronizing pulses and video information on the same transmitted carrier. At different horizontal sweep frequencies, the oscilloscope will allow the various composite signals to be displayed. You should be familiar with the equipment you intend to test so that you will know approximately what type of wave shape to expect, its approximate frequency, and at what point in the circuit your measurement should be conducted.

2-10.2 OSCILLOSCOPE

The cathode-ray oscilloscope provides a visual representation of one electrical signal as a function of another. The usefulness of the oscilloscope lies in its ability to portray, graphically and instantaneously, fluctuating circuit conditions. Operation of the oscilloscope is based upon the formation and control of a beam of electrons to produce a visible trace on a fluorescent screen. Since the electron beam has negligible inertia, the cathode-ray tube responds to much higher frequencies than any other electrical indicating device. However, the frequency response of an oscilloscope is limited by the characteristics of its vertical and horizontal amplifiers. The general purpose oscilloscope is comprised of a cathode-ray tube, a sawtooth sweep oscillator, horizontal and vertical deflection amplifiers, and suitable controls, switches, and input receptacles.

2-10.3 OSCILLOSCOPE PROBES

There are four general types of oscilloscope probes. Some types of waveform measurements cannot be conducted successfully without using the proper probe.

2-10.3.1 High-Voltage Probes

High-voltage probes are generally used when the potentials in the circuit to be measured exceed the input voltage rating of the oscilloscope. Generally speaking, this value is about 600 volts. The use of such a probe is almost mandatory in cathode-ray-tube deflection circuits, in high-voltage rectifier circuits, across damper tubes, etc., found in television, radio, and radar equipment.

2-10.3.2 Low-Capacitance Probes

Low-capacitance probes are especially valuable for observing complex waveforms, partially because of their low stray capacitance as compared with a regular test lead, and partially because of the probe's high-impedance feature.

2-10.3.3 Detector Probes

Detector probes are used in radio frequency circuits that process modulated waveforms, to demodulate the signal at the point of waveform inspection.

2-10.3.4 Direct Probes

Direct probes are standard leads used to observe waveforms in the audio-frequency and power-frequency ranges developed in low-impedance circuits. In the illustrations to follow, any connections (made to an oscilloscope) that are not labeled are to be interpreted as employing direct probes.

2-10.4 LISSAJOUS MEASUREMENTS

Lissajous patterns are a useful method of determining the frequency ratio of one signal to another (sine waves). If one of the signals is known, the other can be determined from the displayed Lissajous pattern. The known signal is applied to the horizontal axis input of the oscilloscope and the unknown is applied to the vertical deflection input. Figure 2-58 shows examples of various Lissajous patterns. In the first five of the above examples, the ratio is always a selected multiple of one. The sixth example shows that odd ratios can also be displayed. The accuracy of frequency measurements obtained by Lissajous patterns is limited by the accuracy of the reference frequency and by the care exercised in obtaining a stationary display and in counting the loops. The practical ratio limit in this type of measurement is 10:1; however, by using extreme care, it is possible to count frequency ratios as high as 30:1. A more detailed explanation of Lissajous patterns is provided in Section 4 of this manual.

2-10.5 PHASE RELATIONSHIPS EFFECT ON LISSAJOUS PATTERNS

Figure 2-59 shows two signals of 1:1 ratio with a varying phase relationship. One of the signals is applied to an oscilloscope's horizontal input, and the other is applied to the vertical input. If the two signals are of the same frequency, the Lissajous display will appear to be stationary. If one of the input signals is slightly drifting off frequency, the display will drift accordingly and slowly rotate through 360 degrees. Section 4 provides a more detailed explanation of phase relationships and measurements.

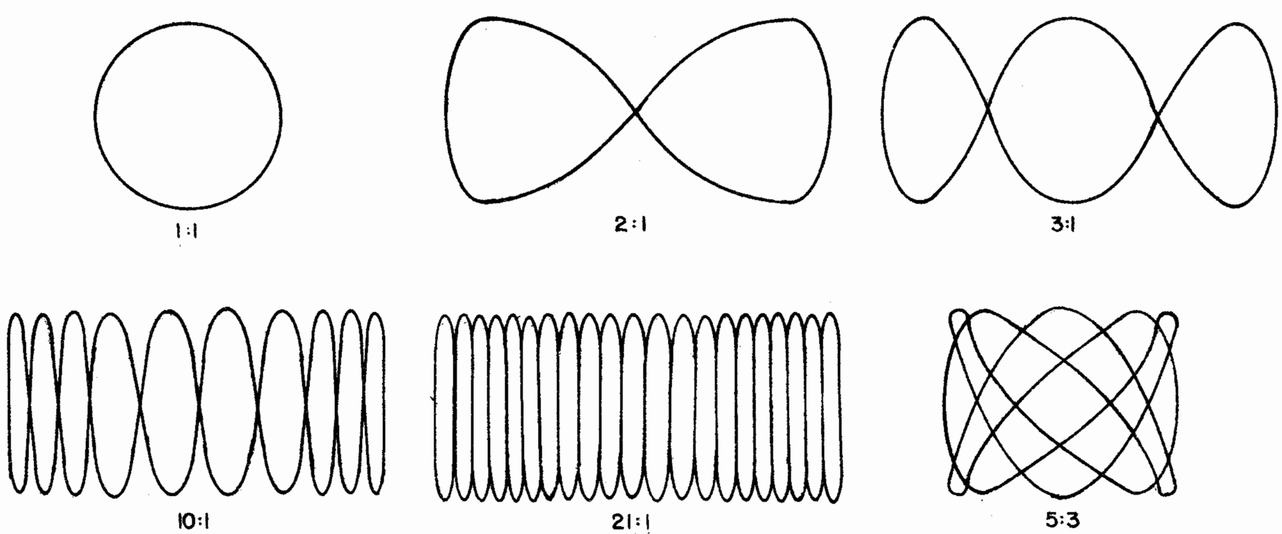


Figure 2-58. Lissajous Patterns, Showing Frequency Ratios

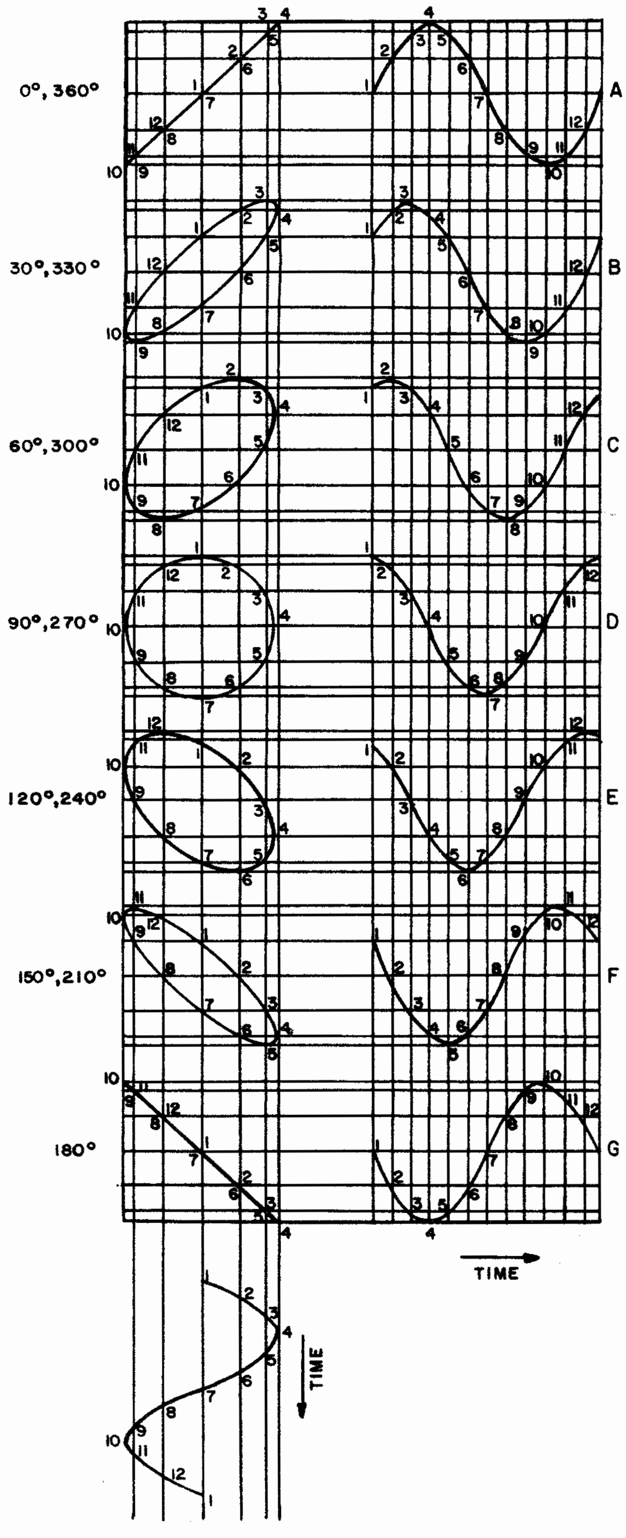


Figure 2-59. Lissajous Patterns of A 1:1 Ratio, Showing Effect on Phase Relationships

2-10.6 SINGLE-SIDEBAND MEASUREMENTS

Distortion and output power are very important factors in single sideband (SSB) applications. The usable power of a SSB transmitter is the maximum peak envelope power obtainable with a specified signal-to-noise ratio. If an SSB transmitter is modulated with a single audio tone, the RF output will have a single radio frequency. If the output of the transmitter is coupled to the vertical plates of the oscilloscope, and the sweep is set to a slow speed, the result will be as shown in Figure 2-60. If distortion on a carrier is present, the

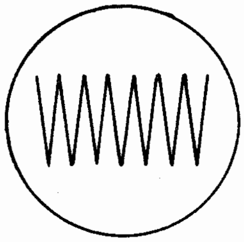


Figure 2-60. Undistorted Transmitter Output Signal

top and bottom of the pattern will display a ripple proportional to the amount of unwanted products as shown in Figure 2-61. If the low point in our display

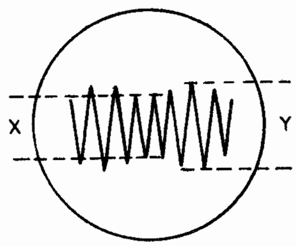


Figure 2-61. Distorted Transmitter Output Signal

(X in Figure 2-61) and the high point (Y) are measured, the ratio of suppression can be determined by the following formula:

$$S = 20 \log \frac{X+Y}{Y-X}$$

2-10.7 OCTOPUS MEASUREMENTS

Ohmmeter troubleshooting of de-energized Printed Circuit Boards (PCB's) requires removal of all but one lead from the circuit of every component under test. This is not only time-consuming but involves considerable desoldering and resoldering, which often compound the problems that go along with heat application, poor soldering techniques, and lead-bending. Obviously, because physical size determines the amount of heat a component can safely dissipate, electronic part miniaturization and microminiaturization have made present-day soldering techniques obsolete. Not only are the components very small, but they are located quite close together, so that desoldering - an old troubleshooting method and a byproduct of the use of the ohmmeter in testing - destroys the inherent reliability of the PCB's. An ohmmeter, moreover, cannot detect a shorted inductor or open capacitor even after the reactive component is lifted from the circuit. Some ohmmeters even generate enough current at low range to damage solid-state components. As these parts decrease in size, their current-handling capacity correspondingly decreases, and the use of ohmmeters becomes even more undesirable. Existing methods of troubleshooting de-energized miniature component boards have proved generally inefficient from the standpoint of both damaged boards and costly man-hours expended in the removal and replacement of components that eventually tested good. In the past, it has been the practice to unsolder components from PCB's and attempt to test with an ohmmeter and replace components. Use of the Octopus helps to minimize the problems encountered in circuit-board measurements.

2-10.7.1 Basic Octopus Construction

An Octopus in-circuit tester can be constructed on a Do-It-Yourself basis using components normally carried by the supply system. Total cost per unit is less than five dollars when buying the individual components commercially. "In-circuit" troubleshooting means exactly what the term implies - components need not be removed from the equipment. This results in a savings in maintenance man-hours and eliminates the possibility of damage caused by soldering-iron heat. Used in conjunction with any standard oscilloscope, the in-circuit tester affords a visual display of component condition. With the power cord, oscilloscope leads, and probe cables protruding from its sides, the tester resembles an octopus--hence its name. The Octopus is designed to quickly test delicate components and does not deliver more than 1.0 milliampere of ac current. It energizes components during test without removal of circuit inter-connections, much the same as they are energized in-circuit during normal service. While the Octopus primarily tests all components for shorts and opens, it can also be used to check front-to-back ratios on junction components (transistors and diodes). Moreover, utilizing Lissajous and combination patterns on the oscilloscope, the Octopus easily analyzes reactive components (capacitors and inductors) that defy ohmmeter analysis. It is useful also in checking circuit continuity (switches, fuses, lamps, printed wiring, etc.) and high-resistance solder points. As can be seen in Figure 2-62, the few parts that go into the construction of the Octopus are all common items. For this

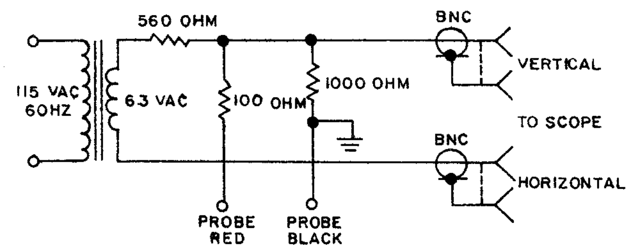


Figure 2-62. In-Circuit Tester Schematic Diagram

reason, and since all the pieces are noncritical, they may be replaced by whatever suitable parts are locally available. Low voltage and low current are necessary for protection of delicate components; the 1000-ohm resistor placed across the 1.0-volt assures a safe current of 1.0 milliampere. The filament transformer delivers 6.3-volts which is dropped to 1.0-volt by resistors. The leads should be color-coded (black for the ground and red for the "hot" lead) and needle-tipped or filed to a sharp point to penetrate the plastic and moisture-fungus-proof (MFP) coating on some PCB's. Dull leads usually fail to make proper contact. Then, to prevent lead hunting, the leads should be permanently attached to the Octopus. The BNC connector jacks are used for the vertical and horizontal outputs. (If further simplification is desired, cables may be permanently fastened). A On/Off switch and indicating neon lamp may be added to the primary input circuit if desired. The outstanding simplicity of the Octopus is one of its most desirable features and also has the ability to protect the PCB's against destructive heat applications and excessive test currents, and to minimize testing man-hours.

2-10.7.2 Octopus Use

Since each basic component being tested projects a different display, the Octopus' operation is the utmost in simplicity. Figure 2-63 illustrates the most

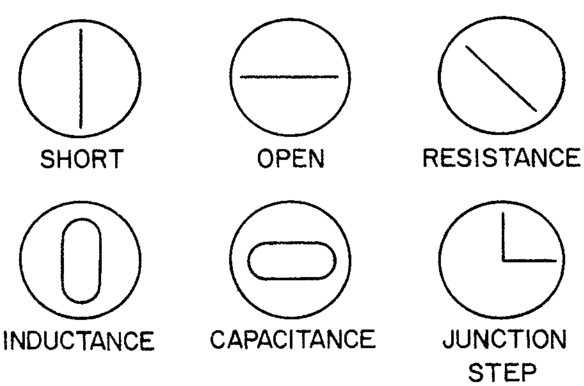


Figure 2-63. Typical Oscilloscope Displays

common oscilloscope displays. When the Octopus tester is to be used, its vertical output is connected to the oscilloscope horizontal input. The oscilloscope vertical and horizontal gain controls should be adjusted to prevent trace ends from going off-screen. Standard operational procedures for any board being tested for shorts requires that the power be removed. If the PCB or chassis under test is grounded, the black lead of the Octopus should be attached to the ground end of the components. Because the Octopus is an ac device, the technician is able to observe reactive components and Lissajous and front-to-back ratios of junction components. It is therefore unnecessary to reverse the leads. When testing transistors, check first from the base to one side, and then from the base to the other side. A collector-to-emitter test would have to pass through two junctions in series, and therefore usually does not produce a usable signal. An ideal single-junction check will produce a 90-degree step display, indicating a very high front-to-back ratio. This means an opening exists in the reverse direction and a short exists in the forward direction. A display that is open more than 90-degrees is something less than perfect. The wider the angle, the less the merit of the junction. (Refer to Figure 2-64). To become proficient in testing components

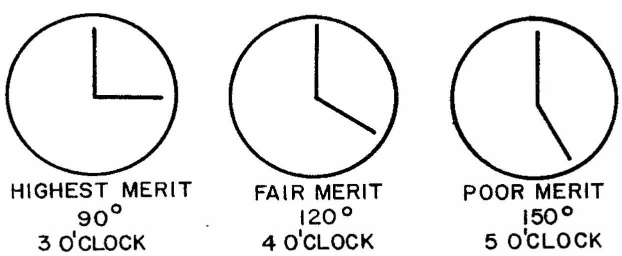


Figure 2-64. Transistor Check-Single Junction

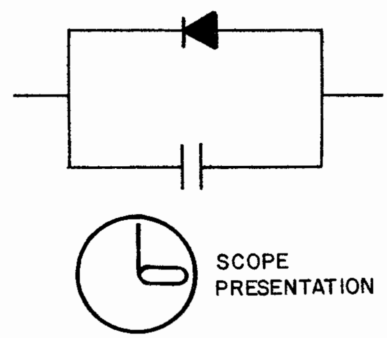


Figure 2-65. Diode Check

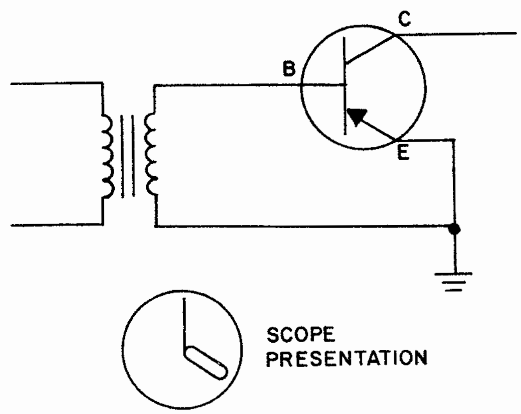


Figure 2-66. Transistor Check-Base to Emitter

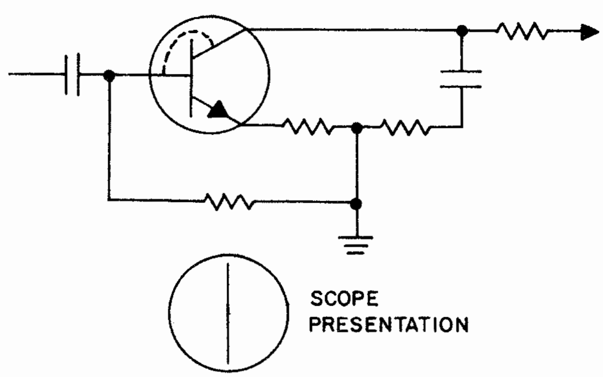


Figure 2-67. Transistor Check-Base to Collector

in-circuit, it is only necessary for the technician to recognize the combination patterns arising from grouped components. If the diode and capacitor pictured in Figure 2-65 were under test, the display shown in that figure would be the result. The oscilloscope presents both a Lissajous (X_C reactance) and a 90-degree junction step, showing that the components are neither shorted nor open. If the transistor circuit shown in Figure 2-66 were under test (base-to-emitter), the trace shown would result. The scope pattern comprises both a junction step and Lissajous (X_L reactance), again informing us that the components are neither shorted nor open. Because of the coil resistance, the junction step appears to be greater than 90 degrees - in fact, approximately 120 degrees. This is common in any circuit that contains a resistance in parallel with a junction component. If the transistor pictured in Figure 2-67 contained an electrical short between the base and the collector, the display shown would result during testing from the base to the collector. To check a potentiometer for noise, connect one probe to the pot arm and the other probe to either end, then manipulate the pot through its range while observing the oscilloscope pattern. (Refer to Figure 2-68.) To distinguish NPN from PNP transistors (Figure 2-69), move the red probe to the transistor base and the

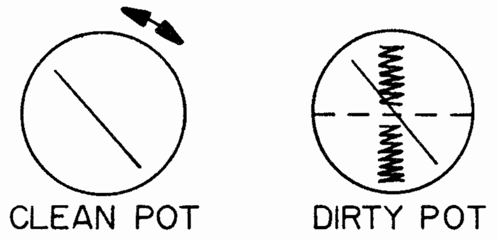


Figure 2-68. Potentiometer Noise Check

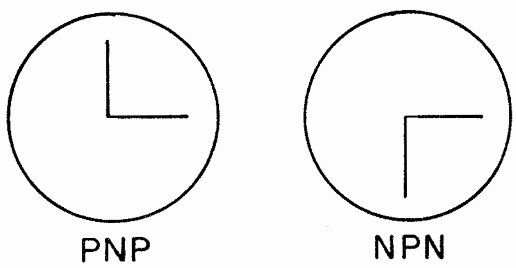


Figure 2-69. Distinction Between PNP and NPN Transistors

black (grounded) lead to either the emitter or collector. If the step pattern opens downward, the transistor is NPN (emitter arrow pointing downward); if the pattern opens upward, the transistor is PNP (emitter arrow pointing upward). The same technique can also be used to determine diode direction. Occasionally it may appear necessary to desolder a part to determine its condition. It has been found that in such instances a "comparison" check with a known good board does away with the need to desolder the suspect component. This comparison method, which gives conclusive results, is recommended whenever there is any question regarding a component's operating condition. Very-small-value capacitors will appear open rather than reactive, and very-small-value inductors will appear shorted rather than reactive. In most cases, however, this is immaterial, since it is still possible to detect a shorted capacitor and any open inductors. These small components may be checked by increasing the gain adjustments on the oscilloscope to the desired amplification. Utilization of the Octopus in troubleshooting will accomplish the following: (1) Reduce maintenance time; (2) Reduce material damage due to present maintenance techniques; (3) Improve maintenance techniques; (4) Increase safety of units by decreasing down-time of equipment vital to safe operation; and (5) Simplify localization of faulty components for corrective maintenance.

2-10.7.3 Additional Octopus Construction Techniques

The "Octopus" in-circuit printed circuit board tester, while an excellent device in itself, can be made simpler, less costly, and somewhat more versatile by eliminating the 6.3-volt filament transformer and substituting a variable frequency audio oscillator as the test voltage source. The 560 ohm and 100 ohm voltage divider resistors may also be eliminated if the audio oscillator output can be fixed at 1.0 volt rms. The tester will then consist of the audio oscillator, a 1000 ohm current-limiting resistor, and an oscilloscope, along with the required test leads and cables. The use of a variable frequency test-voltage source allows the tester to extract meaningful information from components that are either too large or too small in value to be tested with 60 Hz alone. Experience has proven that while a large capacitor appears to be shorted when tested with 60 Hz, it can be made to show an oval pattern when the frequency is decreased, and a small capacitor which appears open at 60 Hz can be checked by increasing the test frequency. Figure 2-70 is a diagram of the tester using a

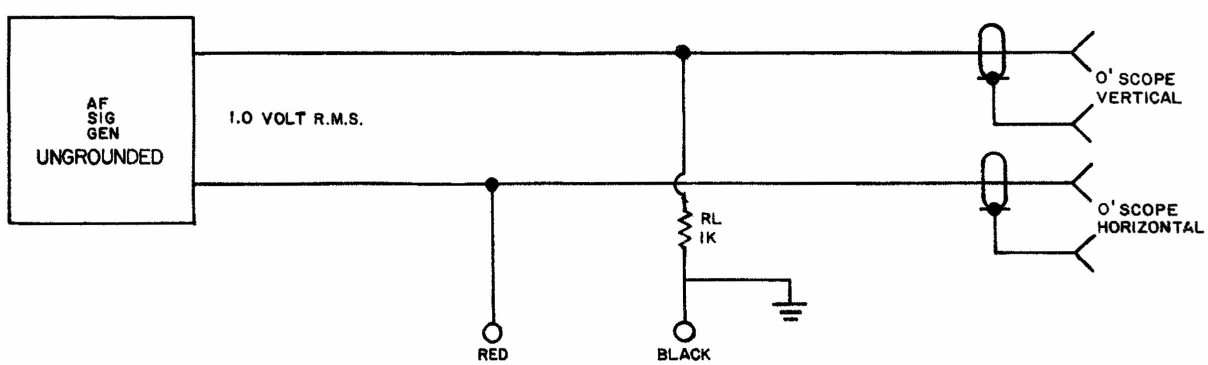


Figure 2-70. Tester Using 1.0 Volt Source

1.0 volt source, a 1000 ohm resistor, and an oscilloscope, while Figure 2-71 depicts a 10.0 volt source with the proper values of resistance necessary to reduce the output to 1.0 volt. In both illustrations the 1000 ohm resistor, RL, is used to limit the current through the device under test to 1.0 ma. Figure 2-72 shows the circuit of an Octopus that can use 115 volt 60 Hz or an audio oscillator for its power and frequency source.

2-10.7.4 Variable Frequency Tests

Figures 2-70, 2-71 and 2-72 are applicable to AF signal generators which provide ungrounded signals and, therefore, have the capability of being operated in the ungrounded mode. However, if an ungrounded-type AF signal generator is not available and it is necessary to make variable frequency tests using a grounded-type generator, an isolation transformer must be connected between the output connectors of the generator and the tester in order to provide the ungrounded voltages necessary for the tests. Figures 2-73 and 2-74 show the connections of the isolation

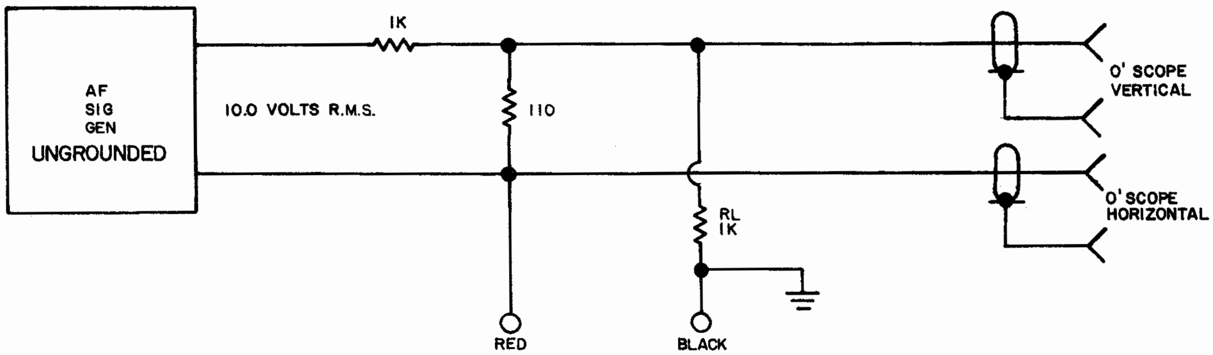


Figure 2-71. Tester Using 10.0 Volt Source

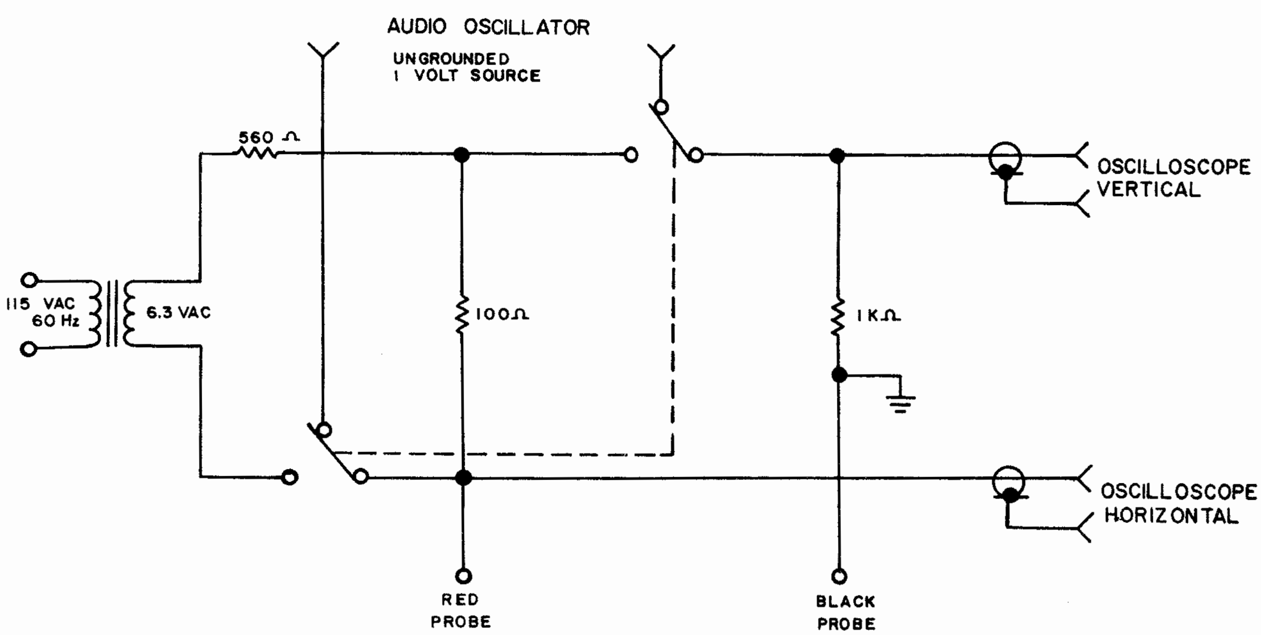


Figure 2-72. Modified In-Circuit Tester (Schematic Diagram)

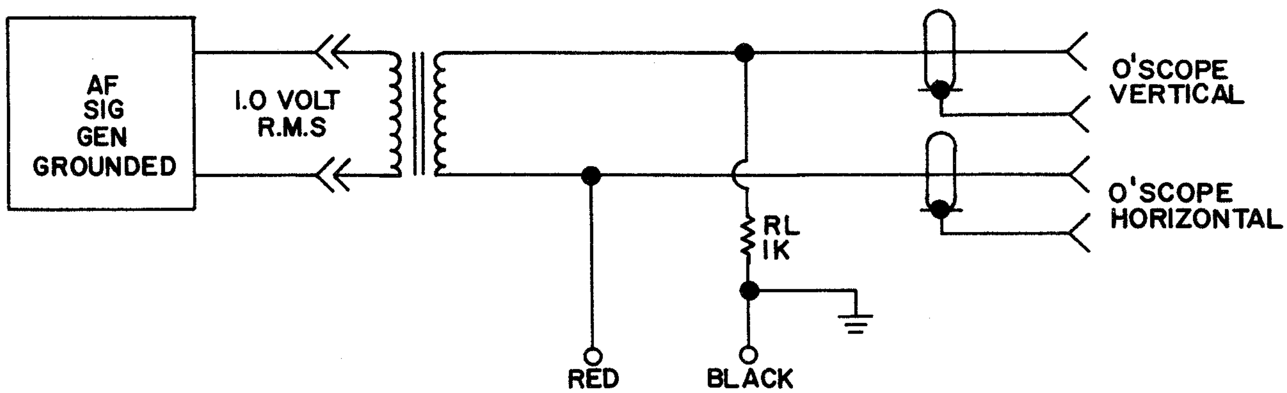


Figure 2-73. Tester Using 1.0-Volt Source

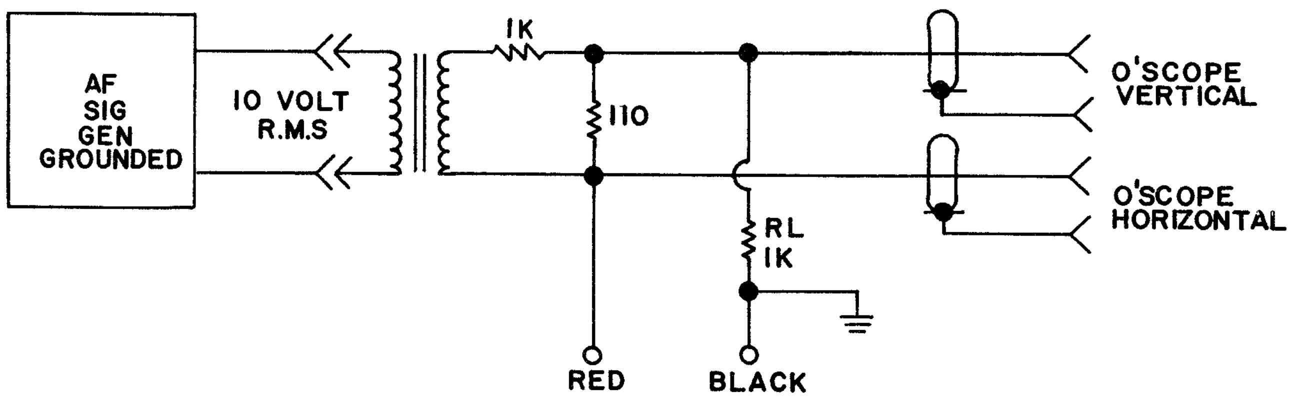


Figure 2-74. Tester Using 10.0-Volt Source

transformer between a grounded-type AF signal generator and either a 1.0-volt or a 10.0-volt source tester.

2-11 MODULATION MEASUREMENTS

Modulation measurements are sometimes required during tuning procedures to adjust transmitting equipment for the proper amount of modulation. During maintenance tests of modulated transmitter equipment, the amount of distortion of the output signal and the modulation level or index should be determined. The modulation level of carrier signals in multiplexing equipment is usually set at the factory or during corrective maintenance procedures. Proper adjustment of the input signal level and automatic signal-level regulation circuits provide the correct amount of modulation. Defects in modulation circuits can be detected by measurements of the quality of the received signals. Corrective maintenance analysis of multiplex equipment modulation circuits can usually be made by signal-level measurements. Some radio transmitters, when operating in the AM mode, must be adjusted for correct modulation during normal tuning procedures. If the modulation level is low, the transmitter is not being operated at its maximum efficiency; on the other hand, modulation in excess of 100 percent produces serious distortion. Since neither of these conditions is desirable, amplitude modulation should be maintained between 60 and 95 percent when possible. The modulator's amplifier gain can be initially adjusted by reference to the modulation meter provided on the front panel of the equipment. The modulation level or index of amplitude-modulated and frequency-modulated radio transmitters which operate in the very-high-frequency range is usually adjusted initially by the manufacturer or adjusted in the course of corrective maintenance. Pulse modulation of radar and radio beacon signals can be measured by waveform displays presented on a standard oscilloscope. The amount of usable energy in a pulsed waveform, as measured by a spectrum analyzer, is also an indication of the quality of pulse modulation. To attain 100 percent amplitude modulation of a radio-frequency carrier with a sine-wave audio frequency, a modulating power equal to one-half of the radio-frequency carrier power is required. Under this condition, the average power of the modulated carrier is equal to 1.5 times the average unmodulated carrier power. The added power is divided equally between the upper and lower sidebands. During the peaks of 100-percent modulation, the amplitude of the carrier becomes doubled, and the instantaneous peak power is equal to four times the instantaneous unmodulated peak power. When voice modulation is employed, only the highest-amplitude peaks can be permitted to modulate the carrier 100 percent. Since many audio-frequency speech components do not modulate the carrier 100 percent, the average power required for voice modulation is less than that required for modulation with a sine wave. It has been determined that voice peaks usually modulate a carrier 100 percent when the modulation increases the average carrier output power 25 percent over its normal value.

2-11.1 AMPLITUDE-MODULATION MEASUREMENTS

The increase of power output is indicated by an increase in antenna current. Thus, the increase can be taken as a measure of the degree of modulation, and can be expressed as a percentage, as illustrated in Figure 2-75. The graph for this figure was developed from the

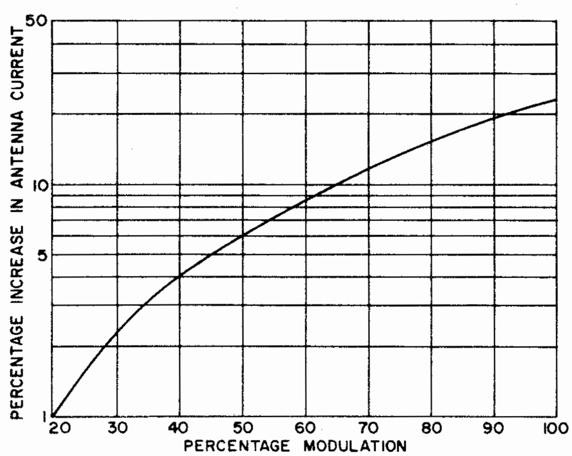


Figure 2-75. Antenna Current Increase with Amplitude Modulation

relationship existing between the carrier power and the increased power resulting from the added modulation power. Since current is proportional to the square root of power, it is possible to calculate the modulation percentage by using the following formula:

$$\text{Modulation percentage} = 100\ 2\frac{Im^2}{Ic^2} - 1$$

where I_m equals the value of antenna current after modulation, and I_c equals the value of antenna current before modulation. The formula for finding the modulation percentage can be expressed another way as follows: Modulation percentage = $100\ (E_{max} - E_o)/E_o$ where E_{max} represents the highest peak voltage, and E_o is the unmodulated carrier voltage. The application of this formula presupposes that the modulating voltage is a pure sine wave. Normal broadcasting, however, is characterized by complex envelope patterns, as illustrated in Figure 2-76. In this light, the formula is

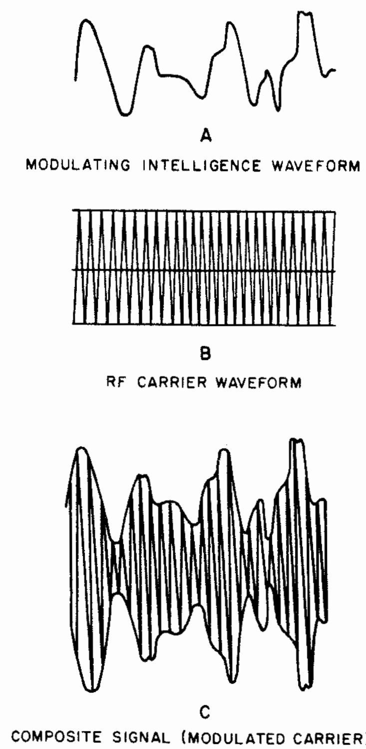


Figure 2-76. RF Carrier Amplitude Modulated by a Complex Waveform

ambiguous. Consequently, it is advisable that the preceding expression be treated as being the percentage of positive peak modulation. When the minimum voltage (E_{min}) rather than the peak voltage (E_{max}) is used to compute percentage modulation, the computed percentage is considered as negative peak modulation. This is shown by the following formula:

$$\text{Modulation percentage} = 100(E_o - E_{min})/E_o$$

Since the preceding two modulation percentages often differ, it is advisable to define the average percentage of modulation as $100(E_{max}-E_{min})/2E_o$ as illustrated in Figure 2-77. It is evident from the preceding definitions

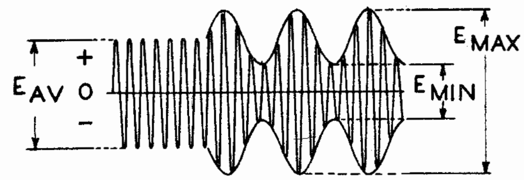


Figure 2-77. RF Amplitude Percentage Modulation

that methods of measuring all three types of modulation percentages must be devised. When differing values are obtained, however, the cause may not necessarily be attributable to unequal positive and negative peaks of a complex modulation wave. Another possibility is a type of distortion caused by carrier shift. Distortion may also be produced by effects other than the modulation process. Some examples of this include parasitic oscillation, nonlinear radio-frequency amplification of modulated signals, and distortion present in the audio amplifiers. These possibilities show that modulation measurements by the antenna current method can sometimes be misleading, even though such measurements may appear entirely normal. Unfortunately, continuous variation of the modulation percentages creates a number of additional problems. For example, there is a need for damping, so that a meter can provide an average reading despite fluctuations. An average reading, on the other hand, will not disclose the presence of transient overmodulation. This shortcoming is serious, owing to the large number of sideband frequencies produced, in addition to the normal ones, whenever overmodulation occurs. Not only do these extra frequencies interfere drastically with other transmissions, but they also may significantly distort the modulation signal. These considerations account for the necessity of using a meter that responds to modulation peaks. Specifically, both positive-peak and negative-peak overmodulation must be indicated. Positive-peak overmodulation occurs when the positive modulation percentage exceeds 100; and negative-peak overmodulation occurs when the negative modulation percentage exceeds 100.

2-11.1.1 Oscilloscope Measurement Methods

The cathode-ray oscilloscope is widely used as an amplitude-modulation monitor and measuring instrument. Since it is capable of presenting visual indications of the modulated output of amplitude-modulated transmitters, the oscilloscope is a fairly reliable equipment for detecting overmodulation and determining the percentage of modulation. For example, the relative error of most measurements taken with a 5-inch cathode-ray tube is about 10 percent. Although such accuracy is adequate for many maintenance checks, the oscilloscope is usually considered more valuable as a monitor of general modulation conditions. It is also used to monitor the amplitude-modulated output of a radio transmitter when photographic records are desired.

2-11.1.2 Types of Modulation Display

Two types of modulation patterns are provided by the oscilloscope, depending upon the hook-up used. These patterns are the wave-envelope patterns, as illustrated in Figures 2-76 and 2-77, and the trapezoidal pattern, as illustrated in Figure 2-78. Figure 2-76 shows an RF carrier when amplitude-modulated by a complex wave, such as that of speech. Figures 2-79 and 2-78 illustrate the effects of over 100% modulation on the carrier wave. The carrier wave envelope pattern is obtained by applying the RF-modulated wave to the vertical input of the oscilloscope. The trapezoidal pattern is obtained in similar manner except that the modulation signal from the transmitter is made to horizontally sweep the oscilloscope, instead of by the sweep signal generated internally by the oscilloscope. Both methods are limited by the inherent frequency response of the oscilloscope; therefore, these methods find greater applicability in the LF to MF ranges.

2-11.2 VHF-UHF MEASUREMENT METHOD

In the VHF-UHF ranges, modulation is normally measured by applying a specific-level 1 kHz tone to the input of the modulation. This, in turn, produces a significant drop in the plate voltage of the modulator's final stage. The correct setting of output plate voltage ensures that overmodulation will not occur.

2-11.3 SINGLE-SIDEBAND MEASUREMENTS

Single-sideband modulation is a form of amplitude modulation in which only one sideband is transmitted with a suppressed carrier. Since balanced modulators are used to provide carrier cancellation, the exact balancing of the carriers to provide cancellation requires a null adjustment. Such a null can be observed and adjusted by using either a detector and indicator,

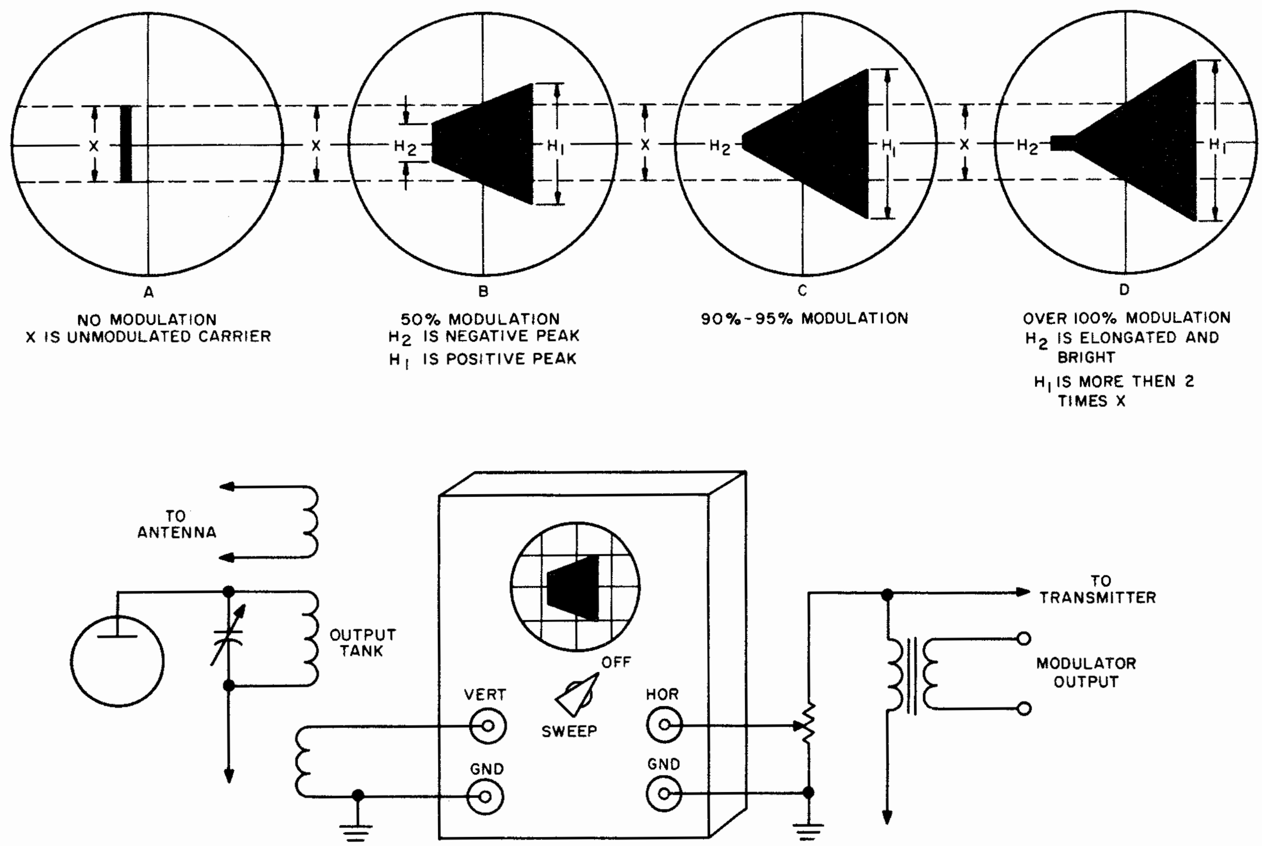


Figure 2-78. Trapezoidal Modulation Patterns

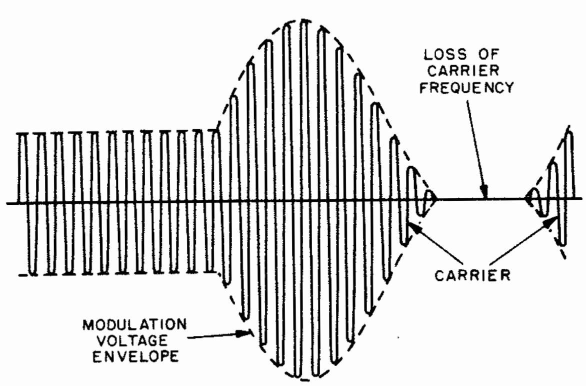


Figure 2-79. Overmodulated RF Carrier

such as a voltmeter (or VTVM), or an oscilloscope, for observation of the output while turning the adjusting screw. Measurements peculiar to sideband technology also include special modulation amplitude and distortion checks. If the sideband modulator is overdriven, mistuned, or the associated linear amplifiers are improperly loaded or overdriven, spurious output frequencies are produced. These are harmonically related to the driving signals, and can cause splatter over a large range of frequencies, thus causing interference to other transmitting stations. To determine the proper amplitude so that the modulation will not cause distortion or splatter, the audio two-tone modulation test is employed. The resulting signals are as illustrated in Figure 2-80. It is possible to make a rough operating adjustment by varying the audio drive from the microphone so that on peak swings a definite value of final plate current is not exceeded. This check depends upon the initial accuracy of calibration and ballistic characteristics of the ammeter in the final stage, plus other factors. The two-tone test is therefore used for initial adjustment and for precise checking, particularly because it will also indicate distortion at the same time. The two-tone test corresponds to the wave envelope method of AM modulation checking. Two signals of equal amplitude but of slightly different frequencies are applied to the sideband modulator input to produce a single tone of approximately 1000 hertz by beating them together. The

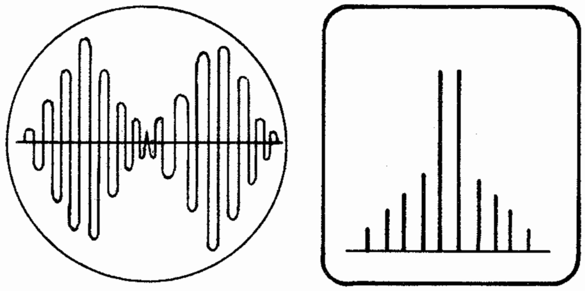


Figure 2-80. Examples of Ideal Two-Tone Test Waveform

output appears as a series of fully-modulated sine waves, similar to 100 percent modulated AM response in AM tests. When the trapezoidal method is used, two opposed triangles appear on the oscilloscope. When equally balanced modulators are used, the triangles are mirror images. Elliptical or straight-line patterns appear when the phase-distortion check is used. Section 3 in this Handbook describes the methods of making the specific tests, and presents specific interpretation of observed waveform patterns.

2-11.4 FREQUENCY MODULATION

In frequency modulation, the carrier amplitude remains constant, and the output frequency of the transmitter is made to vary about the carrier (or mean) frequency at a rate corresponding to the audio frequencies of the speech currents. The extent to which the frequency changes in one direction from the unmodulated, or carrier, frequency is called the frequency deviation.

2-11.4.1 Frequency Deviation

Deviation in frequency is usually expressed in kilohertz, and is equal to the difference between the carrier frequency and either the highest or lowest frequency reached by the carrier in its excursions with modulation. There is no modulation percentage in the usual sense. With suitable circuit design, the deviation may be made as large as desired without encountering any adverse effect, equivalent to overmodulation in amplitude-modulation transmissions. However, the maximum permissible deviation is determined by the width of the band assigned for station operation. In frequency modulation, the equivalent of 100-percent modulation occurs when the frequency-deviation is made equal to a predetermined maximum value. There are several methods of measuring the modulation in frequency-modulated transmissions. Only the frequency-deviation methods are presented here. Some other methods, including the Bessel zero method, are explained in Section 3.

2-11.4.2 Frequency Deviation Measurement

Since frequency and phase types of modulation always occur at a low power level in the radio transmitter, modulation can be checked and measured while the radio-frequency power amplifier circuits are de-energized. Because zero frequency is equivalent to direct current, it is possible to apply a variable dc voltage to the modulator grid and produce proportional changes in the oscillator frequency. A suitable frequency-measuring instrument is set to the maximum or minimum allowable oscillator frequency to the point where a zero beat note is obtained. The value of the dc voltage at this point is equal to the peak ac modulating voltage that would satisfy the maximum allowable condition, and is the equivalent of 100-percent modulation. The final carrier frequency is the oscillator frequency times the multiplication factor of the transmitter frequency-multiplying stages. Hence, the final carrier deviation is the oscillator deviation times the same multiplication factor.

2-11.4.3 Alternate Method

Another method of measuring frequency deviation requires connecting an audio signal generator to the input speech amplifier, as illustrated in Figure 2-81. The electronic multimeter is connected to the output of the speech amplifier and the audio generator is adjusted to provide 1,000 Hz with an output of 36 millivolts from the speech amplifier. A receiver known to be in good operating condition is then set up to receive on the transmitter's frequency. The distortion analyzer to measure the receiver's audio output level and harmonic distortion is then coupled loosely to the receiver and transmitter. Adequate coupling must be employed to ensure receiver limiting. After keying the transmitter, adjust the receiver VOLUME control to any convenient setting. Then, without moving the receiver VOLUME control adjust the audio generator to the frequencies listed below, while maintaining 36 millivolts on the meter. Record the audio voltage and harmonic distortion at each of the following frequencies:

Frequency (Hz)	Frequency (Hz)
500	3,000
1,000	5,000
1,500	10,000
2,000	20,000
2,500	

As the next step in measuring frequency deviation, unkey the transmitter and uncouple the receiver. Connect the FM signal-generator cable to the receiver ANT

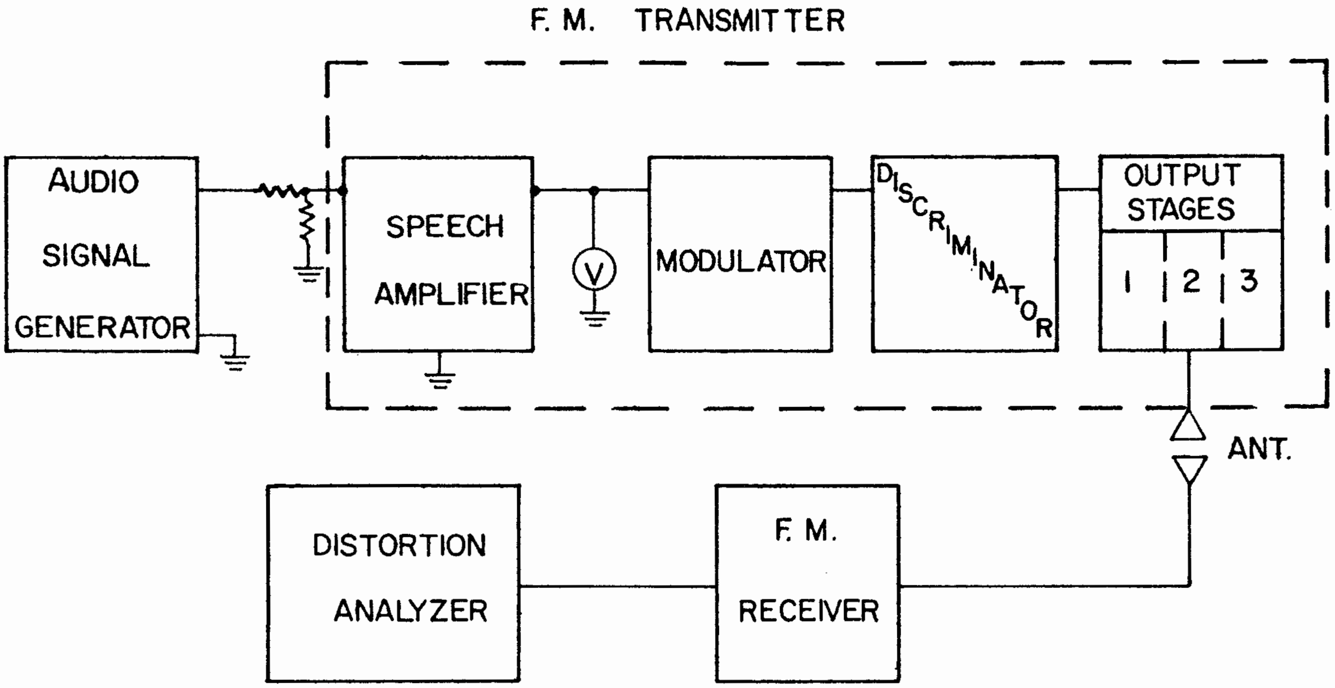


Figure 2-81. FM Deviation and Harmonic Distortion Test Set-Up

connector. Adjust the FM signal-generator to the frequency of the receiver channel at a level sufficient to cause the receiver limiter to function. Reconnect the audio generator to the EXT MOD and GND terminals on the FM signal-generator and adjust the audio generator to each frequency as shown above at full output, then adjust the FM signal-generator to indicate the same audio voltage level as previously recorded. Record the deviation as shown on the FM signal generator and the receiver's harmonic distortion for each frequency. The deviations thus obtained are equal to the deviations of the modulator. A normal deviation is 8 ± 1.5 kHz at 1,000 Hz, but use the deviation obtained at 1,000 Hz as the reference deviation. For deviations of 500, 1,500, 2,000, 2,500, and 3,000 Hz, a normal indication is +0 to -0.5 kHz of the 1,000-Hz reference deviation. For deviations of 5,000, 10,000, and 20,000 Hz, a normal indication is +0 to -1.5 kHz of the 1,000-Hz reference deviation. Subtract the harmonic distortion of each frequency, using the FM signal-generator, from those of the transmitter to obtain the true modulator harmonic distortion. A normal indication is 2 percent harmonic distortion or less. In this method, the final carrier frequency in deviation is already taken into account, and no multiplication is necessary to obtain the final figure.

2-12 TESTING ELECTRON TUBES

In equipment that uses vacuum tubes, it has been found that faulty tubes are responsible for more than 50 percent of all electronic equipment failures. As a result, the testing of electronic tubes assumes considerable importance. The condition of a tube can be determined by substituting a tube known to be good for the questionable one. However, indiscriminate substitution of tubes is to be avoided, as detuning of circuits may result. In addition, a tube may not operate properly in a high-frequency circuit, although it performs well in a low-frequency circuit. Therefore, knowledge of tube-testing devices and their limitations, as well as correct interpretation of the test results obtained, is indispensable to accurate and rapid maintenance. Because the operating capabilities (and design features) of a tube are demonstrated by its electrical characteristics, a tube is tested by measuring those characteristics and comparing them with representative values established as standard for that type of tube. Tubes which read abnormally high or low with respect to the standard are subject to suspicion. Practical considerations, which take into account the limitations of the tube test in predicting actual tube performance in a particular circuit, make it unnecessary to employ complex and costly test equipment having laboratory accuracy. For most applications, the testing of a single tube characteristic suffices to determine whether a tube is performing satisfactorily. Some of the more important factors affecting the life expectancy of an electron tube are:

1. The circuit function for which the tube is used.
2. Deterioration of the cathode (emitter) coating.
3. A decrease in emission, with age, of impregnated emitters in filament-type tubes.
4. Defective seals, which permit air to leak into the envelope and oxidize the emitting surface.
5. Internal short circuits and open circuits, caused by vibration or excessive voltage.

If the average receiving tube is not overdriven, nor operated continuously at maximum rating, it can be expected to have a life of at least 2000 hours before the filament opens. Because of the attendant expansion (and contraction) of the tube elements during the process of heating (and cooling), the electrodes may lean or sag, causing excessive noise or microphonics to develop. Other electron-tube defects are cathode-to-heater leakage and nonuniform electron emission of the cathode. Tube defects, of which only the most common are listed above, contribute to about 50 percent of all electronic equipment failures. For this reason it is good practice for you to eliminate immediately any tube known to be faulty; however, avoid blind replacement of good tubes by fresh spares. Visible evidence of a tube defect is present when the filament is open (glass-envelope tubes), when the plate current is excessive shown by the brighter-than-normal cherry-red glow of the plate, and when the tube becomes soft (gassy), or when arcing occurs between electrodes. Metal-encased tubes can be felt to determine whether the heater is operating. A tube may be tapped sharply while it is operating in a particular circuit to provide an aural indication of loose elements or microphonics.

2-12.1 SUBSTITUTION TEST

Substitution of a tube known to be in good condition is a simple method of determining the quality of a questionable tube. However, in high-frequency circuits tube substitution should be carried out judiciously, one at a time, so that the effect of difference in inter-electrode capacitance of the substituted tubes on tuned (aligned) circuits can be noted. The substitution method of testing cannot be used to advantage in locating more than one faulty tube in a single circuit. If both an RF amplifier tube and IF amplifier tube are defective in a receiver, replacing either one does not correct the trouble. If all the tubes are replaced, there is no way of knowing which tubes were defective. Under these or similar conditions, the use of a test equipment designed for testing the quality of a tube saves valuable time. A number of different types of equipment have been developed for testing the condition of electron tubes. Bridge-type instruments are used in laboratory work for the measurement of three important parameters of grid-controlled electron tubes: amplification factor (μ), plate resistance (r_p), and transconductance (G_m). Diode and rectifier characteristics are checked by measuring the plate current resulting from the application of a specified value of plate voltage. These bridge measurements, as well as the calculations which are a necessary part of the more complete laboratory tests, are tedious and time-consuming. To be of practical use to the technician in the field, a tube tester must provide a simple and quick appraisal of the quality of a tube. Therefore, while using the same basic principles as the laboratory measurements, checks made with field-type tube testers generally employ simplified methods. Field-type tube testers have certain limitations. Although they compare tube characteristics with a predetermined standard, they do not reveal how a tube will operate in a circuit under actual operating conditions. The final, and most accurate indication of the condition of an electron tube is its ability to function satisfactorily in the particular circuit where it is used. Many types of high-power tubes, used for transmitting and rectifying applications, cannot be checked by general-purpose tube testers because of impractical power requirements. These tubes must be checked in the equipment where they are used. Tubes such as reflex klystrons, infrared image converters, and electrometer tubes must be tested by special-purpose tube testers, or in the equipment where they are used. However, field-type tube testers, although limited in the completeness of their tests, are very useful aids to fast troubleshooting, since they serve to evaluate the condition of tubes most generally used in communication and electronic equipment.

2-12.2 TRANSCONDUCTANCE TESTERS

The transconductance type of tester provides a more accurate evaluation of the condition of a grid-controlled tube than does the emission-type tester because it measures the amplification ability of the tube under simulated circuit conditions. The transconductance is measured and then compared with the ratings provided by the tube manufacturer. The meter scale of this type of tube tester is usually calibrated to indicate the transconductance (G_m), either directly in micromhos or indirectly as good, weak, or bad. A voltage or power amplifier tube is considered defective when its transconductance decreases to 70 percent of the value stated in standard tube tables; the oscillator section of a converter tube is considered defective when its transconductance decreases to 60 percent of table values. The term "transconductance" (also called mutual conductance) indicates the effect of the control grid voltage upon the plate current of a tube. This characteristic is expressed mathematically as the ratio of a change in plate current to a small change in control grid voltage, with all other electrode voltages held constant. The equation for transconductance is: $G_m = \frac{\Delta I_p}{\Delta E_g}$, where G_m is the transconductance in micromhos, ΔI_p is the change in plate current in microamperes, and ΔE_g is the change in control grid voltage. When the control grid voltage changes 1 volt, the current change in microamperes is equal to the transconductance in micromhos. For example, if a 1-volt change in control grid voltage produces a 200-microampere change in plate current, the tube has a transconductance of 200 micromhos. Transconductance may be measured by two methods: the static (dc) method, and the dynamic (ac) method.

2-12.2.1 Static Method

In the static (also called the grid shift) method of measuring transconductance, the dc bias voltage on the control grid of the tube under test is changed, and the resultant change in the steady plate current is measured with a dc milliammeter.

2-12.2.2 Dynamic Method

The dynamic method of determining transconductance makes use of a circuit which applies an ac test signal and a dc bias voltage to the control grid of the tube under test.

2-12.3 ADDITIONAL TEST CIRCUITS

The following subparagraphs describe additional test circuits used in electron tube testers.

2-12.3.1 Short-Circuit and Noise Test

It is very important that the test for short-circuited elements be applied to a tube of doubtful quality before any other tests are made. This helps protect the meter (or any other indicator) from damage. It follows logically that if a tube under test has elements which are short-circuited, there is no further need to apply additional tests to that tube. Short-circuit tests usually indicate leakage resistance less than about 1/4 megohm. The proper heater voltage is applied to detect any tube elements which might short as a result of the heating process. The short-circuit test is similar to the test used to detect noisy (microphonic) or loose elements. The only difference between the two tests lies in the sensitivity of the indicating device.

2-12.3.2 Gas Test

In all electron tubes, except some types of rectifier, regulator, and switching tubes, the presence of an appreciable amount of gas is extremely undesirable. When gas is present, the electrons emitted by the cathode collide with the molecules of gas. Electrons (secondarily emitted) are thus dislodged from the gas molecules, and positive gas ions are formed. These ions are attracted by (and cluster around) the control grid of the tube because it is negatively biased and absorbs electrons from the grid circuit in order to revert to the more stable gas molecules (not ionized). If the amount of gas is appreciable, the collisions between the numerous gas molecules and the cathode-emitted electrons release many secondarily-emitted electrons, and the resulting flow of grid current is high.

2-12.3.3 Cathode Leakage Test

The cathode element of an electron tube supplies the electrons necessary for tube operation. Electrons are released from the cathode by some form of energy (generally heat). An indirectly-heated cathode consists of a heater wire (usually a tungsten alloy) enclosed in, but insulated from, a metal sleeve (nickel). This sleeve is coated with an electron-emitting material (usually strontium or barium compounds) on its outer surface, and is heated by radiation and conduction from the heater. Useful emission does not take place from the heater wire. When a tube which uses an indirectly-heated cathode develops noise, it is likely that a leakage path is present between the cathode sleeve and the heater wire. This is because tube design requires that the heater be placed as close as possible to the cathode so that maximum tube efficiency is attained. Continual heating and cooling of the tube structure may cause small amounts of the insulation between the cathode and heater to become brittle or to deteriorate, leaving a high-resistance leakage path between these elements. Under extreme conditions, the insulation may shift enough to allow actual contact of the elements. Since the heater and cathode are seldom operated at the same potential, any form of leakage causes noise to develop in the tube. The cathode is normally maintained at a higher positive potential as the most common type of bias. The heater circuit is usually grounded to the chassis, either on one side of the filament supply or by a center-tap arrangement. Therefore, if a resistance path is present, a leakage current may flow from the heater to the cathode. In this effect, the cathode functions similar to that of the plate of a tube; that is, it receives electrons. Assuming the existence of high-resistance leakage, the current flow from the heater to the cathode will vary with any vibration of the tube because vibration varies the amount of resistance. If the cathode and heater are completely shorted (zero ohms), it is impossible for the tube to develop any cathode bias. A cathode leakage test is sometimes made while a tube is being tested for short-circuited elements or noise. However, some tube-testing instruments incorporate the cathode leakage test as an additional test which is not a part of the short-circuit test.

2-12.3.4 Filament Activity Test

The filament activity test is used to determine the approximate remaining life of an electron tube insofar as the longevity of the cathode emitter is concerned. The test is based on the principle that in almost all electron tubes the cathode is so constructed that a decrease of 10 percent of the rated heater voltage causes no appreciable decrease in emission. On tube-testing equipment incorporating this test there is a two-position switch (filament activity test) which has one position marked "normal" and the other marked "test". The switch remains in the "normal" position for all tests other than for filament activity. When the switch is set to the "test" position, the filament (or heater) voltage applied to the tube under test is reduced by 10 percent. The filament activity test is performed as follows. After the quality test is made, the tube test button is held depressed and the filament activity test switch is set to the "test" position. If the indicator shows a decreased reading after a reasonable time is allowed for the cathode to cool, the useful life of the tube is nearing its end.

2-12.4 TUBE CHARACTERISTIC GRAPHIC DISPLAY

An oscilloscope and test circuit can be used to graphically display the characteristics of low-power electron tubes. The dynamic plate current-voltage characteristic of diode and grid-controlled tubes can be displayed by the methods described in this section. If the oscilloscope is suitably calibrated, the dynamic plate resistance of grid-controlled tubes and the back-to-forward resistance ratio of diode tubes can be calculated.

2-12.4.1 Diode Tube Measurement

A method of presenting diode tube voltage-current characteristics on a cathode-ray oscilloscope is shown in Figure 2-82. An adjustable test signal, obtained from the line power source, is coupled through transformer T, and applied to the tube under test and to

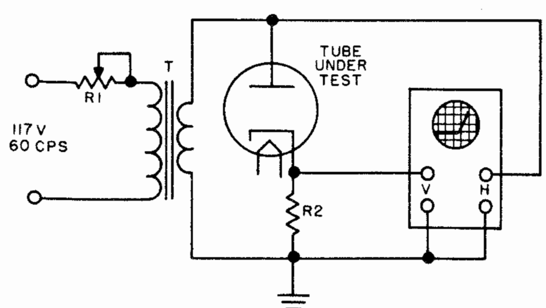


Figure 2-82. Circuit To Display Plate Current-Voltage Characteristic of a Diode Tube

current-measuring resistor R2. The signal voltage applied to the tube controls the horizontal deflection of the oscilloscope trace. The voltage developed across current-measuring resistor R2 is connected to the vertical input of the oscilloscope. Since this voltage is proportional to the current through the tube, the vertical deflection will indicate the tube current. Therefore, the resultant trace on the oscilloscope represents the plate current-voltage characteristic curve. If a graticule is placed over the face of the cathode-ray tube, the oscilloscope can be calibrated to measure voltage and current by the method previously described. The voltage and current can be determined at points on the curve to calculate the back and forward resistance values.

2-12.4.2 Grid-Controlled Tube Measurements

The plate voltage-current characteristic of a grid-controlled tube can be displayed by the circuit shown in Figure 2-83. An adjustable test signal, obtained

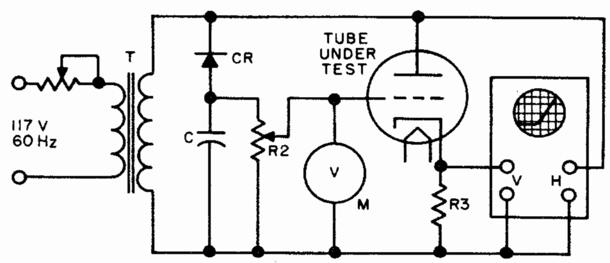


Figure 2-83. Circuit To Display Plate Current-Voltage Characteristic of a Triode Tube

from the line power source, is coupled through transformer T and applied to selenium rectifier CR, filter capacitor C, and potentiometer R. This circuit provides an adjustable grid bias for the tube under test. Voltmeter M is used to measure this bias voltage. The signal from the input transformer is also applied to the plate of the tube under test and to the horizontal deflection amplifier of the oscilloscope. The voltage developed across resistor R3 is applied to the vertical deflection amplifier. Since this voltage is proportional to the current through the tube, the deflection of the oscilloscope trace along the vertical axis will indicate the tube plate current. The horizontal deflection is controlled by the voltage applied to the tube; therefore, the trace on the oscilloscope represents the plate current-voltage characteristic curve. If the oscilloscope is calibrated by the method previously described, the dynamic plate resistance can be determined. This characteristic can be determined by selecting two voltage points on the curve, determining the plate current for these potentials, and calculating the plate resistance by the following equation:

$$r_p = \frac{E_p}{I_p}$$

where r_p is the plate resistance, E_p is the change in plate voltage, and I_p is the resulting change in plate current when the tube grid voltages are kept constant. An example of an oscilloscope pattern for this test is shown in Figure 2-84. When calibrating the oscilloscope, the

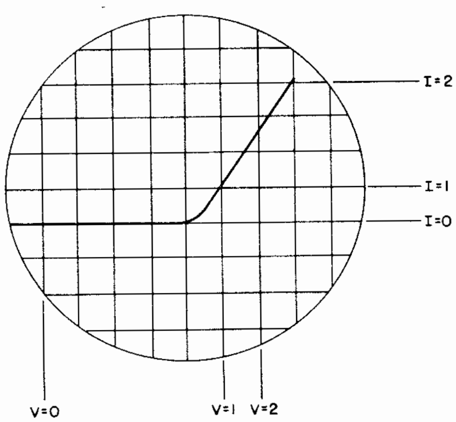


Figure 2-84. Oscilloscope Presentation of Triode Tube Plate Current-Voltage Characteristic

zero current and voltage point can be shifted, by the vertical and horizontal position controls, from the center to the lower-left portion of the screen. This removes from the screen the part of the sweep that occurs when the plate voltage is negative with respect to the cathode. For testing a low-power triode tube with the circuit shown in Figure 2-83, input rheostat R1 may be set so that a 200-volt peak-value ac signal is applied to the plate of the tube. The horizontal gain control is then adjusted so that a voltage change from 0 to 200 volts deflects the trace across four large divisions of the oscilloscope graticule. Each major horizontal division then represents 50 volts. Grid bias resistor R2 may be adjusted so that -2 volts is applied to the grid and indicated on voltmeter M. A 100-ohm resistor can be used for resistor R3, and the oscilloscope vertical deflection is calibrated by the method previously described. For this example, the vertical amplifier gain is adjusted so that deflection of the trace across one large division of the graticule will represent a current of 0.5 mA through the tube. The maximum current shown on the oscilloscope pattern in Figure 2-84 is then 1.25 mA; the r_p of the tube can be determined by using the two voltage points indicated. Thus, V2 is 200 volts, V1 is 150 volts, I2 is 1.25 mA, and I1 is 0.5 mA. Therefore, the value of r_p can be calculated as follows:

$$r_p = \frac{V2 - V1}{I2 - I1}$$

$$r_p = \frac{200 - 150}{.00125 - .0005} = 66{,}000 \text{ ohms}$$

2-12.5 HIGH-POWER HF AMPLIFIER TUBE TESTS

High-power amplifier tubes which operate in the low-to-high frequency range are normally tested in the radio transmitter in which they are to be used. When the tube is operated in a transmitter, its condition can be determined by measuring the grid current, plate current, and power output and comparing the resulting values with those obtained when using tubes known to be good.

2-12.5.1 Klystron Tube Tests

Low-power klystron tubes can be checked for gas, frequency of the output signal, and output power by placing them in the equipment where they are to be used. The beam current, output frequency, and output power are measured with test equipment normally used with the transmitter. The output of klystrons used as receiver local oscillators can be checked by measuring the current in the crystal mixer unit. Klystron tubes that remain inoperative for more than six months may become gassy. This condition occurs in klystrons installed in stored or spare equipment, as well as those stored as stock supplies. Operation of a gassy klystron at its rated voltages will ionize the gas molecules, and may cause excessive beam current to flow. This current may shorten the tube life or produce immediate failure. Gas in a klystron tube can be detected by setting the applied reflector voltage to zero and slowly increasing the beam voltage while observing a meter that indicates the beam current. Excessive beam current for a specific value of voltage is an indication that the tube is gassy. Gassy klystron tubes can usually be restored to serviceable condition by temporary operation at reduced beam voltage. Eight hours or more of reduced voltage operation may be required for klystrons that have been left inoperative for periods in excess of six months. The beam current is also an indication of the power output of the klystron. As klystrons age they normally draw less beam current; when this current decreases to a minimum value for a specific beam voltage, the tube must be replaced. The power output of transmitter klystrons is usually determined by measuring the transmitter power output during equipment performance checks.

2-12.5.2 Traveling-Wave Tube

A traveling-wave tube (TWT) is usually tested in the equipment in which it is used. When installed, it is usually possible to measure the collector current and voltage, and to check the power output for various inputs. Any deviation greater than 10 percent from normal specifications may be considered an indication of a defective tube. Most amplifiers are supplied with built-in panel meters and selector switches so that the cathode, anode, helix, focus, and collector currents may be measured. Thus, continuous monitoring of amplifier operation and tube evaluation is possible. Usually adjustments are provided for the helix, for grid bias, and for collector voltage to permit setting them for optimum operation. If variation of these controls will not produce normal currents, and all voltages are normal, the tube should be considered defective and be replaced with a new tube or one known to be in good operating condition. To avoid needless replacement of tubes, however, it is good testing philosophy to make an additional check by measuring the input and output powers and determining the tube gain. If, with operating conditions normal, the gain level drops below the minimum indicated value in the equipment technical manual, the tube is no doubt defective. In the absence of special field-test sets a laboratory test mock-up may be constructed similar to that shown in Figure 2-85.

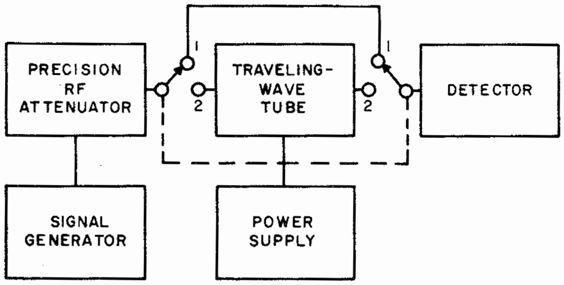


Figure 2-85. Traveling-Wave Tube Test Arrangement

Because of the variations in power and gain between tubes and the large frequency ranges offered, only a general type of equipment can be illustrated. The selected equipment must have the proper range, impedance, and attenuation to make the test for a specific type TWT. To make gain measurements, turn the switch shown in Figure 2-85 to position 1 and set the precision attenuator to provide a convenient level of detector output. Then turn the switch to position 2 and insert attenuation until the detector output level is identical to that obtained without the traveling-wave tube in the circuit. The gain of the traveling-wave tube is directly equal to the amount of added attenuation. When used as an oscillator, failure of the tube to break into oscillation with all other conditions normal is usually a definite indication of a defective tube. In the case of tube use as a receiving amplifier, an increase of noise with a normal or reduced output can also be a possible indication that the tube is failing, but is still usable. All the general rules applying to klystron tubes mentioned previously are also applicable to the TWT.

2-12.5.3 Magnetron Tube Tests

A magnetron tube is tested in the transmitter equipment in which it is to be used. When the magnetron is installed in the transmitter, the condition of the tube can be determined by the normal plate-current measurement, and the power, frequency spectrum, and standing-wave-ratio tests of the output signal. An unusual value for any of these measurements may be an indication of a defective tube.

2-12.5.4 Crossed-Field Amplifier

A crossed-field amplifier tube is usually tested in the equipment in which it is used. Like the klystron, if not operated for more than a few months the tube may become gassy. If a tube is suspected of being gassy, it is recommended that the technician consult the technical manual for the particular piece of equipment in which the crossed-field amplifier is used. The crossed-field amplifier is a relatively new addition to naval radar equipment, but may eventually replace magnetrons and klystrons in radar output power applications.

2-13 TESTING OF SEMICONDUCTORS

Unlike vacuum tubes, transistors are very rugged in that they can tolerate vibration and a rather large degree of shock. Under normal operating conditions, they will provide dependable operation for a long period of time. However, transistors are subject to failure when subjected to relatively minor overloads. Crystal detectors are also subject to failure or deterioration when subject to electrical overloads, and will deteriorate from a long period of normal use. In order to determine the condition of semiconductors, various test methods can be used. In many cases it is possible to substitute a transistor of known good quality for a questionable one, and thus determine the condition of a suspected transistor. This method is highly accurate and sometimes expeditious. However, indiscriminate substitution of semiconductors in critical circuits is to be avoided. When transistors are soldered into equipment, substitution becomes impracticable; it is generally desirable to test these transistors in their circuits. Since certain fundamental characteristics are an indication of the condition of semiconductors, test equipment is available for testing these characteristics with the semiconductors both in and out of their circuits. Crystal-rectifier testers normally test only the forward-to-reverse current ratio of the crystal. Transistor testers are capable of measuring several characteristics, such as the collector leakage current (I_{CO}), the ac gain (beta), and the four-terminal network parameters. The most useful test characteristic is determined by the type of circuit in which the transistor will be used. Thus, the beta measurement is preferred for ac amplifier or oscillator applications. For switching-circuit applications, a direct-current measurement may prove more useful.

2-13.1 TRANSISTOR TESTING

When trouble occurs in transistorized equipment, power supply voltage measurement, waveform checks, signal substitution or signal-tracing methods are normally the first tests to be employed. If a faulty stage is isolated by one of these test methods, voltage, resistance, and current measurements can be made to locate defective parts. When making these measurements, the voltmeter resistance must be high enough to exert no appreciable effect upon the voltage being measured, and current from the ohmmeter must not damage the transistor. If the transistors are not soldered into the equipment it is usually advisable to remove the transistors from their sockets during a resistance test. Transistors should be removed from or reinserted into their sockets only after power has been removed from the stage, since damage by surge currents may otherwise result. Transistor circuits, other than pulse and power amplifier stages, are usually biased so that the emitter current is from 0.5 to 3 milliamperes and the collector voltage is from 3 to 15 volts. The emitter current can be measured by opening the emitter connector and inserting a milliammeter. When making this measurement, you should expect some change in bias due to the meter resistance. The collector current can often be determined by measuring the voltage drop across a resistor in the collector circuit and calculating the current. If the transistor itself is suspected, it can be tested by one or more of the methods described below.

2-13.1.1 Resistance Test

An ohmmeter can be used to test transistors by measuring the emitter-collector, base-emitter, and base-collector forward and back resistances. A back-to-forward resistance ratio on the order of 500:1 should be obtained for the collector-to-base and emitter-to-base measurements. The forward and back resistances between the emitter and collector should be nearly equal. All three measurements should be made for each transistor tested, since experience has shown that transistors can develop shorts between the collector and emitter and still have good forward and reverse resistances for the other two measurements. Because of shunting resistances in transistor circuits, you will normally have to disconnect at least two transistor leads from the associated circuit for this test. Exercise caution during this test to make certain that current during the forward resistance tests does not exceed the rating of the transistor. Ohmmeter ranges requiring a current of more than 1 milliampere should not be used for testing transistors. Many ohmmeters are designed such that on the RX1 range 100 milliamperes or more can flow through the electronic part under test.

2-13.2 TRANSISTOR TESTERS

Laboratory transistor test-sets are used for large-scale experimental work to permit complete evaluation of all characteristics of point-contact and junction transistors. However, for testing transistors during equipment maintenance and repair, it is not necessary to check all of the transistor parameters. A check of two or three performance characteristics is generally sufficient to determine whether a transistor needs to be replaced. In the following discussion, four basic types of transistor tests are covered: the collector leakage current test; the direct-current gain test; the voltage punch-through test; and the alternating-current gain test.

2-13.2.1 Collector Leakage Current Test

Collector leakage current is a function of the temperature and resistivity of the transistor material. Contamination of the semiconductor surface, damage by a short circuit, or overheating can result in excessively large values of leakage current; therefore, this test provides a useful indication of the transistor condition. The collector-to-base reverse current flowing in a transistor with the emitter open constitutes the collector cutoff current, I_{CO}, which is also referred to as the collector reverse current. This current flow is one of the important measures of the quality of a transistor. An excessively high or erratic I_{CO} indicates a defective transistor. Figure 2-86A illustrates a method for determining

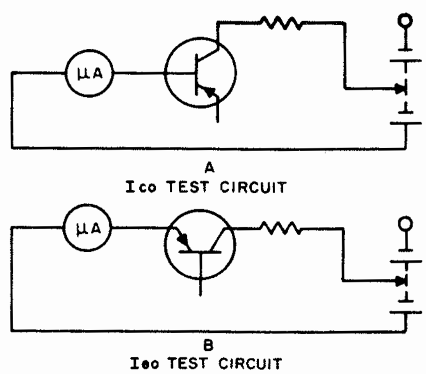


Figure 2-86. Collector Leakage Current Test Circuit

I_{CO}. The collector-base diode is reverse-biased, and I_{CO} is read directly on the direct-current microammeter. Since I_{CO} is measured on a direct-current basis, stray leakage paths in the associated transistor circuit would introduce errors; consequently, I_{co} measurements are made only after the transistor is disconnected from its circuit. The collector-to-emitter leakage current flowing in a transistor with the base open is designate I_{eo}. This leakage current is generally much larger than I_{co}. Figure 2-86B illustrates a method for determining I_{eo}.

2-13.2.2 Direct-Current Gain Test

The direct-current gain frequently decreases as a transistor ages. This results in less amplification for the stage in which it is used, and can also create distortion and circuit mismatching due to changes in impedance. A useful test parameter for a transistor used in low-frequency power-amplifier, switching, control, and logic circuits is the direct-current gain of the transistor when it is used in the common-emitter configuration. This gain is sometimes referred to as the direct-current beta (β). A method for determining the ratio of the collector-to-base current in a common-emitter, PNP-type junction, or N-type point-contact and surface-barrier transistor circuit is shown in Figure 2-87.

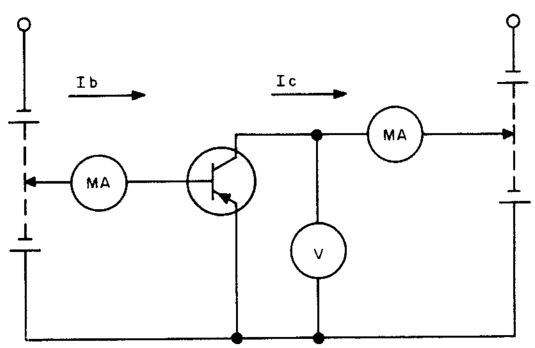


Figure 2-87. Transistor Direct-Current Gain Test

The correct collector and base bias is selected by the variable power supply controls, and the direct-current gain is obtained by calculating the ratio of I_c to I_b. The NPN-type junction and P-type point-contact and surface-barrier transistors can be tested with this method by reversing the polarity of the bias supplies and reversing the meter connections. A transistor test-set using the null indicator method to indicate the direct-current gain on a calibrated scale is shown in Figure 2-88. The polarities of voltages V1 and V2 are such that voltage V3 is the difference of the two. A null detector is used to measure V3, and R1 is adjusted until V3 is zero. Voltages V1 and V2 are then equal, and the current gain equals the ratio of R1' to R2, thus,

$$\text{Current Gain} = \frac{I_c}{I_b} = \frac{V2/R2}{V1/R'} = \frac{R1'}{R2}$$

This provides a linear relation between the current gain and resistance of R1'. A calibrated dial can be connected

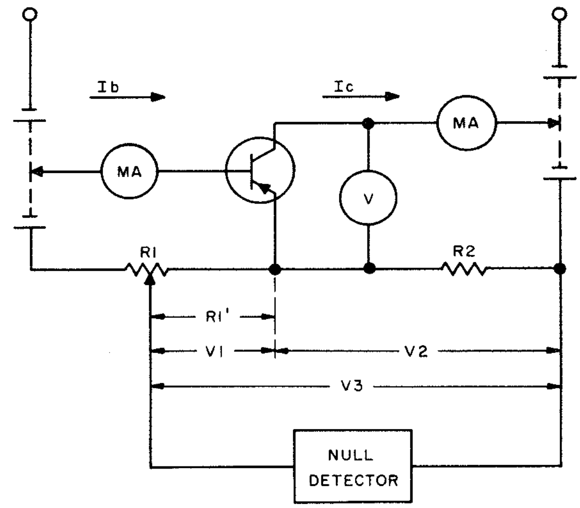


Figure 2-88. Direct Reading Transistor Direct-Current Gain Tester

to potentiometer R1 to indicate the direct-current gain. The maximum value of current gain that can be measured by this test circuit is determined by the ratio of R1 to R2. Since the transistor current gain is a function of the bias, meters connected with adjustable bias supplies are required for preliminary circuit adjustments. Since shunt resistances in the associated circuit of the transistor would introduce errors, the direct-current gain must be measured with the transistor disconnected from the circuit in which it is used.

2-13.2.3 Punch-Through Voltage Test

Another direct-current characteristic which indicates the quality of transistors used for switching circuits is the punch-through voltage (V_{PT}). This is the collection-to-base voltage at which the collector space-charge layer has widened sufficiently to contact the emitter junction. In effect, the base region disappears as the collector space-charge layer contacts the emitter. Transistor action often stops, and a relatively low-resistance path between the emitter and collector is established. Testing this characteristic does not result in a voltage breakdown, and normal transistor action will resume when the collector-to-base voltage is lowered. Figure 2-89 illustrates a test circuit for measuring the transistor punch-through voltage. Potentiometer R3 is adjusted to increase the collector-to-base voltage until a predetermined reference voltage reading, indicative of the punch-through current, is obtained on meter M2. The voltage indicated by meter M1, when this condition occurs, is the punch-through voltage. Resistors R1 and R2 are connected in series with the collector and emitter to limit the punch-through current and thus protect the transistor while

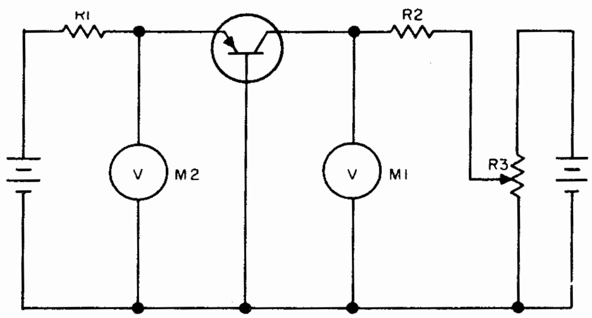


Figure 2-89. Transistor Punch-Through Voltage (V_{PT}) Test Circuit

under test.

2-13.2.4 Alternating-Current Gain Test

To determine the alternating-current gain of a transistor, either the alpha (α) or beta (β) amplification factor can be measured. Alpha is the ratio of collector current change to emitter current change for a constant collector voltage when the collector is effectively short-circuited to the base for alternating current. Beta is the ratio of collector current change to base current change for a constant collector voltage when the collector is effectively short-circuited to the emitter for alternating current. Typical alpha values are 0.95 to 0.99 for junction transistors, and approximately 2 or 3 for point-contact transistors. Values of beta ranging from 50 to 200 are common. Since beta is generally a higher ratio than alpha, it is favored for testing transistors. Alpha can be determined if beta is known and vice versa, since alpha and beta are related by the following equations:

$$\alpha \quad \frac{\beta}{1+\beta} \qquad \beta \quad \frac{\alpha}{1-\alpha}$$

A method for determining the beta of a transistor is shown in Figure 2-90. This method is similar to that

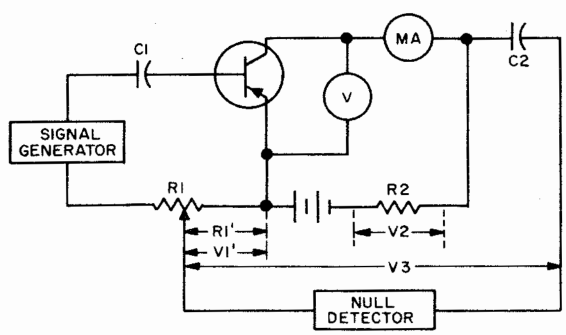


Figure 2-90. Transistor Beta-Test Circuit

described for measuring the direct-current gain of a transistor except that an alternating-current signal is applied to the base. Since blocking-capacitor C2 is connected in series with the null detector, only the alternating-current gain is measured. A calibrated dial can be connected to potentiometer R1 to provide a direct indication of the value of beta. If low-impedance techniques are used for both the input and output circuits to nullify the effects of external circuit impedance, this type of tester can be used for checking the performance of a transistor without disconnecting the transistor from its associated circuit.

2-13.3 TRANSISTOR CHARACTERISTIC GRAPHICAL DISPLAY

An oscilloscope and curve-tracing test circuit can be used to graphically display the current-voltage characteristics of transistors. Commercial test equipment can be obtained, but you can also construct a simple circuit for making this test. Figure 2-91 shows a circuit which you may use to display the collector

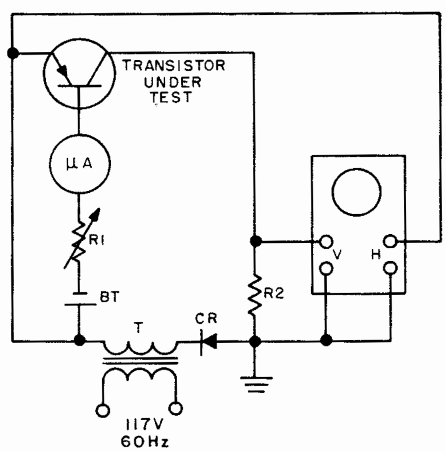


Figure 2-91. Circuit To Display Collector Current-Voltage Curve

current-voltage curve of a PNP junction or N-type point-contact transistor. In this circuit the base current, supplied by battery BT, can be adjusted by potentiometer R1 and measured by micro-ammeter M. When testing a transistor, curves with the base current set at several different values can be constructed for gain or distortion analysis. A 60-hertz signal is coupled from the power line by step-down transformer T. This signal is then rectified by selenium rectifier CR, and the resulting pulsating direct voltage is applied to the emitter and collector terminals of the transistor under test. This test signal is also connected to the horizontal input of the oscilloscope. The voltage developed across current-measuring resistor R2 is applied to the vertical input of the oscilloscope. Therefore, the horizontal sweep represents the voltage applied to the transistor, and the vertical deflection indicates the resulting collector current.

Figure 2-92 shows a typical oscilloscope pattern which

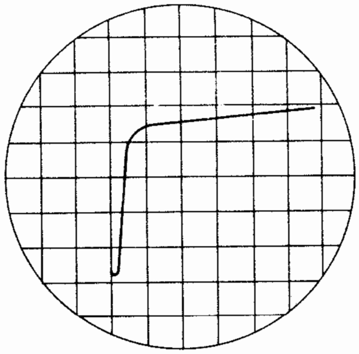


Figure 2-92. Typical Collector Current-Voltage Curve

may be obtained from this test. If the oscilloscope is calibrated, the dynamic collector resistance can be calculated and the linear operating range determined. To measure an NPN junction or P-type point-contact transistor, reverse the connections for battery BT and selenium rectifier CR. However, this will reverse the resulting characteristic pattern displayed on the oscilloscope. The zero current condition will be shifted to the right side of the pattern, and increased current will be indicated by a downward deflection of the oscilloscope trace.

2-13.4 HANDLING OF TRANSISTORS

Transistors, although generally more rugged mechanically than vacuum tubes, are susceptible to damage by excessive heat and electrical overload. The following precautions are to be taken in servicing transistorized equipment:

1. Test equipment and soldering irons must be checked to make certain that there is no leakage current from the power source. If leakage current is detected, isolation transformers must be used.

2. Ohmmeter ranges which require a current of more than 1 milliampere in the test circuit should not be used for testing transistors.

3. Battery eliminators should not be used to furnish power for transistor test equipment because they have poor voltage regulation and, possibly, high ripple voltage.

4. The heat applied to a transistor, when soldered connections are required, should be kept to a minimum by using a low-wattage soldering iron and heat shunts, such as long-nose pliers, on the transistor leads.

5. All associated circuits should be checked for defects before a transistor is rejected.

6. The power must be removed from the equipment before replacing a transistor or other circuit part.

7. When working on equipment with closely spaced parts, conventional test probes are often the cause of accidental short circuits between adjacent terminals. Momentary short circuits, which rarely cause damage to a vacuum tube, may ruin a transistor. To avoid accidental shorts, test probes can be covered with insulation for all but a very short length of the tip.

2-13.4.1 Crystal Diode Testing

Because of the reliability of semiconductor devices, servicing techniques developed for transistorized equipment differ from those normally used for electron tube circuits. Electron tubes are usually considered to be the circuit component most susceptible to failure, and are, therefore, normally the first components to be tested. Transistors are capable of operating in excess of 30,000 hours at maximum ratings without appreciable degradation, and are often soldered into the equipment in the same manner as resistors and capacitors.

2-13.4.2 Substitution Test

Substitution of a crystal diode or transistor known to be in good condition is a simple method of determining the quality of a questionable semiconductor device. This technique should be used only after voltage and resistance measurements made certain that no circuit defect exists that might damage the substituted semiconductor device. If more than one defective semiconductor is present in the equipment section where trouble has been localized, this method becomes cumbersome, since several semiconductors may have to be replaced before the trouble is corrected. To determine which stages failed and which semiconductors are not defective, all of the removed semiconductors must be tested. This can be accomplished by observing whether the equipment operates correctly as each of the removed semiconductor devices is reinserted into the equipment.

2-13.5 CRYSTAL DIODE TESTERS

Crystal diodes, such as general purpose germanium and silicon diodes, power silicon diodes, and microwave silicon diodes, may be tested most effectively only under actual operating conditions. However, crystal rectifier testers are available to determine direct-current characteristics which provide an indication of crystal diode quality.

2-13.5.1 RF Crystal Diode Test

A common type of crystal diode test set is a combination ohmmeter-ammeter. Measurements of forward resistance, back resistance, and reverse current may be made with this equipment. The condition of the crystal rectifier under test can then be determined by comparison with typical values obtained from test information furnished with the test-set or from the manufacturer's data sheets. A comparison of the diode's back and forward resistance at a specified voltage provides a rough indication of the rectifying property of a diode. A typical back-to-forward-resistance ratio is on the order of 10:1, and a forward-resistance value of 50 to 80 ohms is common.

2-13.5.2 Switching Diode Test

To effectively test crystal rectifiers used for computer applications, it is necessary to obtain back-resistance measurements at a large number of different voltage levels. This can be done efficiently by using a dynamic diode tester in conjunction with a cathode-ray oscilloscope to display the diode back-current-versus-voltage curve. Diode characteristics, such as flutter, hysteresis and negative resistance, can easily be interpreted through use of the dynamic voltage-current display.

2-13.6 DIODE CHARACTERISTIC GRAPHICAL DISPLAY

An oscilloscope can be used to graphically display the forward and back resistance characteristics of a crystal diode. A test circuit used in conjunction with Oscilloscope OS-8C/U is shown in Figure 2-93.

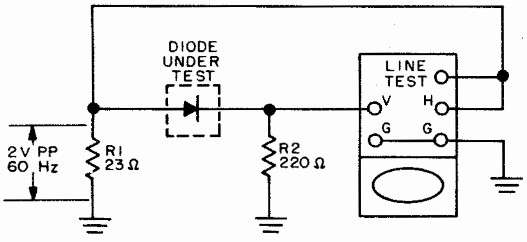


Figure 2-93. Display Circuit Used with Oscilloscope OS-8C/U

This circuit uses the oscilloscope's line-test voltage as the test signal. A series circuit composed of resistor R1 and the internal resistance in the line-test circuit decreases the 3-volt open-circuit test voltage to a value of approximately 2 volts peak-to-peak. The test signal applied to the crystal diode is also connected to the horizontal input of the oscilloscope. The horizontal sweep will then represent the voltage applied to the diode under test. The voltage developed across current-measuring resistor R2 is applied to the vertical input of the oscilloscope. Since this voltage is proportional to the current through the diode under test, the vertical deflection will indicate crystal current. The resulting oscilloscope trace will be similar to the curve shown in Figure 2-94.

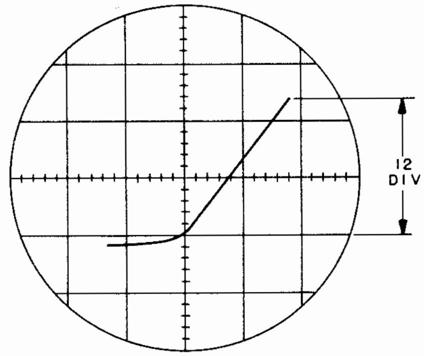


Figure 2-94. Typical Characteristic Curve of a Silicon Diode

2-13.6.1 Reverse Voltage-Current Analysis

An analysis of the reverse voltage-current portion of the characteristic curve for a crystal diode can be made with the method described above or with a diode test-set. This test is very important for crystal diodes employed in computer applications, where stability of operation is essential. Various diode fault conditions that may be detected by this test are shown in Figure 2-95.

2-13.6.2 Regulator Diode Test

To test Zener diodes, a higher voltage than the oscilloscope line-test signal must be used. This test can be made with a diode test-set or with the circuit shown in Figure 2-96. In this circuit, rheostat R1 is used to adjust the input voltage to a suitable value for the Zener diode being tested. Resistor R2 limits the current through the diode. The signal voltage applied to the diode is also connected to the horizontal input of the oscilloscope. The voltage developed across current-measuring resistor R3 is applied to the vertical input of the oscilloscope. The horizontal sweep will therefore represent the applied voltage, and the vertical deflection will indicate the current through the diode under test. Figure 2-97 shows the characteristic pattern of a Zener

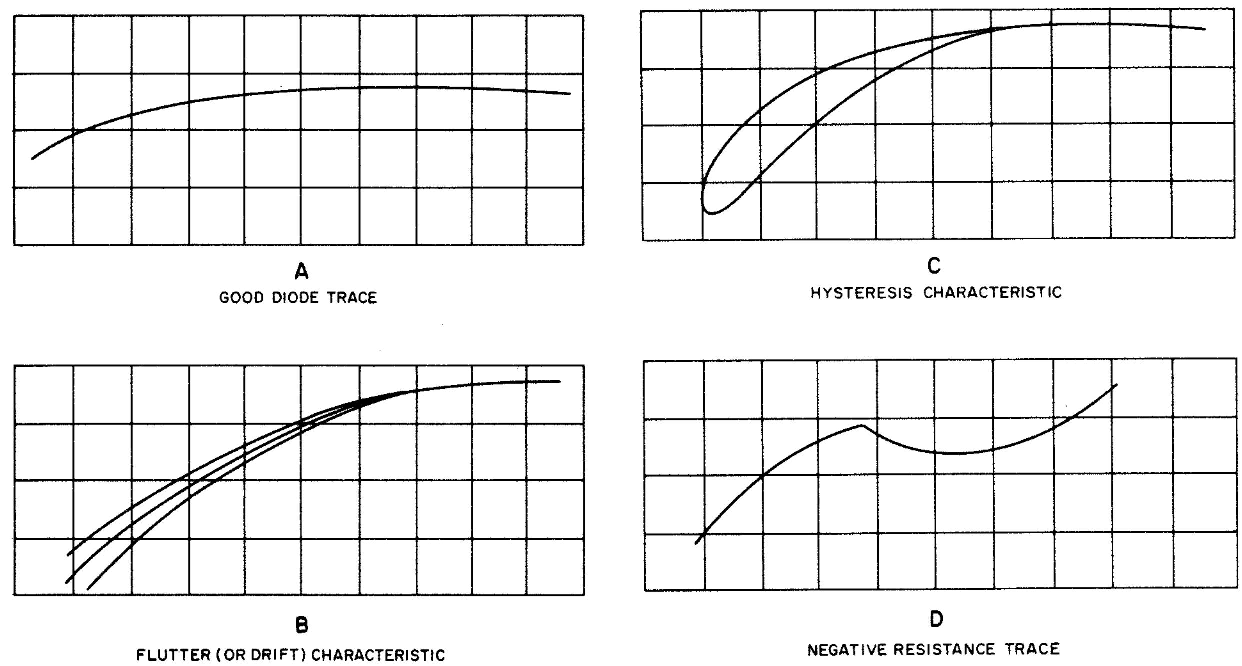


Figure 2-95. Diode Reverse Current-Voltage Characteristics

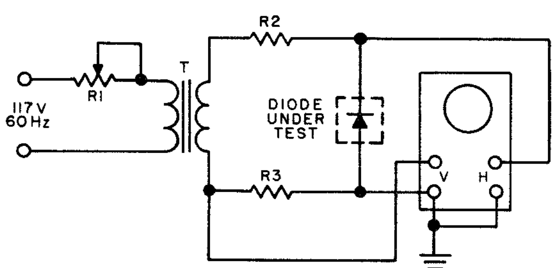


Figure 2-96. Semiconductor Diode Test Circuit

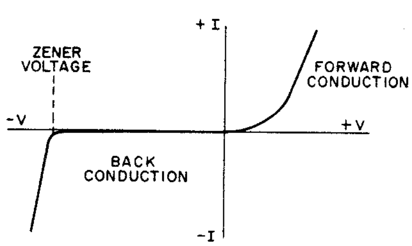


Figure 2-97. Zener Diode Characteristic Pattern

diode; note the sharp increase in current at the Zener voltage (avalanche) point. For the Zener diode to be acceptable, this voltage must be within the limits specified by the manufacturer.

2-13.7 STATIC RESISTANCE MEASUREMENTS

A convenient test for a crystal diode requires only an ohmmeter. The forward-and-back resistance can be measured at a voltage determined by the battery potential of the ohmmeter and the resistance range at which the meter is set. When the test leads of the ohmmeter are connected to the crystal diode, a resistance will be measured that is different from the resistance indicated if the leads are reversed. The smaller value is called the "forward" resistance, and the larger value is called the "back" resistance. If the ratio of back-to-forward resistance is greater than 10:1, the crystal should be capable of functioning as a rectifier. This is a very limited test, and does not take into account the action of the diode at voltages of different magnitudes and frequencies.

2-13.8 SILICON-CONTROLLED RECTIFIER

Many naval electronic equipments use silicon-controlled rectifiers (SCR's) for the control of power. Like other solid-state components, SCR's are subject to failure in service. Most SCR's can be tested with a standard ohmmeter, but the technician must understand just how the SCR functions. As shown in Figure 2-98, the SCR is a 3-element, solid-state device

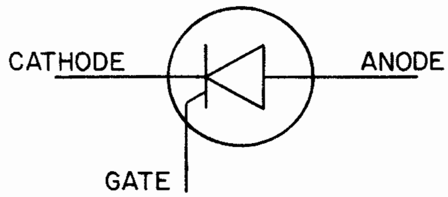


Figure 2-98. SCR Active Elements

whose forward resistance can be controlled. The three active elements shown in the figure are the anode, cathode, and gate. Although they may differ in outward appearance, all SCR's operate in the same way. The SCR acts like a very high resistance rectifier in both forward and reverse directions without requiring a gate signal. However, when the correct gate signal is applied, the SCR conducts only in the forward direction, the same as any conventional rectifier.

2-13.8.1 SCR Test

To test an SCR, connect an ohmmeter between the anode and cathode as shown in Figure 2-99. Start the test at Rx 10,000 and reduce the value gradually. The SCR under test should show a very high resistance, regardless of the ohmmeter polarity. The anode, which is connected to the positive lead to the ohmmeter, is now to be shorted to the gate. This will cause the SCR to conduct, giving a low resistance reading on the ohmmeter. Removing the anode-to-gate short will not stop the SCR from conducting. Removal of either of the ohmmeter leads will cause the SCR to stop conducting, and the resistance reading will then return to its previous high value. Some SCRs will not operate when connected to an ohmmeter. This is because the ohmmeter does not supply enough current. However, most of the SCRs in Navy equipment can be tested by the ohmmeter method. If an SCR is known to be sensitive, the Rx1 scale may supply too much current to the device and damage it. It is advisable to try testing it on the higher resistance scales.

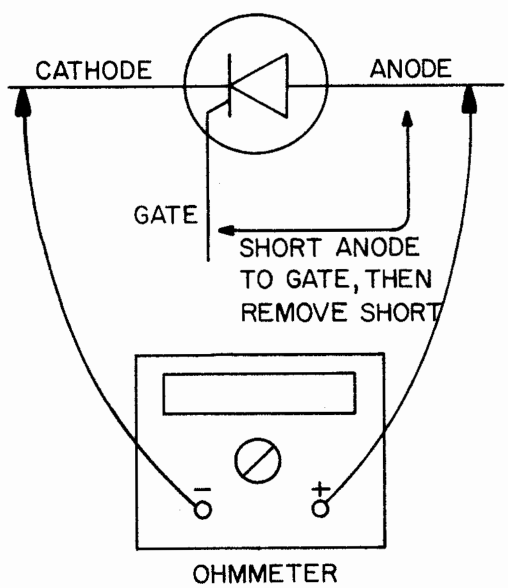


Figure 2-99. Testing an SCR with an Ohmmeter

2-13.8.2 Triac

"Triac" is General Electric's trade name for a silicon gate-controlled, full-wave, ac switch as shown in Figure 2-100. The device is designed to switch from a blocking state to a conducting state for either polarity of applied voltages and with either positive or negative gate triggering. Like a conventional SCR, the Triac is an excellent solid-state device for controlling the flow of power. The Triac can be made to conduct by using the same method as for an SCR, but has the advantage of being able to conduct equally well in either the forward or reverse direction.

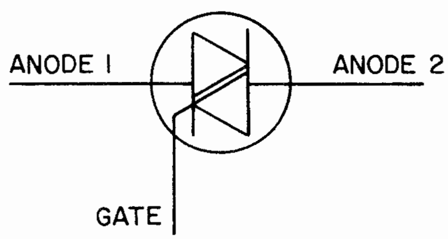


Figure 2-100. Gate-Controlled Full-Wave AC Silicon Switch

2-13.8.3 Triac Test

To test the Triac with an ohmmeter (Rx1 scale), connect the ohmmeter's negative lead to Anode 1 and the positive lead to Anode 2, as shown in Figure 2-101. The ohmmeter should indicate a very high resistance. Short the Gate to Anode 2, then remove it. The resistance reading should drop to a low value and remain low until either of the ohmmeter leads is disconnected from the Triac. This completes the first test. The second

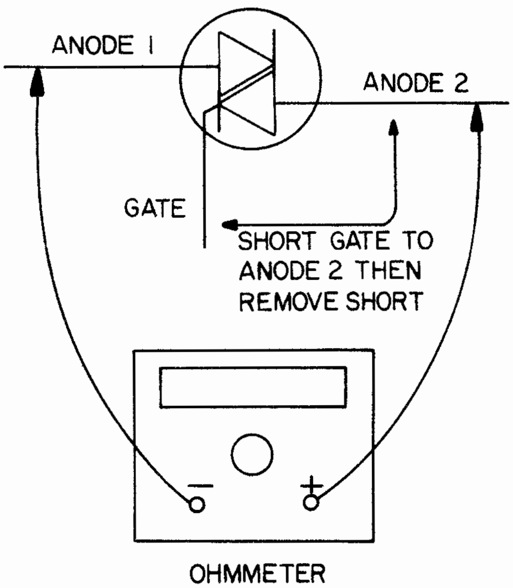


Figure 2-101. First Test

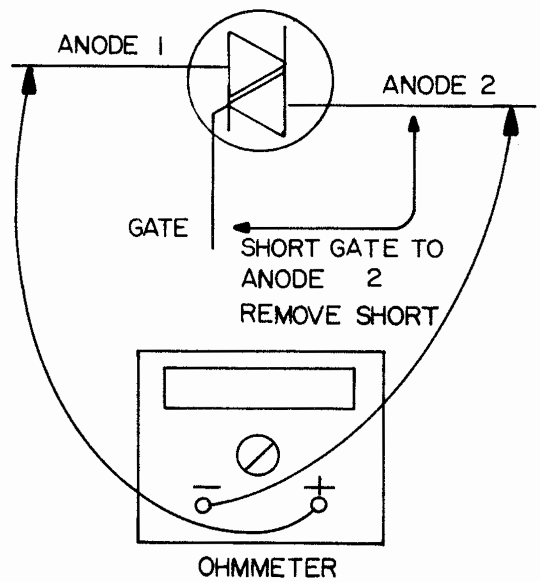


Figure 2-102. Second Test

test involves reversing the ohmmeter leads between Anodes 1 and 2 so that the positive lead is connected to Anode 1 and the negative lead is connected to Anode 2, as shown in Figure 2-102. Again short the Gate to Anode 2, then remove it. The resistance reading should again drop to a low value and remain low until either of the ohmmeter leads is disconnected.

2-13.9 UNIJUNCTION TRANSISTORS

The unijunction transistor (UJT), (Figure 2-103) is a solid-state, 3-terminal semiconductor that exhibits stable open-circuit, negative-resistance characteristics. These characteristics enable the UJT to serve as an excellent oscillator.

2-13.9.1 UJT Testing

Testing a UJT is a relatively easy task if the technician views the UJT as being a diode connected to the junction of two resistors, as shown in Figure 2-104. With an ohmmeter, measure the resistance between Base 1 and Base 2; then reverse the ohmmeter leads and take another reading. Both readings should show the same high resistance, regardless of meter lead polarity. Connect the ohmmeter's negative lead to the UJT's Emitter. Using the positive lead, measure the resistance from the Emitter to Base 1, and then from the Emitter to Base 2. Both readings should indicate high resistances, approximately equal to each other. Disconnect the negative lead from the Emitter and connect the positive lead to it. Using the negative lead, measure the resistance from the Emitter to Base 1, then from Emitter to Base 2. Both readings should indicate low resistances, approximately equal to each other.

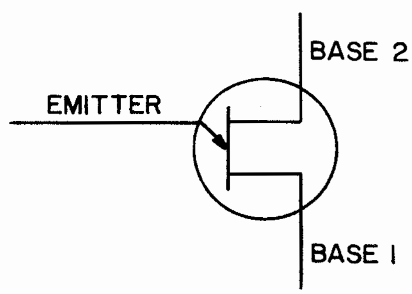


Figure 2-103. Unijunction Transistor

2-13.10 FIELD EFFECT TRANSISTOR

The Junction Field Effect Transistor (JFET) has circuit applications similar to those of a vacuum tube. The device has a voltage-responsive characteristic with a high input impedance. Two types of JFETs that the technician should become familiar with

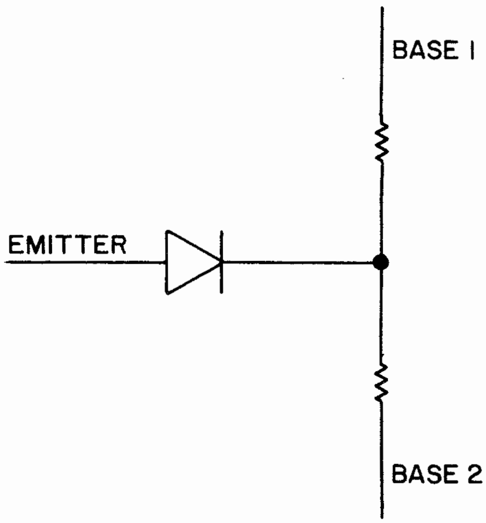


Figure 2-104. Unijunction Transistor Equivalent Circuit

are the junction P channel and the junction N channel types, as shown in Figure 2-105. Their equivalent circuits are shown in Figures 2-106 and 2-107. The only difference in testing these types involves the polarity of the meter leads.

2-13.10.1 N Channel Test

Using an ohmmeter set the Rx1 scale, measure the resistance between the Drain and the Source; then reverse the ohmmeter leads and take another reading. Both readings should be equal (in the 100 to 10,000 ohm range), regardless of the meter lead polarity. Connect the positive meter lead to the Gate. Using the negative lead, measure the resistance between the Gate and the Drain; then measure the resistance

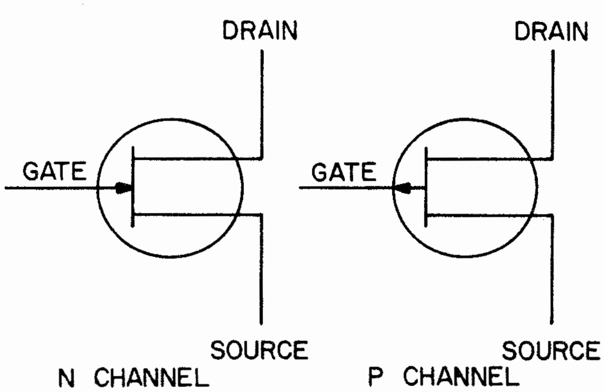


Figure 2-105. Junction FETs

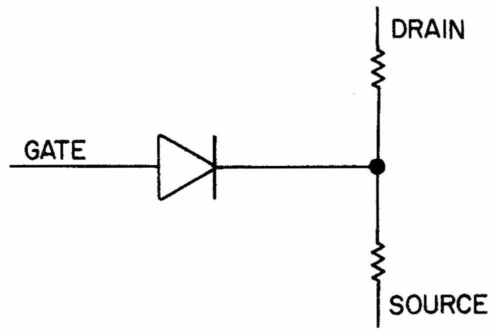


Figure 2-106. N Channel JFET Equivalent Circuit

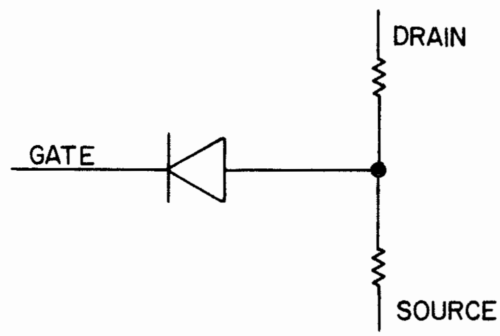


Figure 2-107. P Channel JFET Equivalent Circuit

between the Gate and the Source. Both readings should indicate a low resistance and be approximately the same. Disconnect the positive lead from the Gate and connect the negative lead to the Gate. Using the positive lead, measure the resistance between the Gate to the Drain; then measure the resistance between the Gate and the Source. Both readings should show infinity.

2-13.10.2 P Channel Test

Using an ohmmeter set to the Rx1 scale, measure the resistance between the Drain and the Source; then reverse the ohmmeter leads and take another reading. Both readings should be the same, (100 to 10,000 ohms), regardless of meter lead polarity. Next connect the positive meter lead to the Gate. Using the negative lead, measure the resistance between the Gate and the Drain; then measure it between the Gate and the Source. Both readings should show infinity. Disconnect the positive lead from the Gate and connect the negative lead to the Gate. Using the positive lead, measure the resistance between the Gate and the Drain; then measure it between the Gate and the Source. Both readings should indicate a low resistance and be approximately equal.

2-13.11 MOSFET

Another type of semiconductor the technician should become familiar with is the Metal Oxide Semiconductor Field Effect Transistor (MOSFET) as shown in Figures 2-108 and 2-110. The technician must

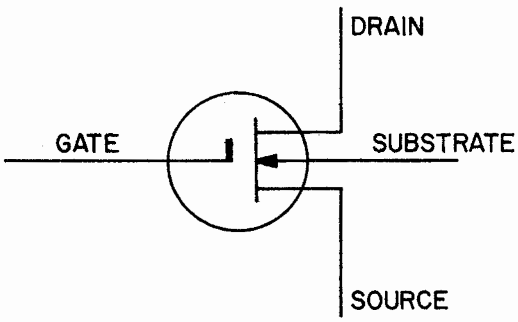


Figure 2-108. MOSFET (Depletion/Enhancement Type)

be extremely careful when working with MOSFETs due to their high degree of sensitivity to static voltages. When working with MOSFETs the soldering iron should be grounded. A metal plate should be placed on the workbench and grounded to the ship's hull through a 400k ohm to 600k ohm resistor. The technician should also wear a bracelet with an attached ground strap and ground himself to the ship's hull through a 400k ohm to 600k ohm resistor. The technician should not allow a MOSFET to come into contact with his clothing, plastics or cellophane-type materials. A vacuum plunger "solder sucker" must not be used because of the high electrostatic charges it can generate. Solder removal by "wicking" is recommended. It is also good practice to wrap MOSFETs in metal foil when they are out of a circuit. To ensure MOSFET safety under test, the technician must use a portable VOM to make MOSFET resistance measurements. A VTVM must never be used in testing MOSFETs. The technician must be aware that while he is testing a MOSFET he is grounded to the ship's hull. Use of a VTVM would thus impose a definite safety hazard because of its 115V 60 Hz power input. When the resistance measurements are complete and the MOSFET is properly stored, unground both the plate on the work bench and yourself. The technician will understand MOSFET testing better if he visualizes it as equivalent to a circuit using diodes and resistors, as shown in Figures 2-109 and 2-111.

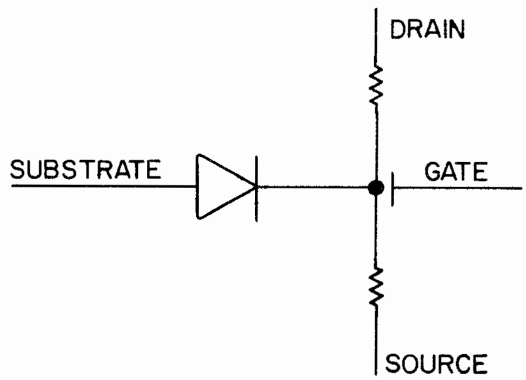


Figure 2-109. MOSFET (Depletion/Enhancement Type) Equivalent Circuit

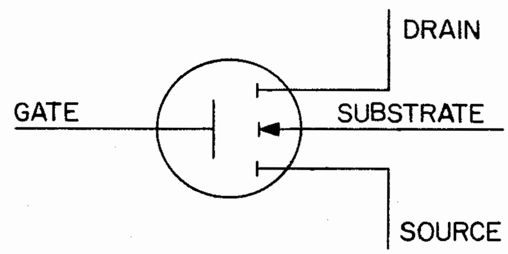


Figure 2-110. MOSFET (Enhancement Type)

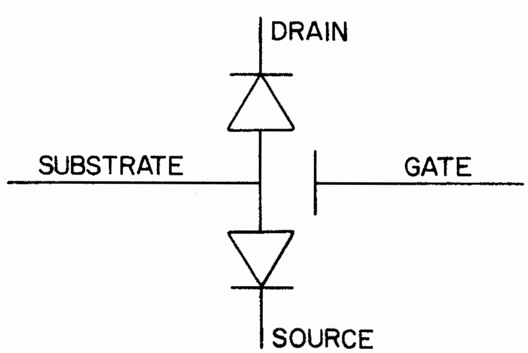


Figure 2-111. MOSFET (Enhancement Type) Equivalent Circuit

2-13.11.1 MOSFET (Depletion/Enhancement Type) Test

Using an ohmmeter set to the Rx1 scale, measure the resistance between the MOSFET Drain and the Source; then reverse the ohmmeter leads and take another reading. The readings should be equal, regardless of meter lead polarity. Connect the ohmmeter's positive lead to the Gate. Using the negative lead, measure the resistance between the Gate and the Drain, and between the Gate and the Source. Both readings should show infinity. Disconnect the positive lead from the Gate and connect the negative lead to the Gate. Using the positive lead, measure the resistance between the Gate and the Drain; then measure it between the Gate and the Source. Both readings should show infinity. Disconnect the negative lead from the Gate and connect it to the Substrate. Using the positive lead, measure the resistance between the Substrate and the Drain, and between the Substrate and the Source. Both of these readings should indicate infinity. Disconnect the negative lead from the Substrate and connect the positive lead to the Substrate. Using the negative lead, measure the resistance between the Substrate and the Drain, and between the Substrate and the Source. Both readings should indicate a low resistance (about 1000 ohms).

2-13.11.2 MOSFET (Enhancement Type) Test

Using an ohmmeter set to the Rx1 scale, measure the resistance between the Drain and the Source; then reverse the leads and take another reading between the Drain and the Source. Both readings should show infinity, regardless of meter lead polarity. Connect the ohmmeter's positive lead to the Gate. Using the negative lead, measure the resistance between the Gate and the Drain, and then between the Gate and the Source. Both readings should indicate infinity. Disconnect the positive lead from the Gate and connect the negative lead to the Gate. Using the positive lead, measure the resistance between the Gate and the Drain, then between the Gate and the Source. Both readings should indicate infinity. Disconnect the negative lead from the Gate and connect it to the Substrate. Using the positive lead, measure the resistance between the Substrate and the Drain, and between the Substrate and the Source. Both readings should indicate infinity. Disconnect the negative lead from the Substrate and connect the positive lead to the Substrate. Using the negative lead, measure the resistance between the Substrate and the Drain, and between the Substrate and the Source. Both readings should indicate a low resistance (about 1000 ohms).

2-14 INTEGRATED CIRCUITS

Integrated circuits constitute an area of microelectronics where many conventional electronic components are combined into high-density modules. Integrated circuits are comprised of active and passive components such as transistors, diodes, resistors, capacitors, etc. Because of their reduced size, use of integrated circuits can simplify otherwise complex systems by reducing the number of separate components and interconnections. Their use can also reduce power consumption, reduce the overall size of the equipment, and significantly lower the overall cost of the equipment concerned.

2-14.1 STATIC ELECTRICITY HAZARDS TO INTEGRATED CIRCUITS

Normal physical movements of personnel, mechanical interfacing, or the flow of liquids or gases can cause static-charge accumulation. The accumulation of these charges on ungrounded items can cause damage if allowed to discharge through an electronic component.

2-14.2 STATIC SENSITIVE DEVICES

Static electricity can cause severe damage to many field-effect type transistors and to many types of integrated circuits. The following paragraphs will acquaint the technician with devices he must be concerned about, and the proper handling and installation procedures for such components.

2-14.2.1 Very Sensitive Devices

These include Microwave semiconductor (MOS or CMOS) devices without input diode protection circuitry on all input circuits; dielectrically-isolated semiconductors with internal capacitor contacts connected to external pins; and microcircuits utilizing N+ guard-ring construction (with metalization crossing over the guard ring).

2-14.2.2 Sensitive Devices

These include all low-power Schottky-barrier and Schottky-TTL devices; all ECL devices; high input-impedance linear microcircuits; all small signal transistors which operate at 500 MHz or higher; all discrete semiconductors which use silicon dioxide to insulate metal paths over other active areas; MOS or CMOS devices with input diode protection on all input terminals; junction field-effect transistors; and precision "ladder" networks.

2-14.2.3 Moderately Sensitive Devices

These include all microcircuits and small signal discrete semiconductors with less than 10 watts dissipation at 25 degrees celcius; and thick-film resistors.

The technician must remember that any assembly containing two or more pins that are electrically exposed to static-sensitive devices must be treated as being itself static-sensitive.

2-14.3 ELECTRICAL EQUIPMENT, TOOLS, SOLDERING IRONS

Soldering irons must be isolated, either by transformer or by direct current, from the power line and grounded. If a "solder sucker" is used, it must be grounded. Use of a grounded roll of wicking wire is preferred over the solder sucker method.

2-14.3.1 Test Equipment

If "active" test equipment is used (115 60 Hz input), it must be grounded. The portable, battery-powered VOM is the preferred equipment.

2-14.4 PERSONAL APPAREL

Smocks, gloves, or finger "cots" made of nylon, plastic or rubber must not be worn when handling static-sensitive devices. The technician must avoid contacting such devices with his clothing.

2-14.5 WRIST-BRACELETS

Personnel handling static-sensitive components and assemblies must wear a skin-contact wrist-bracelet grounded to the ship's hull through a 400,000 ohms minimum to 600,000 ohms maximum resistance.

2-14.6 STATIC-SENSITIVE COMPONENTS

Where size permits, static-sensitive components and associated assemblies shall always be handled by their body/case, and never by their leads. Contact with garments or plastics that are not recommended for use around static-sensitive components must be avoided. In lieu of individual wrapping, static-sensitive components and assemblies must have their exposed leads or pins shorted together. If the component or assembly is small enough, wrapping it in tin-foil provides good temporary protection prior to storing.

2-14.7 INTEGRATED CIRCUIT (IC) TESTING DEVICES

Digital ICs are relatively easy to troubleshoot and test due to the limited numbers of input/output combinations involved. Another advantage is the two-state possibility of the inputs or outputs, with no others to impose problems. Any particular IC can be tested by simply comparing it to a known good one. The following paragraph describes a device that can be of great value in troubleshooting digital integrated circuits.

2-14.7.1 Logic Probes

The ideal logic probe will have the following characteristics:

1. Detect a steady logic level.
2. Detect a train of logic levels.
3. Detect an open circuit.
4. Detect a high-speed transient pulse.
5. Have overvoltage protection.
6. Be small, light, and easy to handle.

Use of a suitable logic probe can greatly simplify the troubleshooting of logic levels through integrated circuitry. It can show you immediately whether a specific point in the circuit is low, high, open, or pulsing. Some probes have a feature that detects and displays high-speed transient pulses as small as 10 nanoseconds wide. These probes are usually connected directly to the power supply of the device being tested, although a few also have internal batteries. Since most IC failures show up as a point in the circuit stuck either at a high or low level, these probes provide a quick, inexpensive way of locating the fault. They can also display that single short-duration pulse that is hard to catch on an oscilloscope. Figures 2-112 and 2-113 show typical probes.

2-14.7.2 Logic Pulse Generator

Another aid in logic troubleshooting is the logic pulse generator. Very similar in shape to the logic probe, it injects a logic pulse into the circuit under test, instead of displaying various logic states. When used in conjunction with a logic probe, a dynamic test can be given to the IC and the results displayed on the logic probe. Some models of the logic pulse generator have a feature that allows single-pulse injection or a train of pulses. Currently, the use of logic probes and logic pulse generators predominantly involves the TTL/DTL Logic types. High-level (HTL, HINIL, MOS, discrete circuits, and relay logic) probes are available that would be compatible with NTDS-type systems. To understand the various display lights used with the logic probe, the technician must refer to the manufacturer notes. There are many different logic probes currently in use, and each manufacturer features his own display setup.

2-14.8 TESTING ICs

Testing ICs employs an approach somewhat different from that used in testing vacuum tubes and transistors. The physical construction of ICs is the prime reason for this different approach. The most-frequently used ICs are manufactured with either fourteen or sixteen pins, all of which are soldered directly into the circuit. It can be quite a job to unsolder all of these pins, even with the special tools designed for this purpose. After unsoldering all of the

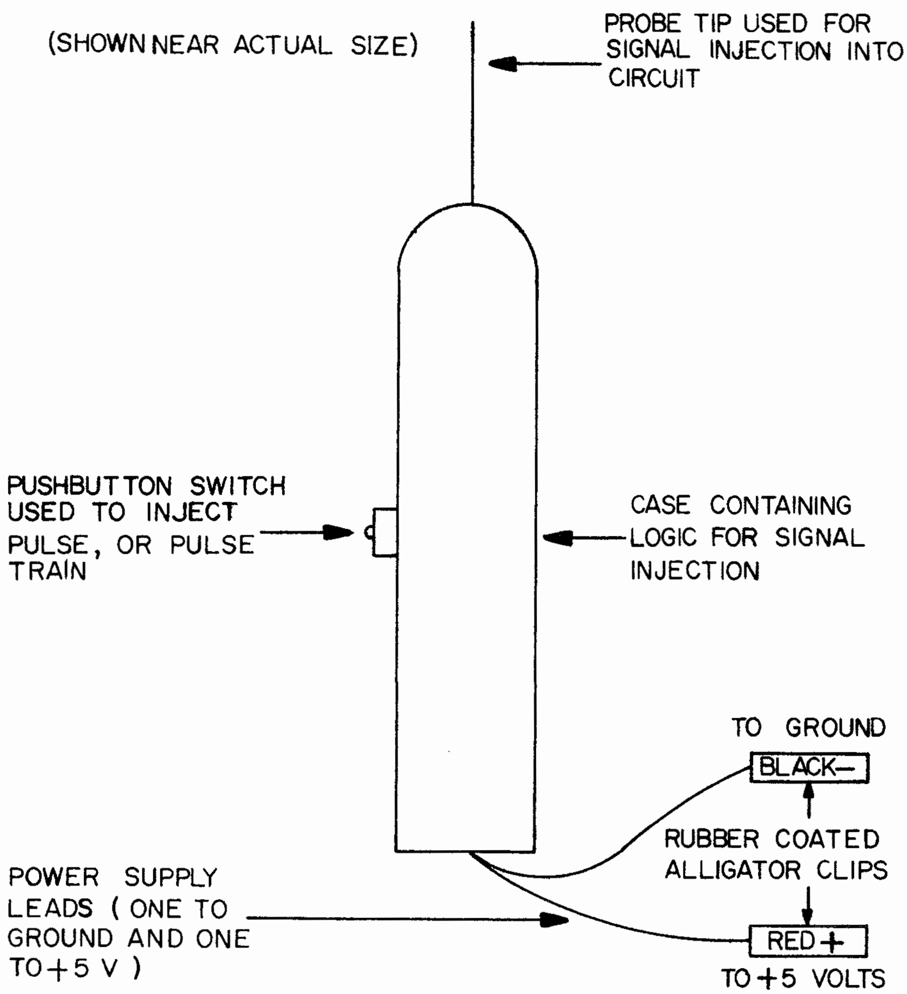


Figure 2-112. Logic Pulse Generator

pins you then have the tedious job of cleaning and straightening them. Although there are a few IC testers on the market, their applications are highly limited. Just as with transistor removal from the circuit for checking on a tester, the IC must be removed to permit testing. When ICs are used in conjunction with external components, these components should first be checked for proper operation. This is particularly important in linear applications, where a change in the feedback of a circuit can adversely affect the component's entire operating characteristics. Any linear (analog) IC is sensitive to its supply voltage (V_{cc}). This is especially the case among those that use bias and control voltages, in addition to a supply voltage. If a linear IC is suspected of being defective, it is very important that all voltages coming to the IC be checked against the circuit diagram of the equipment manufacturer for any special notes on voltages. The manufacturer's handbook will also give recommended voltages for any particular IC. When troubleshooting ICs (either digital or linear) a technician cannot be concerned with what is going on inside the IC. He cannot take measurements or conduct repairs inside the IC. He can therefore consider the IC as a "black box" that performs a certain function. The IC can be checked, however, to see that it can perform its design functions. After checking static voltages and external components associated with the IC, we can check it for dynamic operation. If the IC is intended to function as an amplifier, then its input and output can be measured and evaluated. If it is to function as a logic gate or combination of gates, it is relatively easy to determine what inputs are required to achieve a desired high or low output. Examples of different types of ICs are provided in Figures 2-114, 2-115 and 2-116.

2-15 STANDING WAVE MEASUREMENTS

Standing waves present on transmission lines and waveguides are indicative of an imperfect

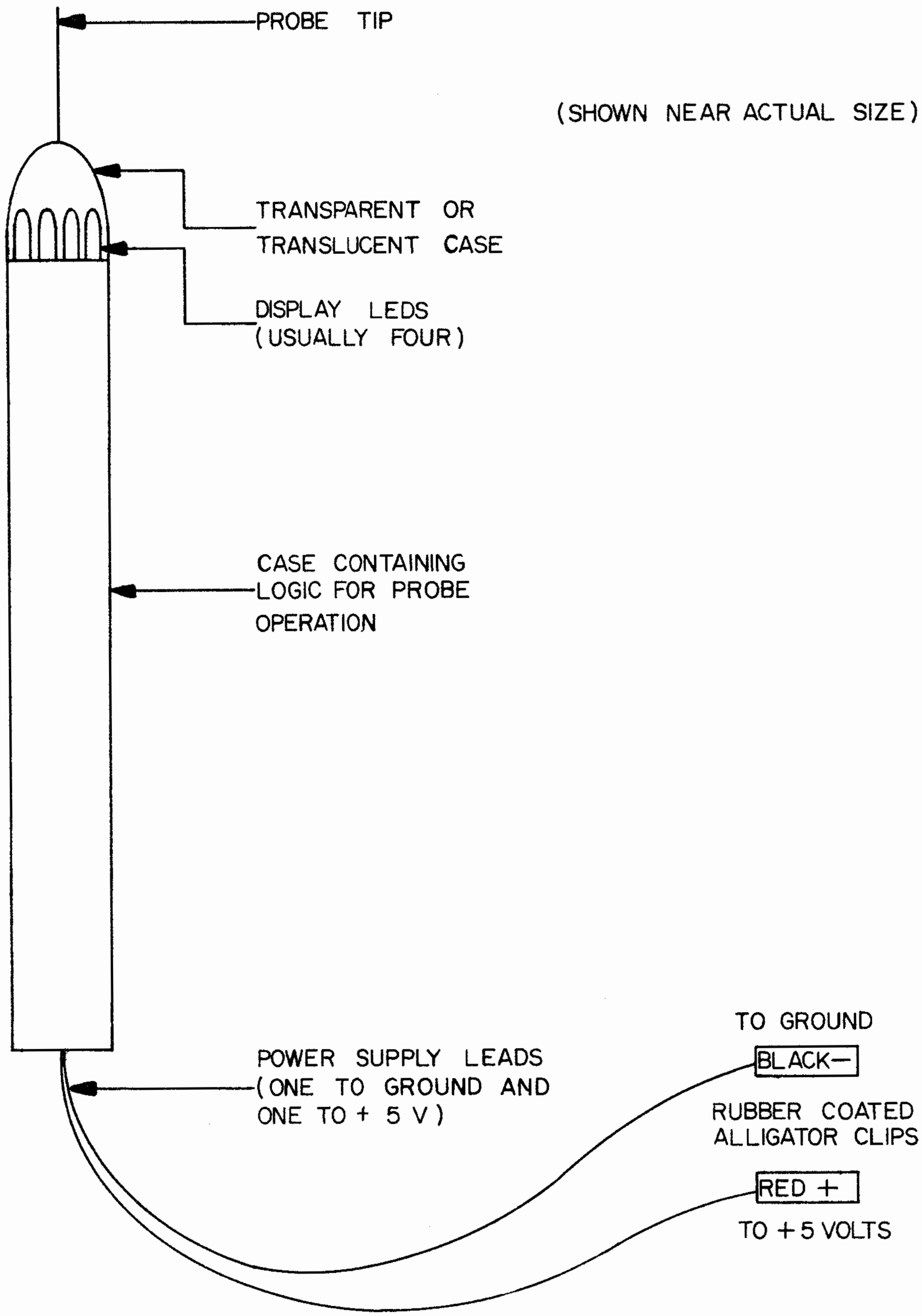


Figure 2-113. Typical Logic Probe

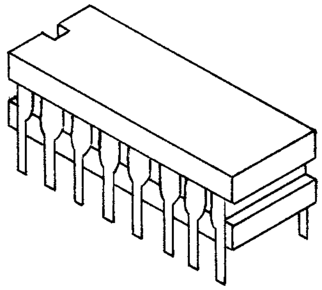


Figure 2-114. DIP-Type IC

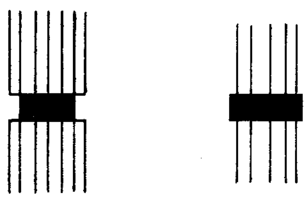


Figure 2-115. Flat Pack IC

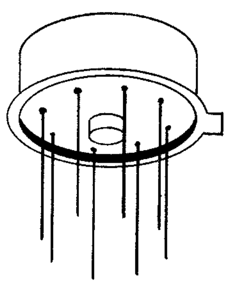


Figure 2-116. IC Can

impedance match between a transmitter or receiver and its antenna. When this condition occurs, the transfer of energy between these units and their respective antennas becomes inefficient. Reflection of energy at the load end of a transmission line gives rise to a wave that travels toward the generator end. This reflected wave varies continuously in phase in much the same way that the incident wave varies in phase. At certain points, a half-wave-length apart, the two waves are exactly in phase and the resultant voltage is at maximum. At points a quarter-wave-length from the maximums, the two waves are in continuous opposition and voltage nodes are produced. The ratio of maximum to minimum voltage at such points is called the "standing wave ratio" (swr). The ratio of maximum-to-minimum current along a transmission line will have the same value as the voltage swr. A high swr indicates that the characteristic impedance of a transmission line differs greatly from the terminating impedance, and a low swr indicates that there is a good impedance match between a transmission line characteristic and the terminating impedance. If it is desired to terminate a transmission line in its characteristic impedance, a swr of 1.0 is optimum. Transmission line swr measurements are often made during installation, tuning, and maintenance of communication equipment. Radio antenna transmission lines can be constructed to have the correct length and wire spacing to provide impedance matching for transmitter and receiver equipment. For maximum transfer of energy, the transmission line characteristic impedance should match the terminating impedance. However, unmatched (resonant) transmission lines are useful as impedance-matching devices. Procedures for checking the current or voltage variations which are the components of the standing waves are dependent fundamentally upon the frequency of the system. In many a situation it is not necessary to determine the actual swr. For example, loading devices such as an antenna are often adjusted for the condition of minimum swr. Absorption wave-meters or neon-lamp indicators are capable of providing a rough check of the swr and the location of standing waves for an open-wire transmission line. Slotted coaxial lines or waveguides in conjunction with an indicator are used for standing-wave measurements in the very-high-frequency to super-high-frequency range. Bridge-type test equipment, when properly calibrated for a specific transmission line, can be used to indicate the swr by measuring the line's input-impedance. For radar applications, a low swr is desired for the following reasons: (1) reflections in the transmission line cause magnetron pulling, and can result in faulty pulsing (this effect is most pronounced when the line is long, as compared with a wavelength); (2) arc-over may occur at the maximum voltage points; and (3) hot spots can occur in the transmission line and cause mechanical breakdown. Since transmission lines for radar equipment are normally coaxial cables or waveguides, slotted lines must be inserted for standing-wave measurements. Measurements of standing waves can indicate the approximate operating frequency, the presence of defective transmission-line sections, and the condition of the antenna.

2-15.1 REFLECTION COEFFICIENT (K)

The reflection coefficient is the ratio between electric fields associated with the reflected and the incident waves at any specified plane in a uniform transmission line between a source and absorber of power. The coefficient is obtained by the formula:

$$K = \frac{Z2 - Z1}{Z2 + Z1}$$

where Z1 and Z2 are the impedances of the source and the load, respectively. If the reflection coefficient (K) is known, the swr can be computed by the formula:

$$SWR = \frac{1 + K}{1 - K}$$

Although the swr is usually read by swr meters, the above formulas will provide the technician with an alternate method if a meter is not available or is in need of repair. For a more detailed explanation of standing waves, refer to Section 5 of this manual.

2-16 FIELD INTENSITY AND NOISE (INTERFERENCE) MEASUREMENTS

The magnitude of the electric field of a radio wave at a given point is known as the "field intensity" (or "field strength") of that wave, and is usually measured in terms of millivolts or microvolts per meter. The field strength of a radio wave is determined by measuring the RF voltage induced in a receiving antenna. Noise and interference are either man-made or natural, the natural sources being static and other noises from interstellar space. Thus, we have noise figures established which determine equipment performance, and the signal-to-noise ratio becomes important in all types of reception through air, water, space and earth. Several types of test equipment are available for the measurement of field strength and noise. They are known as "radio test sets," "field strength meters," and "radio noise meters." These instruments can be used to indicate either the relative or the absolute magnitude of the field intensity of the energy or noise radiated by a transmitter antenna or other device. The equipment necessary for a specific test is determined by the frequency of the signal to be measured and the accuracy required. Field strength and noise measurements are required to determine antenna efficiency, directivity characteristics, and signal coverage. This information is valuable in selecting antenna sites and in detecting spurious harmonic radiation. Interference, either radiated or conducted, can be detected and located by the use of radio test sets. Relative field strength can be measured with rather simple test equipment; sometimes a grid-dip meter will suffice. Other test-equipment circuits utilize a pickup antenna and a diode (or crystal) detector in connection with a microammeter. In circuits using this combination, the meter reading indicates the relative strength of the field acting on the pickup antenna, and is not directly proportional to the field intensity because of the nonlinearity of the detector. More elaborate test equipment, for the measurement of absolute field intensity, compares the voltage induced in a pickup antenna with a voltage generated by a self-contained calibrated oscillator. The antenna is connected to a sensitive receiver, which usually incorporates two calibrated attenuators: one between the antenna and mixer stage, and the other in the first intermediate-frequency-amplifier stage. A meter in the test equipment measures the diode current in the second detector. This meter indicates the field intensity, usually in terms of microvolts per meter. Mutual interference between communication, navigation, and fire control gear aboard the same ship or nearby vessels also has an effect on the performance of communications equipment and must also be considered when evaluating and making tests on such equipment. For example, an equipment having a sensitivity of less than one microvolt can be rendered ineffective by being overloaded by noise interference or spurious interfering signals generated in other equipment.

2-16.1 NOISE GENERATING SOURCES

One of the many factors to be considered in planning for high-frequency radio reception is the predicted circuit reliability. Satisfactory communication is possible only when the signal-to-noise ratio at the point of reception is sufficient to produce results capable of meeting the requirements for the type equipment in use on a given communication circuit (voice, telegraph, teletypewriter, etc). For this reason, the conditions existing at the area where reception of signals is contemplated are of the utmost importance as noise and interference become important limiting factors in determining circuit reliability. Interference external to the receiving equipment is of three types: atmospheric, galactic, and man-made electrical noise.

2-16.1.1 Atmospheric Noise

Atmospheric interference (or noise) is caused by lightning discharges in local storms or by static arriving from distant tropical, snow or dust storms. The level of this noise depends on such factors as the carrier frequency, time of day, location of receiver, season of the year, and weather in the reception area. Frequencies below 30 MHz are those most affected by atmospheric noise, as illustrated in the graph of Figure 2-117.

2-16.1.2 Galactic Noise

Galactic noise originates outside the earth's atmosphere. The sun is the principal source of this type of noise. However, celestial radio-sky background radiation concentrated along the galactic plane, and large numbers of discrete, cosmic sources distributed primarily among the galactic plane, are other sources of galactic noise. Galactic noise ranges between 15 MHz and 100 GHz, but its major effect on reception extends to 250 MHz (Figure 2-117).

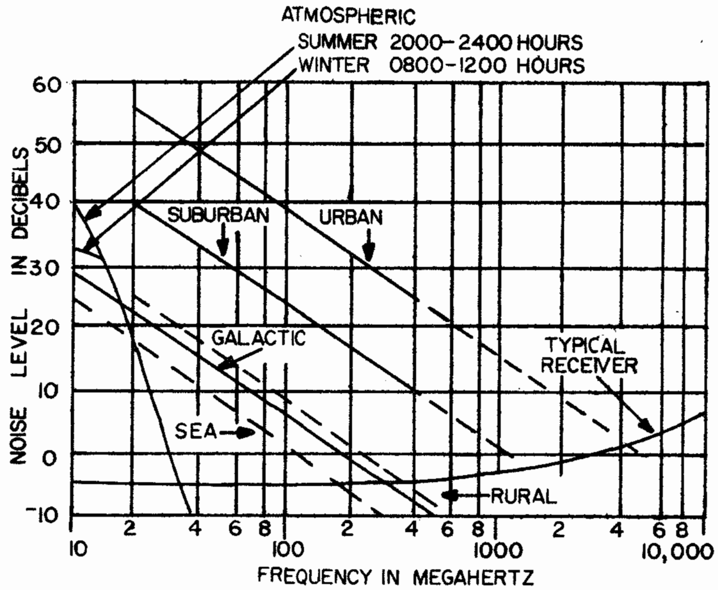


Figure 2-117. Median Values of Average Noise Power Expected From Various Sources (Omni-Directional Antenna Near Surface).

2-16.1.3 Man-Made Noise

Man-made noises, as illustrated in Figure 2-117, produces the most varied and adverse effects upon radio reception, with its severity dependent on how close the noise source is to the receiving equipment. Some major sources of man-made noise include rotating machinery, neon or fluorescent lighting, high-tension power lines, gasoline engine ignition systems, certain high-frequency medical apparatus, and spurious radiation from electrical and electronic equipments. This is termed Electromagnetic Interference (EMI). Interference caused by man-made installations may reach a receiver by any of the following means.

1. Direct radiation. Directly radiated interference is transmitted from the noise sources to the receiving antenna, and does not travel any great distance; it is local to the area.

2. Conduction. Interference may be conducted directly from the source through the power lines to the receiver. Such interference generally occurs in ac-operated receivers in the form of a low-frequency hum or noise, or both.

3. Re-radiation. Re-radiated interference is a common type of interference. Power lines, telephone and telegraph lines, and ungrounded metal structures conduct interference which has been transmitted to them from the noise source by direct radiation, by conduction, or by induction. They then re-radiate the noise directly to the receiving antenna.

2-16.2 ELECTROMAGNETIC INTERFERENCE (EMI)

Of all man-made noises, EMI is the most difficult to combat because it can come from any electrical or electronic equipment. Communications equipment designers have therefore adopted the electromagnetic compatibility concept. This represents the condition which prevails when telecommunication (communication-electronic) equipment is collectively performing its individual design functions in a common electromagnetic environment without causing or suffering unacceptable degradation due to electromagnetic interference to or from other equipment/systems operating in the same environment. When communication equipment design features incorporate this concept and the standards and procedures stated in MIL-STD- 461 and MIL-STD-462 are observed, the EMI is held within acceptable levels.

2-16.2.1 EMI Measurements

The measurement of EMI involves a determination as to how much undesirable electromagnetic energy is being radiated from electrical or electronic equipment, or by its associated antennas or intercabling. Electromagnetic susceptibility, (the degree to which an equipment, system or subsystem reacts to undesirable electromagnetic radiation) is an important factor in the design of communication equipment. Exacting procedures and requirements for EMI measurement are described in MIL-STD-462 and in MIL-STD-461, respectively. These include:

1. Radiated emission test (magnetic and/

or electrical field)

2. Conducted emission test

3. Radiated susceptibility test (magnetic and/or electrical field)

4. Conducted susceptibility test

All equipment capable of generating EMI is required to meet the standards set forth in MIL-STD-461 and in MIL-STD-462 before acceptance for military application. MIL-STD-461 presents the electromagnetic interference characteristics that must be taken into account in designing communication equipment for use by the military, and MIL-STD-462 is the military standard for the measurement of such electromagnetic interference characteristics.

2-16.3 FIELD STRENGTH MEASUREMENTS

Field strength is the effective value of an electric field intensity in microvolts or millivolts per meter, produced at the given point by radio waves from a particular station. The antenna radiation pattern (often called the directional characteristic) is the aggregate data collected from all points. The field strength produced by an antenna is proportional to the current flowing in it. Those parts of the antenna that carry the most current, as a result of standing waves, have the chief radiating effect. (All resonant antennas have standing waves; only terminated types, like the terminated rhombics, have relatively uniform current distribution.) The power gain of an antenna is a measure of the directivity of the field pattern of the antenna under measurement, as compared with the field pattern of a "comparison" antenna (isotropic radiator) that radiates uniformly in all directions. It is the ratio of the power necessary to produce a given field strength at a given point by the "comparison" antenna to the power that must be radiated by the antenna under measurement to obtain the same field strength at the same point. Field strength is measured in volts per meter. Since most field intensities are very small, it is convenient to employ the terms "millivolts per meter" or "microvolts per meter." Thus, a 1-millivolt potential difference would exist between two points 1 meter apart in a 1-millivolt-per-meter field, assuming that the points lie in the direction of the greatest rate of potential change. Therefore, an antenna with an effective height of 5 meters which is subjected to a field intensity of 20 millivolts per meter would develop a 100-millivolt signal.

2-16.3.1 Antenna Gain

The efficiency of a transmitting antenna is usually stated in such terms as "power gain" and "field gain." These terms are based on the field intensity produced by a half-wave antenna in free space at a distance of one mile, under conditions for which there are no reflected waves. Power gain is then defined as the ratio of the power required by a half-wave antenna to produce a particular field strength at a distance of one mile to the power required by the antenna under test to produce the same power; or, in equation form:

$$\text{Power gain} = \frac{\text{Power required with vertical half-wave antenna}}{\text{Power required with antenna under test}}$$

This ratio is usually given in dB (decibels). The antenna field gain of a high-frequency broadcast antenna is the ratio of the effective (free space) field intensity produced at one mile in the horizontal plane (vertical antenna radiating waves vertically polarized), expressed in millivolts per meter for 1 kilowatt antenna input power, to 137.6 mv/m (the field strength from a standard antenna under similar conditions). It is assumed in this definition that no waves are reflected from the earth or surrounding objects. Hence, the field gain of a multi-element antenna expressed as a ratio is:

$$\text{Field gain} = \frac{\text{Field intensity of antenna at 1 mile for 1-kW input}}{\text{137.6 millivolts per meter}}$$

Since power is proportional to voltage squared, the relationship between field gain and power gain is expressed in the following equation:

$$\text{Field gain} = \text{gain}\sqrt{\text{Power gain}}$$

Consequently, a power increase of four times is required in order to double the signal intensity. If it is possible to increase the field intensity by using a multi-element antenna rather than by increasing the power, then less-expensive equipment can be employed and operating costs will be lower.

2-16.3.2 Field Strength

The field strength of a radio wave is determined by measuring the voltage the wave induces in a test antenna. The relationship between this induced voltage and the field strength can be obtained by calculation in the case of a loop of similar antenna, and by measuring the effective height of the antenna in other cases. (The effective height can be described as the calculated true electric height, corresponding to a perfect antenna that will produce the same field strength and is the ratio of the equivalent lumped-induced-voltage that can be thought of as acting in the antenna, divided by the field strength inducing this voltage.) There are two general methods for the determination of the field strength of a radio wave: the standard antenna method, and the standard field generator method. The standard antenna method uses an antenna in which is known (by calculation or experiment) the amount of voltage that will be induced in the antenna by radio waves of known field strengths. The field strength is then determined by measurement of induced voltage. The standard field generator method uses a standard signal generator to produce a radio wave of a known field intensity, which is then compared with the radio wave being measured. The field strength is then determined by the relationship between the two. The loop antenna is the most commonly used antenna for the measurement of field strength of radio waves below 40 MHz. This is because its properties are predictable by calculation; it is directional; it is independent of ground constants; it can be designed for use with low-frequency measurements; and it is portable. A loop antenna is essentially a large coil of any convenient section. It extracts energy from the wave front as a result of phase differences between the voltages induced in the opposite legs. For example, when the plane of the loop is perpendicular at the direction of travel (i.e., the wave front passes through the two legs at the same time), the voltages induced in the two vertical legs are equal and in the same phase. However, being directed around the loop in opposite directions, they cancel each other and result in zero response. As the plane of the loop is brought nearly parallel with the direction of wave travel, the wave front reaches the two vertical legs at slightly different times. This causes a phase difference between the voltages induced in those two legs, resulting in a voltage that circulates current around the loop. This voltage is a maximum when the plane of the loop is parallel to the direction of wave travel. The induced voltage can be calculated for all shapes of loops by the formula below if the loop is small as compared with the wavelength, and if the frequency of the radio wave is no greater than one-third the self-resonant frequency of the loop.

$$\text{Induced voltage (E)} = 2E_oN\,\frac{\text{(loop area)}}{\text{wavelength}}$$

where E_o is the field strength of the radio wave in volts per unit length, and N is the number of turns of the loop. The effective height of the antenna is the ratio of the induced voltage (E) to the field strength (E_o). The loop size that would be required for measurements about 40 MHz is too small for practical use; therefore, loops are rarely used for measurements above this frequency. A half-wave dipole is a more useful antenna for these measurements. Other suitable alternates to the loop antenna are the doublet (which is preferable to the dipole at frequencies where the dipole would be too large), and the short, grounded, vertical antenna (which is best used for the evaluation of weaker fields). However, the vertical antenna has the disadvantage that its effective height must be determined by experiment for each particular installation. The induced voltage for a half-wave dipole can be closely approximated from the formula:

$$E = \frac{\text{wavelength} \times E_o}{\pi}$$

For the doublet, the induced voltage can be determined by the formula:

$$E = \frac{E_oL}{2}$$

provided that the radio wave is no greater than one-third the resonant frequency of the doublet. Its effective height is $\frac{L}{2}$ where L is the length of the doublet. The voltage induced into a short, grounded vertical antenna can be found by the formula used for the doublet ($E = \frac{E_oL}{2}$) if the antenna is considerably shorter than one-quarter wavelength and if L is the length of the grounded antenna. The effective height, as previously noted, is best determined by experimentation. If the vertical antenna is exactly one-quarter wavelength long, the induced voltage may be computed by the formula:

$$E = \frac{\text{wavelength} \times E_o}{2}$$

where E_o is the field strength in volts per unit length. The standard antenna for microwave applications usually consists of a high-gain antenna, such as a horn or parabola, having a known power gain. When the antenna is matched to a load impedance so that the load absorbs the maximum possible power from the antenna, the field strength can be calculated from the equation:

$$E_o = \sqrt{\frac{480\pi P_r}{\lambda^2 G}}$$

where E_o is the field strength
P_r is the load power
λ is the wavelength
G is the power gain of the antenna relative to an isotropic radiator

2-16.3.2.1 Standard Antenna Method

The usual method of measuring the field strength with a standard antenna makes use of a field strength meter incorporating a superheterodyne receiver. The receiver has an adjustable attenuator in the intermediate frequency amplifier for adjusting the gain to the receiver in accurately known increments. This method of measuring field strength is essentially a comparison method in which the signal induced in the antenna is compared with a signal of the same frequency induced into the antenna by an auxiliary signal generator. (The auxiliary, or calibrating, voltage source is often built into the receiver.) The ratio of the two voltages is obtained by the attenuator settings required to maintain a constant output for both signals. The accuracy of this method of measurement is relatively high, since the receiver characteristics (assuming that the mixer is linear) do not affect the measurement. When portability of the measuring instrument is a consideration, the loop antenna is commonly used to develop the input RF signal. The output of the auxiliary oscillator can be coupled to the loop by means of a transformer (Figure 2-118) or applied directly across a resistor in series with the loop. For the sake of simplicity, the voltage transfer of the transformer is assumed to be a 1:1 ratio. The local oscillator must be arranged and coupled to the input circuit such that its output does not vary as a result of tuning. Either the input circuit can be metered by an electronic voltmeter, or the plate circuit of the mixer can be metered by a milliammeter calibrated to indicate a 1-volt signal at the grid. A calibrated attenuator precedes the IF amplifier. This placement of the attenuator avoids saturation of any of the IF stages. Care must be used to prevent overloading of the mixer stage. A detector incorporating a metering circuit follows the IF amplifiers. The steps listed below describe a typical field-strength test.

1. Tune in the signal, and adjust the attenuator to provide a convenient deflection of meter M2. Record this attenuator setting, which will be referred to as A1.
2. Turn on the auxiliary oscillator, and set it to to the frequency of the incoming signal.
3. Adjust the output of the auxiliary oscillator such that a preselected amplitude of the signal, usually 1 volt, is indicated at the grid of the mixer.
4. Readjust the attenuator so as to make the deflection of meter M2 the same as that of step 1. Record this attenuator setting, which will be called A2.

NOTE

It would appear that the signal induced in the loop is (A2 - A1) dB below the oscillator voltage measured at the grid of the mixer. This is not quite the case, however, since there is a resonant rise of voltage in the loop. As a matter of fact, RF amplifying stages are sometimes placed between the loop and the mixer grid. It is convenient to refer to the ratio of the actual signal present at the grid of the mixer to the received loop signal voltage as the voltage transfer ratio. To make proper allowance for this ratio, the following steps should be performed.

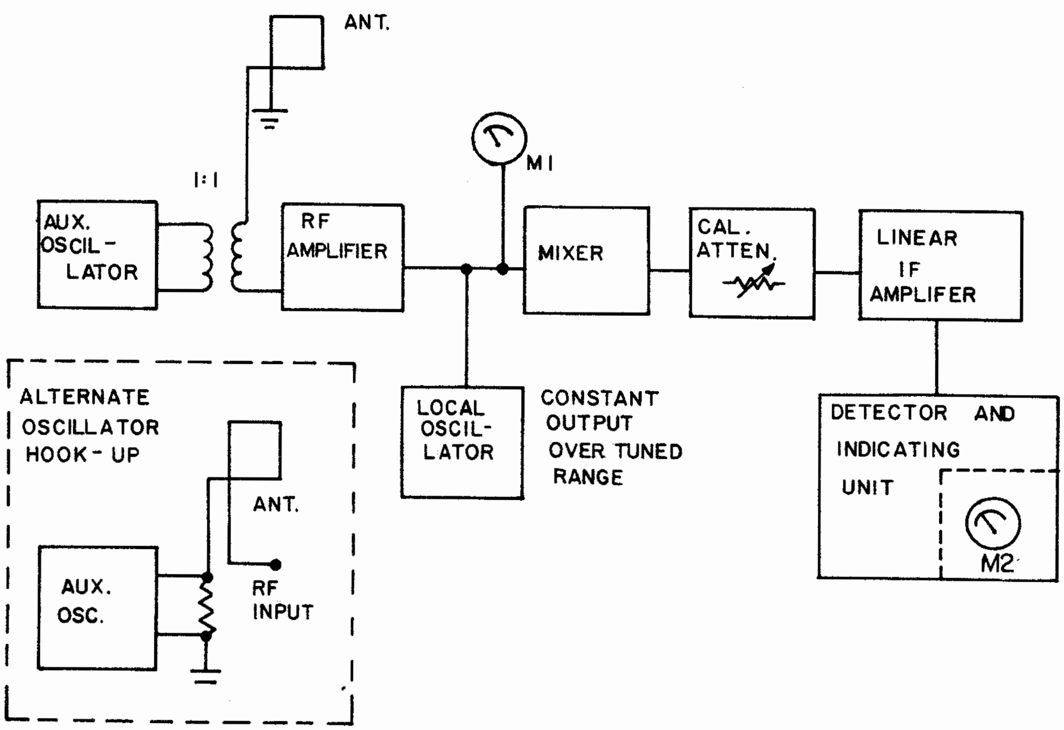


Figure 2-118. Standard Antenna Method for Measuring Field Strength

5. Remove the auxiliary oscillator from the coupling transformer, and connect it directly to the grid circuit. Do not change the output of the oscillator from the setting arrived at in step 3.
6. Readjust the attenuator setting so that meter M2 again shows the same deflection as that obtained in step 1. Call this attenuation A3.
7. Compute the quantity (2A2 - A1 - A3). The loop signal voltage is below the voltage measured in step 3 by this amount in dB.

2-16.3.2.2 Substitution Method

The substitution method of determining field intensity employs a standard signal generator and a sensitive receiver connected to a standard antenna, as shown in Figure 2-119. The receiver is tuned to the unknown signal frequency and the antenna is oriented for maximum response, as indicated on the microammeter connected in the circuit of the second detector. The receiver gain is adjusted for a convenient reading on the meter. The antenna is then turned for a null, where little or no signal is received. The signal generator is then turned on and set for the signal frequency, thereby inducing a voltage in series with the antenna (a loop, in the case illustrated) by means of a 1- or 2- ohm resistor. The output of the signal generator is then adjusted until the receiver meter indicates the same reading as previously obtained from the induced signal. The induced voltage is thus equal to the output voltage of the signal generator. This method of measurement has the disadvantage that the signal generator must be well shielded so that no stray radiation is picked up by either the antenna or the receiver. The substitution method is well adapted to long-wave measurements, and the accuracy of this method is comparable to the adjustable IF attenuator method.

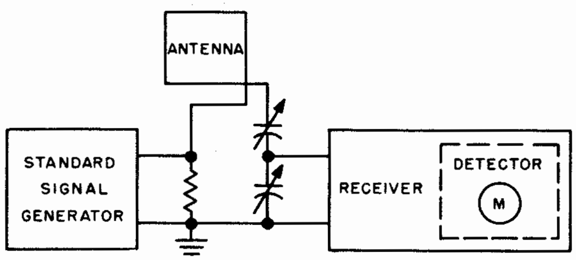


Figure 2-119. Substitution Method of Determining Field Strength

2-16.3.2.3 Standard Field Generator Method

This method of measurement is widely used for measurements at frequencies above 30 MHz. The standard field generator is a compact portable oscillator having a small loop (or other type) antenna provided with a thermocouple meter to measure the antenna current. The antenna must be of such a design that when a known quantity of current or power is transferred to the antenna, the intensity of the field can be calculated from the dimension and construction of the antenna. It is thereby possible to compare the standard field produced with the unknown field, and to calibrate the intermediate-frequency attenuator type of measuring equipment for the higher frequencies. Standard antennas and the formulas for calculating the free space values of field intensity (in the direction of maximum radiated field) of each are as follows:

Loop: $$E_o = \frac{120\pi^2 NAI_a}{d\lambda^2}$$

Short vertical antenna carrying uniform current:

$$E_o = \frac{60\pi hI_a}{d\lambda}$$

Half-wave dipole:

$$E_o = \frac{60I_a}{d} = \frac{7.02}{d}\sqrt{Pa}$$

Directional antenna:

$$E_o = \frac{5.48}{d}\sqrt{PaG}$$

In these equations,

- E_o = field strength (volts per meter) at distance d
- d = distance (in meters)
- λ = wavelength (in meters)
- h = height of antenna, assumed to be less than $\lambda/10$
- N = number of turns in loop
- A = area of loop, sq meters
- Pq = power radiated by antenna (in watts)
- Iq = current flowing in antenna (in amperes)
- G = gain of antenna over isotropic radiator

2-16.3.3 Relative Field Strength Measurements

There are many occasions when it is only necessary to measure relative field strength, such as when plotting an antenna radiation pattern or merely checking the operation of a transmitter. Relative field strength measuring equipments, consisting only of a simple tunable receiver or circuit, are available for this type of measurement. These equipments are calibrated in terms of relative voltages, relative power, or in decibels related to a particular reference level. The equipments are direct-reading, and require only proper tuning and antenna orientation for comparative readings.

2-16.3.3.1 Grid-Dip Meter Method

It is possible to use the grid-dip meter as a relative field-strength meter. For the grid-dip meter to perform the measurement mentioned above, the plate voltage must be turned off, and a loop antenna must be connected to the coil terminals of the instrument. The appropriate plug-in coil is inserted, and the meter tuned to the transmission. If the received signal is sufficiently strong, current will flow in the grid-cathode circuit. The relative magnitude of the field is indicated by the amount of meter deflection. Since the meter deflection may not be linear, the meter should be calibrated if accurate indications are required.

2-16.3.3.2 Simple Meter Application

Simple instruments intended specifically for the measurement of field intensity usually employ a crystal diode. A whip antenna is often used as the pickup antenna. To increase the sensitivity, it is advisable to employ a microammeter as the indicating device. Use of plug-in coils extends the instrument operation over a wide frequency range.

2-16.3.3.3 Advanced Meter Application

If a high degree of sensitivity is necessary, a more elaborate field-strength meter is required. One technique employs a specifically designed receiver having an attenuator calibrated in dB at the input of its first IF amplifier. The output of the mixing stage must be exactly proportional to the RF signal voltage present in the grid circuit, and this property must hold for input amplitudes up to at least 1 volt.

2-16.4 ANTENNA RADIATION PATTERN

The antenna radiation pattern (field strength pattern), when used in radio transmission, can be defined as the relative radiation the antenna produces in different directions. For reception, the pattern is the same, but represents the relative response of the antenna to radio waves arriving from different directions. The various radiation properties of an antenna apply both to transmitting and receiving applications, subject to certain qualifications when the path of the waves between the transmitting and receiving points involves propagation through the ionosphere. Thus, the more effective the antenna for transmitting, the more effective it will be for receiving. Also, the directive properties will be the same for transmission and reception and, in the case of directive antennas, the gain will be the same for both transmitted and received signals. For this reason, antennas are said to follow the theorem of reciprocity. Because of this reciprocity, the directional characteristics of an antenna can be determined either by radiating power from the antenna and measuring the field-strength distribution that results, or by measuring the voltage induced in the antenna as a portable transmitter is moved about it (or as the antenna is rotated with the transmitter stationary). (The former arrangement is usually considered the more convenient.) In performing these measurements, the distance between the transmitter and the receiver should be at least two to three wavelengths. This will reduce any error introduced from induction fields to a minimum. For the high frequencies, a complete pattern measurement requires the use of an aircraft. Measurements taken at the ground level have limited significance, since only the field-strength distribution in the horizontal plane of the vertically-polarized component of the ground wave may be measured; horizontally-polarized antennas at these frequencies radiate virtually no field strength along the earth's surface. The free-space field patterns for the most common types of antennas have been calculated and are readily available from many sources. These patterns can be of great assistance in making field intensity measurements, since a complete pattern plotted experimentally requires an enormous number of readings. Usually, it is only necessary to take readings where it is expected that a deviation from the free-space pattern will occur. The usual procedure for plotting the pattern is to show the radiation as a function of azimuth angle for different values of vertical angle, or vice versa. In the case of highly directional antennas, the most important characteristics are the shape and width of the main lobe, and the magnitudes and directions of the side lobes. The simple beam-width of a microwave parabolic antenna can be determined approximately by calculation. Because of the tremendous gain of a parabolic antenna at microwave frequencies, the information obtained from this calculation is all that is necessary for most applications.

2-17 BATTERY MEASUREMENTS

Electronic technicians are primarily concerned with the uses of batteries; however, checking or testing of storage and dry cell batteries is an important maintenance technique.

2-17.1 STORAGE BATTERIES

When checking lead-acid type storage batteries for their condition of charge or discharge, a specific gravity reading of the electrolyte is taken, using a hydrometer. A specific gravity reading between 1.275 and 1.300 indicates a full-charge condition, assuring that the battery is in good condition. A hydrometer reading of approximately 1.175 indicates a normal discharge condition, and a reading of approximately 1.250 indicates that the battery is approximately half-discharged. Since the acids used in various batteries do not always have the same specific gravity, and since electrode composition may differ, the hydrometer reading at the charged and discharged conditions will vary with the type of electrolyte and battery composition. A general rule to follow is not to discharge a battery more than 100 points (.100 specific gravity) before recharging. The readings of specific gravity given above are based on a sulfuric-acid electrolyte having a temperature of 26.7 degrees (C). For other temperatures, the readings obtained must be corrected by adding 1 point (.100) for every 4.5 degrees above 26.7 degrees (C), and by subtracting 1 point for every 4.5 degrees below 26.7 degrees (C). Although readings of specific gravity are a reliable measure of the condition of a storage battery, cells which indicate normal may prove useless under load. This is usually caused by a high internal resistance. A load-voltage check of the cells, using a cell tester, indicates the actual voltage charge held by each battery cell. Cell voltages should not differ by more than 0.15 volt for 6-volt or 12-volt batteries.

2-17.2 DRY BATTERIES

Dry-cell batteries used for test instruments and portable or field equipments must be checked periodically for loss of power. The actual voltages of dry batteries should be measured with a battery tester for a minimum acceptable voltage before installation. The TS-183/U series of Battery Testers incorporate multiple-range voltmeter, battery-loading resistors, multiplier resistors, and a jack-switching arrangement that connects the load resistors across the voltmeter for a total of 32 different voltmeter-load resistor combinations. This type of tester permits a rapid and accurate measurement of battery potentials under load conditions, ranging in voltage rating from 1.5 volts to 180 volts. A data chart supplied with the battery tester provides information regarding the jack to be used and the minimum acceptable voltages of various batteries used in Navy equipments. Table 2-6 shows general standards of tolerance for dry batteries.

TABLE 2-6. GENERAL VOLTAGE TOLERANCES FOR DRY BATTERIES

RATED VOLTAGE	MAX. VOLTAGE TOLERANCE
1 to 2	0.1
3 to 10	0.3
11 to 15	0.5
16 to 25	1.0
26 to 50	2.0
50 to 70	3.0
70 to 99	5.0
100 to 200	10.0

2-17.3 CARBON ZINC AND ALKALINE BATTERIES

Carbon zinc and alkaline cells are used primarily in portable test equipment, VOMs, flashlights, some portable radios and beacon equipment. The carbon zinc cell provides 1.5 volts and holds its charge for approximately one year in normal service. The alkaline cell provides 1.2 volts and has about twice the stored energy of the carbon zinc cell of the same size. It also has a longer life at a higher discharge rate than the carbon zinc cell. Both types of batteries should be discarded at the first indication of their becoming weak.

2-17.4 MERCURY CELLS

The storage life of a mercury cell varies but is generally classified as being long. The cell's working life is extremely long relative to other types of batteries, and it maintains its full rated voltage (1.34 volts) until just before it is ready to expire, at which point its voltage will drop off sharply. Recharging of mercury cells is possible, but is not recommended because the recharging cycle can vary from one cell to another, and after being recharged their operating lifetime is uncertain.

2-17.5 NICKEL CADMIUM BATTERIES (NICAD)

Nickel cadmium batteries have very high efficiency. They can be recharged hundreds of times, and given the proper conditions may even be recharged thousands of times. They can be stored for a number of years with no significant loss of performance. After just a few charge and discharge cycles, NICAD cells can be brought back to the point where they are just as good as a new battery. Since they are sealed, they are maintenance-free and can be installed in any position. There are two types of nickel cadmium batteries; vented and nonvented. This description deals with the nonvented exclusively because a vented NICAD would have extremely limited application in a shipboard environment. The voltage at the terminals of a NICAD will normally be between 1.25 and 1.30 volts in an open-circuit condition. This value will vary, of course, depending on the state of charge. If the charge has dropped to a low of 1.1 volts, the NICAD should be regarded as being completely discharged and should not be permitted to be discharged further. The majority of small NICADs are rated in milliampere hours, and the large ones are rated in ampere hours. The small NICAD is the one the technician will almost always be concerned with. As a general rule, if the NICAD's charging current is held to 10 percent of its milliampere-hour rating and the time of charge is held at one hundred fifty percent of the time required to establish its full milliampere hour rating, the technician will encounter no difficulty in maintaining NICADs at their maximum charge. For example, a battery rated at 300 milliampere hours should be charged for 15 hours at 30 milliamperes. The battery can be left on extended charge for years provided the charge rate is lowered to less than 10 percent of the NICAD's milliampere rating. The technician should never place a NICAD in a pocket because metal objects (such as keys) can short the cell and cause extreme heat. Never dispose of a NICAD by fire, because they can explode. Never solder a connection directly to the cell because the heat of an iron can damage it. Never overcharge a NICAD cell because an accumulation of gases within its case can destroy it.

2-18 RF ATTENUATOR MEASUREMENTS

All RF attenuators are stamped at the factory as to their frequency range and attenuation factor, and are not to be tampered with in the field. Measurements and/or adjustments are accomplished only by a fleet calibration facility. However, to determine if a RF attenuator is defective, a comparison measurement against an attenuator of known good quality can be made. This is done by applying the output of a signal generator that covers the frequency range of the test attenuator to the input side of the good attenuator, which must be the same frequency as the suspect attenuator. The output side of the good attenuator is applied to a power meter. With a reference value set on the signal generator, record the measured value on the power meter. A test on several frequencies throughout the range of the good attenuator is required. Remove the good attenuator and insert the suspect attenuator in its place. Repeat the test procedure, noting any differences. For a test reference, the outputs should be the same for both attenuators.

2-19 MAGNETIC MEASUREMENTS

For measuring flux density, some fluxmeters use a meter movement with no permanent magnet. The meter movement is placed between the poles of the magnet being tested. The magnetic field strength of the magnet determines the amount of current flow through the meter required for full scale deflection. The current flow is read on a separate, conventional meter whose scale is calibrated in gausses. Other types of fluxmeters use a search coil which is removed from a magnetic field, thereby cutting the lines of force of the field and inducing a current in the search coil. The current is proportional to the number of lines cut and to the number of turns in the search coil. The current is read on a meter whose scale is calibrated in maxwells or gausses. A fluxmeter should always be set to its maximum range before testing a magnet to prevent the meter pointer from going off scale. The meter cabinet should be placed as far from the magnet as the probe cable or the search coil cable will allow, as proximity to powerful magnets may introduce serious errors in the readings. When the gauss meter with a probe-meter type of fluxmeter is used, the probe-meter may be inadvertently placed in a magnetic field so that the meter pointer moves in the wrong direction. A reversing switch is used to reverse the meter so the pointer reads on scale. When the type of flux meter with a search coil is used, this procedure is normally not necessary, as the meter pointer can move in either direction from the zero center.

2-19.1 TS-15C/AP FLUXMETER

Only essential operational features of the TS-15C/AP are given here. The power switch must first be turned off as a precaution against damaging the meter. Attach the probe-meter to the applicable adapter, and mount it between the pole faces of the magnet under test. The probe-meter must be centered, and the face of the meter must be horizontal. If the magnet gap is too large for the adapters provided, use the probe-meter handle. Then insert the probe-meter cable plug into the jack on the front panel of the fluxmeter, and place the fluxmeter cabinet as far from the magnet as the probe cable will permit. Set the measure control to its maximum counterclockwise position, and set the range switch to the maximum range position. Turn on the power switch, and rotate the measure control slowly clockwise while watching the probe-meter. If the probe-meter pointer deflects backward, turn off the power switch and place the normal-reverse switch in its other position. Turn on the power again, and advance the measure control until the probe-meter pointer is aligned with the red mark on its scale, or until the gauss-meter pointer reaches full-scale deflection. If the latter occurs first, turn off the power switch and set the range switch to the next lower range, and then turn the power on again. When the probe-meter pointer is accurately set to the red mark on its scale, the flux density can be read directly in hundreds of gausses on the appropriate gauss-meter scale. When all measurements have been made, turn the power switch off to prevent discharging of the battery. Figure 2-120 shows a typical probe-meter.

2-19.1.1 Magnetic Flux Density Adapters

Magnetic flux density adapters support the probe-meter of a fluxmeter in the position of maximum magnetic flux density between the two poles of the magnet being tested. The magnetic flux density

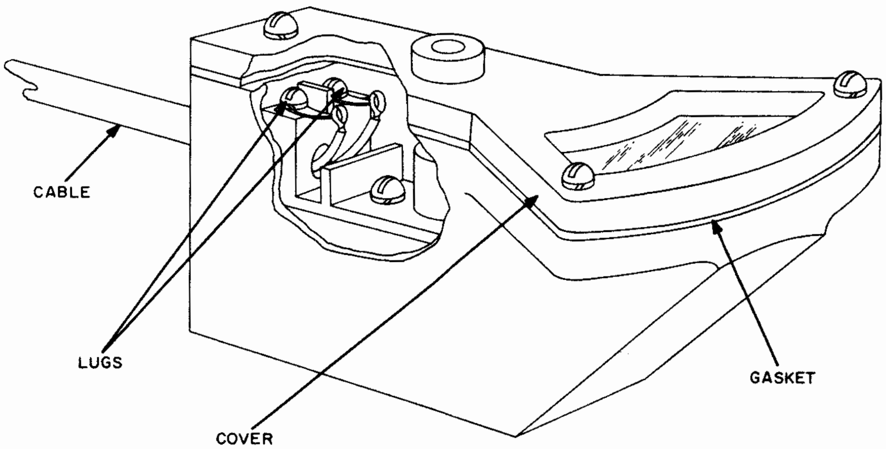


Figure 2-120. Probe Meter

adapter is attached to the probe-meter by a bolt. The probe-meter is then positioned in the magnet gap by clipping the adapter springs around the magnet poles, as shown in Figure 2-121 or by turning the screws on the ends of the adapter until a tight fit is obtained between the magnet poles.

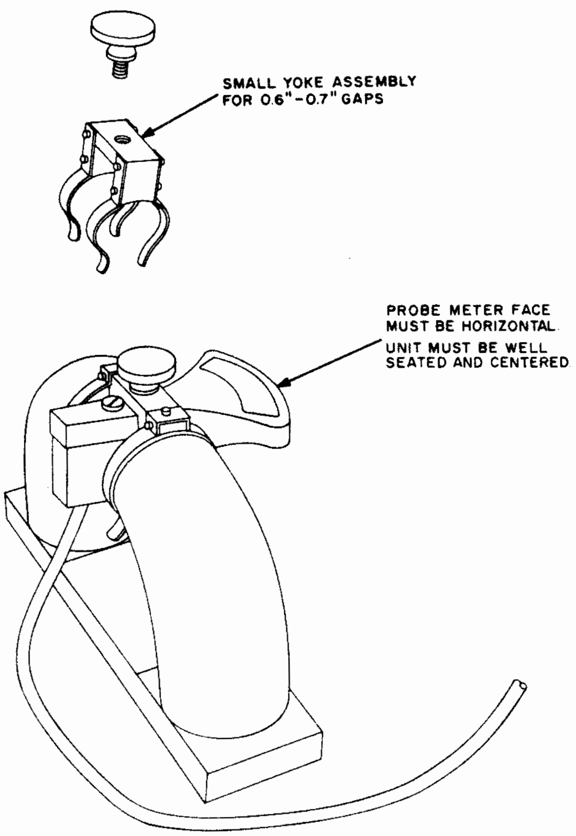


Figure 2-121. Magnetic Flux Density Adapter in Use

2-19.2 SENSITIVE RESEARCH MODEL FM FLUXMETER OPERATION

A complete description of the FM fluxmeter is not given; only essential operational steps are described here. Remove the protective wire shunt across the fluxmeter's terminal posts, and set the pointer on zero by using the left and right zero-return buttons. Connect the search-coil leads to the terminal posts, and set the range switch to its maximum range position. Place the search-coil around the magnet, in the neutral plane of the magnetic field to be measured, as shown in Figure 2-122. Place the fluxmeter as far from the magnet being tested as the search-coil leads will allow, since strong magnetic fields will affect the accuracy of the meter readings. Place the fluxmeter in the horizontal position, as deviations of more than 5 degrees from the horizontal may affect the accuracy. Now reset the fluxmeter pointer exactly to zero. Move the search-coil to a position out of the field of the magnet. As it is moved, the search-coil will cut all the external flux lines of the magnet. Note the reading on the fluxmeter; if it is small, set the range switch to a lower range. Substitute the meter reading in the following formulas to obtain the value of flux, expressed in maxwells, or the value of the flux density, expressed in gausses:

$$\text{maxwells} = \frac{KDR}{T}$$

where:

K = 10,000 maxwells per division
D = meter reading
R = SCALE MULTIPLIER range
T = 10 (number of turns in search coil)
A = 15 (mean area in sq cm of search coil

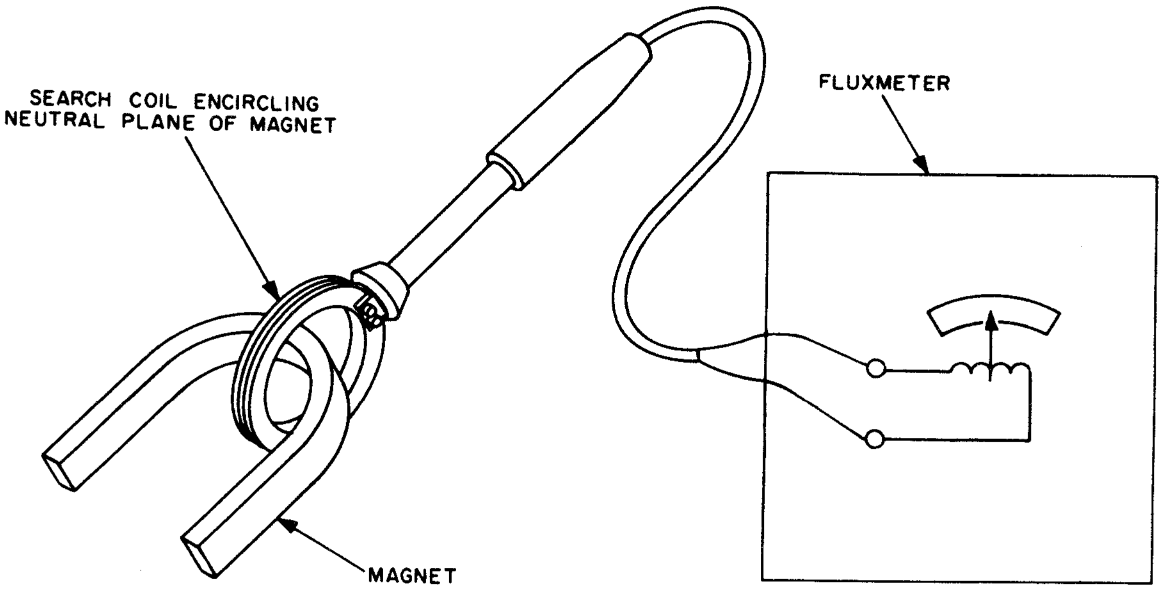


Figure 2-122. Search-Coil in Neutral Plane of Magnet

When all measurements are completed, replace the protective wire shunt across the terminal posts. Figure 2-123 illustrates a fluxmeter.

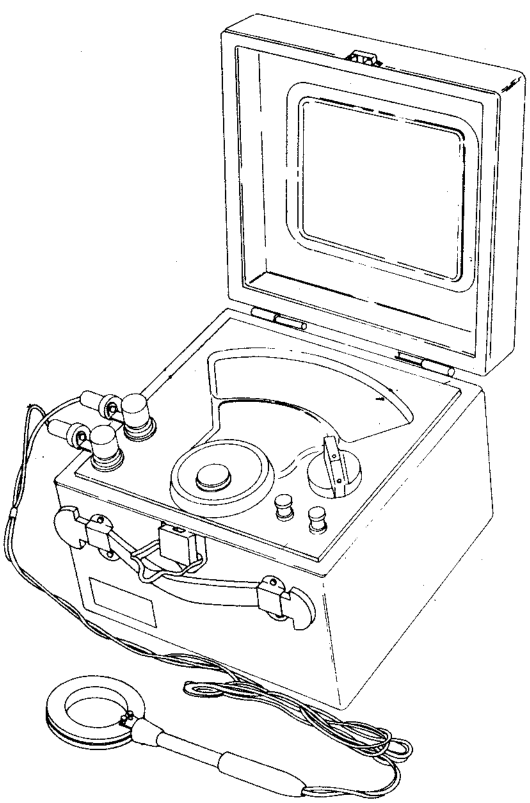


Figure 2-123. Fluxmeter Model FM

2-19.3 HALL-EFFECT METHOD

Another means of measuring magnetic flux density is by use of a Hall-effect device. The operating principle is that a current-carrying semiconductor device has a magnetic field applied across it perpendicular to the flow of current. A voltage, V_H, will be developed perpendicular to both current and magnetic field, as illustrated in Figure 2-124. This voltage can either be applied to a meter calibrated to read gausses directly, or may be determined from the formula:

$$B = \frac{V_H}{I_C}$$

where:

V_H = Hall-effect voltage

and:

I_C = applied current

2-20 VIBRATION

Vibration and vibration testing are two subjects that confront the average technician very rarely in his work experience. This paragraph only briefly describes vibration and its effects. The technician is referred to MIL-STD-202 and MIL-STD-810 for detailed information on this subject. Vibration can cause discomfort and, if severe enough, may even result in death to humans. The following tables (Tables 2-7, 2-8, and

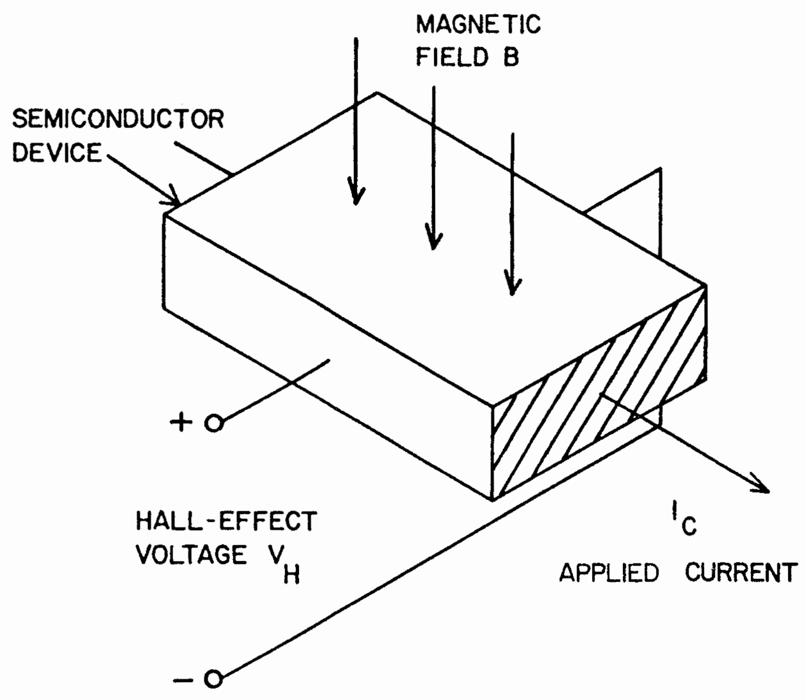


Figure 2-124. Hall-Effect Device

2-9) show some examples of vibration frequency and acceleration effects upon humans.

TABLE 2-7. EFFECTS OF AUTOMOBILE VIBRATION INTENSITY ON A SEATED SUBJECT WEARING A SEAT BELT (FREQUENCIES LESS THAN 100 HZ)

Intensity of Vibration	Effect on Humans
.005 - .10 g	Perceptible
.05 - .5 g	Unpleasant
.6 - 1 g	Very annoying
1 - 2 g's	Tolerable but alarming
3 - 4 g's	Injurious if prolonged

Discomfort occurs at different frequency ranges and in different parts of the body.

2-21 INTERMODULATION DISTORTION MEASUREMENTS

Intermodulation distortion occurs when two or more frequencies become mixed across a nonlinear device. The resultants are the difference frequencies and the sum frequencies, both being components of the originals. Undesirable frequencies can be generated by a mixing of a fundamental frequency with its harmonic(s), or by the mixing of two discrete frequencies. Spurious radiation, arising from close proximity of transmitter and receiver, is a prime source of an undesirable frequency that can cause intermodulation distortion in an electronic circuit. This is particularly the case when antenna couplers are employed. Cross-modulation and parasitic generation are two other sources of undesirable frequencies that may cause intermodulation distortion.

TABLE 2-8. TYPICAL REACTIONS TO VIBRATIONS

Nature of Discomfort	Frequency (Hz)
Respiration difficulty	3 - 8
Abdominal contractions or pain	4 - 12
Muscular contractions and tightness	4 - 20
Chest pains	5 - 9
Lumbo-sacral pain	5 - 12
Speech difficulty	5+
Jaw and throat discomfort	6 - 16
Urge to defecate or urinate	10 - 18

TABLE 2-9. TYPICAL VIBRATIONS OF VEHICLES

Vehicle	Range of Frequencies Hz	Nature of Excitation
Ships	0 - 15	Engine vibrations (diesel or steam)
	0 - 33	Propeller vibrations
Piston-engine aircraft	0 - 60	Engine vibrations
	0 - 100	Propeller vibrations and vibrations due to buffeting and turbulence
Turboprop aircraft	0 - 60	Same as piston aircraft
	0 - 100	Same as piston aircraft
Jet Aircraft	Less than 500	Audible noise frequencies due to jet wake and combustion turbulence; very little engine vibration

2-21.1 CROSS-MODULATION AND PARASITIC GENERATION

Cross-modulation occurs when a signal from adjacent channels crosses over into a second channel and modulates that second channel's frequency. Parasitic generation occurs when regenerative feedback is sufficient to cause a circuit to oscillate, even though it is not designed to oscillate.

2-21.2 INTERMODULATION DISTORTION DETECTION

To determine if intermodulation distortion is present, a two-tone test method is employed. Two sinusoidal frequencies of equal amplitude are introduced into the system under test. The two frequencies are spaced close together with reference to the unit under test. The output of the system under test (an amplifier, receiver or transmitter) is monitored on a spectrum analyzer that is comparable to the characteristics of the suspect system. The resultant display should be an exact reproduction of the input frequencies. If not, some form of intermodulation distortion is present. To determine if external sources are causing the intermodulation distortion, a single frequency signal can be used. If the display on the spectrum analyzer does not show the single frequency, then intermodulation distortion is present. Intermodulation distortion cannot be entirely suppressed, but it can be minimized by shielding components and circuitry, parasitic suppression circuitry, and antenna spacing. These factors are incorporated in the design of the system, and are tested during production. Any shields or parasitic suppressors that are removed by the technician must be replaced before troubleshooting and/or repair can be effective. Antenna locations only pose a consideration when installing a new system. Ship Alt specifications must be observed when new antenna systems are being installed.

2-22 TUNED CIRCUIT ALIGNMENT

Tuned-amplifier, oscillator, detector, and filter circuits must be properly adjusted for optimum performance of communication and electronic equipment. The signal generator, in conjunction with various indicating devices, is used in most alignment procedures for radio receiving equipment. Transmitter oscillators can be tuned to the correct frequency by frequency-measuring instruments, and transmitter amplifier stages can be adjusted by means of output meters or grid and plate current measurements. However, it is sometimes advantageous to tune transmitter amplifier stages by injecting a known signal from a signal generator in the same manner that receiver amplifier stages are tuned. The type of test equipment necessary for a particular tuning procedure is determined by frequency, power level, accuracy, allowable distortion, and modulation requirements. The principal purpose of a signal generator is to provide a known signal with adjustable characteristics. An amplitude-modulation signal for alignment purposes can be generated either internally or externally on most signal generators. The modulating component can be a square wave, a sine wave, or a pulsed signal of variable frequency and amplitude. A frequency modulation function is also incorporated on some signal generators. Audio-frequency signal generators are used for adjusting audio filters, audio amplifiers and multiplexing equipments. An AF signal generator is required in troubleshooting and aligning communication equipment, certain navigational aids, and radar and electronic countermeasures equipment.

2-22.1 TYPES OF CIRCUITS REQUIRING ADJUSTMENT

Circuits usually requiring some adjustment during their alignment include sweep generators, tuned oscillators, RF and IF amplifier stages, and stagger-tuned IF amplifier stages, where incorporated. The need for alignment may be indicated by reduced signal levels, or reduced or distorted signal outputs. However, alignment procedures must not be used before general operating tests have been made. Although every equipment that is operating poorly requires maintenance, it does not follow that every such equipment also needs alignment. Repairs requiring replacement of parts or the redressing of wiring may make subsequent alignment necessary. Therefore, do not attempt alignment until all apparent troubles have been corrected and all defective parts replaced, so that time and effort will not be wasted on ineffective alignment beforehand. Furthermore, haphazard attempts at alignment by inexperienced or careless personnel may do more harm than good, and may increase the time required for making otherwise relatively minor repairs. It cannot be stressed too highly that before any alignment is attempted, all available instructions should be carefully consulted and observed by the technician.

2-23 SYSTEMS TESTING AND MONITORING

Combinations of electronic equipment and facilities are interconnected to form systems capable of performing specific functions. To meet reliability requirements and to comply with operating restrictions, technical personnel must be able to apply general test methods and practices to the installation, tuning and maintenance of these combinations of equipment and facilities. This may entail a knowledge of many types of electronic equipment. Radar, communication, and digital computers when interconnected, may require different maintenance procedures than when operated separately. Revised test procedures may be necessary; any detrimental interactions between equipment or facilities must be corrected; and effective preventive maintenance must be programmed for all equipment and facilities within the system. System quality figures, such as sensitivity and coverage, must be initially determined and measured during equipment preventive maintenance checks to assure efficient operation. System monitoring at specific test points is often used to help localize trouble.

2-23.1 SYSTEM TESTING AND MONITORING METHODS

System testing and monitoring is frequently accomplished by employing an external item of electronic equipment which is designed specifically for testing of a particular system. Some computers and computer systems may incorporate their own monitoring and testing devices, and will inform the operator when and where failure has or may occur. A number of systems have self-repair capabilities built into them, but, generally speaking, these systems are highly limited as to such self-repair capability. The technician must realize that any equipment designed to test, monitor, or repair another system is itself subject to malfunction, consequently will require periodic checks and preventive maintenance. For a more detailed explanation of System Test and Monitoring, the technician is referred to Section 6 of this manual.

2-24 ATTENUATION AND INSERTION LOSS MEASUREMENTS OF TRANSMISSION LINES

Transmission lines utilized on board Navy vessels are subjected to many extremes of weather and to the corrosive effects of salt water. The technician should be aware of the adverse effects this environment causes to transmission lines, and how to determine electrical losses caused by transmission line deterioration.

2-24.1 LOSS MEASUREMENT

Insertion loss measurement to transmission lines requires the use of a good signal generator and an accurate power meter. The method is identical to the insertion loss measurements used on most couplers. When a known frequency, at a predetermined level of power, is inserted into one end of a transmission line, then ideally the same frequency and at the same level of power will be transmitted to the other end of the transmission line. Because all transmission lines contain some degree of resistance, some loss of power will occur during the test. Exposure to the elements over a period of time also causes transmission line deterioration.

2-24.2 OUTPUT MEASUREMENT

The technician must measure the output power of the signal generator at the end of the test cable to be attached to the transmission line. The signal generator must first be checked over the entire range of frequencies that will involve the transmission line tests. When the signal generator is assured, connect the same power meter to one end of the transmission line and the signal generator to the other end. The technician must then scan the transmission line's entire frequency range, watching closely for any excessive losses in power.

2-24.3 TRANSMISSION LINE FORMULAS

1. Coaxial line.

A cross-section of a coaxial line is shown in Figure 2-125. The characteristic impedance of a coaxial line can be determined by the formula:

$$Zo = \frac{138}{\sqrt{K}} \log \frac{D}{d}$$

where:

"D" is the inside diameter of the outer conductor.

"d" is the outside diameter of the inner conductor, and must be expressed in the same units as D.

"K" is the dielectric constant of the insulating material. (Air = 1). (See Table 2-10).

"Zo" is the characteristic impedance.

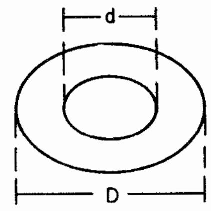


Figure 2-125. Coaxial Line

TABLE 2-10. DIELECTRIC CONSTANTS OF MATERIALS

Material	Dielectric Constant (Approx.)	Material	Dielectric Constant (Approx.)
Air	1.0	Lucite	2.5
Amber	2.6-2.7	Mica (electrical)	4.0-9.0
Asbestos Fiber	3.1-4.8	Mica (clear India)	7.5
Bakelite (asbestos base)	5.0-22	Mica (filled phenolic)	4.2-5.2
Bakelite (mica filled)	4.5-4.8	Micaglass (titanium dioxide)	9.0-9.3
Berium Titanate	100-1250	Micarta	3.2-5.5
Beeswax	2.4-2.8	Mycalex	7.3-9.3
Cambric (varnished)	4.0	Neoprene	4.0-6.7
Carbon Tetrachloride	2.17	Nylon	3.4-22.4
Celluloid	4.0	Paper (dry)	1.5-3.0
Cellulose Acetate	2.9-4.5	Paper (paraffin coated)	2.5-4.0
Durite	4.7-5.1	Paraffin (solid)	2.0-3.0
Ebonite	2.7	Plexiglas	2.6-3.5
Epoxy Resin	3.4-3.7	Polycarbonate	2.9-3.2
Ethyl Alcohol (absolute)	6.5-25	Polyethylene	2.5
Fiber	5.0	Polyimide	3.4-3.5
Formica	3.6-6.0	Polystyrene	2.4-3.0
Glass (electrical)	3.8-14.5	Porcelain (dry process)	5.0-6.5
Glass (photographic)	7.5	Porcelain (wet process)	5.8-6.5
Glass (Pyrex)	4.6-5.0	Quartz	5.0
Glass (window)	7.6	Quartz (fused)	3.78
Gutta Percha	2.4-2.6	Rubber (hard)	2.0-4.0
Isolantite	6.1	Ruby Mica	5.4
Selenium (amorphous)	6.0	Styrofoam	1.03
Shellac (natural)	2.9-3.9	Teflon	2.1
Silicone (glass) (molding)	3.2-4.7	Titanium Dioxide	100
Silicone (glass) (laminate)	3.7-4.3	Vaseline	2.16
Slate	7.0	Vinylite	2.7-7.5
Soil (dry)	2.4-2.9	Water (distilled)	34-78
Steatite (ceramic)	5.2-6.3	Waxes, mineral	2.2-2.3
Steatite (low loss)	4.4	Wood (dry)	1.4-2.9

2-24.3.1 Attenuation Measurements

Attenuation in a coaxial line in terms of decibels per foot can be determined by the formula:

$$a = \frac{4.6 \sqrt{f}\ (D + d)}{D \times d\ (\log \frac{D}{d})}$$

where:

"D" is the inside diameter of the outer conductor (in inches).
"d" is the outside diameter of the inner conductor (in inches).
"f" is the frequency (in megahertz).
"a" is the attenuation (in decibels - per foot line).

2-24.4 ATTENUATION IN WAVEGUIDES

Refer to Section 5 for attenuation and loss measurements in waveguides.

2-25 RECEIVER NOISE MEASUREMENTS

Theoretically, it is possible to amplify a feeble electrical signal by practically any desired factor; however, it is still not possible practically to discern an arbitrarily weak signal because of the presence of random electrical fluctuations, or "noise". If the intelligence signal entering the receiver becomes progressively weaker, it subsides eventually into the fluctuating background of noise and is lost. The limit of sensitivity for low-frequency receivers, as for all receivers, is set by random electrical disturbances. However, in this case, the largest random disturbances with which the signal must compete generally originate, not in the receiver itself, but elsewhere in space. Whatever the external noise source, whether from an electrical apparatus or from interstellar space, these disturbances enter the receiver by way of the antenna. The crucial quantity, therefore, is the ratio of the field strength of the signal in the neighborhood of the antenna to that of the extrinsic noise or interference. The absolute magnitude of signal and interference power available at the antenna terminals are of little importance; only their ratio, which, for example, might be favorably altered by the use of a directional antenna pattern, determines the ultimate performance. More significantly, it explains why the emphasis for low-frequency receivers involves discrimination against some of the external noise (for example, by greater frequency selectivity) rather than by reduction of the noise inherent in the receiver. In the microwave region, substantially all of the noise originates in the receiver, not because microwave receivers are noisier or more imperfect receivers than low-frequency receivers, but because environmental low-frequency noise is enormously greater than high-frequency noise. In fact, such noise in the microwave region is almost wholly negligible; it is the noise that originates in the receiver that interferes with the signal. The inherent noise generated in a receiver (or receiver section of more complex equipment) establishes the minimum limit of signal that a receiver can usefully amplify. Therefore, maximum receiver sensitivity, in most cases, is not determined by the gain of the particular receiver, but by the magnitude of the input circuit noise. The noise is a result of the random motion of the electrons in the antenna and receiver circuits (thermal agitation, resistance noise and/or semiconductor noise) and tubes (tube or shot noise). Thermal, tube and semiconductor noises are considered collectively as receiver noise. Receiver noise exists across the entire radio-frequency spectrum, and its magnitude increases with an increase in temperature. Because the noise is across the spectrum, the noise level increases also with an increase in pass band. In normal operating circuits, only the self-generated noise in the initial amplifier stages is significant, since these stages are subject to maximum amplification. This is true for AM, FM, television, SSB, radar, etc.; although for systems employing FM methods of detection, the noise assumes a lesser degree of importance because receiver noise, along with atmospheric and man-made noise arriving at the antenna, amplitude-modulate the incoming signal. The noise is thus removed in the detection process. Since receiver noise determines the weakest signal that can be practically detected, its behavior and measurement is of fundamental importance for equipment which may be used to receive very low-intensity signals.

2-25.1 NOISE FIGURE

An ideal receiver would be one with no noise other than that caused by thermal agitation. The degree to which a receiver approaches this ideal is indicated by the noise figure of the receiver and may be defined as:

$$\text{Noise figure} = \frac{\text{Signal-to-noise power ratio of ideal receiver}}{\text{Actual signal-to-noise power ratio of receiver output}}$$

For simple test methods, it may be expressed as the ratio of noise power at the input of the receiver required to double the noise output of the receiver; since it is a power ratio, it is usually expressed in dB. Noise figures of 2 to 4 dB are obtainable for very quiet receivers, but ratios of 6 to 12 dB are more typical. This measurement is used primarily for RF receivers, but it can also be applied to devices such as microphones, electromechanical equipment, and photoelectric equipment.

2-25.2 NOISE SOURCE MEASUREMENT METHOD

A noise source for use in measurement is designed to produce a random noise signal which covers a frequency range in excess of the receiver bandwidth. One such instrument uses what is called a temperature-limited diode, operated at temperature saturation, as the noise-signal source. When a diode is operated under these conditions, the noise produced is proportional to the dc input current. Other types of generators employ thermal noise at elevated temperatures, or use certain types of gas discharges. However, most noise sources up to microwave frequencies are based on the shot noise generated by a temperature-limited diode. Regardless of the type used, the dc input reading of the generator can easily be converted to obtain the true noise power. The noise source method of determining the noise figure has the advantage that no knowledge of either the gain or the response characteristics of the amplifier is necessary, since the amount of noise from the noise source is amplified and governed by the effective bandwidth in exactly the same manner as are the thermal and tube noise of the receiver. The noise source method of measurement consists of comparing the noise actually present in the receiver with the calibrated output of the noise source. The noise source is connected to the input of the device under test. The IF output of this device is connected to a noise figure meter which gates the noise source on and off. When the noise source is "on", the noise level is that of the device plus the noise source. When the noise source is "off", the noise level is only that of the device and its termination. The noise figure meter automatically compares the two conditions and displays a noise figure on the indicator directly in dB. Power to operate the noise source is supplied by the noise figure meter. Figure 2-126 is a block diagram for a noise figure test using the above procedure.

2-25.3 FM RECEIVER CONSIDERATIONS

The use of a filter is essential in measuring the noise characteristics of an FM receiver. This necessity arises because the signal-to-noise ratio is improved by a large frequency deviation. Consequently, an FM signal suitably modulated at 400 hertz is applied to the receiver, and the output of the receiver is passed through a 400 hertz rejection filter in order to determine the noise output. The reading obtained in the absence of filtering will usually suffice as the measurement of the useful signal. Express the noise characteristic as the ratio of signal voltage (or power) to noise voltage (or power) in dB's.

2-25.4 RADAR RECEIVER CONSIDERATIONS

In the microwave frequency range in which radar operates, virtually all noise originates in the receiver. The main sources of such noise are the crystal mixer, the preamplifiers, and the local oscillator. Since atmospheric and man-made noise are negligible at microwave frequencies, it is imperative that every effort be made to eliminate receiver noise. The noise source method is therefore primarily used in the microwave range of the frequency spectrum, although the procedure can be used successfully throughout the frequency spectrum.

2-26 RECEIVER GAIN MEASUREMENTS

When troubleshooting an insensitive receiver, it is often necessary to measure the voltage (gain) at the output of an amplifier stage or section as compared to its input. Voltage gain is expressed as the ratio of voltage input to voltage output:

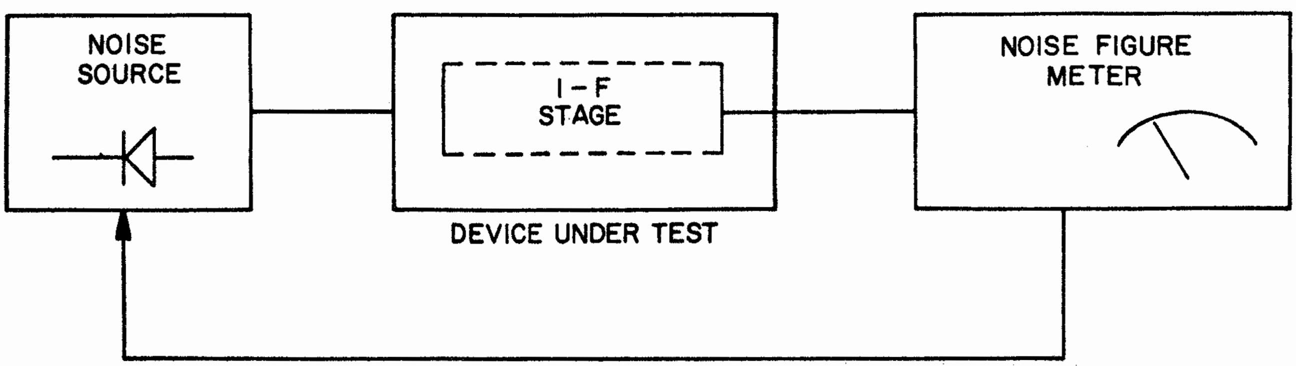


Figure 2-126. Noise Figure Measurement

$$V_G = V_{IN}/V_{OUT}$$

When making gain measurements, it is important that the normal operation of the stage not be disturbed by the test equipment.

2-26.1 VOLTAGE GAIN MEASUREMENT PROCEDURE

To measure the voltage gain of an amplifier, inject a signal into the input of the amplifier, using a signal generator that covers the frequency of the amplifier to be tested. Connect a high-impedance measuring device, such as a VTVM, oscilloscope or spectrum analyzer, to the output of the amplifier. The input signal voltage from the signal generator is then compared to the output signal voltage of the amplifier. The voltage gain is determined from the formula for voltage gain. Note that the VTVM, oscilloscope and spectrum analyzer are all frequency-sensitive devices, and each must be able to cover the frequencies to be measured. Figure 2-127 illustrates a test set-up for measuring the voltage gain of an AM superheterodyne receiver and some typical gains realized.

2-27 MINIMUM DISCERNIBLE SIGNAL MEASUREMENTS

Continuous-wave generator methods of measuring sensitivity do not provide an accurate indication of the ability of a receiver which is designed for the reception of pulse-modulated signals to receive weak pulse transmissions. A better method of determining the sensitivity of a pulse-modulation receiver is by performing a minimum-discernible-signal measurement. Minimum discernible signal (mds) measurements are

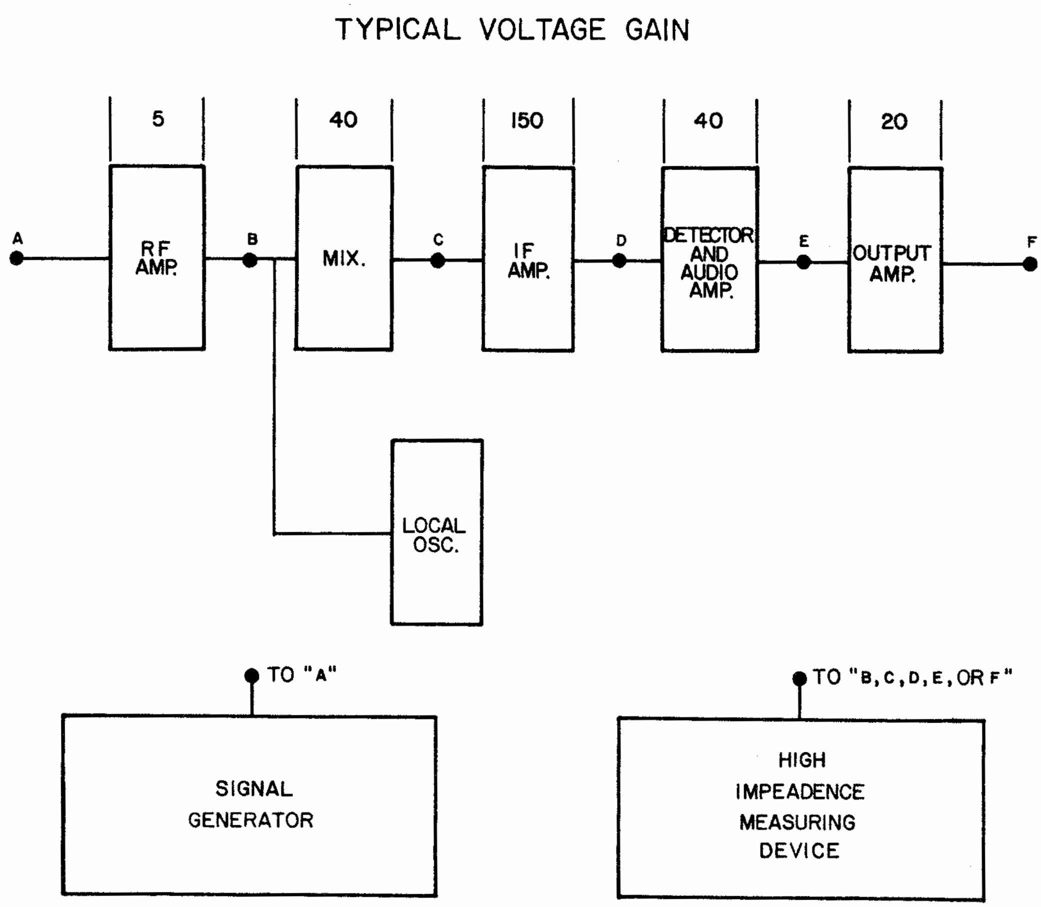


Figure 2-127. Superheterodyne Receiver Stage Gain

generally confined to pulse-type receivers; they provide an indication of receiver sensitivity. The mds measurement actually denotes the weakest signal that will produce a visible, or, in the case of transponders, a usable pulse output. Because the maximum possible sensitivity is dependent upon the amount of receiver noise, a minimum discernible signal measurement will preclude the necessity for making a noise figure measurement. Figure 2-128 shows the block diagram of the mds test. The sig-

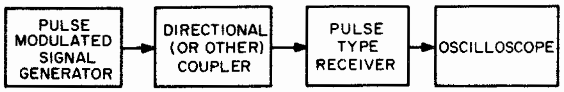


Figure 2-128. Minimum Discernible Signal Measurement

nal output of a calibrated, pulse-modulated signal generator is applied to the input coupler of the receiver under test. The signal generator pulse width and pulse repetition rate are adjusted to a suitable value for the receiver under test. Then connect the scope component of the equipment, if included, to the receiver output, and adjust the receiver gain control for a receiver noise level just below saturation. The power output of the pulse-modulated signal generator is then set for a power output of 1 milliwatt, or any other reference (such as the older standard of 6 milliwatts). The pulse-modulated signal generator attenuation is then increased until the pulse displayed on the indicator is at the point of disappearing. The attenuation resulting from the connecting cables and coupler is added to the attenuator dial reading, and this figure, after conversion to power, is employed in the following formula as P_2 to determine the mds power:

$$P_{mds}\,(dB) = 10 \text{Log} \frac{P_2}{P_1}$$

where:

Pmds = minimum discernible signal power
P_1 = pulse-modulated signal generator reference power

P_2 = total power attenuation

In certain types of equipment such as transponders, the received signal is amplified and employed to key a transmitter (usually an integral part of the equipment). For this equipment it is sometimes convenient to measure the mds during normal operation by feeding in, from a pulse-modulated signal generator, a pulse of a power magnitude just sufficient to cause consistent operation of the transmitter. This value is then used during preventive and corrective maintenance to determine whether the equipment is operating properly. Because of the relatively wide bandwidths associated with pulse-modulation receivers, a still better performance indication can be obtained by determining quantitatively how much noise is inherent in the receiver, since noise is the limiting factor in the determination of maximum sensitivity. This method of checking sensitivity utilizes a noise generator, as the most desirable test equipment, for a signal source. The noise in the receiver is related to a calculable noise figure. The technician is referred to Paragraph 2-25 for a detailed explanation of receiver noise measurements.

2-28 FREQUENCY SPECTRUM MEASUREMENTS

When a Radio Frequency carrier is modulated, the resultant waveform incorporates the sideband components, both above and below the carrier frequency. In single sideband (SSB) transmission, only the resultant sideband is generated. These frequency-generated components are collectively called the frequency spectrum of the generated wave. The measuring instrument for displaying this spectrum is called a spectrum analyzer. Basically, the spectrum analyzer plots the frequency's amplitude against the frequency. The spectrum analyzer resolves the radio frequency signal into its frequency components and displays the result on the screen of a cathode-ray tube. Spectrum analyzers can display a frequency spectrum of from ϕ Hz to ≈ 4ϕGHz, depending on the range and speed of the sweep frequencies. Section 4 provides a more detailed explanation of spectrum analysis and test methods.